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ON THE ELECTRIC CURRENT SYSTEMS IN THE EARTH'S ENVIRONMENT SOME HISTORICAL ASPECTS PART I. : EXTERNAL PART / IONOSPHERE / QUIET VARIATION

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ABSTRACT

In this paper we present some historical aspects of ionospheric electric currents. Our attention is focused on the regular part of these currents at the origin of the Earth's magnetic field daily variation S_R.
The steps described in this paper correspond to advances in fundamental physics, as well as in technology, data interpretation or other factors. The paper covers the period from 1870 to date.

1. INTRODUCTION

The study of ionospheric electric current systems is strongly related to that of the Earth's magnetic field, that is why our first part will present Chapman and Bartels 's work concerning the main historical steps of geomagnetism up to about 1850. In this first part we underline the advances of geomagnetism important for our purpose. In the second part we recall some definitions concerning the variations of the magnetic field to help the reader in understanding the scope of this study. Then we present the main steps. It is not a review but just some flashes with some historical notes.

2. HISTORICAL STEPS IN GEOMAGNETISM : RELATIONS WITH THE IONOSPHERIC ELECTRIC CURRENT

Chapman and Bartels' work (1940) summarized in their book the main steps of geomagnetism history (see table 1).

Long before Jesus-Christ, the Chinese already knew of the existence of the Earth's magnetic field, but it was only at the beginning of the Middle Ages that the earth's magnetic field began to be measured in Europe.

For several centuries, sparse observations of the magnetic field's declination and inclination were made throughout the world.

In 1600, Gilbert introduced the concept of terrestrial magnet, allowing the global approach of the Earth's magnetic field. After Gilbert's work, all the sparse data were related together in a common picture (see figure 1).

Commentaries concerning Gilbert (Chapman and Bartels 's book, page 921) :
"S.P. Thompson, in notes (p 54) to the 1900 English edition, wrote : " Gilbert's extraordinary detachment from all metaphysical and ultraphysical explanations of physical facts, and his continual appeal to the test of experimental evidence, enabled him to lift the science of the

magnet out of the slough of the dark ages, ...However it still gave credence to the nativities of judicial astrology, and the supposed influence of the planets on human destiny."

It is not surprising that Gilbert's work also contained errors more nearly affecting magnetism, such as the conclusion (Chapter 3, book 4) that the variation (i.e. D) in any one place is constant : "Unless there should be a great dissolution of a continent and a subsidence of the land such as there was of the region Atlantis of which Plato and the ancients tell, the variation will continue perpetually immutable".

Gilbert's book was received with great favour in his time, though some parts of it were considered heretical by many because they upheld the Copernican views, of which he was the first English adherent; Galileo's copy book was given to him by " a Peripatetick Philosopher, of great fame, as I believe to free his library from its contagion"; the Jesuit scientists, however, who followed Gilbert in their magnetic writings, were right in repudiating his idea that "The needle was counterpoised by a small piece of brass."

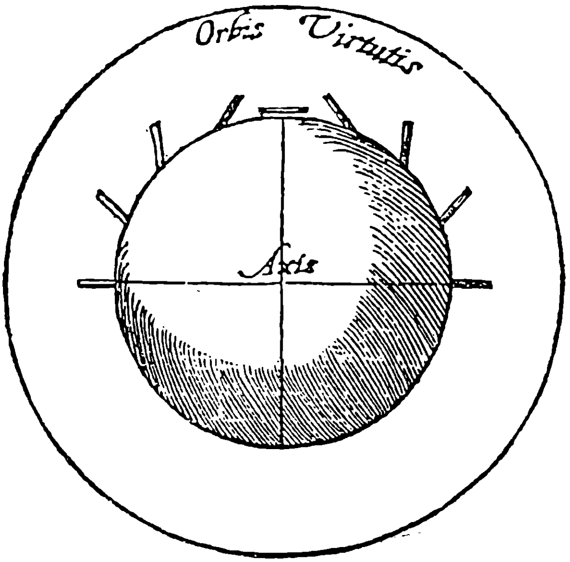

Figure 1 : *Variety in the declinations of iron spikes at various latitudes of a terrella, from Gilbert 1600 (book of Chapman and Bartels, 1940).*

This magnet approach led to the establishment of the first magnetic field map in 1701, by Halley (see figure 2).

During the seventeenth and following centuries, various magnetic field variations were recorded: the secular variation by Henri Gellibrand in 1635, the regular and disturbed daily variations respectively by George Graham in 1722 and Celsius in 1741.

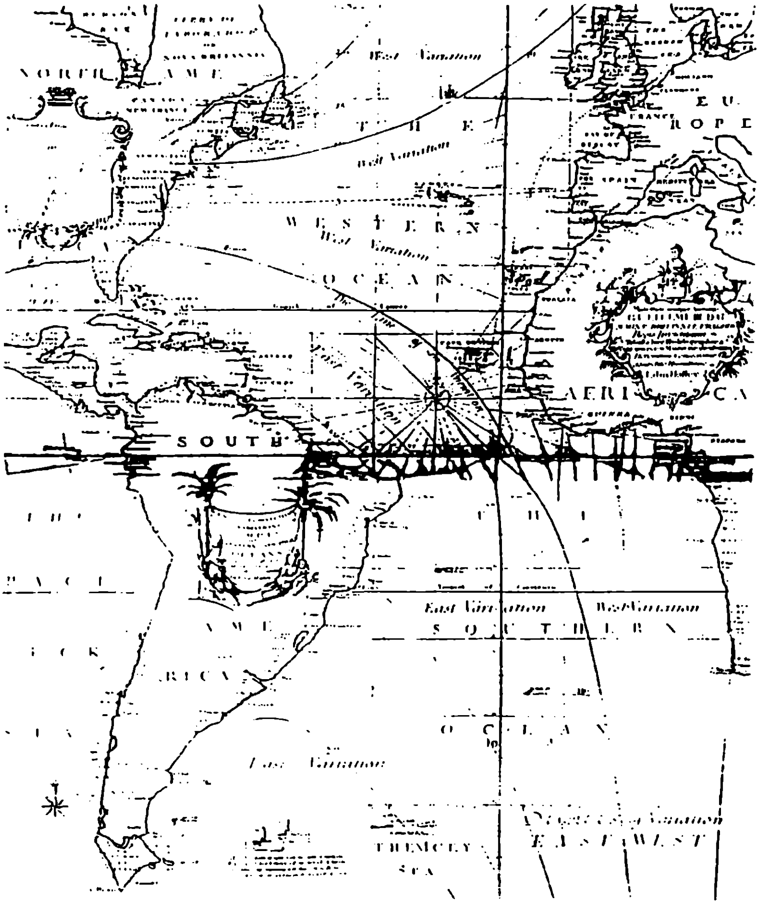

Figure 2 : *First map of the Earth's magnetic field, Halley, 1701 (from the book of Chapman and Bartels, 1940).*

Observation of the daily regular variation of the Earth's magnetic field must be considered the starting point of the study of regular ionospheric electric currents.

From 1700 to 1750, relations were established between the magnetic field variations and the aurora (Celsius 1741) and between the aurora and the magnetic field (Wilcke).

It was not until the beginning of the nineteenth century that A. von Humboldt named magnetic storms all the sporadic phenomena observed on the magnetic field which do not correspond to the daily variation. These variations are related to disturbed ionospheric or magnetospheric current systems beyond the scope of this paper. A. von Humbold can be considered a pioneer for systematic and simultaneous measurement of the magnetic field.

During the same period Weber and Gauss contributed to the development of experimental geomagnetism studies by the creation of the Göttingen Union.

Commentaries from Chapman and Bartels concerning the participation of Weber and Gauss to geomagnetism studies (p 931) :

"The Göttingen Magnetic Union : Gauss and Weber at the new Göttingen observatory, began, in March 1834, to participate in von Humboldt's scheme of simultaneous observations. Later they considered it necessary to make observations oftener than once an hour, and proposed 5-minute intervals. A number of observatories associated themselves with this proposal in what became known as the Magnetische Verein (Göttingen Magnetic Union). Three to six periods of simultaneous observation, each extending over 24 hours, were agreed upon annually."

The systematic observations of the Earth's magnetic field variations simultaneously by different observatories is one of the fundamental experimental steps in the studies of the regular ionospheric current system.

During the second part of the nineteenth century, other relations between the magnetic field and the sunspot cycle (discovered by Schwabe in 1851) were established.

In 1850, nobody thought that electric currents flowing around the Earth could be responsible for the diurnal variation of the earth's magnetic field. People were thinking that telluric currents were the cause of this diurnal variation and measurements of telluric currents were developed throughout the world during the nineteen century.

On the Earth 's Currents ...... By the Rev. Humphrey Llyod (1861) :

"When the discovery by Oersted had made known the connection which subsists between magnetism and current electricity, the idea occurred to many that the magnetism of the Earth, or at least, its diurnal fluctuation, was the result of electric currents traversing its crust. The idea gained much force from the fact, soon after discovered by Seebeck, that electric currents are generated when heat is applied to a circuit composed of different metals; and it was supposed that the phenomena were thus traceable to the thermal agency of the sun, operating in succession upon the conducting substances of which the earth's crust is composed.

The most explicit statement, and chief support of this hypothesis, is contained in a memoir by Professor Christie, published in the Philosophical Transactions in 1827. "

If people were thinking that the regular variation of the Earth's magnetic field was due to internal current, they were also relating the disturbed magnetic variations "magnetic storms" to atmospheric phenomena (external electric currents) as they observed a relation with aurora.

It should be noted here that in 1733 J. Dortous de Mairan, gave the right explanation for aurora phenomena :

J-D de Mairan et l'Origine des Aurores. J-P Legrand :

" L'aurore boréale est un phénomène lumineux ainsi nommé parce qu'il a coutume de paraître du côté nord, ou de la partie boréale du ciel, et que sa lumière, lorsqu'elle est proche

de l'horizon, ressemble à celle du point jour, ou à l'aurore. Sa véritable cause est, selon ce que je pense, la lumière zodiacale. .....

Et Mairan de poursuivre en indiquant que cette matière qui compose l'atmosphère solaire vient rencontrer les parties supérieures de notre air et tombe dans l'atmosphère terrestre à plus ou moins grande profondeur. cette matière s'enflamme soit spontanément, soit "par collision avec les particules de l'air".

3. ON THE EARTH'S MAGNETIC VARIATIONS, IT IS USEFUL TO RECALL SOME FACTS TO UNTERSTAND THE SCOPE OF THIS PAPER

The Earth's magnetic field can be expressed as follows:

B = Bp + Ba + Be + Bt

Bp : main field (core- internal source)
Ba : magnetization field (lithosphere and crust - internal source)
Be : external field (ionosphere, magnetosphere - external source)
Bt : telluric field (earth, coupling between external / internal)

The main field amplitude varies from 30 000 nT to 60 0000 nT between the Equator and the Pole, on the contrary the Ba field amplitude is quasi constant and its magnitude is 20 nT.

The magnitudes of the Be and Bt components due to external sources fluctuate between 10 to 1000 nT depending on latitude and time. They are not independent, the external regular ionospheric currents are at the origin of the regular telluric currents, they are proportional.

The main field Bp varies at the secular time scale and does not contribute to the daily variation of the Earth's magnetic field.

The Be and Bt components have time scale variations from a fraction of second to the solar cycle (11 years). They include the regular daily variation of the earth 's magnetic field generated by circulation of ionospheric currents.

The daily variation of the Earth's magnetic field is composed of a regular part S (solar) and a disturbed part D (disturbed) .

DBe = De + Se and its associated DBt = Dt + St

The disturbed daily variation of the earth magnetic field (beyond the scope of this paper) can be expressed as follows :

$De = D_P + D_R + D_{CF} + D_T + D_{//}$ (Akasofu and Chapman, 1961)

All the disturbed components are associated with an electric current system circulation in the ionosphere, magnetopshere or along the magnetic field lines.

D_P : Disturbed ionospheric current
D_R : Ring current
D_{CF} : Chapman Ferraro currents (magnetopause)

D_T : Tail current
$D_{//}$: Field aligned currents

The geometry of all the external current systems is given in figure 3 from Heikkila, 1972.

The regular part S is considered to be mainly due to the daily regular ionospheric current circulation (scope of our paper). The geometry of this system is given in figure 4.

The various external current systems are generated by different interactions between the sun and the Earth 's environment.

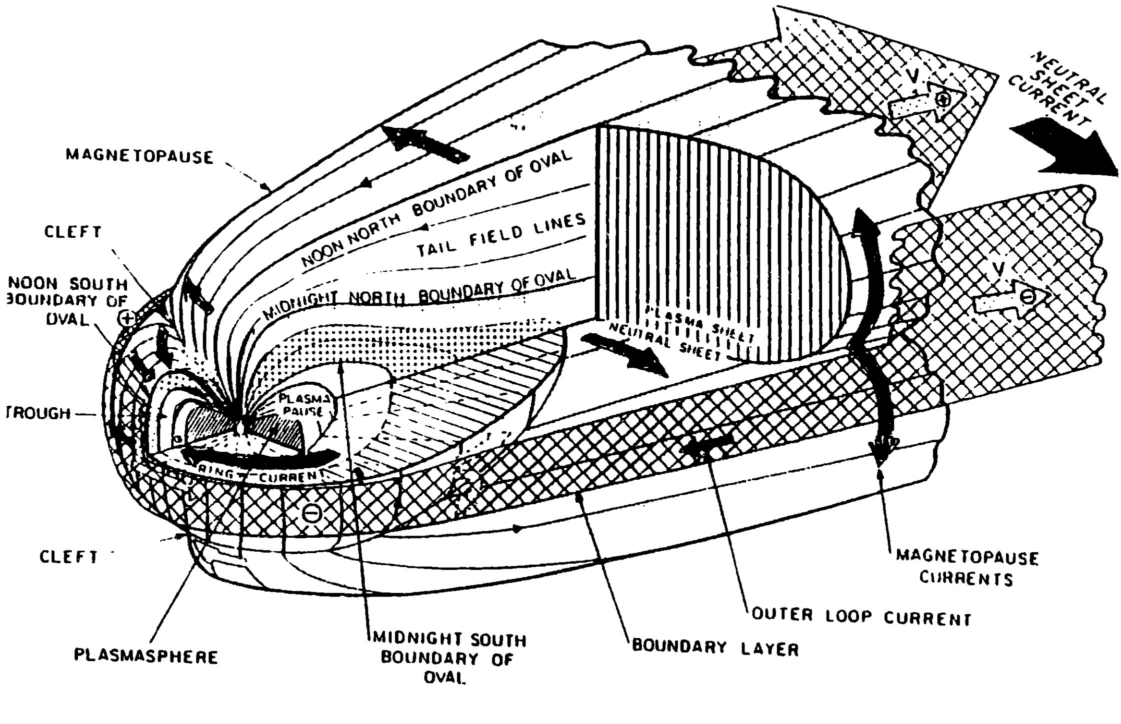

Figure 3 : *Geometry of the magnetospheric current systems at the origin of the D field.*

The S_R current system is related to the atmopsheric dynamo, which generates electric current by the conversion of atmospheric motion into electricity. The D current systems are in general more or less directly related to the solar wind dynamo. In this last case, the motion of the solar wind in the interplanetary medium is the primary generator of electric currents.

4. HISTORICAL STEPS IN IONOSPHERIC ELECTRIC CURRENTS

After all these considerations on the Earth's magnetic field, we can highlight some main steps in the history of electric ionospheric currents.

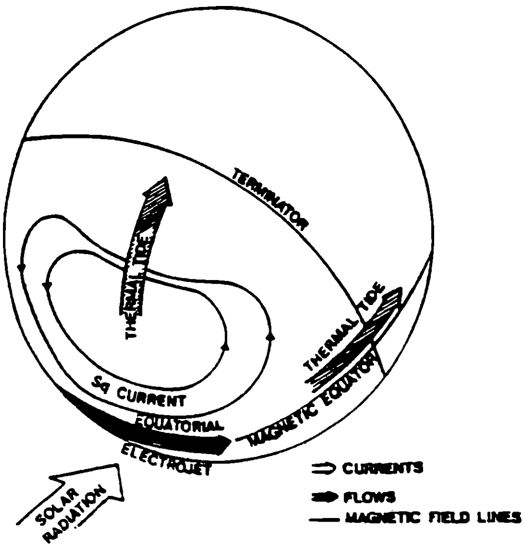

Figure 4 : *Rough geometry of the ionopsheric current system at the origin of the regular variation of the Earth's magnetic field.*

The selected steps are summarized in table 2, they concern : Fundamental sciences : electromagnetism, mathematics, etc .. Technologies : radar, rocket flights Interpretation of observations : concept, theories Conceptual tools : parameterization International organization and choice of classifications Computer organization : data base

Three men played a dominant role in ionospheric current history :

J. Maxwell
B. Stewart
A. Schuster

MAXWELL J. was thinking that the development of experimental science such as geomagnetism was essential for the progress of science

At the end of the nineteenth century, fundamentalist researchers as Maxwell were interested in the development of geomagnetism as a field of experimentation for the electromagnetism theory. A part of his introductory lecture on experimental physics at Cambridge in 1870 is devoted to geomagnetism :

" *But the history of the science of terrestrial magnetism affords us sufficient example of what may be done by Experiments in Concert, such as we hope some day to perform in our laboratory.*

That celebrated traveller, Humboldt, was profoundly impressed with the scientific value of a combined effort to be made by the observers of all nations to obtain accurate measurements of the magnetism earth....

We must reserve for its proper place in our course any detailed description of the disturbances to which the magnetism of our planet is found to be subject. Some of these disturbances are periodic, following the regular courses of the sun and moon. Others are sudden and called magnetic storms, but, like the storms of the atmosphere, they have their known seasons of frequency. The last and the most mysterious of these magnetic changes is that secular variation by which the whole character of the earth, as a great magnet, is being slowly modified, while the magnetic poles creep on, from century to century along their winding track.

We have thus learned that the interior of the earth is subject to the influences of the heavenly bodies, but that besides this there is a constantly progressive change going on, the cause of which is entirely unknown."

It is interesting to notice that in these commentaries, Maxwell related the magnetic variations to the sun, the moon, the atmosphere and the interior of the earth.

And Maxwell also commented on human nature, one of the most important parameters in history of science (not taken into account in this paper) :

" *The men whose names are found in the history of science are not mere hypothetical constituents of a crowd, to be reasoned upon only in masses. We recognize them as men like ourselves, and their actions and thoughts being more free from the influence of passion, and recorded more accurately than those of other men, are all the better materials for the study of the calmer parts of human nature.*

But the history of science is not restricted to the enumeration of successful investigations. it has to tell unsuccessful inquiries and to explain why some of the ablest men have failed to find the key of the knowledge, and how the reputation of others has only given a firmer footing to the errors into which they fell.

The history of the development, whether normal or abnormal, of ideas is of all subjects that in which we, as thinking men, take the deepest interest. But when the action of the mind passes out of the intellectual stage, in which truth and error are the alternatives, into the more violently emotional states of anger and passion, malice and envy, fury and madness; the *student of science, though he is obliged to recognize the powerful influence which these wild forces have exercised on mankind, is perhaps in some measure disqualified from pursuing the study of this part of human nature."*

Maxwell's work on the relations between the electromagnetism laws (1873) was fundamental for the studies of ionospheric currents, and, few years later, the hypothesis of electric currents flowing outside the earth was proposed by B. Stewart (1882-1886), to explain the daily regular variation of the magnetic field.

STEWART B. introduced the concept of external electric current to explain the daily regular variation of the Earth's magnetic field

At this time three other hypotheses were proposed to explain the regular magnetic field variation :

- Direct action of the Sun upon the earth
- Heating effect of the Sun on the chief mass of the Earth's atmosphere (Faraday's hypothesis)
- Earth currents

B. Stewart : On the Cause of the Solar-Diurnal Variations of Terrestrial Magnetism, communication of the Philosophical Society, April 10, 1886.

" *Now, if it be unlikely that these magnetic variations are caused either by the direct magnetic action of the Sun, or by earth-currents, or by the heating effect of the Sun on the chief mass of the Earth's atmosphere, we seem to be driven by the method of exhaustion to look for their cause in the upper atmospheric regions. We shall, however, have to show that there is no improbability in locating their cause in these elevated regions, otherwise our method of exhaustion will have done us no service. In the first place, I need hardly say that if the cause we are in search of be in these upper regions, it must either be in the shape of a set of electrical currents, or in some other shape which we are quite unacquainted; but the nature of this discussion precludes us from entertaining the latter supposition; and we are therefore driven to regard electrical currents as being the only conceivable cause, if the cause is to be located in the upper atmospheric regions.*

I shall now attempt to reply to two imaginary objections that may be raised as to the possibility of such currents. In the first place, it may be said that while undoubtedly rarefied air is a conductor of electricity, yet it is not a good conductor; and where can we look for sufficient potential to drive currents through these upper atmospheric regions? To this I would reply that as a matter of fact we know that there are visible electric currents in the upper atmospheric regions of the Earth. .... I allude to the Aurora which is unquestionably an electric current, and must therefore influence the magnetic needle. "

On Balfour Stewart, who was an universal mind, by Dr Shuster : Memoirs and Proceedings of the Manchester and Philosophical Society (1888), Fourth Series, First Volume, pp 253-272.

"Balfour Stewart's name was first prominently brought before the public by his researches on radiant heat."
" Balfour Stewart was the author of several text -books. His " Primer of Physics", as well as his "Elements of Physics" ..... "Lessons in Elementary Practical Physics", written jointly with Mr W.W. Haldana Gee... An admirable treatise on the "Conservation of Energy" .... Students of Terrestrial Magnetism will for a long time to come to the clear and at the time full account he has given of the present state of the subject in the last edition of the "Encyclopaedia Britannica".
His book "The Unseen Universe, or Physical speculations on a Future State", by Stewart and Tait, was published anonymously at first. It went rapidly through several editions, and in the fourth the authors'names were given.

The following abstract from the preface to the first shows the aim of the book

" Forgetful of the splendid example shown by intellectual giants like Newton and Faraday, and aghast at the materialistic statements now-a-days freely made (often professedly in the name of science), the orthodox in religion are in somewhat evil case.

" As a natural consequence of their too hastily reached conclusions that modern science is incompatible with Christian doctrine, not a few of them have raised an outcry against science itself. This result is doubly to be deplored, for there cannot be a doubt that it is calculated to do mischief not merely to science but to religion.

" Our object in the present work is to endeavour to show that the presumed incompatibility of Science and Religion does not exist. This, indeed, ought to be self-evident to all who believe that the Creator of the universe is Himself the Author of Revelation. But it is strangely impressive to note how very little often suffices to alarm even the firmest human faith."

Balfour Stewart was an active member - at one time the President - of the Psychical Society; believing that every subject must gain by an impartial and philosophical inquiry, and that no subject is beneath the attention of scientific men.

He received the Rumford medal of the Royal Society in 1868. At the time of his death he was President of the Physical Society of London, and of the Manchester Literary and Philosophical Society."

SCHUSTER A. (1851-1934) was the first to separate the internal and external sources of the Earth's magnetic field and to establish the first map of equivalent current system.

A. Shuster : the diurnal Variation of terrestrial Magnetism, received march 20- read 28, 1889 :

" In the year 1839 Gauss published his celebrated Memoir on TerrestrialMagnetism in which the potential on the Earth's surface was calculated to 26 terms of a series of surface harmonics. It was proved in this Memoir that, if the horizontal components of magnetic forces were known all over the Earth, the surface potential could be derived without the help of the

vertical forces, and it is well known now how these latter can be used to separate the terms of the potential which depend on internal from those which depend on external sources....

The use of harmonic analysis to separate internal from external causes has never been put to a practical test, but it seems to me to be especially well adapted to enquiries on the causes of the periodic oscillations of the magnetic needle...

The agreement seemed to me to be sufficiently good to justify the conclusion that the greater part of the variation is due to causes outside the Earth's surface.....

The results of the calculation point not only to an external source, but to an additional internal source, standing in fixed relationship to the external cause"

A. Schuster, with his technical work on the daily variation, proved that external sources are at the origin of this regular variation (Be) and found the associated telluric part induced by external source (Bi).

A. Schuster used one year of data from four stations (Lisbon, Greenwich, Bombay and St Petesburg) and he said :

" *Four stations are sufficient to find with the necessary accuracy the potential on the surface of the Earth, but it would be of advantage if in future similar investigations a greater number of stations could be utilized.* "

Then A. Schuster established the first map of equivalent electric current systems, he supposed that the currents were flowing in a concentric layer having a thickness of about 30 miles and surrounding the earth at 1000 km altitude :

" *If we imagine the variable part of the magnetic force (daily variation) to be produced by a system of surface currents in a conducting sphere concentric with the Earth, and surrounding it, we may, if the potential is known, calculate the distribution of the lines of flow....*

We conclude that we may imagine the daily variation of the Earth's magnetic force to be produced by a system of electric currents in a sphere surrounding the Earth, in which lines of flow are roughly represented in fig. 12 (figure 5, here), the direction being such as that at longitude 60° East the flow is away from the equator. "

Comments on A. Schuster by S. Chapman in Terrestrial magnetism and Atmospheric Electricity (1934), Vol 39. :

" *His own work, on electrical conductivity of gases, had already helped to remove a difficulty then left, as to the possibility of air being able to convey necessary currents. In 1907 he returned to the subject, and elaborated this "dynamo" theory mathematically. He assumed a periodic system of air-currents, associated with the daily barometric variation and calculated their effect, assuming a distribution of electric conductivity in the upper air, depending on the Sun's zenith-distance. He attributed the conductivity to ionization by ultra-violet radiation, and was able to make an estimate of the total conductivity of the current-bearing layer.* "

Remember that at the end of the nineteenth century, the ionospheric layer had not yet been discovered. With the discovery of the ionosphere in 1901 by Marconi, and the concept of ionosphere by Kenelly and Heaviside, a new path for the study of ionospheric electric currents was opened by the access to in situ measurement. And then two experimental paths followed during the next century : (1) access to "equivalent ionospheric current" by using magnetic data from many observatories and (2) development of techniques to measure in situ

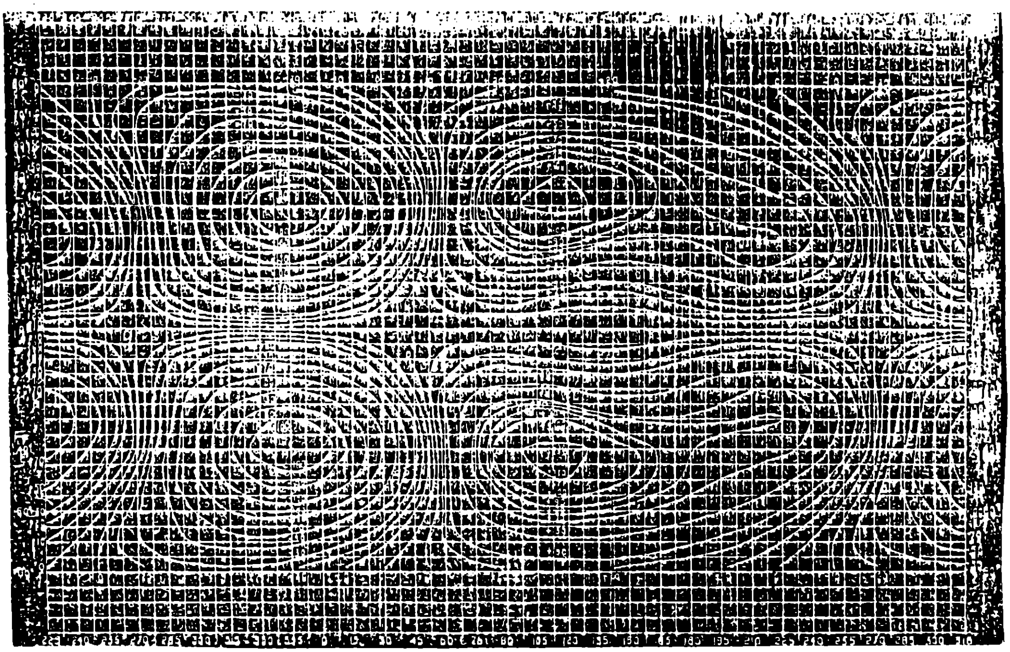

Figure 5 : *Fist map of equivalent current system by A. Schuster in 1889.*

parameters useful for the computation of electric currents. Since 1940, advances in different directions : dynamo theory, conductivity in a partially ionized gas and atmospheric tides, allowed a global physical approach of the daily regular variation of the Earth's magnetic field.

In order to facilitate comprehension we will analyse the development during the twentieth century following three directions:

magnetic data

in situ measurement

theories

MAGNETIC DATA :

In 1905, the classification of the five international quiet days by the international Commission at the Innsbrück Conference, was essential to develop systematic studies on the regular variation.

S. Chapman using the classification given at Innsbrück, established electric current maps using the magnetic field variations averaged over the five quietest days of one month. This current system was named the Sq current system (see figure 6). Many works analysing the solar cycle, seasonal and diurnal variation of the Sq current were done later.

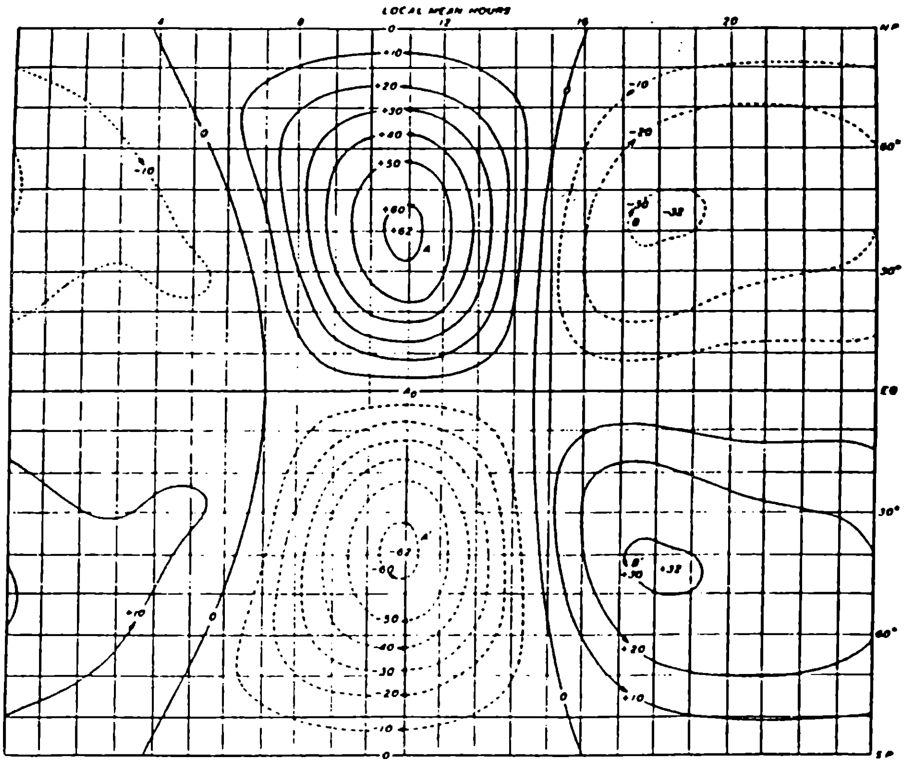

Figure 6 : *Sq equivalent current system (Chapman and Bartels, 1940)*

Equivalent current system

Figure 7 shows the ideal Sq equivalent current system. The electric current system closed separately on each hemisphere. World magnetic variations observed at ground level have been expressed by the equivalent current system on the assumption that the geomagnetic variation fields are only produced by the ionospheric current flowing in a thin infinite two-dimensional layer . The relation between the variation of the Earth's magnetic field (B in nT) and the electric current densities integrated over the dynamo region (J in Amperes per kilometers) is : DB = (2π /10f.J)/, f is a factor taking into account the telluric currents.

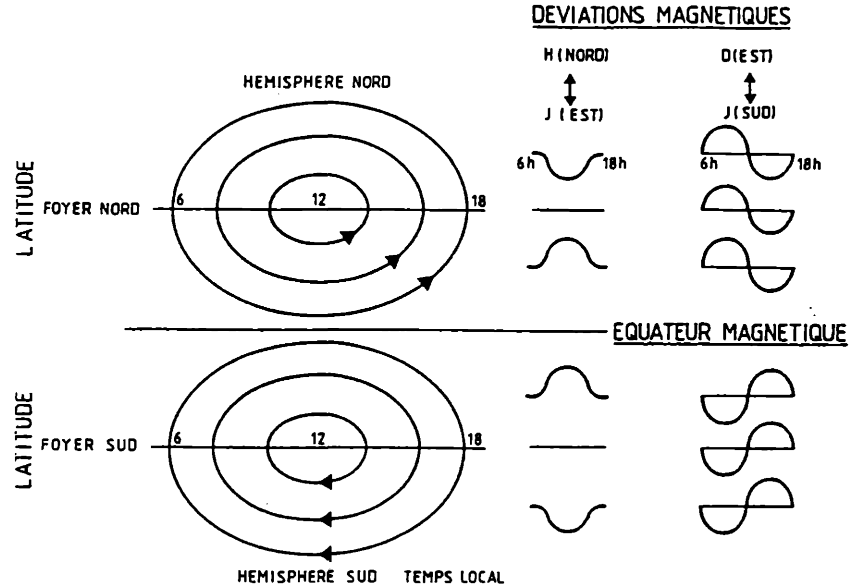

Figure 7 : *Ideal Sq equivalent current system*

Later, in 1962, Price and Wilkins performed the computation of equivalent current systems (figure 8) which revealed the asymmetries of current circulation between the two hemispheres even during quiet time (Van Sabben, 1964, 1966; Fukushima, 1951). This asymmetry implies the circulation of electric current between the two hemispheres and therefore infers the tridimensional nature of the regular current system.

Price and Wilkins : New methods for the analysis of geomagnetic fields and their applications to the Sq field, 1963 :

"Spherical harmonics express an important part of the field in analytic form suitable for theoretical work, such as the separation of the field into parts of external and internal origin. In the methods we have developed, the advantage of an analytic expression is sacrified and the separation of the field is much more laborious, since it involves the numerical evaluation of a large number of surface integrals. This, however, is less important than formerly, now that the burden of heavy numerical work can be greatly eased by modern computers."

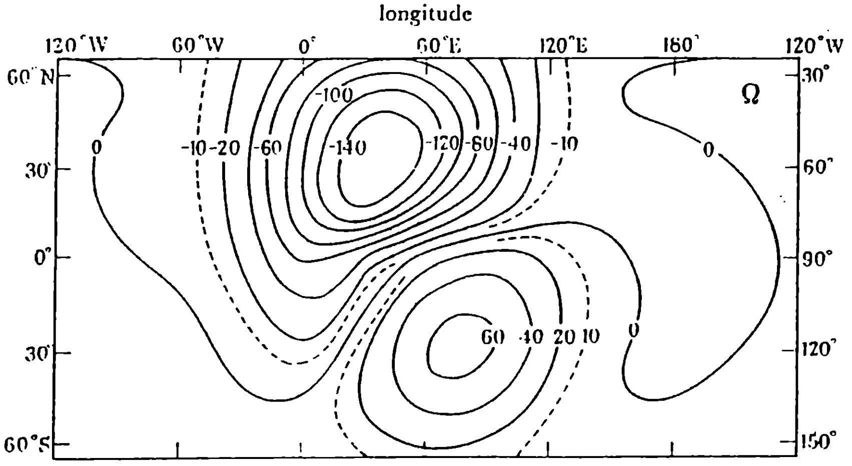

Figure 8 : *Analysis of the geomagnetic fields by Price and Wilkins (1962), showing the asymmetry between the two hemispheres.*

The magnetic field observations were performed all over the world :

In 1931, observation of the magnetic field at Huancayo (near the equator) led to the concept of equatorial electrojet (Chapman in 1951). This current flowing along the equator produces a regular variation with a magnitude one and a half times to twice greater than at middle latitudes.

In 1962, Nagata and Kokubun, proposed the Sq^P equivalent current system for the magnetic variations observed at high latitudes (figure 9). we must recall here that these variations are related to the corpuscular solar source and do not concern this paper.

In 1965, P. N. Mayaud introduced the S_R current system, the difference with the Sq is that this current is not averaged over the five quietest days, but represents the daily regular variation of one day. The analysis of the day-to-day variability of the S_R, in relation to the day-to-day variability of ionospheric parameters permitted detecting the individual magnetic signature of ionospheric phenomena.

Nowadays, ground magnetic variations are still used to derive equivalent current system and remain very useful as they give access to the planetary scale of electric currents.

Commentaries from Y. Kamide in Electrodynamic processes in the Earth's ionosphere and magnetosphere , 1988 (page 611 et 612) :

" It should be noted that the equivalent ionospheric current faces some severe limitations in order to estimate the distribution of the real (not equivalent) current and electric field as summarized by Stern (1977), there are at least three reasons for these limitations. First, even if observational coverage is perfect and all currents are confined to the ionosphere, the equivalent currents provide only an approximation of the true current system. Second, the

influence of the field-aligned current portion of the electric current circuit on geomagnetic variations is far from negligible. Third the electric field is simply related to the current density, since the ionospheric conductivity is a tensor and depends on altitude, solar zenith angle, and any particle precipitation that might be taking place. However, if the ionospheric conductivities can be inferred with reasonable accuracy (this may not be difficult for quiet periods), it is possible to derive the electric potential over the two-dimensional surface."

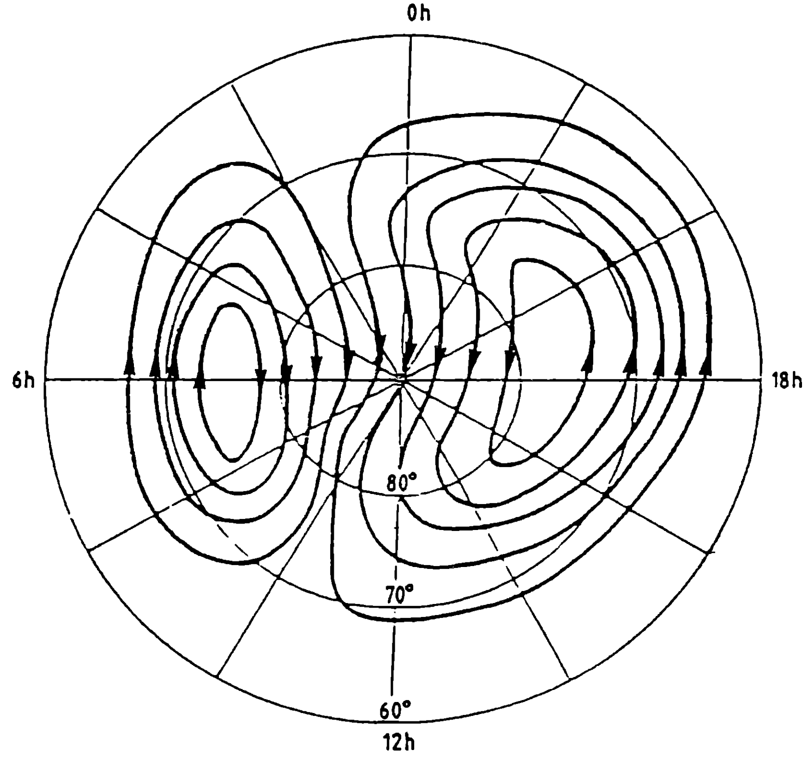

Figure 9 : *S_q^p current system from Nagata and Kokubun 1962.*

IN SITU MEASUREMENTS

From 1925 to 1930, much progress in the field of wave propagation in the ionosphere (Appleton and Hartree) was made and in 1925 the first measurements with the ionosonde technique performed by Breit, permitted knowing the height profile of ionosphere and the electronic density created by the solar ionization.

From 1958 to 1965 new techniques were applied, such as rocket flights (1960-1965) giving access to atmospheric tides (Siebert, 1954, 1956) and incoherent scatter sounder (1958-1966) (W.E. Gordon, 1958; J-P. Dougherty and D.T. Farley, 1960) giving access to electric conductivity, electric field and current as well as atmospheric tides (Vasseur, 1969; Woodman, 1970; Brekke et al., 1974).

From 1960 to date these in situ measurements were and are still used for developing empirical models of the atmospheric parameters (Jacchia, 1964, 1971, MSIS 1986) and ionospheric electric current (Salah and Evans, 1977; Mazaudier and Blanc, 1982). Figure 10 (Mazaudier and Blanc, 1982), shows the diurnal variations of ionospheric electric currents observed in the European sector (Saint-Santin : 44°6N, 2.2°E) and in the American sector (Millstone Hill : 42.6°N, 71.5°W). It is clear that the observations made at European longitude reveal the north-south asymmetry of the regular current system and therefore its tridimensional nature.

THEORIES

From 1940 to 1960, advances in dynamo theory (Chapman) and partially ionized gas theory (Cowling, 1942, 1945) were essential to progress in the knowledge on ionospheric current .

The dynamo theory, including the ionospheric Ohm's law : $J = \sigma (E + Vn \times B)$ expressed the electric current in terms of its constitutive parameters (σ : conductivity, Vn : neutral wind, E : electric field).This theory was first developed on the basis of the experimental studies based on magnetic and ionosonde data. It aimed at understanding the system of Sq ionospheric currents in terms of a global distribution of neutral winds (Kato, 1956; Maeda, 1955). Until 1960, the development of dynamo theories lacked the support of experimental access to the altitude and local time variation of the E region neutral winds and electric fields.

On the basis of wind measurements, the theory of atmospheric tides was developed by Chapman and Lindzen in 1970 and the two-dimensional computation of electric current was performed (Stening, 1969; Tarpley, 1970; Richmond et al., 1976). Figure 11 from Richmond et al., shows the current system computed with the dynamo theory using in situ measurement (top panel) and the current system deduced from the magnetic data (Matsushita 1968- bottom panel).

At the present time, data are set up together in data center and tridimensional models of the ionospheric dynamo are performed in order to reproduce the observations as well as possible .

5. Conclusion

Through some historical aspects the close relationship between the Earth's regular magnetic field variation and the system of ionospheric electric currents at the origin of these variations has been highlighted.

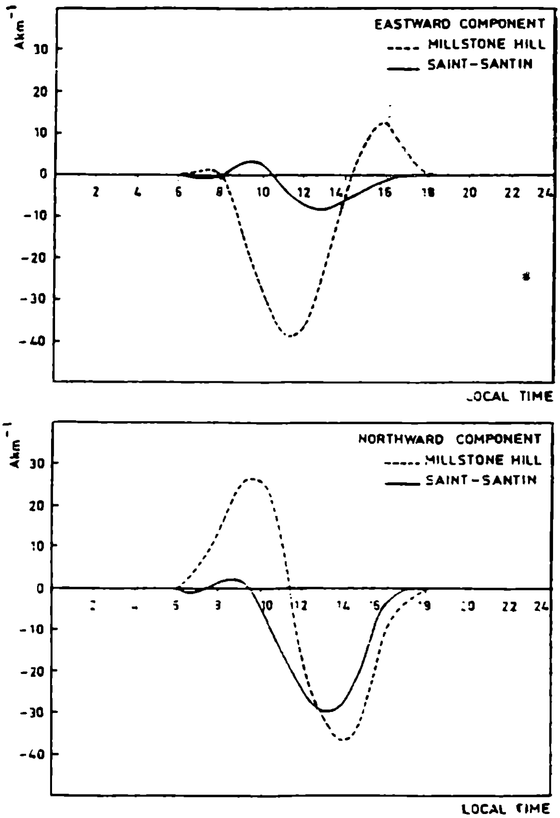

Figure 10 : *Ionospheric electric current measurement from incoherent scatter sounder (Salah and Evans, 1977; Mazaudier and Bland, 1982). The comparison of the current models of Millston Hill (dashed line) and Saint-Santin (solid line) shows rather large differences. The differences in the east-west current can be simply explained by the different magnetic latitudes of the two stations, since Saint-Santin is close to the Sq focus latitude, whereas Millstone Hill is north of it. But the difference in north-south currents requires in addition that a longitude variation of the current system be present.*

i. On geomagnetism we can retain the following :

- sparse data can be related together through a common picture once a concept is formulated (concept of magnet by Gilbert in 1600)
- well-organized data (simultaneous measurements on a global scale) give rise to relations between constitutive parts of the phenomena under study.

ii.. An advance in fundamental physics was essential :

Maxwell's treatise set up the theoretical basis for the study of the ionospheric electric current system, and we must notice that Maxwell in his introductory lecture at Cambridge University, in 1870, had a clear idea of the development of experimental science such as geomagnetism and the importance of experimental data.

iii. Two men played a dominant role :

B. Stewart and A. Schuster (1882- 1910) were the pioneers in the ionospheric electric current studies, in introducing respectively the physical process (atmospheric dynamo) and the dynamo theory and mathematical tools.

iv. A group of researchers using various techniques and developing models worked and still work on this subject :

- From 1882 until now, studies on the global electric current systems were mainly based on the study of two-dimensional equivalent current systems derived from magnetic variations.

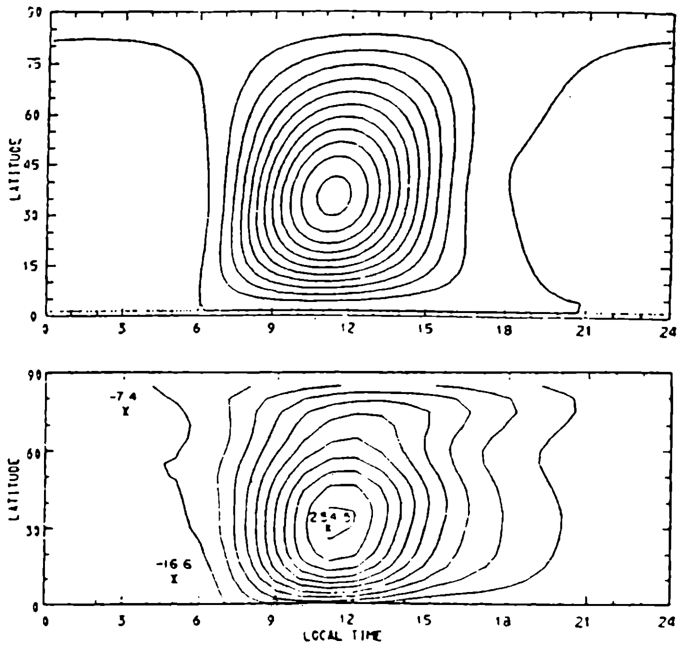

Figure 11 : *Numerical simulations of Electric currrent system (Richmond et al., 1976, figure 10). (Top) Current function in the northern hemisphere produced by the modified $S_{1,-2}$ tidal mode and $S_{2,4}$ mode, with amplitudes and phases as indicated by wind observations. Contours spacing is 10 kA, and the current flows clockwise during the day. (Bottom) Sq current function from IGY geomagnetic data. Contour spacing is 25kA. The difference between the computed and observed current intensities can be largely explained by the difference in the assumed solar cycle conditions (moderate-low) from IGY conditions.*

- After 1900, the discovery of the ionosphere and the development of the technology played a dominant role giving access to in situ measurements of ionospheric parameters. But it is only with the technique of incoherent scatter sounder (years 1970-1980) that scientists were able to derive ionospheric electric current from incoherent sounder data. However these measurements of electric ionospheric current were specific.
- Since 1940, the development of the dynamo theory and numerical simulations using both magnetic data and in situ measurements permits progress in the comprehension of the global three-dimensional ionospheric current system.

