EFFECTS ON THE IONOSPHERE DUE TO PHENOMENA OCCURRING BELOW IT

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Abstract. The terrestrial thermosphere and ionosphere form the most variable part of the Earth's atmosphere. Because our society depends on technological systems that can be affected by thermospheric and ionospheric phenomena, understanding, monitoring and ultimately forecasting the changes of the thermosphere–ionosphere system are of crucial importance to communications, navigation and the exploration of near-Earth space. The reason for the extreme variability of the thermosphere–ionosphere system is its rapid response to external forcing from various sources, i.e., the solar ionizing flux, energetic charged particles and electric fields imposed via the interaction between the solar wind, magnetosphere and ionosphere, as well as coupling from below ("meteorological influences") by the upward propagating, broad spectrum, internal atmospheric waves (planetary waves, tides, gravity waves) generated in the stratosphere and troposphere. Thunderstorms, typhoons, hurricanes, tornadoes and even seismological events may also have observable consequences in the ionosphere. The release of trace gases due to human activity have the potential to cause changes in the lower and the upper atmosphere. A brief overview is presented concerning the discoveries and experimental results that have confirmed that the ionosphere is subject to meteorological control (especially for geomagnetic quiet conditions and for middle latitudes). D-region aeronomy, the winter anomaly of radiowave absorption, wave-like travelling ionospheric disturbances, the non-zonality and regional peculiarities of lower thermospheric winds, sporadic-E occurrence and structure, spread-F events, the variability of ionospheric electron density profiles and Total Electron Content, the variability of foF2, etc., should all be considered in connection with tropospheric and stratospheric processes. "Ionospheric weather", as a part of space weather, (i.e., hour-to-hour and day-to-day variability of the ionospheric parameters) awaits explanation and prediction within the framework of the climatological, seasonal, and solar-cycle variations.

Keywords: coupling, internal gravity waves, ionosphere, meteorological influences, middle atmosphere, planetary waves, seismological effects, thermosphere, tides

1. Introduction

The study of the Earth's upper atmosphere is of interest to scientists from many disciplines, and our present-day knowledge and understanding of the upper at-

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mosphere to its highest levels are the result of the combined contributions of meteorologists, physicists, chemists, astronomers, geomagneticians, radio engineers and space scientists. The range of scientific disciplines involved has, not surprisingly, been matched by an equally extensive variety of experimental approaches, ranging from standard meteorological instrumentation to modern optical, radio and space-vehicle techniques yielding data from distances out to, and far beyond, the limits of the atmosphere. These experimental studies have, over the years, been supplemented by much theoretical work to give the picture which we now have of the physical state of the Earth's upper atmosphere. The terrestrial ionosphere is a part of the upper atmosphere; it is a magnetized cold plasma environment enveloping the Earth whose study is often described as ionospheric aeronomy (Whitten and Poppoff, 1971).

The Chambers Dictionary of Science and Technology defines the term "aeronomy" as "the branch of science dealing with the atmosphere of the Earth and other planets with reference to their chemical composition, physical properties, relative motion and reaction to radiation from outer space". But the International Meteorological Glossary (1991) defines it more precisely: "A term sometimes used to denote that branch of Earth's atmospheric physics which is concerned with those regions, upwards of about 50 km, where dissociation and ionization are fundamental processes".

The principal physical, chemical and electrical properties of the Earth's upper atmosphere are very largely the result of its interaction with solar electromagnetic and charged particle radiations. The ultraviolet and X-ray radiations are absorbed at different levels. The selective absorption of the ultraviolet and X-ray radiation by particular atmospheric constituents gives rise to the unique electrical properties of the upper atmosphere by providing a series of ionized strata (layers) collectively known as the ionosphere. Further ultraviolet radiation is very effectively absorbed lower down in the atmosphere by stratospheric ozone.

Owing to the pervasive influence of gravity, the atmosphere and ionosphere are, to first order, horizontally stratified and conventionally are divided into layers based on the vertical distribution of different parameters. Atmospheric structure can be neatly organised in the form of a representative temperature profile, while the ionosphere is more sensibly organised by plasma density. A schematic representation of the atmospheric regions is shown in Figure 1 (Whitten and Poppoff, 1971).

In the following, we use the terms "upper atmosphere" and "middle atmosphere", which are absent from Figure 1. In the past meteorologists often designated the entire region above the tropopause as the "upper atmosphere", but more recently the term "middle atmosphere" has become popular when referring to the region from the tropopause to the turbopause and even into the lower thermosphere.

In addition to electromagnetic (wave) radiation, the Sun continuously emits streams of energetic electrically charged particles – mainly protons and electrons. This is the so-called "solar wind", an outward flow of charged particles moving at velocities of a few hundred kilometres per second. They interact with the geomag-

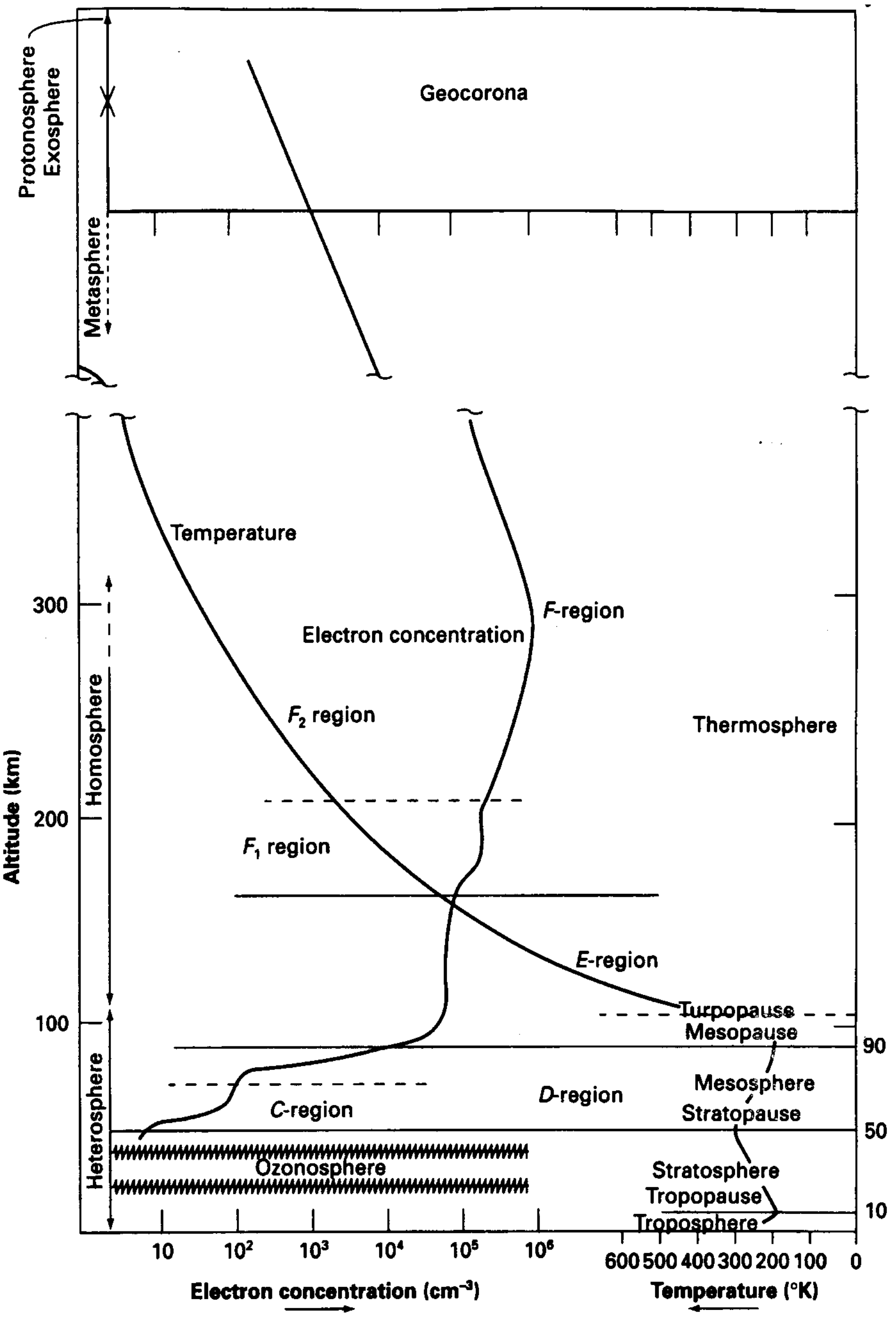

Figure 1. Schematic representation of atmospheric regions. Classification of atmospheric layers in accordance with temperature (right) and electron concentration (left) (Whitten and Popoff, 1971).

netic field in a complicated way, and with the gases of the upper atmosphere. As a result we observe geomagnetic storms, disturbances to long-distance radio-wave communications via the ionosphere, and visible auroral displays at high latitudes. All these events are closely associated with the occurrence of sunspots and show characteristic time variations over 11 years and over 27 days, relating to the sunspot cycle and the period of rotation of the Sun, respectively. We may say that the atmosphere absorbs and redistributes globally the variable components of the solar energy falling on it. The upper atmosphere/ionosphere acts as the intermediary between the plasma-dominated magnetosphere and the bulk of the neutral atmosphere below. This region is highly complex.

Interacting dynamical, chemical, radiative and electrical variations occur there that couple the magnetosphere and the middle atmosphere. To understand how these coupled elements interact to produce the great variability characteristic of the system is one of the major problems in solar-terrestrial relations. For example, the three-dimensional circulation of the thermosphere changes during and following geomagnetic storms; yet the consequences of the change of circulation on the temperature, density, composition and electric currents of the region are poorly understood. Energetic solar particles penetrate the middle atmosphere and produce chemical changes in radiatively important species such as ozone, but their global consequences are not fully appreciated. Deeper in the atmosphere, solar induced variations in the flux of cosmic rays may produce variations in the electrical structure of the lower atmosphere, but the effects of these variations on the Earth's global electrical circuit (including the ionosphere) are not fully understood.

The Earth's ionosphere is a partially ionized gas that envelops the Earth and, in some sense, forms the interface between the atmosphere and space. Since the gas is ionized it cannot be fully described by the equations of neutral fluid dynamics. On the other hand, the number density of the neutral gas exceeds that of the ionospheric plasma and certainly neutral particles cannot be ignored. Therefore the knowledge of only two "pure" branches of physics – classical fluid dynamics and plasma physics – is not sufficient. In addition, atmospheric dynamics, space physics, ion chemistry and photochemistry are necessary in order to understand how the ionosphere is formed and buffeted by sources from above and below, and to deal with electon/ion production and loss processes.

Until recently, the ionosphere was studied as a purely magneto-active plasma without consideration of the general properties of the atmosphere. It was known that the neutral atmosphere (thermosphere) and ionosphere are linked by both electrodynamic and momentum transfer. Nevertheless almost nobody believed that the terms "meteorology" and "climatology" could be applied to the ionosphere. It was thought that no connection existed between events occurring in the troposphere/stratosphere system on the one hand and in the ionosphere on the other. However, it has since become apparent that the composition, chemistry, energetics, dynamics and resulting structure of the lower and upper atmosphere, which are functions of location and time, are so intricately interrelated that it is not really possible to discuss either of them in isolation. Gradually, the viewpoint that the lower and upper atmosphere are substantially uncoupled was rejected (Kazimirovsky et al., 1982). A lot of discoveries and experimental results have confirmed the existence of detailed correlations between the parameters of the lower and upper atmosphere (Bauer, 1958a, b, and numerous references in Kazimirovsky and Kokourov, 1991; Kazimirovsky, 2000).

But what is the reason for the correlations? As one possible physical mechanism the influence of internal atmospheric waves may be considered. The upward propagation of internal atmospheric waves (planetary waves, tides and gravity waves) from the troposphere and stratosphere is an essential source of energy and momentum for the thermosphere and ionosphere. Of course, the study of internal waves is the province of meteorology, a discipline that has enjoyed a long and independent development of its own and has its own complicated problems, sufficiently different from ionospheric physics that the two are regarded as separate but neighbouring disciplines. However, the internal waves launched by weather fronts or any other sources in the troposphere and stratosphere sometimes appear to be capable of penetrating into the ionosphere, where they dissipate their energy. The leakage of wave energy from the troposphere and stratosphere up to at least 100–115 km was introduced as “coupling from below” (Bowhill, 1969) and is considered as a mechanism for the meteorological influence on the ionosphere. This influence has found acceptance and is presented by various models.

The meteorology of the thermosphere differs considerably from that associated with the familiar weather patterns which we experience on the Earth’s surface, although the fluid motions are governed by the same equations as those used by meteorologists studying weather systems. In the thermosphere, temperature increases with altitude, making for a dynamical system that is less dominated by instabilities than is the troposphere, where the temperature gradient is in the opposite direction. Also, the viscous and ion drag forces are very important in the thermosphere, with the former tending to transfer momentum between various altitudes and the latter acting to couple the neutral thermosphere strongly to the ionosphere and, thereby, to the magnetosphere. It is now established beyond doubt that the atmosphere from the ground to the thermosphere behaves as a complex system, coupling fairly closely over wide height ranges.

For aeronomical models, the major questions now posed relate to the interactions or coupling between regions, interactions that are currently only crudely parameterised within the separate models. This is particularly true for the upper atmosphere, where a rich set of physical processes has been identified that couple the various regions together, as well as to the stratosphere and troposphere below and to the magnetosphere above. Therefore, the principal scientific challenge before us today is to understand the coupled system as a whole, including the effects of energy, momentum and compositional interchange between regions.

