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The ionosphere: aeronomical and meteorological aspects

Edward KAZIMIROVSKY
Institute of Solar-Terrestrial Physics, 664033 P/B 4026, Irkutsk, Russia

«Every truth is fated to enjoy only one moment
of triumph between infinity when it is considered
misleading, and infinity when it is considered trivial...»

H. POINCARE

ABSTRACT

An overview in brief of the main ionospheric processes are presented and couplings from below are stressed. The D-region aeronomy, the winter anomaly of radiowave absorption, wave disturbances and regional features of the thermospheric wind regime, the sporadic E-layer occurence and structure, the variations of atmospheric emissions, the global morphology and temporal variability of F-region, F-spread events etc. should be considered in connection with tropospheric and stratospheric processes. There are evidences for interactions between phenomena associated with thunderstorms and ionosphere. The long-term trends in some thermospheric and ionospheric parameteres could be the sequence of the greenhouse gases concentration. Some of experimental ionospheric data may be explained as being the result of the forcing driven by upward propagation of the broad spectrum of internal atmospheric waves (planetary waves, tides and gravity waves) from the numerous tropospheric and stratospheric sources.
Key words: Middle Atmosphere, Ionosphere, Aeronomy, Meteorology, Coupling.

1. INTRODUCTION

The study of the Earth's atmosphere is of interest to scientists from many disciplines and present day knowledge and understanding of the atmosphere from the ground to the highest levels is the result of the combined contributions of meteorologists, physicists, chemists, astronomers, geomagneticians, radio engineers and space scientists. This range of scientific disciplines has, not unexpectedly, been matched by an equally extensive variety of experimental approach from standard meteorological instrumentation to the 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 we now have of the physical state of the earth's upper atmosphere. The sum total of this knowledge is now very extensive and in this paper I can only touch upon a few selected generally accepted topics, especially in the part concerning fundamentals of ionospheric aeronomy.

The Chambers Dictionary of Science and Technology denotes a 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 wave and particle radiation. The ultraviolet and X-radiations are absorbed at varions levels between about 40 and 200 km. The selective absorption of the ultraviolet and X-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. Other ultraviolet radiation is very effectively absorbed lower down in the atmosphere by ozone.

In addition to electromagnetic - wave radiations the sun also emits continuously 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 kilometers per second. They interact with the geomagnetic field in a complicated way, and with the gases of the upper atmosphere. As a result we can observe the geomagnetic storms, the disturbances to long-distance radio-wave communication via the ionosphere and the visible auroral displays at high latitudes. All these events are closely associated with the occurence of sunspots and show characteristic time variations over 11 years and 27 days, respectively, related to the sunspot cycle and the period of rotation of the sun. We may say that the atmosphere absorbs and redistribute globally the variable components of the solar energy falling on them. 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 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 can not be fully described by the equations of the 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 only of 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 to understand how the ionosphere is formed and buffeted by sources from above and below and to deal with production and loss processes.

Meanwhile until recently the ionosphere was studied as a merely magnetoactive plasma without consideration of the general properties of the atmosphere. It was known that the neutral atmosphere (thermosphere) and ionosphere are linked by electrodynamic and momentum transfer. Nevertheless almost nobody beleived that the terms «meteorology» and «climatology» can be applied to the ionosphere, it was thought that no connection existed between events, occuring in the troposphere/stratosphere system on one hand and in the ionosphere on the other hand. Meanwhile, however, it has 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 each of them in isolation. Gradually, the viewpoint that the lower and upper atmosphere are substantially uncoupled was rejected. A lot of discoveries and experimental results have confirmed the existence of detailed correlations between the parameters of the lower and upper atmosphere (*Kazimirovsky and Kokourov, 1991*).

But what is the reason of correlations? As part of a 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 at least up to 100-115 km was introduced as «coupling from below» (*Bowhill, 1969*) and is considered as a mechanism of the meteorological influence on the ionosphere. This influence has been assumed and is presented by various models.

The meteorology of the thermosphere differs considerably from the associated with the familiar weather patterns we experience at the Earth surface, although the fluid motions are governed by the same equations as those used by meteorologists studying the weather systems. In the thermosphere temperature increases with altitude, making for a dynamical system that is less dominated by instabilities than 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 strongly couple the neutral thermosphere to the ionosphere and thereby, to the magnetosphere. It is now established beyond doubt that the atmosphere extends from the ground to the thermosphere, behaving as a complex system coupling fairly closely over wide height ranges.

For the aeronomical models, the major questions now posed relate to the interactions or coupling between regions, interactions that are currently only crudely parameterized within the separate models. This is particulary true for the upper atmosphere, where a rich set of physical processes have 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 modem climatological research. For instance, it is still unsolved 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 upper boundary - thermosphere/ionosphere. May be such changes are left 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-atmosphere 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 very interesting problem «The role of the Sun in Climate Change» requires the special consideration elsewhere.

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

Many of the ionospheric phenomena cannot be explained in terms of photochemical processes, solar particle injections or solar flare effect. It seems likely that there are some events due to effect of atmospheric oscillations, such as winter anomaly of radiowave absorption, E-sporadic layer occurrence and structure, thermospheric wind regime, the variations of atmospheric emissions, travelling ionospheric disturbances, day-to-day midlatitude ionospheric variability, F-spread event etc.

The purpose of this paper is to review shortly some fundamentals of ionospheric aeronomy and some observational backgrounds for the suggestion of a genuine link between processes in the lower atmosphere and 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 author 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. THE IONOSPHERE - BASIC CONCEPTS

The Earth's atmosphere and ionosphere must be considered as a part of solar-terrestrial environment. This is the region of space closest to the planet, a region close enough to affect human activities and to be studied from the Earth. It is not only the familiar atmosphere of meteorology nor is it the interplanetary space of astronomy, though it interacts with both. The atmosphere and ionosphere are greatly affected by energy arriving from the Sun. This system is a region of interactions and boundaries; interactions between solar and terrestrial magnetic fields, between magnetic fields and charged particles; and boundaries between regions dominated by different energetics, structure and dynamics. So, heliosphere, magnetosphere, ionosphere and atmosphere, while they keep their identities and have their own territories with specific physical/chemical processes, are closely interacting and exchanging energy and material. Basic interaction channels between the principal domains of the solar-terrestrial system from the Sun up to troposphere are shown on *fig. 1* (*STEP, 1990*).

