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Practical Implications of Space Weather

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(Abdu)

Space weather is basically a manifestation of the complex processes that control the solar terrestrial relationship. It relates to the highly variable state of the ambient conditions of our space environment spanning from the interplanetary medium to the earth's magnetosphere and ionosphere-thermosphere system. During solar disturbances the processes of energy and mass ejection from the solar active regions into the interplanetary space that eventually impact on the earth's magnetosphere set the stage for the development of events that determine the variabilities/vagaries of space weather. Observations by satellites have identified cause-effect chain of events associating solar flare and related coronal mass ejection (CME) events as responsible for storm disturbances in interplanetary, magnetosphere, ionosphere and thermosphere parameters, that together constitute a space weather event.

Space weather disturbances can lead to ensuing disruptions of space applications and technological systems on ground and in space. The basic parameters of space weather that are responsible for the impacts and effects encountered/observed on earth and in space are listed in Table-1.

The Items in the column of "Practical effects on Space Application and Technological Systems" are described briefly below:

Surges/induction in Electric Power Grids:

During severe magnetic storms (Kp ≥ 7), damaging electric currents can be induced in power grids, particularly at high latitudes. (Albertson an vanBaalen, IEEE Trans. Power Apparatus and Systems, PAS-89, 578,1970; Kappenman and Albertson, IEE Spectrum, 27, no.3 27, 1990; Zanatti et al., Geophys. Res. Letts., 21, 1867, 1994). The effects vary from simple tripping of circuit breakers resulting in temporary electric power blackouts of cities, to destruction of expensive power station transformer banks and major industrial power disruption. The problem occurs when the storm –induced currents appear in three –phase transformers that are electrically connected by long transmission lines. Destructive localized heating occurs in the windings, capacitor banks get overloaded and trip-out, protective relays fail, and power transmission is degraded or lost completely (W. B. Campbell, Societal Impact of Geomagnetic Storms, Report, Oct 1996).

The great magnetic storm (Kp index of 9^+) that occurred on 13 March 1989, produced major field fluctuations centered near south-east Canada and north-east USA, and caused damage to power distribution transformers that resulted in nine-hour black out of the 21,000 MW Quebec electric power system (Blais and Metsa, Solar-Terrestrial Prediction Workshop- IV Workshop Ottawa, May

1992, NOAA Dept of Commerce Pub. v.1, 108-130, 1993). The same storm also destroyed transformers in the U.S.A. at Salem Nuclear Plant of the Public Service Electronic and Gas Company.

Fig.1 is a picture of the nuclear plant transformer that was one phase of a 1200 MVA bank that exists on the Delaware River in New Jersey. (The loss of production from the plant cost customers up to $400,000 per day during a 6-week outage.

Fig.2 shows the internal damage of this transformer. Although the large copper strands were rated at 3000 amperes, the saturation of the steel core created stray flux that created hot spots and the consequential meltdown.

Fig.3 shows the mechanism for the strong induced current that causes the damage. The intense ionospheric electrojet currents (at ~100 km altitude) descend to lower latitudes during storm conditions. The ionospheric current induces large currents in the conducting seawater. When adjacent power systems on land are located over high resistivity igneous rock, the induced currents enter and exit power systems through the transformer neutral grounding points.

Induction in long pipe lines:

At high latitudes large lengths of pipelines run parallel to the direction of auroral electrojet current, which therefore induces currents in the pipeline, which is a conductor. The pipe line parts are either buried underground or often in large parts runs on the ground with electrically insulating surface coating applied on the pipe. Often small cuts in the surface coating can occur when the pipelines are placed on the ground. A fluctuating current induced from geomagnetic disturbance, travels between the pipe and the ground, which, when directed appropriately causes pipe erosion. The amount of corrosion is dependent upon the frequency and amplitude of the storm- time source current, the exposed area of the pipe, the material in which the pipe is embedded, the frequency dependence of the corrosion process and the frequency dependence of the local earth induction (Campbell, Surveys Geophys., 8, 239, 1986). For high latitude pipelines the effect of corrosion from the induced geomagnetic storm current probably maximizes with the 5- to 30- minute period field fluctuations. The high latitude pipeline are believed to be corroding faster than originally anticipated for not having taken into account the effect of induced current in the original design.

Pipeline over low latitudes also go through corrosion process due to current generated from difference in contact potential at ground points or by induction from nearby man-made systems. Most of such corrosion effects are avoided by proper application of an overriding current to make all exposed areas negative with respect to the ground. Corrosion engineers need to make periodic adjustment of the pipeline potential. Such adjustments will be improper when done during magnetic disturbances that can induce currents in the pipeline, as a result increasing the pipeline corrosion (W. B. Campbell, Societal Impact of Geomagnetic Storms, Report, Oct 1996).

Satellites: damages, degradations and tracking:

Major effects of high-energy particles are electronic parts and materials degradation, CD and sensor degradation solar cell degradation, single event effect, sensor interference and internal electrostatic discharging caused by electrons. The energetic particles involved are electrons with energies in the hundreds of keV and above and protons above 1 MeV per nucleon. The source of these particles is solar energetic particle event, galactic cosmic rays and radiation belts. (see, for further details, Feynman and Gabriel, J Geophys. Res., 105, 10543, 2000). On-board computers in space systems have life times mostly determined by the accumulated radiation damage.

It is presently thought that many failures of spacecraft circuitry are caused by disturbance –time internal dielectric charging of satellite components and the resulting subsequent discharge.

During some storms the magnetospheric compression causes geo-synchronous satellite orbits at 6.6 R_e to be outside of the magnetospheric boundary. As a result numerous geo-synchronous satellite operation anomaly have been observed.

An illustration of spacecraft charging by electrons injected into geostationary orbit during the early phase of a geomagnetic sub-storm is shown in **Fig. 4.**

Storm-time thermospheric temperature and wind variation cause increased density at the satellite orbits around 500km and less. The resulting change in the orbital velocity can cause transitory tracking loss. The accumulated such effect could cause satellite orbital decay faster than original prediction that did not include realistic prediction of the thermospheric response to storms.

Astronaut in Space:

Energetic particles can affect astronauts in polar orbits, and on some occasions also passengers and crew in high latitude polar flights. **Fig. 5** shows a global distribution from satellite observations of $\geq$1MeV electrons show large fluxes over high latitudes (and in the region of influence of south Atlantic anomaly) during a storm in June 1991.

Ionosphere-Thermosphere System

Communication:

HF communication via ionosphere between ground-based stations as well trans-ionospheric information exchange (between satellites and ground stations) can undergo drastic modification including fading, blackout and outage during space weather disturbances, due to ionospheric response to magnetospheric storms. Over the equatorial region such responses involve enhancement or inhibition of the ionization anomaly and plasma bubble instability processes. The following is a series of figures that show such responses and some of the effects that they can produce on the transe-ionospheric propagation conditions.

Fig.6-a: Magnetic variations over Fortaleza, Brazil during the magnetic storm of August 1998.
-b: Ionospheric response as seen in the Digisonde data over the equatorial site Sao Luiz, Brazil.
    -c: Ionospheric response as seen in the Digisonde data over the low latitude site Cachoeira Paulista,
    -d &e: GPS observation over Cachoeira Paulista of irregulariy development during the storm.
    -f: Airglow signature signature during the storm (to be included)

Navigation/Global Positioning System:

Position determination using GPS satellites can be affected by the ionospheric changes in response to magnetic storms. The positive and negative phases in density and TEC over middle and low latitude can introduce errors in time delay measurements and hence in position determinations. Some examples of the ionsopheric response features and errors in position determination are shown in Fig. 7 a, b, c etc..

Table-1: Cause – Effect Parameters of Space Weather

SPACE WEATHER

- MAJOR CAUSES AND CONSEQUENCES

-

Solar Origin of Space Weather Disturbances	Space Weather Parameters	Space Weather Effects Ionosphere-Thermosphere	Practical effects on Space Application and Technological Systems
- EUV Radiation; - Solar wind, high speed streams originating from Coronal holes; - Flares; - Coronal Mass Ejection; - Solar Proton Events;	-Solar Activity Flares; -Solar Coronal Mass Ejection; -Solar and Galactic Energetic Partcles; -Solar Wind (Pressure, density, velocity); -Magnetospheric Particles; -Radiation Belt; -Interplanetary Magentic Field; -Magnetospheric electric fields; -Geomagnetic Disturbances;	-Perticle precipitation, Auroral electric fields: Plasma drift and ion drag, Enhaced auroral elctrojet; -Joule heating, chemical heating; -Thermosphere upwelling: Equatorward expansion/ propagation of disturbed thermospheric composition, winds and gravity waves; -Direct penetration, and disturbance dynamo, electric fields at equatorial latitudes; -	-Surges/induction in Electric Power Grids; -Induction in Pipe lines; -Satellites: damages, degradations and tracking; -Astronauts in Space; -Navigation/Global Positioning System; -Communication;

TABLES of NOAA SPACE WEATHER SCALES

A)

Category		**Effect**	**Physical Measure**	**Average Frequency (1 cycle – 11 years)**
Scale	Descriptor	Some or all of these effects are possible		
	Geomagnetic Storms		Kp values*	No. of storm events; (numbr of storm days)
G 5	Extreme	Power systems: grid systems can collapse and transformers experience damage. Spacecraft operations: extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents reach hundreds of amps, HF (high frequency) radio propagation impossible in many areas for one to two days, satellite navigation degraded for days, low-frequency radio navigation out for hours, and the aurora seen as low as the equator.	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible voltage stability problems, portions of grids collapse, protective devices trip. Spacecraft operations: experience surface charging and tracking problems, orientation problems need corrections. Other systems: induced pipeline currents effect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and the aurora seen as low as the tropics.	p = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage correction required, false alarms triggered on protection devices, and high "gas-inoil" transformer readings likely. Spacecraft operations: surface charging on satellite components, increased drag on satellite, and orientation problems need corrections. Other systems: intermittent satellite navigation and low-frequency and low-frequency radio navigation problems, HF radio intermittent, and the aurora seen as low as mid-latitudes.	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems affected. Spacecraft operation: corrective actions required by ground control; changes in drag affect orbit predictions. Other systems: HF radio propagation fades at higher latitudes, and the aurora seen as low as 50 degrees.	Kp = 6	1700 per cylce (900 days per cycle)

G 1	Minor	<u>Power systems</u>: weak power grid fluctuations. <u>Spacecraft operations</u>: minor impact on satellite operations <u>Other systems</u>: the aurora seen at high latitudes (60 degrees); migratory animals begin to be affected.	Kp = 5	1700 per cylce (900 days per cycle)

*may change to use other measures, such as DST, as basis.