The analysis of “traditional” meteorological and ionospheric data is not only of interest for the exploration of purely theoretical aspects of the stochastic atmosphere system, but also of relevance for modern climatological research. For instance, it is still an unanswered question as to how much the general state of the middle, and thus the lower, atmosphere and its circulation systems are influenced by changes with various timescales at the atmospheric upper boundary – the thermosphere/ionosphere. Such changes may be felt even in the troposphere. Since the upper atmosphere is generally a good indicator of solar activity, one might assume that correlation between tropospheric and ionospheric parameters possibly indicates such a solar-atmospheric or solar-weather effect. Although it is easier to picture upward dynamic coupling, because of the much greater energy density that resides in the lower atmosphere relative to that of the upper atmosphere, it is possible that changes in the upper atmosphere can give rise to significant changes in the lower atmosphere. The subject of solar activity effects on tropospheric weather is still a controversial one. Less controversial, however, is the possibility of solar activity effects on climate. But the very interesting problem, the role of the Sun in climate change, requires special consideration elsewhere.

Our main concept is that the science of the whole atmosphere-ionosphere system is greater than the sum of its component parts. The scientific focus is placed on the interactive processes between the various physical regimes. This concept is the basis of International Solar-Terrestrial Energy Program (STEP) and post-STEP activity, involving a comprehensive study of the mutual linkages between the various regions of space in addition to the traditional study of the individual regions themselves.

Many ionospheric phenomena cannot be explained in terms of ionizing radiation variations, photochemical processes, solar particle injections or solar flare effects only. It seems likely that there are some events due to the effect of atmospheric oscillations, such as the winter anomaly of radiowave absorption, sporadic-E layer occurrence and structure, the thermospheric wind regime, the variations of atmospheric emissions, travelling ionospheric disturbances, day-to-day midlatitude ionospheric variability, spread-F events, etc.. As well, the atmosphere and ionosphere are linked dynamically, radiatively and chemically. This is the reason why in the following paragraphs we discuss atmospheric dynamics and the ionosphere from the meteorological perspective. Aeronomy is now the study of upper atmosphere physical and chemical processes, including ionospheric processes. Electrical engineers are interested in the propagation of radio waves, physicists in plasma processes, chemists in the dissociation and diffusion of atmospheric molecules and atoms, meteorologists in dynamics, and so on. As the body of knowledge grows, it becomes apparent that all aspects are important and that, in fact, all processes are interdependent. In upper atmosphere research, as in no other field, the disciplines of electrical engineering, meteorology, chemistry and physics are intertwined (Whitten and Popoff, 1971; Danilov et al., 1987; Hargreaves, 1992; Johnson and Killeen, 1995; Wickwar and Carlsson, 1999; Solomon, 2000; Forbes, 2000).

The purpose of this paper is to review the observational background to the suggestion of a genuine link between processes in the lower atmosphere and the ionospheric response. Attention is concentrated on the waves which are thought to couple the lower atmosphere with the thermosphere/ionosphere system. Detailed explanations of the observations and theories are not provided. Of course, the survey presented here will be affected by the personal biases of the authors and the limitations of space. Since the discussion is intended to be rather "tutorial" in nature, only a few key references to the literature will be given, and the interested reader can consult these for more detailed discussion and for links to the more extensive literature.

2. Internal Atmospheric Waves

One exciting aspect of modern ionospheric research is the significant role of the lower atmosphere in upper-atmospheric variability. This forcing could come from internal atmospheric waves (planetary waves, tides, internal gravity waves). Planetary waves represent a well-documented group of atmospheric waves, a class of stationary and zonally travelling structures of global scale, which have periods of a few days (typically 2-30 days). Such waves appear, for example, in surface pressure data, in standard analyses of upper tropospheric radiosonde data, and in satellite stratospheric data. A significant part of the energy of planetary wave disturbances of the troposphere may propagate into the upper atmosphere, and the effective index of refraction for the planetary waves depends primarily on the distribution of the mean zonal wind with height.

The International Reference Atmospheric Model (CIRA-1990) includes the description of stationary planetary waves up to 85 km altitude with the following general features:

1. Wave amplitudes are small in the tropics throughout the year, slightly larger in the summer season at mid and high latitudes, and much larger during the winter season.
2. Maximum amplitudes occur at about 60–70° North or South latitude during local winter.
3. Amplitudes are generally largest in the stratosphere and lower mesosphere, but they remain relatively large up to the lower thermosphere.

There is one important peculiarity in the theory of planetary wave propagation that is associated with the existence of critical surfaces, or critical layers, where the basic zonal wind matches the zonal phase speed of the wave. Both dissipation and non-linearity become very important in this critical layer. It may be expected to be an enhanced dissipative region for planetary waves, or under some conditions to become a perfect reflector of this kind of wave.

The most spectacular manifestations of planetary wave activity in the middle atmosphere, associated with strong coupling between the stratosphere and lower atmosphere, occur during stratospheric sudden warming events. The zonal mean climatological temperature and zonal wind configuration are dramatically disrupted, with polar stratospheric temperatures increasing rapidly with time, leading on occasion to reversals of zonal-mean winds from westerlies to easterlies (Naujokat and Labitzke, 1993). Current theories suggest that a major sudden warming is initiated by the anomalous growth of a planetary-wave disturbance (mainly comprising wave-number 1 and 2 components) that propagates from the troposphere into the stratosphere and interacts strongly with the pre-existing circulation there. The stationary planetary waves that propagate energy upward also transport heat equatorward (Andrews et al., 1987).

Our understanding of all the observed details of these events, the necessary conditions for their occurrence, and the interannual variability between one stratospheric winter and another is still by no means complete. Much further work will need to be done before a full understanding of the phenomenon is attained. In general, the implications of the theory for the modelling of planetary waves and for the interpretation of atmospheric observations are not yet absolutely clear. New experimental information concerning the behaviour and effects of planetary waves, especially in the lower and upper thermosphere, is very important. Since the seasonal and year-to-year variability of planetary wave activities cannot be simply explained by the steady-state propagation theory, the variations of forcing in the lower atmosphere could be important.

Atmospheric tides are global-scale oscillations that are primarily forced by variations of heating due to absorption of solar radiation by atmospheric water vapour in the troposphere, ozone in the middle atmosphere and molecular oxygen (O_2) in the lower thermosphere. The solar and lunar gravitational forcing that produces ocean tides is much less important for the atmosphere.

The migrating tides (diurnal, semi-diurnal, etc.) can propagate to great depths in the atmosphere and can attain large amplitudes at some heights, especially in the thermosphere. The semi-diurnal tide plays a particularly important role in the lower thermosphere, where the global temperature and density variations are dominated by this oscillation. At higher altitudes the semi-diurnal tide is dissipated by viscosity and ion drag. In the upper thermosphere, at 300 km, the amplitude of the semi-diurnal tide decreases, and thermospheric density variations are dominated by the diurnal tide that has been forced by the thermospheric absorption of EUV solar radiation. In modern theoretical calculations the semi-diurnal tide in the thermosphere is considered to be a result of propagation from below (e.g., Forbes et al., 2000). The non-migrating tides (associated, for example, with orography and geographically-fixed tropospheric heat sources) give longitudinal differences in tidal structure.

In classical tidal theory (an inviscid atmosphere, background temperature independent of latitude) the governing equation is separable, giving rise to vertical and latitudinal structure equations. But in the real atmosphere, with winds and meridional gradients of temperature, the governing equation may only be solved numerically. At present, modellers try to include in their models seasonal, latitudinal and longitudinal variations, realistic temperature and wind structures, molecular and eddy diffusion, acceleration and heating of the mean flow by tides, the effect of tides on minor constituent concentration, and hydromagnetic coupling, all for a viscid, rotating, spherical atmosphere (e.g., Forbes, 1991).

Internal gravity waves (IGW) are disturbances which are allowed to propagate as a consequence of buoyancy forces present in the atmosphere. The temperature and wind structures determine the propagation characteristics of the waves. Many seasonally and latitudinally varying sources for middle atmosphere gravity waves have been identified. These include airflow over orography, severe weather fronts, cyclones, instabilities in the planetary boundary layer and in jet stream shears, turbulent motions at different scales, and thunderstorms (e.g., Vincent, 1990; Gavrilov, 1992).

At the height of the mesosphere and/or above 85–90 km, internal gravity waves may be “saturated” and may even break, with the concurrent deposition of energy and momentum. The “trapping” of IGW is also possible, and for this reason IGW could be ducted in the region near the mesopause. It is now believed that the level of gravity wave activity determines the mean state of the mesosphere. Moreover, in the lower thermosphere the waves manifest themselves in wind, temperature, density, pressure, ionization, vertical profiles of Na, measurements by lidars, and airglow fluctuations in the 80–120 km height range, and their amplitudes are so large that they can dominate at these altitudes (e.g., Krassovsky, 1977; Vincent, 1990; Gavrilov, 1992).

It is now recognised that internal gravity waves play an important role in determining the mean circulation and thermal structure of the middle and upper atmosphere. There are theoretical models (e.g., Gossard and Hooke, 1975) explaining the interaction between gravity waves and oscillations of ion velocity and temperature, and the influence of gravity waves on electron density and temperature, the generation of ionospheric irregularities, etc (e.g., Djuth et al., 1997).

3. The Lower Thermosphere/Ionosphere

The atmospheric layer located between (approximately) 60 and 100 km altitude can be defined as a transition region, where different fundamental physical mechanisms, dominant in the lower and upper height regions, coexist, showing complicated atmospheric characteristics. For instance, the D-region is the weakly ionized (mainly in daytime) ionosphere at 60–90 km, and serves as the interface between the neutral and ionized atmospheric layers. The D-region is the lowest-lying ionospheric region and hence is produced by the most penetrating ionizing radiation (galactic cosmic radiation, X-rays, the intense solar hydrogen Lyman-alpha emission line and extreme ultraviolet solar radiation). It is a region of weakly-ionized plasma and high neutral species number-density as well as complex ion-interchange and electron attachment and detachment reactions (the latter processes are the distinguishing feature of the D-region). Perturbations of this region greatly affect the absorption of high frequency radio waves and the reflection of low-frequency radio signals.

Various techniques are available for exploring the plasma density of the D-region. Much observational evidence has accumulated showing that its behaviour is far less simple and straightforward than the regular "Chapman-layer-like" behaviour controlled only by solar energy influx and the geometry of its penetration into the atmosphere. Its diurnal and (especially) seasonal variations sometimes demonstrate significant abnormalities, particularly in winter. At the same time ground-based, rocket and satellite soundings of temperatures and winds in the upper mesosphere-lower thermosphere (MLT-region) exhibit variation patterns with temporal and spatial scales which can be described by the term "meteorology". Thus, nowadays it is possible to introduce into practice the term "meteorological control" to explain some events in the D-region (Taubenheim, 1983; Danilov et al., 1987). This means that the lower ionosphere exhibits not only solar control but also strong non-solar control which is partly meteorological in nature.

The most suitable data for the study of meteorological effects upon the D-region are ground-based radio propagation observations, because they provide records continuous in time; data from individual rocket launches are also invaluable. The experimental basis for intensive investigations of the coupling has so far been ionospheric radiowave absorption and dynamical regime measurements (prevailing winds and wave-like fluctuations) in the MLT region. The radio signals reflected from or propagated through the ionosphere experience absorption, or attenuation, of electromagnetic wave energy due to the collision of ionospheric electrons with neutral atoms. Without considering the details of magneto-ionic theory it can be summarized that the absorption varies directly with the product of the plasma density and the collision frequency, and inversely with the transmitted radiowave frequency. The most commonly investigated D-region absorption data are produced by the A3 method, which is described in detail by Schwentek (1976). This technique involves measuring the attenuation of MF radiowaves radiated from a distant transmitter with constant power.

The best known manifestation of a meteorological influence upon the D-region is the winter anomaly, i.e., the excessive enhancement of both the average level and, especially, the day-to-day variability ("spikes") of radio-wave absorption in winter, noted by many investigators even in the early years of ionospheric science. An example of the winter anomaly in terms of the absorption at a constant solar zenith angle during 1967–1969 is shown in Figure 2 (Taubenheim, 1983).

There are two components: (1) "normal" winter anomaly with a rather slow increase and decrease, i.e., the average daytime absorption for a typical winter day is higher than for a typical summer day; (2) superimposed spikes, or "excessive" winter anomaly. In spite of the fact that enhancements of absorption may be con-

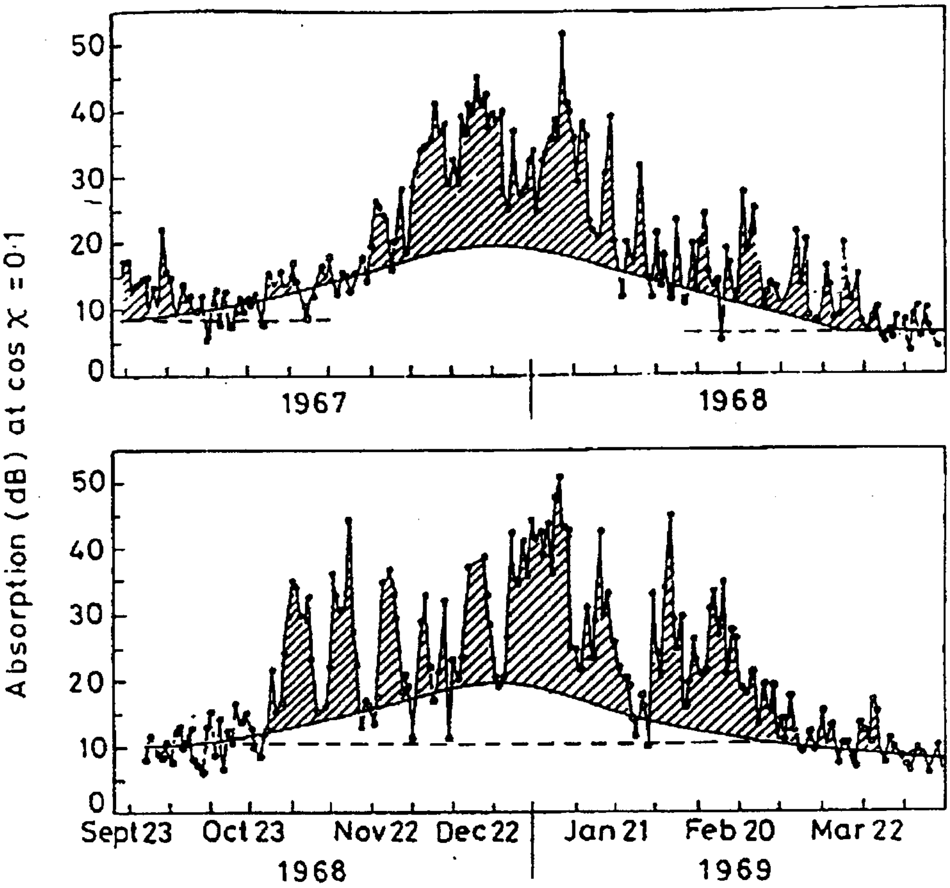

Figure 2. Winter anomaly of ionospheric radio wave absorption in terms of the absorption at a constant zenith angle χ during 1967–1968 for a northern hemisphere site. The dashed line extrapolates the trends from summer (Taubenheim, 1983).

nected with increased electron density and/or collision frequency in the ionospheric plasma, it is nowadays assumed that the winter anomaly is connected primarily with enhanced electron density at the mesopause level and above.