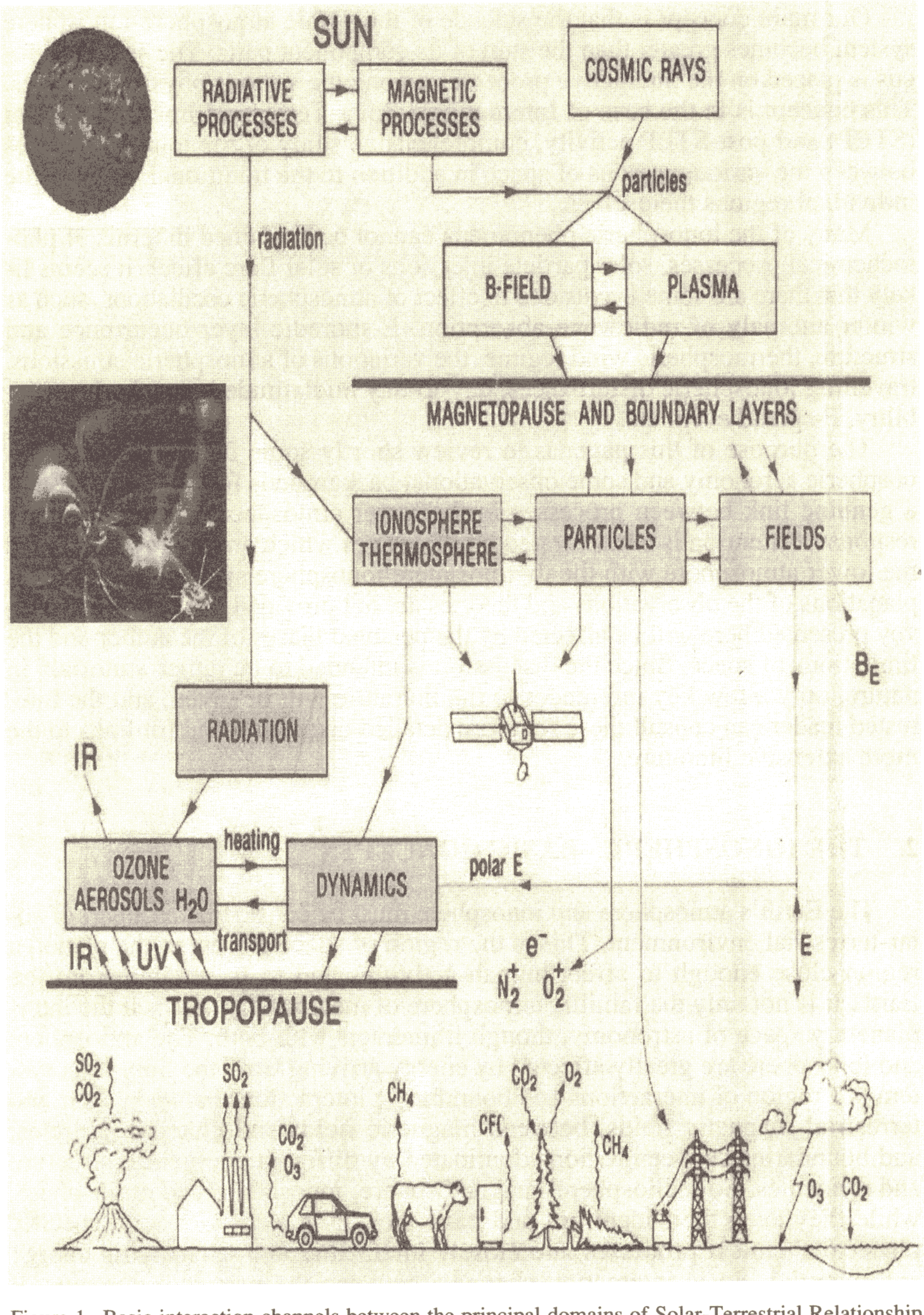

Figure 1. Basic interaction channels between the principal domains of Solar-Terrestrial Relationship System: Sun and solar wind, magnetosphere and ionosphere, middle atmosphere and troposphere.

Owing to pervasive influence of gravity, the atmosphere and ionosphere are to first order horizontally stratified and conventionally divided into layers based on the vertical structure of different parameters. Atmospheric structure can be neatly organized by a representative temperature profile, while the ionosphere more sensibly organised by the number density of plasma. Schematic representation of atmospheric regions is shown on *fig. 2* (*Whitten and Poppoff, 1971*).

In the following text we use terms «upper atmosphere» and «middle atmosphere», which are absent on *fig. 2*. In the past meteorologists often designated the entire region above the tropopause as the «upper atmosphere». But rather recently the term «middle atmosphere» became popular in referring to the region from the tropopause to the turbopause and even to lower thermosphere.

It is known that the minor species occur in the middle and upper atmosphere such as argon, ozone, atomic oxygen, nitric oxide, hydroxyl radicals, hydrogen and helium and that at even higher altitudes the atomic species become the major constituents as a result of the radiation-atmosphere interactions. These interactions are complicated and intricate. The most energetic radiations ionize the atoms and molecules that they encounter; less energetic radiations dissociate molecules and excite atoms and molecules; the last energetic radiations excite molecules and detach weakly bound electrons from negative ions. The frequency and relative importance of these reactions depend on the spectral irradiance of solar and galactic emissions as well as on the distribution of atmospheric constituents and temperatures; these are known to vary with the time of day, latitude, season, solar sunspot cycle, and irregular solar disturbances.

The ionized atmosphere of the earth is composed of a series of overlapping layers. In each layer there is an altitude of maximum density, above and below which the ionization density tends to drop off. The typical electron density profiles for sunspot maximum and minimum, day and night, are shown on *fig. 3* (*Kelley, 1989*). In daytime the extreme ultraviolet (EUV) radiation in the solar spectrum is incident on a neutral atmosphere that is increasing exponentially in density with decreasing altitude. Since the photons are absorbed in the process of photoionization, the beam itself decreases in intensity and increasing neutral density provides a simple mechanism for generation of the basic large scale layer of ionization shown on *fig. 3*. The peak plasma density occurs in the so-called F2 layer and attaines values as high as 10^6 cm^{-3} near noontime. The factor that limits the peak density value is recombination rate, the rate in which ions and electrons combine to form a neutral molecule or atom. This in turn very much depends on the type of ion that exists in the plasma and its corresponding interaction with the neutral gas.

The profile on *fig. 3* is valid only for midlatitude. In the equatorial region, the profile is distorted by the geomagnetic field, and in the polar region, the profile is distorted by ionization by energetic particles, magnetospheric coupling, and other effects.

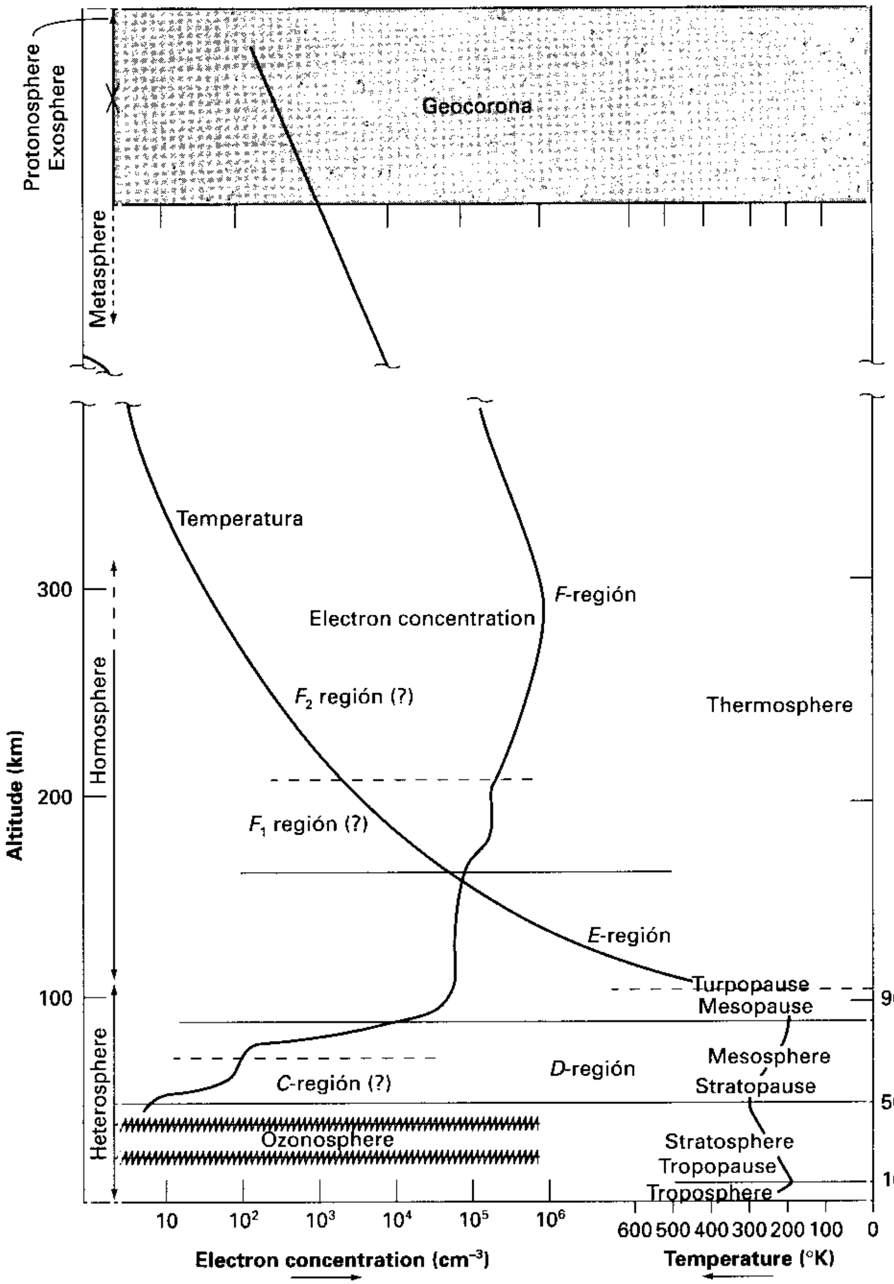

Figure 2. Schematic representation of atmospheric regions. Classification of atmospheric layers in accordance with temperature (right) and with electron concentration (left).