B) NOAA SPACE WEATHER SCALES

Solar Radiation Storms			Flux level of ≥10 Me V particles (ions)*s	Number of events when flux level was met; (number of storm days**)
S 5	Extreme	<u>Biological</u>: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); high radiation levels to passengers and crew in commercial jets at high latitudes (aproximatedly 100 chest x-rays). <u>Satellite operations</u>: loss of some satellites, memory impacts cause loss of control, serious noise in image data, star-trackers unable to locate sources; permanent damage to solar panels. <u>Other systems</u>: No HF (high frequency) communications possible in the polar regions, and position erros make navigation operations extremely difficult..	10^5	Fewer than 1 per cycle
S 4	Severe	<u>Biological</u>: unavoidable radiation hazard to astronauts on EVA; elevated radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 10 chest x-rays). <u>Satellite operations</u>: memory device problems, noise on imaging systems, star-trackers cause orientation problem, and solar panels degraded. <u>Other systems</u>: blackout of HF radio communications throuhg the polar cap and increased navigation errors over several days.	10^4	3 per cycle
S 3	Strong	<u>Biological</u>: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in commercial jets as high latitudes receive low-level radiation (approximately 1 Chest x-ray). <u>Satellite operations</u>: likely single-event upsets, noise in imaging systems, permanent damage to exposed components/detectors, and decrease of solar panel currents. <u>Other systems</u>: degraded HF radio propagation through the polar cap and navigation position errors.	10^2	25 per cycle

S 2	Moderate	Biological: none. Satellite operations; infrequent single-event upsets. Other systems: small effects on HF propagation through the polar cap and navigation at the polar cap impacted.	10^2	25 per cycle
S1	Minor	Biological: none. Satellite operation: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle

*Flux levels are 5 minute averages. Flux in particles. S^{-1}. $Ster^{-1}$. Cm^{-2}

**These events can last more than one day.

C) NOAA SPACE WEATHER SCALES

Radio Blackouts			GOES X-ray peak Brightness by Class and by flux*	Number of events when flux Level was met; (number of storm days)
R 5	Extreme	HF Radio: Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. No HF radio contact with mariners on en route aviators. Navigation: Low-frequency navigation signals used by maritime and general aviation systems experience outages on teh sunlit side of the Earth for many hours, causing loww in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 ($2x10^{-3}$)	**Fewer than 1 per cycle**
R 4	Severe	HF Radio: HF radio communication blackout for one to two hours on most of the sunlit side of Earth. HF radio contact lost during this time for mariners and en route aviators. Navigation: Outages of low-frequency naviagation signals cause increased error in positioning for mariners and general aviators for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth..	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communication signals, loss of radio contact for mariners and en route aviators for about na hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about na hour, affecting maritime and general aviation positioning.	X1 (10^{-4})	175 per cycle (140 days per cycle)

R 2	Moderate	HF Radio: Limited blackout of HF radio communication signals on sunlit side, loss of radio contact for tens of minutes for mariners and en route aviators. Navigation: Degradation of low-frequency navigation signals for tens of minutes affecting maritime and general aviation positioning.	M5 ($5x10^{-5}$)	350 per cycle (300 days per cycle)
R 1	Minor	HF Radio: Weak or minor degradation of HF radio communication signals on sunlit side,occasional loss of radio contact for mariners and en route aviators. Navigation:. Low-frequency navigation signals degraded for brief intervals affecting maritime and general aviation positioning.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

*Flux, measured in the 0.1-0.8 nm range, in $W.m^{-2}$.