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Table I. *Summary of important events in the history of geomagnetism up to about 1850 from CHAPMAN and BARTELS, 1940*

A.D. 1030-93	The Chinese encyclopaedist Shon-Kua described the magnet pointing south
About 1187	Alexander Neckman of St. Albans described the magnetic compass
About 1450	Sun dials in Nuremberg showed marks for magnetic declination
About 1492	German roads maps containing the figure of a compass indicating the declination
1538-41	Joao de Castro, on a voyage to the East Indies, made forty-three determinations of magnetic declination
1544	Letter from Georg Hartmann of Nuremberg, referring to the magnetic inclination
1576	Robert Norman *The Newe Attractive*
1600	William Gilbert, *De magnete*
1635	Henri Gellibrand discovered the secular variation of declination
1672	Daniel Tilas died (inventor of the Swedish mining compass for magnetic prospecting)
1698-1700	Halley's voyages in the Atlantic Ocean on the *Paramour Pink*
1701	Halley's sea chart of the whole world
1721	William Whiston's charts of inclination
1722	**George Graham discovered non-secular time-variations**
1741, April 5	Simultaneous magnetic observations by Celsius at Upsala and Graham at London; discovery of the relation between magnetic disturbances and aurora
1759	**Solar daily** variation found to be greater in summer than in winter (by Canton)

1770	Wilcke observed thar auroral rays are parallel to the magnetic inclination
1782	Cassini found that the **daily variation** of the declination is independent of the daily variation of air-temperature
1799-1804	A. von Humboldt's expedition to America
1819	Hansteen's *Untersuchungen über den Magnetismus der Erde*
1820-35	Arago's observations of the magnetic declination at Paris
1826	Poggendorff introduced readings by means of mirror and scale
1837	The earth inductor invented by Weber
1838	Gauss *Allgemeine Theorie des Erdmagnetismus*
1839	Llyod introduced the magnetic balance for recording the variations of the vertical intensity
1836-41	**The Göttingen Magnetic Union**
1839	Establishement of the British Colonial Observatories (Sabine)
1846	Charles Brooke constructed photographic apparatus recording magnetic variations
1850	Kreil found the lunar daily variation of declination at Prague
1851	Schwabe discovered the sunspot cycle
1852	Sabine found the effect of the sunspot cycle on the disturbances of declination at Toronto, 1841-48.

Table II: *Summary of important events in the history of regular ionospheric electric currents (S_R magnetic field) up to about 1993*

1722	**George Graham discovered non-secular time-variations**
1873	Treatise on electricity, Maxwell *lecture by 1870 at Cambridge University*
1882-1886	Concept of Atmospheric dynamo *lecture by B. Stewart*
1886-1907	Maps of external current systems (A. Schuster) Establishment of the dynamo theory mathematically *Lecture, figure*
1901	Radio beacon (Marconi) Ionosphere postulated by Kenelly and Heaviside
1905	Classification of the 5 international quiet days International Commission at the Innsbrück Conference
1919	Sq equivalent current system (S. Chapman)
1925-29	Wave propagation in the ionosphere (E.V. Appleton, Hartree)
1925-26	First measurements with ionosonde (G. Breit and M. Atuve, E.V. Appleton and M.A.F. Barnett)
1931	First observations of H component of the magnetic field at Huancayo -> equatorial electrojet (1951-S. Chapman)
1940	Application of dynamo theory to ionosphere (S. Chapman) (Maeda, Y. Kato)
1945	Conductivity in partially ionized gas (T.G. Cowling)
1950-65	Rocket flights, in situ measurement of atmospheric tides M. Siebert
1958-60	Theory of incoherent scattering of radiowaves by a plasma W.E. Gordon, J.P. Dougherty, D.T. Farley

1960-	Starting point for the developement of atmospheric models Jacchia (1960) ----------> MSIS (1986)
1962	Asymmetries of the two hemispheres => $J_{//}$ A.T. Price and G.A. Wilkins, D. Van Sabben, N. Fukushima
1962	Equivalent current system S_q^P , Nagata and Kokubun
1965	Concept of the S_R and its day-to-day variability (Mayaud)
1970	Theory of atmospheric tides (S. Chapman , R.S. Lindzen)
1969-1976	Computation of ionospheric electric currents from available wind data, R.J. Stening, J.D. Tarpley, A. Richmond
1967-1970	Equatorial counter electrojet (Gouin and Mayaud)
1963-	Observations with incoherent scatter sounder network 1969 : neutral winds (G. Vasseur) 1970 : electric fields (R. Woodman) 1974 : electric currents (A. Brekke et al.)
1977-1982	Semi empirical models of quiet ionospheric electric current Salah and Evans 1977, Mazaudier and Blanc, 1982
1980-	Tridimensional global simulations of ionospheric electric currents

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EMANUEL LIAIS: A SCIENTIST OF TWO CONTINENTS

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Geomagnetism has a prominent place in the History of Science, because it has been often a fruitful seed in human enterprises, from the Great Navigations to the Space Age. In particular, Geomagnetism is linked to important events in the History of Brazil. Its influence can be detected one century before the official discovery of the country.

Sagres School, the first astronomical and geophysical national institute of Western Europe, was a landmark in the great Portuguese oceanic adventure. The wisdom of its creator, the Infante Dom Henrique, recognized the importance of the compass in the intrepid voyages of the 15th and 16th centuries (Campos, 1943).

There are strong evidences of a close association between Sagres' navigators and the adventurous vikings. It is very probable that some Portuguese sailors had been in viking vessels, as a consequence of the happy marriage of Filipa, Henrique's cousin, with Eric of Pomerania (Barreto, 1987).

The "variation of the needle variation" or, in modern language, the "declination change", was a common method to obtain longitudes, and it was well known at Sagres. It is conceivable that the scholars from Sagres knew that in the 15th Century, isogonic lines were close to meridian direction in the Southern Atlantic, but they had somewhere an East-West direction in the Northern Atlantic. This regional peculiarity of the geomagnetic field could be a strong reason to underestimate the distance between Europe and the unknown Continent, America, a probable argument for Portuguese choice of a Trans-African route to India, and for the refusal of Colombus' project by the Lisbon Crown (Barreto, 1991).

As a consequence of the economical and political importance of the navigations, it is easy to understand the scarcity of clear historical documents about them. Geography and Cartography were classified subjects, and Portugal used Sagres' experience to expand its power over the New World.

During the first two centuries of Brazilian History, there are few examples of scientific activities, in many cases related to flora and fauna, crude charts where magnetic declination is indicated in a very simple way. When Admiral Pedro Alvares Cabral arrived at the lovely Porto Seguro Bay, his surgeon, physicist and astronomer, Joao Emeneslau, determined the latitude and the "needle variation" of the paradisiac place.

The short but brilliant work of George Marcgrave at Mauricio City in Northeastern Brazil, from 1637 to 1644, represents the operation of the first astronomical observatory in America (Moraes, 1956). The remarkable scientific project of Marcgrave (Marcgrave, posthumous works, 1942) was not completed because the exceptional administration of Prince Mauricio de Nassau-Sieben was terminated for political reasons (Nogueira, 1900). The dream of a Dutch Western India and a great scientific civilization in South America vanished. It was a frustration to know that the main portion of Marcgrave's observations and writings were lost with him. However, according to Lalande, Bigourdan and Flamstead, two centuries later, Marcgrave's writings were found at the "Dépot des Plans" in Paris and at Cadiz, Spain (Moraes, 1956). From some old chronicles (Pingré, 1901) there was a large series of magnetic declination data in Marcgrave's records.

In spite of their incidental nature, scientific activities were carried out in Brazil by distinguished Europeans. La Condamine, Couplet and Halley are examples of such men. Edmond Halley, during his famous trip to the Southern Hemisphere, between 1698 and 1700, constituted a real turning point in the History of Geomagnetism.

In the middle of the 18th Century, the necessity to explore a new land induced the Portuguese Crown to send to the Colony many geographers and cartographers, such as Parigai, Cieira, Pithon, Basco, Alpoin (Carvalho, 1985). It was a crude beginning of Astronomy and Geophysics in Brazil. However, the efforts to establish a regular scientific practice with those specialists were insufficient to be considered as the birth of scientific research. It was necessary to create a true national scientific institution and the conditions for the entry on the scene of the main actor in our story: Emmanuel Liais.

At the end of the 18th Century, the development of Brazil, an old colony, now a Vice-Kingdom, required a permanent operation of two scientific services: a good time keeping system and a reliable control of the "magnetic variation". In 1781, Bento Sanchez Dorta and Francisco de Oliveira Barbosa arrived in Rio de Janeiro to install a Royal Observatory, to provide those services that were crucial for the increasing movement in Brazilian harbours. They intended to use the precarious instruments and installations used by Jesuit priests in Rio downtown (Arend, 1962). In spite of their efforts, Dorta and Barbosa could not complete their mission, and they left Rio in 1788.

Few years later, in 1808, a great change occurred in the Brazilian political structure, when the Portuguese Royal Family arrived in Rio de Janeiro to escape from Napoleon's troops. Brazil turned out to be the core of a Kingdom. The new political and cultural circumstances permitted the creation of important institutions, such as the Public Library, the Royal Printing House, the Naval and Military academies. In the Royal Military Academy a well-elaborated course on Astronomy and Cartography was given by Manoel Ferreira de Araujo Guimarães, the author of a thick compendium with many explanations on Terrestrial Magnetism.

In spite of the efforts of the great scholar, José Bonifacio de Andrada, to create a University, this important source of wisdom could not be achieved. Scientific research had an amateurish and erratic sense. All astronomical or geophysical activities were restricted to routine tasks at an old Jesuit church, in an unofficial way. It must be said that Geophysics was considered as a secondary branch of Astronomy, and its results were surrounded by a superstitious atmosphere.

Brazilian political autonomy was a natural consequence of that displacement of the Royal power, not a warlike movement as had occurred in other Latin-American countries, because the Prince of Portugal became the first Brazilian Emperor, with the name of D. Pedro I (Pedro the First). José Bonifacio de Andrada had a prominent action in that peaceful political change.

José Bonifacio was a distinguished scientist, whose works on Mineralogy were well recognized in Europe. In spite of his notable ideas to improve Science and Culture in Brazil, he was banished to Europe, because the Emperor's stormy temperament was difficult to be controlled. As fertile seeds , Bonifacio's projects grew in Pedro the First mind. Five years after the Independency, the Academy of Fine Arts, the Imperial Post Office, the General Council of the Empire, the Supreme Court of Justice, the Imperial Military Academy and the Imperial Observatory were created.

The practical needs of a new and large nation were stronger than scientific inquires when Science had not a weighty position as assumed at the end of the 19th Century. To prepare skillful cartographers, to preserve local time carefully for longitude determination, and to obtain correct magnetic declination data to be used in navigation and in land surveying, were the main goals of the new Observatory. Those objectives outlined the future activities of the current Department of Geophysics and the National Observatory Time Service, one of the best at present.

In October 15, 1827, the young and impetuous Emperor promulgated a Decree creating the Imperial Observatory and, as a tropical paradox, unofficial astronomical activities had been almost interrupted for an incredible bureaucratic reason: there was not a person to accept the post of Director. Araujo Guimarães, professor of Astronomy at the Militar Academy was a very important personality to serve in such a humble position. Only eighteen years later the new Emperor, D. Pedro II (Pedro the Second) appointed Eugenio Fernando Soulier de Sauve as the first Director of the Imperial Observatory of Brazil.

There are few historical references to the works of Sauve, who died in 1850. From his reports to the Director of the Military Academy and his notes, it is possible to know that he taught Cartography and Terrestrial Magnetism. This last activity could be deduced from his administrative reports, where he insisted on the necessity of other site for the Observatory, because the old building at the top of "Morro do Castelo" (Casttle Hill) presented a strong "needle instability".

Antonio Manoel de Mello replaced Sauve and, in 1852, started the publication of the "Imperial Observatory Ephemeris", a historical series, which is published today under the tittle "Efeméryrides do Observatório Nacional".

Between 1865 and 1868, Antonio Joaquim Curvello d'Avila did his best to improve Observatory conditions, in spite of the difficulties provoked by the horrors and bloodshed of the Paraguayan War.

From its origin up to the 1870 decade, the Imperial Observatory was a kind of institution dedicated to "scientific services", since research was not included in its normal activities. On the other hand, the Observatory's History was changed by the occurrence of very blissful circumnstances duly detected by clever Emperor D. Pedro II. He discovered, at the eleventh hour, the opportunity to invite Emmanuel Liais, the leading man in this story, to manage his Observatory.

If Liais had been only a great astronomer, an excellent naturalist, a competent engineer and an efficient statesman, his name would be briefly quoted here, because these notes intend to analyze his importance in the History of Geomagnetism. Liais made an important contribution to Terrestrial Magnetism, although his activities in this science are not his most notorious work.

To understand Liais' scientific importance it is necessary to make a short review of the Science in the middle of the 19th Century.

Emanuel Liais: A Scientist Of Two Continents

Newton's Principia, published in 1687, is an authentic milestone in the History of Science. It was followed by a series of magnificent works from Euler, MacLaurin, Lagrange, Laplace, Gauss.

Consequently, in the middle of the 19th Century, Science was placed in an unprecedented place in the convictions of Mankind. It could be possible to say that Pythagoras and Kepler's dreams were the main rules of Nature's behavior.

Mechanical principles would be the guide of Human Faith, and Determinism arrived at the frontiers of the Absolute. It could be possible, through complete knowledge of the mathematical equations, to predict all physical events in the Universe, including human conduct. If this inmense power could be given to Man, it could be a signal of our mental impotence, perhaps the end of the concepts of innocence and sin, love and hate, possibly a dangerous approach to "Scientific astrology".

However, it was essential to obtain concret proof of such theories. A young French mathematician, Urbain Le Verrier, furnished that proof in 1846 when he indicated the correct position of an unknown planet, using only mathematical, mechanical and calculation tools.

Le Verrier's success was a tremendous shock for the structure of Science and it is easy to understand his fast ascension to Paris Observatory Directorship, after Arago's death. The scientific community and the general public in the World gave to Urbain Le Verrier an incontestable authority as the genius who established, for all time, the mathematical supremacy over the apparent variability of natural phenomena.

On the other hand, some discrete experiences and discoveries indicated other kinds of phenomena with an unimaginable variability of natural events. Some astronomers decided to work on fields different from classical Astrometry, the observational basis of Celetial Mechanics. Those works were the origin of the future breakdown of Determinism in Science. The good fortune of Neptune discovery had obscured the works of Fraunhoffer, Secchi, Huyggens, Fizeau, Foucault and Jansen. We must say that Astrophysics came to life, but it was not recognized as an exact science until the studies of Homer Lane, Schwarzchild, Russel, Hertzprung and Eddington.

In a broader sense, Physics in the 20th Century penetrated into the fantastic field of Quantum Mechanics and Relativity with Planck and Einstein. Now, Le Verrier's certainty of a regular mathematical behavior of the world could be disbelieved.

Another shock to scientific concepts occurred simultaneously with Neptune's discovery: Charles Darwin's Origin of the Species.

There are some differences between Le Verrier's and Darwin's scientific works. Le Verrier was admired for having proved the orderliness of Nature, but Darwin was reproved for having destroyed the old beliefs of eternal stability of living creatures. Le Verrier was an authentic theoretician, who refused to observe his own discovery, but Darwin was a reliable observer of Nature. Le Verrier gave orders to natural phenomena, but Darwin asked Nature to answer his questions at its own convenience.

It was in that spectacular scene in the scientific stage that our hero, Liais, performed his role.

Emmanuel Liais was born in Cherbourg on February 15, 1826, son of a modest merchant, Anténor Liais and Mathilde-Francoise Dorey. During his childhood and up to 26 years old he lived at Cherbourg, which was one of the passions of his life.

Since the early days of his youth, Liais demonstrated an extraordinary ability for the exact sciences, mainly in their experimental aspects. A quick glance at a list of Liais' articles published between 1850 and 1854 (Ancellin, 1986) discloses his multiple interests from Celestial Mechanics, Climatology, scientific instruments and observational methods to the improvements of many kinds of electrical devices. In all Liais' writings there is a strong emphasis on experimental aspects of the events.

In 1852 Liais visited Paris Observatory for the first time. He caused a strong impression on Arago, the old and respected Director. Liais, in his article "Influence de la Mer sur les climats" gave a vivid description of Arago, who was very sick in the last days of his life (Ancellin, 1986). In one of his last wills he promised Liais a place in his Observatory.

After Arago's death, Le Verrier, a national name in France, was appointed Director of the Paris Observatory. He maintained Arago's promise and Liais was appointed Assistant Astronomer in 1854. Only three years later he rose to the status of Titular Astronomer and received the title of "Chevalier de la Legion d'Honeur".

The fast professional ascent was due to an intense and original scientific work. Le Verrier, who was parsimonious concerning explicit quotations about his colleagues and assistants, was prodigal in references to Liais' work. If this initial good relationship between Le Verrier and Liais could be considered as the recognition of fine work, on the other hand, it was a source of dislike on the part of the other astronomers (Barreto, 1987), because Liais was falsely considered as a "creature of Le Verrier".

A remarkable book about Liais' life (Ancellin, 1986) gives a clear view of Science in the middle of the 19th Century. Ancellin's description of the contrast between Le Verrier and Liais is a good example of the indescribable encounter of theoretical and experimental Science, a characteristic of the last Century.

After that friendly beginning, step by step, Liais and Le Verrier relations deteriorated. Two remarkable reasons for that disruption were the strong temperament of both wise men and the differences in their scientific behaviors.

During Arago's time, Paris Observatory was a kind of a Garden of Eden, as a consequence of the affability and amenity of the Director. According to Flamarion (1911), Arago was a sort of candid patriarch, not an energic Director, the exact opposite of Le Verrier.

Le Verrier changed Paris Observatory in a drastic way. A strong centralization could be noticed in all activities, including the important "Bureau des Longitudes". If Liais had been a peaceful man, or if he had a mild temperament, scientific inquiry was not born. A similar question occurred few centuries before, between Tycho Brahe and Kepler, but the later had the necessary perseverance to suffer Brahe's bad temper, in order to receive the great heritage of a priceless set of observations.

Differences and similarities could be found in Liais and Le Verrier. Both were conscious of their high scientific level. Both had very fast careers and very strong temperaments. On the other side, they had few but serious differences. Le Verrier had great political influence, mainly during Napoleon the Third Government, and Liais was linked to republican circles. Le Verrier suffered from a chronic stomach illness and Liais was a healthy man. Those similarities and differences are important to explain the subsequent events in Liais' life and the reasons why he could be considered a scientist of two Continents.

Emanuel Liais: A Scientist Of Two Continents

Le Verrier took into account Arago's references and the previous works of Liais to appoint him Head of the Meteorological Division of Paris Observatory.

It is interesting to remember that, in the middle of the 19th Century, Terrestrial Magnetism was considered a branch or, at least, a correlative subject of Meteorology. One of the main contributions of Liais to Science was his attempt to separate Geomagnetism from Meteorology. In three consecutive articles (Liais, 1851, 1852, 1853) published in the "Annales de l'Academie des Sciences Naturelles de Cherbourg", he proposed and applied and observational method to measured the height of the Polar Aurora , in order to prove that such a spectacular phenomenon occurs above the atmospheric regions where meteorological events took place.

As a consequence of his correct interpretation of geomagnetic and meteorological phenomena, Liais used different methods and scientific treatments to both kinds of events. In some sense, he anticipated by three quarters of a century the creation of the IATME (International Association of Terrestrial Magnetism nad Electricity) (Aldredge, 1981) the predecessor of IAGA .

Few months after his appointment to the Meteorological Division, in 1855, Liais presented to Le Verrier a detailed project to reorganize the respective service at the Paris Observatory. The use of telegraph to forecast meteorological conditions was a revolutionary improvement to increase the percentage of accuracy.

However, it was difficult to convince the Director about the importance of a complete change in the meteorological activities of the Observatory. In spite of the scant interest of Le Verrier in those activities, in 1858 Liais finished a complete reorganization of French Meteorology.

Liais in his "L'Éspace Céleste "(1881) presents clear indications about the beginning of his dispute with Le Verrier. He said that it was easy to explain Le Verrier's aversion to Meteorology, because "a man dedicated to the rigid rules of Celestial Mechanics cannot understand atmospheric mutability, a function of many unknown variables". Only observational means could furnish a reasonable value of that function.

Liais extended the use of the telegraph to longitude determinations (Du Moncel, 1874), in order to avoid the difficult and precarious methods of Moon occultations and the eclipse of Jupiter's satellites. A large network of longitude stations was used on French territory. Later, he used that method in his second country, Brazil.

Besides, his activities in Meteorology during four years, Liais spent a great part of his time to improve scientific instruments and methods. Du Moncel (1874) gives a detailed description of those works, where Liais gave strong attention to important points: the increase of precision and the facility to obtain measurements.

This intention is present in his works on electromagnetic clocks, impersonal micrometers for meridian transits and on geomagnetic variometers.

Liais associated his electromagnetic clock with an impersonal micrometer, in order to obtain a precision of one hundredth of a second in a meridian transit of stars. Such a device was used until recent times (Barreto, 1960) with good results. To build that equipment, Liais developed a prototype proposed by Carl Braun according to an original idea of Rédier (Barreto, 1987).

Since those early years at the Paris Observatory, Liais had the revolutionary idea of using an altazimuthal instrument to obtain simultaneously time and latitude. Such an original instrument was completed during his stay at the Imperial Observatory of Brazil. Today it is a fine ornament in a room of the National Observatory. On the other hand, the Liais' altazimuth is the ancestor of the impersonal astrolabe created one century later by another great French astronomer, André Danjon (Barreto, 1975).

To complete the description of Liais' life between 1855 and 1858 at the Paris Observatory it is necessary to quote his important works on Terrestrial Magnetism. Besides his original effort to dissociate Geomagnetism from Meteorology, Liais started a real scientific research in that science: his work to install variometers with photographic recordings. His variometers were not the first ones to be operated, but they were the first ones to be used in continuous operations for many years.

The success of the new variometers was so great that Le Verrier presented to the Paris Academy of Sciences an enthusiastic report where he gave complete credit to Liais. Perhaps it was the last time that Liais' work was recognized by the Director.

The relations between Liais and Le Verrier evolved from a very small divergence to a strong rupture. Written quarrels, oral altercations were very common in 1858. There are many stories, perhaps historical anecdotes, about that incredible scientific war, such as a traditional helicoidal staircase exclusive of the Director and a fictitious intramercurial planet supposed by Le Verrier and erased from Science by Liais. The rigid temper of Le Verrier could not resist Liais flexible and funny dialectics. Today, one and a half centuries later, we must regret such loss of time by two scientific geniuses.

Possibly the starting point of that historical dispute was a communication made by Le Verrier to the Academy of Sciences, in 1858, about meteorological results. The name of Liais was omitted from the paper.

That omission must be compared with a previous Le Verrier paper also presented to the Academy in August 1856, where he quoted Liais' results obtained with his micrometer associated to his electromagnetic clock. Le Verrier said: "the chronographic instrument built by M. Liais furnished very precise results. I cannot present here all details of such an ingenuous device created by M. Liais to overcome many technical difficulties...".

A careful analysis of both papers could locate in time the beginning of the intellectual dispute, very common among scientists, in the main, among astronomers.

At this point of our story, we must cross the Atlantic Ocean, in order to meet a very singular person living in Rio de Janeiro, the Capital of a large and new country: the Second Emperor of Brazil, Pedro the Second or, as he preferred to be called, Pedro de Alcantara or, finally, as he is known by some historians, Pedro of Brazil (Oliveira Torres, 1957; Barreto, 1987).

The temper of the second Emperor was the opposite of that one of his father. If the First was an ardent lover with frequent explosive decisions, the Second was a virtuous husband with calm and careful resolutions. The First resigned from two thrones, the Brazilian, to his elder son and the Portuguese to his daughter, but he was proud of his power and royalty. He was a King in two continents.

Pedro of Brazil considered his royalty as a painful moral obligation or, using his own words: "I would prefer to be a school teacher than an emperor".

He was able to speak fluently many living languages besides being an expert on Latin and Greek. However, his great passion was science and its applications. It was in his honor that a minor planet discovered in Nice, during one of his trips to France, was named "Brasilia". The strong support given by Pedro to his recent invention was the reason for the success of Graham Bell's telephone. Few months after the return of Pedro de Alcantara from Philadelphia Fair, where he met Bell, a small telephone network was installed in Rio de Janeiro.

The Second Brazilian Emperor was an assiduous pen-pal of many European and North-American scientists. The great Simon Newcomb was one of his best friend. After the visit to Philadelphia Fair, Pedro visited Washington D.C. solely to talk with Newcomb and to visit the Naval Observatory Time Service. In a legend about that visit (Guimarães, 1961), Pedro invited Newcomb to spend some months at the Imperial Observatory of Brazil, in order to see some improvements of the Brazilian Time Service. It is easy to understand that such improvements had been made by a special man: Liais.

As a consequence of his intense correspondence with foreign scientists, Pedro had an extensive knowledge of world-wide scientific events, including the noticeable dispute between Le Verrier and Liais. This was a happy coincidence for the Imperial Observatory of Brazil.

Precisely, in 1858, when the situation at the Paris Observatory was almost insupportable, Pedro the Second sent an invitation to Liais to work in Brazil. Since the Imperial Observatory was, at that time, a small institution for so great a scientist, Pedro offered Liais a contract with many scientific and technical activities. The proposed plan of work included a detailed survey of the São Francisco Valley with geological prospection, geodetic and topographic measurements, determination of magnetic declination and a final report about the economical potentialities of that vast region. Besides that great work, Liais would prepare some projects to improve Brazilian harbours and railroads. Finally, Liais was invited to be a permanent scientific advisor of the Emperor. This last item included the reorganization of the Imperial Observatory.

Liais accepted the offer and his first mission was the observation of the total Solar Eclipse of September 7, 1858, at Paranaguá, Southern Brazil. The observations gave to Liais the material to publish five interesting papers in the "Comptes Rendues des Séances de l'Academie des Sciences de Paris".

Ancellin (1986) reports that in some letters to his good friend Le Jolis, Liais said that he had frequent talks with the Emperor about the results of the eclipse. Some interesting conclusions are presented in those papers, such as (Barreto, 1987):

-an observational evidence that the Solar Corona is physically linked to the Sun, as a part of its atmosphere;

-the coronal light is polarized;

-there was a considerable difference (about 42 seconds of time) between the observed and calculated duration of the eclipse. In a short citation, Liais remembered that the instants of the event were calculated by using Le Verrier tables.

The second task of Liais was an ample cartographic work in the province of Pernambuco. In order to expedite field observations, Liais created a "movable observatory", whose main instrument was an altizimuth, a mixed theodolite-transit instrument designed to perform his original method quoted above as the predecessor of the Danjon-astrolabe.

This "mobile observatory" was installed at the city of Olinda, where Liais observed sunspots and discovered on February 26, 1860, a comet with a double tail (Liais comet).

Pedro de Alcantara received the news from Olinda with great enthusiasm and he went to that distant place (2000km from Rio) to visit his friend and scientific adviser.

In July 1860 Liais returned to Rio de Janeiro on board the vessel "Cruzeiro do Sul" where he observed a great comet discovered in Europe, 13 days before. Just after his arrival in Rio, he went to the "Morro de Castelo" (Castelo Hill) where the Imperial Observatory was installed, in order to observe that spectacular comet, the Great Comet of 1860. Those observations resulted in two papers published in the "Comptes Rendus".

During the next year, 1861, another great comet provoked exaggerated excitement among laymen. The comet was discovered on May 26, 1861 in Dydney, and it was very bright, covering a large part of the sky.

From his careful observations, Liais calculated the comet's orbit, and it was possible to prove that the Earth had crossed a great part of the tail. In an interesting paper, Liais presented his results and conclusions that there is no danger or poisonous materials in a comet's tail, because nobody noticed that encounter of our planet and a space vagabond, in reality "a bag of nothing" in Liais'words.

According to his contract, Liais would return to France in 1864. Three years was a short period to complete the most important part of his mission, the survey of the São Francisco Valley. In spite of the prospecting difficulties of that work, Liais found enough time to continue his scientific dispute with Le Verrier.

As an effect of the splendid success of Neptune's discovery, the Director of the Paris Observatory spent a great part of his busy time on arduous calculations to find another planet, looking for some small irregularities of familiar planetary orbits. Mercury was a very fine object for this research, because its well-known orbit exhibits such irregularities. Today we ascribe that abnormal behavior to a relativistic effect.

However, Le Verrier attributed to an unknown planet, situated between the Sun and Mercury, the source of those irregularities. Perhaps, the great astronomer went so far in his beliefs, and christened the intruder as "Vulcano".

In spite of the distance between Rio de Janeiro and Europe, Liais sent a paper to the "Astronomiches Nachrichten", where he attributed to an optical illusion the pretended observation of a Vulcano transit over the solar disk. That observation was reported by a modest vicar, who lived in a small town, far from Paris. The Director of the Paris Observatory went to that distant village, excited by a possible observational proof of his calculations. He suffered a strong deception when he saw the precarious instruments of the humble priest.

Such an event was a magnificent gift to Liais. In that paper, published in Germany, Liais was sarcastic and irreverent. A legend presented by Flamarion described Le Verrier's astonishment when he discovered that the modest priest was squint-eyed.

As a consequence of the article published in a country that was "the great French adversary", the political situation of Liais in France was very bad. The French Emperor, Napoleon the Third, refused Liais an ascent in the "Legion d'Honeur" and, a few years later, a place in "l'Academie des Sciences". On the other hand, another Emperor, Pedro do Brazil, appointed Liais chevalier of the "Ordem da Rosa", the most important aristocratic title of the Brazilian Empire.

Emanuel Liais: A Scientist Of Two Continents

Before his first return to France, in 1864, Liais executed the best work of his life, the São Francisco Valley Survey. Margaritha Trouven van Krenenbroeck, his extraordinary wife, was a perfect companion during the trip to inland Brazil. Besides her strong personality, Margaritha was a skillful and ingenious painter. For this reason, she played an important role in illustrating Liais' writings.

During the arduous expedition to São Francisco, Liais suffered a serious disease, and Margaritha performed all scientific observations, including the measurement of magnetic declinations. For this reason, that beautiful little woman, with lovely green eyes and charming brown hair, was the first South-American lady expert in Geomagnetism (Durand, 1866).

Some years later, in 1874, Margaritha died in France, as a victim of a tropical fever, a result of the trips in her second homeland (Durand, 1874).

The masterpiece of Liais, the book "L'Espace Céleste ou description de l'Univers accompagné de récits des voyages enterpris puor en compléter l'étude", includes a detailed report of the São Francisco Valley Survey. Another magnificent book is the "Traité d'Astronomie Appliquée et de Géodesie Pratique". If this second book is essentially a scientific treatise, the first is a broad essay about the Central-Eastern Brazilian Region, as an extension of concepts about the Earth and the Universe.

From 1864 to 1867, Liais lived in France where he wrote the main parts of those books, and improved the theory of his altazimuthal method to obtain latitude, longitude and to prepare star catalogues.

In 1867, Liais returned to Brazil with the difficult task of organizing the Imperial Observatory. It was a very complicated mission, because bureaucratic problems were present. The Observatory was responsible to two ministries: Ministry of War for the elaboration of the "General Chart of the Empire", and the Ministry of the Navy, for time keeping and magnetic declination measurements. In spite of strong support from the Emperor, it was difficult to conciliate many opposite and contradictory opinions. Frequently, Liais decided in favor of the Army and, in consequence, he earned the antipathy of the powerful Admirals.

The main administrative query of Liais occurred many years later with the most important man of the Empire, the Duke of Caixas, the powerful Commander of the Brazilian Army during the Paraguayan War and hero of a dozen of battles. When the Duke refused a credit to the Observatory, Liais used his own money to continue his scientific activities (Barreto, 1987).

Liais could not stand bureaucratic disputes and he returned to France in 1871. The political and economical situation in France suffered strong changes in 1870. In particular, Paris Observatory presented an unsustainable turbulence. A group of French astronomers, including Villarceau, Wolf, Loews, André, Lévy Rayet, Tisserand, published an article "Mémoire sur l'état actuel de l'Observatoire Imperial". That writing was worse than the most caustic of Liais' criticisms, because the later ones had mainly a scientific aspect.

In spite of those attacks, Le Verrier resisted in his strong place as Director of the Observatory, Senator, Academician and a good friend of the French Emperor, "Napoleon le Petit".

However, the Franco-Prussian War started on July 19, 1870, and it ended quickly and badly, when the French Emperor, on September 1st, 1870, became a prisoner of Von Moltke, the winner of the Metz and Sedan Battles.

Paris Observatory gained another Director, Charles Delaunay, a friend of Liais, who was invited to return to his previous position.

In August 1872, Delaunay suffered a tragic accident on trip Paris-Cherbourg, and the Observatory Directorship was a possible option for Liais.

Notwithstanding that incomparable opportunity, Liais was embarrassed, because he had on his hand a fraternal invitation from his Brazilian best friend. Pedro de Alcantara proposed to Liais a permanent appointment as Director of the Imperial Observatory of Brazil, without bureaucracy and under exclusive responsibility to the Ministry of Interior, with easy access to the Emperor. Besides those facilities, Pedro promised him the use of the Emperor's private funds in addition to the normal budget of the Observatory.

Liais faced a great dilemma: to be the Director of a small observatory in a new country or to direct one of the most important scientific institutions of the world.

The Southern location of Rio de Janeiro was the key for Liais' choice. In spite of all foreseeable difficulties in Brazil, it would be possible to organize the best observatory in the Southern Hemisphere and perhaps, the first in the History of Astronomy where a real "Observatory of the first order" could be operated, according to Liais'astronomical concepts.

The choice was not an easy decision, because Liais suffered a heavy pressure from his French friends and the Parisian newspaper (Ancellin, 1986).

After many months of troubled reflections, Liais decided to return to Brazil for the third time. In fact, a decisive step for this option was the visit of Pedro the Second to Paris in 1872.

Pedro looked up Liais and, in an unforgettable meeting, he reminded Liais of his promise to organize the Imperial Observatory of Brazil.

Both friends went to the popular journal "Le Moniteur Universel" and the Emperor introduced his friend Emmanuel as the present Director of the Imperial Observatory of Brazil.

During his stay in Paris, between 1871 and 1874, Liais was not scientifically inactive. Many letters were sent to José Maria dos Reis, a competent mechanician, to explain all details for building his "great altazimuthal instrument". A prototype was sent to Europe and, in 1873, Liais presented it to the Universal Fair in Vienna. It was considered an original and revolutionary instrument.

On the other hand, Liais published many interesting books and papers, such as "Climats, Géologie et Geographie Botanique du Brésil", "Sur l'analyse spectrale de la lumiere zodiacale et sur la Coronne des eclipses", "Sur les observations méridiennes absolues dans les basses latitudes de l'Hemisphere Austral".

An unusual book was also published by Liais: "Suprémacie intelectuelle de France: réponse aux allegations germaniques", where he followed Victor Hugo in the broad patriotic movement to save France from its deep depression after the 1870 defeat. Another Liais facet was exposed: the patriot, a real Frenchman of the 19th Century, and an artificer of the heroic moment of the Third Republic in 1914.

Notwithstanding those multiple activities, Liais found time to prepare the Observatory for his return. Several letters were interchanged with the Viscount of Prados, who was his temporary substitute.

Prados followed Liais' instructions and started a site survey to move the Observatory from the "Morro de Castelo", since that place "...was not a good site for heavy telescopes or for performing the delicate magnetic measurements...". It was the first trial to find a place that would meet some important requirements: a free horizon, a reasonable climate and the proximity of the harbour, in order to attend naval needs.

In Europe, Liais ordered many modern instruments and he suggested to Prados some improvements in the old buildings at the summit of Castelo.

Some years later, in the introduction to the first volume of the "Annals of the Imperial Observatory", Liais (1882) said that Prados was "...very competent, dynamic and a notable Director...". In an interesting comment, he reported that Prados refused the salary of Director, because he considered himself a mere substitute.

Before his return, Liais suggested to Prados to send to Europe two or three young assistants, in order to obtain a Doctor's Degree on Astronomy or Geodesy. Julião de Oliveira Lacaille and Francisco de Oliveira Junior were the first Brazilian astronomers with a Doctor's Degree from the Sorbone University.

The much desired altazimuthal instrument was completed by José María dos Reis and a modern set of magnetic instruments was acquired by Prados, using his own money.

Liais arrived at Rio de Janeiro on November 14, 1874 and, for seven years, he performed a considerable change in his Imperial Observatory. From a modest station dedicated to simple routine operations, the Imperial Observatory was transformed into one of the most important in the world. Using Liais' words, it was a real "Observatory of the First Order", where it was possible to determine the astronomical fundamental frame and the precise positions of fundamental stars with its own observational data. Liais stated that an "Observatory of the First Order" was able to maintain the "absolute time" reference. Many years later, Danjon (1954) considered such attributes as the definition of a "Fundamental Observatory". It is curious to note that both French astronomers created their own instruments based on the same principle.

It is difficult to report here all the scientific works performed by Liais in those seven years. When we look at a specialized bibliography (Gama, 1977; Ancellin, 1986; Morize, 1987; Barreto, 1987) and the old Liais' reports, we wonder about his titanic activities coming from a completely administrative organization of the Observatory and the Commission of the General Chart of the Empire, to the publication of important scientific papers. In spite of that difficulty, it is indispensable to quote briefly two examples of those works: the determination of the difference in longitude of Rio and Paris and the attempt to install the first magnetic observatory in Latin-America.

In the first example, Liais obtained a remarkable scientific result and a notable victory against his opponents. In the second instance, he was defeated by the bureaucratic vampire, allied with those adversaries.

In 1878 the Imperial Observatory started a vast program on geodetic measurements. It was planned to determine the precise values of longitudes of many points in the Brazilian coastline. It is important to remember that it was very difficult to take such measurements a century ago, when there were no radio facilities.

First of all, it was necessary to establish a very accurate value for one point, referred to an international data basis. For this purpose, Liais projected an electrical link between Rio de Janeiro and Europe, using an existing submarine cable. In a detailed report, Liais explained the method and he concluded that one important result would be a comparison between previous Mouchez' data with the new ones. Another interesting point of that report was the reference about the advantages that could be obtained by the North-American technicians and engineers in using the Imperial Observatory facilities and know-how.

Some time before the beginning of the work, in 1874, Liais designated astronomer Manoel Pereira Reis to measure the difference of longitudes of Rio and Barra de Pirahy. The assistant obtained good results and Liais intended to appoint him to coordinate all field works of the program. However, Reis was not very enthusiastic with such a job and, without any reason, he refused to continue the measurements.

A possible explanation for that refusal could be Reis' affinities with naval authorities. The Navy was not happy with the Imperial Observatory's program, because it was related with all Brazilian ports, and the naval authorities supposed that, at least, the "sailor" Pereira Reis would be in charge of the work at the harbour, not in the interior of the country, an Army land.

Liais sent a strong and hard memorandum to Reis, asking him about the reasons for that refusal. No answer was given to the Director, and Reis left the Observatory, in order to teach Astronomy and Navigation at the Naval Academy (Ancellin, 1986).

It was the starting point of a lifelong dispute and, probably, the reason for Liais' return to France in 1881. Manoel Perira Reis commenced an insidious campaign against the Imperial Observatory. His relations with the newspapermen were used for that purpose, and it is easy to understand the low level of such disputes. It must be said that Liais mantained a very ethical position and he ordered his assistants to keep complete silence.

In spite of that serene disposal, some of Liais' assistants, possible Lacaille, Souza Jacques and Cruls (Barreto, 1987) answered the attacks with sarcastic and burlesque mockeries, using words derived from Greek and Latin ("polimacróticos = big ears" for instance).

On the other hand, the longitude program continued at a good race. The difference of longitudes between Rio and Paris was obtained with a probable error of about 3 seconds, a notable value one century ago. A detailed explanation of that important geodetic work was published in the Imperial Observatory Annals and is discussed by Barreto (1987). Pereira Reis contradicted Liais' results and the dispute was scientific, for the honour of both men. A careful analysis of the previous results presented by Mouchez, Manoel de Mello and the U.S. Comission of Longitudes confirmed the accuracy of the new values.

The work on longitudes had not impeded the continuation of other scientific activities of the Observatory, as could be noticed in several Liais reports. Regular observations of sunspots were started and a very original research on visual double stars was initiated by Luís Cruls, an active and competent Belgian astronomer, who was to be the successor of Liais. Cruls' observations on double stars were the first in the Southern Hemisphere, and they were recorded in the files of the Lick Observatory, the international center for that subject at the time (Barreto, 1987).

However, Liais was not satisfied because he intended to install a complete and modern geomagnetic observatory. He tried to perform magnetic observations at Castelo Hill, using old magnetometers. However, the conditions of the soil were a serious obstacle to reasonable precision. Besides, strong parasite currents provoked considerable compass deviations, there were many local anomalies.

For those reasons, Liais planned to move the magnetic equipment to a new site, not far from Castelo. He obtained from the Government authorization and reasonable funds to buy new magnetic instruments. That administrative success would be followed by full-time assistance of a competent specialist. For this reason, Liais contacted the well-known Dutch geomagnetist Van Rickjervosel, who accepted the invitation.

Soon after his arrival, Van Rickjervosel studied two possible sites to install the new magnetic observatory: Castelo Hill and Santo Antonio Hill. Both had similar elevations and they were distant one from the other about 1 km. Today both hills do not exist because they were demolished to give way to large modern avenues.

Santo Antonio had a better shape than Castelo, because of its plane summit. Van Rickjervosel agreed with Liais about the adventages of Santo Antonio, and a small and cheap project was prepared.

At this point of our story, the malign bureaucratic monster was used by the enemies of the Imperial Observatory. When Liais asked the Government for the necessary authorization to build a few modest pavilions for the installation of the magnetic instruments, he received and absurd answer. Such constructions would not be authorized because all the area of Santo Antonio Hill had been reserved for the installation of a new and well-equipped Naval Observatory ("the first serious astronomical institution in Brazil" in the words of the newspapers), that would be directed by Manoel Pereira Reis. It was an incredible shock to Liais, who left his country and opportunity to direct a great observatory in order to spent the rest of his life in Brazil.

In February of 1881, Liais received the notice of his mother's death. In a letter to Le Jolis (Ancellin, 1986), Liais said that he was "strongly depressed after the depth of the two angels in his life: Margaritha and his mother".

Personal misfortune combined with strong scientific deceptions and he decided to return to France. However, before his departure, Liais gave Luís Cruls full detailed instructions and advice to continue his notable project for an "Observatory of the First Order", including the Geomagnetism in Brazil.

Van Rickjervosel was impeded from performing his mission to install a new magnetic observatory but, in spite of this disappointment, he performed other important work: the magnetic survey of a large area in Eastern Brazil, including the São Francisco Valley. As a result of that great work, Van Rickjervosel elaborated the first set of magnetic charts of Brazil for the epoch 1883. Using Liais data and other old values, he outlined provisional values of secular variation. Van Rickjervosel's results were very important for later studies on secular variations (Godoy, 1972; Barreto 1989I; Barreto, 1989II).

Some years after his last return to France, Liais was elected Mayor of Cherbourg (Ancellin, 1986) and he ended his useful life as politician.

Today Liais lies beside his beloved Margaritha at the Hardinvast Cemetery, Cherbourg, under the shadow of bamboos and palm trees imported from his second homeland. An inscription on his tombstone reads: *"Here lies Emmanuel Liais, Astronomer, Explorer and Naturalist, Directeur-Adjoint of Paris Observatory and Director of the Imperial Observatory of Brazil".*

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HISTORICAL REVIEW OF ARGENTINE ACTIVITIES IN GEOMAGNETISM AND AERONOMY

Otto Schneider

1. PRELIMINARY REMARKS

Research in the disciplines embraced under the general concept of Geomagnetism and Aeronomy belongs in Argentina, with very few exceptions, to the XXth Century. Changes in the administrative and academic organization of such work have frequently occurred all over the world, partly as a consequence of the explosive development of techniques and theories, and partly in the framework of the ever changing historical scenarios within the participating nations. This also applies to the case of Argentina, still a young country. With the exception of a very few outstanding leaders, organizers and teachers we must, alas, refrain from quoting the numerous individual scientists and technicians who have contributed to this development; it is impossible to do justice to all of them, but many names will appear in the references. Suffice it in the present context to remark that they were recruited, in addition to geophysicists proper, among physicists, geologists, geodesists, mathematicians, astronomers, engineers, and members of the armed forces.

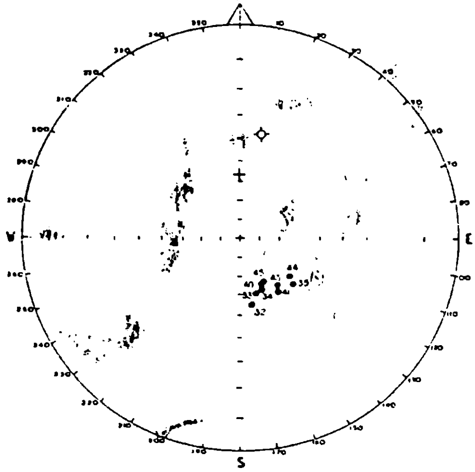
2. OUTLINE OF AREAS

It was unavoidable that in the historical evolution much effort, perhaps to an excessive degree, went into the pursuit of just producing data not always duly exploited. This is particularly regrettable in view of the notorious S-N unbalance caused by relative scarcity of information from the southern hemisphere, especially in higher mid-latitudes.

Quite naturally, the earliest activities belonged to the domain of geomagnetism at large. Studies in this area implied both permanent observatories and temporary stations, as well as local, regional and nation-wide surveys, most of which will be enumerated in some detail in the later sections. They contribute, of course, to global representations of the main field, its anomalies and secular variation, furnishing at the same time basis values for the variations and for applied Geophysics.

In the mid-fifties, following suggestions from the already flourishing British study-group on Paleomagnetism at Newcastle-upon-Tyne, and with their active participation, this branch of geomagnetic research was started in Argentina. Its scope embraces field compaigns to secure rock samples under specified prescriptions, laboratory treatment of the samples, and theoretical interpretation.

As an early example of the many hundreds of specimens collected and laboratory-cleansed, Fig.1 shows the angular distribution of the thermoremanent magnetization for a sampling site of basalts of suprapliocene age in the Pampa de Zapala, Prov.of Neuquén, in comparison with the present field direction. The sampling campaigns covered pace by pace the whole Argentine territory including several sites in the Antarctic; some samples were also collected on the Malvinas Islands (or Falklands, in the British nomenclature) prior to the unfortunate military event some years ago.