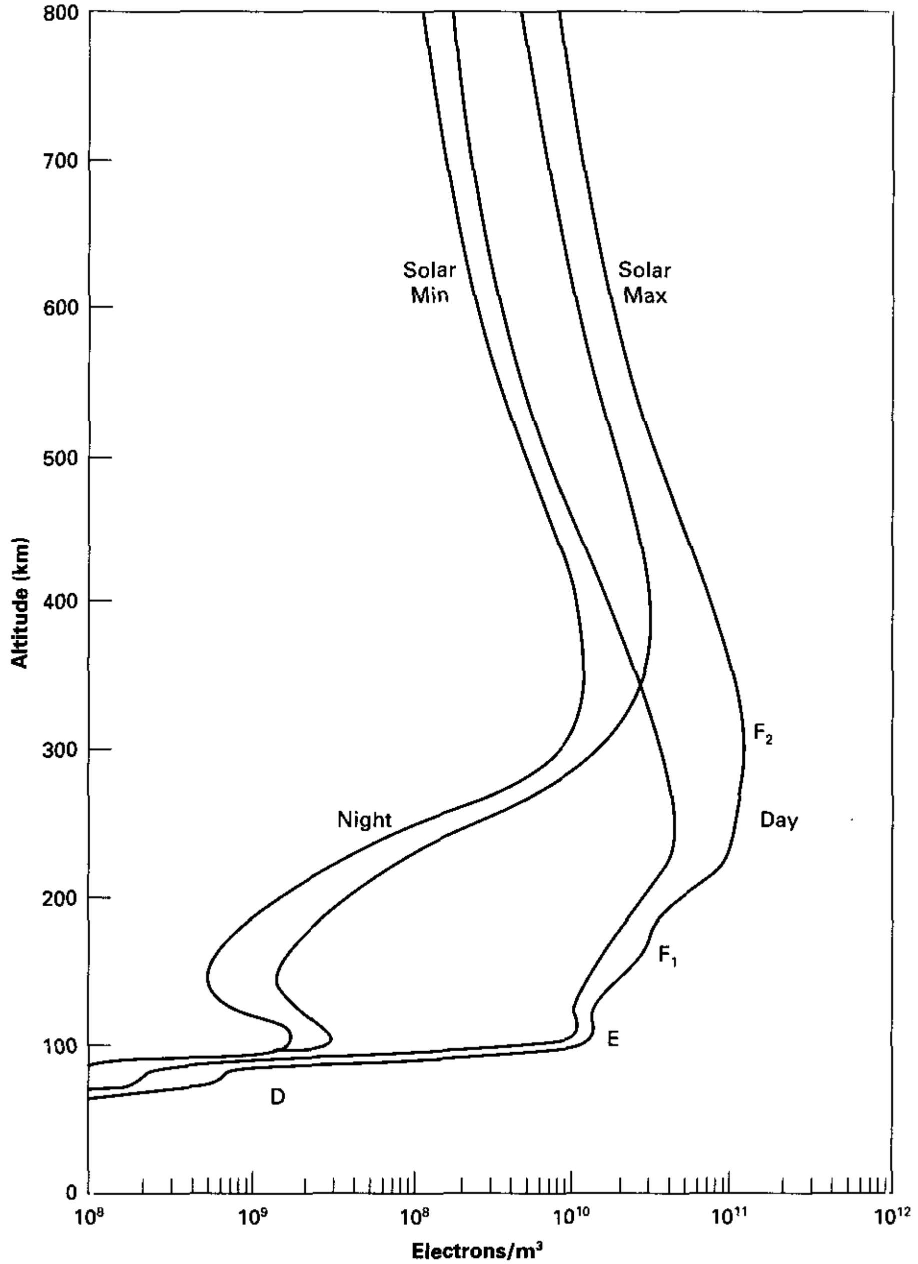

Figure 3. Typical midlatitude electron density profiles for sunspot maximum and minimum, day and night. Different regions of the ionosphere are labelled D, E, F1 and F2.

The ionosphere may be defined as the part of the earth's upper atmosphere where ions and electrons are present in quantities sufficient to affect the propagation of radio waves. (*Davies, 1990; Hansucker, 1991*). It extends down to perhaps 50 km and thus overlaps the mesosphere and thermosphere; the symbols D, E, F1 and F2 are used to distinguish its various parts. It has no well-defined upper boundary, but merges into the magnetosphere and the protonosphere which is composed principally of ionized hydrogen. The ionosphere is formed by the ionization of atmospheric gases such as N_2, O_2 and O. There is a dynamic equilibrium in which the net concentration of free electrons, electron density, depends on the relative speed of the production and loss processes. In general terms the rate of change of electron density N is expressed by a continuity equation:

$$\frac{\partial N}{\partial t} = q - L - \mathrm{div}\,(N\bar{V}) \tag{1}$$

where q is the production rate, L – is the loss rate by recombination, and $\mathrm{div}(N\bar{V})$ expresses the lost of electrons by movement, $\bar{V}$ being their mean drift velocity. During the day the intensity of ionizing radiation varies with the elevation of the Sun, and the electron density responds. At night the source of radiation is removed and the electron density decays.

Below and near 100 km, N_2 and O_2 have the same ratio as in the lower atmosphere regions and dominate the gas. Near 110 km (E-region) the amount of atomic oxygen reaches that of O_2, and above about 250 km the atomic oxygen density also exceeds that of N_2. This trend is due to the photodissociation of O_2 by solar UV radiation coupled with the absence of turbulent mixing above turbopause. Near the peak in the plasma density the ions are nearly all O^+, corresponding to the high concentration of atomic oxygen in the neutral gas. Below the peak NO^+ and O_2^+ become more important dominating the plasma below about 150 km. At nighttime, in lower altitudes regions, where molecular ions dominate, the density is sharply curtailed. The O^+ plasma density, on the other hand, is sustained through the night. The sunrise and sunset effects are very dramatic at the lower altitudes but are almost nonexistent in the F-region.

The substantial difference in ion behaviour is due to the fact that molecular ions have a much higher recombination rate with electrons than do atomic ions. The two reactions that occur in a recombination are of the type

$$NO^+ + e^- \rightarrow N + O \tag{2}$$

and

$$O^+ + e^- \rightarrow O + h\nu \tag{3}$$

The former process is called dissociative recombination since the molecule breaks apart, while the latter is termed radiative recombination since emission of a photon is required to conserve energy and momentum. The former process has a reaction rate nearly 1000 times higher than the latter, which results in a much shorter lifetime for molecular ions than for atomic ions. Since the molecular ions are much shorter lived, when their production is curtailed at night, rapid recombination quickly reduces the plasma concentration. The O^+ ions at higher altitudes often survives at night at concentrations between 10^4 and 10^5 cm^{-3}.