Why do we consider that the winter enhancement of electron density has an internal ("meteorological") nature? It is because:

- It occurs in both the northern and the southern hemispheres during their respective winter months.
- The correlation between the time variations of D-region ionization and solar Lyman-alpha fluxes (measured by the AE-E satellite), which is weak but detectable during the summer months, is completely missing during the winter.
- The amplitude of interdiurnal variations of absorption in the winter months cannot be explained by solar Lyman-alpha variations, although there is also a geomagnetic activity contribution to the interdiurnal variation.

- The temporal and spatial scales of anomalous absorption wave-like structures are compatible with planetary wave patterns (e.g., De la Morena and Kazimirovsky, 1996).

There are two different "scenarios" concerning D-region meteorological control (e.g., Taubenheim, 1983; Offerman et al., 1982):

1. In the first scenario,
   - The general enhancement of D-region electron densities is caused by enhanced downward eddy diffusion of NO (nitric oxide) accumulated in the polar night thermosphere.
   - In addition, at heights below 85 km, the electron production rate is reduced by the inhibition of cluster ion formation by warm mesopause temperatures.
   - Independently, "patchy" (with respect to time and longitude) downward transport of excess NO into the D-region is affected by diffusion and/or bulk motions connected with planetary wave patterns. Displacement of these patches by enhanced horizontal winds, possibly launched by transient perturbations from below, causes rapid changes of the NO distribution within 1–2 days.
2. In the second scenario,
   - Winter meteorology at D-region heights is predominantly controlled by the circumpolar vortex of zonal westerly winds, reaching from the stratosphere up into the lower thermosphere. This cyclonic vortex is always tied in with:
     a) Warm mesopause temperatures, inhibiting cluster ion formation.
     b) Downward vertical wind components (bulk motion).
     c) Low pressure near the mesopause, decreasing optical depth for solar UV radiation and hence increasing ionization rate.

All three of these conditions act in the same direction – to increase the D-region electron density.

In this second scenario the enhanced eddy diffusion in winter raises the average background level of D-region ionization, and every global or local perturbation of the zonal vortex flow (for instance, induced by planetary wave energy transfer from below) causes a prompt decrease, or even "breakdown", of the winter anomaly in the D-region.

Each of the two scenarios has its own advantages and disadvantages. However, it still seems necessary to improve the empirical base in order to better define coupling processes throughout the atmosphere during the winter anomaly.

Numerous case studies of the stratosphere-lower ionosphere coupling in middle latitudes have analyzed the stratospheric temperature variations and lower ionosphere plasma density (radiowave absorption). The correlation between the temperature increment in the stratosphere and ionospheric absorption during the winter sudden warmings was noticed in both hemispheres long ago. Figure 3 (from Shapley and Beynon, 1965) demonstrates the superimposed epoch analysis comparing temperatures at the 10 hPa level, here termed 10 mb temperatures, over Berlin and radiowave absorption over Lindau (Germany). The increase of absorption for

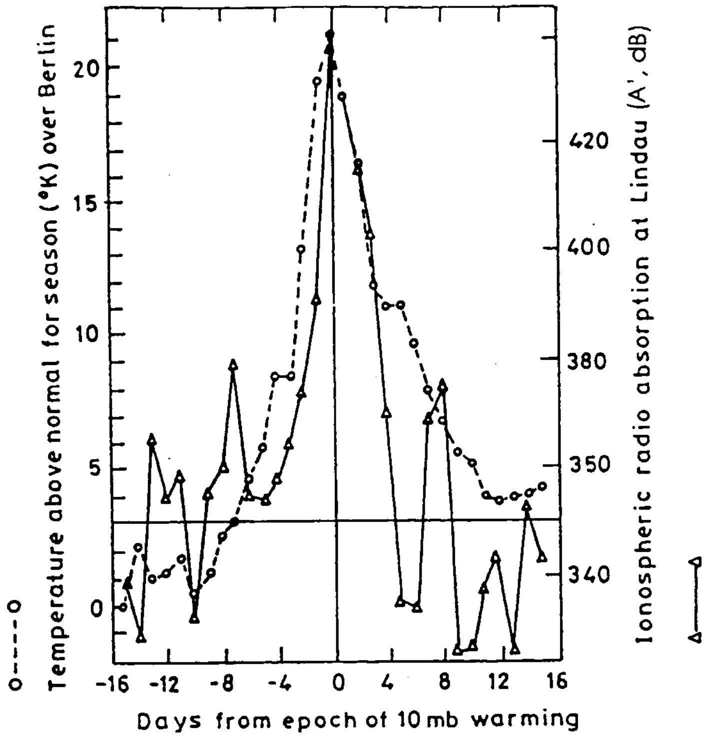

Figure 3. Superimposed epoch analysis comparing 10 mb temperature over Berlin and radiowave absorption over Lindau (Germany) (Shapley and Beynon, 1965).

the day of the 10 mb warming is evident. D-region electron density changes accompanying a winter stratospheric warming at 25–30 mb in June and July for New Zealand (Christchurch, 43° S, 173° E) are shown in Figure 4 (Gregory and Manson, 1975).

It is interesting to note that, for rather low latitudes, the response of absorption to the stratospheric temperature rise does not occur for all types of warmings, but only for the strong final warmings connected with radical changes in atmospheric circulation. This is demonstrated in Figure 5 for El Arenosillo, Spain (37°6′ N, 6°44′ W) (De la Morena and Kazimirovsky, 1996).

It is noteworthy that in principle we can observe the inverse correlation between both parameters in such a way that the appearance of a stratospheric warming (i.e., temperature rise at the fixed stratospheric level) coincides significantly with the decrease of the absorption in the D-region (e.g., Lastovicka, 1983). Possibly, the variability of the absorption could depend on the region (Lastovicka and De la Morena, 1987), on the meridional wind variability in the D-region (Lastovicka et al., 1990) and even on the variation of stratospheric level with the increase of the temperature. But there is a key difference between those who report a related increase of absorption and those who report a decrease of absorption. The former

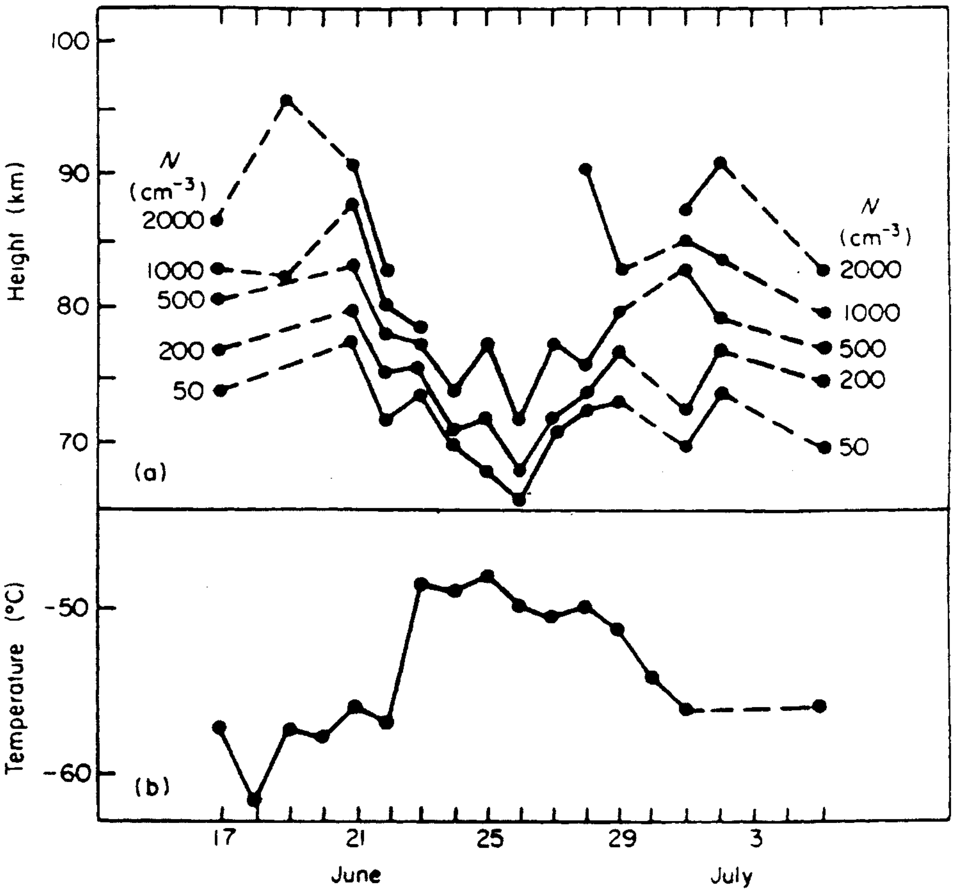

Figure 4. Ionospheric D-region changes accompanying a winter stratospheric warming in June and July 1963, at Christchurch, New Zealand (43° S, 173 ° E). (a)Noon electron concentration N. (b) Stratospheric temperature at 20–30 mb level (about 25 km altitude) (Gregory and Manson, 1975).

effect concerns local stratospheric warmings, while the latter concerns major global stratospheric warmings with changes in circulation and not necessarily a local stratospheric warming.

The height dependence of the correlation between ionospheric absorption and stratospheric temperature was recently observed for Antarctica (Pietrella et al., 2001), for Terra Nova Bay station, located close to, or even inside, the polar cusp region depending upon the time of day. This means that in this region the ionospheric variability could be predominantly controlled by interaction with the magnetosphere, in which case it would be difficult to distinguish between the ionospheric variability due to meteorological effects coming "from below" (if they exist) and the principal cause due to the influx of charged particles that increase the electron density and hence the ionospheric absorption. Nevertheless, during periods with rather low solar activity ($F_{10.7} < 100$) we found by multiregression analysis

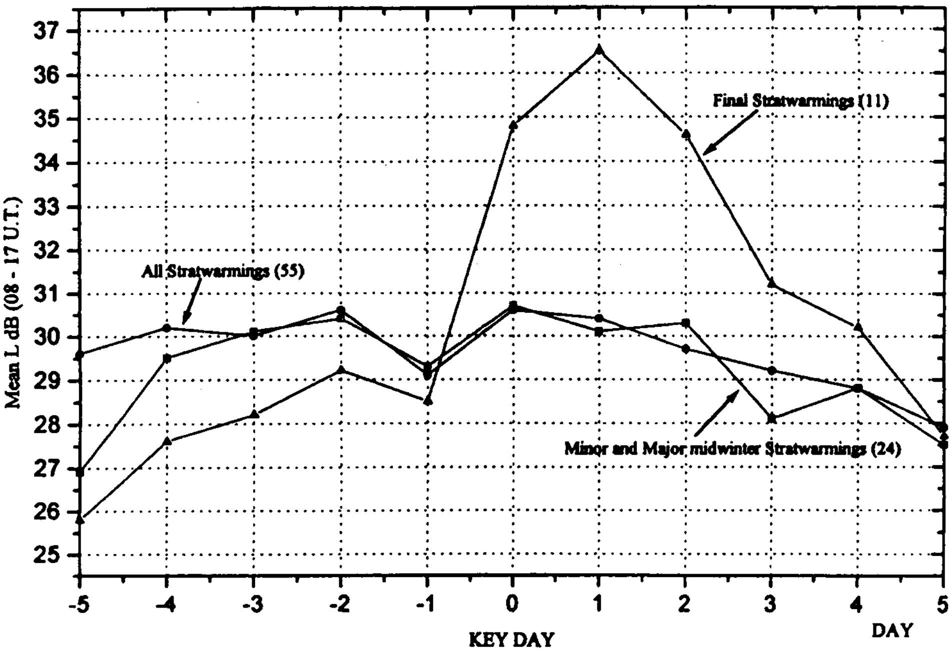

Figure 5. Effect of stratospheric winter warmings (Stratwarmings) on daytime absorption of radio waves, A3 method. Transmitted frequency: $f = 2830$ kHz; period: 1976–1993; station: El Arenosillo, Spain (37.1° N, 6.7° W). Key day: day of maximum stratospheric temperature on 30 mb level (De la Moreno and Kazimirovsky, 1996).

(with statistical significance) that at stratospheric heights between 15 and 22 km the influence of the stratospheric temperature on ionospheric absorption seems to be more important than those due to solar and geomagnetic activity. Moreover, the superimposed epoch analysis has shown that the behaviour of the ionospheric absorption response to rising stratospheric temperature is different for the lower and upper stratosphere. On the average, for the 13–18 km range the ionospheric absorption increases after the stratospheric temperature maximum (so called "zero day") but, on the contrary, in the 19–26 km range the ionospheric absorption decreases after the "zero day". It is appropriate to mention here the recent comparison of planetary waves in the stratosphere, mesosphere and ionosphere over Antarctica by Lawrence and Jarvis (2001).