Figurel. *An early example ofpaleomagnetic thermoremanent field direction (Valencio 1965).*

Both in planning the strategy of campaigns and ensuing laboratory work and interpretation, a close and fruitful coordination was maintained with geologists and specialists in dating by means of isotopes or other evidence. This permitted integrating the results in the broader context of other geochronological studies, as well as in regional and global tectonics, and speculations on the evolution of the main geomagnetic field in the geological past.

Overcoming an initial lukewarm enthusiasm on the part of some traditionally oriented geoscientists, the group attained a vigorous expansion, installed up-to-date equipment, and produced conspicuous research results, giving rise to the establishment of the renowned Laboratorio de Paleomagnetismo, which is named after its founder Daniel A.Valencio. A short obituary tribute was paid elsewhere (Schneider, 1987). Being also a center of technical and academic training it soon attracted students, technicians, and permanent or visiting research colleagues from Argentina, other Latin-American countries and abroad. The Laboratory is associated with the chair in Geophysics at the Facultad de Ciencias Exactas y Naturales, Buenos Aires University, and receives support from the Consejo Nacional de Investigaciones Científicas y Técnicas.

After his untimely death in 1987, Valencio was followed in his function by his first and most active disciple (since the late fifties), Juan Francisco Vilas, who is with us at this Assembly.

In contrast with the scope of the paleomagnetic center, which covers the full range from field work, through laboratory processing till theoretical interpretation, other groups and institutions have concentrated their work either on just observation, or processing, morphological analysis, modeling or interpretation, using data from both national and foreign sources. This applies especially to the studies on geomagnetic time variations with periods much shorter than those of the secular change.

A reasonably balanced equilibrium prevails in upper atmosphere studies, on which we shall report later on. Activities in this domain, along with theoretical research on aeronomic aspects in the narrow sense of the term, comprise ground-based and in situ observations of ionospheric parameters, auroral and airglow phenomena, their modelling and morphological and statistical analysis, generally in relation with solar and geomagnetic activity and interplanetary space conditions.

For brevity, we must refrain from including in our review subjects such as Cosmic Radiation, which in the course of the historical evolution has lost contact with IAGA's terms of reference. Argentine studies in this field go back to the forties of our century.

As elsewhere, there have been many side-connections between the activities in diverse branches of Geomagnetism and Aeronomy, as well as with neighbouring sciences such as geology, oceanography, cartography, atmospheric physics, heliophysics, space research, along with nautical applications and mineral-field exploration.

3. GEOMAGNETIC OBSERVATORIES

In chronological order, long series of both absolute observations and time variations were obtained at the following stations:

Observatory	Geographic Lat.(S)	Long.(W)	Period in operation (1)
Isla Año Nuevo (New Year's Island)	54.6°	64.1°	1902-1917
Pilar	31.7°	63.9°	1904-present
(2) Orcadas del Sur (South Orkneys)	60.7°	44.8°	1904-present
La Quiaca	22.1°	65.6°	1920-present
Las Acacias	35.0°	57.7°	1957-present
Trelew	43.2°	65.3°	1957-present
(3) Base General Belgrano	78.0°	38.8°	1969-present

Notes: (1) With occasional interruptions; (2) Z-component failing for some time; (3) no absolute values, but exploitable time variations.

An experimental series (of time variations only) was also obtained for some years at Tucumán (geogr.lat.: 26.9°S; long.65.2° W).

In general, at all these sites (except Base General Belgrano and Tucumán) the classical types of absolute instruments and analogue recorders have been used, but none had fully automatic output. Graphs showing the secular variation by annual mean values are given by Vestine et al. (1948) for Isla Año Nuevo (1902...1916), Pilar (1905...1945) and La Quiaca (1920...1933); more up-dated individual annual means for the whole network were listed by the Institute of Geological Sciences, UK (1981). Hourly values of the 3 field components from Isla Año Nuevo for the whole period on diskettes are held by the Instituto Antártico Argentino and the Data Center for Geomagnetism and Spacemagnetism, Kyoto University, Japan.

Among the observatories listed above, Pilar has played an outstanding rôle as the centre of organization and supervision of geomagnetic activities at large in Argentina and for several years as the seat of the continental reference point for the intercomparison of instruments (Lützow-Holm, 1956). Thanks to the regularity and reliability of its observations under the leadership of Olaf Lützow-Holm it has attained high renown.

More than three decades before the foundation of Pilar a Professor of Physics at Córdoba University, Oscar Doering, following a recommendation by the International Congress of Meteorology, Rome, April 1879, and successive meetings of the International Polar Commission and perhaps also motivated by Gould's first sporadic field measurements (see Section 4), published a brochure on the convenience of establishing a magnetic observatory at Córdoba (Loyarte 1924). Doering's initiative failed to succeed, possibly for lack of appropriate instruments; however, he himself made many field observations from 1882 onwards.

Figure 2. *Isla Año Nuevo observatory shortly after its foundation in 1902.*

A similar precursory example of its later intense engagement in geomagnetism exists at La Plata. Soon after its foundation as part of the University in the eighties, the (originally just "Astronomical") Observatory had a set of absolute instruments for D, H and I (made by Brunner), along with photographic variation recorders which were run in a temperature-isolated cabinet (Anonymous, 1891).

As for Isla Año Nuevo, the earliest long-standing Argentine geomagnetic observatory, Fig.2 shows its buildings shortly after its inauguration (Anonymous, 1903).

4. SPORADIC GEOMAGNETIC FIELD OBSERVATIONS

Benjamín A.Gould, founder of the astronomical observatory at Córdoba and of the Servicio Meteorológico Nacional (Schneider, 1991), was the first to make isolated field observations at two sites in the interior of the country, Córdoba and Rosario, in the summer of 1882/3. Similar sporadic observations, generally just visual, beginning about 1951, aimed at either local small scale surveys or determinations of the daily variations as a function of latitude; they included:

a) about one tenth of the repeat stations occupied during the regular national surveys (see section 5);
b) many sites in the Antarctic visited by Slaucitajs and his collaborators as well as observers of the Servicio Meteorológico Nacional (Deception Island; Melchior; Gerlache Strait; South Sandwich Islands; the Antarctic Península at large; the nunataks east of the Filchner Ice Shelf;
c) a two-months campaign in the surroundings of La Quiaca observatory (in 1958);
d) three weeks of continuous time variations at the coastal site Mar del Plata, by the Servicio de Hidrografía Naval (in 1965);
e) a few days near the rocket-launching field of Chamical, Province of La Rioja (in 1964);
f) seven points in the Province of San Juan, by the "Instituto Sismológico Zonda" in combination with a "deep sounding" project of the Carnegie Institution of Washington;
g) a N-S profile on board the icebreaker "General San Martín" during the 1966 Antarctic campaign.

5. GEOMAGNETIC SURVEYS

The Oficina Meteorológica Argentina, forerunner of the present Servicio Meteorológico Nacional, apart from a few sporadic regional field observations in the XIXth century, started systematic territorial geomagnetic surveys in the very first years of our century, shortly after incorporating the Orcadas del Sur (South Orkneys) observatory and the foundation of Pilar. The first isogonic map, based on 90 sites, was for epoch 1908 (Fig.3); the following one, epoch 1914,comprised 144 points. From epoch 1931 onwards, the charts included the three relevant geomagnetic elements (Dirección de Meteorología, Geofísica e Hidrología, 1933, serie A, publ. No.1). To illustrate the volume of these painstaking surveys, suffice it to say that between 1931 and 1971 a total number of 708 points were visited, including 1st, 2nd..., 6th reoccupations.

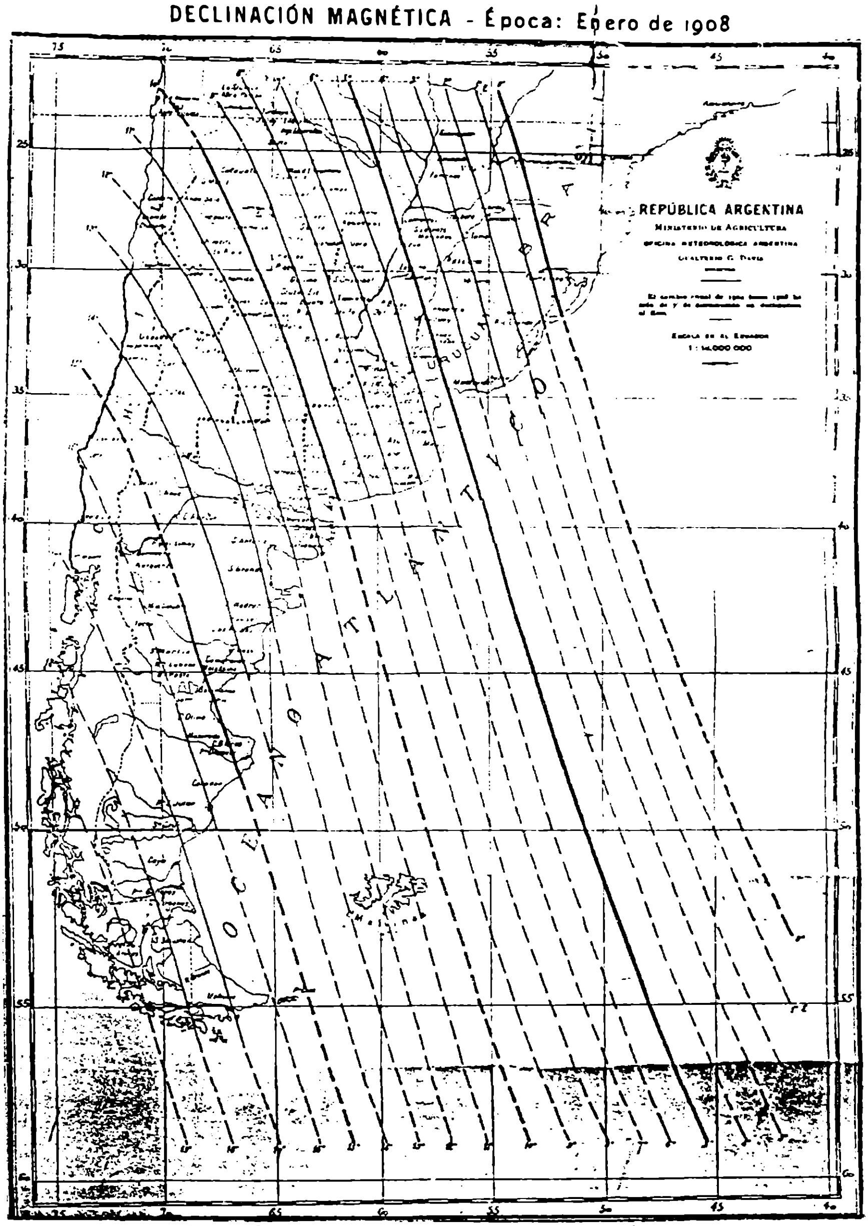


Figure 3. *One of the first Argentine isogonic charts.*

The Department of Terrestrial Magnetism, Carnegie Institution of Washington, during its world-wide geomagnetic surveys also included the Argentine territory in its campaigns between 1911 and 1926. Many of the sites appropriately coincided with those of the national surveys just mentioned; during the interval 1917 till 1926, in particular, these numbered 70 points.

The Servicio de Hidrografía Naval (SHN), made several specifically geomagnetic surveys, sometimes along with gravimetric and seismological observations. Though generally confined to areas of regional extent, taken together they form an integral survey of the South-Western Atlantic Ocean down to subantarctic latitudes, which is of interest in view of the South-Atlantic anomaly. These operations began soon after the IGY and used towed carriers equipped with modern magnetic sensors of diverse types. The cartographic representations at first showed only the total force, but in later years isogonic maps for epochs 1965 and 1979 were published, preceded by a former one, for epoch 1946, which was based on older observations by the Navy, complemented with data from the Servicio Meteorológico Nacional.

Some of the surveys implied coordination with, or contributions to US operations (such as the "Project Magnet" for the World Magnetic Survey, 1962/3) and the National Oil Field Agency (YPF). The SHN also gave support to several aeromagnetic surveys such as those carried out by YPF since 1952. For more information on operational details and references on partial interpretations see Schneider and Sánchez (1980), who also give some historical and statistical data on the geomagnetic operations executed by YPF. Both this official agency and private companies engaged in Exploration Geophysics, used of course geomagnetic methods, though less predominantly in recent years. However, only the geomagnetic operations of YPF reached, in some cases, an extent that would justify the denomination of surveys, and this only in a narrow regional sense.

6. IONOSPHERIC OBSERVATIONS

Starting in 1950, ionospheric observations comprised vertical soundings, absorption, signals in VLF and from beacon satellites, forward scatter and whistlers. With diverse grades of participation and direction they have been carried out in a nation-wide network of 9 permanent or temporary stations straddling a latitude range from 25°S to the Antarctic Base General Belgrano (78°S), the latter along with the near-by Ellsworth station, which after the IGY was operated under a joint program with the US National Science Foundation from 1959 till 1962. The Nestor in this chain is the observatory at Vicente López, near Buenos Aires, known by the acronym LIARA, founded by the Navy in 1950. Later followed the remaining stations since the IGY, some of them under the LIARA, the Universities of Tucumán, San Juan, and La Plata, as well as the National Commission of Space Research, in several cases with the active support and coordination of the Consejo Nacional de Investigaciones Científicas y Técnicas. About half of the vertical sounding stations used the TRIO sounder, developed by the LIARA. The LIARA and a N-S chain of stations under its supervision (Trelew; Ushuaia and Deception Island in the Antarctic) also participated in the exploration of the ionosphere from above by regular observations of the Canadian satellite Alouette in 1964.

Absorption, a special feature of ionospheric conditions, has been the objective of cosmic noise recordings in 27.6 Mc/s at Base General Belgrano, since 1964; more recently, similar observations were started at San Martín (lat. 68°08'S; long.67°04'W).

7. AERONOMY, AIRGLOW AND AURORA

Airglow observations started at San Juan during the IGY, originally using an all-sky photometer loaned by the US Environmental and Space Sciences Administration (ESSA). Later on, beginning in 1966, a N-S chain of three stations equipped with zenith photometers was established near the 70°W meridian: Abra Pampa (_ 23°S), El Leoncito, near San Juan (_ 32°S) and Bariloche (_ 41°S). These produced valuable data till (and beyond) 1971, except Bariloche, which ceased observing after 1969; they worked with narrow-band interference filters in 4 spectral domains covering the classical oxygen and principal sodium emissions. For more complete references and analysis of some of the data see Schneider and Sánchez (1980, pages 118/9).

The increasing interest in Antarctic subjects stimulated the instalment of a broad program of auroral research beginning shortly before the IGY, with systematic visual observations at the Base General Belgrano, a site specially suited for auroral work owing to its position just outside the northern rim of the auroral zone. This was completed since the IGY with regular all-sky camera recordings and continuous photometric measurements of the main spectral emissions. In addition a Perkin-Elmer spectrograph was operated at Ellsworth under the joint program with the US National Science Foundation in the years 1960 through 1962.

Emphasis was laid on recognizing, whenever possible, the morphological features and latitudinal evolution of auroral displays by securing the permanent attention of meteorological observers and amateurs including the continental South-American territory. This network was set up under the coordination of the IAA[1], where a permanent Division of Upper Atmosphere Physics had been formalized in the IQSY. A noteworthy example of the results obtained was the low-latitude extent of the display observed in both hemispheres on occasion of the spectacular disturbances of mid March 1989 (Schneider 1989; 1990).

In situ observations of the upper atmosphere by means of balloons, rockets and satellites were made by an important number of institutions and study groups comprising in diverse combinations the Comisión Nacional de Investigaciones Espaciales
(CNIE); the Comisión Nacional de Energía Atómica (CNEA); the Instituto de Astronomía y Física del Espacio (IAFE); the Laboratorio de Radiación Cósmica, Tucumán University; the Escuela Superior Técnica del Ejército; the Universidad Tecnológica Nacional (UTN); the Instituto de Matemática, Astronomía y Física (IMAF) at Córdoba University; the Comisión Nacional de Estudios Geo-Heliofísicos (CNEGH); the Universities of Cuyo, La Plata and Buenos Aires; the Centro Nacional de Radiación Cósmica, and the Instituto de Investigaciones Aeronáuticas y Espaciales (IIAE) of the Air Force.

Balloon-borne observations in the upper troposphere and stratosphere up to heights of over 30 kms were made since the early sixties covering the whole continental territory and exceptionally the Antarctic and off-shore sites in the South-Atlantic. The carriers had volumes of up to 500.000 m3. The experiments comprised Cosmic Radiation; X-rays; "bremsstrahlung" electrons; _-radiation from solar flares; solar neutrons, and ionizing radiation at large.

Altitudes between 50 and 270 kms were reached by some 150 rocket-soundings since 1962, which in addition to the above mentioned aspects aimed at the observation of winds and

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[1] Instituto Antártico Argentino, which was also responsible for the activities summarized in the foregoing paragraph.

specific ionospheric parameters. Many of the balloon and rocket soundings were launched from the permanent bases at El Chamical (La Rioja Province) and Mar Chiquita (Buenos Aires Province).

Beginning with the launching of the Explorer XXII on 9-X-64, and later successive similar spacecraft, the ionospheric research group at Tucumán University have been observing the Faraday rotation and scintillations of the signals from beacon-satellites in search of the total electron content and of the atmospheric and ionospheric irregularities, respectively. A parallel series of such observations was obtained at Ushuaia, Tierra del Fuego, in 1964.

For further details cf. Schneider and Sánchez (1980).

8. TROPOSPHERIC AND TERRESTRIAL ELECTRICITY

The early name of the IAGA was IATME, claiming competence in the field of terrestrial electricity at large, along with Geomagnetism. In accordance with this scope, research on subjects such as tropospheric electricity, the electrostatic charge of the Earth, and earth currents was often carried out in connection with geomagnetic studies in several countries. In Argentina the Meteorological Service made observations of dispersion (Wulf; Elster and Geitel); ion content (Ebert); mobility (Ebert); conductivity (Gerdien); potential gradient, and atmospheric nuclei at La Quiaca, Tucumán, Pilar, Mendoza, and Buenos Aires, starting in 1924 at Pilar; a half-yearly series of conductivity measurements was also secured on Deception Island during the IGY. In addition, the Jesuit observatory of San Miguel made similar observations of thunderstorm electricity and atmospherics as well as earth-current recordings.

Closely related to the field of terrestrial electricity, magneto-telluric phenomena deserve a mention in the present context. In the strict usual sense of the term, these studies involve combined simultaneous measurements of the magnetic and electrical components of electromagnetic field variations; surveys of this type addressed to establishing vertical profiles of the internal electric conductivity were made in Argentina since the early seventies by diverse very active groups located at San Miguel, Mendoza and Buenos Aires.

Sophisticated spectral analyses of geomagnetic variations alone also permit determining similar profiles down to considerable depths; a leader in this branch of deep soundings has been a group at the Physics Department of Buenos Aires University.

9. TEACHING

Geomagnetism and Aeronomy are considered in the various pre-and postgraduate courses offered in the curricula of General and Applied Geophysics, Geodesy, and Civil Engineering by many of the national, provincial and private universities such as Buenos Aires, La Plata, Rosario, Mar del Plata, Córdoba, Mendoza, San Juan, Tucumán and others. However, only La Plata, in its Facultad de Ciencias Astronómicas y Geofísicas, has a chair explicitly specialized in Geomagnetism, established in the late forties; it was held by L.Slaucitajs during his 20 years of activities at La Plata. For more details on the teaching of Geophysics at large, see Valencio and Schneider (1986).

10. THREE PIONEERS

As an exception to the general rule of anonymity here adopted, we must pay an explicit homage to three meritorious colleagues who are no longer with us: Olaf Lützow-Holm, the founder and life-long head of Pilar and Supervisor of geomagnetic observations at large; Leónidas Slaucitajs, initiator of the chair of Geomagnetism and Atmospheric Electricity at La Plata University and founder of the observatories at Las Acacias and Trelew; and Daniel A. Valencio, founder of the Laboratory of Paleomagnetism at Buenos Aires University and leader of a flourishing research group there. Biographical notes are given elsewhere (Schneider and Sánchez, 1980, for the first two; Schneider 1987, for Valencio). All of them have served on the Executive Committee of IAGA, a recognition of their lasting realizations in the field of Geomagnetism and Aeronomy.

11. RESEARCH - SOME EXAMPLES

Research groups engaged in activities beyond the mere acquisition and handling of original data exist at some ten University chairs and several official institutions such as the Weather Service (Servicio Meteorológico Nacional) through its Institute of Geophysics; the Hydrographic Office (Servicio de Hidrografía Naval); the Naval Ionospheric Laboratory (LIARA); the Argentine Antarctic Institute (IAA); the Institute of Astronomy and Space Physics (IAFE); the Institute of Geochronology and Isotope Geology (INGEIS); the regional Centre CRICYT of the National Research Council (CONICYT) and others under the same nation-wide organization, as well as several individual free-lance investigators. They have been active since the first decades of our century, covering practical the whole scope of phenomena which come under the terms of reference of IAGA.

As it is impossible to do justice here to all of them, let it suffice to peruse in broad lines the main areas, which comprise: terrestrial and atmospheric electricity including magneto-tellurics; physico-chemical Aeronomy; magnetospheric and ionospheric Physics (including analysis of absorption deduced from cosmic noise variations); the main geomagnetic field and its secular variation; rock magnetism and paleomagnetism (backed by objective age determinations based on isotope analysis); and geomagnetic solar and lunar variations and perturbations.

The wealth of publications which reflect these studies range from mere reports, descriptions, elaborate research papers to challenging communications of new results, theories and speculations. They comprise, individually or in diverse combinations, aspects such as: the morphology of the phenomena, including their distribution according to latitude, altitude and depth; the genesis and dynamics of the processes involved as well as their interactions; solar-terrestrial relationships; modeling; statistical variability, along with suggestions for the development and improvement of the methods of processing and analysis (which generally comprise correlation, harmonic and spectral analysis, and the method of superposed epochs).

To finish, let us consider a few cases of results pertaining to studies of geomagnetic time variations. The first example (Fig.4) represents a tentative series of local daily character figures obtained by combining and normalizing semi-quantitative assessments of the disturbance level in the 3 components recorded at Isla Año Nuevo. The diagram, which is arranged according to solar rotations, shows the activity values for a short initial interval of the 16 years of available data. It is expected that the full series of daily activity indices from a poorly covered southern latitude will be a welcome addition to the world-wide scheme of character figures for the early years of our century.

Observatorio Año Nuevo
Grado de actividad geomagnética

Rotación Solar	Año	Fecha	1º Día																											
																								2	-	1	2	3	2	3
949	1902	M	9	1	-	4	4	2	2	2	2	?	-	1	1	2	2	2	5	4	2	2	.	1		2	2	2	2	2
50		A	5	2	1	2	2	2	5	6	3	2	2	-	2	2	-	2	5	3	2	2	-	-	-	-	2	-	2	2
51		M	2	2	2	2	2	2	2	4	5	3	-	-	2	2	-	1	2	2	2	-	-	1	2	2	2	2	2	2
52		M	29	2	2	2	2	-	-	1	1	2	2	1	-	2	2	2	2	1	4	3	2	2	1	-	1	2	2	2
53		J	25	2	2	2	2	4	2	2	2	1	2	-	-	2	4	3	2	2	2	2	2	4	3	-	2	2	-	2
54		J	22	2	5	7	5	4	2	2	2	-	-	-	2	2	2	2	1	-	1	2	4	3	-	-	-	-	2	2
55		A	18	2	-	2	5	6	3	2	2	2	1	1	1	1	2	2	3	2	2	2	2	-	-	-	-	-	2	-
56		S	14	-	2	2	2	4	5	6	3	5	3	-	2	-	2	2	4	3	2	2	2	2	2	1	-	2	-	2
57		O	11	5	3	2	-	-	1	2	3	1	2	2	2	4	4	3	3	2	2	4	5	6	2	2	2	-	-	2
58		N	7	2	2	2	-	1	2	2	2	4	3	2	2	2	1	4	4	5	6	3	2	2	2	-	1	2	2	2
59		D	4	2	2	-	2	2	4	2	2	2	3	2	2	2	2	2	2	2	2	5	6	3	2	2	2	2	2	2
60		D	31	-	2	4	3	4	3	2	-	2	2	4	2	2	2	2	2	2	2	4	3	2	2	2	4	3	2	4
61	1903	E	27	2	1	-	2	1	-	2	-	-	2	2	4	5	2	2	2	4	3	2	2	3	2	1	2	3	4	3
62		F	23	1	2	2	2	-	-	3	2	1	2	3	3	4	3	2	2	2	4	3	2	1	-	-	2	1	2	2
63		M	22	4	2	-	-	-	-	2	2	5	3	2	2	2	2	5	8	5	4	8	3	3	2	2	2	2	1	2
64		A	18	3	3	1	2	-	2	1	2	5	3	2	-	-	-	-	2	5	7	7	3	3	2	-	-	-	2	2
65		M	15	3	5	4	1	-	2	3	3	4	4	3	2	3	3	3	3	1	5	7	5	3	1	2	-	2	-	2
66		J	11	2	-	1	-	-	5	4	3	4	3	4	4	4	3	2	-	-	5	7	5	3	3	2	2	5	4	2
67		J	8	-	2	4	4	2	2	3	3	4	3	4	6	2	2	2	2	-	4	6	7	7	3	1	2	2	2	2
68		A	4	5	3	1	2	2	3	4	6	4	6	5	3	3	3	3	1	2	6	7	5	3	4	6	3	2	-	3
69		A	31	2	2	2	-	4	5	3	4	5	4	3	4	4	3	2	2	-	2	2	5	7	3	4	4	3	2	2
70		S	27	2	3	4	2	4	3	3	3	5	5	6	3	2	3	4	7	7	5	3	3	3	3	3	3	2	2	3
71		O	24	3	4	6	2	2	4	6	▮	7	5	6	7	3	4	3	3	5	7	3	3	3	2	2	3	5	7	3
72		N	20	3	4	6	4	2	2	2	2	4	3	3	5	7	3	5	5	3	5	4	3	4	3	3	5	4	2	2
73		D	17	2	2	2	4	2	2	2	2	2	2	2	2	5	7	7												

Clave:

- 1 2 3 4 5 6 7 8 ▮

Figure 4. *First sketch of a 16-year series of preliminary local daily character figures for Isla Año Nuevo.*

The next graph (Fig.5) shows a N-S profile, from La Quiaca to the South Pole, of horizontal plane vectograms of the quiet solar daily variation at maximum solar activity.

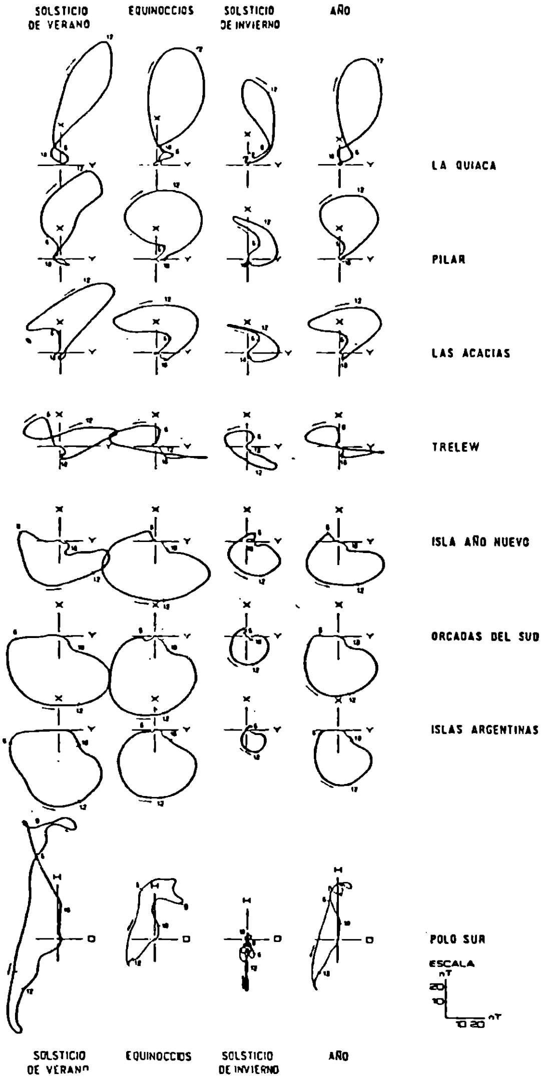

Figure 5. *North-South profile of horizontal plane Sq vectograms, including two stations (Islas Argentinas and South Pole) which are not under Argentine administration.*

Remarkable features are: 1) the enhanced amplitudes at La Quiaca, influenced by the equatorial electrojet; 2) the atrophied course of the variations at Trelew; 3) the inverted sense of rotation south of Trelew; 4) the enhanced annual modulation with increasing latitude; 5) the anomalous behaviour at the South Pole, illustrating the contamination by non-Sq effects within the polar cap. Trelew is located under the focus of the equivalent ionospheric current system, which was the main reason Slaucitajs had in mind when selecting this site.

Our last illustration (Fig.6) shows the lunar diurnal variation of declination at Isla Año Nuevo as a function of lunar time and lunar age. The isolines are in units of 10^{-2} nT; the ascending straight lines correspond to local noon and midnight, respectively. Notice the following features: 1) the predominantly semi-diurnal form of the geomagnetic tides; 2) its confinement to the sunlit hours of the day; 3) the systematic phase shift in the course of a lunation (vertical sections), an eloquent illustration of Chapman's phase-law, established early in our century.

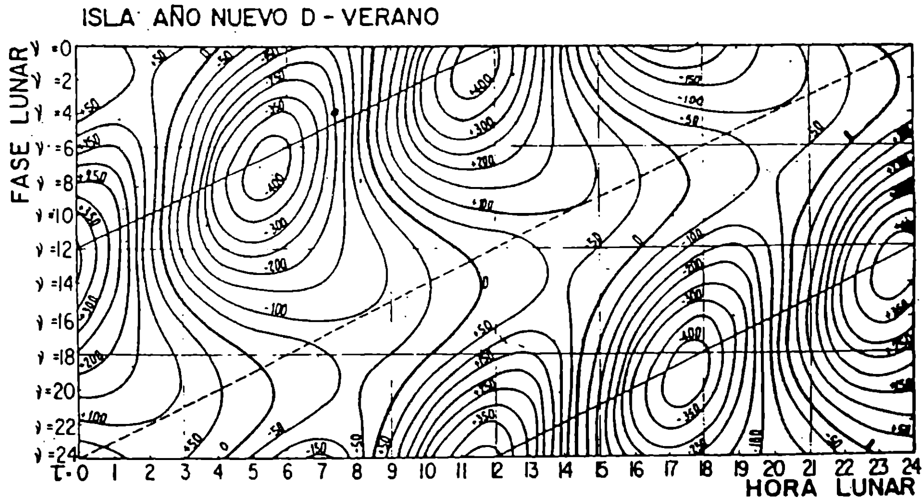

Figure 6. *Lunar geomagnetic tides in Declination at Isla Año Nuevo, summer, low solar and geomagnetic activity. Units: 10^{-2}nT.*

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AN OVERVIEW ON THE STUDY OF THE EQUATORIAL ELECTROJET

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ABSTRACT

In this work, a balance on the present status of the study of the equatorial electrojet is presented. Particular attention is paid to a better understanding of what one can expect from the worldwide cooperation for the International Equatorial Electrojet Year, (IEEY) regarding the theoretical and experimental aspects. It will be seen that our limited knowledge of this phenomenon is due to the impossibility of the existing observatories to provide data with satisfactory time and height resolutions for all parameters required to test the theoretical models. We also investigate the possibility that equatorial phenomena related with the electrojet may contribute to evaluate some of these parameters.

1. INTRODUCTION

The interaction between the neutral and ionized parts of the upper atmosphere, at equatorial latitudes, is responsible for the generation of a wide range of phenomena: sporadic E layers, equatorial electrojet, spread F, plasma instabilities, etc. (see review by Rishbeth, 1979). Sporadic E layers result from a vertical tidal wind which under special conditions can confine ionization in a narrow layer located somewhere in the height range 90-115km (see Zamlutti, 1983). The equatorial electrojet is attributed to the action of tidal winds, which moving the ionosphere across the magnetic field, provoke the appearance of a current flowing along it (see review by Forbes, 1981). This occurs mainly in the height range 100-160 km. Plasma microinstabilities are produced by perturbations, on the electrostatic field responsible for the electrojet current (see Farley, 1963). Fluid type instabilities are due probably to two stream or to gradient drift amplifications processes also present at the same altitude range, namely 90-115 km (Fejer and Kelley, 1980). Equatorial spread-F is due to a collisional Rayleigh-Taylor type instability driven by an electrostatic field in the range 250-450 km (see Ossakow, 1991) which amplifies the gravity waves oscillations transferred to the ions and electrons by the neutrals. Interrelations among all these local phenomena are still not completely established in spite of the considerable efforts made so far (see Richmond, 1992 for references). The reason is that the local phenomena are sometimes strongly related to the global dynamics of both the ionosphere and thermosphere (see for example Takeda and Maeda, 1980; Fejer, 1986). A complete study of the coupling processes was presented by Schunk (1988) considering the global dynamics of the regions contained within the plasmaphere limits.

The equatorial electrojet, as part of the global upper atmosphere dynamics, can be properly studied if its theoretical model includes both the hydrodynamic and electrodynamic aspects of the problem in a self-consistent manner. This was done by Zamlutti et al (1989) and is now being implemented in numerical models (see Richmond et al 1992). The first results (Richmond et al 1992) reveal the ability of the model to study the neutral and plasma dynamics and electrodynamics in the vicinity of the magnetic equator. The past history of electrojet models can be found in Forbes (1981). Other potential models to study the global dynamics are those of Namgaladze et al (1990) and Roble et al (1988).

The new trend of trying to predict electrojet characteristics using global models can change the importance of the local measurements of electrojet behavior. Since these measurements are now used to improve the specifications of the inputs of the global models, it will be imperative to rely on high quality data rather than to worry about good space time coverage with poor resolution.

In this paper we overview the major theoretical and experimental aspects of the study of the equatorial electrojet, with emphasis on the new trends of this study. As for the theoretical aspects we compare the grounds of the new with the old theories to establish the expected differences. Regarding the experimental aspects we comment on the importance of the data collected by different techniques to complement our study.

2. THEORETICAL ASPECTS

The basic equations which describe the global self-consistent equatorial electrojet structure were presented by Zamlutti et al (1989) as:

$$\partial \underline{h}/\partial t = \delta \underline{h} - \nabla . \underline{\underline{\phi}} + \underline{f}(\underline{a}) \qquad (1)$$

$$\frac{\partial}{\partial t}\begin{pmatrix} \varepsilon_0 \underline{E} \\ -\underline{B} \end{pmatrix} = \nabla x \begin{pmatrix} \mu_0^{-1} \underline{B} \\ -\underline{E} \end{pmatrix} - \begin{pmatrix} j \\ \underline{O} \end{pmatrix} \qquad (2)$$

where $\underline{h}$ represents a 5-dimensional vector whose components are the density, the three space components of the momentum and the energy. The symbol δ stands for the local rate of change of the parameter which follows it. The matrix ϕ is the matrix of the fluxes of the respective parameters. The hydrodynamic parameters, h_j, are affected by the action of electric, $\underline{E}$, and magnetic, $\underline{B}$, fields. The interrelationship of these fields is described by Maxwell equations, Eqs. 2, where ε_0 and μ_0 represent respectively the permitivity and permeability of the vacuum and j denotes the local macroscopic current. Their effect on the hydrodynamic equations was specified here by the vector function of the acceleration, $f(\underline{a})$.

To completely specify the above system of equations we must characterize the various parameters involved. We start with the acceleration which is given by:

$$\underline{a}_i = \underline{g} + (e/m_i)(\underline{E} + \underline{v}_i \times \underline{B}) \qquad (3)$$

where $\underline{g}$ is the acceleration of gravity, e is the electron charge, m_i is the mass of the considered particle species and $\underline{v}_i$ its flow velocity. The first components of the vectors are:

$$h_{1i} = \rho_i = n_i m_i \, , \quad \delta h_{1i} = q_i - l_i , \quad f_{1i}(\underline{a}_i) = 0$$

where ρ_i is the density of mass, n_i its number density, q_i its production rate and l_i its loss rate. The next three vector components can be comprised into vectors as:

$$\begin{pmatrix} h_{2i} \\ h_{3i} \\ h_{4i} \end{pmatrix} = \rho_i \underline{v}_i , \quad \begin{pmatrix} \delta h_{2i} \\ \delta h_{3i} \\ \delta h_{4i} \end{pmatrix} = \sum_j \rho_i \nu_{ij} \left(\underline{v}_i - \underline{v}_j \right), \quad \begin{pmatrix} f_{2i}(\underline{a}_i) \\ f_{3i}(\underline{a}_i) \\ f_{4i}(\underline{a}_i) \end{pmatrix} = \rho_i \underline{a}_i \;,$$

where ν_{ij} is the collision frequency of particle species i with particle species j. The last components of the vectors are:

$$h_{5i} = n_i k T_i , \quad \delta h_{5i} = Q_i - L_i , \quad f_{5i}(\underline{a}_i) = \rho_i \underline{a}_i . \underline{v}_i ,$$

where k is the Boltzmann constant, T_i the particle temperature, Q_i and L_i the rates of production and loss of energy respectively. The matrix of the fluxes is such that one may separate them for the three hydrodynamic equations. One then gets:

$$\left(\nabla . \underline{\underline{\phi}} \right)_{1i} = \nabla . \left(\rho_i \underline{v}_i \right)$$

$$\begin{pmatrix} \left(\nabla . \underline{\underline{\phi}} \right)_{2i} \\ \left(\nabla . \underline{\underline{\phi}} \right)_{3i} \\ \left(\nabla . \underline{\underline{\phi}} \right)_{4i} \end{pmatrix} = \nabla . \left[\rho_i \underline{v}_i \underline{v}_i + \left(n_i k T_i \underline{\underline{I}} + \underline{\underline{\tau}}_i \right) \right]$$

$$\left(\nabla . \underline{\underline{\phi}} \right)_{5i} = \nabla . \left[1.5 \left(n_i k T_i \right) \underline{v}_i + \underline{q}_i + \underline{\underline{\tau}}_i . \underline{v}_i \right]$$

where $\underline{\underline{\tau}}_i$ is the stress tensor and $\underline{q}_i$ is the heat flow vector. There $\underline{\underline{I}}$ stands for the identity matrix. The stress tensor and heat flow vector are given by:

$$\underline{\underline{\tau}}_i = -\eta_i \left[\nabla \underline{v}_i + \left(\nabla \underline{v}_i \right)^t - (2/3) \left(\nabla . \underline{v}_i \right) \underline{\underline{I}} \right]$$

$$\underline{q}_i = -\lambda_i \nabla T_i$$

where η_i is the coefficient of viscosity, λ_i is the thermal conductivity and superscript t denotes transposed. The last parameter to be identified is the current $\underline{j}$ which is given by:

$$\underline{j} = \left(\sum_{ions} n_i \, \underline{v}_i \right) - n_e \, \underline{v}_e$$

where subscript e represents electrons.

The system of Eqs. (1) and (2) constitutes the mathematical description of the new trend to study the equatorial electrojet, which is called thermosphere-ionosphere-electrodynamic general circulation model in Richmond et al (1992). The reader may easily verify that the behavior of neutrals, ions and electrons, in the range 90-600km of altitudes, can be described by fluid dynamic equations of the form of Eqs. (1) (Schunk, 1977).

To retrieve the traditional formalism to study the equatorial electrojet we must simply consider the steady state for Eqs. (2) as well as for the momentum components of the ionized particles in Eqs. (1). When this is done we are excluding the possibility of studying simultaneously the existence of associated plasma instabilities.

The study of plasma microinstabilities can be done independently of the fluid type formulation of Eqs. (1). In fact these instabilities are studied splitting the particles' distribution function, $f(\underline{r}, \underline{v}, t)$, into two parts:

$$f = f_0 + f_1 \qquad (4)$$

(see Farley, 1963) where f_0 is the basic distribution function which governs the derivation of the fluid equations and f_1 is a perturbation which produces the plasma microinstabilities.

Perturbation f_1 depends partially on the perturbations of the electric field, $\underline{E}$, and partially on the basic distribution function, f_0 , (see Gary, 1984). At the equatorial electrojet altitudes, where collision frequencies are large, the dependence of f_0 cannot be negleted (see Gary, 1984). It is, therefore, understandable that most of the equatorial phenomena be interconnected. However, one may assume that the small perturbations due to microinstabilities do not disturb the basic electrojet flow. In this case, the hydrodynamics and electrodynamics equations constitute a self-consistent set of equations to determine the dynamics and electrodynamic characteristics of the upper atmosphere.

The solution of the system of Equations (1) and (2) in a global scale with improved resolution at equatorial latitudes seems, to date, the best form to theoretically study the equatorial electrojet. Numerical computations of this system have already started (see Richmond et al., 1992) but are still using the steady state approach for Eqs. 2 (see Richmond and Roble 1987). The success of this method depends on the accuracy to determine the driving mechanisms of Eqs. (1), namely, the chemical (q_i) and thermal (Q_i) local action of solar radiation on the upper atmosphere.

The theoretical predictions of the equatorial electrojet are limited by:

a) The numerical accuracy to solve the system of Eqs. (1) and (2).

b) The fitting of the inputs q_i and Q_i to existing conditions.

c) The approach or the time scale considered to account for the system memory (the dependence of the actual parameters on what happened in the past).

d) The simplifications used by the considered method to approach the system of Eqs. (1) and (2).

The advances in numerical modeling of the upper atmosphere behavior at equatorial latitudes (Richmond et al., 1992) are encouraging and expectations exist that a signficant progress can be achieved during the IEEY.

3. EXPERIMENTAL ASPECTS

If on the one hand the theory has evolved considerably in the past 10 years, on the other hand experimental techniques have had only moderate improvement. Reasons are manifold but the critical one is the high cost of equipments to provide high resolution data. We will now start our comments with ground-based techniques.

3.1 - GROUND-BASED TECHNIQUES

There are essentially two equipments which provide useful data to study the equatorial electrojet: magnetometer and radar.

a) Magnetometers

Magnetometers are probably the oldest type of equipment to study the equatorial electrojet. They are even related to the history of this phenomenon (see Forbes, 1981). The triaxial fluxgate magnetometers presentely used are essentially composed of a primary coil which, under the influence of the earth's magnetic field, transfer to a secondary coil its induction that is transformed into an electric signal. The system operates with saturated nucleus and provides information about the variations of the earth's magnetic field, necessary to compute the current flowing in the electrojet region. Unfortunately the current derived from these measurements is a height integrated value and besides contains a component from the current flowing within the earth's. The height integrated value includes not only the electrojet current but also another component due to currents flowing in the magnetosphere (see Kamide et al. 1981). At equatorial latitudes this last component may be neglected and the separation of the space and ground components can be made using a meridional chain of magnetometers (see Forbes, 1981). However, as commented on by Rastogi (1992) the space and the ground components of the current may be due to magnetospheric currents. This increases considerably the complexity of the interpretation of magnetometer data.

Among the advantages of this equipment we mention its low cost and widespread use. The disadvantage is that it provides only height integrated values of the current of difficult interpretation. One can expect magnetometers to contribute only with complementary data to be used in combination with other equipment measurements, during the IEEY besides providing a continuous monitoring of the electrojet phenomenon. It is expected that the electrojet current can be utilized effectively to study the Earth's conductivity using magnetometer data (Reddy, 1992).

b) Radars

Radar now constitutes a very important ground equipment to be used in the study of upper atmosphere phenomena. It operates in the HF, VHF or UHF ranges and the prices, quality and complexity are intimately connected. These characteristics are basically determined by two factors:

a) The required altitude resolution.

b) The nature of the target particle response.

As far as altitude resolution is concerned, one wishes an altitude resolution better than 5km which is about half the thickness of the electrojet width. Regarding the nature of the target particle response radars may observe coherent or incoherent scatter echoes. Echoes from the equatorial electrojet region are essentially coherent (see Fejer and Kelley, 1980) and are stronger when compared to incoherent scatter echoes (about 0^7 times).

Coherent scatter transmitters and receivers are much less expensive than those used in incoherent scatter since their operational system is similar to those of the usual reflection type radars. They are designed to operate in CW mode for bistatic measurements or else in pulsed mode for monostatic measurements. The description of these techniques is found in Evans (1969). The bistatic radars have the transmitter and receiving antennas at different sites and so the scattering volume is determined by the intersection of the two antenna beams. The monostatic radar use the same antenna for transmission and reception having its scattering volume controlled by the pulse width. Satisfactory antenna beams for electrojet measurements cannot be wider than 1° (pencil beams) and pulse widths no larger than 15 μsec.

Radars provide measurements of the Doppler shift, Δf, between the transmitted and received frequencies, produced by the target motion. The line-of-sight phase velocity is expressed by:

$$V_r = C\Delta f / 2f \tag{5}$$

where C is the velocity of light (in vacuo) and f is the transmitted frequency (Balsley, 1969). When this velocity is computed for the electrojet it refers to the electron velocity and may be used to derive the electric field (Viswanathan, 1990). However, since the electrojet is dominated by irregularities one observes a frequency spectrum instead of a single frequency shift (see Fejer and Kelley 1980). This spectrum gives information on the two-stream instability and the gradient drift instability, from which it is possible to determine the electrojet drift velocity (Balsley, 1969, 1973). A recent review on radar studies of the equatorial electrojet was publiched by Viswanathan (1990).

In spite of the fact that the radar constraints for good quality data collection are well known, they have not been obtained in most of the radar equipments (see Fejer and Kelley, 1980). The reason is the high cost required to get good altitude resolution together with reasonable signal strength. Therefore, it is necessary to understand what is actually measured when poor altitude resolution is employed. We give next a guide rule for these cases:

a) For beamwidth larger than 5^{o} it is the geometrical and physical characteristics of the experiment which determine the altitude resolution as in Ierkic et al. (1980). The resulting data is height integrated over the entire electrojet altitude range.

b) For beamwidths around 3^{o} the altitude resolution is determined by the antenna characteristics and it is possible to separate the upper and lower portions of the electrojet in the analysis of the data as in Fejer et al. (1980).

c) For beamwidths about 1^{o} the altitude resolution is determined by the antenna apperture and it is possible to determine the height structure of the electrojet as in Balsley and Farley (1973) or in Fejer et al. (1975).

The poor quality radar data of item a can be used only to identify the ionosphere component of the currents measured by the magnetometers. One can use the measured height integrated values of the phase velocity or compute height averages. The radar results of item b can be employed to separate the lower collision affected part of the electrojet from the upper instabilities dominated portion of this phenomenon (see Fejer and Kelley, 1980). The radar data of item c provide information about the height structure of the electrojet and constitute the most complete ground-based result which can be collected about it.