Photoionization by solar UV radiation is not the only source of plasma in the ionosphere. Ionization by energetic particles impact on the neutral gas is particularly important at high latitudes. The primary reactions, however, are only the initial reactions of a long and complex web of events. Several hundreds of known reactions occur simultaneously and from the frustrating inconsistencies that sometimes are noted between theory and observations, we might suspect that hundreds of unknown reactions are also involved. Nevertheless, it is possible (only for brief description) to get the overview of the main peculiarities of the ionosphere, shown at Table 1. (*Rishbeth and Garriott, 1969*). Here α_{eff} is so called an effective recombination coefficient that represents all recombination reactions. If dN/dt and N are measured and q is calculated (as is often done) α_{eff} is computed by using the relationship

$$\frac{\partial N}{\partial t} = q - \alpha_{eff} N^2 \tag{4}$$

Ion production (D region): Ionization by solar X-rays, or Ly (ionization of NO. Enhanced ionization following solar flares due to X-ray ionization of all species. Electron attachment to O and O_2 forms negative ions; ratio of negative ions to electrons increases with depth and at night.

Recombination (D region): Electrons form negative ions, which are destroyed by photodetachment (daytime only), associative detachment ($O + O^-$ (O_2 + e), and mutual neutralization ($O^- + X^+$ (O + X).

Ion production (E): Ionization of O_2 may occur directly by absorption in the first ionization continuum ($h\nu > 12.0$ eV). Coronal X-rays also contribute, ionizing O, O_2, and N_2. Nighttime E and sporadic E (thin patches of extra ionization) are due to electron and meteor bombardment. Some Es radio reflections may be due to turbulence in normal E layer.

Recombination (E): Dissociative recombination O_2^+ + e (O + O and NO^+ + e $\rightarrow$ N + O.

Ion production (F1): Ionization of O by Lyman «continuum» or by emission lines of He. This ionization probably accompanied by N_2 ionization, which disappears rapidly after sunset.

Recombination (F1): O^+ ions readily transfer charge to NO and perhaps to O_2^+. Most of the ionization is thus in molecular form and dissapears by dissociative recombination.

Table 1: *The ionosphere*

Region	*Nominal height of layer peak*	$N_{e(max)}$ (cm^{-3})	α_{eff} (cm^{-3}/sec)
D	90 Lower following solar flare	1.5×10^4 (noon) absent at night	3×10^{-8}
E	110	1.5×10^5 (noon) $< 1 \times 10^4$ (night)	10^{-8}
F1	200	2.5×10^5 (noon) absent at night	7×10^{-9}
F2	300	10^6 (noon) 10^5 (midnight)	$10^{-10} - 10^{-9}$
		Height and electron density highly variable. Large daily seasonal, and sunspot-cycle variations are combined with general erratic behaviour	Variable; probably decreases with increasing-height

Ion production (F2): Ionization of O by same process producing F1; F2 formed because α_{eff} decreases with increasing height; F2 region produces little attenuation of radiation. Additional ionization processes may contribute in F2 that are attenuated in F1.

Recombination (F2): Recombination of molecular ions as in F1; but limiting process is here charge transfer, giving an attachment-like recombination law.

The D-region is probably the most complex region in an ionosphere. There is considerable doubt that distinct layer exist in this region, but there is no doubt that perturbations of this region are closely related to internal atmospheric/meteorological processes. The middle atmosphere, thermosphere and ionosphere make a complex coupling system. The dynamical and chemical processes in this system are controlled by various types of energy sources: solar UV and EUV energies, energies originating in the solar wind-magnetosphere interaction and dynamical energies of upward propagating atmospheric planetary waves, tides and internal gravity waves. The thermal energies of the thermosphere and ionosphere heated by solar EUV, auroral particles and Joule heating heat conduction, downward eddy diffusion and electromagnetic processes, while atmospheric gravity waves, tides and planetary waves transport energy and momentum into the mesosphere and thermosphere from the lower atmosphere. The altitude range between 80 and 150 km is particularly interesting since the region couples almost equally to both the middle atmosphere and the magnetosphere.

Because our society is becoming increasingly dependent on technological systems that can be affected by ionospheric phenomena during geomagnetic storms, the ionosphere, its electrodynamics, and its coupling with the neutral atmosphere and the magnetosphere are being studied as part of a coordinated international program of «space weather» research.

The brief but thorough description of the ionospheric electrodynamics was made by *Richmond, 1998,* partly quoted below.

The ionosphere electron density is highly variable, depending not only on the ionization sources but also on ion-neutral chemical transformations, ion-electron recombination, and plasma transport by neutral winds, electric fields, and diffusion. The positive-ion number density is essentially identical to the electron density in the E and F regions, but is greater than the electron density in the D-region, where negatively charged ions are also present.

The ionospheric electrical conductivity is highly anisotropic, owing to the strong influence of the geomagnetic field on charged-particle motion. At high altitudes, where collisions between ions and neutral air molecules and infrequent, the ions and electrons gyrate around magnetic-field lines, though they are free to move parallel to the field, so the direct-current conductivity along the magnetic field is much larger than the conductivity perpendicular to the field at all heights above 90 km. At lower altitudes, collisions between the ions and neutrals become more frequent, decoupling the electron and ion motions in the plane perpendicular to the magnetic field, so that more significant amounts of current can flow in that plane. The direct-current conductivity perpendicular to the magnetic field is largest at heights of 90-150 km during the day and in the nighttime auroral zone. Further anisotropy of conductivity occurs due to Hall effect which causes the direction of the current to deviate from that of the electric field an effect maximizing around 100 km altitude.

The two main sources of global-scale electric field generation in the ionosphere are the ionospheric wind dynamo and the solar-wind/magnetospheric dynamo. A third source, thunderstorm activity, is beleived to contribute only in a minor way, though at night it may be locally important. Winds in the thermosphere move the conducting medium through the geomagnetic field, producing the electromotive force that drives currents and sets up polarization electric fields. That dynamo action is weighted toward the 90-150 km height range during the day. At night, however, the E-region transverse conductivity is greatly diminished, so that F-region dynamo action above 200 km becomes more important. The ionospheric currents are strongest on the dayside of the Earth.

When the dynamo effects in the two hemispheres are unbalanced, the currents are connected by a magnetic field-aligned current.

The solar wind/magnetospheric dynamo draws its energy from the kinetic and thermal energy of the solar wind and magnetospheric plasmas and depends strongly on the direction of the interplanetary magnetic field that is embedded in the solar wind. The ionospheric electric fields and currents produced by this mechanism are usually much stronger than those of ionospheric wind dynamo, and are highly variable in time.

The thermospheric winds experience a significant drag force as the electric currents they generate flow through the geomagnetic field. This force is known as «ion drag» because it results from collisions between ions and neutral molecules moving at different mean velocities.

At middle and low latitudes, winds in the ionospheric dynamo region tend to be dominated by global oscillations. Above 140 km, daily wind oscillations with magnitudes over 100 m/s are driven primarily by the absorption of far-ultraviolet solar radiation. Between 90 and 140 km the oscillations are strongly influenced by upward propagating global waves, called atmospheric tides, that are generated by solar heating at lower altitudes: in the upper ozone layer and in the troposphere. As the tides propagate into regions of exponentially decreasing air density, their amplitudes can grow, reaching values of 100 m/s or so in the lower thermosphere before the waves dissipate. The generation and propagation conditions for these waves tend to favor the arrival of semidiurnal (12-hour) tides over diurnal (24-hour) tides in the dynamo region.

Upward propagating planetary waves are also believed to influence winds in the lower thermosphere, but their relative importance there has not yet been established.

Variations in the sources of the winds, as well as variations in the propagation conditions of tides and planetary waves through the middle atmosphere, are responsible for variability of the thermospheric winds.