During the last 15–20 years a significant number of papers appeared in which observations of regular or quasi-regular fluctuations observed both in the neutral and in the ionized components of the middle atmosphere and lower ionosphere were presented. In some of these papers an attempt was made to connect fluctuations in the D-region or E-region of the ionosphere with similar fluctuations of meteorological parameters in the lower parts of the atmosphere. We suggest that the well-correlated fluctuations in the ionized and neutral components of the D-region, mesosphere and stratosphere are probably due to the large-scale upward-propagating planetary disturbances generated in the troposphere (see numerous references in De la Morena and Kazimirovsky, 1996).

The seasonal variation in the amplitudes of quasi-periodic fluctuations of ionospheric parameters (with periods of planetary waves, tides, internal gravity waves) show that the amplitudes are usually maximum in winter, when the conditions for upward leakage of internal waves (i.e., the wind and temperature profiles between troposphere and thermosphere) are optimal (e.g., Taubenheim, 1983). It was shown that the quasi-periodic fluctuations observed in absorption are caused not by fluctuations in the solar ionising flux but probably by planetary waves in the stratosphere/troposphere (e.g., Pancheva et al., 1989; Arnold and Robinson, 2000). Later the model for the transformation of planetary waves of tropospheric origin into waves in absorption in the lower ionosphere was developed (Lastovicka et al., 1994).

An example of typical 7–8 and 12–13 days absorption fluctuations is presented in Figure 6 (Pancheva et al., 1991). The main features of the amplitude variations are very similar at all three radio-frequencies (the measurements were provided by the A3 method for three radio paths in Bulgaria, the Czech Republic and Spain) for 7–8 day fluctuations, while for 12–13 day fluctuations such similarity is observed only in December–January. $H_{1,2}$ in Figure 6 are the amplitudes of the 30 hPa height waves 1 (full line) and 2 (dashed line) at 60° N. The intervals of amplification of the fluctuations coincide well with stratospheric warmings during the winter under consideration. The first “minor” warming developed with two phases: around 10 January 1986 (H_2 peak) and 20 January 1986 (H_1 peak). The second “minor” warming took place around 18 February 1986, and the major “final” warming occurred after 20 March 1986, both occurring as a consequence of H_2 intensification. The cold winter of 1985/1986 coincided with an enhanced tendency for the development of an elongated polar vortex, that is a pronounced planetary-scale height wave H_2 (Naujokat and Labitzke, 1993). It can be clearly seen in Figure 6 that almost every amplification of the quasi-stationary planetary waves H_2 in the stratosphere leads to the activation of 7–8 day variations in the ionospheric absorption. The behaviour of the longer-period fluctuations in absorption shows a response to the simultaneous amplification of both height waves (H_1, H_2) in the stratosphere. Therefore, we can conclude that the quasi-periodic fluctuations observed in the ionospheric absorption are really connected with the large-scale planetary disturbances generated in the lower atmosphere, which cause the stratospheric warmings.

Ionospheric dynamics certainly must be sensitive to coupling from below. The close connection between the circulation in the lower thermosphere, mesosphere and stratosphere, (e.g., as observed by radar and rocket measurements) demonstrates a consistent cross-section of the wind field from 20 to 110 km (e.g., Meek and Manson, 1985).

It is generally accepted that, while the International Reference Models of the zonally averaged upper mesosphere/lower thermosphere wind field are still use-

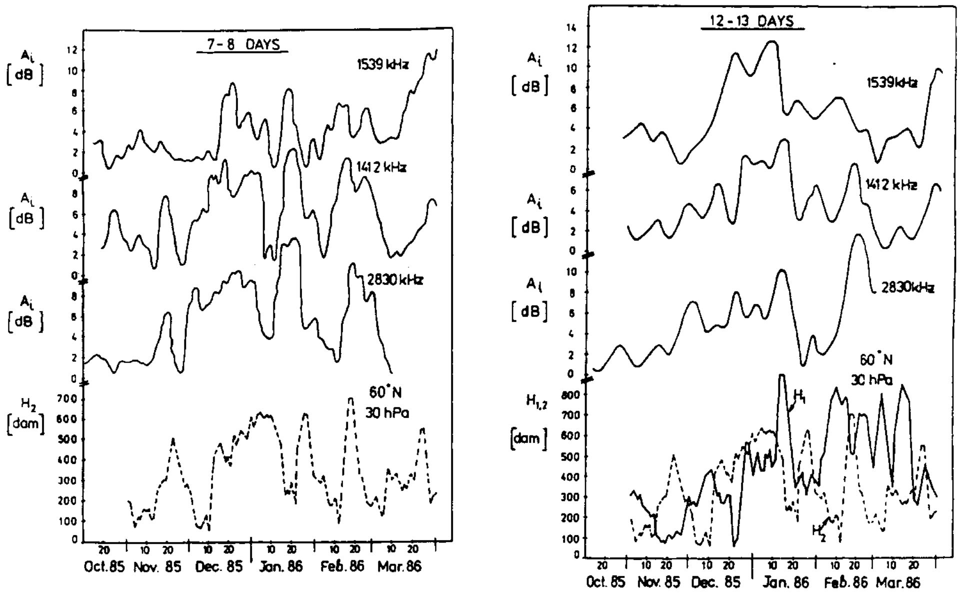

Figure 6. Time variations of amplitudes of radiowave absorption fluctuations (T = 7–8 and 12–13 days) for 1539 kHz, 1412 kHz and 2830 kHz and for the 30 hPa height wave 1 (full line) and height wave 2 (dashed line) at 60° N, winter period 1985/1986 (Pancheva et al., 1991).

ful for many purposes, significant discrepancies exist between them and new experimental data. The latter demonstrate, in addition to seasonal and latitudinal variations, longitude dependent variations and, in addition to tides, planetary waves and intra-seasonal quasiperiodic fluctuations. It is evident that sometimes the specific regional features of the wind regime are very important.

If, as has been demonstrated, there is meteorological control of the lower ionosphere, we may expect the existence of a longitudinal effect on the dynamical regime due to the well-known longitudinal inhomogeneity of lower atmosphere processes and due to longitudinal differences in the conditions for the upward propagation of internal atmospheric waves from the lower atmosphere. The longitudinal effect has been revealed on the basis of simultaneous upper mesosphere/lower thermosphere wind measurements (D-region) along one circle of latitude at two or more sites (e.g., Kazimirovsky et al., 1988).

It has been well known since the first analyses of wind variations in the mid-latitude lower thermosphere that diurnal velocity variations can be described as the sum of the prevailing wind, diurnal wave and semidiurnal wave (e.g., Sprenger and Schminder, 1967). The existence of diurnal and semidiurnal tides in the MLT-region was demonstrated in numerous theoretical models as well (e.g., Forbes, 1991).

Figure 7a demonstrates prevailing wind (V_0) monthly averaged variations for Observatory Badary (East Siberia, 52° N) and Observatory Collm (Central Europe, 52° N). The systematic climatological distinctions are evident, especially for the zonal circulation (V_{ox}). During winter the average wind over Eastern Siberia is about twice as strong as that over Central Europe. The seasonal variation of the zonal circulation depends on longitude as well: the autumn minimum over Siberia occurs earlier than that over Europe, and the spring minimum is accompanied by a reversal of the wind over Europe but not over Siberia. The observed longitudinal effect may be partly interpreted as resulting from large-scale stationary planetary waves formed in the lower thermosphere. In this case the longitudinal variation of the prevailing wind is due to the existence of such waves.

Figure 7b shows that the seasonal variation of the monthly averaged semidiurnal zonal tide amplitudes (V_{2x}) at both observatories are very similar, with small discrepancies, mainly in the summer months. The systematic climatological distinctions (but with a similar character to the seasonal variations) are evident for semidiurnal meridional tidal amplitudes (V_{2y}), which are systematically larger over East Siberia than over Central Europe. The longitudinal variation of semidiurnal tidal amplitude is a consequence of the longitudinal variation of zonal flow (Kazimirovsky et al., 1988, 1999).

The zonal and meridional prevailing winds in the lower thermosphere reversed westwards and southwards in a period of less than a week during stratospheric warmings. There is an increase of the semidiurnal tidal amplitude and phase shift compared with undisturbed winter conditions. The response could depend on longitude as well as on the intensity and location of the warming area (e.g., Kazimirovsky et al., 1988). The response of the prevailing zonal wind for three observatories located at the same geographic latitude (in Canada, Central Europe and East Siberia) is demonstrated in Figure 8.

Planetary waves contribute significantly to the variability of MLT winds. In the mesosphere and lower thermosphere, wave fluctuations are sufficiently large often to mask the prevailing or mean state of the atmosphere. Tropospherically forced planetary waves with periods of between 2 and 30 days have been observed to penetrate up to heights near 110 km under favourable conditions. A full range of wave periods has been identified, but the most commonly reported periods fall into four well-defined intervals, which are 14–20 days, 9–12 days, 4–7 days and 1.6–2.2 days. These are often referred to as “16-day”, “10-day”, “5-day” and “2-day” oscillations, respectively, although a precise determination of the periods involved is often not possible (Forbes and Leveroni, 1992). The observed periods vary around these values in an apparently random way, possibly due to Doppler shifting by the mean winds. Thus, they form “period bands” (Lastovicka, 1997a). It is usually assumed that these transient oscillations of the wind field in the lower thermosphere are caused by Rossby-gravity normal modes generated in the lower atmosphere (Vincent, 1990).

What might be the preferred carrier of upward influence (especially for planetary waves) across the mesopause to the lower thermosphere and ionosphere? Atmospheric tides are the most likely candidate. The direct upward propagation

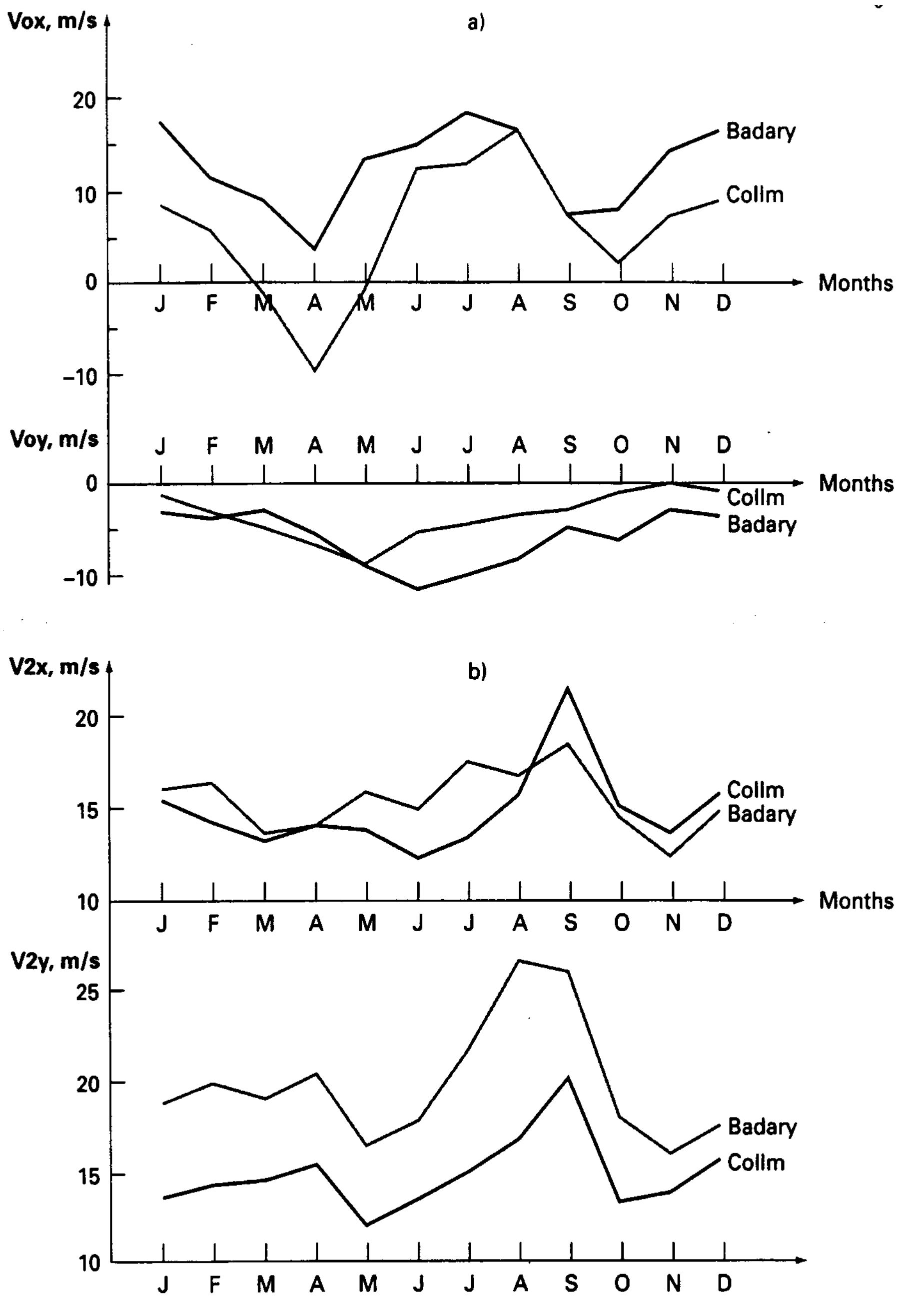

Figure 7. The non-zonality in the wind field in the lower ionosphere (Kazimirovsky et al., 1999). Observatory Badary, East Siberia, 52° N, 1975–1995. Observatory Collm, Central Europe, 52°N, 1979–1997. Data are monthly averaged. V_{ox}: prevailing zonal wind. V_{oy}: prevailing meridional wind. Positive direction: eastward and northward. V_{2x}: amplitude of the zonal semidiurnal tide. V_{2y}: amplitude of the meridional semidiurnal tide.