The disadvantage of high quality radars is their high cost for both installation and operation. The advantage is that it provides a good space-time coverage for the behavior of the equatorial electrojet besides providing a satisfatory amount of information which includes: phase velocities, electric fields, frequency spectra, height structure and type of instabilities. A significant contribution is expected from these radars to elucidate mainly the following problems:

a) Dependence of phase velocity of Type I waves on the electron velocity and elevation angle
b) Interrelationship of Type I and Type II waves.
c) Effects of winds on the equatorial electrojet.
d) Disturbance-time electric fields.

according to Reddy (1992).

3.2 - IN-SITU TECHNIQUES

In situ probes carried on space vehicles can provide significant scientific data which would otherwise not be known. At the equatorial electrojet altitudes these data are obtained from instruments carried on rockets.

In principle the same instruments used in ground type observations can be carried on rockets. Thus magnetometers and radar receivers can be used, with proper case to reduce their weight and to adapt them to quick measurements required because of rocket motion.

Besides, more appropriate devices and instruments have been designed for spacecraft measurements of:

a) Electron particle characteristics;
b) Ion particle characteristics;
c) Neutral particle characteristics;
d) Electrical characteristics.

These equipments use electrical, magnetic and sometimes chemical properties of the plasma in order to evaluate their characteristics. Next we will comment on them.

a) Electron probes

These probes are designed to measure electron density and temperature. The usual Langmuir type probes use the DC characteristic which is established between the polarization voltage applied to a metal electrode immersed in a plasma and the resulting electron current (Sayers, 1970). Sweeping the applied voltage from negative to positive values it is possible to evaluate the electron temperature (retarding potentials) and the plasma electron density (accelerating potentials). The accuracy of this type of data is quite satisfactory for density evaluations (Schlegel, 1992) and even for temperature derivations (Sayers, 1970).

Other types of probes are sometimes employed as for example the RF impedance or capacitance probes, which behave, like antennas. The simple measurement of the RF impedance as a function of the frequency allows the determination of the plasma resonances, from which the electron density can be determined. High accuracy can be obtained in this way (Sayers, 1970). Capacitance type probes use metallic sensors as the frequency determining element of a stable RF oscillator in which the frequency variation is used to determine the electron density (Heikkila et al. 1968). The accuracy of this type of probes is equivalent to that of the Langmuir probes (Muralikrishna and Abdu, 1991).

High accuracy rocket measurements are required as far as electron characteristics are concerned (Pfaff, 1991). One can expect these requirements to be fulfilled for electron density data with RF impedance type probes. For temperature measurements of the low temperature plasma of the E region they will be obtained with difficulty (Schlegel, 1992).

b) Ion probes

Ion density and temperature measurements can be performed with Langmuir probes operating with negative bias. However, more effective devices were developed as the retarding potential analyser which is essentially a negatively biased grid surrouding a probe positive with respect to the ionosphere (Sayers, 1970) and is recommended for temperature measurements with 10% accuracy. More reliable data on ion density is obtained with mass spectrometers mainly those of the quadrupole type (Steinweg et al. 1992). The quadrupole consists of four circular rods, spaced in a parallel array, where RF and DC voltages are applied such that the ions injected along the axis of the rod structure are selected by their mass to charge ratio. A mass spectrum is obtained sweeping the rod voltages. The ion density is determined by the ion current collected at the end of the rod axis trajectory. The obtained accuracy is of the order 20% (Sayers, 1970).

The accuracy in determining the ion characteristics at present is satisfatory to meet the requirements for the equatorial electrojet (Pfaff, 1991). One can thus expect reliable data about the ions from rocket measurements.

c) Neutral particle characteristics.

Neutral densities are determined by impact ionization of these particles by means of an electron stream with high energy (16-18eV). Since the ion production rate is proportional to the gas density it is possible to determine this density collecting the produced ions in a retarding potential analyzer or mass spectrometer (see Arnold et al. 1977). The accuracy of these measurements can be about 40% (Friker and Lubken, 1992). The neutral temperature relates to the density by means of the differential equation:

$$d(nT)/dz = -nmg/k \tag{6}$$

(Hedin, 1965), which, integrated, yields the desired temperature. In practice an iterative procedure is necessary between the computation of densities and temperatures (see Friker and Lubken, 1992). The accuracy of temperature derivations is the same as that for densities, namely, 40%.

The requirements of accurate measurements for determination of neutral number densities to study the equatorial electrojet (Pfaff, 1991) are not expected to be met during the IEEY.

d) Electrical characteristics.

The DC electric field and currents in the lower ionosphere can be measured using an electric field double probe and a magnetometer. The DC electric field probe consists of two spaced electrodes which, when immersed in a plasma, present a voltage difference proportional to the plasma electric field. Only the component of the electric field along the axis of the two electrodes can be determined. The measurements are strongly affected by many sources of voltage differences unrelated to the desired electric field (Fejer and Kelley, 1980). Nevertheless these measurements contain essential information being thus extremelly valuable (Pfaff, 1991). The AC electric fields can now be determined by an spherical metallized plastic probe divided into six spherical segments which are connected at the center to constitute three electric dipoles perpendicular to each other (Rose, 1992). The AC electric fields are essentially the wavelike perturbations which drive the instability processes and are therefore important data for the understanding of the electrojet phenomena (Pfaff, 1991). There is no mention for the actual accuracy of the electric field data, however, a noise level of 0.5 mV/m seems always to be present.

The DC current density is measured using a triaxial fluxgate magnetometer (see Lükr, 1992). This equipment monitors the changes in the field magnitude when traversing the current sheet. The data processing involves a length procedure in order to determine the current density from the measurement (see Lükr, 1992). The results seem rather convincing to expect this type of data to be collected during the IEEY.

As could be observed, in situ data taking involves an electronic apparatus which faces many problems that range from the short period available to collected data to the highly complex structure of the observed medium. As for the data processing many drastic assumptions are made in order to derive the desired parameter from the obtained data. Nevertheless good expectations that rocket data may help to solve some outstanding problems in electrojet physics were expressed by Pfaff (1991). Most of these expectations are based on the possibility of in situ measurements of electric fields and density perturbations with satisfactory accuracy. They may be categorized as:

a) Observations of the basic electrojet structure, which include the determination of the vertical and horizontal DC electric fields, for the purpose of solving the problem of the nature and relations of the vertical electric field.

b) Observations of the unstable microscopic behavior of the electrojet, which include the determination o the AC electric fields and density perturbations, for the purpose of examining the spectral characteristics of primary and secondary wavelike phenomena and possible relations among them.

4. DISCUSSION

Our present knowledge about the equatorial electrojet phenomenon is limited both theoretically and experimentally. On the theoretical side we are constrained by the present capability of the computer programs, for modeling the upper atmosphere dynamics, to handle the large amount of complex interactions at the same time with the necessary space resolution. On the experimental side the parameters are computed grounded on the simplified expressions derived from the steady state model besides being measured most of the time with unsatisfactory space resolution. Nevertheless we have now a fair idea about the diving local mechanism for the phenomenon, a reasonable steady state model providing a macroscopic view of it and perturbation type derivations to explain the microscopic behavior of the electrojet (e.g. Forbes, 1981; Fejer and Kelley, 1980).

Based on this bounded knowledge balances about the actual unsolved problems and expectations for the IEEY were made by Rastogi (1992), Reddy (1992) and Pfaff (1991). We will consider now these evalutations grounded on what was presented in Sections 2 and 3.

The equatorial electrojet is classically attributed to the appearance of an electric field in the E layer dynamo region, where the ions are constrained to move with the neutral air wind because of the strong ion-neutral interaction $(\nu_i \rangle \Omega_i)$ whereas the electrons are free to move by the action of electromagnetic forces $(\nu_e \langle \Omega_e)$. Undergoing different forces electrons and ions move with different velocities and this produces a current flowing with magnitude:

$$-\underline{j} = n_e \underline{\mathrm{v}}_e - \sum_i n_i \underline{\mathrm{v}}_i . \qquad (7)$$

It is then quite desirable to measure the actual electron and ion densities as well as their respective tridimensional velocities. The simultaneous measurement of the current density is very useful to test the theory and also the equipment accuracy. The importance of measuring simultaneously all these parameters was stressed by Pfaff (1991) although not being so rigorous as to require the measurement of all ionized particle velocities. Ground measurement expectations are more modest with ionized particle densities derived from ionogram records and an integrated current density obtained using magnetometers (Rastogi, 1992).

Electric currents and fields are related by Ohm's law which in the present case is written as:

$$\underline{j} = \underline{\underline{\sigma}} \cdot \left(\underline{E} + \underline{u} \times \underline{B} \right), \tag{8}$$

valid within the equatorial electrojet range. Here $\underline{\underline{\sigma}}$ is the conductivity tensor. Therefore, to test the consistency of this simple steady state model the vector measurements of both the wind velocity and the electric field are required. This was pointed out by Pfaff (1991) for in situ observations of the electrojet phenomenon. Ground type observations just evaluate the electric field from radar measurements and use the wind velocities computed from model approximations for the thermosphere (Rastogi, 1992; Reddy, 1992). The conductivities are also evaluated from model calculations of ionized neutral interactions.

The expectations concerning the steady state model for the IEEY expressed by Pfaff (1991), Reddy (1992) and Rastogi (1992) are just that more accurate measurements of the mentioned parameters can be made to improve our limited knowledge about the phenomenon under consideration. Critical problems appear when the geophysical conditions are not favorable to employ steady state models, mainly during sunrise and sunset periods.

The equatorial electrojet irregularities are explained in terms of two-stream and gradient drift instability processes. Both of these processes are developed in terms of a linear fluid perturbation theory (see Fejer and Kelley, 1980; Farley, 1985) the relevant aspects of this theory are:

a) A wavelike perturbation, proportional to $exp\,[i\,(\underline{k}_i \cdot \underline{r} - \omega\, t)]$, is imposed on the electric field which drives similar wavelike perturbations in densities and velocities of the ionized particles.

b) The plasma oscillations may grow, becoming an instability. A dispersion relation is established which links ω to $\underline{k}_1$ and determines the conditions under which instabilities occur (Fejer et al., 1984). It is expressed by:

$$\omega_r = \underline{k}_1 \cdot \underline{v}_d (1+\psi)^{-1} \tag{9}$$

for the oscillation frequency and

$$\gamma = (1+\psi)^{-1}\left[\nu_i^{-1}\psi\left(\omega_r^2 - k_1^2 C_s^2\right) + \omega_r \nu_i \left(k_1 L \Omega_i\right)^{-1}\right] - 2\alpha\, n_e \tag{10}$$

for the growth rate. Here:

$$\underline{v}_d = \underline{v}_e - \underline{v}_i, \quad \psi = \nu_e \nu_i (\Omega_e \Omega_i)^{-1}, \quad C_s^2 = k(T_e + T_i)/m_i, \quad L = n_e(\partial n_e/\partial z)^{-1}$$

with Ω = gyro-frequency, α = recombination coefficient.

These aspects show that the important parameters to be determined in the study of irregularities are:

1) The amplitude of density perturbations
2) The amplitude of the electric field perturbation
3) The power spectrum of the irregularities
4) The electron density profile
5) The electric field profile

A combined experiment involving in situ and ground type measurements can give important information on these parameters. There are other parameters like electron and ion temperatures and collision frequencies which are of interest but of difficult evaluation with the presently available facilities. The above requirements were expressed by Farley (1985), who stressed the importance of other theories, besides the linear one mentioned above, to explain mainly two aspects of the observation, namely:

a) The appearance of vertically propagating waves.
b) The existence of saturation in the amplitude of instabilities.

Many questions concerning the behavior of irregularities were raised and may be found in Farley (1985). Pfaff (1991) summarized them and four aspects need to be emphasized:

i) There are somobserved spectral features which need further examination and concern to the linear theory of types 1 and 2 irregularities.

ii) The occurrence of vertically propagating waves in the equatorial electrojet require additional observations and a responsible mechanism to explain them.

iii) Much understanding is necessary about the nature of broad-band turbulence during night-time.

iv) The possibility of a plasma heating by instabilities.

The expectations concerning the study of the irregularities of the equatorial electrojet, expressed mainly by Pfaff (1991) are that the combined theoretical and experiment efforts during the IEEY be successful, to explain the above-mentioned aspects. This is a hard task regarding ground type observations since the required measurements are close to equipment sensibility. In situ measurements face a similar problem with the small currents available to evaluate the ionospheric parameters. As for the theory, the low plasma density $(\approx 10^3\, cm^{-3})$ brings it to the uncomfortable position where fluid type models do not allow satisfatory modeling

From what has been seen throughout this work, one can infer that:

a) The equatorial electrojet is a localized phenomenon undergoing influences from the global dynamics.

b) It can be described as a macroscopic current flow with irregular microscopic structure dominated by instabilities.

c) Fluid type models and perturbations on them yield satisfactory results to describe their daytime macroscopic and microscopic behavior.

d) The kinetic approach should be preferred for the studies of the equatorial electrojet irregularities during night-time.

5. CONCLUSIONS

An overview on the theoretical and experimental aspects of the equatorial electrojet was presented with a final balance on the present knowledge about the phenomenon and the prospective forms of studying it. Concerning the theory, the bulk flow behavior can be described using fluid type global models and the daytime microscopic behavior derived from perturbations imposed on the parameters by a driving electric field disturbance. Night-time irregularities are better described using the kinetic approach. As far as experimental observations are concerned the present accuracy of the measurements do not allow a complete consistent set of data to be obtained, so that a test of all the features of the phenomenon be possible between theory and experimental results.

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DYNAMICS OF THE EQUATORIAL IONOSPHERE-THERMOSPHERE SYSTEM AS INVESTIGATED THROUGH NIGHT AIRGLOW TECHNIQUES

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ABSTRACT

The dynamics of the nocturnal equatorial F-region has been investigated to a substantial extent in the last few decades by means of airglow diagnostic tools such as photometers, optical imagers and Fabry-Perot interferometric systems. This paper concerns a concise review on those airglow studies.

1. INTRODUCTION

The presentation in the following sections on the relevant topics that have been studied in the past three decades utilizing airglow data, will follow the following order:

-Dynamics of the ionospheric plasma bubbles
  -Ve drifts
  -projections onto the equatorial plane
  -geometric studies

-Particle precipitation
  -atomic and molecular processes in the low-latitude aurorae
  -heating effects during storms

-Spread-F
  -range spread-F and ionospheric irregularities
  -neutral temperature enhancements

-Thermospheric winds and temperatures
  -meridional and zonal wind components
  -seasonal, solar cycle and local time variations
  -variations of the wind patterns with latitude

-The Equatorial Ionization Anomaly
  -the formation of the equatorial red arcs

Photometric data, that is, data on the spatial and temporal variations of just the airglow intensity have been used more extensively in the past few decades than optical interferometric wind and temperature data.

The locations of some of the presently well-known Fabry-Perot optical interferometric stations in operation at low latitudes which have been used in ionospheric studies are as follows:

1. Kwajalein Atoll, Marshall Islands (9.4^{o}N, 167.5^{o}E, 8.6^o dip latitude)
2. Arequipa, Peru (16.5^{o}S, 71.4^{o}W, 3.5^{o}S dip)
3. Arecibo, Puerto Rico (66.8^{o}W, 18.6^{o}N, 50^{o}dip)
4. Mount Abu, India (24.6^{o}N, 72.7^{o}E)
5. São José dos Campos/Cachoeira Paulista, Brazil (23.0^{o}S, 45.0^{o}W, dip -30^o for the epoch 1992)

2. DYNAMICS OF THE IONOSPHERIC PLASMA BUBBLES

2.1 The behavior of the eastward velocity, Ve, of the equatorial plasma depletions in the nocturnal F region over South America

In a recent study by Sobral et al., (1991; see also Sobral et al. 1985, 1990) on the eastward motion of ionospheric plasma depletions utilizing ground measurements of the atomic oxygen 630 nm airglow in the period of January 1988 to January 1990 at the low latitude station Cachoeira Paulista (23^{o}S, 45^{o}W), they concluded that:

1. The eastward velocity Ve of the postsunset ionospheric plasma depletions is seen to decrease, in average, from about 150 ms^{-1} at 2015 LT to 75 ms^{-1} at 0145 LT,

2. Both Ve and its latitude gradient tend to increase with increasing solar activity,

3. The magnitude of Ve tends to decrease with height, in the equatorial plane at the rate of 0.205 ms^{-1} and such height gradient tends to remain constant during the night.

Utilizing two nights of red line observations at the Haleakala Observatory, Hawaii, VanZandt and Peterson (1968) detected the Ve magnitudes of 175 km h^{-1} (49 ms^{-1}) and 400 km h^{-1} (111 ms^{-1}).

Mendillo and Baumgardner (1982) found Ve to decrease from 190 ms^{-1} at 2100 LT to 80 ms^{-1} at 0100 LT over Ascencion Island.

Weber et al. (1978), utilizing all-sky 630 nm imaging found Ve magnitudes in the range of 50-100 ms^{-1} along the Peruvian coast. They observed one case, after local midnight, in which the depletion drifted westward (see also Weber et al, 1982).

Sipler et al. (1983) observed Ve magnitudes in the range of 0 ms^{-1} to 240 ms^{-1} over the Kwajalein Atoll and compared those measurements with neutral wind measurements. They observed the Ve magnitudes for one given depletion to be smaller than the neutral wind speed. They found this fact somewhat surprising, considering that the zonal wind is the primary forcing mechanism for the generation of the downward polarization electric field that causes the **ExB** eastward drift of the depletion.

Basu et al. (1991) compared zonal irregularity drifts and neutral winds measured near the magnetic equator in Peru.

More recently, Basu et al. (1991) compared zonal irregularity drifts and neutral winds measured near the magnetic equator in Peru.

Other early measurements of ionospheric drifts were described by Sipler et al (1981).

2.2 The geometry of the equatorial plasma depletions

Utilizing all-sky OI 630 nm images, Mendillo and Tyler (1983) found the depletions to be tilted about 40^o towards the west in the upward direction or at a rate of 0.6^o longitude west per 100 km height range over Ascencion Island (8.0^oS, 14.4^oW). The tilts were seen to increase with local time and they are possibly associated with poleward decreasing zonal thermospheric wind magnitudes (Anderson and Mendillo, 1983).

Weber et al. (1983) investigated plasma depletions at conjugate points utilizing data from the following instrumentations: all-sky imaging photometers at the wavelengths of 630 nm and 777.4 nm, ionosonde, in-situ density data from the AE-E satellite and scintillation data from the AFGL Airborne Ionospheric Laboratory. In a former observational campaign near the Peruvian coast, Weber et al. (1978) found that the depletions often extended themselves more than 1200 km in the north-south direction and 50-200 km in the east-west direction.

Rohrbaugh et al. (1989) studied the development of plasma bubbles at Mount Haleakala (Hawaii) utilizing 777.4 nm and 630.0 nm images.

3. PARTICLE PRECIPITATION

3.1 Optical Observations of particle precipitation:

Energetic atomic O, H and He, arising from charge transfer with trapped ions in the inner magnetosphere, were observed to precipitate at mid, low and equatorial latitudes with mean energy in the range of 1-100 keV (Tinsley, 1979, 1981; Tinsley et al. 1982, 1986, 1988; Rohrbaugh et al. 1983; Rassoul et al. 1992).

Rohrbaugh et al. (1983) found that the time variations of the emissions of H Balmer-beta emission at 486.1 nm and N_2^+ 1N at 428.1 nm indicate that there is more O precipitation than H precipitation during storms main phases and, on the other hand, H^+ loss is faster than O^+ and He^+ in the inner ring current during the whole duration of the precipitation event. They also found that precipitation increases with increasing latitude in the low to mid latitude range.

Tinsley et al. (1984, 1986, 1988) detected ring current particle precipitation at Cachoeira Paulista (22.7^o S, 45.0^o W, dip -30^o for the epoch 1992) in Brazil during magnetic storms through ground measurements of the $N2^+$ emission.

Rohrbaugh et al. (1983) have detected particle precipitation increases of the OI ($3p^5P$-$3s^5S$) emission at 777.4 nm over the background OI 777.4 nm component due to radiative recombination, the latter being inferred from ionosonde data as equal to $.0018\ (f_0F_2)^4$.

3.2 Thermospheric heating resulting from particle precipitation:

Tinsley et al., (1988) reported evidence, based on particle precipitation data, that both mid-latitude ring current source and high-latitude Joule heating source are involved in the thermospheric heating observed above Arequipa during the storms of May 11-12, 1983, June

12-13, 1983 and August 7-8, 1983.

Rohrbaugh et al. (1983) reported a lower limit for energy deposition of about 0.05 mWm^{-2} during the storm events of April 1982 and July, 1982 which occurred at 12^o dip latitude.

4. SPREAD-F

4.1 Association of range spread-F events with plasma depletions:

Statistical studies of ionosonde and optical (630 nm) data from the low-latitude station Cachoeira Paulista (Sobral et al. 1980a,b, 1981) show that the plasma depletions signatures on the 630 nm airglow is always accompanied by range spread-F and that the range spread-F occurrence at the low-latitude station Cachoeira Paulista is caused by field-aligned plasma depletions.

Sahai et al. (1981) compared the behavior of the atomic oxygen 777.4 nm and 630 nm emissions during the occurrence of ionospheric plasma depletions over Cachoeira Paulista.

Meriwether et al. (1986) pointed out that the incidence of irregularities over Peru during winter is low due to the height of the F-layer that remains constant and because the zonal neutral wind is eastward during the night which tends to inhibit the growth of irregularities in the absence of upward drifts.

In a more recent work Mendillo et al. (1992) suggest that the equatorward winds observed at Kwajalein (Marshall Islands) can alter the airglow pattern over that site. The forcing effects of equatorial winds on the ionospheric plasma, they claim, can cause a stabilizing effect on the irregularity growth rates.

The OI 630 nm airglow intensity variation with solar cycle has been monitored by Sahai et al. (1988a). During higher solar activity period, as expected, they found more intense airglow. Storm effects in the nocturnal F-region over Cachoeira Paulista have been reported by Sahai et al. (1988b).

4.2 Spread-F and thermospheric neutral temperature:

Fabry-Perot data on the F-region temperature at Mount Abu (24.6^o N, 72.7^o E) (Rajaraman et al., 1978, 1979) show thermospheric temperature increases of up to 200^oK during sunset in the presence of spread-F and no temperature increase in the absence of spread-F.

5. THERMOSPHERIC WINDS AND TEMPERATURES

5.1 Winds:

The neutral wind speed measurements discussed below concern separate data on the meridional and zonal components of the neutral wind in the nocturnal F-region.

Wind velocities observations over Arequipa by Biondi et al., (1991; se also Biondi et al., 1990a, b) over 2/3 of a solar cycle (1983-1990) led to the following conclusions:

1. The wind patterns vary more markedly with season than with solar cycle.

2. The zonal flows are predominantly eastward throughout the night (westward flows briefly appeared in 1986), except for solar minimum equinoxes when weak westward flows occur in early and late night. The peak eastward velocity increases toward solar maximum; at solar minimum winter solstice they are 100-130 ms^{-1} (1983, 1984 and 1986) and at solar maximum they reach up to 200 m^{-1} (1988, 1989 and 1990).

3. The authors compare the remarkable solar cycle variations that they observed at Arequipa with the opposite conclusion stated by Burnside and Tepley (1989) for the winds over Arecibo: "nocturnal and seasonal variations in the neutral wind field...are remarkably unaffected by changes in the solar cycle".

4. The increases in the pressure gradients in the vicinity of the subsolar point might be expected to lead to higher wind velocities at solar maximum; however, the observed increases with increasing solar cycle are small, suggesting that increased ion drags plays a role in slowing down the wind speeds.

5. The meridional winds over Arequipa present small velocity magnitudes throughout the solar cycle and are much smaller in magnitude than the zonal winds.

6. At the equinoxes, the early-night southward (poleward) flow that appears during solar minimum is changed to equatorward flow at solar maximum.

7. A weak transequatorial flow from the summer to the winter hemisphere early and late in the night, and nearly-null velocities otherwise are observed in most of the years of their observation period (1983-1990). During solar minimum and solar maximum equinoxes the meridional flow is poleward and equatorward, respectively.

Herrero and Meriwether (1980) studied the meridional gradients of the atomic oxygen 630 nm airglow over Arecibo, relating them to the dynamics of the ionosphere-thermosphere system over Arecibo.

Burnside and Tepley (1989) observed following features of the wind field over Arecibo:

1. Well-defined seasonal and nocturnal variations of the zonal flows over Arecibo.

2. The nocturnal zonal winds are predominantly eastward throughout the solar cycle except during summer, when a reversal to westward frequently occurred after local midnight during the second and third quarters of the years 1980-1985.

3. Over Arecibo, the largest equatorward velocities are observed in summer and either a reduction of the wind velocity or a reversal is observed after midnight during summer and equinoctial months, causing the so-called "midnight collapse" of the ionosphere over Arecibo (see also Sobral et al, 1978).

Burrage et al. (1990) measured nocturnal thermospheric winds at low latitudes utilizing Atmosphere Explorer (AE-E) satellite measurements of the $O(^1D)$ 630-nm.

Biondi and Sipler (1985) analysed horizontal and vertical winds and temperatures in the equatorial station Natal, Brazil during the period of August-September, 1982 (see also Biondi and Sipler, 1984).

Bittencourt et al. (1976) studied height gradients of the tropical F-region winds utilizing OGO-4 data on the OI 135.6 nm and OI 630 nm emissions.

5.2 Temperatures (Tn):

Gupta et al. (1986) measured the equatorial thermospheric temperatures through spectroscopic methods utilizing rocket released atomic sodium. The experiments were carried out over the near equatorial station at Srihatoka (13^o 41' N, 80^o 14' E, dip lat. 5.5^o N). They found enhanced thermospheric temperatures during a storm sudden commencement.

Biondi and Meriwether (1985) studied the thermospheric temperature variations over Arequipa utilizing 62 nights of Tn data obtained by a Fabry-Perot interferometer. The measurements were found to be larger than the MSIS 1 (Hedin 1977) by 180^oK and such a discrepancy increased to about $400\text{-}500^oK$ during strong geomagnetic activity. They concluded that enhanced temperature may result from energetic neutral particles from the ring current or from auroral sources such as gravity waves or neutral winds. Measurements carried out over the Kwajalein Atoll in the Pacific zone also showed higher values than those of MSIS 1 by about 330^oK.

There are less discrepancies, however, between Fabry-Perot Tn and incoherent scatter Tn data (Cogger et al., 1970; Hernandez et al., 1975).

Hernandez and Killeen (1988) studied kinectic temperatures in the upper atmosphere.

Biondi et al. (1988) studied in detail the dynamics and coupling of the equatorial thermosphere and the F-region ionosphere in Peru, utilizing simultaneous Fabry-Perot interferometer and incoherent scatter radar observations on the magnetically disturbed days 24 and 25 September 1986. They compared zonal plasma drift measurements with zonal neutral wind measurements obtained by the incoherent scatter radar and the Fabry-Perot interferomter, respectively. They found that the two motions were not correlated during evening twilight but they became correlated later in the night. They attributed the increasing correlation between those two velocities to a decreasing Pedersen conductivity which leaded to a subsequent control of the F-region dynamo over the F-region ionospheric zonal drift.

Note: Michelson interferometers have also been used for measuring thermospheric winds and temperatures but since they have been used only at high latitudes their results are out of scope here (for information on those studies the reader is suggested to see Wiens et al., 1988 ; Thuillier et al., 1990).

Sobral (1978) used artificially induced HF heating effects on the OI 630 nm airglow intensity during ionospheric heating experiments at Arecibo in order to determine the collisional quenching rate of the metastable atomic oxygen. Sobral et al. (1992) has studied the atomic processes which lead to the quantum yields of the $O(^1D)$ and $O(^1S)$. And more recently, Sobral et al. (1993) has utilized the OI 557.7 nm and 630 nm from rocketborne measurements to estimate the quenching effects of the $O(^1D)$ by $O(^3P)$.

6. THE EQUATORIAL ANOMALY

The equatorial ionization anomaly (EIA) consists of two bands of enhanced electron concentration which run $\pm$ 20^o parallel to the magnetic equator. Associated with it are two bands of enhanced OI 630 nm which have been studied through OI 557.7 nm and 630 nm airglow (Barbier, 1958, 1961; Barbier et al., 1961, 1962; Weill, 1967; Kulkarni, 1974).

The optical studies of the EIA have not gained much attention since those early studies.

Sridharan et al. (1991) measured electron density biteouts that are possibly related to the upward drifts that lead to the fountain effect and the subsequent creation of the EIA. Their measurements were performed at the equatorial station Sriharitoka (5.5^{o} dip latitude) in India utilizing OI 630 nm dayglow measurements.

7. CONCLUSIONS

Summarizing, in the author's view the relevant contributions of the airglow studies to the improvement of the knowledge of the dynamics of the ionosphere-thermosphere system at equatorial and low latitudes may be stated as follows:
1) Extensive measurements of the variations of the zonal velocity Ve, geometry and dynamics of equatorial plasma depletions in the nocturnal F region. Determination of Ve variations with season, solar cycle and local time.
2) Measurements of the low latitude aurorae caused by precipitating ring current particles and their thermal effects in the thermosphere.
3) Verification of the simultaneous occurrence of spread-F with ionospheric plasma depletions; of neutral winds as an spread-F inhibiting factor and temperature enhancements during spread-F occurrence.
4) Measurements of thermospheric wind velocities and temperatures.
5) The development of postsunset Equatorial Ionization Anomaly.

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IEEY PROJECT: THE AMERICAN SECTOR

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ABSTRACT

A description of the activities and efforts related to the International Electrojet Year (IEEY) in the American Sector (190°E-330°E) is given with a focus on the participation of the Latin American stations that are located in the EE belt.
IEEY period: September 1st, 1991 to March 31, 1993*.
* Extended to December 31, 1993.

1. THE IEEY IN PERU

Incoherent and coherent scatter radar observations have been concurrently carried out with geomagnetic observations utilizing the Peruvian magnetometer network. The objective was to compare the magnetometer signatures with E-fields measured by the radar and to study electrojet and counter-electrojet electrical forcing systems under quiet and active magnetic conditions.

The period of observation of the experimental campaign cited above was that of the regular world days, namely, 16-18 March, 1993.

During that period, simultaneous measurements of F-region vertical drifts and coherent backscatter measurements of the E-region were performed at the Jicamarca Observatory.

The other observational campaigns related to IEEY in the Peruvian territory consisted of observations with the Peruvian coastal magnetometer network. The objective of that campaign was the analysis of the characteristics of the equatorial electrojet in Peru and the study of the interaction of the electrojet regions with current systems flowing in the ionosphere and in the internal mantle.

The Peruvian magnetometer stations are located in the following cities: Huancayo, Anoon Observatory, Piura, Casma, Cañete, Guadalupe, Yauca, Arequipa and Tacna.

2. THE IEEY IN BRAZIL

The International Workshop on the IEEY Data Organization and Analysis was held at INPE headquarters, at São José dos Campos, Brazil, during the period October 19-23, 1992.

A large number of theoretical and experimental papers on studies of the equatorial eletrojet have been presented in the workshop cited above. About 16 scientists from abroad participated in this symposium.

The symposium audience recommended setting up an international data bank aiming the studies of the equatorial electrojet under the international coordinatorship of Dr. Christine Amory-Mazaudier.

Sobral

Observational campaigns of the equatorial electrojet in the Brazilian region:

Regular observations utilizing magnetometer and ionosonde were performed in São Luis and Fortaleza.

It has been recently set up a network of magnetic equatorial magnetic stations in Brazil, that is, a chain of eight fluxgate magnetometers which have been deployed on ground perpendicularly to the direction of the magnetic dip equator near the 60^{o} west meridian. The profile ranges from Porto Velho (8.8^{o}S, 63.9^{o}W, 6.3^{o} dip) to Cuiabá (15.35^{o}S, 56.05^{o}W, -10.7^{o} dip) (see also Table 1). Eight stations at Porto Velho, Ariquemes, Ji Paraná, Pimenta Bueno, Comodoro (Colibri), Pontes e Lacerda and Cuiabá in August 1992 were installed. Only five stations worked simultaneously during October, November and December 1992. Since the stations are operated unattended some of them suffered mishandling of curious neighbors and at one station the battery was stolen. The stations under went repairing in March 1993 and only in the second week of July all the eight stations were working together. Hopefully good data from August 1993 onwards are expected.

Also four equatorial magnetic stations are operated on the eastern coast of the country. Those stations are Belém (1.4^{o}N, 48.4^{o}W, +7.6^{o} dip), São Luis (2.6^{o}S, 44.2^{o}W, 0.9^{o} dip), Teresina (5.1^{o}S, 42.7^{o}W, -5.4 dip) and Eusébio (3.9^{o}S, 38.5W, -8.4^{o} dip).

Acknowledgements. The information on the Brazilian magnetometers and ionosondes shown above were kindly provided by Dr. Nalin Trivedi (Instituto Nacional de Pesquisas Espaciais/ INPE) and Dr. M. A. Abdu (INPE), respectively, and the information on the Peruvian side were kindly provided by Dr. Ronald Woodman (Instituto Geofisico del Peru).

IEEY Proyect: The American Sector

STATION NAME	GEOGRAPHIC COORDINATES		DIP ANGLE DEGREES
PORTO VELHO	8.80S	, 63.9W	+6.3
ARIQUEMES	9.56S	, 63.04W	+4.0
JI PARANÁ	10.85S	, 61.95W	+1.5
PRES.MEDICI	11.20S	, 61.80W	+0.5
PIM. BUENO	11.60S	, 61.20W	-0.6
VILHENA	12.72S	, 60.13W	-2.9
COLIBRI	13.70S	, 59.80W	-5.2
PONTES E LACERDA	15.26S	, 59.2W	-8.3
CUIABÁ	15.35S	, 56.05W	-10.7
BELÉM	1.40N	, 48.40W	+7.6
SÃO LUIZ	2.60S	, 44.20W	+0.9
EUSÉBIO	3.90S	, 38.50W	-8.4
TERESINA	5.10S	, 42.70W	-5.4

Table I. *Brazilian Magnetometer Stations*

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A ROCKET-BORNE LANGMUIR PROBE RESPONSE TO CONTINUOUS AND PULSED SWEEP MODES

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ABSTRACT

Nightime ionospheric electron density and temperature are measured using a rocket-borne Langmuir probe (LP) launched on board a SONDA III rocket from the Brazilian equatorial rocket launching station in Alcântara-MA, at 23:51 hrs (LT) on May 31, 1992. A sweep voltage varying between -1V and +2.5V is applied to the spherical LP sensor alternately in continuous and pulsed modes. In the continuous mode the effect of contamination of the sensor surface on the current collected by the sensor is clearly seen in the current-voltage characteristics and thereby on the electron temperature estimated, while this effect is practically absent in the pulsed mode operation. An electron temperature profile estimated from the LP data is compared with the IRI90 model profile.

1. INTRODUCTION

In-situ measurement of plasma density and temperature by Langmuir probes (LP) is known to be hampered by problems that originate from sensor geometry, sensor surface contamination, secondary electron emission from the probe surface, formation of plasma sheath surrounding the sensor surface, absence of proper return path for the current collected by the sensor etc (For details see Holmes and Szuszczewicz, 1975; Oyama, 1976 and references therein). Experiments have clearly shown that contaminated LPs consistently show hotter electron distributions than actually present in the medium. In conventional continuous sweep mode operation the LP measurements are affected by temporal variations in the probe's effective work function (Wehner and Medicus, 1952; Hirao and Oyama, 1972; Holmes and Szuszczewicz, 1975). Variation in the surface condition of the probe - the probe surface contamination effect - results in hysteresis in the current-voltage characteristics. Holmes and Szuszczewicz (1975) developed a new technique known as the Pulsed Plasma Probe technique to eliminate these problems and to improve the reliability of LP measurements. Szuszczewicz and Holmes (1975) conducted laboratory experiments using a LP operated alternately in continuous and pulsed sweep modes to determine the effectiveness of this new technique in eliminating the surface contamination effects and the associated hysteresis in LP current-voltage(I-V) characteristics. They reported that the pulse technique is, in fact, superior to the conventional continuous sweep approach.

A LP along with several optical diagnostic experiments was launched on board a Brazilian SONDA III rocket on May 31, 1992 at 2351hrs (LT) from the equatorial rocket launching station located in Alcantara (2.31°S, 44.4°W). The main scientific objective of the experiment was to study the nighttime equatorial ionosphere under quiet time conditions. The launch criterion was dictated by ground based airglow photometers and a Laser Radar operated at the launch site. At the time of launch an ionosonde at a nearby station, Fortaleza (3.9^{o}S, 38^{o}W), about 650km away from Alcantara, indicated rather quiet ionospheric conditions without the presence of Spread-F irregularities. The flight details are summarized below.

Launch site	: Alcantara
Launch day/time	: May 31, 1992; 2351hrs(LT)
Launch azimuth(mean)	: 37.9 degrees
Launch elevation	: 63.77 degrees
Apogee altitude	: 282km
Flight duration	: 510 seconds
Horizontal range	: 410km

With the technical objective of comparing the performance characteristics, the LP experiment was operated alternately in continuous and pulsed sweep modes. The experiment functioned satisfactorily during both the ascent and descent of the rocket and measured height profiles of electron density and electron temperature. A brief description of the LP experiment and the results of a comparative study of the LP performance in the continuous and pulsed mode operations are presented here.

2. EXPERIMENT DETAILS

A gold plated metallic sphere of diameter 35mm mounted at the extremity of a short deployable boom made of fiberglass material was used as the LP sensor. The boom was mounted close to the outer edge of the mount plate inside the rocket nose cone and kept folded in vertical position before the launch. It was deployed to horizontal position soon after the ejection of the nose cone. The payload segment of the SONDA III rocket is shown schematically in Figure 1.

A sweep voltage varying between -1.0V and +2.5V in the continuous mode and between -0.5V and +1.25V in the pulsed mode in a period of about 2.6s is applied to the LP sensor to obtain both the electron density and the electron temperature. The continuous and pulsed sweeps are applied alternately in order to study the performance characteristics of the LP sensor in the two modes. In the continuous sweep mode the sensor potential remains at -1.0V for 41ms, increases linearly with time to 2.5V in about 1.5s and then remains at 2.5V for another 1.1s. In the pulsed sweep mode a train of short period pulses with peak amplitudes varying the same way as in the continuous sweep is applied to the sensor. The sensor potential in the pulsed mode has an amplitude almost half the corresponding amplitude in the continuous mode. That is to say, in the pulsed sweep mode the sensor remains at -0.5V for 41ms, increases linearly with time to about 1.25V in 1.5s and then remains at 1.25V for 1.1s.

The narrow pulses applied in the pulsed sweep mode have pulse widths of 160 μs and a repetition period of 640 μs. During the inter pulse period of 480 μs the LP sensor is maintained at zero potential with respect to the rocket body that is considered ground for all the potential measurements. During the period of 160 μs when the pulsed potential is applied to the sensor, the current collected by it is measured through a gate of width 40 μs using a very high input impedance current to voltage converter amplifier and a sample and hold circuit. The same system is used to measure the current collected by the sensor during the continuous sweep mode also. The block diagram of the electronic system is shown in Figure 2. For covering the large dynamic range of the sensor current varying in the range of a few nano amperes to several tens of microamperes, the current to voltage converter amplifier operates in two ranges, one with a gain of unity and the other with a gain of around 40. The output of the current to voltage amplifier is processed through three different channels to study the slowly varying as well as fast varying components in the sensor current.

3. RESULTS AND DISCUSSION

The I-V characteristic curves of the LP sensor observed at approximately 70, 100 and 200 seconds after launch corresponding to mean altitudes of around 100km, 150km and 260km are shown in Figures 3, 4 and 5 respectivley for both continuous and pulsed sweep modes of operation of the LP. The variation in the relative strength of the current collected by the sensor as a function of the potential applied to it for the potential range of 0V to +1.5V (1.25V in the pulsed mode) is shown in these figures. It should be noted here that in the

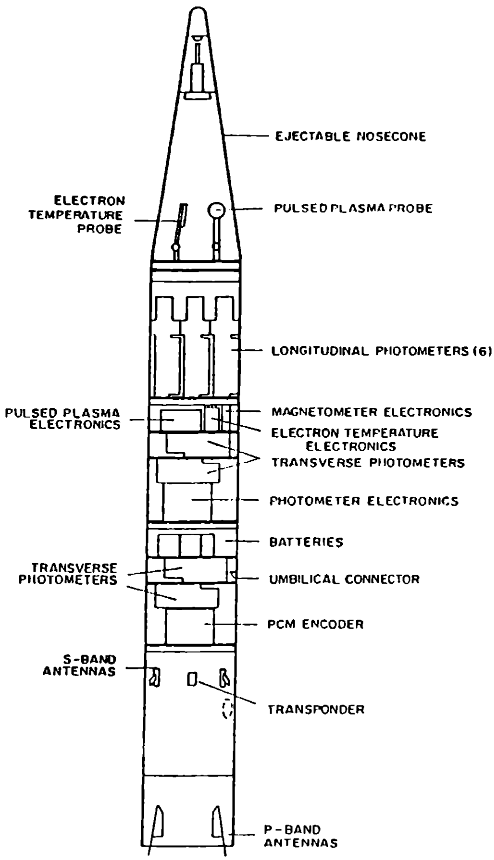

Figure 1. *Payload segment of the SONDA III rocket showing the location and mounting of the Langmuir Probe and other optical diagnostic experiments with their associated electronics systems.*

electronic system used for the signal processing, positive as well as negative current collected by the sensor is converted into a varying negative potential at the output of the current to voltage converter. In other words positive current collected by the sensor is folded on to the same side that represents the negative current collected by it. Thus the current minimum observed in all the curves, in fact corresponds to more or less zero current and therefore to the floating potential of the sensor.

The current collected by a spherical sensor immersed in a plasma is given by the approximate relation (see Spencer et al 1962),

$$I = \frac{Ane}{4}\left[\left(\frac{a}{r}\right)^2 v_s - \bar{v}_e exp\,(\frac{eV}{kT_e})\right] \tag{1}$$

where A is the surface area of the sensor, n is the ambient plasma number density, e is the magnitude of the electronic charge, a is the radius of the plasma sheath shell surrounding the spherical sensor, r is the radius of the sensor, v_S is the sensor speed with respect to the ambient medium, v_e is the mean thermal velocity of electrons, V is the sensor potential with respect to the ambient plasma, k is the Boltzmann constant and T_e is the electron temperature. The first term within the brackets in equation (1) represents the positive ion current and the second term the electron current collected by the LP sensor. For positive sensor potentials if one assumes that the positive ion current is negligible compared with the electron current (the consequences of this approximation will be discussed later) and thereby neglects the positive ion term in equation (1), one can get the simple relation,

$$ln|I| = ln(Ane\bar{v}_e / 4) + \frac{eV}{kT_e} \tag{2}$$

Using equation (2) one can estimate the electron temperature from the slope of the linear portion of the ln(I) vs V characteristic curve. If I_1 and I_2 are the electron currents collected at sensor potentials V_1 and V_2 one can get from equation (2),

$$T_e = \frac{e}{k} \cdot \frac{V_2 \quad V_1}{ln|I_2| - ln|I_1|} \tag{3}$$

The electron temperature values thus estimated for continuous as well as pulsed mode operations of the LP are shown in Figures 6 and 7 for the upleg and downleg of the rocket trajectory respectively. Also given in Figures 6 and 7 is the IRI90 model estimate of the electron temperature. The following important observations can be made from these figures.

1. Electron temperature estimates made from the pulsed mode operation of the LP differ considerably from those made from the continuous mode operation.

2.IRI90 model temperature profile matches reasonably well the pulsed mode T_e profile, though at altitudes below about 150km the two profiles deviate considerably one from another.

To understand clearly these observations one has to look back into the limitations of the conventional LP technique. LPs operated with slow varying sweep are known to be affected by temporal variations in the effective work function of the probe resulting mainly from the probe surface contamination (for details see Holmes and Szuszcewicz, 1975 and references therein). Oyama (1976) presented a theoretical formulation of the problem using an equivalent circuit for the contamination of the probe surface, and tried to verify these theoretical results from laboratory experiments. He finds that the probe surface contamination results in considerable overestimation of T_e when the probe is operated at a sweep rate less than a few Hz and that this effect reduces considerably when the probe potential is swept at a higher rate, typically above 10Hz. The effect of surface contamination on a slow varying probe potential is to introduce a potential drop across the contamination layer and thereby to reduce the effective potential seen by the ambient plasma . T_e value estimated from the example given in figure 5 of Oyama (1976) using the equation 3 is at least an order of magnitude higher than the T_e value of 600^oK estimated by him using a clean probe and the value of 610^oK estimated using an unclean probe operated at a fast sweep rate (see figure 6 of Oyama, 1976). Szuszcewicz and Holmes (1975) report that their laboratory studies with conventional LPs give T_e estimates at times a factor of 2 higher than the estimates made using their pulsed technique. Thus one can easily find an explanation for the observation (1) above. Since the present sensor potential sweep rate is about 0.4Hz, much lower than the 10Hz limit observed by Oyama (1976), almost a factor of 2 difference between the T_e estimates made from the pulsed and continuous modes of operation of the LP can be attributed to the effect of probe surface contamination.

The fact that the electron temperature values estimated from the pulsed sweep mode operation of the LP are much closer to the IRI90 model estimates (observation 2 above) confirms the experimental results of Szuszczewicz and Holmes (1975) with a laboratory plasma that the pulse technique is superior to the conventional continuous sweep method. However the large deviation of the IRI90 temperature profile from the pulsed mode LP profile needs to be explained. Oyama and Hirao (1976) report a similar enhancement in the E-region T_e profile over the model neutral temperature profile and attribute this to the existence in this region, of two groups of electrons with different temperatures (see also Oyama and Hirao, 1985). Oyama et al (1983) also report that their T_e profile estimated from their electron temperature probe deviates considerably from the model neutral temperature in the lower E-region (100-120km) and attribute this to the additional heating of electrons caused by the currents that flow in this height region (see also Schlegel et al, 1983). But they find it difficult to explain why these deviations are larger at midlatitudes than in the equatorial region where the intense electrojet current flows. They also suggest that the high energy electrons identified probably with field aligned currents that flow into the winter hemisphere along the geomagnetic field lines and spread at the heights of around 150km, are also partly responsible for the enhancement in T_e observed in the E-region altitudes. Abe et al (1993) estimate model T_e profiles for the auroral region taking into account the joule heating due to perpendicular electric fields and solar EUV radiations. They find that the joule heating and solar EUV radiations can cause an enhancement in T_e at lower altitudes including the E-region. There is no reason why this effect should not be observed at equatorial latitudes where perpendicular electric fields are known to exist. Therefore, there are sufficient reasons to believe that the deviation in the pulsed mode T_e profile from the model profile at altitudes below 150km is genuine and is probably due to the IRI90 model being unrealistic in this region.