The ideas above described provide a set of basic concepts that may be expected to govern the behaviour of the ionosphere. The structure of the ionosphere covers all the scales of space and time that are open to observation; the total picture is therefore a complex one. Nevertheless we may observe the regular variations that tend to repeat from one day to the next, or from one year to the next. Historically, ionospheric observations have been compared with simple Chapman theory for the production of an ionospheric layer, and major departures from the theory were called «anomalies». But some of the classical anomalies have been explained by taking large-scale movements of ionization into account. The causes of some of the others remain in doubt, though in most cases possible causes are known and the problem now is to identify the correct mechanism from among several candidates. (*Hargreaves, 1992*).

The behaviour of the ionospheric *E-layer* is close to simple theory. On average, the peak electron density varies with solar zenith angle χ as $(\cos \chi)^{1/2}$. In fact the E-region does not quite disappear at night. The region remains weakly ionized with electron density about $5 \cdot 10^3$ cm^{-3}, compared with 10^5 cm^{-3} by day. The night ionization is irregular with height. Even during the day the electron density does not always vary smoothly with height, and narrow layers called *sporadic-E* can develop. Typical sporadic-E layers are only a few kilometres thick at middle latitudes. The main cause is thought to be a change of wind speed with height, a wind shear, which in the presence of the geomagnetic field can act to compress the ionization. Sporadic-E layers are detected at many latitudes, and several different kinds are recognized. The different diurnal and seasonal patterns are observed at high, middle and low latitude, and each type arises from a different mechanism.

The *D-region* also exhibits strong solar control, but its behaviour strongly depends on the very complex photochemistry of the D-region. The popular way of observing the long-term variation of the D-region is to measure the absorption of radio waves reflected from the E-region. The absorption depends on both the electron density and collision frequency. When looking at the seasonal variation of radio absorption an «winter anomaly» appears, which again involves the complex ion chemistry of the D-region and related to meteorology of the stratosphere (see below).

The behaviour of *F2 region* appears to be «anomalous» in many ways if it is considered only against the Chapman theory. It is necessary to include the vertical diffusion of plasma in order to understand the existence of the F2 region at all. The major classical «anomalies» of the F2 region at middle latitudes are as follows:

1. The diurnal variation may be asimmetrical about noon.
2. The diurnal variation is not repeatable from day to day.
3. The seasonal variation is «anomalous» in several ways - the maximal electron density at noon are sometimes greater in winter than in summer (seasonal anomaly); the averaged over the whole Earth electron densities are greater in December than in June (annual anomaly); the electron content is abnormally high at the equinoxes (semi-annual anomaly).
4. A substantial F2 region is maintained at night.

It is not possible or necessary to go into a full discussion of all the complexities of the behaviour of the F2 regions, but we should note that all models are based on: chemical changes, diurnal heating and cooling, winds and electric fields, effects related to the sunspot cycle. More recent work has led to an appreciation of the importance of ionization movement, including thermosphere - ionosphere interactions. (*Rishbeth, 1998; Wickwar and Carlson, 1999*).

Finally, the atmosphere and ionosphere are linked dynamically, radiatively and chemically. It is the reason, why in the following paragraphs we discuss the atmospheric dynamics and lower ionosphere from the meteorological positions. Aeronomy is the study of upper atmosphere physical and chemical processes including ionospheric processes. Electrical engineers are interested in nosphere are the ionospheric wind dynamo and the solar-wind/magnetospheric dynamo. A third source, thunderstorm activity, is beleived to contribute only in a minor way, though at night it may be locally important. Winds in the thermosphere move the conducting medium through the geomagnetic field, producing the electromotive force that drives currents and sets up polarization electric fields. That dynamo action is weighted toward the 90-150 km height range during the day. At night, however, the E-region transverse conductivity is greatly diminished, so that F-region dynamo action above 200 km becomes more important. The ionospheric currents are strongest on the dayside of the Earth.

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The thermospheric winds experience a significant drag force as the electric currents they generate flow through the geomagnetic field. This force is known as «ion drag» because it results from collisions between ions and neutral molecules moving at different mean velocities.

At middle and low latitudes, winds in the ionospheric dynamo region tend to be dominated by global oscillations. Above 140 km, daily wind oscillations with magnitudes over 100 m/s are driven primarily by the absorption of far-ultraviolet solar radiation. Between 90 and 140 km the oscillations are strongly influenced by upward propagating global waves, called atmospheric tides, that are generated by solar heating at lower altitudes: in the upper ozone layer and in the troposphere. As the tides propagate into regions of exponentially decreasing air density, their amplitudes can grow, reaching values of 100 m/s or so in the lower thermosphere before the waves dissipate. The generation and propagation conditions for these waves tend to favor the arrival of semidiurnal (12-hour) tides over diurnal (24-hour) tides in the dynamo region.

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Variations in the sources of the winds, as well as variations in the propanon-linearity become very important in this critical layer. It may be expected to be enhanced dissipative region for planetary waves or under some conditions the critical layer remains a perfect reflector of planetary waves.

The most spectacular manifestations of planetary waves activity in the middle atmosphere, associated with strong coupling between stratosphere and lower atmosphere, occur during stratospheric sudden warming events. The zonal-mean climatological temperature and zonal wind configuration is dramatically disrupted, with polar stratospheric temperatures increasing rapidly with time, leading on occasion to reversals of zonal-mean winds from westerlies to easterlies.

Current theories suggest that a major sudden warming is initiated by an 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 southward (*Andrews et al., 1987*).

Our understanding of all the observed details of these events, the necessary conditions for their occurence, 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 implication of the theory for the modelling of planetary waves and for interpretation of atmospheric observations are not yet absolutely clear and new experimental information concerning the behaviour and effects of planetary waves, especially in the lower and upper thermosphere is very important.

Atmospheric tides are global-scale oscillations, which are primarily forced by variations of heating due to absorption of solar ultraviolet radiations 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 through great depths of the atmosphere and can attain large amplitudes at some heights especially in the thermosphere. The semidiurnal tide plays a particularly important role in the lower thermosphere, where the global temperature and density variations are dominated by this mode. 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 the modern theoretical calculations the semi-diurnal tide in the thermosphere is considered as a result of propagation from below.

The non-migrating tides (associated, for example, with orography and geographically fixed tropospheric heat sources) would give to longitudinal differences in tidal structure.

In the classical tidal theory (inviscid atmosphere, background temperature is independent of latitude) the governing equation is separable, giving rise to vertical and latitude structure equations. But in the real atmosphere with winds and meridional gradients of temperature the governing equation may be solved only numerically.

Now the modellers try to include in the models the 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, hydromagnetic coupling - all for viscid, rotating, spherical atmosphere (*e.g. Forbes, 1991*).

Internal gravity waves (IGW) are disturbances which are allowed to propagate as a consequence of buoyant forces present in the atmosphere. The temperature and wind structures determine the wave's propagation characteristics.

Many sources for middle atmosphere gravity waves have been identified. These include airflow over orography, severe weather fronts, instabilities in the planetary boundary layer and in jet stream shears, turbulent motions of different scales, thunderstorms.

At heights above 85-90 km the internal gravity waves may be «saturated» and even be breaked with deposition of energy and momentum. The «traping» of IGW is also possible, for this reason one would expect IGW to be ducted in the region near 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 and airglow fluctuations in the 80-120 km height range and the amplitudes are so large that they can dominate at these altitudes (*e.g. Vincent, 1990; Gavrilov, 1992*).

Recently the effect of gravity waves have been investigated successfully to estimate the contribution of these sources of variations in the within an hour and hour to hour variability of f_0F2 i.e. critical frequency corresponding and proportional to maximal electron concentration in the ionosphere (*Boska et al., 1996;1999*). Fluctuations for electron density on the fixed heights can be caused either by fluctuations in the ionized matter (i.e. gravity waves) or by fluctuations in the ionizing radiation, high-energy electrons related to geomagnetic / magnetospheric activity, etc. But we can believe that at middle latitudes and for rather quiet geomagnetic conditions the fluctuations in the period range 10 min - 3 hours are not of solar or magnetospheric origin.