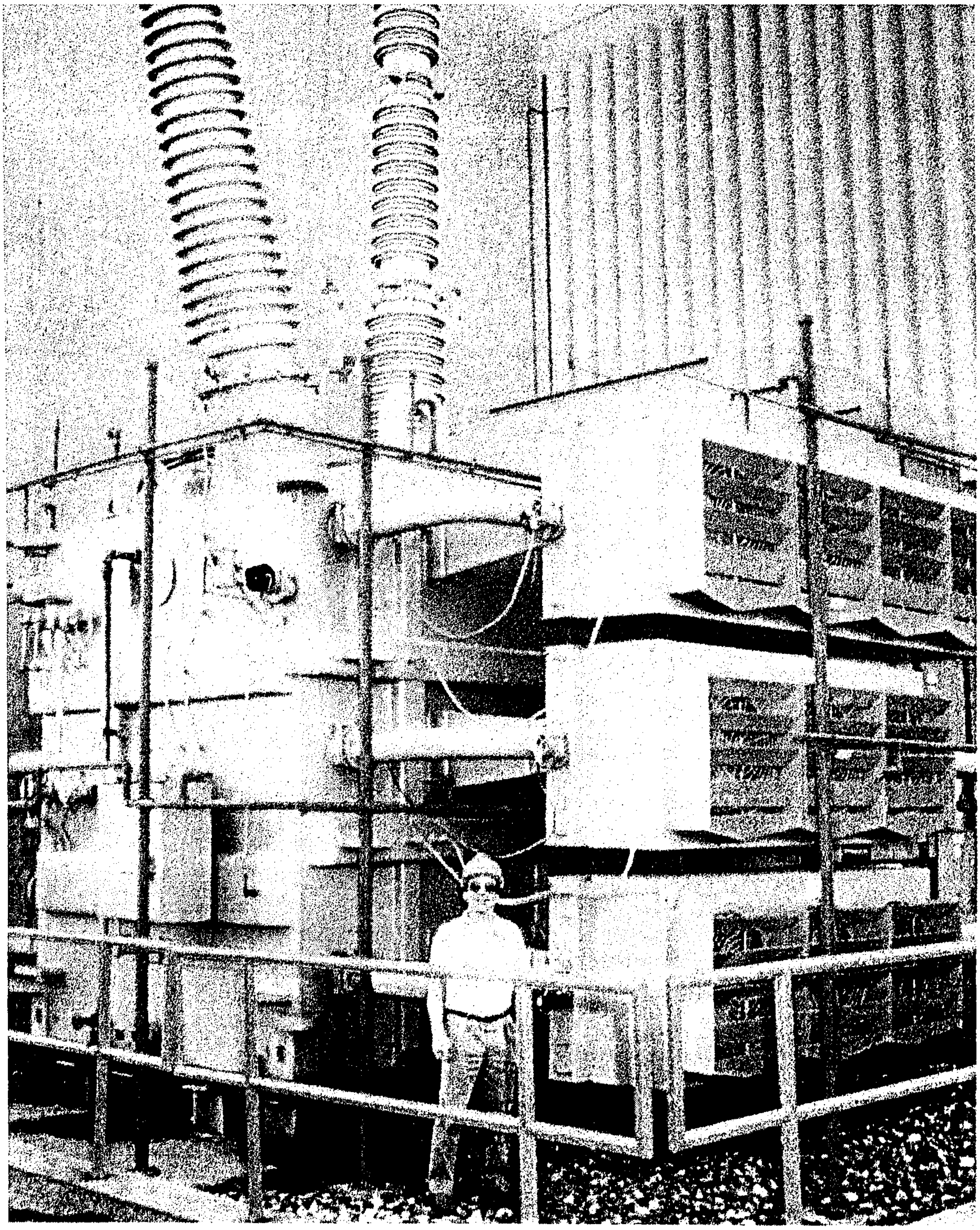


Fig. 01

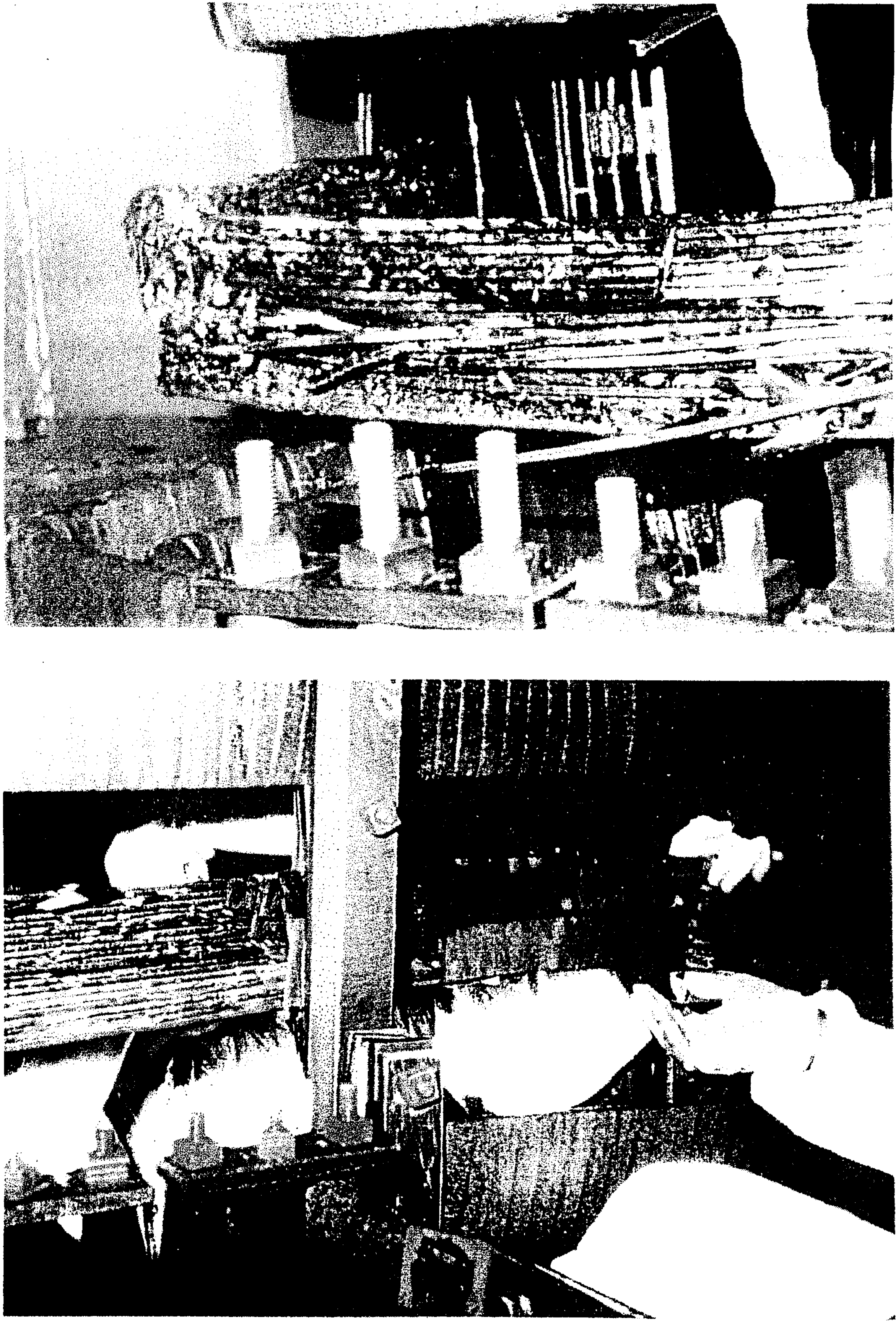


Fig. 02

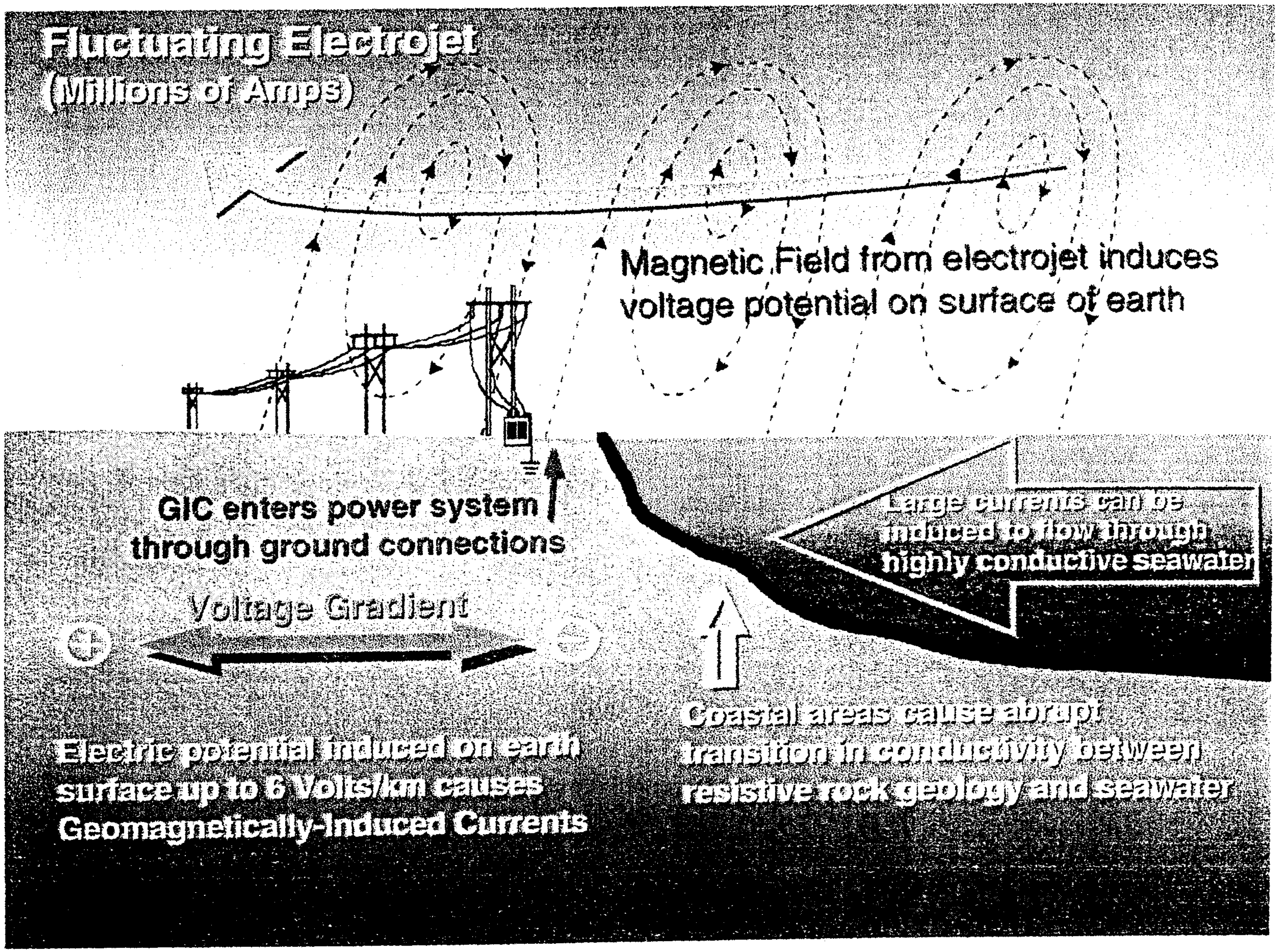
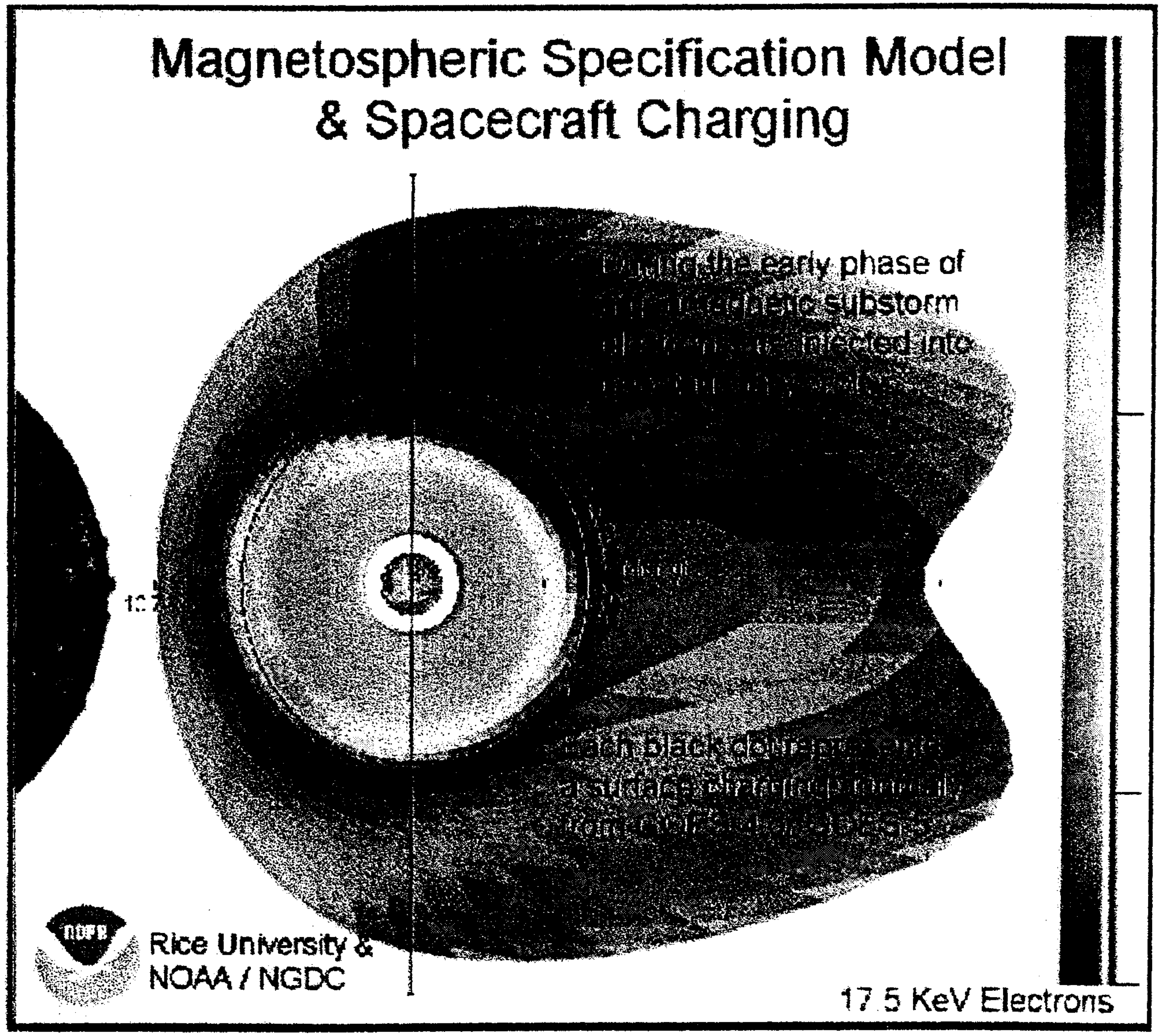

Fluctuating Electrojet
(Millions of Amps)
Magnetic Field from electrojet induces voltage potential on surface of earth
GIC enters power system through ground connections
Voltage Gradient
+
−
Large currents can be induced to flow through highly conductive seawater
Coastal areas cause abrupt transition in conductivity between resistive rock geology and seawater
Electric potential induced on earth surface up to 6 Volts/km causes Geomagnetically-Induced Currents