It should also be noted here that equation (2) relating the electron temperature to the potential applied to the LP sensor and the current collected is only an approximate one and is based on several not-so-realistic assumptions. Muralikrishna et al (1994) studied the consequences of assuming that the positive ion current is negligible and report that this can result in overestimating, leaving unaltered or even underestimating the actual electron temperature. But this is a second order effect and the deviation caused by this in the T_e profile, when compared with that caused by the probe surface contamination, seems to be negligible. From these considerations it seems to be quite logical to conclude that the pulsed mode operation of an LP gives realistic estimates of the electron temperature as indicated by its closeness to the IRI90 model profile especially at altitudes above 150km. Also, the deviation of the model profile from the pulsed mode LP profile below 150km seems to be due to inadequacies in the IRI90 model resulting from several factors like scarcity of experiment data, non inclusion of the joule heating effect in the model and inadequate knowledge of the dynamical processes operating in this region.

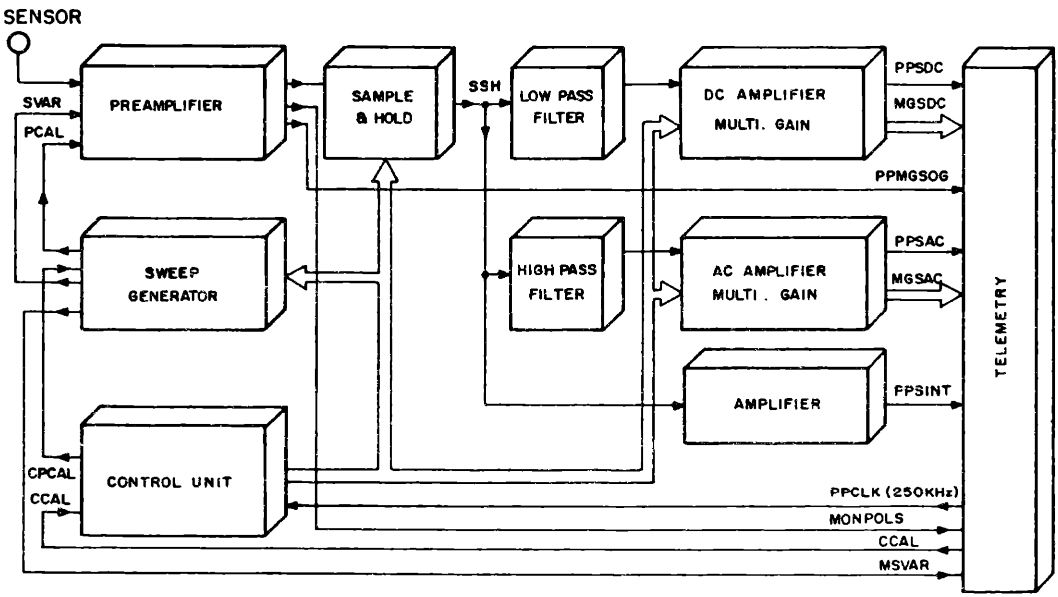

Figure 2. *Block diagram of the Langmuir Probe electronics system.*

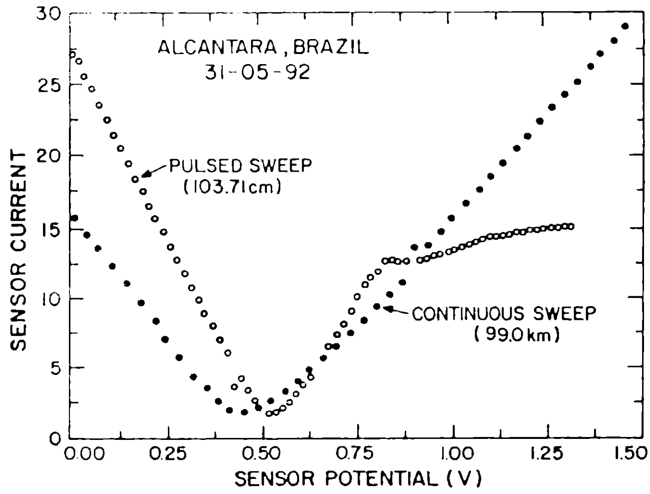

Figure 3. *Observed current-voltage characteristic curves for continuous and pulsed sweep mode operations of the Langmuir Probe corresponding to the height region of around 100km.*

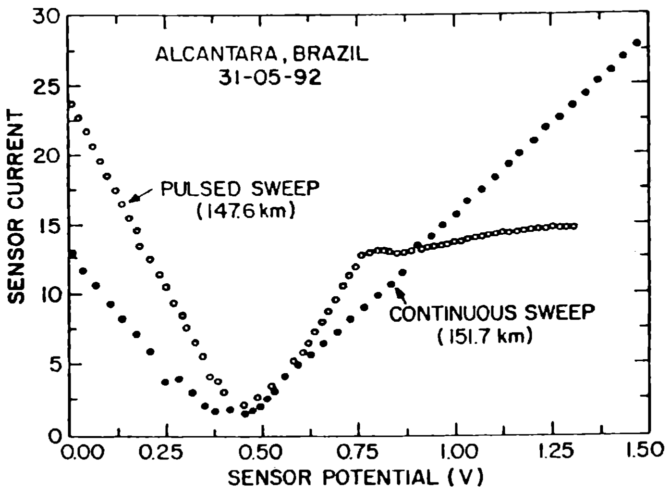

Figure 4. *Observed current-voltage characteristic curves for continuous and pulsed sweep mode operations of the Langmuir Probe corresponding to the height region of around 150km.*

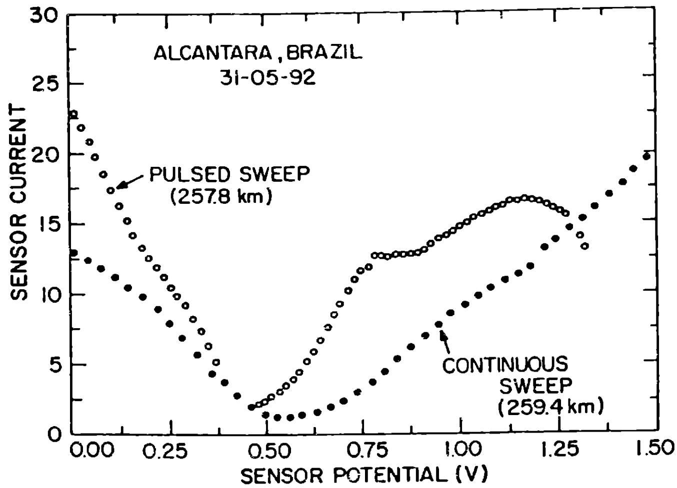

Figure 5. *Observed current-voltage characteristic curves for continuous and pulsed sweep mode operations of the Langmuir Probe corresponding to the height region of around 260km.*

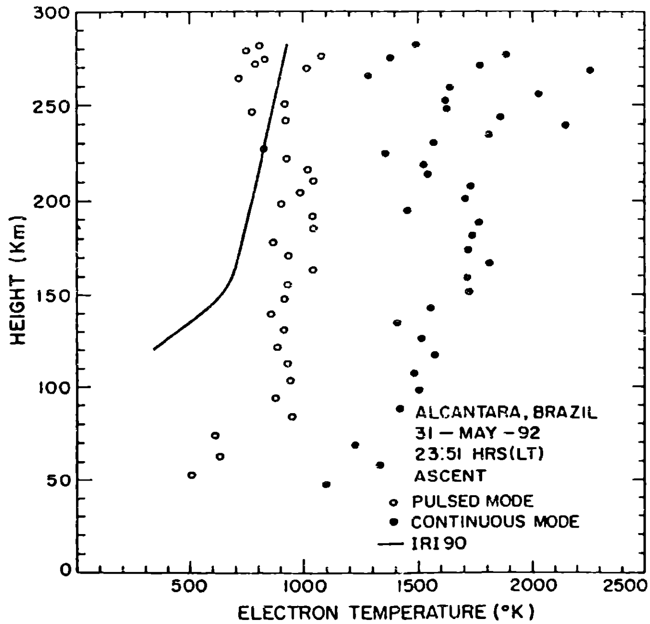

Figure 6. *Height profile of the estimated electron temperature for continuous and pulsed sweep mode operations of the LP compared with the IRI90 model profile for the upleg of the rocket trajectory.*

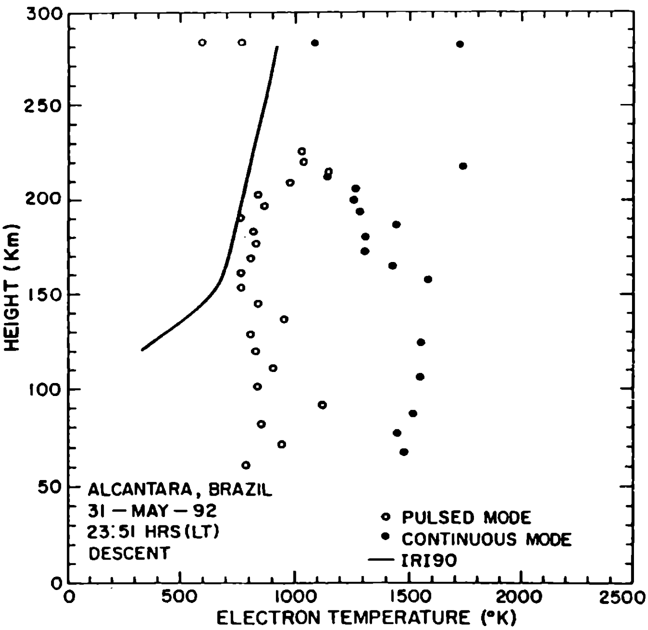

Figure 7. *Height profile of the estimated electron temperature for continuous and pulsed sweep mode operations of the LP compared with the IRI90 model profile for the downleg of the rocket trajectory.*

4. CONCLUSIONS

From this comparative study of the Langmuir Probe performance in continuous and pulsed sweep modes of operation one can see that there is a marked difference in the current-voltage characteristic of a Langmuir probe operated in pulsed mode when compared with that operated in continuous mode. In conformity with the laboratory observations of Szuszczewiz and Holmes (1975) the effect of surface contamination on the LP current-voltage characteristic seems to be practically absent in the pulsed mode operation of the LP. The IRI model electron temperature profile for the equatorial region seems to be unrealistic, especially for altitudes below 150km, giving electron temperatures lower than those estimated from the LP measurements.

Acknowledgements. The rocket experiment reported here was made possible through an active collaborative programme between the Instituto de Aeronautica e Espaço - IAE/CTA and the Instituto Nacional de Pesquisas Espaciais - INPE/MCT. The authors would like to thank Engineers Sinval Domingos, Agnaldo Eras and Narli Baesso and several other technical personnel of INPE, CTA and CLA for their dedicated efforts in the development, preparation and launching of the payload. This work was partially supported by the FNDCT under contract FINEP 537/CT and by CNPq under process

300253/89-3(RN). The authors would like to thank the referee for making several useful suggestions for the improvement of this paper.

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A FAST CAM DRIVEN ABSORPTION CELL BASED ROCKET-BORNE NITRIC OXIDE DETECTOR

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ABSTRACT

A nitric oxide(NO) detector, making use of a newly developed fast cam-driven absorption cell system is developed for launch on board a Brazilian SONDA III rocket, to measure the height profile of the NO gamma band dayglow emission intensity and thereby to estimate the height profile of the number density of atmospheric NO in the equatorial region. Two absorption cells, one of them containing the gas NO and the other nitrogen are brought in front of the photocathode of a photomultiplier(PM) tube alternately using a cam system. Each cell remains in front of the PM tube for an interval of time fixed by the cam shape. The cam is designed to optimize the time needed for positioning the cells one after the other and also to simplify the operation of the step motor responsible for the movement of the absorption cells. The advantages of this new system over the conventional wheel mounting are also presented.

1. INTRODUCTION

The gamma band dayglow arises from resonance fluorescence of atmospheric NO by solar MUV radiation. The brightest emission band is the (1,0) band near 214.8nm which has an apparent emission rate exceeding 1kR at the base of the mesosphere. Tohmatsu and Iwagami (1975, 1976) developed a rocket-borne nitric oxide self absorption cell for determining the height profile of nitric oxide in the earth's atmosphere, by measuring the intensity of some of the gamma band emission lines from NO. Their NO self-absorption cell makes use of the self absorption effect of NO gas contained in a quartz cell. This cell also acts as a sharp rejection filter for discriminating the gamma band emissions from a continuous background. Two identical quartz cells, one containing NO gas and the other some other gas like nitrogen are alternately brought in front of the photocathode of a properly selected photomultiplier tube and the difference in the flux collected by the PM tube can be used in estimating the gamma band intensity profile from which the height profile of the NO number density can be determined.

An absorption cell system similar to the one used by Tohmatsu and Iwagami (1975, 1976) has been developed by the authors for launch on board a Brazilian SONDA III rocket. A new cam system positions the two quartz cells in front of the photocathode of a Hamamatsu head-on type R431S solar-blind photomultiplier tube. This replaces the conventional mounting of the cells on a rotating wheel whose rotation is generally controlled by a step motor. General features of the NO detector, the basic concepts on which the cam design is based and its advantages over the conventional system are presented here.

2. EXPERIMENT DETAILS

Block diagram of the NO detector is shown schematically in Figure 1. The fore-optics consists of a solar baffle-honeycomb collimator to prevent stray light from falling on the photocathode of the PM tube and to restrict the field of view of the photometer, a narrow band interference filter and a pair of absorption cells with quartz windows, one of which contains NO gas and the other nitrogen both at a pressure of about 100 torr. The collimator, that does not contain any optical component other than a honeycomb view-limiter has an overall length of 120mm and a diameter of 38mm. The honeycomb view-limiter mounted inside the collimator close to the PM tube, is made up of cylindrical tubes of about 3mm diameter and 35mm length providing a circular view cone of about 10o. The interference filter has a pass band of 20nm centered at 214nm with a transmission factor of above 18% in the pass band. The filter pass band includes the atmospheric NO gamma band fluorescent emission lines. The metallic absorption cells, cylindrical in shape, are 35mm long and 30mm in diameter and are provided with quartz optical flats of 25mm diameter and 1.3mm thickness at the entrance and exit windows. One of the cells is filled with NO and the other with nitrogen. While the NO gamma band emission lines produced by transitions between vibrationally excited states and the zero level of NO molecules (see Tohmatsu and Iwagami, 1976) are absorbed by the NO gas in one of the quartz cells, the incident radiation passes practically unaffected through the other cell containing nitrogen gas. The radiation transmitted by either of the cells falls on the photocathode of a PM tube where it is converted into an electrical signal. The PM tube used is Hamamatsu R431S head-on type, has a Cs-Te photocathode that is solar blind and has a spectral response in the range of 160nm-320nm. It has a photocathode of 25mm useful diameter with maximum response at 210nm. The output signal from the PM tube, in the form of pulses with amplitudes proportional to the number of photons incident on the photocathode, is amplified, processed in a data acquisition unit and then transmitted to the ground station by the on board telemetry system. In principle the difference in the intensity of the signals transmitted by the two absorption cells is a measure of the intensity of the NO gamma band emission lines absorbed by the NO cell. The movement of the two absorption cells in front of the PM tube is controlled by a cam system driven by a 180rpm, 7.5o/step step motor . The advantages of such a system over the conventional wheel mounting will be discussed later.

As mentioned earlier, the expected output from the PM tube is a sequence of short period pulses with an inter-pulse period equal to the dwell period of each absorption cell in front of the PM tube. Amplitude of each pulse is a measure of the integrated number of photons falling on the photocathode of the PM tube through the filter-absorption cell combination. For the purpose of analysis two consecutive pulses in the pulse sequence are to be considered at a time. The amplitude of one of them is proportional to the integrated photon flux received through the NO cell and that of the other is proportional to the integrated flux received through the nitrogen cell. Knowing the spectral response and other optical characteristics of the detector from laboratory calibrations one can estimate the integrated intensity of the NO gamma band emission lines absorbed by the NO cell. The NO number density profile can then be deduced from the height profile of these NO gamma band emission lines. The basic principle of operation of a detector of this type along with relevant theoretical aspects are given in Tohmatsu and Iwagami(1976).

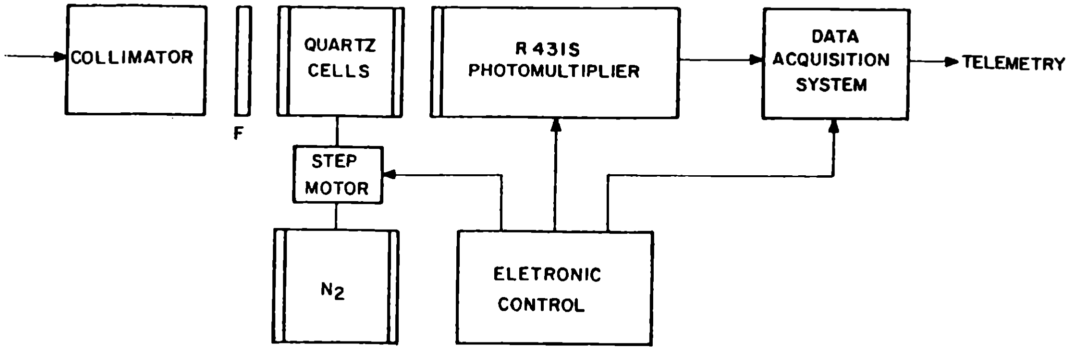

Figure 1. *Block diagram of the rocket-borne nitric oxide detector showing the important subsystems.*

Mechanical details of the NO detector are shown in Figure 2. The most important innovation in the present system is in the mounting of the two quartz cells in front of the PM tube. Unlike the case of the conventional wheel mounting, in the present system the two cells are mounted on a disc close to each other and the movement of the disc is controlled by a cam system (Figure 3). This disc undergoes an oscillatory motion bringing the two cells alternately in front of the photocathode of the PM tube for a predetermined time interval. This oscillatory motion of the disc is produced by the cam coupled to the disc by a shaft. The cam rotates around its own axis. The profile of the cam is chosen in such a way as to keep either of the cells in front of the PM tube for a fixed and equal duration of time, the transfer times from one cell to the other also being equal.

The most important aspects taken into consideration in designing the cam profile are the following.

(1) The period for which each cell remains in front of the tube must be about 30 ms.

(2) The transfer time from one cell to the other must be as short as as possible.

(3) The motor responsible for the movement of the cells should not be subjected to excessive torques. This can be achieved only by increasing the transfer time of the cells and by selecting a smooth curve for the transfer part of the cam profile.

From the above considerations, a constant speed of 180 rotations per second is chosen for the cam. The cam profile is chosen to bring each of the cells in front of the PM tube three times during every rotation. This gives rise to the following sequence of events, the time of the first event being chosen arbitrarily.

(1) NO cell is in front of the photocathode of the PM tube for about 28ms.

(2) The NO cell is replaced by the nitrogen cell in about 28ms.

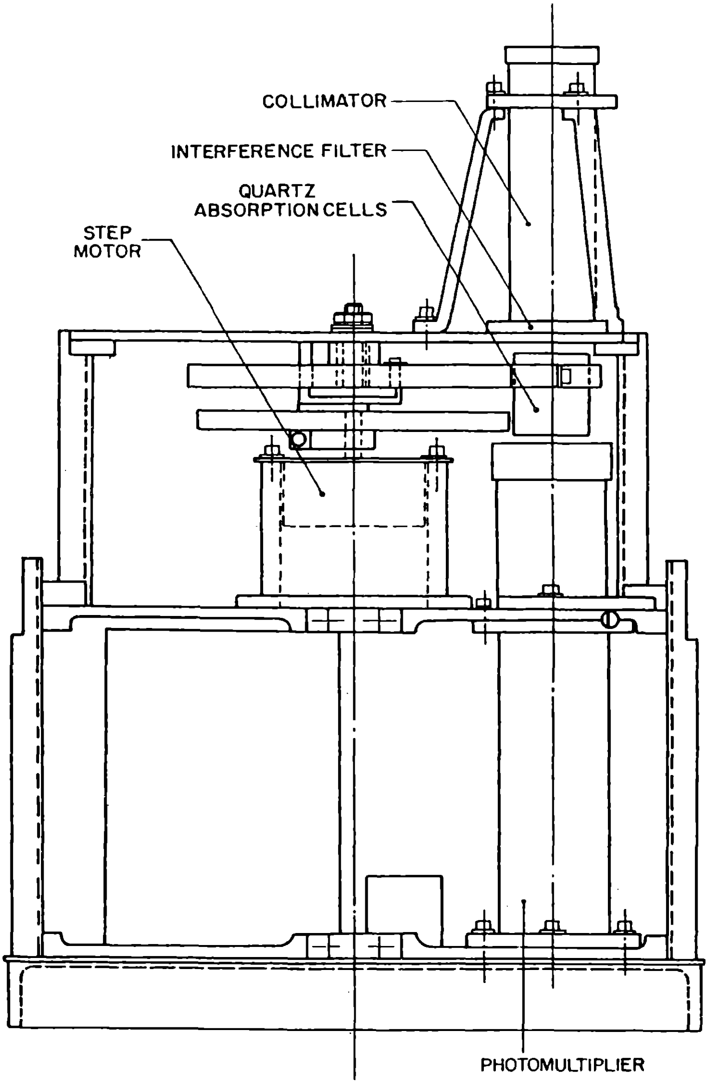

Figure 2. *Mechanical design drawing showing the mounting of the mechanical components including the cam system on the payload segment of a SONDA III rocket.*

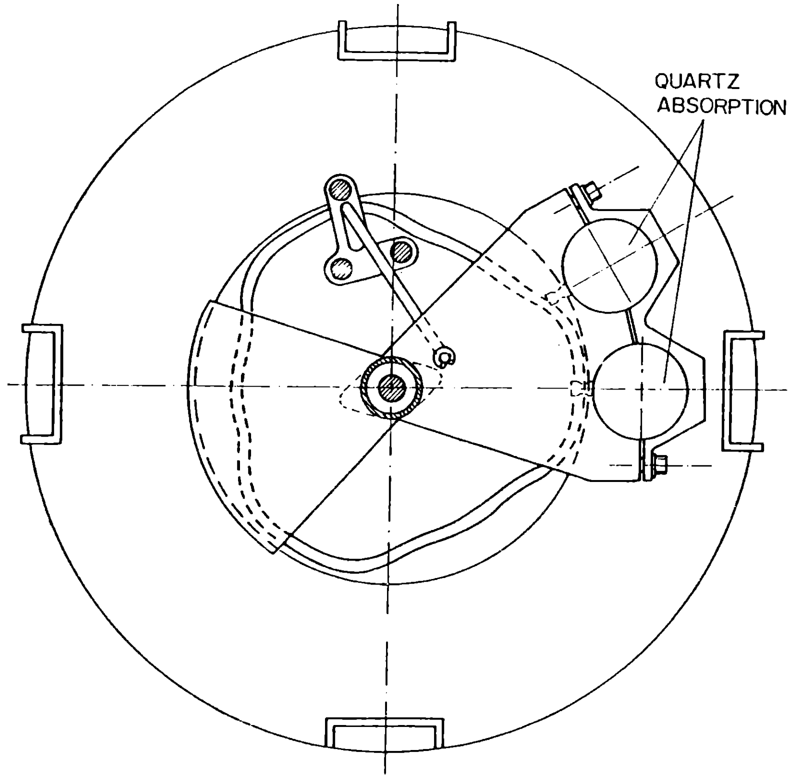

Figure 3. *Schematic representation of the cam system showing the cam profile and the shaft that moves the disc on which the two quartz cells are mounted.*

(3) The nitrogen cell is in front of the photocathode of the PM tube for about 28ms.
(4) The nitrogen cell is replaced by the NO cell in about 28ms.
(5) The sequence starts over again with Event (1).

3. CAM PROFILE

Shown in Figure 4. is a linear plot of the cam profile for one full rotation of the rotor. The profile segment that controls the movement of the shaft and the disc is chosen as shown below.

- Segments A, E and I are circular with 50mm radius and represent angular segments of the rotor corresponding to say θ = 0-30°, 120°-150° and 240°-270° respectively. The circular segment causes the corresponding cell to remain fixed in front of the PM tube.
- Segments C, G and K are also circular with 60mm radius and represent angular segments of the rotor corresponding to θ = 60°-90°, 180°-210° and 300°-330° respectively.

- Segments B, D, F, H, J and L are cycloidal in shape governed by the basic equation,

$$y=\frac{10}{\pi}\left[\frac{\pi\varphi}{30}-\frac{1}{2}sin\frac{\pi\varphi}{15}\right]$$

where y is the displacement in millimeters to be added to 50mm in the case of segments B, F and J and to be subtracted from 60mm in the case of segments D, H and L. φ is the angular variation from 0 to 30°.

It should be mentioned here that the cycloidal part of the cam profile was selected after analysing the mechanical performance characteristics of various other types of curves. The major advantage of the cycloid is the smooth variation of the gradient along it from one point to another. The gradient is what decides the variation in the motor torque needed for the movement of the shaft along the cam profile. Thus a smooth variation in the gradient guarantees smooth variation in the motor torque.

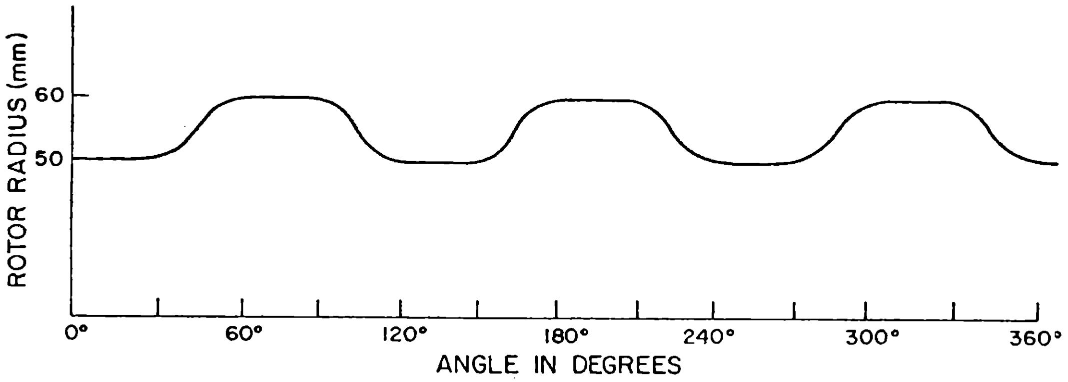

Figure 4. *Linear plot of the cam profile.*

4. ADVANTAGES OF THE CAM SYSTEM

Several problems associated with the conventional wheel mounting of the cells can be resolved by the introduction of the cam drive. Some of the advantages of this new system are the following.

(1) The cam system avoids jerky mechanical movements of the motor as well as the mount wheel of the cells. In the new system the motor rotates continuously.

(2) The cycloidal transfer profile chosen for the replacement of one cell by the other guarantees a smooth transfer and thus maintains practically a constant torque for the motor during the whole operation period. In the conventional wheel mount the motor experiences sudden changes in the load and hence has to operate with a highly nonuniform torque.

(3) The cam system guarantees alignment of the cells in front of the optical system while the conventional wheel mounting necessitates additional monitoring of the alignment.
(4) With the new system one can reduce the measurement period with each cell without increasing the motor rotation rate. For example, in the present case, for each rotation of the cam the absorption cells are changed three times. In the conventional wheel mount the cells are changed only once during every rotation of the wheel.
(5) Either a step motor or a continuous motor can be employed to drive the cam system.
(6) Cell or calibration source movements can be programmed in advance by proper choice of the cam rotor profile. The order in which each one of them should align with the optical system can also be easily programmed.
(7) Compared with the conventional wheel mounting the new cam system is more compact and thus occupies less physical space.

Advantage (4) above of the new cam-driven system implies possibilities to obtain better height resolution for the measurements. In the experiments reported by Tohmatsu and Iwagami(1975, 1976) a pair of data points, one with the NO cell and the other with the nitrogen cell was obtained in more than 1.6s, 0.8s being the time period for which each cell was in front of the PM tube. Such a system, when used on board a rocket moving with a velocity of 2km/s in the height region of interest will represent a height resolution of 3.2km. The new cam-driven system gives a pair of data points in 112ms thereby reducing the height resolution to less than 250m. However one must remember here that the sensitivity of the PM tube puts a lower limit on the height resolution that can be achieved. Since the cam-driven system changes the cells in front of the PM tube at least three times faster (for each cam rotation the cells are changed three times while in the conventional wheel mount the cells are changed only once for each rotation of the wheel) than the conventional system and therefore gives a height resolution at least 3 times better than the conventional system.

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SOLAR VARIABILITY EFFECTS ON CLIMATE

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ABSTRACT

One of the key tasks in climate research at the present time is to separate anthropogenic effects from natural change. Solar variability is one possible cause of natural change in addition to other external phenomena such as volcanic eruptions and, on a long-term scale, orbital changes and celestial body impacts. The topic of "sun-weather relationships" has followed a long and tortuous history of scientific speculations and controversy since the continuous observation of sunspots began in the 17th century. It was not until recently that more systematic studies with long-term data bases of meteorological, climatological and solar parameters led to an increasing, statistically robust, body of evidence for a causal connection between some manifestations of solar variability and changes in the troposphere and the climate system. While of planetary scale, the strength and sign of pertinent correlations have distinct geographic, seasonal and other temporal characteristics. Most likely, several trigger mechanisms are at work simultaneously, but their relative importance may depend on the time-scale envisaged and on competing processes such as volcanic eruptions. In this paper we will summarize the most frequently formulated criticisms, review the most recent results on relevant solar variability effects at the 11-year, secular, and short-term time scales, and discuss proposed mechanisms such as enhanced Hadley circulation, charged particle ionization effects on clear-air conductivity, and electric field effects on the microphysics of cloud formation.

RESUMEN

En la actualidad, una tarea clave de la investigación climática es la de separar los efectos antropogénicos de los cambios naturales.
La variabilidad del sol es una posible causa del cambio natural junto con otros posibles fenómenos de orden externo como por ejemplo las erupciones volcánicas y en escalas de tiempo mas largas cambios orbitales y el impacto de cuerpos celestes. El tema "relación sol-clima" ha seguido una larga y tortuosa historia de especulación científica y controversias desde que en el siglo 17 se empezaron a observar en forma contínua las manchas solares. Recientemente, sobre la base de estudios más sistemáticos y bases de datos de períodos largos de parámetros meteorológicos, climatológicos y solares se dispone de un cuerpo de evidencias amplio y estadísticamente robusto de la conexión causal entre algunas manifestaciones de la variabilidd solar y cambios en la tropósfera y el clima. En la escala planetaria, la intensidad y signo de las correlaciones poseen distintas características geográficas, estacionales y otras temporales. Muy probablemente, distintos mecanismos de "trigger" operan simultaneamente, pero su importancia relativa puede depender de la escala de tiempo considerada y de procesos competitivos como las erupciones volcánicas. En este trabajo, haremos un resumen de las críticas mas frecuentes, veremos los resultados recientes más relevantes de los efectos de la variabilidad solar de 11 años, secular, y escala de tiempo corta; y discutiremos mecanismos propuestos como la circulación de Hadley ampliada, efectos ionizantes de partículas cargadas sobre la conductividad del aire limpio, y efectos del campo eléctrico en la microfísica formación de nubes.

1. INTRODUCTION

The topic of "sun-weather relationships" has followed a long and tortuous history of scientific speculation and controversy. As soon as sunspots became the subject of systematic observation after Galileo's invention of the telescope, scientists began to wonder about the possible effects of these "blemishes" on terrestrial weather. Yet from the very beginning, the efforts to discover Sun-weather relationships carried the stigma of "bad science". This was in part due to the fact that the only scientific paradigm available was to correlate selected meteorological parameters with time-dependent features on the Sun and hope that the correlation would hold up in the future. And in most cases it didn't!

It was not until the first decades of this century that more systematic studies were begun using long-term data bases of meteorological, climatological and solar parameters. An early example is the study of the global distribution of annual rainfall difference between sunspot cycle maximum and minimum, given in the book by Clayton (1923); later, Roberts (1975) discussed statistics on the occurrence of droughts in Nebraska, which showed a tendency to occur near that sunspot minimum which followed a magnetically negative maximum (of the 22-year Hale cycle). Clayton's study clearly showed that if a physical relationship existed between the 11-year sunspot cycle and tropospheric phenomena, it had to exhibit a regional dependence. Roberts' paper brought in the overall magnetic configuration of the Sun (because of the correlation with the Hale cycle), and it also showed a phase-locking to the quasi-periodic character of the solar cycle (frequency modulation), a statistically significant fact given the low probability that an atmospheric periodicity unrelated to the Sun would track the changes in solar cycle length just by chance.

During the seventies it became apparent that it was necessary to clearly divide the study according to three classes of solar variations: 1. the 11-year sunspot cycle (and, eventually, the related 22-year magnetic Hale cycle); 2. the long-term secular changes of sunspot cycle amplitude (the Gleissberg "cycle"); 3. short-duration, sporadic events, such as solar flares and the Sun-controlled solar wind shocks and reversals of the interplanetary magnetic field. Concerning secular effects, Eddy (1976) published a classical paper revealing the remarkable correlation of winter temperatures in London and Paris with the Gleissberg cycle (traced back in time to the 12th century by using as proxy indicator of solar activity the C-14 concentration in tree rings). This paper received particular attention because it linked the "Little Ice Age" in the 17th century and the cold period in the 15th century with the Maunder and Spörer minima, respectively, in which few sunspots were seen for several decades. Regarding short-term variability, Wilcox et al. (1974) published a study of changes of the northern hemisphere "vorticity area index" ("VAI", a quantitative measure of low-pressure troughs) at the times of magnetic sector boundary passages (interplanetary magnetic field reversals), showing statistically significant decreases of the VAI from 2 days before to one day after the passage during winter months (this correlation, however, did not subsist during the eighties).

These and many other studies (e.g., Hines and Halevy, 1977; Bucha, 1988) could not dispel the general skepticism about the subject per se, particularly on part of the meteorological community. It is only in recent years that the availability of statistically robust results and the formulation of plausible trigger mechanisms to explain the observed correlations have placed the field in a more respectable standing with the general scientific community.

The study of solar variability effects on the immediate human environment is now an important and integral part of the ICSU/SCOSTEP Solar Terrestrial Energy Program 1990-1997 (STEP) (Roederer, 1992). The present paper will discuss the most frequently formulated criticisms of solar activity-climate studies and review some important recent results. For detailed literature references, the reader is referred to the articles cited in this paper.

2. MOST FREQUENT CRITICISMS AND "FREAK FACTS OF NATURE"

The study of solar variability effects on climate has been subjected to severe criticism that can be grouped into several distinct categories. While this criticism was well founded on historical grounds, much of it can now be dispelled on the basis of recent studies.

The power involved in solar variability is too small! Indeed, the total solar electromagnetic power deposited in the Earth's environment is more than 10^{12} MW, whereas the variable components of electromagnetic and particle energy impinging on the Earth system represent only 10^4 MW to 10^6 MW, i.e., only a tiny fraction of the main energy flux. Furthermore, the variable energy components mainly affect the magnetosphere and upper atmosphere which are only very weakly coupled to the troposphere. The energy argument, however, is not valid for highly non-linear, complex systems such as the coupled atmosphere-ocean-biosphere. It is well known that complex systems can behave chaotically, i.e., follow very different paths after the smallest change in initial or boundary conditions, or in response to the smallest perturbation. In a highly non-linear system with large reservoirs of latent energy such as the atmosphere-ocean-biosphere, global redistributions of energy can be triggered by very small energy inputs, a process that depends far more on their spatial and temporal pattern than on their magnitude. Moreover, such a system may exhibit sudden transitions between some "eigenstates" of quasi-equilibrium; recent data from the Greenland ice sheet clearly show this for the Northern Hemisphere atmosphere prior to the Holocene period (Dansgaard et al., 1993).

We cannot think of any mechanisms responsible for solar-climate effects! This is an "unscientific" argument; there are abundant historical examples of processes which were studied, accepted or used, but for which the responsible mechanism was not known for a long time (e.g., dinosaur extinctions, plate tectonics, or atomic spectral line emissions which, although "prohibited" by classical electrodynamics, had been in use in science and technology many decades before their explanation by quantum mechanics). Besides, the argument as a whole does not hold anymore: trigger mechanisms are presently being formulated and studied.

It's all just a coincidence! Historically a quite valid argument, but it does not hold anymore: there are too many statistically robust results the probability of which to occur all by chance is extraordinarily small. This in particular applies to those correlations which stay in phase with the quasi-periodicity of solar activity. Predictions based on recent studies covering a limited period of time were verified when new, later, data came in (e.g., Labittzke and van Loon, 1993) or when more data reaching into the past were included (e.g., Friis-Christensen and Lassen, 1993).

The intervals for which data are available for correlation studies are too short! This is a valid criticism when applied to some of the recent studies of 11-year cycle effects. The band-width of uncertainty in the determination of the period using data from a time-interval of, say, only three solar cycles is ± 2 years; therefore, any intrinsic atmospheric periodicity between 9 and 13 years could be expected to show an acceptable correlation with the solar cycle (e.g., see the discussion in Salby and Shea, 1991). Until now, however, no plausible decadal cycle variation of the atmosphere unrelated to the Sun has been identified or proposed.

The "So what?" question. It has been argued that whereas solar variability-climate effects do exist, they are so small that they are unimportant for forecasting purposes (e.g., Pittock, 1979). Leaving aside the question of whether they are really that small, this is yet another "unscientific" argument: every global and coherent response should be considered important for the physical understanding of the atmospheric system!

In addition to the above criticisms which the researchers in this field may continue to face, there are some "freak facts" of Mother Nature that conspire to make physical interpretations especially difficult.

1. All solar emissions exhibit 11-year periodicity; this makes source identification more difficult. For instance, could an 11-year periodicity in the atmosphere be due to the 11-year variability of solar irradiance, or could it be due to the cumulative effect of short-term events (like solar flares), whose occurrence also exhibits an 11-year periodicity?

2. The amplitudes of the last two solar maxima (both in terms of sunspot number and total irradiance) were nearly identical. This makes it difficult to model solar irradiance (for which absolute satellite measurements are available only after 1978) and its relation to sunspot number, a fact that in turn prevents using the latter as a proxy to estimate total solar irradiance values in the past.

3. The time lag between annual average temperature over land and the mean sea-surface temperature (governed by the ocean response time), and the time lag between the 11-year running means of solar cycle amplitude (the Gleissberg cycle) and solar cycle duration, are both of the order of 10-15 years. This obscures the discriminability among proposed mechanisms (see Section 4.2).

4. The beat period between the 26-28 month quasi-biennial oscillation (QBO) and the biennial period (24 months) is 12-14 years, i.e., of the same order as the solar cycle period. In principle, this can decrease statistical discriminability in QBO-stratified time-series (aliasing effect, Teitelbaum and Bauer, 1990), but it is of little importance due to the strongly quasi-periodic character of the QBO (see section 4.1).

5. GCM calculations show that random stochastic variations of the mean atmospheric temperature can have similar amplitudes and time scales as the observed variations. This makes the distinction between unpredictable intrinsic variations and those driven by external and anthropogenic forcing difficult.

6. The "ultimate freak fact" is that key parameters such as the global temperature, sunspot cycle amplitude, greenhouse gas concentrations and sunspot cycle frequency all show a net increase since the late 1800's. This poses extra difficulties in the determination of the differential climate sensitivity to the various possible forcing factors.

3. THE VARIABLE INPUT CHANNELS

Figure 1 depicts schematically the most important energy input channels from the Sun, their continuous or sporadic variability and the regions in the terrestrial atmosphere that can be affected by this variability. Solar magnetohydrodynamics regulates all forms of variability, including that of the intensity of the cosmic ray flux, the configuration of the high-latitude ionospheric electric field and the precipitation of energetic trapped electrons, all of which are controlled by the interplanetary magnetic field (IMF). The variability of the two photon channels at left is controlled by surface structures, such as faculae and plages (radiation emitters) and sunspots (blockers), whereas the particle channels are mainly controlled by processes in the coronal plasma. Finally, the Earth's internal magnetic field, which is variable on a secular scale (including an approximately 6,000-year oscillation of the main dipole moment), also influences the fluxes of the charged particles penetrating the atmosphere. Not considered at all in the figure (and in this paper) are the variations of solar insolation due to periodic changes in orbital and rotational parameters of the Earth (leading to the Milankovitch cycles). Also not considered are the natural 27-day periodicities related to solar rotation. The atmospheric processes sketched in Fig. 1 will be discussed in Chapter 5.

An important discovery (e.g., Willson and Hudson, 1988) was the small but significant 11-year modulation of the "solar constant" (total irradiance in W/m^2 at 1 a.u.). Figure 2. (from Kyle et al., 1993) shows monthly mean values of the total irradiance as measured with a radiometer on Nimbus 7, together with the Wolf sunspot number. The 11- year modulation comes from two sources of mutually counter-acting effects: enhanced emissions from bright faculae during solar maximum and enhanced blocking by sunspots (obviously the former wins over the latter). In addition, a long-term variation is speculated to exist, caused by the possible growth and decay of the global facular network on the solar surface (White et al., 1992). Fig. 2 shows that the overall relationship between total irradiance and sunspot number during one cycle is clearly non-linear and is different during the descending and ascending phases of solar activity. It is important to note that the UV band of the photon spectrum exhibits a much larger 11-year variability than that shown for the total irradiance (Donnelly,1991).

Since the two recent solar maxima shown in Fig. 2 are of nearly the same amplitude ("freak fact No. 2"), nothing can be concluded from these measurements about the long-term variation of irradiance. Using the satellite measurements and an isolated value of solar irradiance obtained by Kosters and Murcray (1979) in a 1968 balloon flight, Reid (1991) established a linear relationship between total solar irradiance and the envelope of the 11-year sunspot cycle (which he used in model calculations of long-term change of sea surface temperatures; see Section 4.2). This relationship, however, would imply a value of the solar constant $11 W/m^2$ lower during the cold period of the 1600's, an unrealistically large change. Lean et al. (1992), for instance, estimate that the excess facular radiation from a complex magnetic surface configuration as it exists in the contemporary Sun contributes about 1.5 W/m^2. However, using observations from solar-like stars, these authors conclude that for non-cycling stars (e.g., in a Maunder minimum-like state) the irradiance should be further reduced, below that derived for a total removal of network magnetic flux; their final estimate of the Maunder minimum total irradiance reduction is about 2.7 W/m^2 below the contemporary solar minimum value. These estimations are quite significant from the climatic point of view: GCM calculations show that at least half of the global temperature increase since the Little Ice Age could be explained by solar radiative forcing (Rind and Overpeck, 1993).

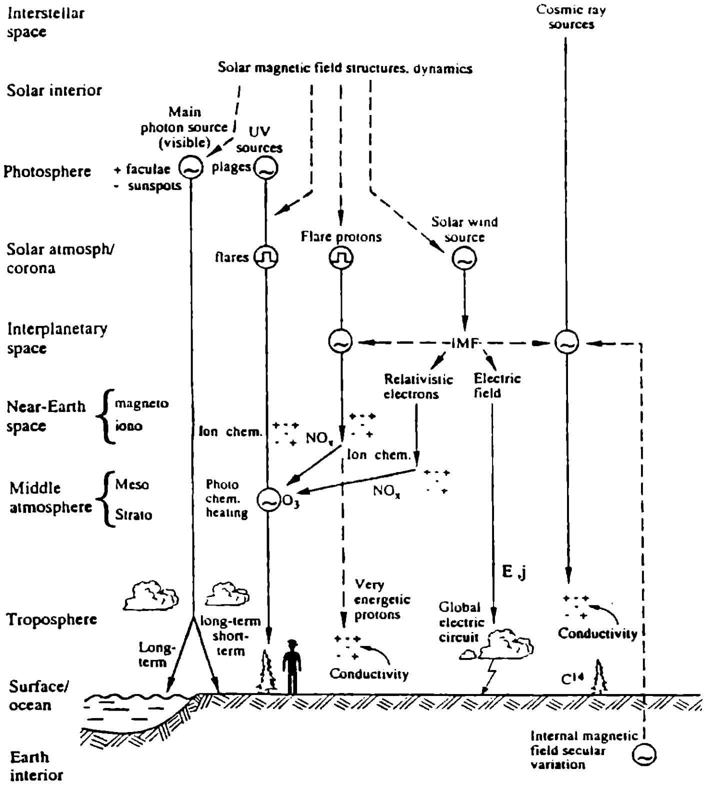

Figure 1. *Sketch of the channels of energy input from the Sun (and beyond), indicating their continuous or sporadic variability (wavy and square-wave signs respectively), and the regions in the terrestrial atmosphere that can be affected by this variability.*

Coronal holes, coronal mass ejections and solar flares are transient manifestations of solar activity at different time-scales; although in themselves aperiodic, they do occur with frequencies tied to the 11-year cycle. They all have important effects on solar wind density, speed and magnetic field configuration (the IMF). Energetic protons from large flares can penetrate the atmosphere down to sea level; shock waves emitted by flares "sweep away" cosmic rays, causing important decreases of their intensity at Earth (the so-called Forbush decreases); sudden changes in the direction of the IMF alter the transfer of solar wind energy into the magnetosphere and can cause magnetic storms and aurorae; changes in the IMF also alter ionosphere, thus affecting the "global electric circuit" in the entire atmospheric system. The higher solar wind speed and the enhanced magnetic irregularities during solar maximum are responsible for a general decrease of the cosmic ray flux, which therefore is anti-correlated to solar activity. During magnetic storms, the magnetosphere "squeezes out" high energy electrons transiently trapped in the Earth's magnetic field (Baker et al., 1987), which subsequently precipitate into the upper atmosphere, preferentially in the region of the so-called South Atlantic Anomaly (where the Van Allen radiation belt comes closest to the atmosphere).