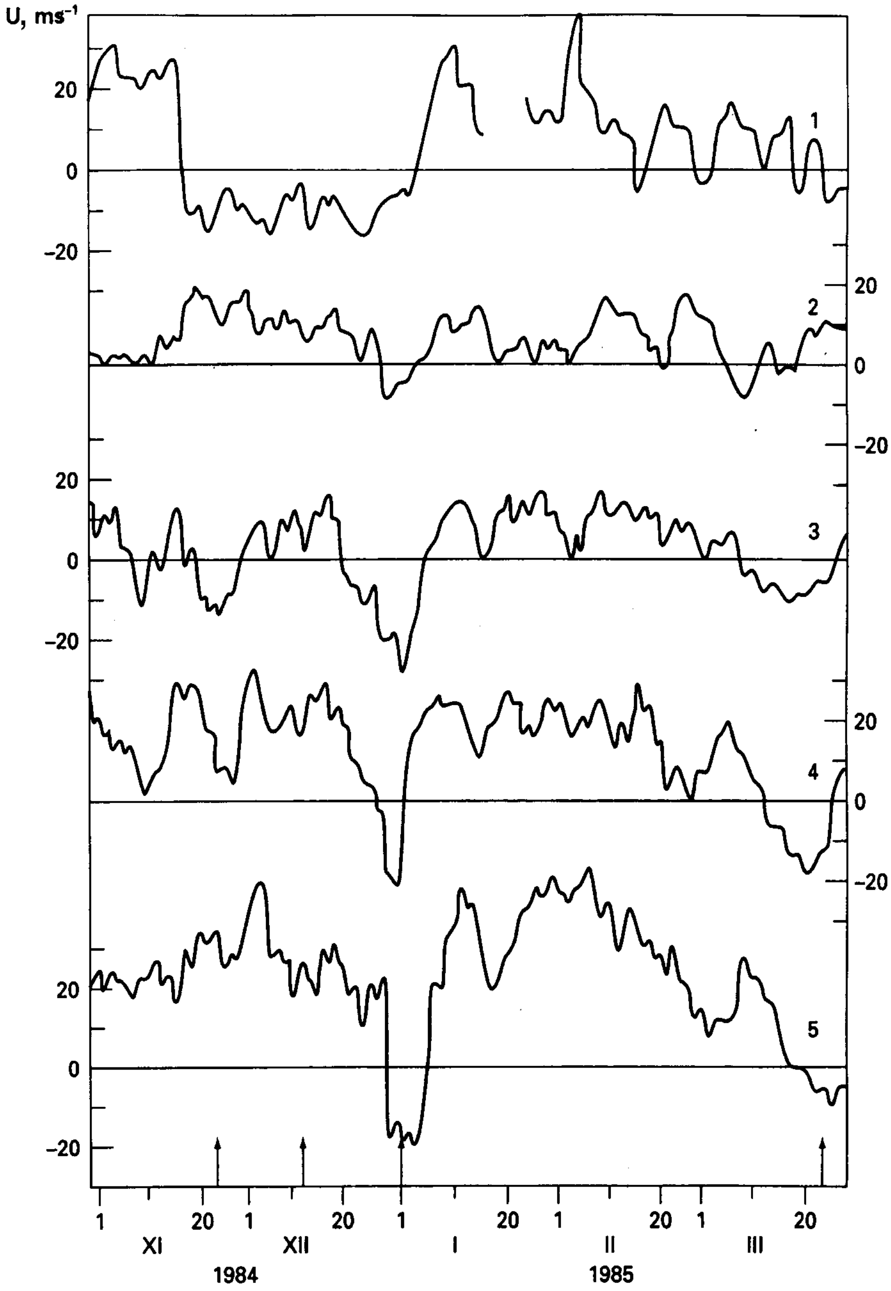

Figure 8. The response of the prevailing zonal wind (U, m/s) in the lower ionosphere to stratospheric warmings during winter 1984/85 (rather low solar activity). Positive direction: eastward. Arrows: days of stratospheric warmings (Kazimirovsky et al., 1988). (1) Observatory Badary, East Siberia, 52°N (2) Observatory Collm, Central Europe, 52°N. (3) Observatory Saskatoon, Canada, 52°; height, 97 km. (4) Observatory Saskatoon; height, 89 km. (5) Observatory Saskatoon; height, 80 km.

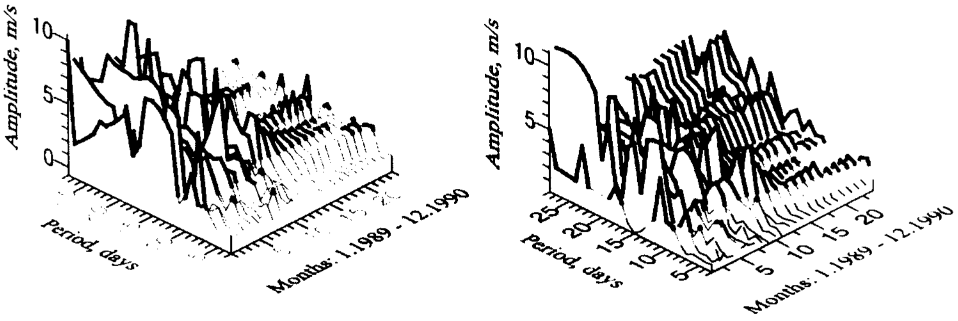

Figure 9. Lower thermosphere zonal prevailing wind dynamical spectra: Left; Observatory Badary (East Siberia, 52° N); Right, Observatory Collm (Central Europe, 52° N).

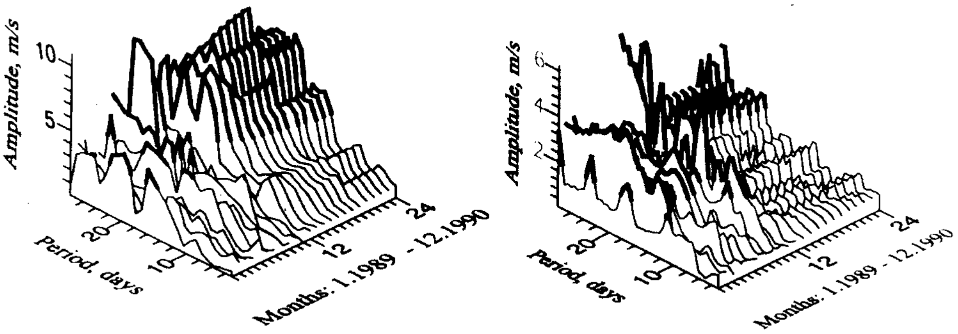

Figure 10. Lower thermosphere zonal wind (semidiurnal tidal amplitude variations) dynamical spectra: Left; Observatory Badary (East Siberia, 52° N); Right, Observatory Collm (Central Europe, 52° N).

of planetary waves well into the thermosphere above the lower thermosphere is inhibited by atmospheric viscosity. Recent model calculations (e.g., Muller-Woordag et al., 2000) reproduce the planetary wave type oscillation via modulated tides to heights near and somewhat above 200 km. The non-zonal modulation of stratospheric and mesospheric tides penetrating to the lower thermosphere appears to generate a quasi-stationary planetary wave by demodulating the tides through energy dissipation in the lower thermosphere (e.g., Forbes, 1991). The modulation of the prevailing wind and semidiurnal tide with the periods of planetary waves is shown for two midlatitude observatories (Badary and Collm) in Figure 9 and Figure 10. The dynamical spectra were calculated for a two-year interval with a data "window" of one month. The spectra of fluctuations are very wide and variable, and evidently they are different for the different longitudes.

The general concept of significant longitudinal structure in the MLT winds was supported and developed during the international MLTCS (Mesosphere and Lower Thermosphere Coordinated Study) campaigns (Manson et al., 1990; Manson et al., 1991), and the international DYANA Project (Singer et al., 1994; Portnyagin et al., 1994). Clear longitudinal effects were observed either for the prevailing wind or semidiurnal tides. The recent cooperative "CRISTA/MAHRSI Campaign" also dealt partly with upper mesosphere/lower thermosphere wind measurements and has revealed some regional distinctions (e.g., Kazimirovsky et al., 1997). Determination of the sources of planetary scale perturbations of the mesosphere and lower thermosphere is one of the topics in the ongoing International Program PSMOS (Planetary Scale Mesosphere Observing System).

Nevertheless, the processes operating in the MLT-region are still insufficiently understood. Probably they include quasistationary planetary scale waves, or PSW (Jacobi et al., 1999; Forbes et al., 1999), but our current understanding of the non-zonal dynamic processes contains numerous unresolved contradictions. Further experimental and theoretical investigations in this field will greatly help to extend our knowledge of the MLT-region's spatial structure. A coordinated program of simultaneous measurements of winds might be carried out at a carefully chosen series of sites comprising an East-West chain spanning a large sector of longitude. Such measurements, in conjunction with results of the long-term zonal-mean modeling, could be used to determine PSW parameters and to estimate the relative contribution of non-migrating tides. It would improve our understanding of the vertical coupling between different atmospheric regions and the coupling mechanisms between tropospheric/stratospheric non-zonal circulation systems and similar systems that may exist in the MLT-region.

3.1. THE E-REGION

The next ionospheric region, the E-region, intermediate between the D-region and the F-region, is rather less studied with regard to processes of coupling from below. Nevertheless, we have some evidence concerning intensive gravity waves in the variations of the electron density and ion velocities at heights 100–140 km (e.g., Nygren et al., 1990), measured by incoherent scatter radars. The sporadic ionisation in the E-region, so-called E_s (sporadic E-layer), on days of meteorological fronts sometimes tends to occur more frequently and with higher electron concentration than for the preceding and following days.

The generation of E_s is usually connected with neutral wind shear, which is the reason why the dynamics of the E-region could be crucial for E_s. The daily averaged departures of the sporadic E parameters f_bE_s and $h'E_s$ from the corresponding monthly means have been found to decrease during winter-time circulation disturbances connected with stratospheric warmings. The computed neutral wind shear also shows decreased values during these disturbances. Both effects may be due to a decrease in the attenuation of acoustic-gravity waves (AGW), as a consequence of which the vertical wavelength increases and the E_s-producing wind shear decreases, with the growth of vertical energy flux (Bencze, 1980, and numerous references in Kazimirovsky and Kokourov, 1991).

4. Upper Thermosphere/Ionosphere

This topic is rather more speculative than that of the lower thermosphere/ionosphere. Nevertheless, some ideas about dynamic coupling between the weather at ground level and F-region behaviour appeared long ago (Beynon and Brown, 1951; Martyn, 1952). Of course, attempts to forecast the surface weather from ionospheric data were too optimistic to be true. But it is evident that planetary, tidal and gravity waves launched by various sources in the troposphere and stratosphere actually penetrate into the F2 region. There are short-term correlations between meteorological and ionospheric parameters as well as a number of statistically significant correlations that together may be regarded as circumstantial evidence on a long-term basis. The ionospheric response to forcing from below should be anisotropic and subject to diurnal and seasonal variations, and should vary with both geomagnetic and geographic latitude and longitude.

In fact, we know that both seasonal and daily, global and regional composition changes at thermosphere/ionosphere heights can occur even during geomagnetically quiet periods. It is assumed that corresponding changes of the turbopause height are responsible for the respective observations. But the turbopause height variations could be sensitive to the meteorological dynamical influence from below. Of course, it is generally accepted that there is significant turbulence in the region 80-120 km, although there is still some debate as to its temporal and spatial morphology. The main sources of turbulence are probably gravity waves and tides (including those propagating from below), and these generate turbulence by processes such as non-linear breaking, shear instabilities and critical level interactions.

We believe that the signature of planetary waves can be recognized in the global distribution of the electron density (N_e) in the F2 region. The regional structure (the so-called continental effect) of N_e, which can be interpreted in terms of the manifestation of the climatic properties of the underlying atmosphere, has been discussed on many occasions (e.g., Danilov et. al., 1987). The longitude-dependent distribution of noon critical frequency foF2 values (corresponding to maximal electron concentration) is reasonably well approximated by the sum of planetary waves with zonal wave-numbers $n = 1$ and $n = 2$. Moreover, it has been shown that the seasonal variations of planetary wave amplitudes in foF2 and in geopotential at the 10 mb level are closely correlated but with changeable time lag (Kazimirovsky and Kokourov, 1991).

Studies of the coupling between ionospheric and stratospheric parameters sometimes yield ambiguous conclusions due to the masking effect on the ionosphere of various geophysical factors, such as ionizing radiation from the Sun, energetic charged particle fluxes, cosmic rays, etc. Thus it is desirable to carry out the analysis in such a manner that variations caused by these factors are removed. We have proposed, and successfully applied, the following technique. Two stations are selected which have similar geographic or geomagnetic latitudes but which are sufficiently well spaced in longitude for it to be likely that there will be substantial differences in the meteorological characteristics of the lower atmosphere. For each day the differences in the ionospheric characteristics (e.g., foF2, $f_{\min}$, absorption of radiowaves, etc.) between these two stations are determined, as well the differences in the meteorological characteristics (e.g., stratospheric temperature, height of isobaric surface, etc.). In the comparison of the time variations of these differences we may suppose that the effect of geophysical factors, which are almost the same for the two stations, is largely eliminated. In contrast, the meteorological effect due to the different climatology for these two well-spaced locations will be stressed and thus can be identified. If meteorological factors do indeed have an influence upon the variations of ionospheric parameters, we should see a close correlation between the variations of the differences described above.

An example of the application of this technique exists for foF2 and stratospheric dynamics. It is well known that the winter cyclonic vortex in the stratosphere is highly dynamic and changeable. Northern subtropical areas of high pressure, when moving northward, may deform and sometimes even split into two independent cells. This circumstance leads to a substantial difference between the values of stratospheric pressure at two sites located at the same latitude but at different longitudes. Does the behaviour of the F2 ionospheric layer reflect this? Figure 11 presents the seasonal variation of daily values of the differences in noon foF2 values (ΔfoF2) between two sites near 55° N and separated longitudinally by 2000 km (Moscow and Sverdlovsk, in the Urals) and the seasonal variation of daily values of the corresponding differences in the height of the 30 hPa surface (Δh_{30}). We can see that during winter and around the equinoxes the values of Δh_{30} and ΔfoF2 are greater than during summer. By the method of "superposed epochs" it was found that negative extrema of ΔfoF2 correspond to positive extrema of Δh_{30} and vice versa (Kazimirovsky and Kokourov, 1991).