Fig. 03



Magnetospheric Specification Model & Spacecraft Charging

During the early phase of
a geomagnetic substorm
electrons are injected into
[illegible]

Each black dot represents
a satellite [illegible]
[illegible]

Rice University &
NOAA / NGDC

17.5 KeV Electrons

Figure courtesy of The National Geophysical Data Center

Fig. 04

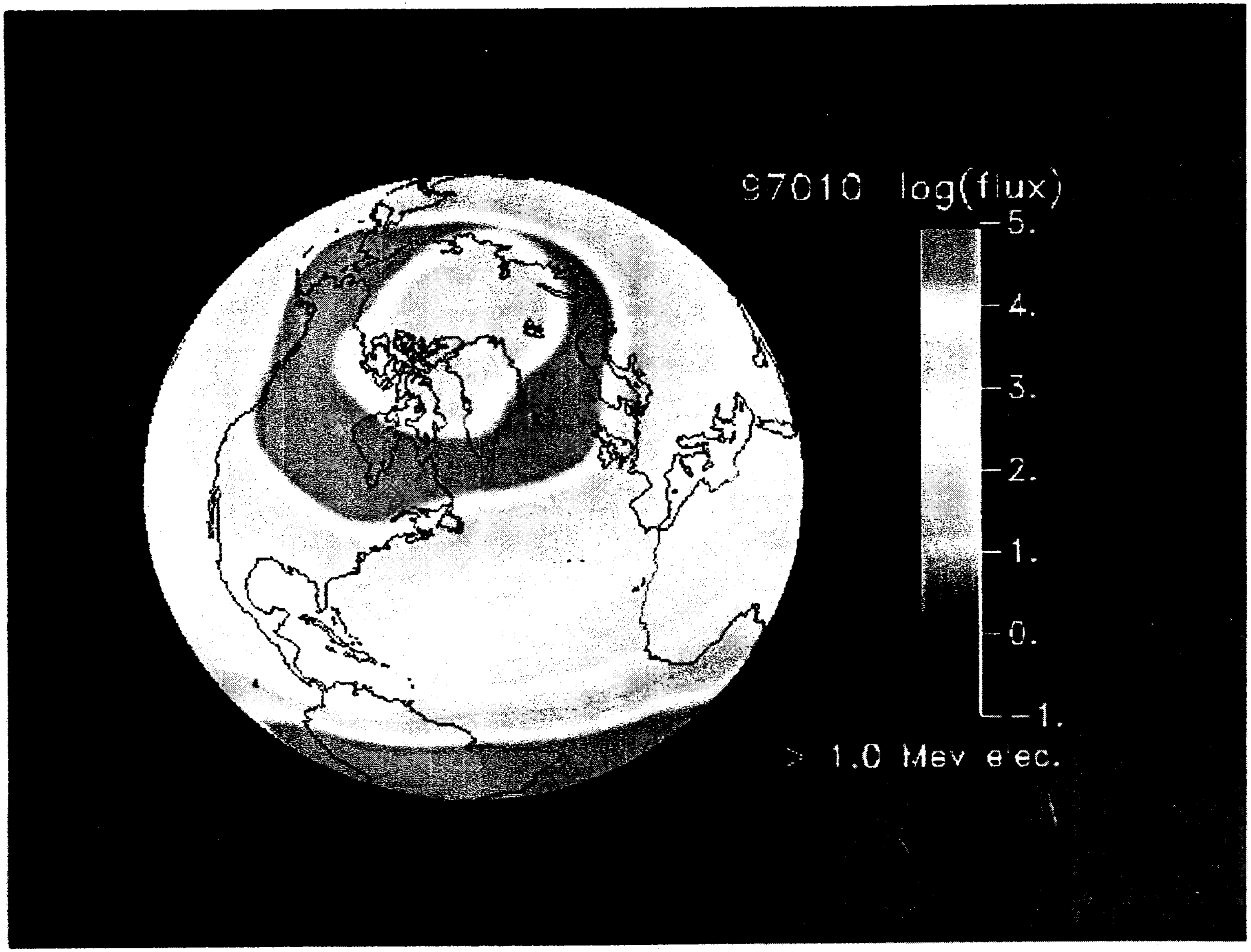
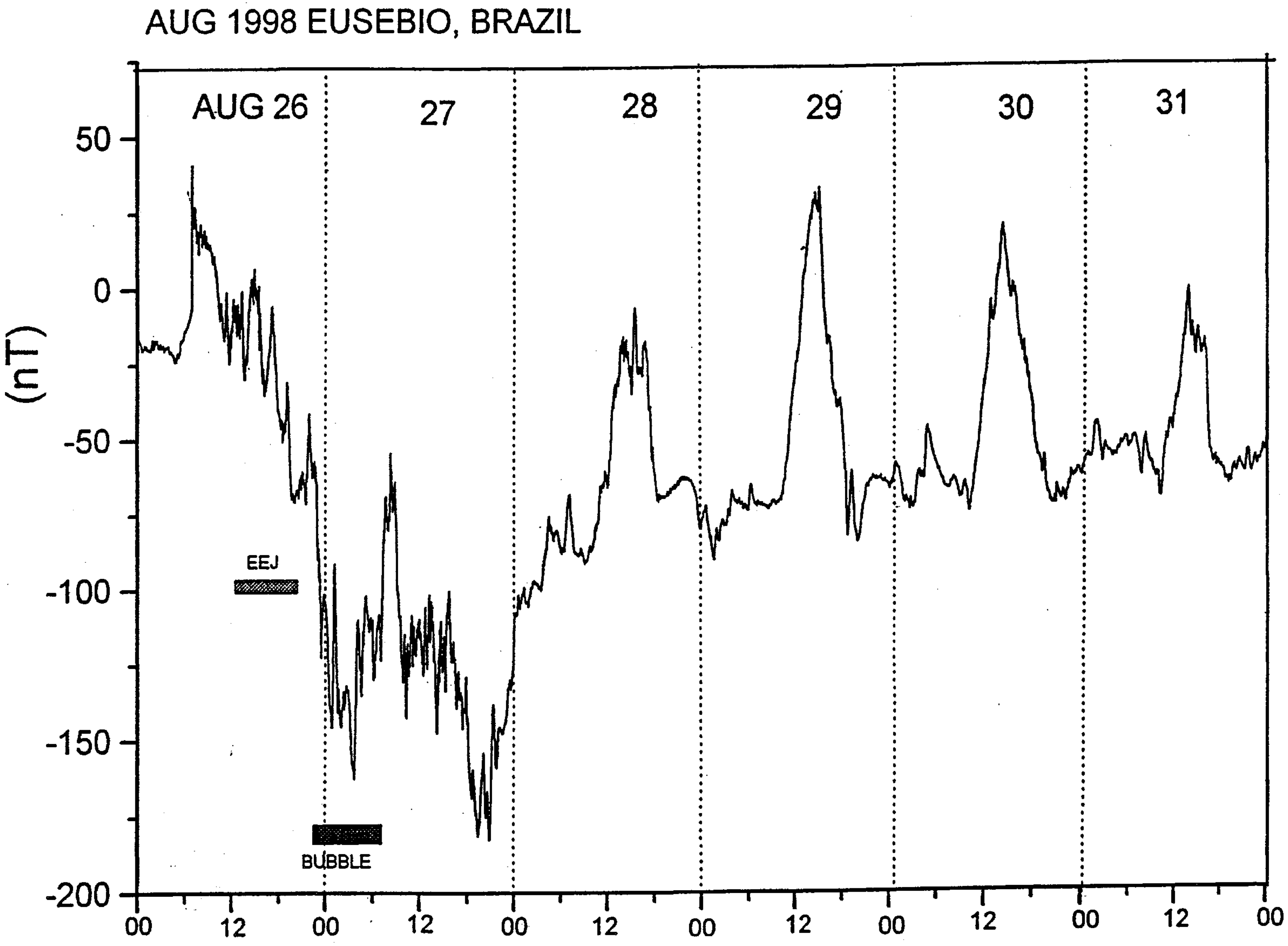


Fig. 05


AUG 1998 EUSEBIO, BRAZIL
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31
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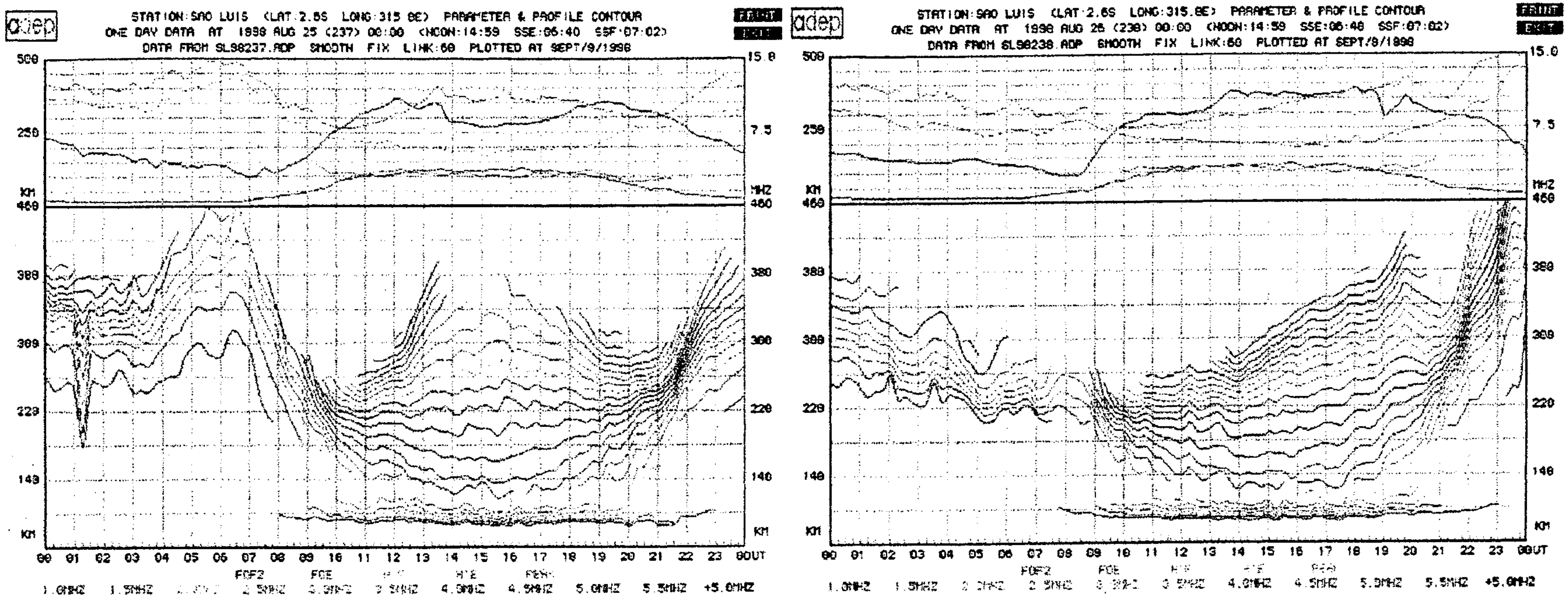
Fig. 06a