Figure 3 shows the "good old" monthly average sunspot number curve. This is the only indicator of solar activity that can be traced back reliably to the 17th century (Nesmes-Ribes, 1993). It is important to note, however, that it does not represent equally well all aspects of solar variability: the solar activity at different sunspot minima and its direct effects such as geomagnetic disturbance may be rather different, even if it does not manifest itself in the observed sunspot number directly. The sunspot number is not a single-frequency sinusoidal function of time; rather it has a notable amplitude modulation (given by the envelope of the curve in Fig. 3) and a frequency modulation as well (solar cycle length values ranging from 9-12 years). Notice also that the ascending and descending phases have varying slopes. Thus, solar

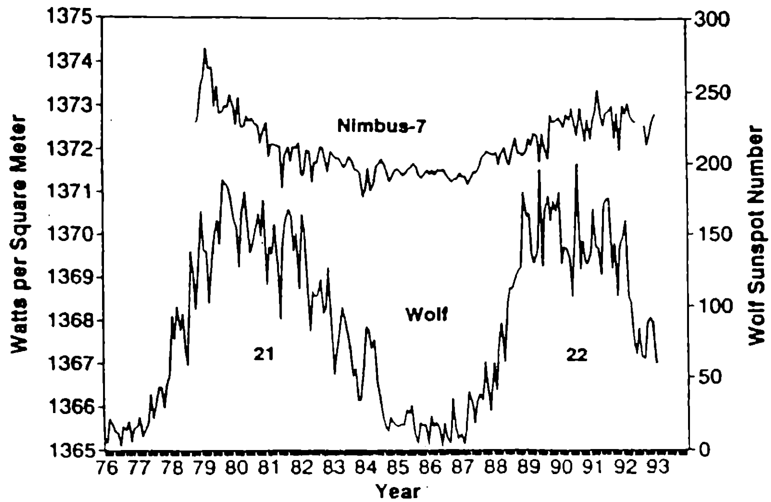

Figure 2. *Monthly mean solar irradiance values and sunspot numbers (from Kyle et al., 1993).*

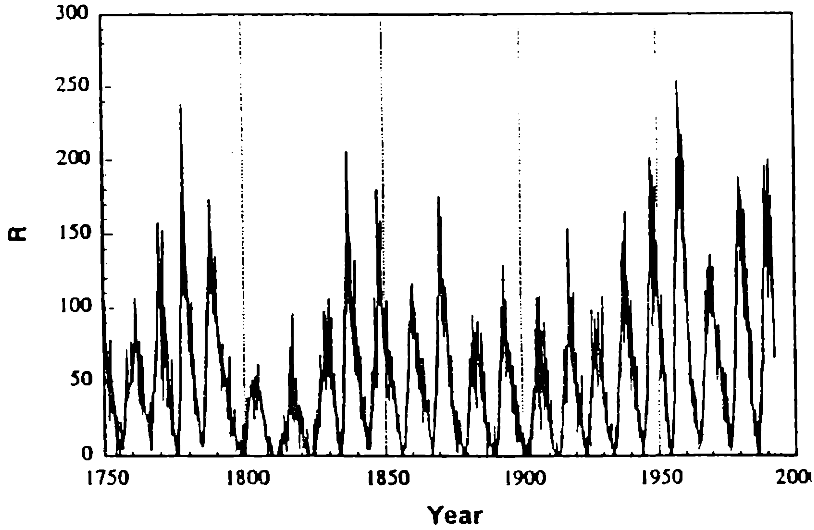

Figure 3. *The monthly mean sunspot number **R** during 2 1/2 centuries.*

cycle amplitude, length and, for instance, maximum time rate of change are important parameters for solar-terrestrial correlations studies. The envelope of the sunspot curve of Fig. 3 follows by 10-20 years a similar-looking curve of (minus) the solar cycle length (shown in Fig. 8); this is approximately the same time-lag that exists between the average global land and sea-surface temperatures ("freak fact No. 3"). Today, the 10.7 cm radiowave flux is often used instead of sunspot number as a measure of solar activity.

4. RECENT RESULTS

4.1 11-Year Cycle

A breakthrough in solar variability effects on climate came in 1987. K. Labitzke of the Free University of Berlin had been engaged in a systematic study of the northern polar stratosphere and its relationship to the quasi-biennial oscillation (QBO) of the equatorial stratosphere (Labitzke, 1982). The QBO refers to the winds at different layers of the tropical stratosphere, which reverse their direction (East to West) with a quasi-periodicity of about 26-28 months (the higher layers leading the lower ones). For the winter hemisphere, this really represents two possible dynamic states of the stratosphere, one in which the equatorial part of a given layer rotates in the same sense as the polar vortex (the west QBO phase) and one in which it contra-rotates; each state presents very different conditions for the propagation of kinetic and thermal energy and momentum toward the higher latitudes. In particular, it was found that the polar vortex was strong and stable, thus colder, during the contra-rotating west phase than during the contra-rotating east phase when major disruptions (major mid-winter warmings) tended to occur in the polar stratosphere. But there were winters in which the reverse situation arose; they happened to correspond to epochs of solar maximum. Indeed, Labitzke (1982) found that all major mid-winter warmings that occurred during the west phase happened only at times of solar maximum.

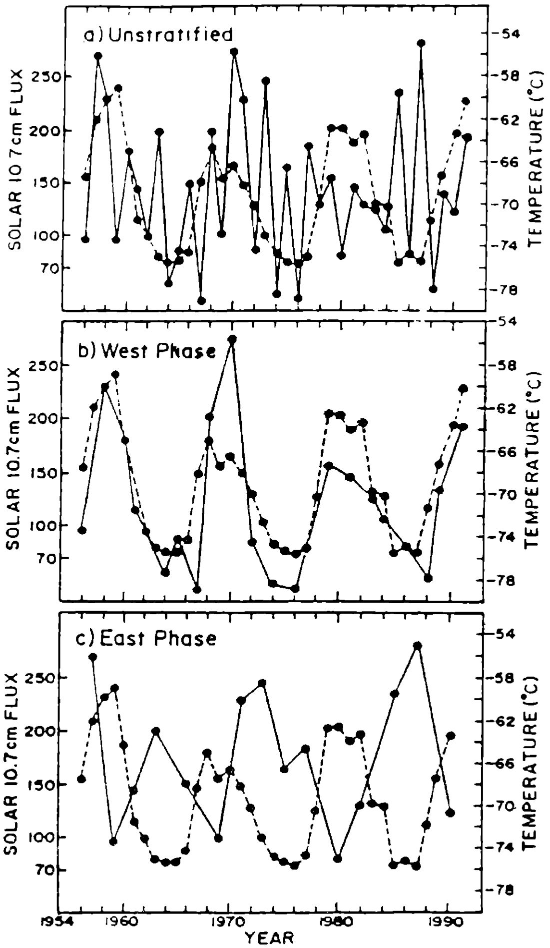

Figure 4. *10.7 cm solar radio wave flux (broken line -in units of 10 W m Hz) and the mean 30 mb temperature at the North Pole during winter (January-February). a): All years; b): Years with west phase of the QBO (westerly winds at the equatorial 50-40 mb level during January-February); c): Years with east phase (easterly winds). Updated from Labitzke (1987).*

Analyzing the temperature of the 30 mb level at the North Pole during January and February for three solar cycles, Labitzke (1987) found an astounding correlation/anti-correlation with solar activity (as expressed by the 10.7 cm flux) when the data were stratified according to the west/east phase of the QBO (defined by the equatorial wind at the 50-40 mb level). Figure 4 is an updated version of these results. It is thus clear that high solar activity introduces a radical perturbation in the process responsible for the global coupling between the tropical and the polar regions of the stratosphere in winter.

Labitzke and H. van Loon from NCAR embarked in a systematic study extending the region under analysis towards lower latitudes, down into tropospheric altitudes, and to the other seasons. Concentrating on the height of the 30 mb level as an important indicator of the integral behavior of the air column below, they identified a clear geographic dependence of the correlation with solar activity; in particular, during mid-winter and east years of the QBO, the basic correlation pattern exhibits a crescent-shape region of positive correlation of the 30 mb level height along 30° N over the Pacific, with a pattern of anti-correlation centered over the Arctic. During the west years, the only important correlation (positive) is found over the Arctic. A consistent average geographic pattern of correlation with solar activity subsists for all data regardless of the QBO phase, as shown in Figure 5 (Labitzke and van Loon, 1993).

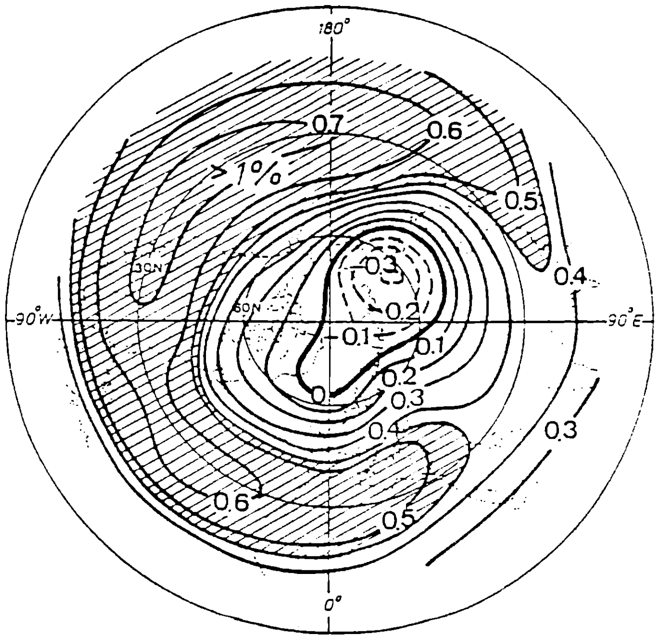

Figure 5. *Contours of equal correlation coefficient between the annual mean height of the 30 mb level (1958-1992) and the 10.7 cm solar flux (hatched area: local statistical significance greater than 1%). From Labitzke and van Loon (1993).*

Figure 6 shows the average change of temperature from solar maximum to solar minimum as a function of geopotential height for Lihue (Hawaii), which is situated under the maximum correlation area of Fig. 5. Different epochs during the year are shown (the reversal at the tropopause at about 100 mb is an inherent property of the atmosphere). The annual mean temperature difference in the troposphere between solar maximum and minimum is substantial, 1.8° C at 300 mb; even at the surface it is 0.9° C in summer. The large positive correlation between 30 mb height and solar flux in the Pacific region is thus mainly due to the difference in tropospheric temperature between the extremes of the 11-year sunspot cycles; this is significant for the identification of trigger mechanisms responsible for solar-climate relationships (see Chapter 5). As to the aliasing effect mentioned in "freak fact No. 4", it does not apply to a strongly period-modulated variation such as the QBO (Tinsley and Heelis, 1993).

An intriguing result is that of Mendoza et al. (1991) concerning statistics of the occurrence of El Niño events from 1700 to 1985. It had been noted earlier (Pérez-Enríquez et al., 1989) that the most intense events have occurred during periods of anomalous solar activity and that in general El Niño/Southern Oscillation (ENSO) events tend to gather around peaks of auroral activity during the descending phase of solar sunspot cycle. Mendoza et al. analyzed the frequency of occurrence of ENSO events according to intervals of sunspot gradient values (time derivative expressed in sunspot number change per year). They conclude that 63% of the ENSO events occur during the descending phase of the solar cycle, and that there are twice as many events occurring one year after the maximum rate of sunspot decline

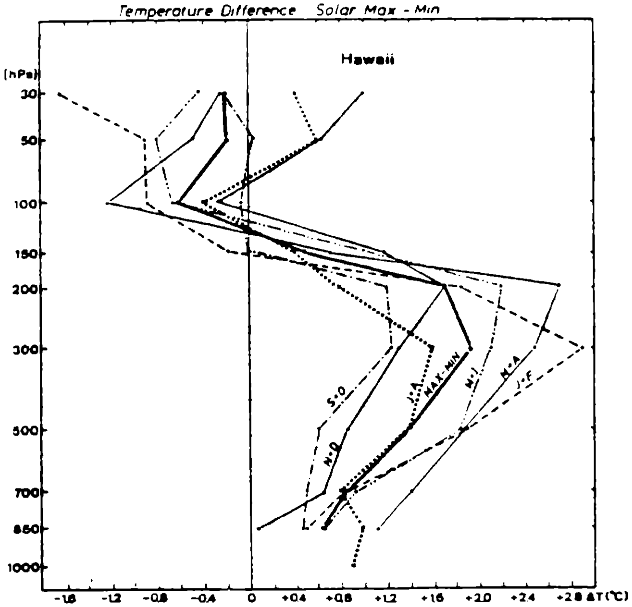

Figure 6. *The average change of temperature from solar minimum to maximum as a function of atmospheric depth, for Lihue (Hawaii), through the year and in the annual mean (heavy line), for a 36-year series. From Labitzke and van Loon (1993).*

(maximum negative gradient) than what would be expected by random occurrence (see Figure 7). While at least part of the first result can be explained by the asymmetry of the sunspot number curve with respect to each maximum (notice in Fig. 3 that the sunspot number rise is usually faster and of shorter duration than the decay), the second result is more significant. Indeed, the authors conclude from a computer experiment that the probability for the peak in Fig. 7 to occur by chance is less than 0.4%.

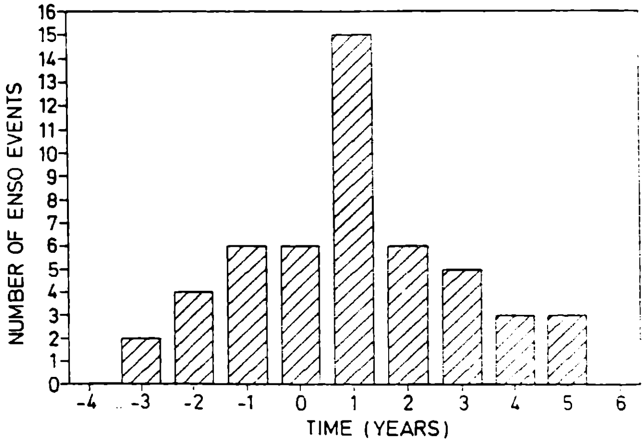

Figure 7. *Histogram of El Niño events around the year of maximum rate of sunspot decrease during the descending phase of the solar cycle, for the period 1700-1985. From Mendoza et al. (1991).*

4.2 Long-Term Variations

The annual average Northern Hemisphere land air temperature curve of Jones et al. (1986) (or Hansen and Lebedeff (1987) for the global temperature), popularly known as the "global warming curve", is usually interpreted by non-scientists (and the media) as being entirely due to an anthropogenically enhanced greenhouse effect. However, it is clear that not all of the global temperature variation in the last 100 years could have been of anthropogenic origin: 1. most of the increase during this century (78%) took place before 1940 when the rate of increase of CO_2 was much lower than at present; 2. there was a steady temperature decrease between 1940 and the early seventies while the CO_2 kept increasing at an accelerated rate; 3. the global temperature had already been rising during the two previous centuries since the Little Ice Age. Still, it came as a surprise when Friis-Christensen and Lassen (1991) published a paper on the correlation between the global temperature and the length of the solar cycle, which at first sight seemed to indicate that the entire temperature behavior during the last 100 years could be due to solar variability (although the authors never stated this - see "freak fact No. 6").

Recently, Friis-Christensen and Lassen (1993) extended this correlation back to 1750 using Northern Hemisphere temperature data by Groveman and Landsberg (1979). They also re-computed the solar cycle length curves using a filtering procedure to take into account earlier criticism of the determination of solar cycle length as a time-dependent parameter. As Figure 8 shows, the remarkable relationship between average annual temperature and solar cycle length persists. In their 1991 paper, the authors noted the similarity of the global temperature anomaly and the 11-year running mean of the sunspot number, but pointed out the fact that the temperature curve was leading the sunspot number curve by up to 20 years, which of course ruled out any causal connection between the two. But as shown in Fig. 8, this time shift disappears when sunspot cycle length is used, implying that it is the cycle length and not the sunspot number that appropriately represents the climate-relevant part of solar variations (for instance, the changes in irradiance). Both the 11-year running mean sunspot number and cycle length do track each other well, but the cycle length leads by 10-15 years (see "freak fact No. 3").

Another study of long-term correlations was conducted by Reid (1991), who used the sea surface temperature record as a climate change indicator. Despite some questions about quality of data before the beginning of the century, global average sea surface temperature variations have certain advantages: because of the thermal inertia of the ocean, they do not exhibit short-term variations as the land temperatures; they do not have to be corrected for effects from recent urban growth; they exhibit greater spatial coherence; and they represent samples from an area covering 70% of the Earth's surface. As mentioned in the previous Chapter, Reid derived an empirical relationship between solar irradiance and sunspot number and, using a one-dimensional columnar model of the coupled atmosphere-ocean system, computed the theoretical average sea surface temperature, shown in Figure 9 together with the experimental data. The calculation consisted of the integration of a heat diffusion equation in the ocean column governed by a set of coefficients and subjected to given coupling and boundary conditions at the top and bottom of the ocean, respectively; this equation was integrated forward in time from the late 1600's, and is shown to fit well the measured average temperature variations (Fig. 9).

As Reid pointed out, the experimental average sea surface temperature follows in general lines the global land temperature, but it is delayed with respect to the latter by 10-15 years. This is three times the value of the time constant for radiative equilibrium of the ocean mixed layer used by Reid in the model calculation. It is reasonable to assume that if one were to use the solar cycle length, which precedes the envelope of the sunspot number by 10-15 years (see "freak fact No. 3"), one would have to use a larger (and perhaps more realistic) value of the ocean response time to achieve a good fit. Another point worth re-examining is the unrealistically large secular variation of solar irradiance used in Reid's calculations (Chapter 3); an appropriate amplification mechanism might have to be introduced on the atmospheric side of the model (see next Chapter).

Finally, concerning very long-term changes, Anderson (1992) reported on a possible connection between surface winds, solar activity and the Earth's internal magnetic field. The author has identified an association between an enhanced 100-200 year solar cycle periodicity (as revealed in the C-14 record in tree rings) and fluctuations in surface wind intensity on a 200 year time scale (as revealed in the thickness of varved sediments in a Minnesota lake). This association existed only during the mid-Holocene 5000-7500 years ago; when the Earth's magnetic dipole moment went through the last minimum, i.e., when the intensity of the solar-activity-modulated cosmic rays entering the atmosphere was at a maximum.

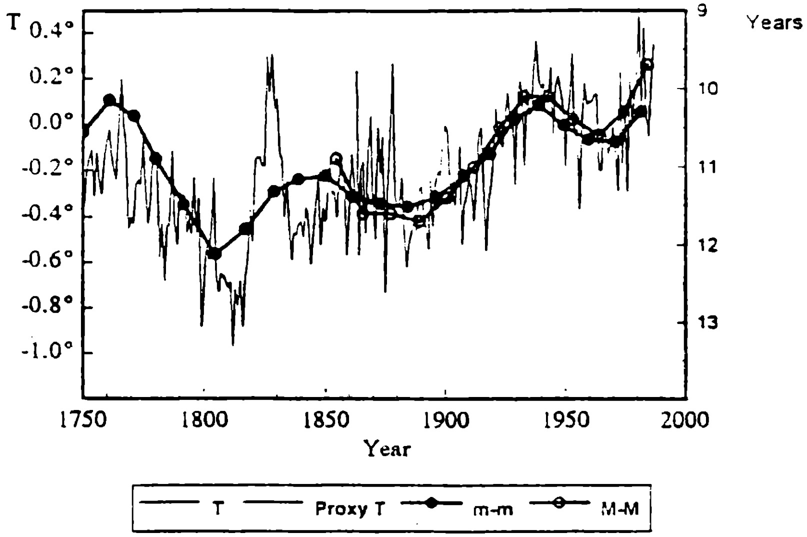

Figure 8. *Annual average values of the Northern Hemisphere temperature (thin curve) and appropriately filtered values of the sunspot cycle length (solid curves, determined independently by means of sunspot minima (m-m) and maxima (M-M); note reverse scale). See Friis-Christensen and Lassen (1993).*

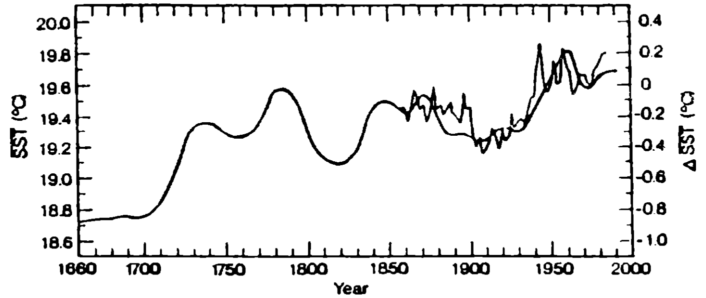

Figure 9. *Global average sea-surface temperature calculated from Reid's model, and the observed time series (Reid, 1991).*

4.3 Short-Term Variations

The studies of possible effects of short-term solar-activity-related variations on the tropospheric system are on much less firm footing than the 11-year cycle and longer-term correlations, despite the fact that, in principle, the former would be easier to identify statistically than the latter because of the unique signatures of each one of the possible solar input on a day-to-day time-scale. These studies are mostly isolated efforts by individual scientists, each one of which has chosen one given pair of solar-atmospheric variables out of the many possible ones; a concerted, internationally coordinated approach is still missing.

One example is Schuurmans' (1991) study of the temperature in the troposphere (500 mb level) and lower stratosphere (200 mb) over De Bilt, The Netherlands, and its behavior during 72 solar proton events that occurred in the interval 1955-1984. The author finds that for the east phase of the QBO there is a clear reduction of the temperature at the 200 mb level of about -2.4° C that persists at least 3 weeks after the proton event . No measurable effect is seen during west QBO. Comparing the behavior of the 200 to 500 mb levels, the author argues that the cooling in the lower stratosphere is not due to a dynamically related warming of the troposphere; rather, he postulates a solar-induced heat sink operating at 200 mb.

Another example is the work by Pudovkin and Babushkina (1992) who studied atmospheric transparency variations during the interval 1961-1984 associated with geomagnetic disturbances, using monthly actinometric data from a network of meteorological observatories in three latitudinal bands of the former Soviet Union. They find a considerable increase in ground-level solar radiation intensity (increase in transparency) in the auroral zone, 1-2 days after the onset of a geomagnetic storm. The authors speculate that this may be due to chemical changes in the stratosphere as the result of storm-associated Forbush decreases of cosmic ray intensity.

5. MECHANISMS

As stated in Chapter 2, because of energy balance considerations, the mechanisms responsible for solar variability effects on climate should be trigger-mechanisms which catalyze or control the release of latent energy, thus leading to a large-scale re-distribution of energy in the atmospheric system. To explain the observed effects, one must look for amplification processes that respond by a factor of at least one million to small variations of energy inputs. There are three basic candidates for mechanisms, sketched in the lower part of Figure 1 and discussed below.

5.1 Total Irradiance Variations

These variations correspond to the main photon channel at left in Fig. 1. Their 11-year variation is shown in Fig. 2; a bigger change can be expected on a long-term, secular scale (Chapter 3). Labitzke and van Loon (1993) proposed the modulation of the Hadley cell circulation as a possible mechanism, based mainly on the fact that the middle and upper troposphere under the crescent-shaped region between 20° N and 45° N in the Pacific-Atlantic area shown in Fig. 5 is consistently warmer during solar maximum (e.g., see Fig. 6). This points to an enhanced Hadley circulation in which the troposphere in the Intertropical Convergence Zone is warmed more by an increased release of latent heat during solar maximum. The reversal of the temperature effect at and above the tropopause in Fig. 6 indicates that the primary enhanced heating process resides within the tropopause (because the vertical temperature difference profiles in Fig. 6 are indeed similar to the profiles of differences between non-solar related strong and weak Hadley circulation periods). The control by the QBO of wave and energy propagation characteristics to higher latitudes in the winter hemisphere (Section 4.1) would be responsible for the 11-year modulation of the polar stratosphere (Fig. 4). In the summer hemisphere, in absence of a well-defined polar vortex, the coupling between the equatorial and polar stratosphere is less complex, and the atmosphere exhibits a behavior parallel to the 11-year cycle regardless of the phase of the QBO (van Loon and Labitzke, 1990). This is yet another argument in favor of the Hadley circulation modulation hypothesis.

In principle, long-term solar variability effects on climate such as shown in Fig. 8 and 9 should be "easier" to explain because the input power variations could be expected to be several times larger than those found for the 11-year cycle (Chapter 3). However, it is not yet clear (although quite suggestive) whether the above Hadley cell modulation mechanism would also be applicable at this time scale. GCM model calculations do show that a total irradiance change of about 2 W/m^2 can have an effect on global temperature of about half that of doubling the CO_2 concentration.

5.2 Solar UV Flux Changes

Given that the UV flux powers the dynamics of the stratosphere via ozone absorption (e.g., Hood et al., 1993), and given the large variability of the solar UV flux, it is reasonable to expect this flux to play a fundamental role in driving stratospheric variability (e.g., Kodera et al., 1991). Such role may be a contributing factor, but it could not explain other important findings by Labitzke and van Loon, such as shown in Figs. 6 and 7. It may, however, be related to the behavior of the polar stratosphere in winter during the west phase of the QBO, when its temperature is positively correlated with solar activity (Section 4.1).

Finally, we may speculate that the long-term variability of solar UV radiation may have an effect on climate via the response to UV of the phytoplankton in the oceans' euphotic zone, which is believed to play a fundamental role in the global control of ocean uptake and release of CO_2.

5.3 Atmospheric Ionization and Global Electric Circuit

The flux of galactic cosmic rays is the dominant source of continuous ionization in the troposphere and the lower stratosphere; because of the modulation of this flux by the interplanetary magnetic field, this ionization is variable. Fig. 1 depicts several possible solar-controlled ways in which the ionization can change. This ionization determines atmospheric conductivity, which in turn regulates the clear-air vertical electric field and electric current between the ionosphere and ground. The latter, at high latitudes, is magnetically connected to the solar wind and its electric potential is controlled by the IMF. The electrical connections in the system polar ionosphere/ mid-latitude and equatorial ionosphere/ atmosphere/ ground is called the "global electric circuit". Tinsley has proposed a mechanism (e.g., Tinsley and Heelis, 1993) connecting atmospheric electricity and the rate of contact ice nucleation in clouds, which can operate on a time scale of hours. This theory is based on the fact that the rate at which the charging of water droplets proceeds will depend on the vertical atmospheric current and therefore be responsive to both the cosmic ray flux and the local ionospheric potential. Tinsley's "electrofreezing" mechanism postulates that variations in the amount of such charge affect the rate of initial ice generation at the top of clouds, with ensuing effects on cloud formation.

6. FINAL THOUGHTS

Achieving a scientific understanding of the inner workings of the terrestrial environment is one of the most difficult and ambitious endeavors of humankind, rivaling in complexity the harnessing of nuclear energy, the conquest of space, and the understanding of the human brain. Unfortunately, the more we learn about the environment, climate and anthropogenic effects, the more political problems emerge. Lawyers, judges and politicians are expected to render verdicts and make decisions on the basis of scientific concepts they grasp poorly and without a clear understanding of the scientific method, the inherent experimental uncertainties, and the natural limitations of scientific predictability.

One of the key tasks in climate research at the present time is to learn to separate anthropogenic effects from natural change. Solar variability is one possible cause of natural change in addition to other external phenomena such as volcanic eruptions and, on a long-term scale, orbital changes, celestial body impacts and tectonic plate motion. The unpredictable intrinsic variations of a highly non-linear system such as the atmosphere also must be counted as a "natural" change. Thus, before far-reaching policy decisions are made concerning the impact of future climatic change on human society (and the impact of human activity on climate change), a scientific understanding of possible external influences, however minor at first sight, is of crucial importance. We are still very far from achieving this goal. A truly interdisciplinary, integrated cooperative effort must be developed in STEP in which solar physicists, atmospheric scientists and space physicists work closely together, in coordination with other international programs such as the International Geosphere-Biosphere Program.

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SOUND RANGE-DEPENDENT PROPAGATION: AN EXPERIMENT ON DOWN-SLOPE PROPAGATION OVER THE ARGENTINIAN CONTINENTAL SLOPE.

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ABSTRACT

A range dependent acoustic down-slope propagation loss (TL) experiment was conducted in 1989 over the Argentinian Continental Slope, along a 50 km track, using two TRACKER aircrafts from the AntiSubmarine Warfare (ASW) squadron. One aircraft flew a prearranged track dropping 1.8 lb of TROTYL explosive charges, while the second aircraft remained in the area of a deployed calibrated passive sonobuoy, used as sonar receiver. Recorded broadband signals were analyzed with FFT techniques in selected 1/3 octave bands between 100 Hz and 400 Hz. A code based on the parabolic equation method (PE) was used to model the down-slope propagation losses. A reasonable agreement was obtained when theoretical predictions were compared with experimental evidence. This agreement improves at low frequencies. Moreover, at high frequencies the greater the range the better fit is observed.

RESUMEN

En 1989 se ha realizado una experiencia sobre el Talud Continental Argentino para medir pérdidas por propagación acústica (TL) en un medio cuyas propiedades físicas dependen de la distancia, en una extensión de 50 km, usando dos aviones TRACKER de la Escuadrilla Naval Antisubmarina. Uno de los aviones arrojaba cargas explosivas de 1.8 libras de TROTYL, siguiendo un rumbo prefijado, mientras el otro permanecía en el área de sembrado de la sonoboya, actuando como sistema receptor. Las señales en banda ancha fueron analizadas con técnicas de FFT, en bandas de 1/3 de octava entre 100 Hz y 400 Hz. Para modelar las pérdidas por propagación se ha utilizado un código basado en el método de la ecuación parabólica. Se obtuvo un ajuste satisfactorio al comparar las predicciones teóricas con la evidencia experimental. Este ajuste es mejor a bajas frecuencias. A altas frecuencias, se observa un acuerdo mayor para grandes distancias.

1. INTRODUCTION

The study of sound propagation numerical modeling at a shallow continental margin area, down the continental slope, and into the deep ocean, has been in continuous expansion over the past 15 years (Jensen and Ferla, 1989). When powerful digital computers became available in most research institutions, the development of more accurate solutions of the wave differential equation that governs the propagation of sound in complex range-dependent environments was stimulated. Many numerical codes based on different wave-theory solutions such as normal modes or parabolic equation techniques began to be widely used by the international acoustic community.

Therefore, we are confronted with the fundamental problem of how to ascertain that any numerical solution generated by a complex computer program is an accurate solution of our realistic physical phenomenon. Considering the theoretical aspect of the problem, it must be pointed out that closed-form analytic solutions are not available for checking the numerical results even for the most simple range-dependent environments. On the other hand, there are relatively few reports of down-slope sound propagation losses in the literature due to the experimental difficulties associated with sea measurements.

This paper discusses an off-shore Argentinian coast experiment performed during the fall of 1989 in a joint program with the AntiSubmarine Warfare squadron (ASW) of the Argentinian Navy. This experiment was designed as another step to provide a basis for propagation loss model evaluation. The present work, which is part of a long-term research program on sound propagation in shallow waters and nearby areas is believed to report the first quantitative information on the Argentinian Continental Slope underwater sound propagation.

2. EXPERIMENT AND DATA ANALYSIS

Measurements of down-slope propagation from shallow sources to a deep ocean buoy receiver were conducted using two TRACKER aircraft. Data were gathered along a 50 km track as shown in Fig. 1. One aircraft flew a prearranged track dropping 1.8 lb SUS (Signal Underwater Sound) MK 64 MOD 0 charges of TROTYL at range intervals of approximately 5 km. The average explosion depth was about 60 feet. The second aircraft remained in the area monitoring a hydrophone suspended from a deployed calibrated passive sonobuoy, at 60 feet below the sea surface. Fig. 2 schematically shows the source-receiver configuration.

The bathymetric and bathytermographic profiles, as well as the salinity values were measured from a ship, called Ocabalda. Fig. 3 shows the environmental data with the computed sound-speed profiles. Three distinct bathymetric regions characterize the experiment area: a 2.2 degrees slope (continental slope) between two essentially flat zones at a depth of approximately 120 m (continental shelf) and 1000 m (deep ocean). The geometric configuration gives rise to acoustic energy that is essentially bottom limited, since the explosives were detonated within the steep negative sound-speed gradient near the ocean surface. Geological sampling (Vozza, 1974) in the area has shown that the seabed is mainly fine sand.

A calibrated passive sonobuoy SSQ 57-A detected and amplified the shot arrivals to module a self-contained FM transmitter. The FM signals from the sonobuoy were transmitted to the associated sonobuoy receiver (R 1170/ARR 52 A) in the aircraft. The demodulated broadband signals from the receiver were recorded on a TEAC R 71 magnetic tape recorder.

At the laboratory, the acoustic signals were converted into digital data records through a general purpose analog to digital equipment (HP 1000 with 4 kHz-sampled data system) and processed with an "ad-hoc" written analysis software. Digital data plots were then generated, such as the ones shown in Fig. 4.

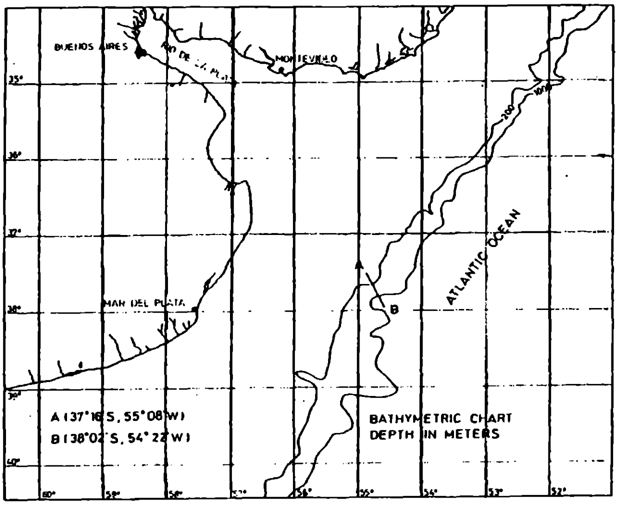

Figure 1. *Chart showing the track for the propagation experiment.*

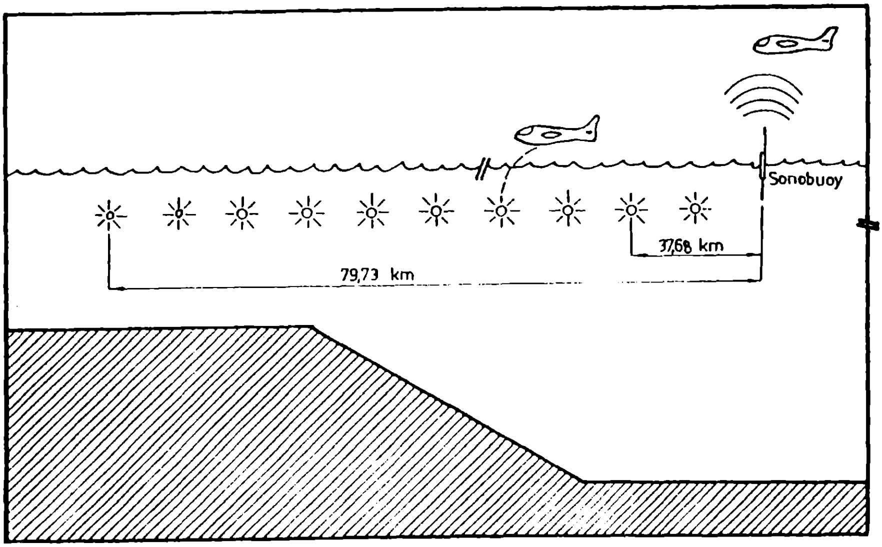

Figure 2. *Schematic source-receiver configuration.*

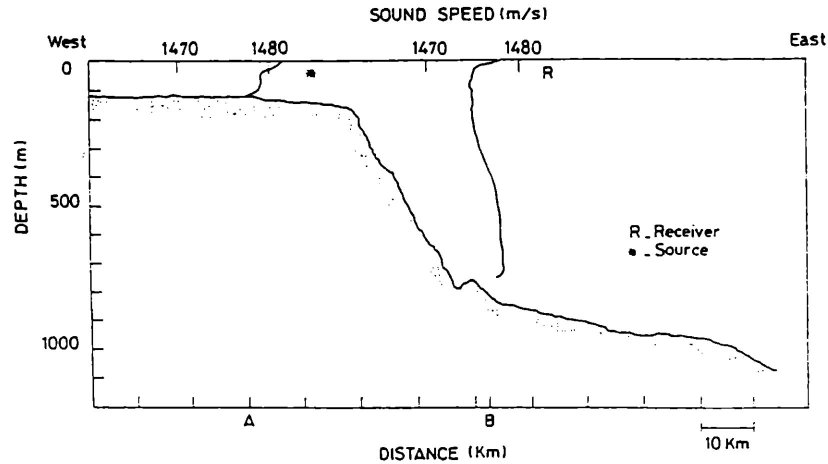

Figure 3. *Bathymetry and sound speed profiles.*

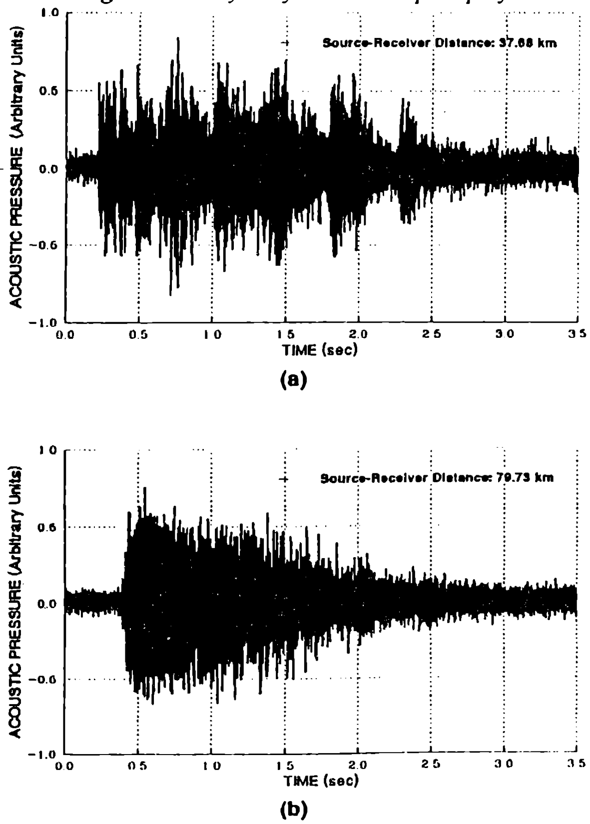

Figure 4. *Digitized broadband acoustic signals for the sonobuoy in deep waters and the explosive detonated: (a) in deep waters; (b) over the continental shelf.*

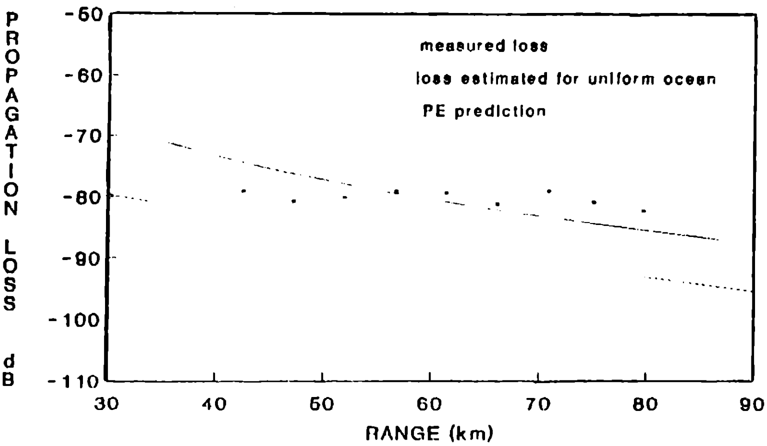

Figure 5. *Measured propagation loss (closed squares) and estimated loss for a range-independent oceanic environment, for 200 Hz. Comparison with PE method predictions.*

FFT transforms were computed, squared and averaged to provide estimates of the total acoustic energy in 1/3 octave bands from 100 Hz to 400 Hz. The Weston (Weston, 1960) data were used to determine source levels of SUS charges in the required 1/3 octave bands. The difference between the source level and the measured intensity level, for a given 1/3 octave band, was found for computing the propagation loss for each source (see Fig. 5).

No data is shown in Figs. 6, (a) and (b), neither for source-receiver distances less than 40 km nor for distances longer than 90 km, because it was previously checked that charges dropped inside approximately a 40 km range caused saturation of the hydrophone pre-amplifier receiver while charges dropped outside, approximately a 90 km range, were below the signal/noise threshold . This resulted in the discarding of data records outside the 40 km to 90 km range.

3. THEORETICAL BACKGROUND

The parabolic equation (PE) method has proved to be an efficient approach for solving underwater sound propagation problems in range-dependent environments because it replaces the reduced wave equation, which is a boundary value problem, with an initial value problem. Since the PE was first applied to underwater acoustics (Tappert, 1977), it has undergone extensive development including many improvements in accuracy (Lee, 1984).

A higher order PE code based on a Padé series was used for modeling the propagation loss measurements in this experiment. Variations with range in bottom density and attenuation, as well as in water and bottom sound speeds, were included following the procedure described by Collins, 1989. A brief review is made of the derivation of the PE, which has been numerically solved through standard techniques of finite differences to obtain computed propagation losses (directly connected with the acoustic pressure, Urick, Chap. II, 1983) for the experimental oceanic environment.

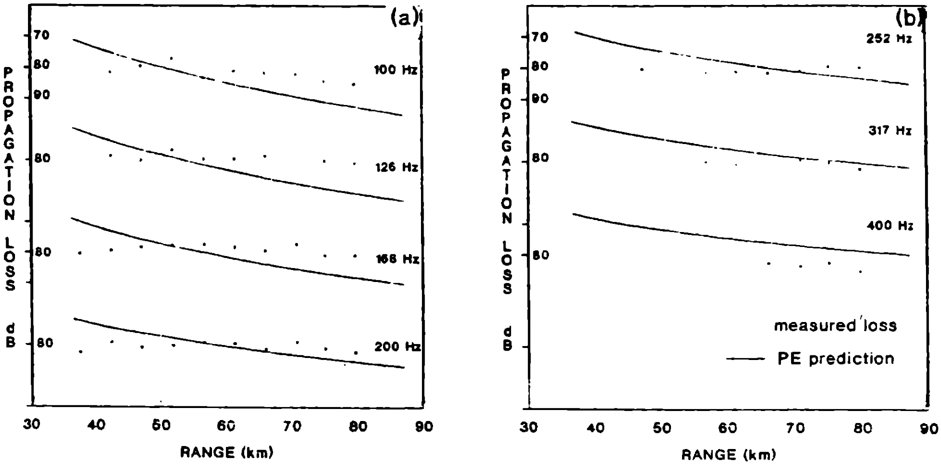

Figure 6. *Comparison of PE model results with measured propagation loss values for 1/3-octave-band between: (a) 100 Hz - 200 Hz, (b) 200 Hz - 400 Hz.*

When a time harmonic dependence is assumed for the acoustic pressure, it may be factored as

$$P(\vec{r},t) = P(\vec{r})\cdot e^{(-i\omega t)} \qquad (1)$$

where t is time, $\vec{r}$ is the Cartesian position vector, and ω is the circular frequency. The reduced wave equation that governs the propagation of sound in range-dependent oceanic environments is

$$\rho \quad \vec{\nabla}\cdot((1/\rho)\vec{\nabla}(P)) + k^2 \; P = -4\pi \quad \delta(\vec{r}-\vec{r}_0) \qquad (2)$$

where P is the acoustic pressure, point $\vec{r}_0$ is the source location; ρ is the water density; and k is the complex wave number. The acoustic complex pressure P is assumed to satisfy the pressure-release boundary condition $P=0$ at the sea surface and the outgoing radiation condition at infinity.

Under the assumption that azimuthal variations are negligible, Eq. (2) may be expressed in cylindrical coordinates as

$$\frac{\partial^2 \rho}{\partial z^2} - \frac{1}{\rho}\frac{\partial \rho}{\partial z}\frac{\partial P}{\partial z} + \frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\frac{\partial P}{\partial r} + k^2 \; P = -\frac{2}{r}\delta(r)\delta(z-z_0) \qquad (3)$$

with z being the depth below the sea surface and r being the horizontal distance from a source at depth . In Eq. (3), small variations of density with range have been assumed so that is ignored.

The parabolic approximation (PA) begins assuming the possibility of expressing the solutions of Eq.(3) as the product of two functions, that is

$$P(r,z) = r^{-1/2} \cdot Q(r,z) \tag{4}$$

where $Q(r,z)$ is weakly dependent on r. After some algebra, substitution of Eq.(4) into Eq.(3), applying the farfield approximation $k_0 >> 0$ and dropping terms $O(r^{-2})$, leads to

$$\frac{\partial Q}{\partial r} = i\, k_0\, (1+X)^{1/2}\, Q \tag{5}$$

$$X = \frac{1}{k_0^2}\left(k^2 - k_0^2 + \frac{\partial^2}{\partial z^2} - \frac{1}{\rho}\frac{\partial \rho}{\partial z}\frac{\partial}{\partial z}\right) \tag{6}$$

with $k_0 = \omega / C_0$ where C_0 is a reference sound speed.

It must be pointed out that for range-independent domains the equation (1) factors exactly to equation (5). However, for range-dependent environments the differential parabolic equation (5) is an accurate approximation for the cases in which the range-dependence is smooth.

A family of Padé series is used. That is,

$$(1-X)^{1/2} - 1 = \sum_{j=1}^{n} \frac{a_{j,n}\, X}{1 + b_{j,n} X} + O(X^{2n+1}) \tag{7}$$

where n is the number of terms in the Padé expansion and the corresponding coefficients are given by

$$a_{j,n} = \frac{2}{2n+1} \sin^2\left(\frac{j\pi}{2n+1}\right) \tag{8}$$

$$b_{j,n} = \cos^2\left(\frac{j\pi}{2n+1}\right) \tag{9}$$

4. RESULTS AND DISCUSSION

Fig. 4 (a) shows 3.75 s of a recorded signal that has been digitized at a 4000 Hz sampling frequency , for an explosive source detonated in the deep ocean basin at a range of 37.68 km (Fig. 2). The ninth bottom reflected arrival, corresponding to deep water propagation, is distinctly identified in this broadband signal. As it is reasonable, it can be seen that the signals arriving after a large number of reflections reach the sonobuoy later, while time-intervals between two successive arrivals increase with the number of bottom interactions. The digitized signal shown in Fig. 4 (b) corresponds to an explosive source detonated at a range of 79.73 km (Fig. 2), in the continental shelf region, propagating over the continental slope till it is received at the sonobuoy. However, this broadband pressure signal seems to be a dispersed signal typical of shallow water propagation. That is in agreement with the 30 km of strong bottom interaction that takes place in shallow waters before the acoustic energy enters the deep ocean zone.

Fig.5 illustrates the advantage of modeling measured propagation loss in the experiment area, with a range-dependent propagation model, as the PE method, comparing with any traditional range-independent method. Following Dosso and Chapman (1987), the dashed curve shows the estimated losses due to geometrical spreading, attenuation in the water column and bottom interaction for a range-independent ocean over an assumed flat seabed of 880 m depth.

The sum of these three effects (Urick,1983) leads to propagation loss (or transmission loss, TL) given by

$$TL(r) = 10\log(r\, r_0) + 0.777 + \alpha\, r\ 10^{-3} + \alpha_b\, r\, 10^{-3} \qquad (10)$$

where the range r is expressed in meters; r_0 was taken to be 880 m; the logarithmic absorption coefficient α, was calculated to be 0.008 dB/km for a frequency of 200 Hz, according to the modified Thorp formula published in Urick, 1983. The bottom absorption coefficient, α_b, was estimated to be 0.173 dB/km by comparing the theoretical propagation loss due to the first two terms of Eq. (10) with the loss measured over the deep ocean basin out to about 37.68 km. This source-receiver distance was precisely selected as being the only range, among the detonation positions, corresponding to a whole propagation path in deep waters, and consequently, reasonably well predicted by (10). The excess loss for this range was assumed to be due to bottom interaction and the calculated value for α_b was used to compute the fourth term in (10).