For some time the network of ionosonde stations in Europe has been dense enough to study the meteorological behaviour of the upper ionosphere (Bibl, 1989). Even the average behaviour of the F-region ionization shows substantial changes with location. In Europe the local gradients in ionization can differ by a factor of 2 between two locations separated by 1000 km. This is important for understanding the meteorology of the ionosphere and for precise radio predictions.

The existence of quasi-periodic oscillations in the ionospheric F-region (2–35 days) which may be connected with planetary wave activity in the lower atmosphere is statistically evident in foF2 variations. Figure 12 (Apostolov et al., 1998) demonstrates the averaged periodograms of foF2 in the period range from 30 hours to 40 days for the whole of solar cycle 21, calculated as the mean of 126 spectra of successive 4-month intervals shifted by 1 month. The four stations considered lie latitudinally between 42° N and 60° N. There are well-expressed maxima close to 6 (4–7), 9 (7–11), 14 (11–16) and 29 (21–35) days. Relatively minor peaks occur near 2.5 (1.25–4) and 19 (16–21) days.

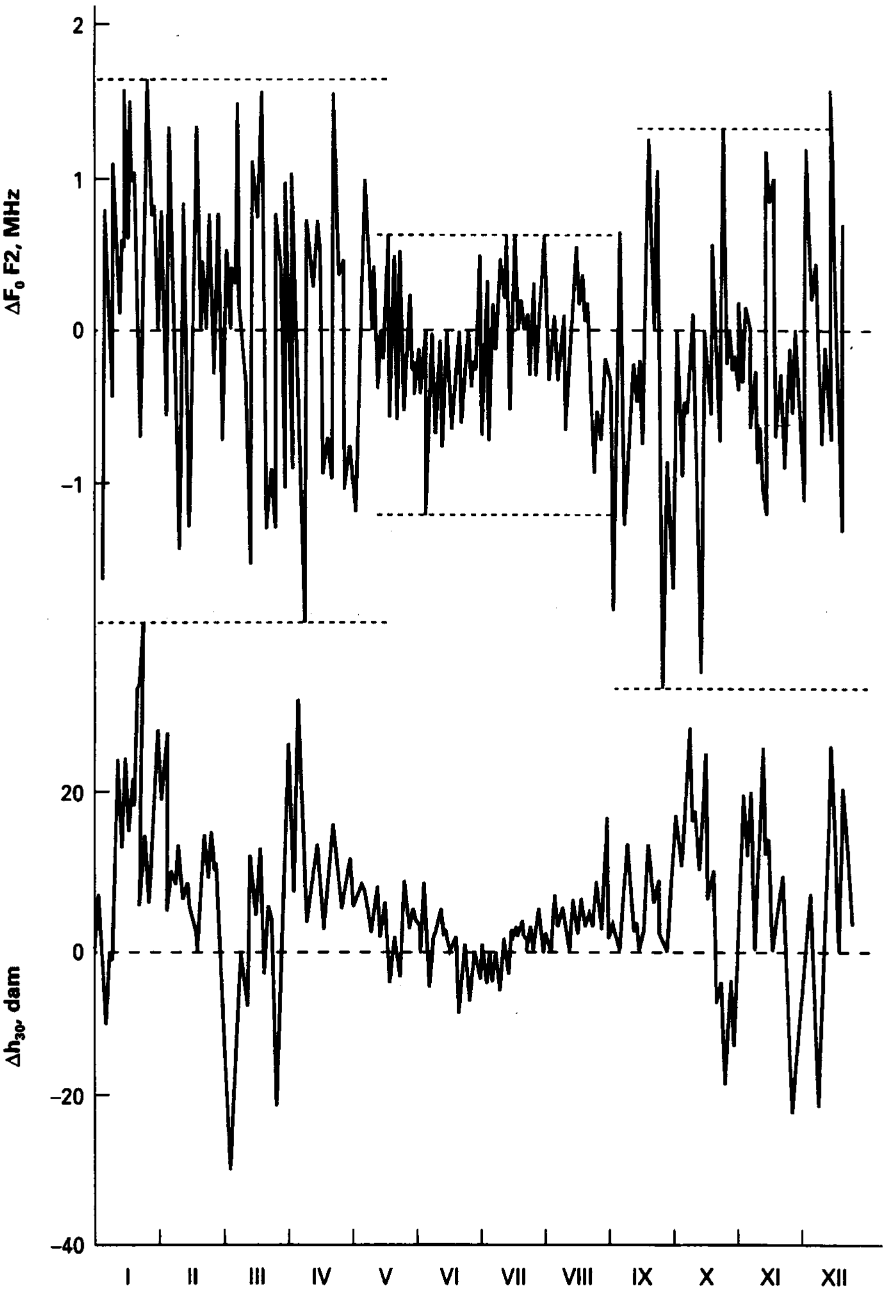

Figure 11. Stratospheric effects on the ionospheric F-region. Daily values of the difference in noon values of foF2 and in heights of an isobaric surface at 30 hPa for two stations: Moscow (East Europe) and Ekaterinburg (Ural Mountains), both located near 55° N. I, II, III ... XII-months, 1969 (Kazimirovsky and Kokourov, 1991).

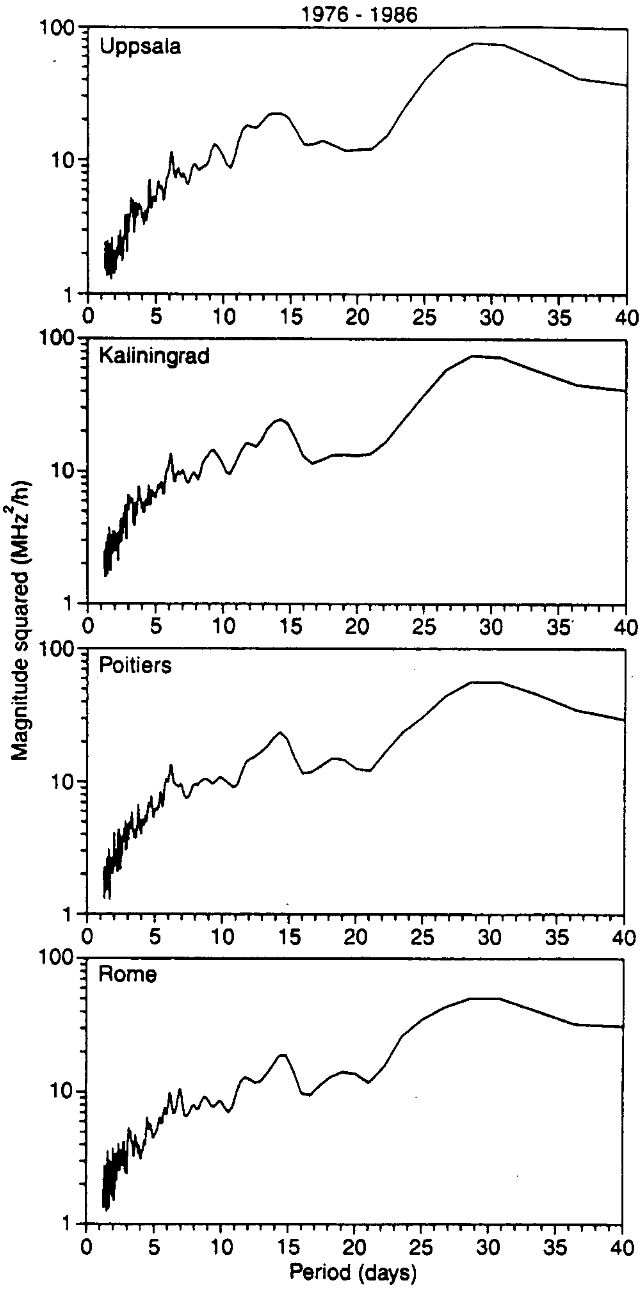

Figure 12. Averaged periodograms of foF2 in the period range from 30 hours to 40 days for the whole of solar cycle 21, calculated as the mean of 126 spectra of successive 4-month intervals shifted by 1 month (Apostolov et al., 1998).

Well studied quasi-periodic oscillations with periods from 2 to 6.5 days have the following characteristics. The probability of existence and the occurrence frequency are maximum during local summer. The oscillation amplitude is maximum near the equinoxes. The dominant zonal structure of the oscillations at middle latitudes is a westward-travelling wave with zonal wave-number $n = 1$ and $n = 2$. These quasi-periodic oscillations contribute significantly to the day-to-day variability of foF2, and their contributions depend on solar cycle, season and latitude (Altadill, 2000).

On the other hand, the solar cycle variation of planetary wave type oscillations in foF2 appears to be induced by the solar cycle dependence of foF2 itself (Lastovicka and Mlch, 1996). As far as the physical cause of planetary scale waves in foF2 is concerned, it seems possible that it is a consequence of the indirect propagation of planetary waves in the neutral thermosphere (Rice and Sharp, 1977; Forbes et al., 1999).

Travelling ionospheric disturbances (TIDs), which are the quasi-periodic, spatially large-scale or medium-scale electron density perturbations, possess a horizontal component of propagation velocity. It is generally accepted now that they are caused by the passage of internal gravity waves. The sources of these waves could be diverse but they must be below the F-region since the wave energy (i.e., group velocity) invariably is found to be directed upwards. It is appropriate to mention that gravity waves caused by the terminator or a solar eclipse (e.g., Altadill et al., 2001) could be generated in the F-region at heights near 200 km.

From the earliest days of HF communications the presence of travelling ionospheric disturbances (TIDs) and ionospheric irregularities (including spread-F events) were apparent, and now we know that both are closely connected with internal gravity waves. At the same time, the solar cycle and seasonal variations of oscillations at different heights and their similarity to changes of gravity wave activity in the F2-region and lower ionosphere (Boska and Lastovicka, 1996) are such that a common source of waves in the lower and upper ionosphere of tropospheric and stratospheric origin can be postulated under some circumstances. Also, planetary wave type oscillations in the F2 region can be caused by the modulation of upward-propagating tides and gravity waves, so even the possibility of the prediction of these oscillations from wind measurements in the lower thermosphere/ionosphere could be discussed (Lastovicka 1997a; 1998).

Sources of gravity waves have been identified which include severe weather disturbances, earthquakes and nuclear and industrial explosions (see references in Kazimirovsky and Koukorov, 1991). In the experiments conducted by some investigators, for the majority of the waves the reverse group path can be followed down to the tropopause level. A comparison with meteorological data shows that many of the possible source regions of the observed waves appear to lie in the proximity of the jet stream, or to be close to regions of typhoons, thunderstorms, tornadoes, hurricanes, convectively unstable cold polar air, subtropical heavy rainfalls, tropospheric mesoscale convective complexes (MCC) events, the

Intertropical Convergence Zone in Africa, etc. A possible generation mechanism is the non-linear interaction of shear flow instabilities in the jet stream and penetrative convection (Waldock and Jones, 1987; numerous references in Kazimirovsky and Kokourov, 1991; Hung et al., 1991; Manzano et al., 1998; Hocke and Tsuda, 2001).

TIDs can also be related to tropospheric vortices. Recently such observations were provided from China where TIDs were statistically analyzed on the basis of observations from an HF Doppler array. The backward ray tracing showed that the sources of TIDs were located on the edges of Qinghai-Tibet Plateau, i.e., on the lee side of the elevated terrain of the plateau where the vortices are most likely to be produced (Wan et al., 1999).

Spread-F events on ionograms are often connected with wave-like structures of F-region irregularities induced by upward propagating AGWs of meteorological origin. This is especially true for equatorial spread-F. For instance, spread-F occurrence in the African area was investigated by means of non great-circle radio wave propagation on the trans-equatorial path. The distribution of the horizontal velocity, the horizontal wavelength of the quasi-periodic structures, and the tilt of the irregularity patches led to the conclusion that these structures of the equatorial F-spread are connected with AGW in the equatorial region (numerous references in Gershman et al., 1984). Small-scale ionospheric plasma events associated with severe weather-related gravity waves were observed *in situ* as well (Kelley, 1997).

Variations of Total Electron Content (TEC) over low-latitude stations sometimes (e.g., Shoedel et al., 1973) also show wave-like structures coincident with unusual ground pressure variations with the same period, and an amplitude much greater than the amplitude of the normally observed short-period changes in TEC. The strong correlation between the oscillations of the ground pressure and the TEC suggests that the AGW were generated by a singular tropospheric event and propagated to ionospheric heights without significant changes of period. This was clearly observed by Schoedel et al. (1973) at three African stations. Thus we have the possibility of an association between atmospheric disturbances at ground level and in the ionosphere (Goodwin, 1980). Gravity waves in the F-region, excited by the passage of cold fronts, were observed by Sauli and Boska (2001).

Recently the effect of gravity waves has been successfully investigated through an estimation of their contribution to the “within-an-hour” and “hour-to-hour” variability of foF2 (Boska and Lastovicka, 1996). Figure 13 (Boska et al., 1999) shows the AGW spectra for El Arenosillo, Spain, for one day. In principle, the fluctuations of the electron density at fixed heights can be caused by fluctuations in the ionized matter (i.e., gravity waves), by fluctuations in the ionizing radiation, by high-energy charged particles related to geomagnetic/magnetospheric activity, etc.. However, we believe that at middle latitudes and for quiet geomagnetic conditions the fluctuations in the period range 10 minutes–3 hours are not of solar or magnetospheric origin.