adep
STATION:SAO LUIS (LAT:2.5S LONG:315.8E) PARAMETER & PROFILE CONTOUR
ONE DAY DATA AT 1998 AUG 25 (237) 00:00 (NOON:14:59 SSE:06:40 SSF:07:02)
DATA FROM SL98237.ADP SMOOTH FIX LINK:60 PLOTTED AT SEPT/9/1998
500
250
KM
460
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140
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00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00UT
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1.0MHZ 1.5MHZ 2.5MHZ 3.0MHZ 3.5MHZ 4.0MHZ 4.5MHZ 5.0MHZ 5.5MHZ +5.0MHZ
adep
STATION:SAO LUIS (LAT:2.6S LONG:315.8E) PARAMETER & PROFILE CONTOUR
ONE DAY DATA AT 1998 AUG 26 (238) 00:00 (NOON:14:59 SSE:06:48 SSF:07:02)
DATA FROM SL98238.ADP SMOOTH FIX LINK:60 PLOTTED AT SEPT/8/1998
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MHZ
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KM
00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00UT
FOF2
FOE
1.0MHZ 1.5MHZ 2.0MHZ 2.5MHZ 3.0MHZ 3.5MHZ 4.0MHZ 4.5MHZ 5.0MHZ 5.5MHZ +5.0MHZ

Fig. 06b

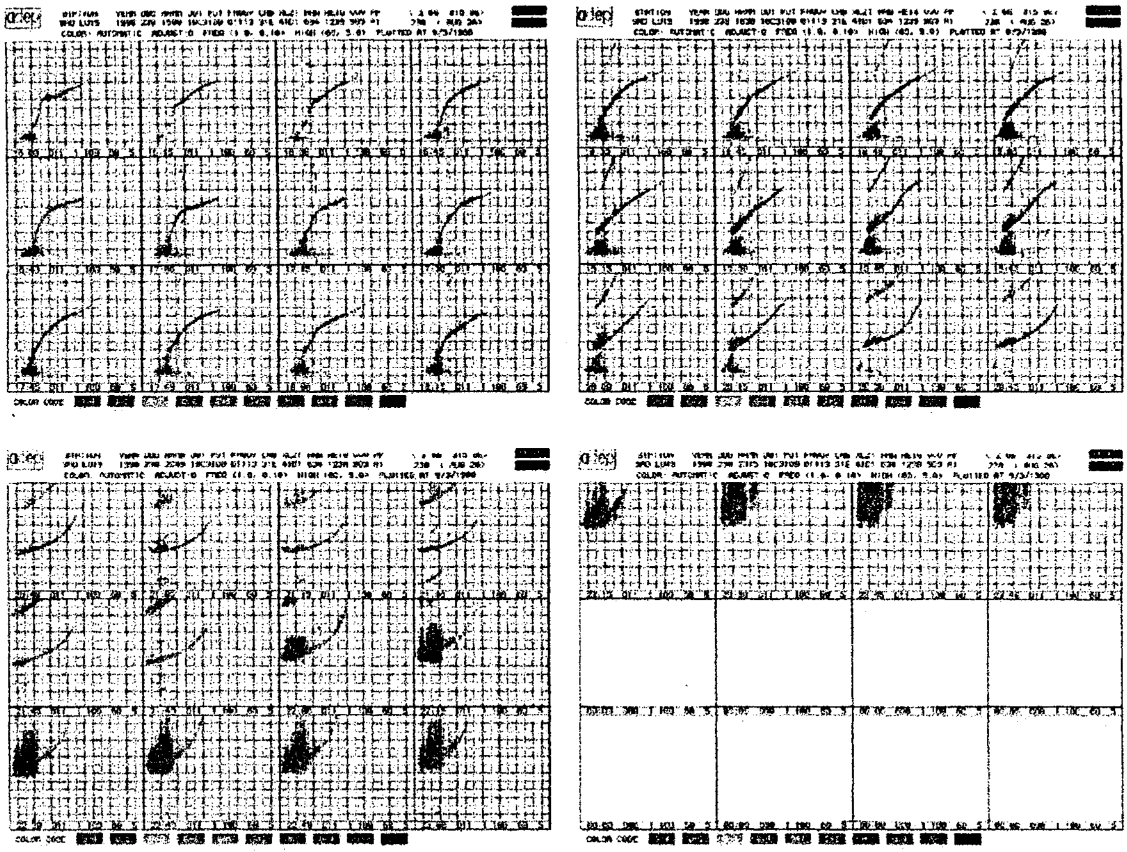
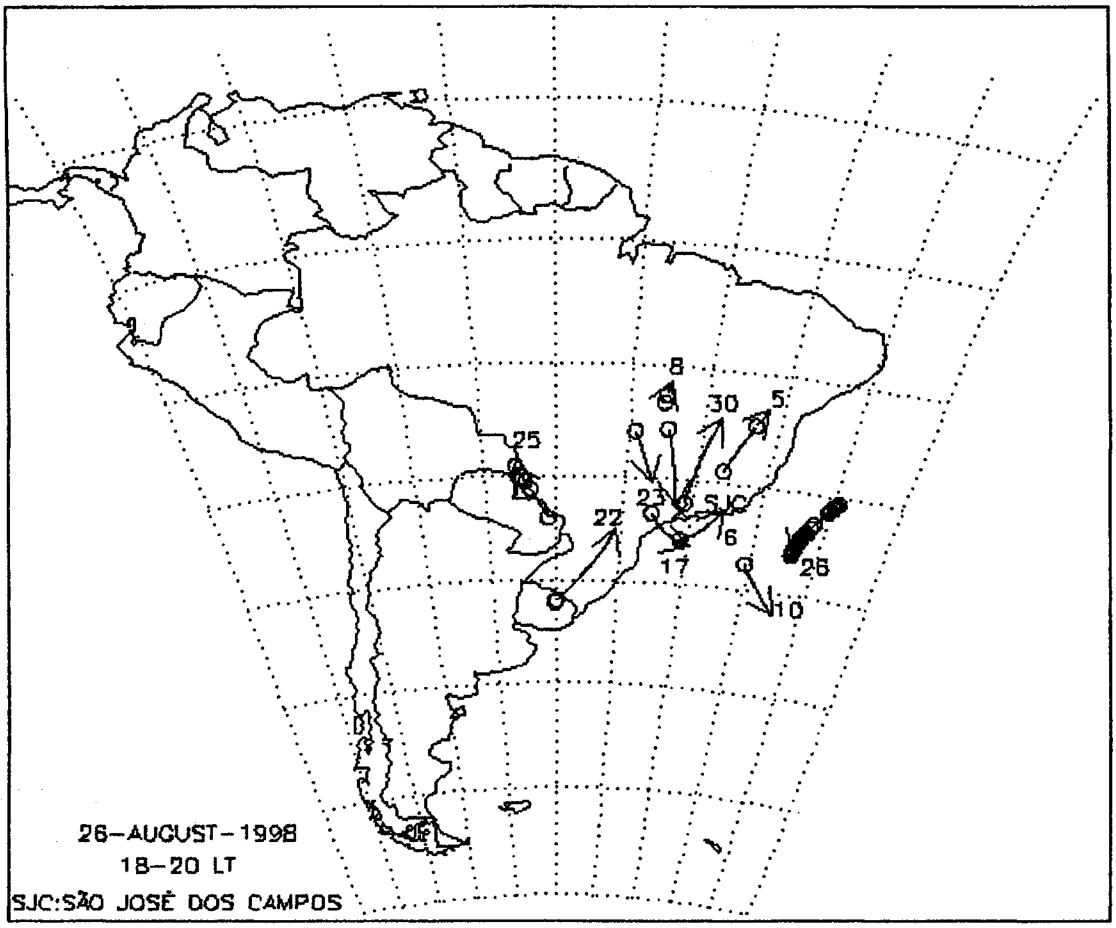