From Fig. 5 it follows that the effects of bathymetry and spatial variability of sound speed profiles, included in the PE method used, should not be neglected when considering propagation through the experiment area. The estimated loss for an uniform ocean of 880 m depth exceeds significantly the measured values reaching a difference of approximately 10 dB for distances greater than 70 km. As it was expected, the curves predicted by the PE model show a better fit with the experimental data.

The data obtained for the whole experiment are shown in Fig. 6. The solid smoothed curves shown in Fig. 6 for 1/3 octave bands between 100 Hz and 400 Hz were computed by using a range-dependent PE calculation. The oceanic environment was represented by a two-layer model consisting of the water column over a sedimentary seabed, described as a viscoelastic solid (Blanc and Novarini, 1990). The measured bathymetric profile, shown in Fig. 3, was taken into account for the propagation loss computations. From the two measured speed profiles shown in Fig. 3, interpolated profiles were obtained to simulate a gradual range-dependence of the sound speed along the experimental track. For fine sand sediment, a compressional sound speed of 1798 m/s, a density of 2.008 g/cm^3 and a compressional wave attenuation of 0.89 db/λ in the bottom, were estimated from tabulated values (Baqués and Blanc, 1993).

The results presented in this paper provide an experimental evidence of the capability of the PE method to model sound propagation over the Argentinian Continental Slope, in the 100 Hz to 400 Hz frequency interval. As it can be seen in Fig. 6, the agreement between measured propagation loss values and PE predictions improves at low frequencies since for increasing frequencies, theoretical predictions underestimate experimental data. This feature is due to the limitations of the PE approximation. Moreover, for high frequencies a light better fit is observed at great ranges.

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THE AURORAL BREAK-UP AS RELATED TO THE INTERPLANETARY PARAMETERS AND THE GEOMAGNETIC ACTIVITY

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ABSTRACT

In the present study, we used as a significant indicator of the auroral break-up the "sudden equatorward shift" in arcs or displays. For the dark months of May and June of 1971, auroral observations at Base General Belgrano (78,0° S; 38,8° W) were used.
Four-hourly sequences centered at the break-up (t=0) were studied for the following quantities:
a) The magnitude of the interplanetary magnetic field (B), b) The southward component of the interplanetary magnetic field (Bz), c) The solar wind speed (V), d) The solar wind electric field (the westward component: E), e) The auroral electrojet magnetic activity indices (AE, AL, AU).
On the basis of the seven substorms studied, one may deduce that an appreciable increase of geomagnetic activity occured about 40 minutes after the energy arrival at the magnetosphere , but it is not enough strong to take place the break-up, it will happen after another period of 35 minutes.
This result confirms that a substorm only occurs after a build-up process.
The present paper also confirms the possibility of using the auroral zone geomagnetic activity for estimating the solar wind velocity

RESUMEN

En el presente trabajo usamos como indicador de la ruptura de aurora al "sudden equatorward shift" en arcos o displays. Para los meses oscuros de mayo y junio de 1971, se usaron observaciones aurorales en la Base General Belgrano (78,0° S; 38,8° W)
Se estudiaron las secuencias de cuatro horas centradas en la ruptura (t=0) para las siguientes variables:
a). La amplitud del campo magnético interplanetario (B), b) La componente sur del campo magnético interplanetario (Bz), c) La velocidad del viento solar (V), d) El campo eléctrico del viento solar (la componente oeste: E), e) Los índices de actividad magnética del electrochorro auroral (AE, AL, AU)
Sobre la base de las siete subtormentas estudiadas uno puede deducir que ocurrió un incremento apreciable de la actividad geomagnética aproximadamente 40 minutos después de la llegada de la energía a la magnetósfera, pero no han sido lo suficientemente fuertes para tener lugar durante la ruptura, eso sucederá después de otro período de 35 minutos.
Este resultado confirma que una sub-tormenta solo ocurre después de un proceso tipo "build-up".
El presente trabajo también confirma la posibilidad de usar la actividad geomagnética de la zona auroral para estimar la velocidad del viento solar

1. INTRODUCTION

Numerous papers have been published that relate Interplanetary magnetic field (B) (Perreault et al. 1978, Foster et al. 1971. Rostoker and Fälthammar 1967, McPherron 1991, Lopez and Lui 1990) wind, plasma parameters and geomagnetic activity. They suggested the importance of the southward component (B_Z) of the Interplanetary magnetic field to produce geomagnetic disturbances. There are many examples of geomagnetic substorms during which the characteristics of the solar wind plasma did not change significantly. In 1971,Arnoldy (1971) showed that there is a close relationship between the north-south component of B and substorm activity. Therefore, it is reasonable to infer that there is also a close relationship between B_Z and the development of the main phase. Burton et al. (1975) proposed that the time evolution of the magnetosphere could be studied through the linear rectifier model of B_Z. Perrealut and Akasofu (1978) estimated the rate of the total energy dissipation (U_t). During storms and substorms U_t is closely related to the Poynting flux (ExB/4__). A large increase of U_t is associated with substorm activity, their accumulated effects can be understood as a geomagnetic storm phenomenon.

We studied the relationship among B, Solar wind parameters, AE index and the sudden changes of auroral morphology, generally called auroral break-up. We analyzed 7 geomagnetic substorms as observed at the Base General Belgrano (78° S,38.8° W), a site close to the northern border of the southern auroral zone. We considered the sudden equatorward shift as the indicator of the auroral break-up.

2. SELECTION CRITERIAS

We studied the auroral observations from the southern winter months of 1971 at Antarctic Base General Belgrano, because the data obtained at this Station (during the above mentioned period), is complete. The interval suitable for recording of aurora was found for every day. The sky should be sufficiently dark for a number of stars to be identified on the all-sky image. Periods with bright moonlight were rejected. The sky should be clear, though intermediate periods with partly cloudcover were accepted, if existing auroral activity could clearly be identified. Periods with shortlived clearance during long intervals with completely covered sky were rejected. After the commencement of the frequent auroral substorms the violent movement of the auroral forms and their distortion from a regular appearance were considered. Large regions with diffuse auroral light were observed in connection with the auroral substorms and on the morning side of the auroral oval. However, even during such conditions it was possible to find extended auroral forms embedded in the diffuse light. The auroral displays, evaluated in this way, are considered to be representative for the auroral break-up, as observed at Base General Belgrano. We have studied a) all-sky camera recordings of 1 minute intervals and b) visual observations every 15 minutes, which have observed the whole sky above 10° as locally visible. The skyline of this place is completely free, but a great number of photos were not workable, because the camera was installed in a low place, and it was perturbed by the frequent blizzards. To analyze auroral displays we have chosen the auroral electrojet magnetic activity indices AE, AL and AU (World Data Center 1975), Interplanetary magnetic field (magnitude and north-south component), and Solar wind speed (World Data Center 1977).

Initially we selected 18 substorms observed from May to June 1971, each of them had AE index values greater than 250 nT at the instant of the appareance of a sudden equatorward shift, but only 7 events with continuos interplanetary data records were studied.

3. INTERPLANETARY MAGNETIC FIELD, SOLAR WIND AND GEOMAGNETIC SUBSTORMS

We studied the average temporal evolution (for the 7 substorms above mentioned)

a) Magnitude of Interplanetary magnetic field
b) North-south Interplanetary magnetic field component
c) Solar bulk wind speed
d) Westward solar wind electric field component
e) Auroral electrojet activity index AE, AL and AU

We confirmed also the smooth linear relation between the ratio AL/AU and the Solar wind speed.

These five parameters were intercompared by considering that all of them are independent. The time scale used was of 7.5 minutes. The superposed epoch method was applied to obtaining the average magnitude. We defined the time zero as the instant of a sudden equatorward shift was detected at Base General Belgrano.

In 6 of the substorms studied we found that B_Z was negative during the four hours around break-up time. The other case showed that B_Z changed from positive (before t=0h) to negative values (after t = 0h).

4. RESULTS

Figures 1 to 5 show the temporal evolution of the studied parameters during four-hourly intervals centered at the instant of auroral break-up.

The average values indicate the following aspects:
a) the quasi-constant level of the mean Interplanetary magnetic field magnitude during the last 220 minutes and its small decrease during the first 20 minutes of the studied interval.
b) the negative values of the B_Z component. It decreases from t= 120 minutes till t=15 minutes. It has a minimum value around 35 minutes before auroral break-up. c) the constant values of the mean solar wind speed during 4 hours around the break-up time. d) the solar wind electric field (E) (the westward component only) decreases during the first 20 minutes. Then it has a small maximum with some 20 minutes. It increases from t=-75 minutes to t=-26 minutes. Then it increases up to 86 minutes. e) the average development of AE index practically increases during the 240 minutes around t=0h. We can notice that it shows a steady rise starting some 90 minutes before the auroral event and culminating after it. Fig. 6 shows the slight linear relation between the ratio AL/AU and the solar wind speed. The square fit predicts that AL/AU=(1.3±0.2)*V with an uncertainty of one standard-deviation. This smooth relation agrees with Maezawa (1979) prediction.

To find the relationship among the different parameters studied in a)...e) and their linking with the indicator of the auroral break-up it is important to analyze the temporal variations before and after the appearance of the sudden equatorward shifts

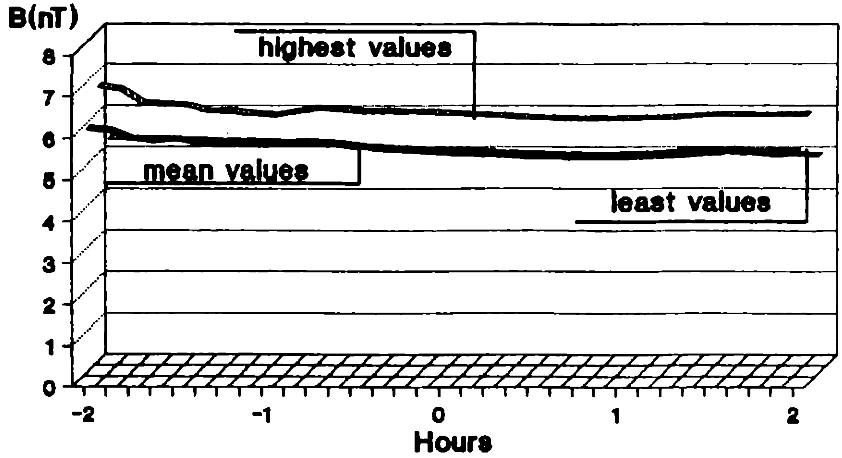

Figure 1. *Average temporal evolution of the Interplanetary Magnetic Field (Magnitude) around the instant that was observed a sudden equatorward shift at Base General Belgrano(t=0h). The number of isolated substorms included in this graph was equal to seven.*

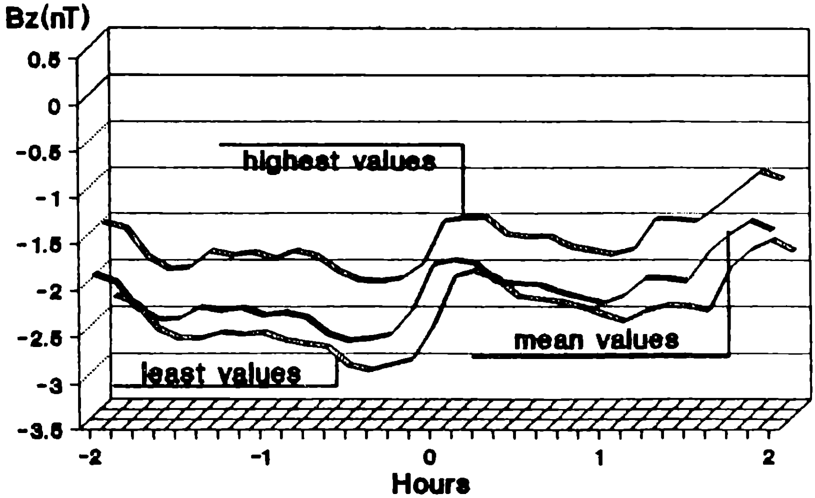

Figure 2. *Temporal evolution of the mean substorm (seven events) of B south component. The time t=0h corresponds at the observation of a sudden equatorward shift at Base General Belgrano. We studied seven events.*

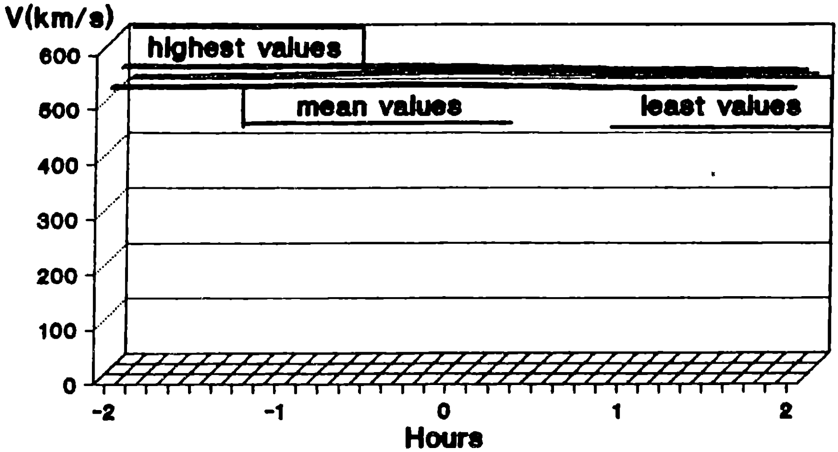

Figure 3. *Average temporal evolution of the Solar Wind Speed, during the 4 hours around break-up time, as observed at Base General Belgrano. This graph represents the average values for seven cases.*

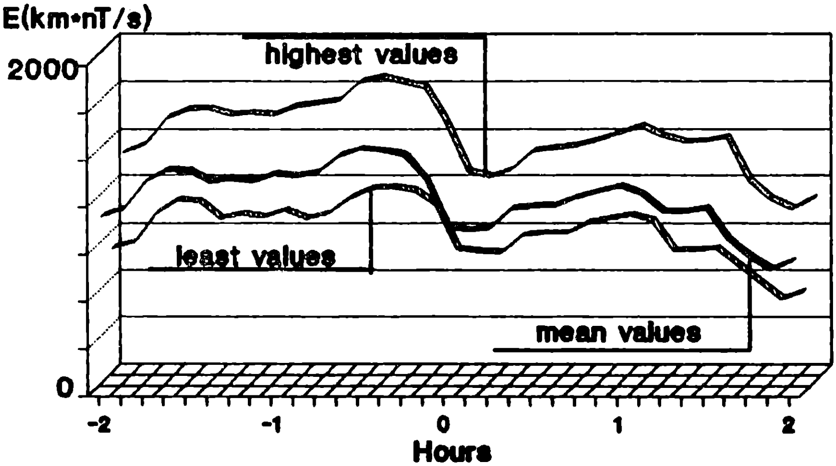

Figure 4. *Temporal evolution (of seven events) of the westward component of the solar wind electrical field from two hours prior till two hours after break-up, as detected at Base General Belgrano.*

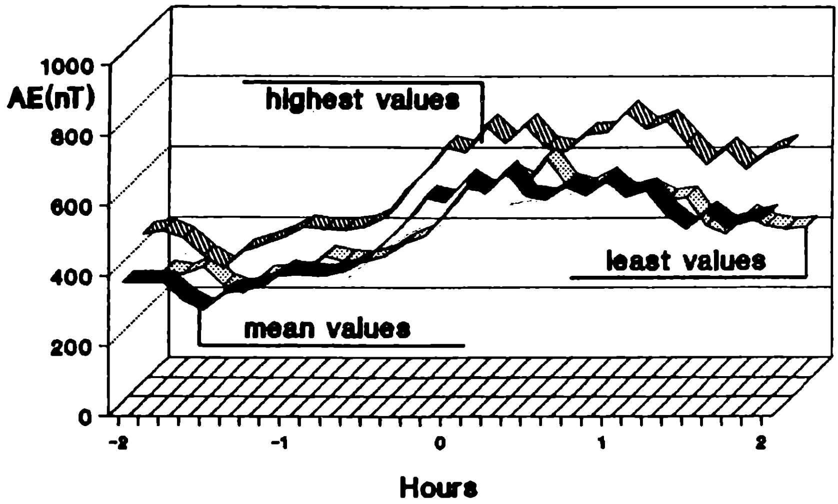

Figure 5. *Mean AE index values vs. break-up time, for the seven substorms studied in the present work. It represents the total current of the two ionospheric auroral electrojets.*

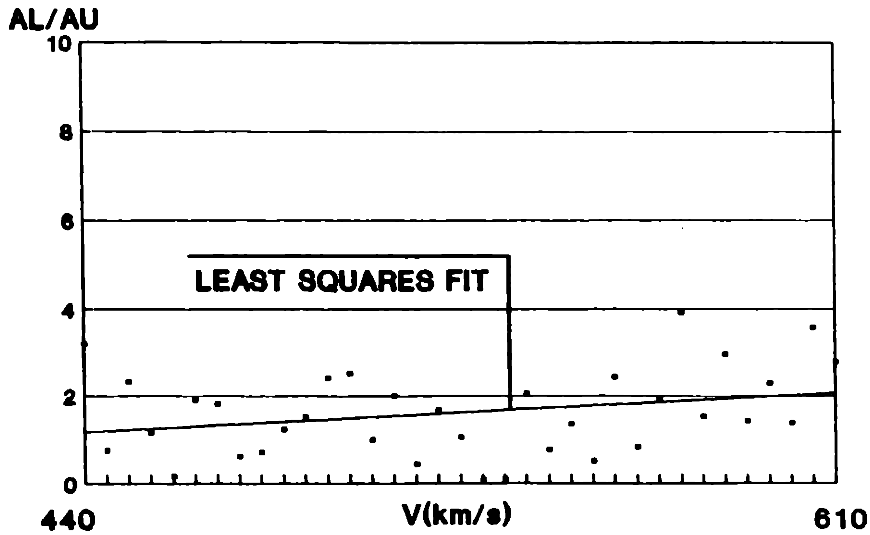

Figure 6. *Relation between the ratio AL/AU vs. V for all the values used in the present study. (Maezawa 1979). The slope is enlarged by the different characteristics of the seven substorms studied.*

5. CONCLUSIONS

According to previous studies (Silbergleit and Schneider 1992 a,b), the sudden equatorward shifts are good indicators of auroral break-up.They are related with high latitude increase of geomagnetic activity. In the present work, we studied the geomagnetic activity through the auroral electrojet activity indices AE. The graph can be used to identify three average substorm phases, according to Akasofu's model. We can observe the appearance of the pseudo break-up around some 60 minutes before break-up. The rise begins in advance of some 35 minutes to break-up time, and in the present work it is in coincidence with an important decrease of Bz values.Then, we can infer that the Base General Belgrano is spatially situated under the ionospheric auroral electrojet currents during the seven studied events.

The average development of the component of the electric field of the solar wind (E_y), has its maximum value about forty minutes (lead over) the maximum geomagnetic activity. So, we could deduce that it is necessary an ionospheric minimum energy threshold to produce geomagnetic substorms.

The mean temporal evolution of B_z component (and E) shows a secondary minimum (maximum), (for the present work), we can think that it is caused by other possible auroral break-up indicator (i.e. appearance of rayed structure, sudden increasing of brightness, variation of spectral composition...).

Also we concluded that some solar wind parameters do not change significantly during the four hours studied (i.e.: Solar wind speed, Interplanetary magnetic field magnitude).

To verify the possibility of using the auroral zone geomagnetic activity for estimating the Solar wind speed, we plotted the ratio AL/AU versus V. From the Fig. 6 we could think that AL and AU indices have an alike dependence on the Solar wind speed. Finally we proposed to research this relation using a high number of substorms.

Acknowledgement. We would like to thank Dr. Otto Schneider for his interesting ideas and discussions, to Dr. Ness for providing us the interplanetary magnetic field vector and solar wind data, to World Data Center-A in sending the above mentioned satellite's data and to the Instituto Antartico Argentino to access the auroral observations and to the Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales (UBA), for working facilities.

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RESULTS FROM THREE GPS CAMPAIGNS IN TIERRA DEL FUEGO

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ABSTRACT

During January and February 1990, 1991 and 1992 an important collaboration took place between the Río Grande Astronomical Station (Estación Astronómica de Río Grande - EARG) and the Royal Institute and Observatory of the Spanish Navy (Real Instituto y Observatorio de la Armada de España - RIOA).
Using RIOA GPS receivers a single base between one point in EARG (Río Grande) and another point located at the Centro Austral de Investigaciones Científicas (CADIC, Ushuaia) was measured several times.
Measured distances repetitivity is about 0.7 ppm (9 cm) and in components, 1 ppm. These results will permit the planning of an appropriate network to be measured with GPS which will contribute to the determination of crustal movements in the Tierra del Fuego region.

RESUMEN

En los meses de enero y febrero de los años 1990, 1991 y 1992 se realizó un trabajo de colaboración entre la Estación Astronómica Río Grande (EARG) y el Real Instituto y Observatorio de la Armada de España (RIOA).
Con posicionadores GPS pertecientes al grupo español se midió reiteradamente una misma base entre un punto situado en la EARG (Río Grande) y otro situado en el Centro Austral de Investigaciones Científicas (CADIC, Ushuaia).
La repetitividad de las distancias medidas es del orden de 0.7 ppm (unos 9 cm) y en componentes, de 1 ppm. Esto permitirá planificar una red apropiada en la región fueguina para la determinación de movimientos tectónicos utilizando GPS.

1. INTRODUCTION

The plate boundaries in the Tierra del Fuego and Antarctic regions are more or less established (Dalziel, 1984) but the real relative movements of these plates are still a problem to be solved. Modern geodetic tools such as GPS must play an important role to determine long term tectonic movements. In this study, a first attempt to establish a precise GPS baseline in Tierra del Fuego is discussed. An introduction to this work with more details about the structure of the region may be found in Brunini et al. (1990).

During January and February of the years 1990, 1991 y 1992 an important collaboration took place between the Río Grande Astronomical Station (Estación Astronómica de Río Grande - EARG) and the Royal Institute and Observatory of the Spanish Navy (Real Instituto y Observatorio de la Armada de España - RIOA).

The RIOA group operated GPS receivers during their Antarctic campaigns, while the EARG team operated one receiver on Tierra del Fuego island. Each year, for a few days, a single base between one point in EARG (Río Grande) and another point located at the Southern Scientific Research Center (Centro Austral de Investigaciones Científicas - CADIC, Ushuaia) was measured. Two double frequency receivers (TRIMBLE 4000 SLD) were used.

During the 1990 campaign, only L1 phase measurements were obtained from one of the receivers so no results will be shown for that period, although they are within the expected errors.

During the 1991 and 1992 campaigns several sessions of at least two hours each were observed. During 1992, a new baseline between one point located next to Fagnano lake (near EOLO building) and the point at CADIC, was measured for the first time.

2. SOFTWARE AND PROCESSING TECHNIQUES

Original raw data as recorded by the TRIMBLE receivers was converted into an ASCII file with reconstructed epochs, phases and ranges, using software developed at La Plata (Canosa, 1990). Observational data so reformatted was processed using the Berna University Software version 3.0 (Rothacher et al., 1988).

The strategy used for the reduction of the data, as suggested by the authors of the software, was the following:

1. Pseudo range measurements were processed to obtain clock parameters which are introduced into the data files used later in phase processing.

2. One orbital arc was calculated for each satellite adjusting all the broadcast ephemeris obtained during the observational period (typically two day long arcs were obtained). In this way, the orbital information used to process different sessions is homogeneous.

3. Data filtering and cycle slips repairing were carried out on the L1 and L2 phase observation files.

4. Final processing was done using phase double differences of the combination "L3" (ionosphere free linear combination).

5. For the ambiguity handling, a "sigma dependent" resolution was used. This strategy consists, in the first step, in calculating all the ambiguities and their associated errors as real numbers. If one integer is close enough to the obtained real value that is contained in interval I (I = real value plus or minus three times the formal error) then the ambiguity is said to be resolved. The integer value so obtained is no more an unknown quantity in the following iterations.

It is interesting to note here that ambiguity resolution is not guaranteed, especially in long baselines. In the case of EARG - CADIC baseline processing, final solutions adopted include several sessions in which some of the ambiguities remained as real values because no integers satisfied the condition established in 5.

Session	X	Y	Z	D	H	amb. res.
1991:						
61/4	5.61	4.63	9.46	8.91	4.76	3/0
61/5	5.36	4.39	9.32	9.12	4.46	3/1
61/6	5.75	4.46	9.36	8.87	4.62	3/3
61/7	5.43	4.62	9.57	9.08	4.81	3/3
62/1	5.29	4.77	9.51	9.02	4.81	3/3
62/2	5.62	4.67	9.58	8.94	4.88	5/3
62/4	5.48	4.55	9.44	9.02	4.68	3/1
62/5	5.49	4.48	9.39	9.03	4.60	3/2
1992:						
67/1	5.49	4.52	9.46	9.04	4.68	5/1
67/2	5.44	4.77	9.31	8.83	4.67	5/5
averages	5.50	4.59	9.44	8.99	4.70	
standard deviations	0.13	0.13	0.10	0.09	0.12	

Table I. *CADIC GPS point coordinates. Results of individual sessions, averages and standard deviations.*

3. RESULTS AND COMMENTS

The results of all the sessions processed are presented in table 1. The first column indicates the date and session (an arbitrary designation); for example, in the first row, 61 is the day of the year, and 4 is the session number. Columns two, three and four show the last digits of the coordinates x, y, z respectively, in meters. Columns five and six show the last digits of the length of the baseline and the ellipsoidal height respectively. The last column shows the number of ambiguities and the number of those which have been resolved, for example, the first row 3/0 indicates that there were 3 ambiguities, but after processing none of them could be resolved. This means that the adopted solution for the session has 3 real values for the ambiguities. The last two rows show the column averages and standard deviations, respectively.

The results shown in table I are CADIC (Ushuaia) coordinates which are the unknowns of the problem because EARG (Rio Grande) coordinates have been adopted as the origin of the baseline. However, these adopted coordinates play a major role in the solution of the baseline parameters, because they remain fixed in the computation and this implies that they are supposed to be well known.

There are two important concepts related to the adopted origin. The first one is obvious; if the coordinates of the origin are changed, those on the other extreme of the baseline change too (but not exactly in the same way!). In this case, if another set of coordinates is adopted for EARG fundamental point, the coordinates in table I will also change.

The second point to stress is that a change in the origin is not exactly transferred to the unknown point coordinates. All the free parameters of the baseline computation (3 coordinates and ambiguities) will be affected by the change in the origin. It is usually accepted that the accuracy of 1ppm in the relative coordinates of the extremes of a baseline is only possible if the origin is known with an accuracy of a few meters.

The adopted coordinates of the fixed point at EARG were obtained during the 1984 MERIT Doppler Campaign (Perdomo R. and Del Cogliano D., 1988). They were obtained from doppler measurements to the TRANSIT System satellites. These coordinates were transformed to WGS84 using the parameters published in the Department of Defense World Geodetic System 1984 (1987). The single point position obtained directly from GPS measurements coincide with the transformed doppler position within the estimated errors.

The adopted coordinates for the point called EARG GPS1 in the WGS84 system are the following:

$$X = 1429883.76$$
$$Y = -3495363.41$$
$$Z = -5122690.40$$

and the estimated accuracy is 3 meters.

A DORIS beacon has been operating continuously at EARG since 1989. The absolute position of this beacon will contribute in the near future to upgrading the absolute position of the point EARG GPS1.

The coordinates of the CADIC point, obtained as the simple average of the individual values shown in table I are the following:

$$X = 1360235.50$$
$$Y = -3422364.59$$
$$Z = -5190059.44$$

$$D = 121318.99$$

where D is the distance between the two points.

As the results in table I show, measured distances repetitivity is about 0.7 ppm (9 cm standard deviation) and for the components X, Y, Z, repetitivity is 1 ppm. It is interesting to note that this is also the same order of magnitude for the ellipsoidal height (12 cm standard deviation). These results give realistic estimations of the real errors of these determinations.

So, using the methodology and equipment here mentioned, it would be possible to measure distances of 50 km with errors of 3 cm. This error can be lowered if a network containing several points is measured and adjusted. It seems evident that the next step is the design of a network to be measured with GPS, with points situated at lower distances and with a geographic distribution appropriate to the determination of all the components of the eventual crustal movements in the Tierra del Fuego region.

Acknowledgments. This work was supported by CONICET, the University of La Plata, the Naval Hydrographic Service (Servicio de Hidrografia Naval) and Tierra del Fuego Province. The authors are indebted to EARG staff for their efforts during field campaigns. They also want to thank CADIC logistic support, and specially Lic. C. Schroeder for his cooperation in the operation of the receivers at Ushuaia.

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PERSISTENCE IN SURFACE OVERFLOW OF ANDEAN RIVERS

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ABSTRACT

The temporal structure of both deficit (negative) and excess (positive) periods in surface overflow of Andean rivers were analyzed by studying the runs.
In Southern areas (in the province of Neuquén and the Southern part of the province of Mendoza), positive and negative groups of anomalies have been found to diminish geometrically over the years. In the Northern areas (in the province of San Juan and Northern part of the province of Mendoza) persistence occurs in negative runs only. This behaviour is produced by the influence of the basins located in an arid zone, because of the heterogeneity in the structure of the precipitation in this region.

RESUMEN

En este trabajo se analiza el comportamiento de la persistencia en el escurrimiento superficial de los ríos andinos, usando el método de rachas de eventos con anomalías positivas o negativas.
Se ha encontrado que las rachas positivas o negativas tienen en la zona más austral (provincia de Neuquén y sur de Mendoza) un decaimiento de tipo geométrico con los años; en cambio hacia la zona más septentrional (provincia de San Juan y norte de Mendoza) aparece la persistencia solamente en las rachas negativas o de sequías. Este comportamiento no se encuentra en la estructura de la precipitación que cae en la cuenca, por lo tanto se infiere que el mismo sería debido a la regulación que ejercen las cuencas del norte, inmersas en una región de clima árido.

1. INTRODUCTION

As a result of the severe drought registered in the Andean rivers of the Central Cordillera during the late 60s and early 70s in the provinces of San Juan and Mendoza (Argentina), a great research effort was directed towards understanding the nature of this phenomenon. Basic hydrologic studies were conducted to understand the interannual variability regime of both river overflow and rainfall (Menegazzo et al., 1985; Carletto et al., 1985, 1987; Minetti et al., 1989). In addition, the interaction between regional atmospheric circulation, rainfall and river overflow have also been studied by Minetti et al. (1982), Minetti and Sierra (1989) among others.

One of the most relevant aspects involved in the structure of the overflow time series of central Andean rivers is the persistence in change exhibited by annual events of rivers located to the north of this group, which can be geographically placed in the Northern part of Mendoza and San Juan provinces (Carletto et al., 1985). Due to recent droughts (in the 80s), this subject is once more under study. The objective is to probabilistically estimate the continuation of a negative event when a similar episode, although of different length, has previously occurred.

Similar studies were performed in other areas by Downer et al. (1967), Saldarriaga and Yevjevich (1970) among others.

The obtained results will be most important for the utilization of reservoirs and regulation of available water.

2. DATA AND METHODS

The series of annual overflows of Andean rivers, from Jachal to Limay rivers, supplied by Agua y Energía Eléctrica (1981) and by the Department of Hydraulics of San Juan province, for the 1909-86 period, were used for the analysis.

These series were transformed into stationary series of the first order by eliminating their respective tendencies with second degree polynomial smoothing (Brooks and Carruthers, 1953; Yevjevich and Jeng, 1967, 1969). In all cases the least squares method was used. This technique prevents the possibility of finding either positive or negative prolonged anomalies. Next, the number of events showing values above or below this tendency -which was regarded as normal value- were estimated. Such events or runs were afterwards evaluated as a function of time as one-, two-, three-year runs, or more, according to Yevjevich (1972). In agreement with the same author and Mood (1940), the distribution of events or runs has been smoothed to a geometric type model, assuming that each event (+ or -) is independent of the other.

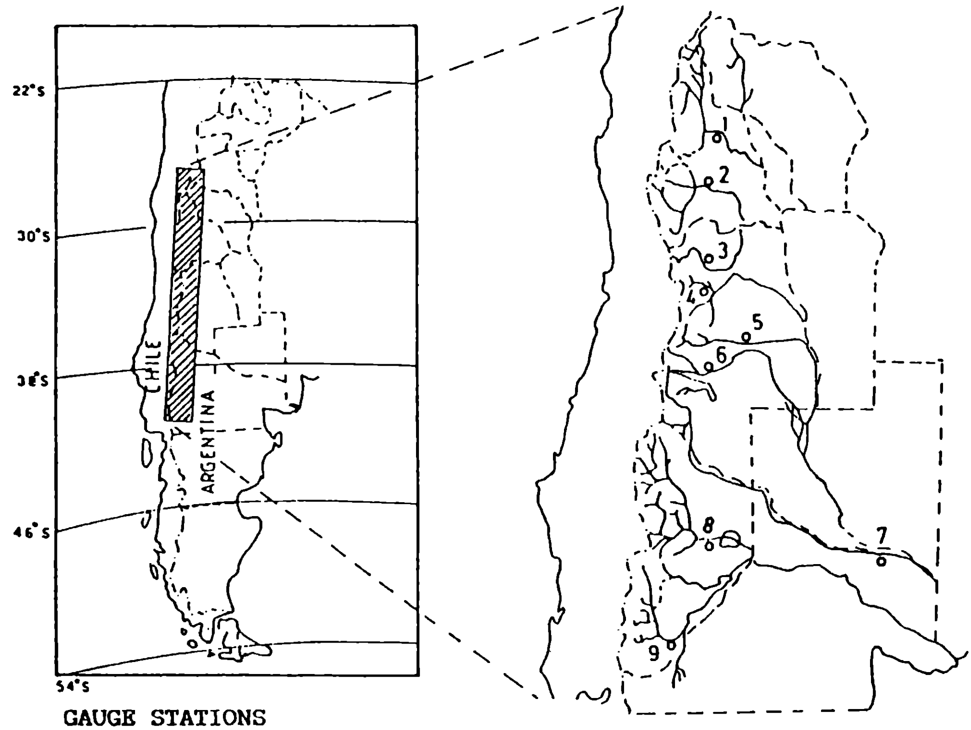
3. RESULTS AND DISCUSSION

Figure 1 shows the area under study, and the river basins listed in Table I. According to Carletto et al. (1985) 55% of Central Andean rivers, from the Limay to the Jachal, show significant autocorrelations at the first lag (lag 1), while their autocorrelation at the second lag (lag 2) corresponds to the criterion of $r_1^2 \approx r_2$ approximately. This allows us to infer that these processes are persistent and in a first approach respond to an autoregressive model of the first order. In other words, persistence or inertia to changes exists in more than half of these rivers, especially in the Northern ones located in an arid zone.

In addition, a previous work by Carletto et al. (1987) reported that river overflows in the Northern arid zone were less aleatory, with an increment of deterministic components (tendencies to jumps) that deserved further investigations. One of these deterministic components is a secular tendency, which is mainly present in Northern rivers. In this case, the secular tendency has been filtered prior to the analysis of runs.

Persistence remains in the structure of these time series and events are more frequent in deficit (negative anomalies) than in excess overflow (positive anomalies). Rainfall series have not a similar behaviour. Minetti and Carletto (1990) reported that the area involved was affected by the dominance of fast changes (high frequencies) in the interannual rainfall variability with dominant oscillations below five years, which were incompatible with persistence.

Drought episodes occurring in the late 80s reopened this matter, showing the importance of evaluating the probability of occurrence of consecutive deficit or excess overflows, in order to use this information in agriculture and energy requirements.



GAUGE STATIONS

1- Pachimoco (Jachal River)
2- Km 47 (San Juan River)
3- Usina Cacheuta (Mendoza River)
4- Valle de Uco (Tunuyan River)
5- Los Reyunos (Diamante River)
6- La Angostura (Atuel River)
7- Pichi Mahuida (Colorado River)
8- Paso de los Indios (Neuquén River)
9- Paso Limay (Limay River)

0 100 200 300 400 500 Km

FIGURE 1. *Map of the study area. The location of the gauge stations for the Andean rivers is also shown.*

RIVER	Basin Surface Km^2	Gauge Station Location	Years Records
JACHAL	25,500	30°13'S: 68°50'W	51
SAN JUAN	25,670	31°13'S; 68°63'W	74
MENDOZA	9,040	33°01'S; 69°07'W	71
TUNUYAN	2,380	33°47'S; 69°15'W	66
DIAMANTE	4,150	34°34'S; 68°34'W	47
ATUEL	3,800	35°02'S; 68°52'W	74
COLORAD	22,300	38°50'S; 61°50'W	62
NEUQUEN	30,200	38°32'S; 69°25'W	76
LIMAY	26,400	40°32'S; 70°26'W	77

TABLE I.. *Some hydrological and geographical characteristics of the studied rivers*

Positive (excess) and negative (deficit) runs of the observed overflow are shown in Tables II and III; they are also plotted in figure 2. From these, it can be seen that excepting Jachal, San Juan and Mendoza rivers, all of them located in the Northern region, Andean rivers exhibit an important drop in the frequency of occurrence of long runs. The mentioned rivers are located in the most arid zone, where two and three-year negative runs prevail.

Figure 3 shows frequency of occurrence of runs with lengths equal to or above those specified in the abscissas (in years) for negative events, compared with a theoretical geometric model according to eq. (1), Yevjevich (1972).

$$f(x) = q^{(x-1)}\, p \,(1) \qquad (1)$$

where:
q = frequency of occurrence of a negative or positive event
p = 1 - q
x = length of runs in years

RIVER	1	2	3	4	5	6	7	8	9	TOTAL (+)
JACHAL	3	2	1	1	0	0	0	0	0	14
SAN JUAN	9	6	0	1	1	0	0	0	0	30
MENDOZA	8	4	1	0	0	1	0	0	0	25
TUNUYAN	9	4	0	1	0	0	0	0	0	21
DIAMANTE	2	1	0	2	1	0	0	0	0	17
ATUEL	8	5	1	1	1	0	0	0	0	30
COLORADO	9	7	1	0	0	0	0	0	0	26
NEUQUEN	7	7	2	0	0	0	0	0	1	39
LIMAY	8	5	3	1	1	0	0	0	0	36

TABLE II.. *Set of positive runs (excess).*

RIVER	1	2	3	4	5	6	7	8	TOTAL (-)
JACHAL	1	0	3	0	0	1	0	1	24
SAN JUAN	3	5	4	2	1	1	0	0	35
MENDOZA	5	1	5	1	0	2	0	0	38
TUNUYAN	5	4	2	1	1	1	0	0	28
DIAMANTE	2	0	0	1	1	0	0	1	19
ATUEL	6	5	3	1	2	0	0	0	39
COLORADO	9	4	2	1	1	0	0	0	32
NEUQUEN	8	6	1	1	0	0	1	0	34
LIMAY	8	5	3	1	0	1	0	0	37

TABLE III. *Set of negative runs (droughts).*

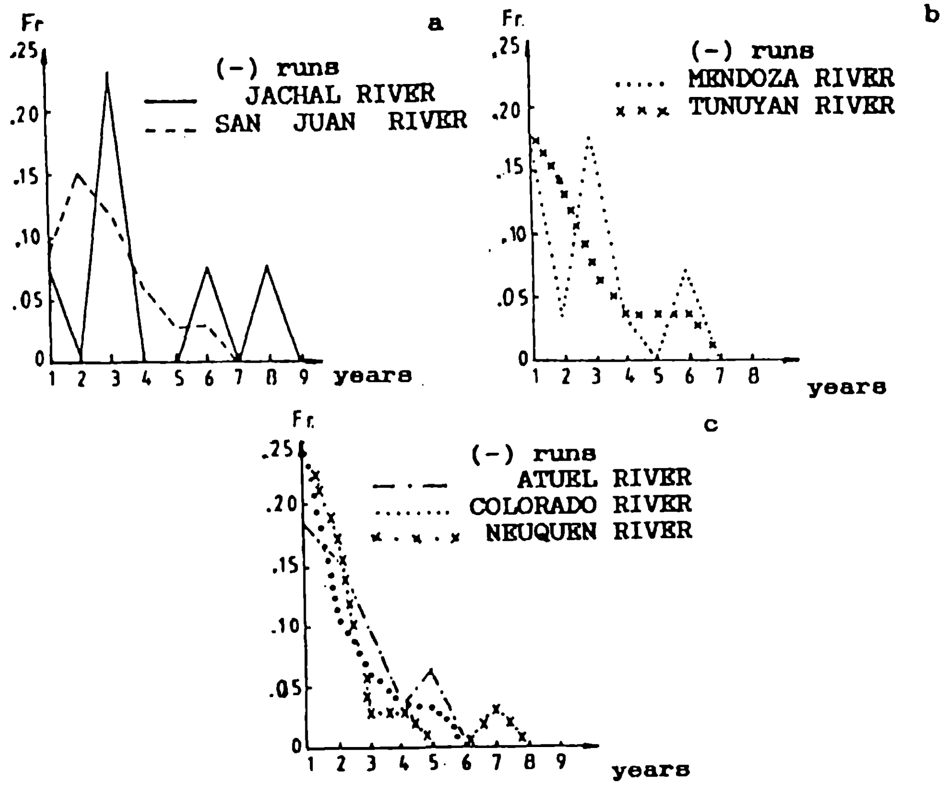


FIGURE 2. *(a): Relative frequencies of negative runs in Andean rivers of the Northern Central Cordillera; (b) Central part of Central Cordillera; and (c) Southern of the Central Cordillera.*

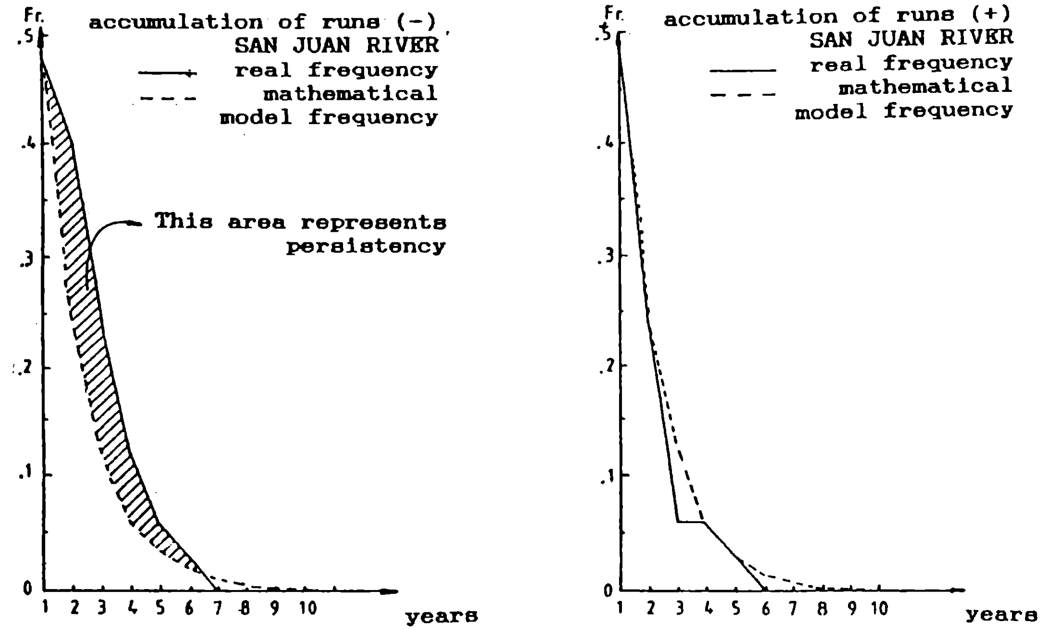


FIGURE 3. *(a): Accumulated relative frequencies of negative runs, with lengths equal to or above those specified in abscissa axis for San Juan river, in the North of the study region; (b) accumulated relative frequencies of positive runs.*

Figure 3 also shows that negative runs of San Juan river have higher probabilities than those obtained by applying the theoretical method that assumes the independence of events. This fact is not observed when dealing with positive runs. This loss of randomness resulting from an increment of persistence would be, in the case of negative runs, the component transforming from normal to log-normal or exponential, all of them models of distribution of overflow occurrence in Andean rivers, from South to North (Carletto et al., 1987). Figure 4 shows that negative runs of Neuquén rivers fit very well with the observed data, in such a way that a statistical verification test is unnecessary.

In several works, it has been reported that Northern basins exhibited an important water retention and subsequent regulatory behaviour. This is particularly valid in the case of large excess events such as those observed in the hydrological cycles of 1921-22 and 1941-42. However, in an arid zone similar to the one described here, one year with little water excess following a long drought period, does not suffice to replenish water level in the basin, and drought conditions continue to be manifested in the overflow.

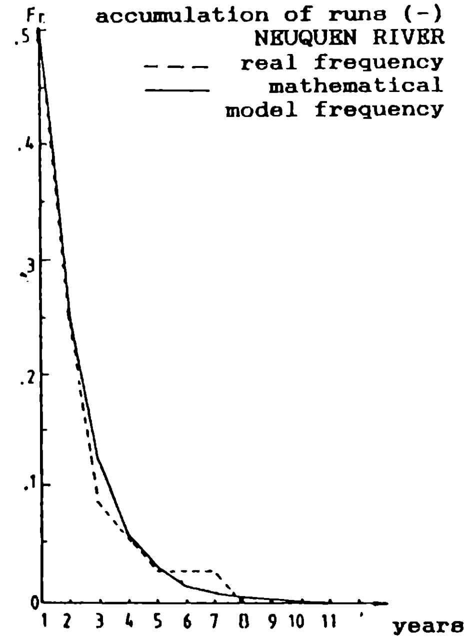


FIGURE 4. *Relative frequencies equal to or below those specified in abscissa axis, for Neuquén river in the South of the study region.*

4. CONCLUSIONS

From the results obtained it can be concluded that:

1- No persistence is observed in positive runs (excess) in Andean rivers. In general these events occur separately.
2- Negative runs (deficits) involve an increment in persistence from South to North.
3- Negative runs prevail in the Northern region with two or three year groups.
4- The persistent behaviour of droughts, and the non stationarity (tendencies) in the overflow of Northern rivers, would be the causes of randomness loss in the structure of data series.

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CLIMATOLOGÍA DE LA PRECIPITACION EN LA REGION PAMPEANA: I. VARIABILIDAD DECÁDICA, TENDENCIAS Y EVENTOS EXTREMOS

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RESUMEN

Se analizan las series mensuales de precipitación de localidades ubicadas en la región pampeana con información que supera los 88 años de registros, detectándose en los promedios móviles de 11 años de totales anuales, una zona de fuertes tendencias positivas, especialmente a partir de la década del 50 y en el trimestre estival.