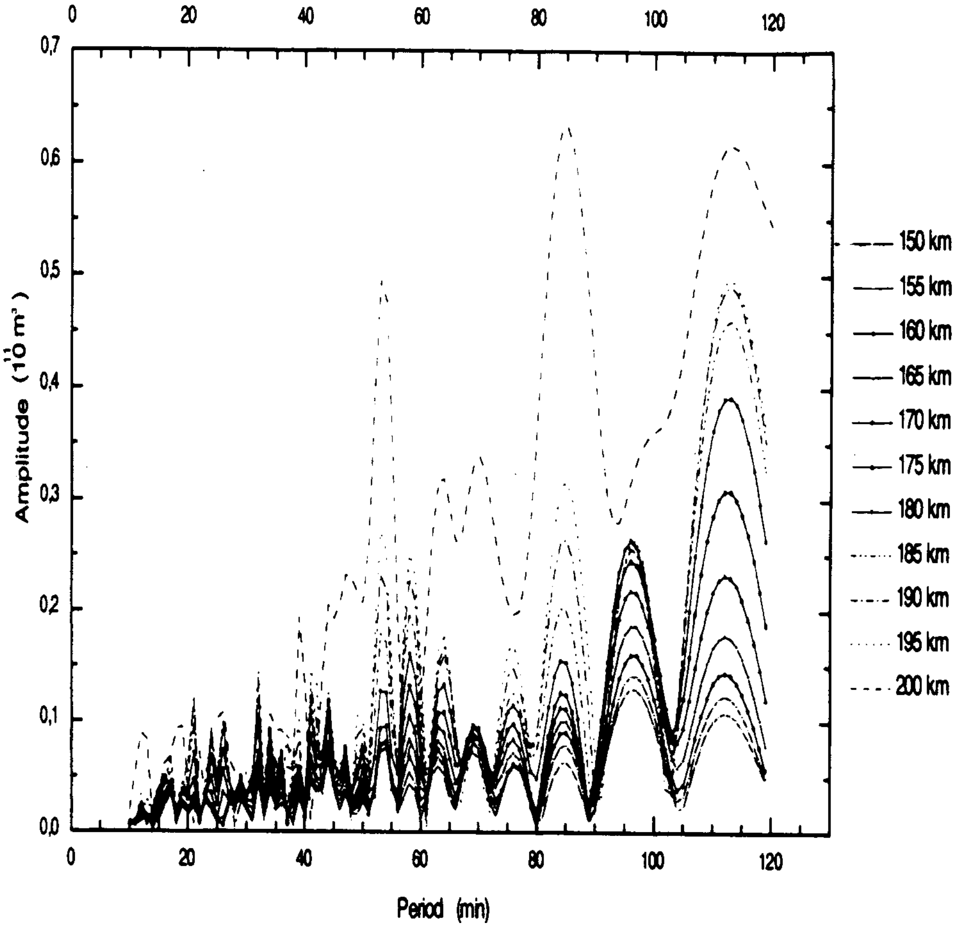

Figure 13. Atmospheric Gravity Wave spectra in the variations of electron concentration at fixed levels. Digisonde-256, El Arenosillo, Spain (37.1° N, 6.7° W), December 14, 1997, 06UT–18UT (Boska et al., 1999).

5. Thunderstorms and Upper Atmosphere/Ionosphere

The widely accepted classical ideas of atmospheric electricity are:

- Thunderstorms are the main generators in the global electric circuit, causing an electric potential between the Earth and the ionosphere of about 200–500 kV.
- Any influence of thunderstorms and other electrical events near the ground on the atmospheric layers well above the conducting region (the “electrosphere”) near 60–70 km is forbidden.

We know that the classical hypothesis has not yet been proved beyond doubt. Moreover, it is now widely recognized that current systems driven by global thunderstorms and by magnetospheric plasma phenomena coexist in the middle atmosphere and above. Some recent models of thunderstorm current systems and experiments show that most of the return current from a thunderstorm generator that penetrates the tropopause flows globally through the ionosphere and along plasmaspheric magnetic field lines (e.g., references in Sentman and Westcott, 1995).

Lightning generates broad electromagnetic frequency spectra. Some of the wave energy propagates into the ionosphere/magnetosphere system, where it interacts with ambient plasma particles. We have evidence that thunderstorms are important in the global ionospheric energy budget. Thundercloud electric fields influence the E-region and F-region of the ionosphere (Suess and Tsurutani, 1998).

Recent observations have shown that intense lightning produces a number of interesting and unexpected effects in the middle and upper atmosphere above thunderstorms. Some new and diverse classes of energetic electrical effects of thunderstorms have been documented over the past 5–10 years. Two of these classes, called red sprites and blue jets, are optical emissions excited by lightning. Together they span the entire distance between the tops of some thunderstorms and the ionosphere. These newly discovered classes of natural electric phenomena provide evidence that thunderstorms are both more energetic and capable of electrically interacting with the upper atmosphere and ionosphere to a far greater degree than had been appreciated in the past.

Sprites are very large luminous flashes that appear within the mesospheric D-region directly over active thunderstorm systems and are coincident with cloud-to-ground or intracloud lightning strokes (Rodger, 1999). Triangulation of their locations and physical dimensions using simultaneous images captured from widely spaced aircraft shows that their upper boundaries can extend into the ionosphere. The brightest region of a sprite is red and generally lies in the altitude range 65–75 km. Above this there is often a faint red glow or wispy structure extending upwards to about 90 km, to the night-time E-region ledge.

Jets are sporadic optical emissions, deep blue in colour. Following their emergence from the top of the thunderclouds, blue jets propagate upward in narrow cones, fanning out and disappearing at about 50 km over a lifetime of about 300 ms.

All theories proposed to date concerning red sprites involve lightning discharges being either a causative agent or a simultaneous but non-causative consequence of electrical breakdown triggered by cosmic rays. Intensive efforts, both experimental and theoretical, are underway to determine the physical mechanisms at work in the production of thunderstorm-ionosphere effects. It is unclear whether the absorption within the ionosphere of the energy flowing upward from the lower atmosphere is capable of producing effects that are sufficiently dynamically significant for them to qualify as being a strong link between these layers. However, several long-lived secondary effects within the neutral upper atmosphere may occur by way of Joule heating, photoexcitation, or electron impact excitation or ionization. Understanding where these new electrical processes fit into the solar-terrestrial system and Earth's global electrical circuit is a challenging problem that spans traditional discipline boundaries involving the lower and upper atmospheres (Sentman and Wescott, 1995, and references therein).

Evidence for a direct interaction between phenomena associated with thunderstorms and the ionosphere includes perturbations of electron density and temperature (increase of ionization in the E-region, sporadic-E occurrence, increase of temperature and electron density in the F-region), excitation of electrostatic wave turbulence and enhanced optical emissions. There are some ideas about the physical mechanisms involved, e.g., the upward acceleration of electrons at the moment of a lightning discharge, ionization by energetic particles, etc. (e.g., Pasko et al., 1997).

There is theoretical and experimental evidence for magnetospheric electron precipitation stimulated by lightning via radio waves, particularly in the ELF-VLF range (less than 30 kHz). Because the precipitating particles may be the cause of dissociation and ionization processes, lightning-stimulated precipitation constitutes another way for thunderstorms to influence the ionosphere. There are VLF signatures of ionospheric disturbances associated with "sprites" (e.g., Rycroft, 1994).

Recently a numerical model of the interaction created in the bottom of the ionosphere above a strong horizontal (cloud-to-cloud) lightning discharge was published (Cho and Rycroft, 2001). This simulation allows us to better understand the formation of spatially structured sprites as a function of height via the ratio of the ELF/LF wave electric field (radiated by the current in the discharge) to the atmospheric neutral density. It is interesting to note that ULF-VLF electric fields were detected in the ionosphere over the main maximum of ionisation over powerful Pacific Ocean typhoons (Mikhailova et al., 2000).

Thunderstorms can generate AGW as well. Reverse group ray tracing computations of AGW observed by an ionospheric Doppler sounder array show that the wave sources are in the neighbourhood of storm systems. AGW at ionospheric heights are observed when severe thunderstorms occur within a radius of several hundred km of the ionospheric reflection points. The convective regions may be embedded in the stratiform anvils of thunderstorms. It is also known that the zones of maximum occurrence of spread-F over West Africa and South America coincide closely with the zones of high thunderstorm activity (e.g., references in Kazimirovsky, 1983).

6. Long-Term Ionospheric Variations as a Possible Consequence of the Greenhouse Effect

Releases of trace gases due to human activity have the potential for causing a major change in the climate of the Earth. However, there is no doubt that the subject of global climate warming due to the so-called "greenhouse effect" has led to controversy, speculation and confusion. Despite the many uncertainties that remain, the consensus amongst most scientists knowledgeable about these matters is that global warming will occur. Some questions remain concerning the timing and the magnitude of change but there are few, if any, who dissent from this general conclusion.

The troposphere is expected to warm, the stratosphere to cool, and the ozone content to decrease. The consequences of these processes on the atmosphere above 60 km are a topic of current research and overall results indicate that global change resulting from trace gas variations (e.g., CO_2 and CH_4 doubling) is not only confined to the lower atmosphere but also extends well into the mesosphere, thermosphere and ionosphere (Golytsin et al., 1996). The projected changes should also lead to some alterations in global circulation, latitudinal distributions of temperature and composition, and the response of the atmospheric system to solar and auroral variability (e.g., Thomas, 1996).

Changes occurring in a thin layer of sodium vapour, about 90 km above the Earth, could be revealing the far-reaching effects of greenhouse gases (between 1972 and 1987 its mean height fell by nearly a kilometre). Although it is not possible to state with absolute certainty that the changes in the sodium layer's structure are an indication of global cooling in the middle atmosphere, the behaviour of the layer clearly justifies systematic observation in years to come (e.g., Clemesha et al., 1997).

The changes of occurrence frequency (a considerable increase) of noctilucent clouds caused either by changes in water vapour concentration or by changes in temperature, are possibly an indication of long-term anthropogenic changes. We also should consider the possible effect of anthropogenic changes in the mesosphere that could result from aerosols and trace gases diffusing upward into it, where they can change the aeronomy. Polar Summer Mesosphere Echoes (PSME) as observed by incoherent scatter radars might prove to be sensitive tracers for such anthropogenic changes (e.g., Thomas, 1996).

Long-term trends in planetary wave activity at altitudes of about 80-100 km, which are of possible anthropogenic origin, have been studied extensively with the use of almost 30 years of absorption measurements along various radiopaths in Europe. Trends are more pronounced in the daytime than at night-time (e.g., Lastovicka, 1997b). Using different radar observations, Bremer et al., (1997) detected trends in the prevailing wind components and the amplitudes of the diurnal and semidiurnal tidal wind components in the MLT-region, at heights between about 85 and 100 km. These trends, however, cannot be explained directly by an increase in the greenhouse effect. However, the well-known decrease of the stratospheric ozone content may play an important role in producing the trends in the tidal characteristics. Data from Antarctica can be very useful to study this topic (Jarvis, 2001).

According to model predictions (e.g., Rishbeth and Roble, 1992), doubling of the greenhouse gas concentration should lead to a significant cooling of the up-

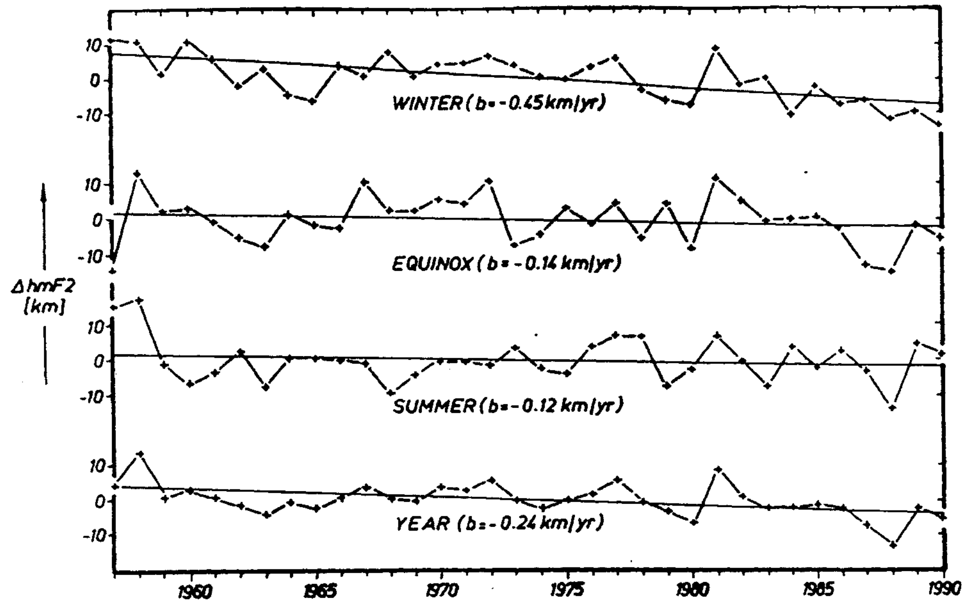

Figure 14. Seasonal and yearly trends of hmF2 at Juliusruh (Germany) after elimination of solar and geomagnetic influences (Bremer, 1998).

per atmosphere and resultant changes in F2-region parameters – a decrease of the height of maximum electron concentration (hmF2) by about 15 km, with only small changes in foF2. Long-term changes in hmF2 and foF2 which were in accordance with model predictions (at least qualitatively) were reported for some ionospheric stations in the northern and southern hemispheres, but the results do not provide a consistent pattern. Figure 14 shows an example of seasonal and yearly negative trends of hmF2 determined from ionosonde data from the mid-latitude ionospheric station at Juliusruh (Germany), from 1957 to 1990, after the elimination of solar cycle and geomagnetic influences. Trends for winter and the whole year are statistically significant with a confidence level of more than 99% (Bremer, 1992). More recently, Mikhailov and Marin (2000) and Marin et al. (2000, 2001) have analysed the long-term trends of foF2 and hmF2 over 30 northern hemisphere ionosonde stations during the interval 1965–1991. Whereas the majority of the observed foF2 trends seem to be negative, the hmF2 trends are seen to be positive. In the opinion of these authors a global warming in the lower atmosphere, accompanied by a cooling in the upper atmosphere due to the greenhouse effect, cannot be the cause of the observed trends. However, such long-term trends could be explained by an increase in F2-layer storm activity as a result of the increased geomagnetic activity observed during the time period analysed. In a recent article, Mikhailov et al. (2002) insist on the lack of man-made foF2 trends. Further studies are necessary, together with a thorough testing of the homogeneity of the data (e.g., Rishbeth, 1997; Ulich and Turunen, 1997; Bremer, 1998; Danilov, 1998; Jarvis et al., 1998).