Fig. 06c


8
30
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25
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SJC
22
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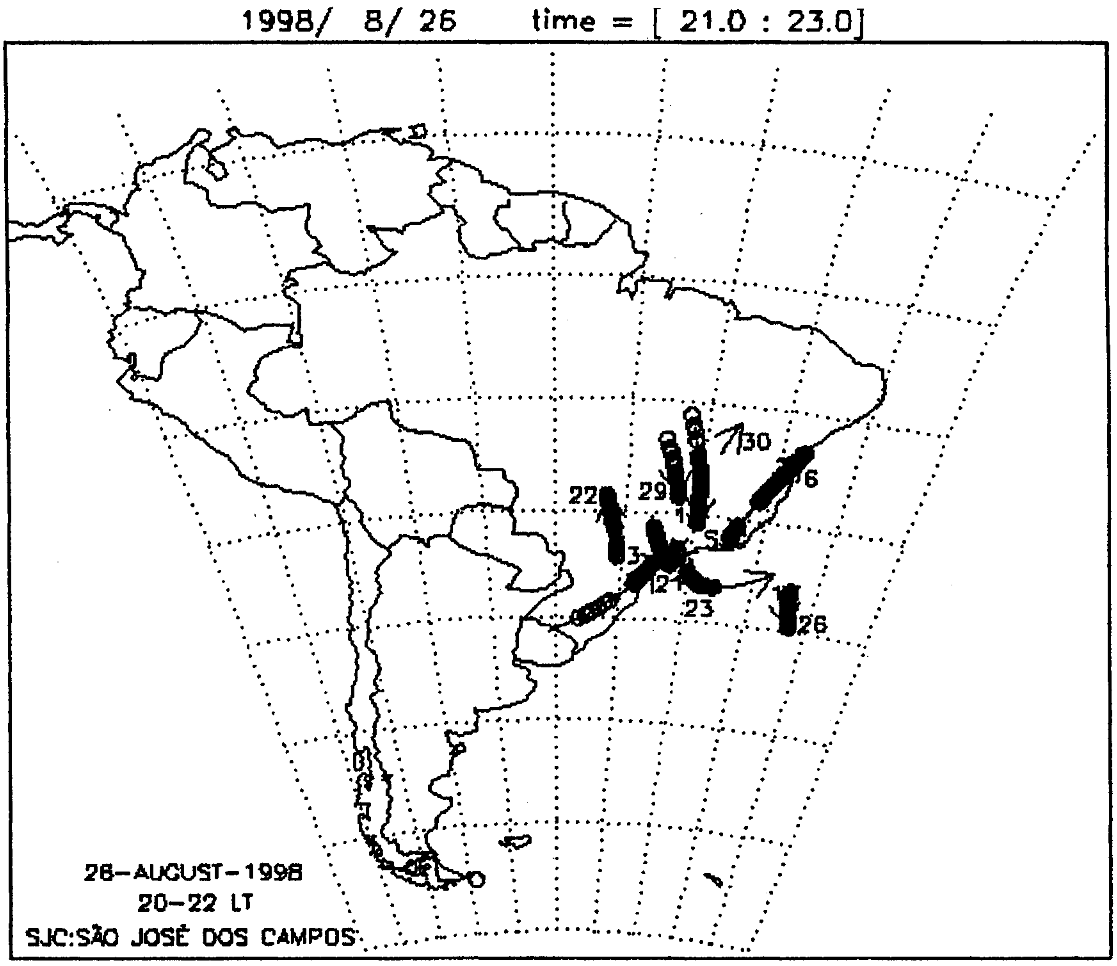
26-AUGUST-1998
18-20 LT
SJC:SÃO JOSÉ DOS CAMPOS

Fig. 06d


1998/ 8/ 26 time = [21.0 : 23.0]
30
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28-AUGUST-1998
20-22 LT
SJC:SÃO JOSÉ DOS CAMPOS

Fig. 06e

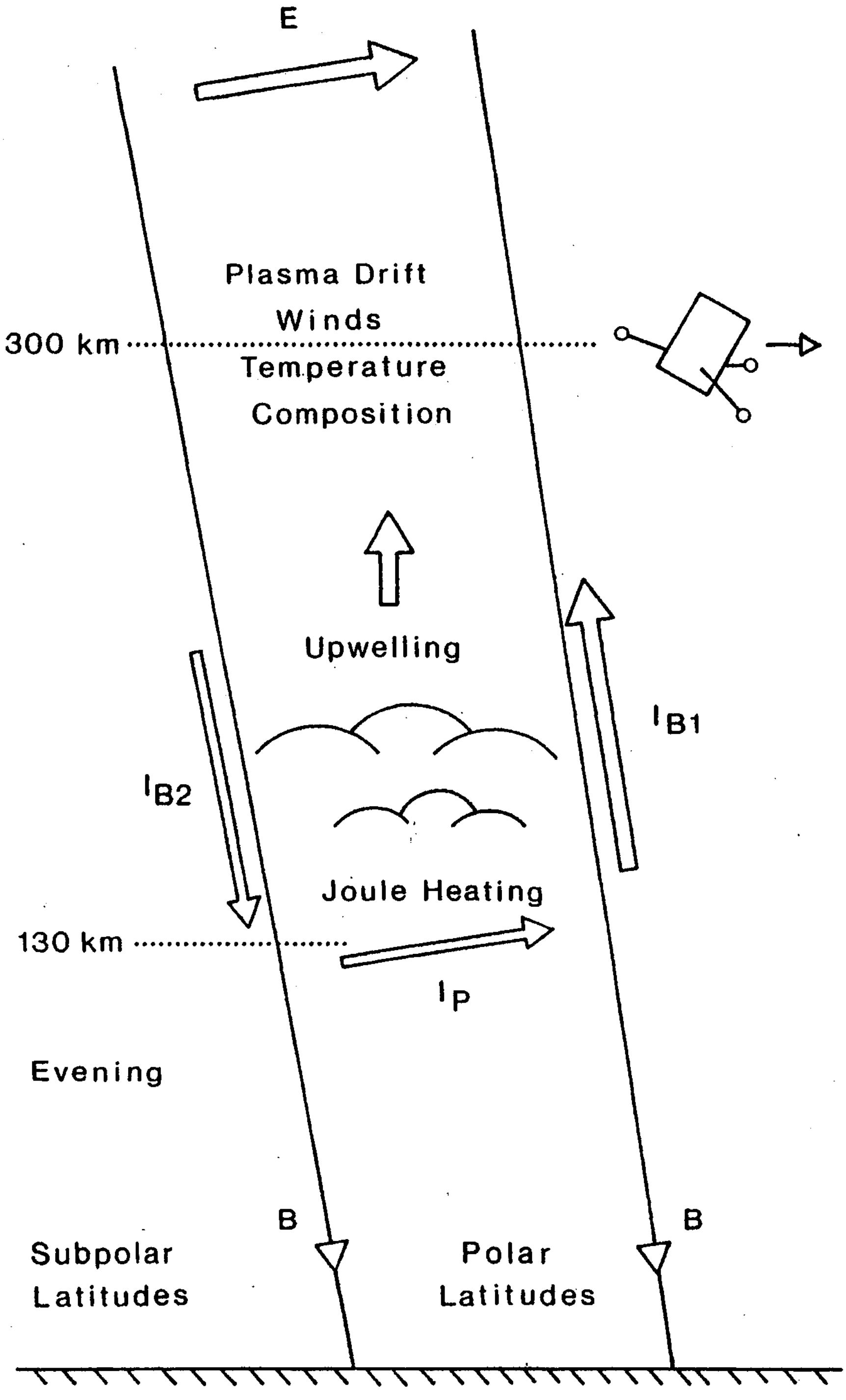
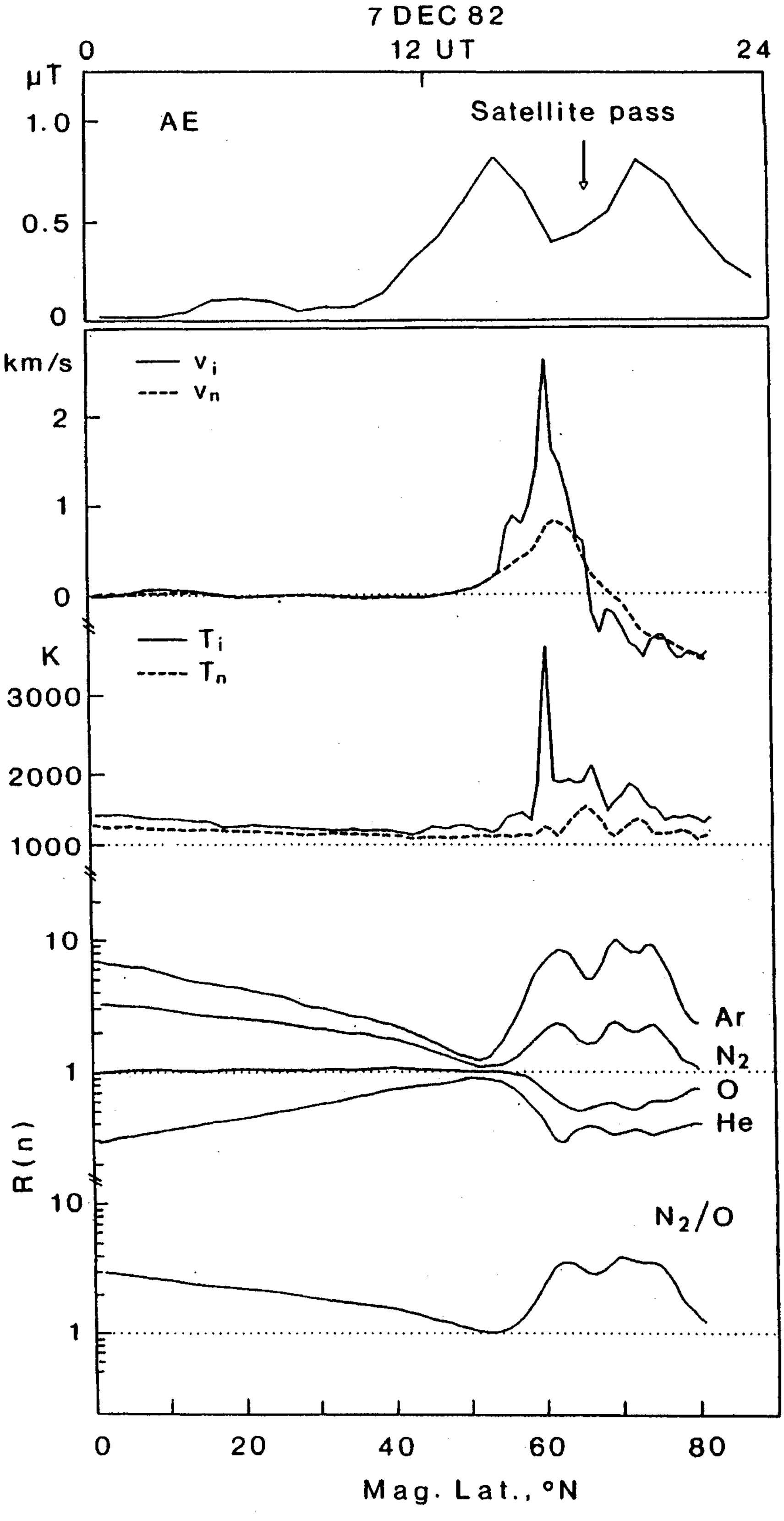