There is much uncertainty as to individual gravity wave sources as well as the wave's ultimate fate.

3.2. Meteorological control of the lower ionosphere

An atmospheric layer, located at about 60 to 120 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 atmosphere at 60-90 km weakly ionized (mainly at daytime) is the interface between the neutral and ionized layers.Turbulent diffusion is dominant below about 100 km, while molecular diffusion process overwhelms in an upper height range. Therefore, different processes seem to compete in this height region, making the atmospheric behaviour quite interesting. Their detailed mechanisms, however, have not be clarified yet to a lack of an accurate in-situ measurement technique.

What experimental evidences suggest the existence of an at least temporary coupling between the two levels of the atmosphere? (*Danilov et al., 1987*).

1. The significant correlations of ionospheric and stratospheric / tropospheric parameters - e.g. radiowave absorption from one side and stratospheric temperature, height of isobaric surfaces, total ozone content etc. from the other side (*e.g. Kazimirovsky et al., 1982*).
2. The response of radiowave absorption, upper mesosphere and lower thermosphere winds, E_s, optical mesosphere / lower thermosphere emissions on the stratospheric warmings, meteofronts, jet streams etc. (*e.g. Kazimirovsky and Kokourov, 1991*).

— The zonal and meridional prevailing winds at the lower thermosphere reversed westwards and southwards in a period less than a week during stratwarmings. There is an increase of the semi-diurnal tide and phase shift comparatively with undisturbed winter conditions. The response depends on the intensity and location of warming. (fig. 4).

— Radiowave absorption changes during and after stratospheric warmings. (*Lastovicka and De la Morena, 1987*).

— On the frontal days E_s sometimes tends to occur more frequently and with higher critical frequency than for preceding and following days.

— The daily averaged departures of the sporadic E parameters f_bE_s and $h'E_s$ from the corresponding monthly median have been found to decrease during winter-time circulation disturbances connected with stratwarmings. The computed neutral wind shear shows decreased values during these disturbances. The effect may be connected with the decrease of attenuation of AGW, in consequence of which the vertical wave-length increases and the E_s producting wind shear decreases (growth of vertical energy flux).

— Effects in the variations of optical emissions intensity.

3. The quasi-periodical fluctuations observed in absorption and winds which are caused not by fluctuations in the solar ionizing flux, but probably by planetary waves in the stratosphere. There is a model of the transformation of planetary waves of tropospheric origin into waves in absorption in the lower ionosphere (*Lastoviska et al., 1993*).
4. The seasonal variation in the amplitudes of quasi-periodical fluctuations of ionospheric parameters (with periods of planetary waves, tides, internal gravity waves), which are maximal in winter when conditions of upward lea-

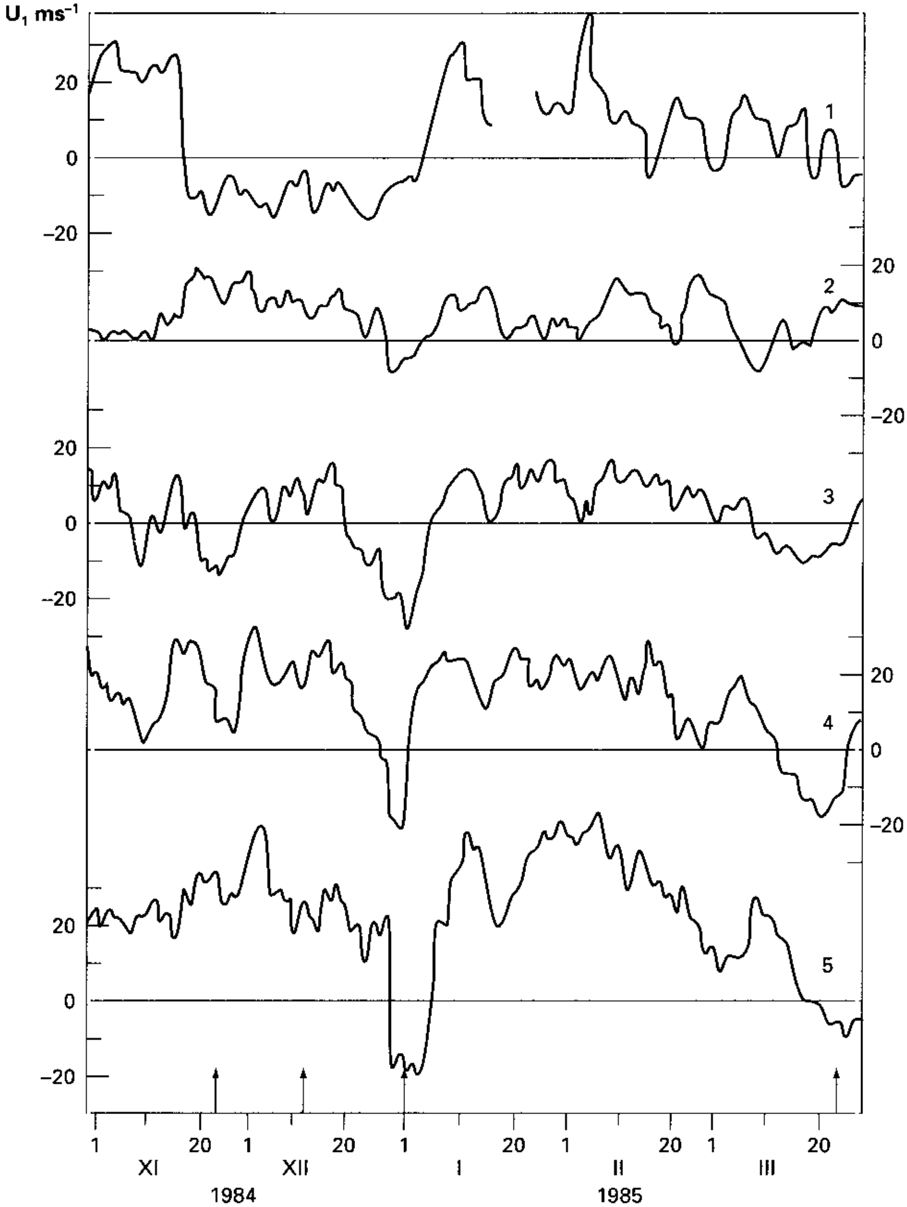

Figure 4. The response of the prevailing zonal wind (U m/s) in the lower ionosphere on the stratospheric warmings during winter 1984/85 (rather low solar activity). Positive direction: eastward. Arrows: days of stratospheric warmings. 1. Observatory Badary, East Siberia, 52°N. 2. Observatory Collm, Central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

kage of internal waves (depending on the wind and temperature profiles between troposphere and thermosphere) are preferable (*e.g. Taubenheim, 1983*).

5. The close connection between the circulation in the lower thermosphere, mesosphere and stratosphere, e.g. near-by radar and rocket measurements give the consistent cross-sections from 20 to 110 km (*e.g. Meek and Manson, 1985*).

6. The existence of a longitudinal effect on the dynamical regime of the lower thermosphere/ionosphere due to longitudinal inhomogeneties of the lower atmosphere processes, which may be traced up to the mesosphere and thermosphere (prevailing winds, tides, response to stratwarms, dates of the seasonal reverses). The longitudinal effect observed may be interpreted as resulting from large-scale stationary planetary (fig. 5) waves formed at lower thermospheric heights. In this case the longitudinal variation of prevailing wind is due to existence of such waves at the mesopause level, while the longitudinal variation of semidiurnal tidal amplitude is a consequence of the longitudinal variation of zonal flow (*Kazimirovsky et al., 1988; 1999*). In principle, in the lower thermosphere beside the numerous variations of the dynamical parameters, the own (generated in-situ) long-term wave-like motions (including planetary waves) may exist.