7. Ionospheric Anomalies Apparently Related to Earthquakes and Their Use as Possible Seismic Precursors

The possible influence of earthquakes on the ionosphere is a special case of the “effects due to phenomena occurring below it” reviewed in this article. It constitutes an important and controversial subject that forms part of a broader topic (“seismo-electromagnetic effects") in which very different physical phenomena – variation of electric and magnetic fields near the seismic source, changes in telluric currents, VHF electromagnetic emissions before the earthquake, acoustic wave generation during the earthquake, etc. – are involved. The topic is far from new. Changes in magnetic susceptibility caused by compression were analyzed by Wilson in 1922 and the application of magnetometric methods in seismology and the use of atmospheric electric potential variations as a possible earthquake precursor were proposed by Kalashnikov and Bonchkovsky, respectively, in 1954. The Alaskan earthquake of March 1964 provided the first observations of ionospheric phenomena apparently generated by a seismic event (Davies and Barker, 1965; Leonard and Barnes, 1965; Row, 1966). Since then, many different ionospheric and magnetospheric anomalies have been associated with moderate or great earthquakes, and in recent years several reviews have been devoted to the description of the different phenomena associated with this subject (see, for instance, Park et al., 1993; Hayakawa and Fujinawa, 1994; Gokhberg et al., 1995; Johnston, 1997; Hayakawa, 1999; Herraiz et al., 2000; Varotsos, 2001).

The more important ionospheric anomalies related to seismic activity are observed prior to earthquake occurrence, and because of this they can be considered as being able to act as precursors. Nevertheless, it should be stressed that lately the seismological community has become more opposed to accepting that a particular physical phenomenon can be considered to be an earthquake precursor (Wyss, 1997) and even sceptical about the possibility of earthquake prediction (Geller et al., 1997; Kagan, 1997). This must be kept in mind when reviewing the possible earthquake-related ionospheric effects. In fact, not even the VAN (Varotsos, Alexopoulos and Nomicos) method (Varotsos and Alexopulos, 1984a,b; 1987), which is the electromagnetic proposal with the highest impact on seismology, has been accepted officially as an earthquake prediction technique. By analysing telluric current anomalies, these authors claim to have succeeded in the short-term prediction of several earthquakes in Greece. However, their statements are far from being accepted by seismologists (Geller, 1996, 1997) because they do not fulfil the requirements established by IASPEI (International Association of Seismology and Physics of the Earth’s Interior) (Wyss, 1997) and because the origin of the observed anomalies does not seem well established (Pham et al., 1999). Something similar happened with the increase in the background noise level of VLF waves ($3 \leq f \leq 30$ kHz) that was another phenomenon proposed to IASPEI as an earthquake precursor (Yoshino, 1997) but discarded after evaluation. Such criticism does not lessen the interest of research on the relationships between earthquakes and the ionosphere, but underlines the need to be wary of unfounded conclusions.

For the purposes of our review, ionospheric perturbations due to seismic sources can be classified into three groups:

- Anomalies in the parameters or in the behaviour of ionospheric layers.
- Variations in the characteristics of VLF and LF radio waves and in their transmission via the Earth-ionosphere waveguide.
- Emissions of VLF and ELF ($f \leq 3$kHz) electromagnetic waves in the epicentral region that are observed in the ionosphere.

In every case, the comparison of results given by different authors is very complicated because the data are obtained and analyzed using very dissimilar techniques.

Phenomena in the first group are generally small in size and can be easily masked by other ionospheric perturbations of different origin. Thus these anomalies are usually more noticeable at night and under quiet magnetic conditions. Logically, their low magnitude diminishes their capability to become a real seismic precursor. The first measurements of these anomalies were carried out by ground-based ionosondes located not far from the seismic area (although in several cases anomalies were claimed to have been observed at distances from the epicentre greater than 2500 km) but in recent years most observations have been obtained by topside sounding from satellites (Pulinets, 1998a). The main anomalies in this first group occur in values of foF2 and foE before an earthquake (Parrot et al., 1993, and references therein), sporadic E layer characteristics (Liperovskaya et al., 1994; Ondoh, 2000), F2 peak height (Pulinets and Kim, 1998; Sorokin and Chmyrev, 1999a) and E layer plasma density (Kim and Hegai, 1997; Chmyrev et al., 1999; Liu et al., 2001). The sign and the characteristics of these anomalies vary from one case to another, which diminishes their applicability. In many cases these perturbations take place 1–5 days before the earthquake. A summary of these anomalies and some differences between them and other kinds of ionospheric perturbations can be found in Pulinets (1998b). Recently, Hayakawa et al., (2000) conducted a preliminary but detailed analysis of the correlation between the global seismic activity distribution and plasma density variations recorded on board the Russian satellite Intercosmos 24. The large size of the database analyzed (cold plasma density averaged from about 10^7 points and earthquakes with magnitude greater than 5.0 occurring between 1989 and 1991) gives the results a good statistical grounding. With this information, the authors found a significant correlation between seismicity and plasma density at altitudes varying from 500 to 800 km for magnetically quiet days ($Kp < 3$) and during daytime hours (10–16 LT).

It is worth considering that, in the case of the F2 layer, some disturbances seem to be similar to those induced by military operations in the Persian Gulf War (Liperovsky et al., 1994). This confirms the importance of the anthropogenic impact on the ionosphere and raises the necessity of eliminating this influence before conducting the study of possible seismic effects (Liperovskaya et al., 1994).

The application of sub-ionospheric VLF/LF characteristics and propagation anomalies to earthquake prediction (the second group of perturbations) was introduced by Russian investigators who, using signals from the Omega transmitters (10–15 kHz) and the Omsk-Liberia and Omsk-Reunion links, found significant anomalies of amplitudes and phases preceding earthquakes with magnitude higher than 4 (Gokhberg et al., 1989). Ninety per cent of the perturbations before seismic events were observed at night. The anomalies reached 20 ms for phase delays and 100% for amplitudes, lasted 1.5–7 hours and were observed 1–5 days before the earthquakes. These perturbations confirmed the appearance of anomalous areas in the lower ionosphere preceding the seismic event. Use of this technique has been continued by many authors (see, for instance, Molchanov et al., 1998; Hayakawa and Molchanov, 2000) but seriously questioned by others (e.g., Rodger et al., 1999). The method seems to be useful only for crustal earthquakes with the epicentre located inside the Fresnel zone (Varotsos, 2001). Recently, Biagi et al. (2001) have reported variations in the attenuation of LF radio signals observed at ground-based receivers.

The existence of electromagnetic emissions originating during the pre-seismic period (the third group of perturbations) was first observed at ground level (Gokhberg et al., 1982; Yoshino et al., 1985) and, as we mentioned above, was unsuccessfully proposed to IASPEI as a seismic precursor in 1997. Specific observations of VLF radiation in the upper ionosphere over seismo-active areas made onboard satellites were initiated by the low-apogee Intercosmos 19 satellite in the late 1970s. This satellite crossed zones of well-located seismic activity and detected an anomalous increase in the intensity of radiowave emissions with frequency ranging between 0.1 and 16 kHz (Larkina et al., 1983, 1989). The reliability of the results was evaluated using the parameter D, defined as

$$D = 1 - \frac{\text{probability of an accidental effect in the spatial interval studied}}{\text{probability of a seismic event in the same interval}}.$$

According to this definition, $D = 1$ is the value corresponding to an absolutely reliable effect. The D values obtained by Larkina et al., (1989) vary between 0.8 and 0.9. This kind of observation has been continued by many other satellites over very different seismic areas (see, for instance, Molchanov et al., 1992; Chmyrev et al., 1997; Mikhailov et al., 1997a, b; Sorokin and Chmyrev, 1999a; Kim and Hegai, 1999; Borisov et al., 2001). Although in some cases no clear correlation between anomalous electromagnetic radiation in the upper ionosphere and seismic activity in the area below was established (Henderson et al., 1993: Rodger et al., 1996), the large number of cases in which this correlation seems clear gives strong grounds for belief in a real influence of earthquakes on the ionosphere. Satellite-based measurements have also led to the detection of electric fields and hydromagnetic waves in the ionosphere over seismo-active areas (Chmyrev et al., 1989).

The diversity of the phenomena described above indicates that the physical processes involved in their generation must be multiple and complex. It is not our aim in this short overview of the topic to present the explanations proposed for the phenomena, and we refer, for example, to Parrot et al. (1993); Pulinets (1998b); Sorokin and Chmyrev (1999b) and Varotsos (2001) to provide different stages and perspectives on these explanations. Here we are only going to summarise the main steps in understanding the problem.

First considerations necessarily refer to the mechanisms that generate the electric and magnetic anomalies in the hypocentral area preceding earthquakes. At this point, due to the low efficiency of stress variations in generating electromagnetic signals, the existence of some other physical processes is required. Emanation of chemical substances (mainly radon, light gases and aerosols with a high metal content) from the Earth has been considered a strong candidate by many authors. Changes in the chemistry of the near-ground layer caused by these emissions can alter the electrodynamic characteristics (particularly the electrical conductivity) of the atmosphere over the seismo-active area and cause strong modifications (up to hundreds of V/m) of the vertical electric field near the surface (Kim et al., 1994). The anomalies observed in the transmission of VLF waves over the seismic area can be explained by these changes in the electrodynamic conditions as well.

The second step concerns the transmission of the electromagnetic anomalies from the epicentral area to the ionosphere. Kim et al. (1994) solved this problem for a strong electrostatic field (assumed to have a Gaussian-like distribution) and showed that the efficiency of the penetration depends directly on the extent of the seismic source area, being noticeable only when its scale exceeds 100 km and the initial vertical field exceeds 1000 V/m. They also observed that the efficiency at night is much greater than in the daytime.

The final step (effects on the ionosphere) can be explained as resulting from the influence of this quasi-stationary electric field. The electron temperature of the E layer is increased by Joule heating, giving rise to small-scale ionospheric anomalies (Pulinets, 1998b) and acoustic gravity waves (Hegai et al., 1997) that generate a dissipative instability at the Brunt-Vaïsala frequency and give rise to periodic irregularities in the horizontal conductivity. Observed ELF waves can be explained in either the context of the interaction of these irregularities with the electric field and Alfvén waves (Chmyrev et al., 1999) or, according to Borisov et al. (2001), as the result of the emission in the upper ionosphere of whistler mode waves. These latter waves are generated by the interaction of thunderstorm-related electromagnetic radiation and irregularities in ionospheric conductivity in the lower ionosphere with an earthquake-related origin.

To summarise the ideas presented in this section we can say that there exist several ionospheric phenomena that can be seriously considered as expressions of earthquake generation, but that the statistical significance of a connection between seismological and ionospheric activity has not been proved (Rodger et al., 1996) and, with present knowledge, these ionospheric phenomena cannot be used for earthquake prediction purposes. Another problem is that identical ionospheric phenomena may often occur in the absence of any related seismic activity, being caused by quite different agents.

8. Summary

The ionosphere, embedded in and tightly coupled to the thermosphere, is strongly influenced by couplings from other geophysical regions. In addition to ionizing energetic solar radiation from above, both the magnetosphere and plasmasphere greatly affect the ionosphere through the precipitation of soft and energetic charged particles, heat conduction, and fluxes of thermal particles. Below, the middle atmosphere affects it through upwardly propagating waves (gravity waves, tides and planetary waves). Exploring these couplings effectively furthers our understanding of at least the dominant processes and interactions that play such an important role in determining the character of this part of the Earth's environment.

Perhaps the major advance in recent years has been the acceptance of meteorological processes as at least a potential cause of ionospheric variability, and not something from the realm of science fiction. Hopefully, progress will be even more rapid in the decades to come. Studies of meteorological effects in the ionosphere are actively under way and the main aim of this review paper is to stimulate these investigations. Whilst some details about coupling between the middle atmosphere and ionosphere are moderately well understood, there are large gaps and deficiencies in our current understanding. Further measurements and modelling are undoubtedly required. Measurements of quantities associated with neutral particles in the ionosphere are particularly important if this coupling is to be better understood. But due to the current paucity of efficient experimental methods for measuring neutral properties of the ionosphere, the importance of modelling studies in parallel with new observations must also be recognized.

We expect to see the further breakdown of the traditional isolation of the ionosphere from the lower atmosphere. Since the upper atmosphere generally provides a good indication of solar activity, we might assume that a correlation between tropospheric and ionospheric parameters indicates such a solar activity-weather link. The question of the lower/upper atmosphere coupling is a major challenge for ionospheric physics to which the growing science of aeronomy and meteorology may be able to make an important contribution.

The only appropriate way to place this relationship on firm ground is via the study of causal mechanisms. Because of the complexity of possible relationships it is clear that a multi-disciplinary approach is required in future investigations, that is contributions in the fields of meteorology, climatology, aeronomy, ionospheric physics, atmospheric electricity, and plasma physics are needed. Further regional, national and international cooperative efforts are required to organise a global monitoring system for atmospheric oscillations using various new techniques. Continuous observations from such networks would permit planetary waves, atmospheric tides and gravity waves to be resolved, and the hypothesis that such motions propagate upward from the lower atmosphere or whether they are generated *in situ* could be examined critically using observational data.

Ionospheric weather (hour-to-hour and day-to-day variability of ionospheric parameters) awaits explanation and prediction in the framework of climatological, solar cycle and seasonal variations. If we are to understand and possibly forecast the ionospheric variability, then all factors, including the coupling from below, need to be considered.

What is desired is a quantitative understanding of all the significant couplings, trigger mechanisms and feedback processes. Of practical concern are chains of processes that have final results important to life on Earth, have effects on communications and technological activities, and make an impact on the conduct of scientific observation of natural phenomena.

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