E
Plasma Drift
Winds
300 km
Temperature
Composition
Upwelling
I_B1
I_B2
Joule Heating
130 km
I_P
Evening
B
B
Subpolar Latitudes
Polar Latitudes

Fig. 07a


7 DEC 82
0
12 UT
24
μT
1.0
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AE
Satellite pass
km/s
2
1
0
v_i
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3000
2000
1000
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10
1
R(n)
Ar
N_2
O
He
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1
N_2/O
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20
40
60
80
Mag. Lat., °N

Fig. 07b

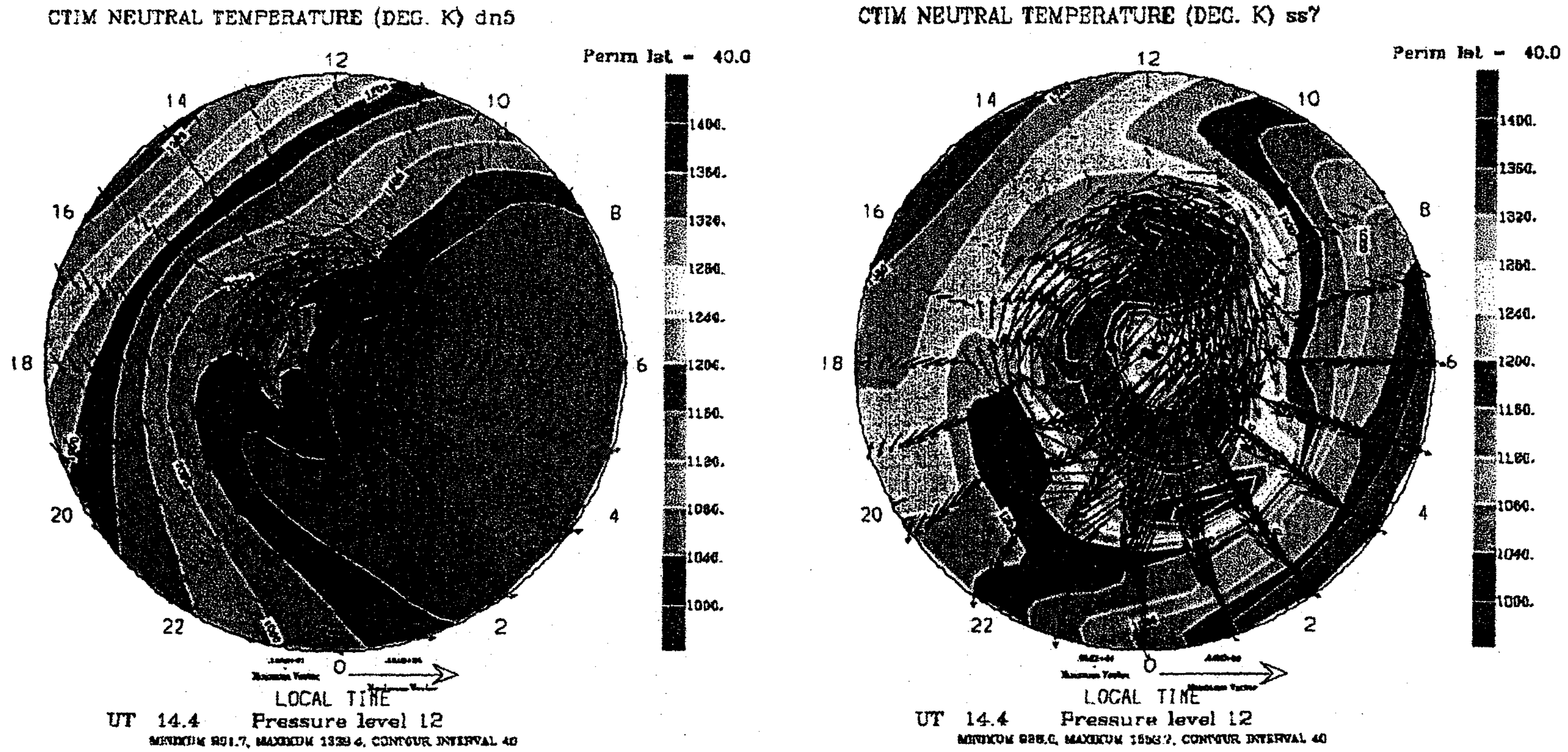
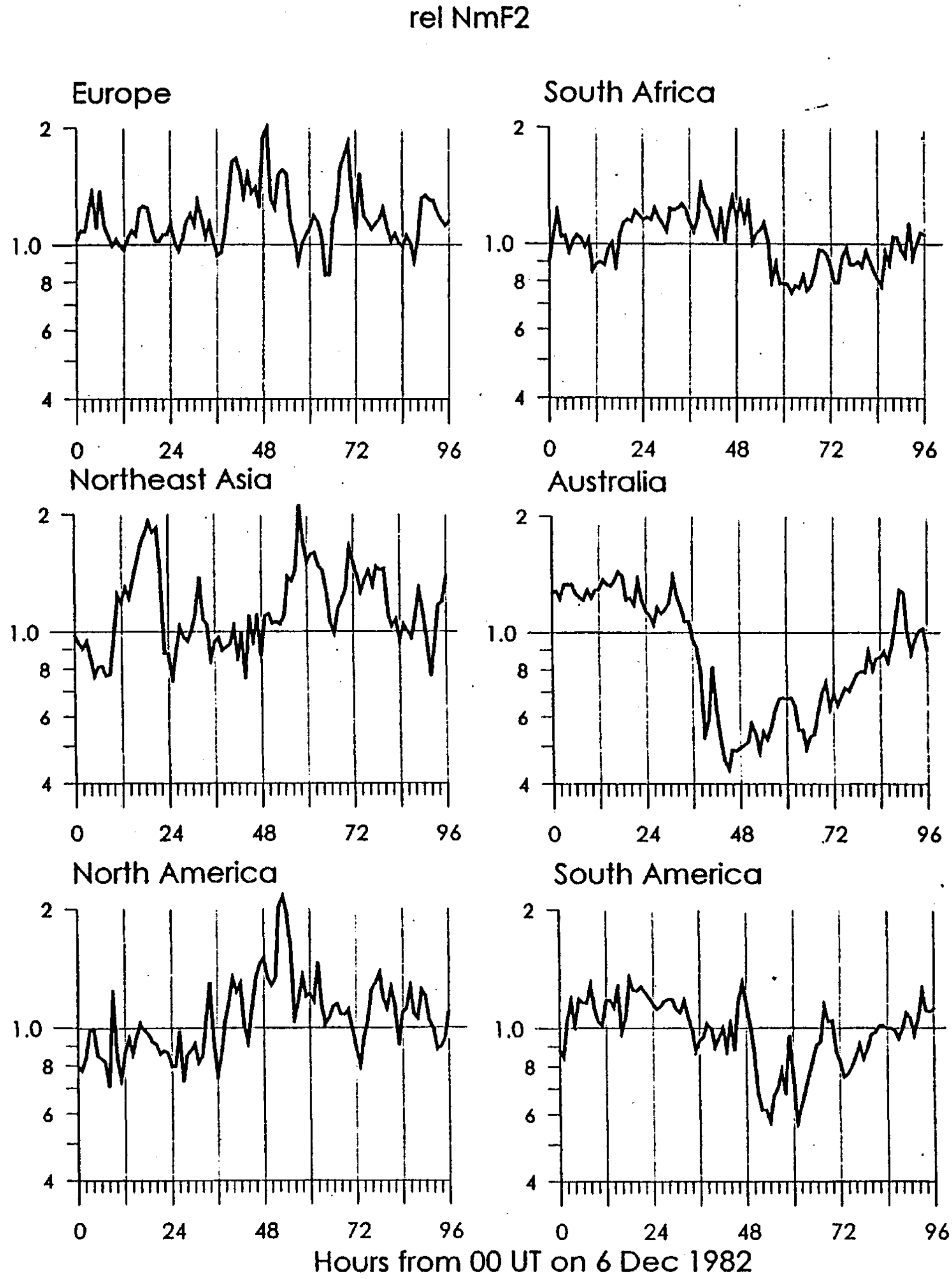


Plate 1. Example of the response of neutral temperature and winds in the upper thermosphere from a numerical simulation of a storm in December 1982. On the left is the quiet day, and on the right is the same UT a few hours into the storm interval.

Fig. 07c



The response of the ratio of storm time NmF2 to the monthly median for six midlatitude longitude sectors for a storm in December 1982.