Who may be a preferable carrier of upward influence across the mesopause on the lower thermosphere? The atmospheric tides are the most probable candidate. The non-zonal modulation of the stratospheric and mesospheric tides penetrating into the lower thermosphere appears to generate a quasi-stationary planetary wave by demodulating the tides by energy dissipation at the lower thermosphere (*e.g. Forbes, 1991*).

7. The winter anomaly of radiowave absorption in D-region, i.e. excessive enhancement of both the average level and especially the day-to-day variability of ionospheric radiowave absorption in winter noted by many investigators (*e.g. Taubenheim, 1983, Danilov et al., 1987*).

There are two components - 1) «normal» winter anomaly with rather slow increase and decrease, i.e. in average daytime absorption for usual winter day is higher than for usual summer day; 2) superimposed spikes, «excessive» winter anomaly.

In spite of enhancements of absorption may be connected with increasing of electron density N and/or collision frequency in ionospheric plasma, it is nowadays assumed that the winter anomaly is connected primarily with enhanced electron densities at the mesopause level and above.

Why we assume that the winter enhancement of electron density has internal («meteorological») nature?

1. It occurs on both the northern and the southern hemispheres during the respective winter months.

2. There are numerous facts about close interrelation of D-region events, stratospheric temperature variation and sudden warmings, change or even a reversal of direction of the wind in the upper mesosphere and lower thermosphere.

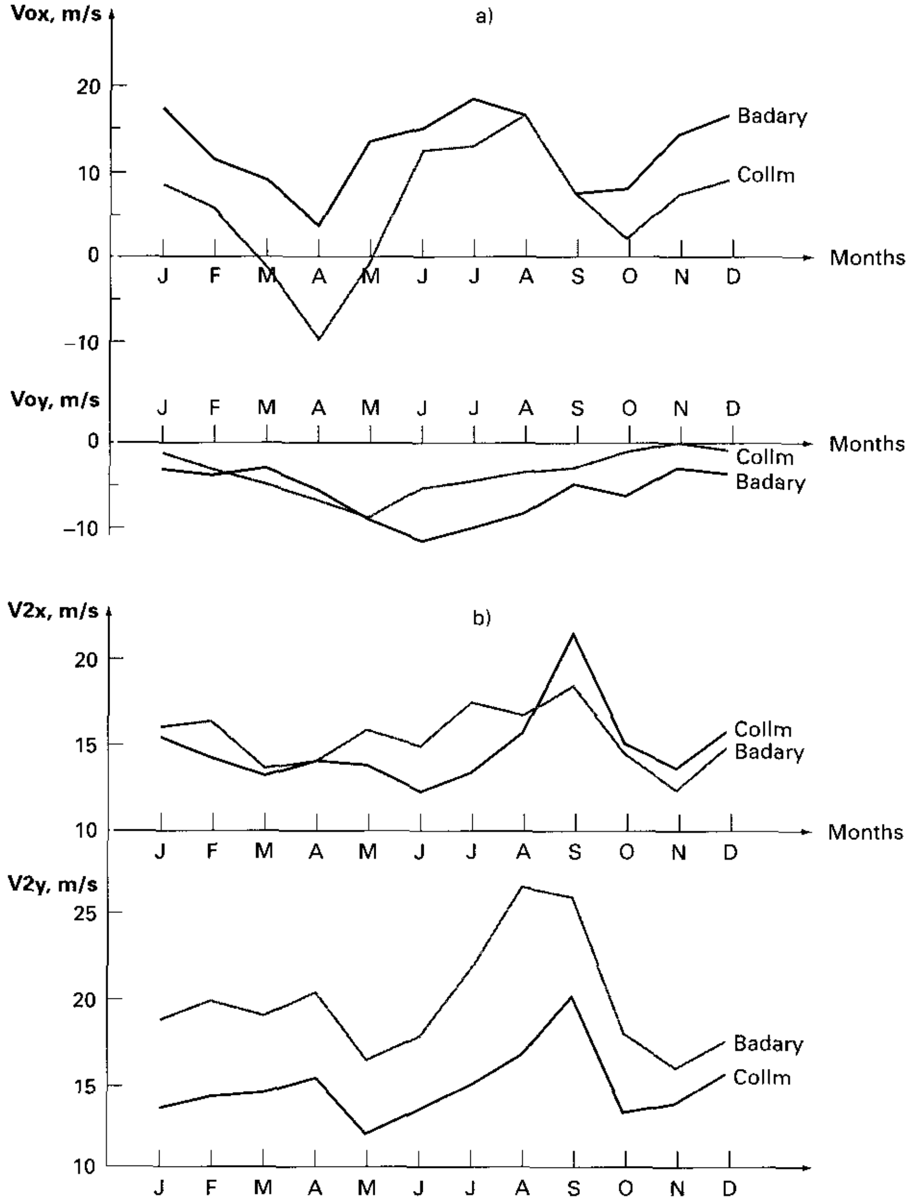

Figure 5. The nonzonality in the zonal wind field in the lower ionosphere, which is interpreted as the consequence of coupling from below. Observatory Badary, East Siberia, 52°N. Observatory Collm, Central Europe, 52°N. Data are monthly averaged for 1975-1995 (Badary) and 1979-1997 (Collm). V_{ox} – prevailing zonal wind. V_{oy} – prevailing meridional wind. V_{2x} – amplitude of the zonal semi-diurnal tide. V_{2y} – amplitude of the meridional semidiurnal tide.

3. The correlation between the time variations of D-region ionization and solar L-alpha fluxes (measured by AE-E satellite), which is weak but detectable during summer months, is completly missing during winter.
4. The amplitude of interdiurnal variations of absorption in winter months can not be explained by solar L-alpha variations.
5. The time and spatial scales of anomalous absorption, wave-like structures, are compatible with planetary waves pattern. (*e.g. De la Morena and Kazimirovsky, 1996*).

There are some «scenarios», concerning the D-region meteorological control (*e.g. Taubenheim, 1983, Offerman et al., 1982*).

3.2.1. «Concerted» Scenario.

- The general enhancement of D-region electron densities is caused by enhanced downward eddy diffusion of NO, accumulated in the polar night thermosphere.
- In addition, at heights below 85 km, the electron rate is reduced by inhibition of cluster ion formation because of warm mesopause temperatures.
- Independently, «patchy» (with respect to time and longitude) downward transports of excess NO into D-region are effected by diffusion and/or bulk motions connected with planetary wave patterns. Displacement of these patches by enhanced horizontal winds, possible launched by transient perturbations from below, causes rapid changes of the NO distribution within 1-2 days.

3.2.2. «Unitary» 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 with:

1. Warm mesopause temperatures, inhibiting cluster ion formation.
2. Downward vertical wind components (bulk motion).
3. Low pressure near the mesopause, decreasing optical depth for solar UV radiation and hence increasing the ionization rate.

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

In this scenario the enhanced eddy diffusion in winter raises the average background level of D-region ionization and every global or local perturbations 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 D-region.

Both scenarios have their own merits and demerits. It seems necessary still to improve the empirical base to define coupling processes throghout the atmosphere during winter anomaly.

3.3. How does a thunderstorm couple energy into the upper atmosphere and ionosphere?

The widely accepted classical hypothesis were:

1. The thunderstorms are the main generators of the global electric circuit, causing an electric potential between earth and the ionosphere of about 200-500 kV.
2. The influence of thunderstorms and electrical events near the ground on the atmospheric layers well above the perfect conductor («electrosphere») near 60-70 km is forbidden.

We know that the classical hypothesis has not yet been proved without doubt. Moreover, it is not widely recognized that the current system 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 return current from a thunderstorm generator that penetrates the tropopause flows globally through the ionosphere and along plasmaspheric magnetic field lines.