Se definen estadísticamente los extremos de precipitación anual en base a una distribución Weibull triparamétrica y se determinan las zonas de probabilidad de ocurrencia de déficit y excesos. Se caracterizan los años extremos como aquellos en que más del 50% del área total soportó déficit o exceso de precipitación. Se resume el comportamiento de los años climáticos en una serie temporal de porcentajes de áreas bajo condiciones extremas, destacándose un año de déficit para la región, 1910-1911, y cinco años con excesos de precipitación, 1914-15, 1918-19, 1946-47, 1968-69 y 1972-73 .

ABSTRACT

Monthly precipitation series from the Pampa region with record lenghts greater than 88 years are analyzed using moving averages over eleven years. A zone of strong positive trends, particularly started in the fifties during the summer season is detected.

Extremes of yearly precipitation are statistical defined by means of a three parametric Weibull distribution. Areas of probabilities of deficit and excess of annual rainfall are determined. An extreme year is defined as the year in which more than 50% of the total area suffered precipitation deficit or excess. A summary of the behavior of the climate years is presented as a temporal series of the area percentage of the region under extreme conditions. It is observed that years 1910- 1911 are extreme of deficit while 1914-15, 1918-19, 1946-47, 1968-69 and 1972-73 are extreme years of excess of rainfall in the region.

1. INTRODUCCIÓN

La porción del país seleccionada para el presente trabajo comprende una extensión aproximada de 612.000 Km^2, donde se encuentran los campos de mayor producción agrícola y ganadera de Argentina. Esta región incluye la Provincia de Buenos Aires, Centro y Sur de Santa Fe y Entre Ríos, Sudeste de Córdoba y Este de La Pampa. Históricamente las exportaciones de carnes y granos han desempeñado un papel muy importante en la economía del país, especialmente a partir de la década del sesenta. Desde entonces la agricultura argentina comienza un proceso de transformación importante que se mantiene hasta nuestros días, a pesar del impacto negativo que produjo sobre los precios internacionales la implementación de la política de subsidios desde 1985 hasta el presente. La recuperación de la actividad agrícola tiene su causa reconocida en la asimilación por parte del productor de maquinarias agrícolas, técnicas agronómicas, semillas mejoradas y agro químicos; todo ello acompañado de un proceso de expansión del área sembrada, a expensas de la liquidación del stock ganadero, como consecuencia de las adversas condiciones de los mercados internacionales para nuestras carnes, especialmente luego de 1977 (Cellario, 1990) y de favorables condiciones climáticas para toda la región. La característica destacada de este cambio la constituye el cultivo de oleaginosas y en particular la incorporación de la soja en la región, produciendo un cambio en la distribución del área sembrada para los diferentes granos. La zona pampeana es un excelente indicador histórico de los cambios producidos en la agricultura del país, tanto por la aptitud de suelos y clima, como por la infraestructura disponible. Debido a su importancia económica, la distribución de las precipitaciones en la Pampa Húmeda, su régimen estacional y variabilidad espacio-temporal, han sido objeto del interés de algunos investigadores desde hace varias décadas (Prohaska, 1952; Marchetti, 1952; Díaz, 1953; Vasino, 1954 y Hoffman, 1970). Los autores han estudiado en trabajos previos la fluctuación de las precipitaciones en la zona de transición Pampa Húmeda/Seca a lo largo del presente siglo y las contribuciones a la variabilidad debido a diferentes rangos de frecuencias (Krepper y Scian, 1986). Mediante la utilización de un análisis por componentes principales se estudió la variabilidad espacial de la región, encontrándose que la misma tiene un carácter netamente intranual (Krepper y otros, 1989). Uno de los objetivos perseguidos en el presente trabajo consiste en profundizar las características climatológicas de las precipitaciones como así también la probabilidad de ocurrencia de extremos en los totales anuales y la secuencia de presentación de los mismos a lo largo del presente siglo.

2. DATOS Y TRATAMIENTO DE LA INFORMACIÓN

Para el presente trabajo se utilizaron series de totales mensuales de precipitación, correspondientes a 40 localidades seleccionadas entre las que cuentan con registros más prolongados (al menos 88 años). La Figura 1 muestra la distribución espacial de las estaciones utilizadas. Es bien conocido para la región que su régimen pluviométrico presenta en general un mínimo invernal y dos máximos, a principio del otoño y fines de primavera. Comparando los regímenes anuales de las distintas localidades estudiadas es posible distinguir aquellas con influencia marítima (costeras) de las que sufren una estación seca bien definidas (tipo continental) durante el invierno. Prohaska (1952) propone una forma de analizar tanto la influencia continental como la marítima, que consiste en estudiar el mes de ocurrencia de los máximos de precipitación en los regímenes medios. El citado autor diferencia de esta forma diferentes regiones de acuerdo a las influencias ejercidas por el Anticiclón del Atlántico y la baja del NO. Sin embargo, el alto grado de variabilidad de la precipitación para las bajas frecuencias (especialmente para un rango de fluctuaciones interdecadales), no permite extraer conclusiones definitivas de acuerdo a este método.

La mencionada variabilidad interdecadal en el campo de las precipitaciones puede ser fácilmente visualizada en la Figura 2, donde se presentan las isoyetas medias anuales para los períodos 1901-10, 1911-20, 1921-30, 1931-40, 1941-50, 1951-60, 1961-70, 1971-80 y 1981-88.

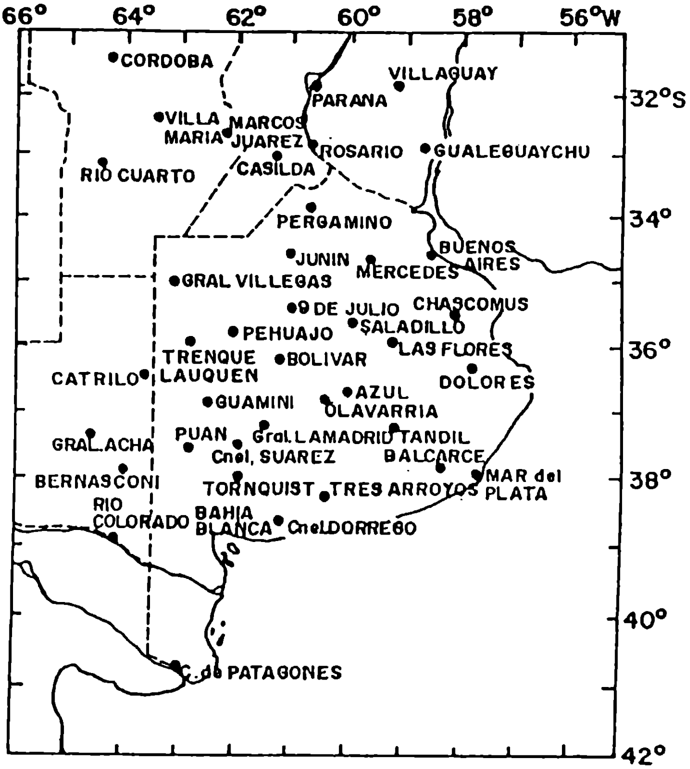

Figura 1. *Localización de las estaciones.*

De la observación de la Figura 2 podemos apreciar los profundos cambios experimentados por los campos medios a lo largo del siglo presente. Claramente se pueden individualizar tres subperíodos:

i) Una primera década extremadamente seca que contrasta notablemente con el resto del período de estudio. Durante la misma únicamente al norte de los 32°S las precipitaciones medias en la Mesopotamia excedían los 1000 mm, mientras que una tercera parte de la Provincia de Buenos Aires y todo el sur de Córdoba recibían en promedio lluvias inferiores a los 600 mm.

ii) Un subperíodo de 40 años, hasta 1950, que sigue al anterior, durante el cual se produce un mayor aporte pluviométrico en toda la región, aunque signado por una notable variabilidad interdecadal. Las mayores fluctuaciones se producen sobre el NE de la región bajo estudio, donde la isoyeta media correspondiente a los 1000 mm sufre traslaciones superiores a los 3° en latitud.

iii) Las cuatro décadas finales (aunque la última es incompleta) conforman una porción de la serie con un marcado incremento de las precipitaciones medias anuales y un mayor grado de estabilidad entre décadas. Esta última parte del siglo contrasta con la escasez de precipitaciones a comienzos del mismo, característica que probablemente se extendiera a las postrimerías de la centuria pasada. Sin embargo, esto último no puede ser confirmado plenamente por los autores, ya que es escasa la cantidad de estaciones con series pluviométricas cuyo origen se remonta al siglo XIX.

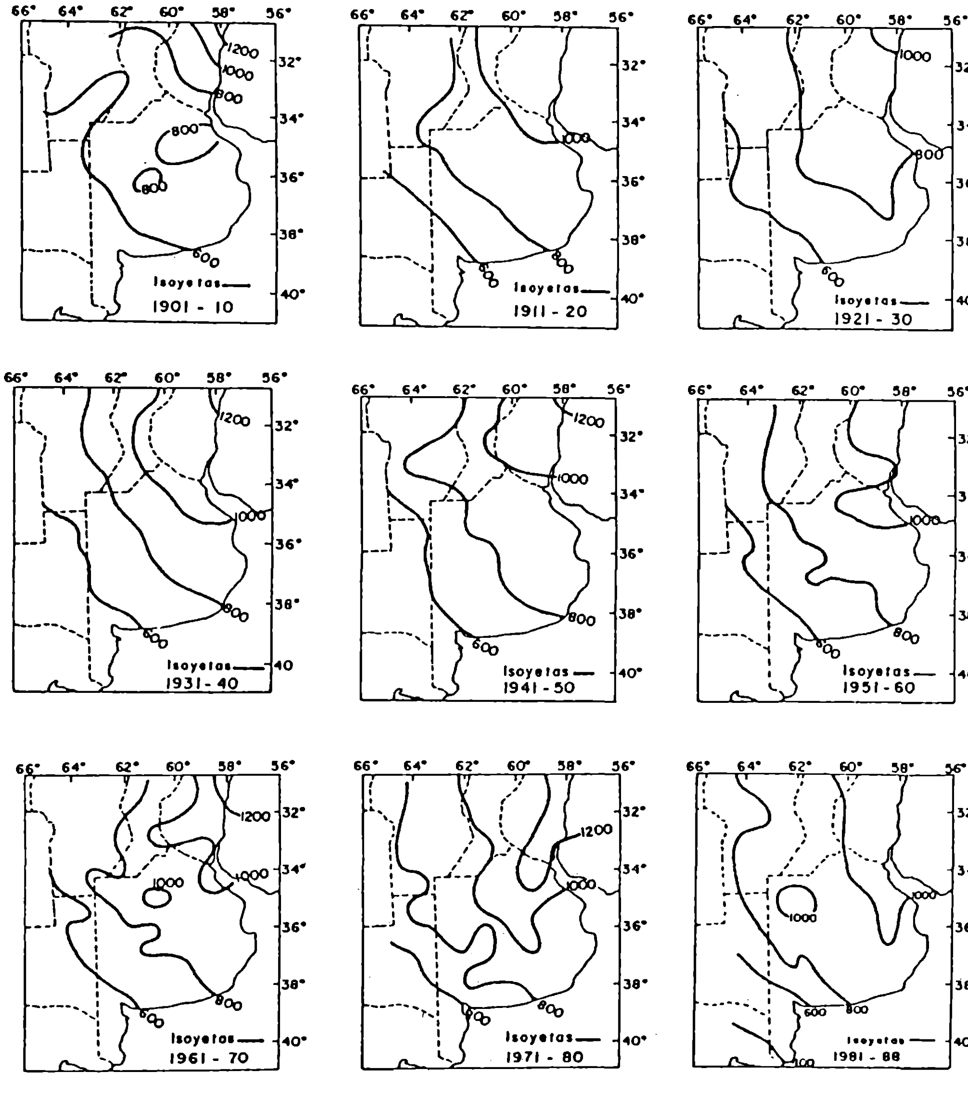

Figura 2. *Isoyetas medias decádicas*

En particular, la isoyeta de 600 mm puede servir de indicador de la forma en que el límite de la transición entre la Pampa Húmeda y Seca (Krepper y Scian, 1986) se ha desplazado hacia el Oeste (ver Figura 3) incorporando nuevas regiones potencialmente aptas para cultivos de secano. A los efectos de determinar los rasgos más característicos de las precipitaciones durante el siglo, se calculó la serie promedio de la región, para los totales anuales de lluvia (ver Figura 4). Dicha serie presenta una tendencia lineal positiva del orden de 1,2 mm/año, confirmándose lo mencionado por algunos autores que investigaron el tema: Schwerdtfeger y Vasino (1954), Krepper y Scian (1986). Esta característica no tiene una distribución espacial homogénea, pues en particular en una amplia subregión que comprende el Centro y Oeste de la Provincia de Buenos Aires, Noreste de La Pampa y Sur de Córdoba, dicha tendencia lineal aumenta notablemente hasta alcanzar un valor promedio de 2,6 mm/año (Krepper y otros, 1991), tal como se muestra en la parte inferior de la Figura 4.

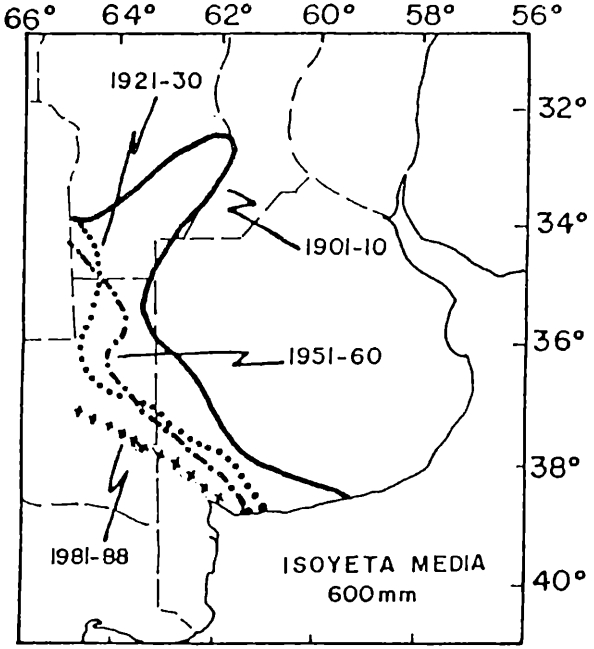

Figura 3. *Isoyeta media de 600 mm, posiciones sucesivas.*

El comportamiento individual de cada estación y sus fluctuaciones de largo período no pueden ser estudiados adecuadamente mediante ajustes polinómicos debido al alto grado de variabilidad interanual que presentan las series. En su lugar se decidió aplicar promedios móviles centrados sobre un período de $T_0 = 11$ años, y analizar las series resultantes. En términos del análisis de filtros digitales esto equivale a aplicar un pasabajos del tipo computacional (two side), con frecuencia de corte $f_c \sim 0{,}041$/año y función de transferencia o ventana espectral del tipo:

$$\Gamma(f)^2 = \text{sen}^2(\Pi f T_0) / (\Pi f T_0)^2 \qquad (1)$$

con corrimiento de fase nulo ($\theta_0 = 0$). Las series filtradas mantienen, sin grandes modificaciones, las características asociadas a las bajas frecuencias ($f \ll f_c$) y a las tendencias seculares presentes en las series originales.

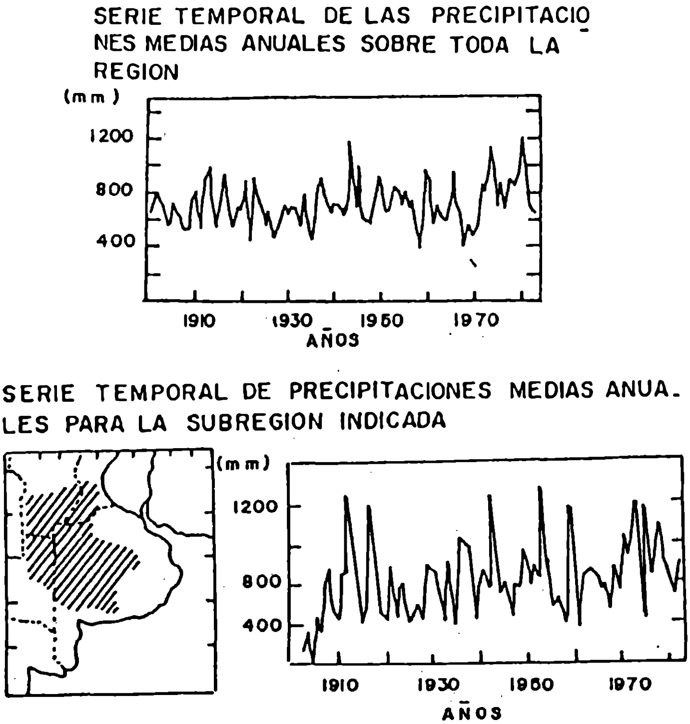

Figura 4. *Series temporales medias sobre distintas regiones.*

La Figura 5 muestra los registros totales anuales de precipitación, para el récord de datos existentes en algunas localidades superpuestos a la señal resultante luego de aplicar promedios móviles. La heterogeneidad de los comportamientos en bajas frecuencias de las series de precipitación, pone en evidencia el grado de variabilidad que aún persiste en este rango del espectro. Otra característica notable en las figuras lo representa el hecho que las tendencias distan mucho de poder ser expresadas por una función lineal, al mismo tiempo que no se distinguen periodicidades o cuasi-periodicidades generalizadas. Esto último tiene una importante implicancia pues nos anticipa la falta de ciclos de largo período en el régimen de precipitación que puedan afectar al área de estudio en su totalidad.

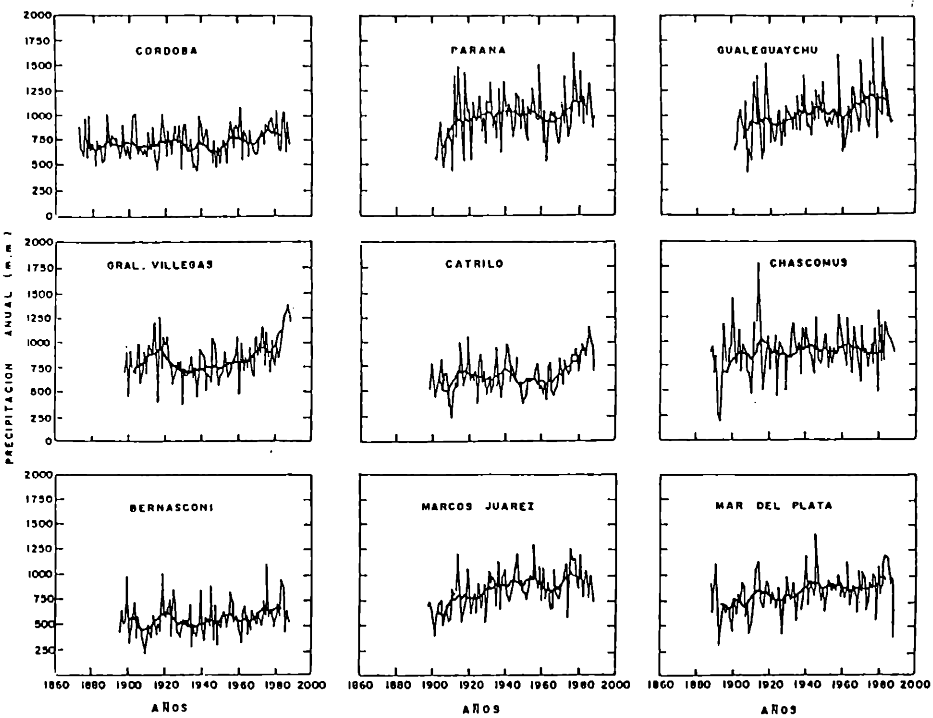

Figura 5. *Tendencias de la precipitación anual*

Es decir que las fluctuaciones de bajas frecuencias en los regímenes de precipitación, parecerían tener un efecto sólo local o zonal. Previamente a continuar con el análisis del comportamiento de las precipitaciones, debe mencionarse el hecho que el año calendario divide la época de lluvias (octubre-marzo) en dos partes, por lo que se decidió utilizar de aquí en más un año climático o "agrícola" que comience en el mes de julio y termine en junio. En particular el NO de la Provincia de Buenos Aires es probablemente la zona donde las tendencias positivas en las series de precipitación se hacen más pronunciadas, especialmente a partir de la década del 50. Un estudio estacional de las lluvias caídas muestra que el incremento de largo período en las precipitaciones anuales medias del área es debido principalmente al comportamiento de las lluvias de verano (enero-febrero-marzo) (ver Figura

6). Cabe recordar que estas precipitaciones han sido las causantes de las mayores inundaciones registradas en la historia de la región, durante el mes de marzo de 1987.

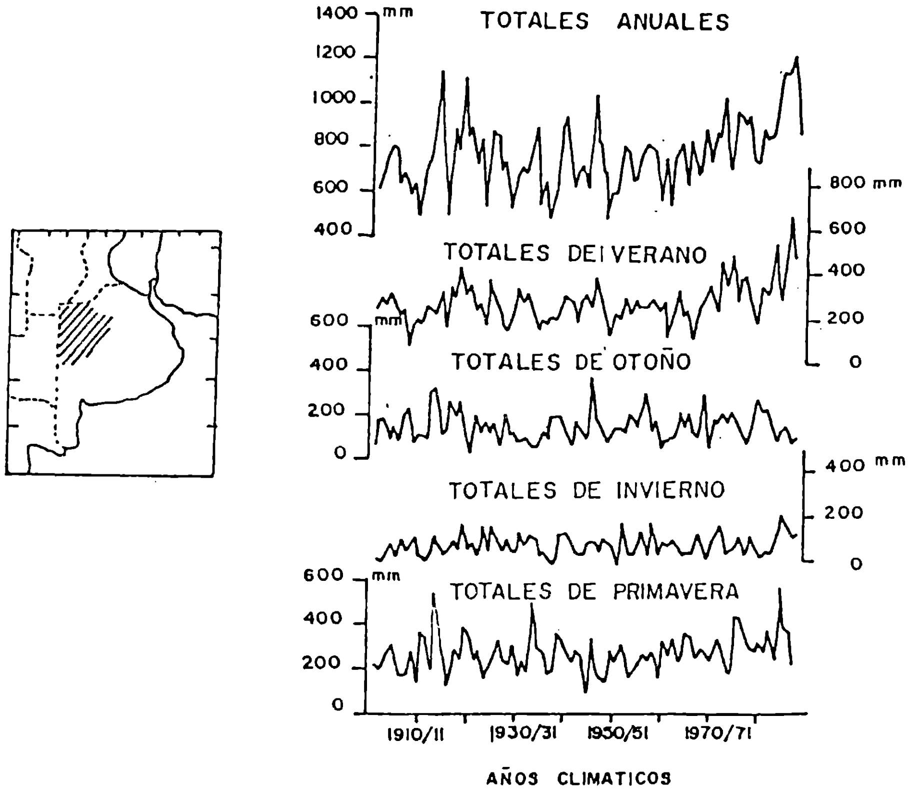

Figura 6. *Precipitación media estacional.*

3. DISTRIBUCIONES EXTREMAS DE LA PRECIPITACIÓN ANUAL

El área bajo estudio está caracterizada por grandes fluctuaciones anuales de la precipitación, las que necesariamente tendrán un efecto directo sobre la producción agrícola de esta importante región ganadera del país. La definición de extremos desde el punto de vista estadístico implica la selección previa del modelo analítico de distribución de probabilidades que mejor ajuste los datos. Normalmente no existe una razón teórica explícita que indique qué tipo de distribución debería ser utilizada, quedando librado a las características de los datos o al mejor ajuste la elección definitiva. En las circunstancias presentes, un alto porcentaje de las series utilizadas poseen Kurtosis negativas, lo que en principio desalentaría el uso de funciones tipo gama y lognormal. La Figura 7 muestra en el plano de las kurtosis vs. asimetrías, la distribución de los correspondientes momentos muestrales para cada estación pluviométrica, como así también las relaciones teóricas correspondientes a las distribuciones estandarizadas de Weibull, Gama y Lognormal.

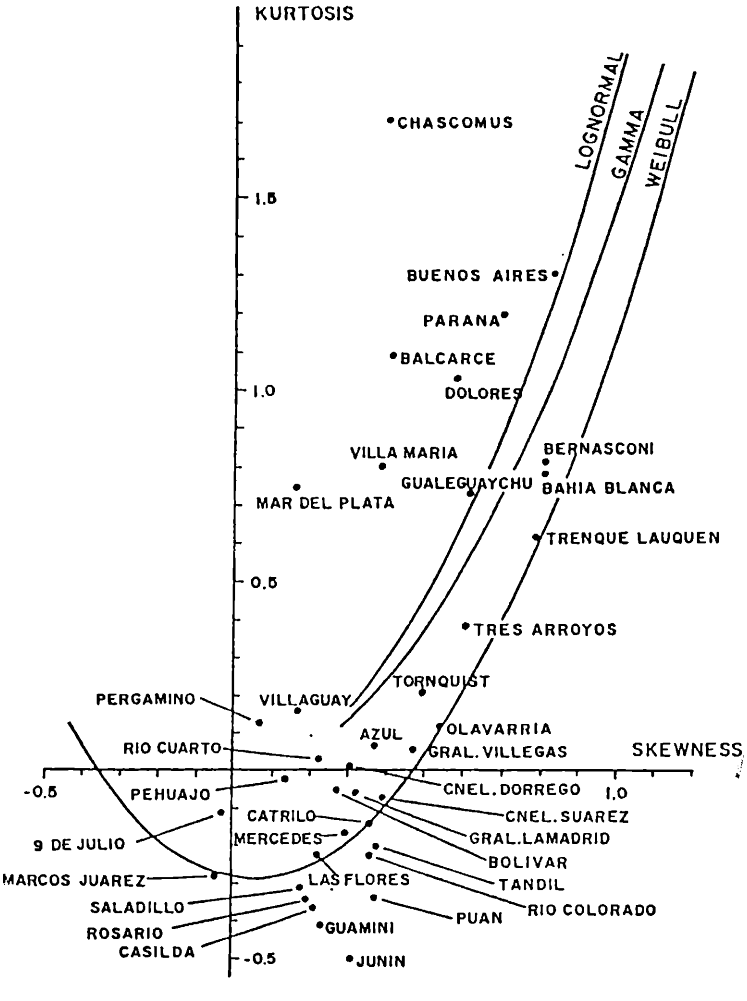

Figura 7. *Caracterización de las localidades.*

De la observación de la figura se desprende que la mayoría de las estaciones, de acuerdo a sus momentos de tercero y cuarto orden, se ajustarían mejor a una distribución tipo Weibull que a las restantes. Cabe aclarar que análisis de este tipo no deben tomarse como absolutos para decidir el tipo de distribución a emplear, ya que el cálculo de los momentos estadísticos de orden superior es muy sensible a la presencia de valores extremos. Sin embargo, es precisamente el poder determinar la probabilidad de ocurrencia de dichos valores extremos el objetivo perseguido, por lo que deberemos seleccionar una distribución suficientemente flexible en su forma. La distribución elegida fue la de Weibull triparamétrica (Weibull, 1951; Johnson y Kotz, 1970) cuya función acumulativa tiene la forma:

$$\text{Prob}\,[X_1 < X\,] = 1.0 - \exp[-((X_1 - A_1\,) / A_2)^C] \quad (X_1 > A_1\,) \qquad (2)$$

donde A_1 es el parámetro de posición, A_2 el de escala y C el denominado parámetro de forma. Tales parámetros fueron determinados individualmente para cada estación ajustando la distribución teórica a la experimental mediante un método de regresión no lineal, basado en un algoritmo propuesto por Marquardt (Marquardt, 1963). El motivo para seleccionar un modelo de Weibull triparamétrico en lugar del tradicional de dos parámetros se basa en el hecho que las precipitaciones anuales en la región nunca son nulas y que el ignorar la existencia del parámetro de posición introduce una deformación importante en la parte inferior de la distribución.

El criterio estadístico adoptado para seleccionar los valores extremos de precipitación anual, X_1 (déficit) y X_2 (exceso), fue el siguiente:

$$\text{Prob}\,[X_1 < X < X_2\,] = 75\% \qquad (3)$$

bajo la condición que $[X_1 - X_2\,] =$ mínimo.

La función densidad de probabilidades de Weibull puede ser escrita como:

$$P(X) = C\,A_2^{-1}\,(X - A_1\,) / A_2)^{C-1}\,\exp[-((X - A_1\,) / A_2)^C] \qquad (4)$$

que para el caso de $A_1 = 1$ y $A_2 = 1$ adquiere la forma estandarizada

$$f(X) = C\,\,(X^{\,C-1}\,)\,\exp[-X^C] \qquad (5)$$

Para evaluar el comportamiento de estos límites con respecto al parámetro de forma, se compararon los mismos con respecto a los puntos de inflexión de una distribución de Weibull estandarizada (Johnson y Kotz, 1970). En la Figura 8 se ha representado la dependencia de las áreas bajo la curva f(X), fuera de los puntos de inflexión y de los límites de precipitación previamente determinados según ec. (3). Una ventaja adicional que representa la utilización de distribuciones del tipo de las definidas en (2) consiste en el hecho que es posible asignarle cierto significado físico o estadístico a los distintos parámetros obtenidos a través de un ajuste numérico. El parámetro adimensional C determina la forma de la función densidad de probabilidad (ec.4), donde para $C > 1$, $p(X) \rightarrow 0$ cuando $X \rightarrow A_2$. En cambio, para $C = 1$, la ec. (5) se transforma en una distribución exponencial, alcanzando su valor máximo, $p(A_1\,)=A_2^{-1}$, cuando $X = A_1$. Cabe destacar el hecho que para valores próximos a 3,4, la distribución de Weibull se toma simétrica (normal) y los extremos seleccionados coinciden con los puntos de inflexión. Por otra parte, cuando el parámetro de forma C toma el valor 2,0, el punto de inflexión inferior desaparece y la distribución de Weibull adquiere las características de una

Gama. Esta propiedad fue determinante para no utilizar las inflexiones como valores límites, ya que para cualquier distribución con parámetro de forma menor que 2,0 (como de hecho existen) implicaría la imposibilidad de definir el extremo inferior. El parámetro A_1 , con dimensiones de mm de agua caída, representa el limite inferior de la distribución estadística. Para valores de precipitación anual inferiores a A_1, el modelo de Weibull propuesto en ec. (2) no está definido. Durante el proceso numérico de cálculo de A_1, A_2 y C se tuvo cuidado que no se generaran parámetros de posición superiores al mínimo de la serie muestral. De ocurrir esto, se fijaba el valor de A_1 con el mínimo del récord, dejando que el proceso de regresión no-lineal determinara los restantes parámetros. Por su parte A_2 actúa en la distribución escalando las diferencias entre las precipitaciones anuales y el mínimo estadístico (A_1).

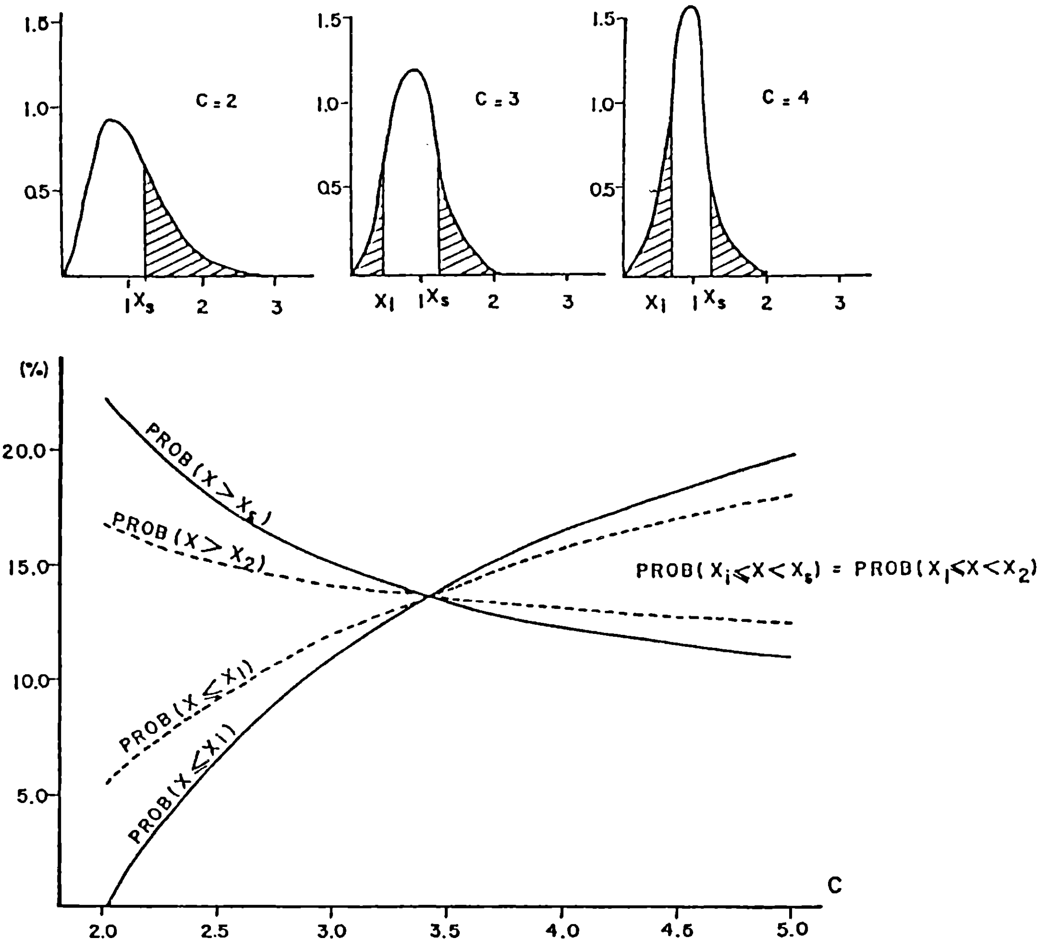

Figura 8. *Comportamiento de los puntos de inflexión de una distribución de Weibull (línea llena) y de valores extremos (línea de puntos), con respecto al parámetro de forma.*

La Figura 9 muestra los mapas correspondientes a los límites superiores e inferiores (X_1 y X_2) y a las probabilidades de ocurrencia de déficit y excesos en la oferta natural de agua. Cabe recordar que de acuerdo a la definición dada en la ec. (3), la probabilidad de ocurrencia de precipitaciones anuales entre los extremos prefijados es del 75%, pero debido a las asimetrías de las distribuciones individuales, las probabilidades de precipitaciones deficitarias o excesivas no tienen porque ser iguales, aunque sus sumas deben ser del 25%.

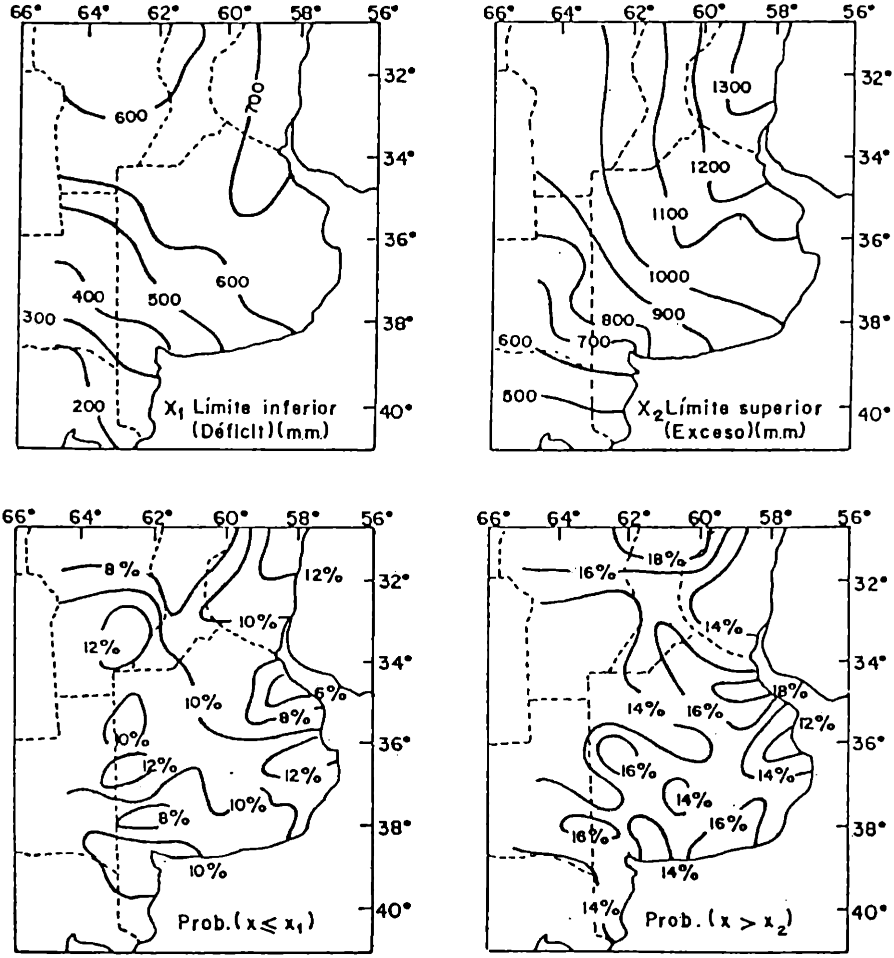

Figura 9. *Mapas correspondientes a los límites superiores e inferiores (X_1 y X_2) y a las probabilidades de ocurrencia de déficit y excesos en la oferta natural de agua.*

El procedimiento seguido para determinar los extremos de precipitación es netamente estadístico y no contempla factores agro climáticos, lo cual implica que dichos valores no pueden ser interpretados como límites de sequías o de extremos de humedad. Es por este motivo que se habla de déficit o excesos en la oferta de agua, en forma de precipitación; cualquier otra interpretación implicaría tener en cuenta la "administración" que suelos y biota hacen del recurso. Comparando los mapas de la Figura 9, se observa que en la zona mesopotámica las precipitaciones más frecuentes oscilan entre 700 y 1300 mm, es decir, dentro de una variación de 600 mm, rango que se reduce a menos de 500 mm para la zona central de nuestra área de estudio y a unos 250 mm para la región Sur. Por otra parte los mapas de probabilidades ponen de manifiesto la existencia de amplias regiones donde la probabilidad de ocurrencia de déficit es la mitad que la correspondiente a excesos, pero el caso inverso es infrecuente. Esto implica que, en general, la región en su totalidad está sujeta a probabilidades inferiores de déficit respecto a las correspondientes a excesos.

Cabe preguntarse de qué forma se han producido, a lo largo del presente siglo estos eventos extremos, en particular, si los mismos han ocurrido coincidentemente en determinadas regiones, y qué extensión del área bajo estudio se vio afectada en cada caso. Es decir, desde un punto de vista netamente estadístico, se ha considerado a cada localidad como independiente de las restantes, utilizando el argumento tradicional que la precipitación es un parámetro altamente aleatorio y de carácter local, pero en ningún momento se han evaluado las condiciones de precipitación sobre toda la región. En consecuencia, un año puede ser definido como "extremo" si y sólo si gran parte de la región ha sufrido tales condiciones.

Para determinar las características de las precipitaciones anuales sobre toda la región bajo estudio, a lo largo del presente siglo, se determinó por año el porcentaje del área total con precipitaciones por encima de X_2 y por debajo de X_1 respectivamente. De esta forma se caracterizaron los "años extremos" como aquellos en que más del 50% del área total (más de 300.000 Km^2) soportó déficit o exceso de precipitación. La Figura 10 resume el comportamiento de los sucesivos años climáticos desde julio de 1901. Para el caso de déficit, únicamente el año 1910-11 puede definirse como un año de extremadamente escasas precipitaciones, pues el 59,5% del área total sufrió tales condiciones. Los años definidos como excesivamente húmedos fueron el 1914-15, 1918-19, 1946-47 y 1972-73.

La Figura 11 muestra los detalles de las regiones afectadas por condiciones de déficit o excesos, durante los años extremos definidos anteriormente.

Observando en detalle la Figura 10 se puede dividir el período total en tres partes, coincidentes con los subperíodos comentados al estudiar las contribuciones medias decadales.

I) La primera década a comienzos de siglo, puede definirse como un período sumamente seco, pues en promedio el 21,6% del área total sufrió escasez de lluvias y sólo excesos, el 1,8%.

II) Las cuatro décadas siguientes, hasta 1950, se caracterizan por la alternancia de rachas de años húmedos y secos, presentando en promedio el 7% con déficit y el 12% del área con excesos.

III) A partir de 1950 hasta el fin del período, se manifiesta un neto predominio de rachas húmedas, considerablemente largas donde, en particular los últimos 12 años, conforman la mayor de ellas. Durante este lapso sólo el 3,4% del área total presentó características medias deficitarias, mientras el 20,3% corresponde a precipitaciones en exceso.

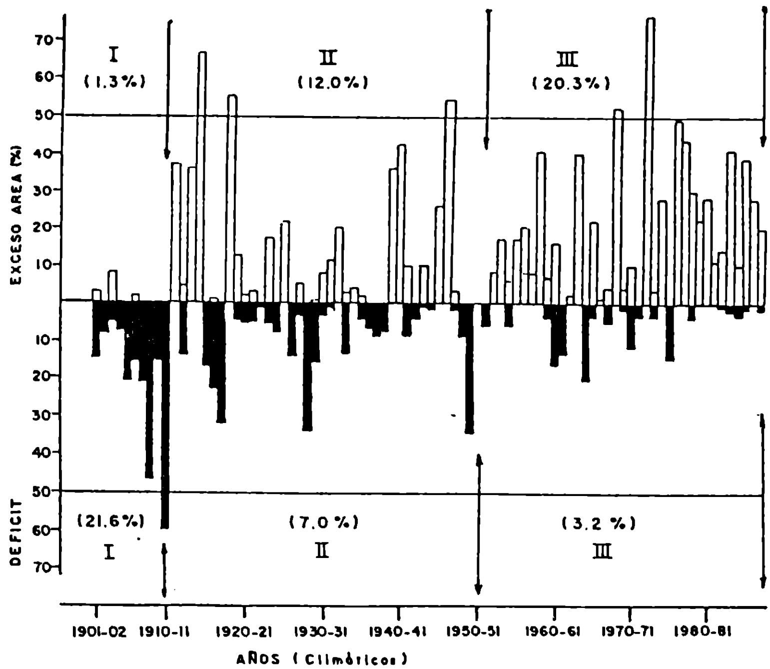

Figura 10. *Serie temporal de los porcentajes del área total bajo condiciones extremas.*

4. CONCLUSIONES.

La Pampa Húmeda, en general, ha experimentado a lo largo del siglo, importantes cambios en la cantidad promedio de lluvia recibida anualmente, variaciones que en algunas localidades ha representado un incremento superior al 50%, al comparar la primera década con el período 1981-88. Este cambio climático experimentado en los campos, de precipitación, ha tenido como consecuencia la incorporación de nuevas regiones del país a la producción agrícola. En particular, en algunas regiones tales como el NO y centro de la Pcia. de Buenos Aires y Sur de Santa Fe, las mayores tendencias ocurren a partir de 1950, coincidiendo con una recuperación de la actividad agrícola cuya causa fundamental es debida a la incorporación de nuevas técnicas agronómicas. Sin embargo, las buenas condiciones climáticas permitieron la introducción de los cultivos oleaginosos que han producido en los últimos años un cambio notorio en la distribución de las áreas sembradas y en la composición de los cultivos.

El desplazamiento de la isoyeta de 600 mm puede dar una idea de cómo evolucionó el límite entre la Pampa Húmeda y Seca, mostrando la incorporación al sector productivo de una importante porción de la Provincia de Buenos Aires, La Pampa y Córdoba, donde los regímenes medios actuales son muy superiores a los registrados a principio de siglo.

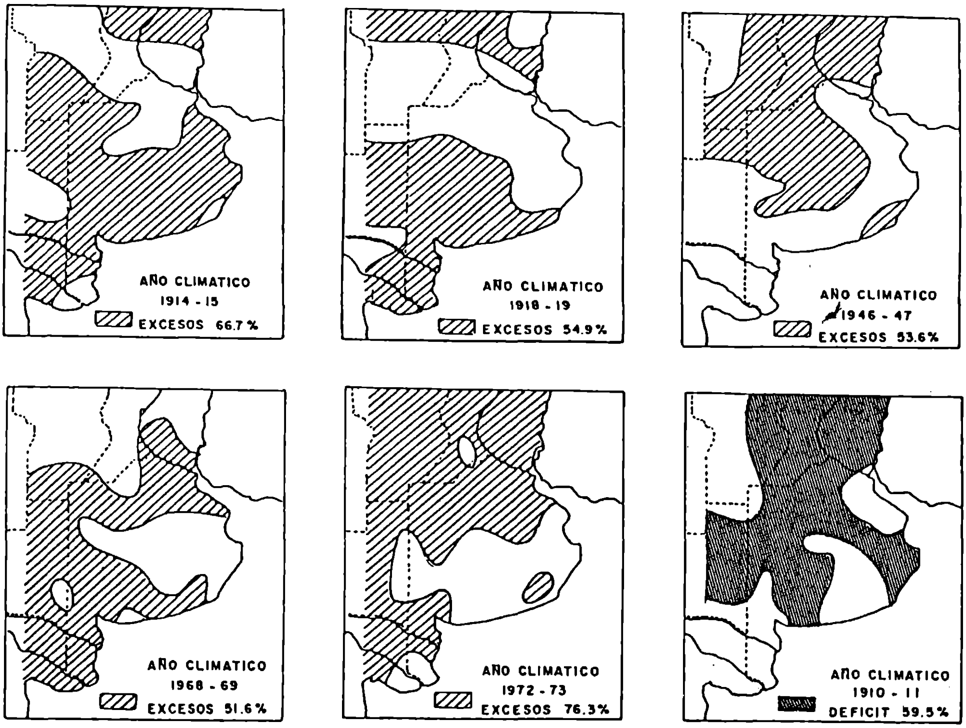

Figura 11. *Regiones afectadas por déficits y excesos durante años extremos.*

La determinación estadística de los valores límites de precipitación y el cálculo de probabilidad de ocurrencia de déficit y excesos en los totales anuales de precipitación permite obtener cierta medida del riesgo hídrico para cada localidad. A los fines del uso agrícola, el estudio debería referirse a períodos intra-anuales, coincidentes con el ciclo vegetativo total de los diferentes cultivos. Las características de las precipitaciones anuales a lo largo del presente siglo, se determinaron mediante el porcentaje del área total con precipitaciones deficitarias y excesivas respectivamente. Tal análisis permite caracterizar tres períodos bien definidos, a saber: una primera década a comienzos de siglo, que puede definirse como seca; un segundo período correspondiente a las cuatro décadas siguientes, hasta 1950, que se caracteriza por la ocurrencia alternada de años secos y húmedos; por último, el período que abarca desde 1950 a 1988, donde predomina un marcado incremento de las precipitaciones anuales. La escasez de datos pluviométricos durante el siglo XIX no permite extender los estudios más allá del inicio de la centuria presente, lo cual impide preveer cualquier tipo de comportamiento de largo período (secular) en las series de precipitación.

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