Fig. 07e

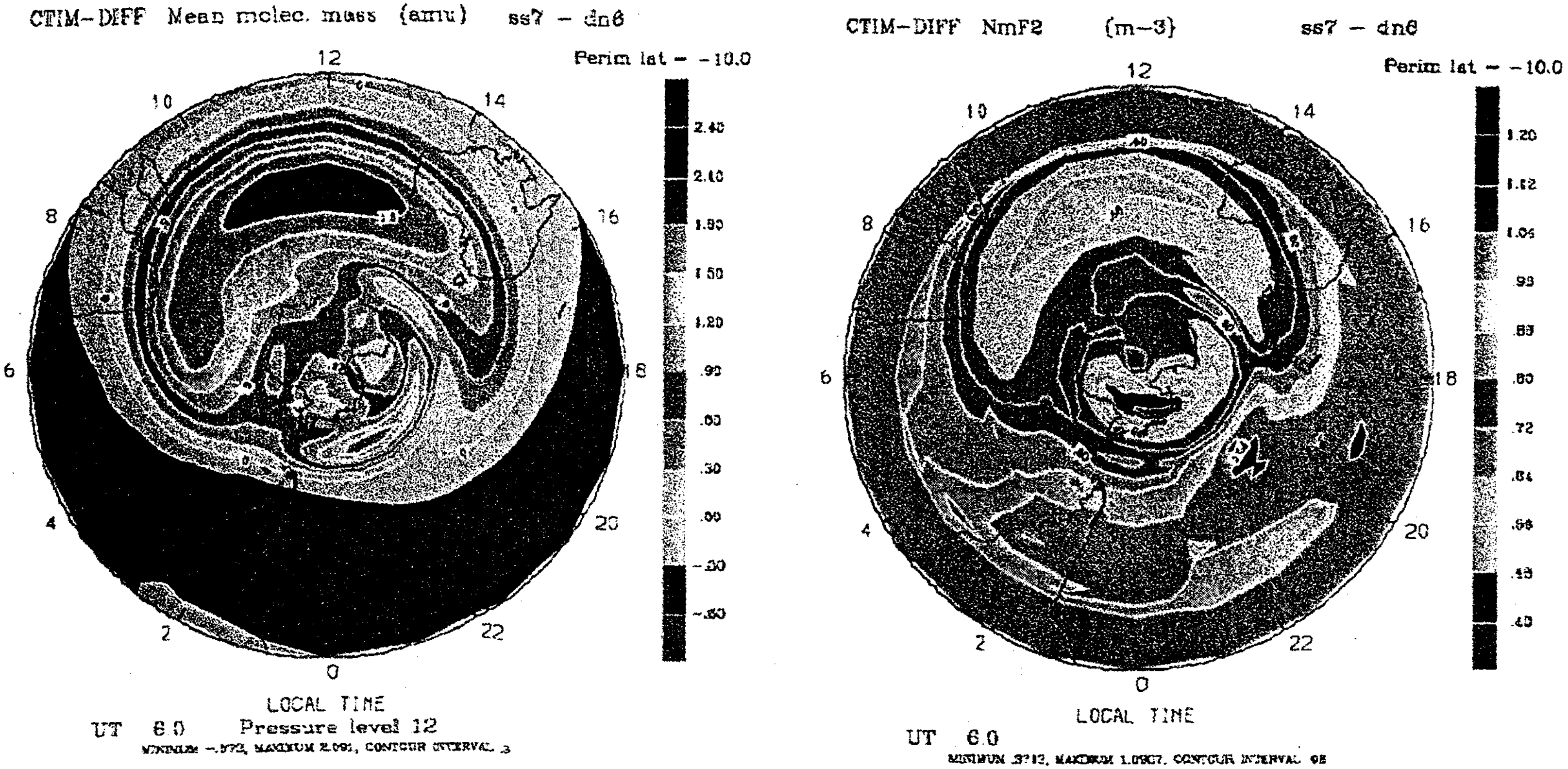
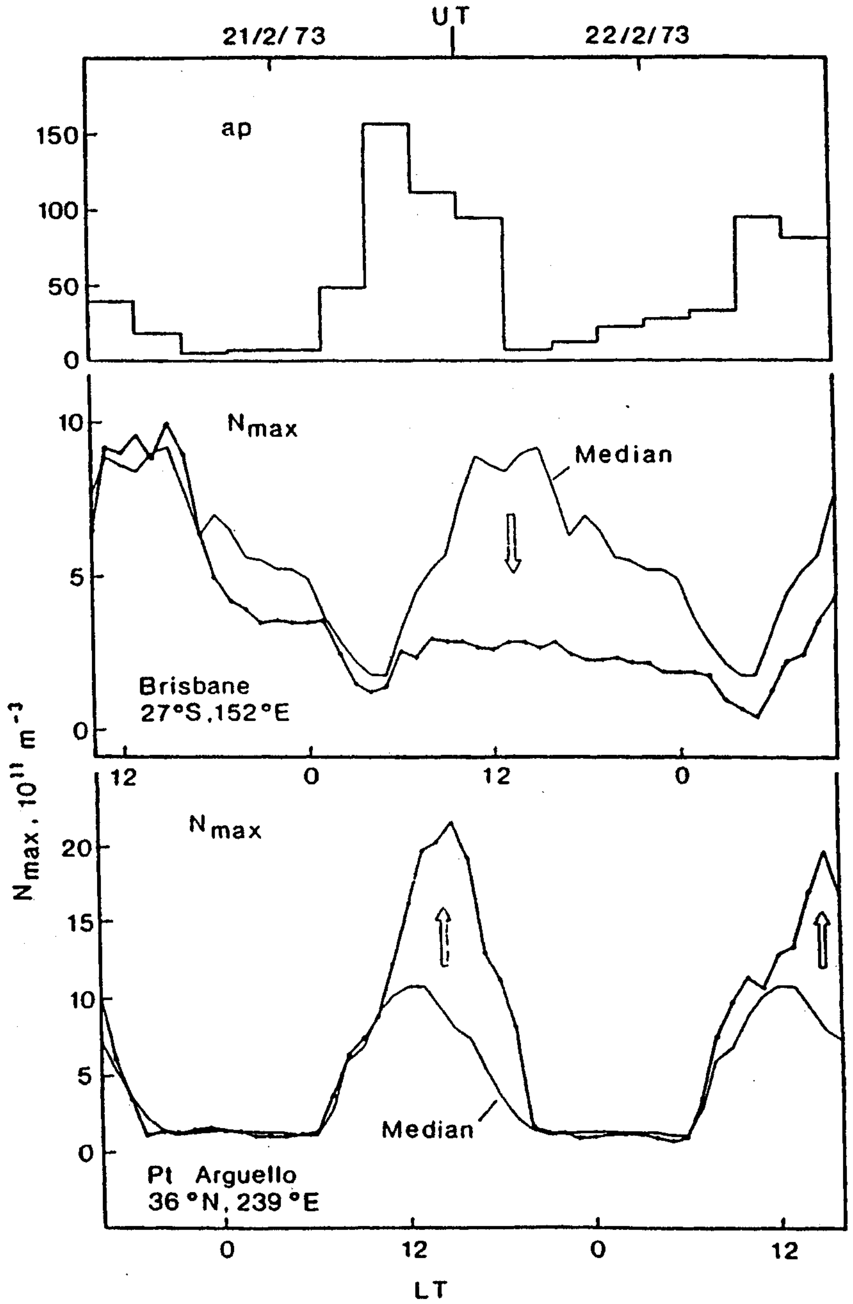


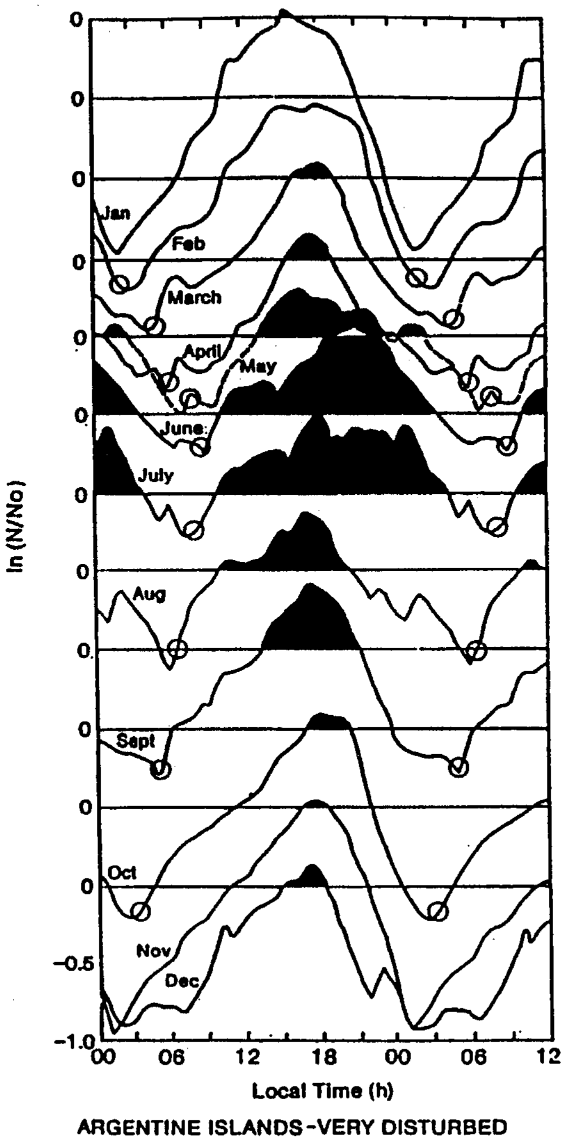
Plate 6. Illustration of the high correlation between the regions of enhanced molecular species in the neutral gas (on the left hand side) and the decrease in the ratio of the storm to quiet NmF2 (on the right hand side).

Fig. 07d



The ionospheric response to a storm in February 1973 at two midlatitude stations, taken from Prölss [*1980*]. The southern hemisphere station of Brisbane recorded a strong "negative storm"; the station at Pt. Arguello, in the North, recorded a "positive storm."

Fig. 07f



The average seasonal and local time variations in ln(N/No), where N/No is the observed storm/quiet ratio of peak F2 layer electron density, at Argentine Islands (65° S) for 1971-1981, taken from Rodger et al. [*1989*]. The zero level (N/No)=1 is shown for each month, and the shading denotes times of increased electron density where (N/No)>1.

Fig. 07g

GPS - SÃO JOSÉ DOS CAMPOS - BRAZIL JANUARY 27 1998