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

Recent observations have shown that intense lighthing produces a number of interesting and unexpected effects in the middle and upper atmospheres above thunderstorms.

Some new and diverse classes of energetic electrical effects of thunderstorms have been documented over the past 5 years. Two of these classes called red sprites and blue jets, are large-scale optical emissions excited by lightning. Together they span the entire distance between 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 has been appreciated in the past.

Sprites are very large luminous flashes that appear within the mesospheric D-region directly over active thunderstorm systems coincident with cloud-to-ground or intracloud lighting strokes. Triangulation of their locations and physical dimensions using simultaneous images captured from widely spaced aircrafts has shown that their terminal altitude extends to the ionosphere. The brightest region of a sprite is red and lies in the altitude range 65-75 km. Above this there is often a faint red glow or wispy structure extending upward to about 90 km, to the nighttime E-region ledge.

The jets are sporadic optical ejections,deep blue in color, that appear to erupt from the vicinity of the overshoot. Following their emergence from the tops of the thundercloud, blue jets propagate upward in narrow cones, fanning out and disappearing of about 50 km over a lifetime of about 300 ms.

Theories proposed to date concerning only red sprites all involve lightning discharges acting either as a casuative agent, or as a simultaneous but non-casuative consequence of electrical breakdown triggered by cosmic rays. Intensive efforts, both experimental and theoretical, are underway to determine the physical mechanisms at work to produce thunderstorm (ionosphere effects. It is unclear whether the absorption within the ionosphere or magnetosphere of the energy flowing upward from the lower atmosphere is capable of producing effects that are dinamically significant enough to qualify as a strong link between these layer. 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 in the solar-terrestrial system and Earth's global electrical circuit is a challenging, and inherently multidisciplinary, problem that spans traditional discipline boudaries separating the lower and upper atmospheres. (*Sentman and Wescott, 1995*).

The evidences for direct interactions between phenomena associated with thunderstorms and ionosphere include perturbations of electron density and temperature (increase of ionization at E-region, E-sporadic occurence, increase of temperature and electron density in F-region), excitation of electrostatic wave turbulence, enhanced optical emissions. There are some approximate hypothesises about the physical mechanisms - e.g. upward acceleration of electrons in the moment of lightning discharge, ionization on by particles etc. (*e.g. Pasko et al., 1997*).

There are theoretical and experimental evidences about magnetospheric electron precipitation simulated by lightning via radio waves, particularly in the ELF-VLF range (less than 30 kHz). Because the precipitating particles may be the reason of dissociation and ionization processes, it is the next channel of thunderstorm influence on the ionosphere. We have VLF signatures of ionospheric disturbances associated with «sprites» (*e.g. Rycroft, 1994*).

Atmospheric Acoustic-Gravity Waves are associated with severe local thunderstorms, tornadoes and hurricanes. Reverse group ray tracing computations of acoustic-gravity waves observed by an ionospheric Doppler sounder array, show that the wave sources are in the neigborhood of storm systems. AGW at ionospheric heights are observed when severe thunderstorms are within a radius of several hundreds kilometers of the ionospheric reflection points, the convective regions may be imbedded in the stratiform anvils of thunderstorms. It is interesting that the zones of maximal occurence of F-spread over West Africa and South America coincide well with the zones of high thunderstorm activity (*e.g. Kazimirovsky, 1983*).

3.4. Meteorological influences on the F-region

This topic is much more speculative than for the lower ionosphere. Nevertheless, the ideas about dynamic coupling between weather at the ground level and F-region behaviour appeared long ago (*Beynon and Brown, 1951; Martyn, 1952*). Now it is evident that planetary, tidal and gravity waves launched by various sources in the troposphere and stratosphere really penetrate into the F2 region. There are short-term correlations between meteorological and ionospheric parameters, and a number of statistically significant correlations, that may be regarded as circumstancial evidence on the long-term basis. The ionospheric response to the forcing from below should be anisotropic and subject to diurnal and seasonal variations, and should vary with geomagnetic and geographic latitude and longitude.

We believe that planetary waves sign could be recognized in the global distribution of the electron density (N_e) in the F2 region. The regional structure (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 (*Danilov et al., 1987*). The longitude-dependent distribution of noon f_oF2 values is reasonably well approximated by the sum of planetary waves n=1 and n=2. Moreover, it was shown that the seasonal variations of planetary waves amplitudes in f_oF2 and in geopotential at 10 mb level are closely correlated with changeable time lag.

Studies of coupling between ionospheric and stratospheric parameters sometimes yield the ambiguous conclusions due to the masking effect on the ionosphere from the various geophysical factors, such as ionizing radiation of the Sun, energetic particles fluxes, cosmic rays etc. Thus it is desirable to make the analysis in such a manner that variations caused by these factors are removed. We have proposed and successfully realized the following technique. Two stations are selected which have close geographic or geomagnetic latitudes but are well spaced in longitude so that they are likely to have substantial differences in meteorological characteristics of the lower atmosphere. For each day the differences are determined in the ionospheric characteristics (e.g. f_oF2, f_{min}, absorption of radiowaves etc.) between these two stations and the same differences in the meteorological characteristics (e.g. stratospheric temperature, height of isobaric surface etc.). From the comparison of the time variations of this differences one may suppose that the effect of geophysical factors, which are almost the same for two stations, is eliminated to a considerable extent. On the contrary the meteorological effect due to different climatology for these two 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 have the close correlation between variations of the differences above described.

The example can be demonstrated for f_oF2 and stratospheric dynamics. It is well known that the winter cyclonic vortex in the stratosphere is very dinamic and changeable. The subtropical areas of high pressure when moving northward, may deform and sometimes even split it into two independent cells. This circumstance leads to a substantial difference in the values of stratospheric pressure at two sites, located at the same latitude but at different longitudes. Does the behaviour of F2 ionospheric layer reflect this phenomena? Fig. 6 presents the seasonal variation of daily values of differences in noon f_0 F2 (Δf_0F2) between two sites near 55° N spaced in longitude by 2000 km and the seasonal variation of daily values of the corresponding differences in height of 30 hPa surface (Δh_{30}). We can see that both during winter and equinoxes the values of Δh_{30} and Δf_0F2 are greater than those during summer. By the method of «superposed epochs» it was found that negative extrema of Δf_0 F2 correspond to positive extrema of Δh_{30} and vice versa. (*Kazimirovsky and Kokourov, 1991*).

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

As far as the physical cause of planetary scale waves in foF2 is concerned, it seems possible that this is the sequence of planetary waves in the neutral atmosphere (*Rice and Sharp, 1977; Forbes et al., 1999*), in thermospheric density.

From the earliest days of HF communications the presence of travelling ionospheric disturbances (TID) and ionospheric irregularities (including F- spread event) were revealed and now we know that both are closely connected with internal gravity waves. The sources of these waves have been identified which include severe weather disturbances (typhoons, thunderstorms, tornado, hurricanes), earthquakes, nuclear and industrial explosions. In the experiments provided by some investigators, for the majority of the waves the reverse group path can be followed down to the tropopause level, and comparison with meteorological data has shown that many of the possible source regions of the observed waves appear to lie in proximity to the jet stream, or to be close to regions of the convectively unstable cold polar air. The possible generation mechanism is the non-linear interaction of shear flow instabilities in the jet stream and penetrative convection (numerous references in *Kazimirovsky and Kokourov, 1991*).

TID can be related to tropospheric vortexes. Recently such observations were provided in China where TIDs were statistically analyzed under the base of observation of an HF Doppler array. The backward ray tracing shows that the sources of TIDs are located in the edges of Qinghai-Tibet Plateau, i.e., in the lee sides of the bulging terrain of the plateau where the vortexes are more probably produced.(*Wan et al., 1999*).

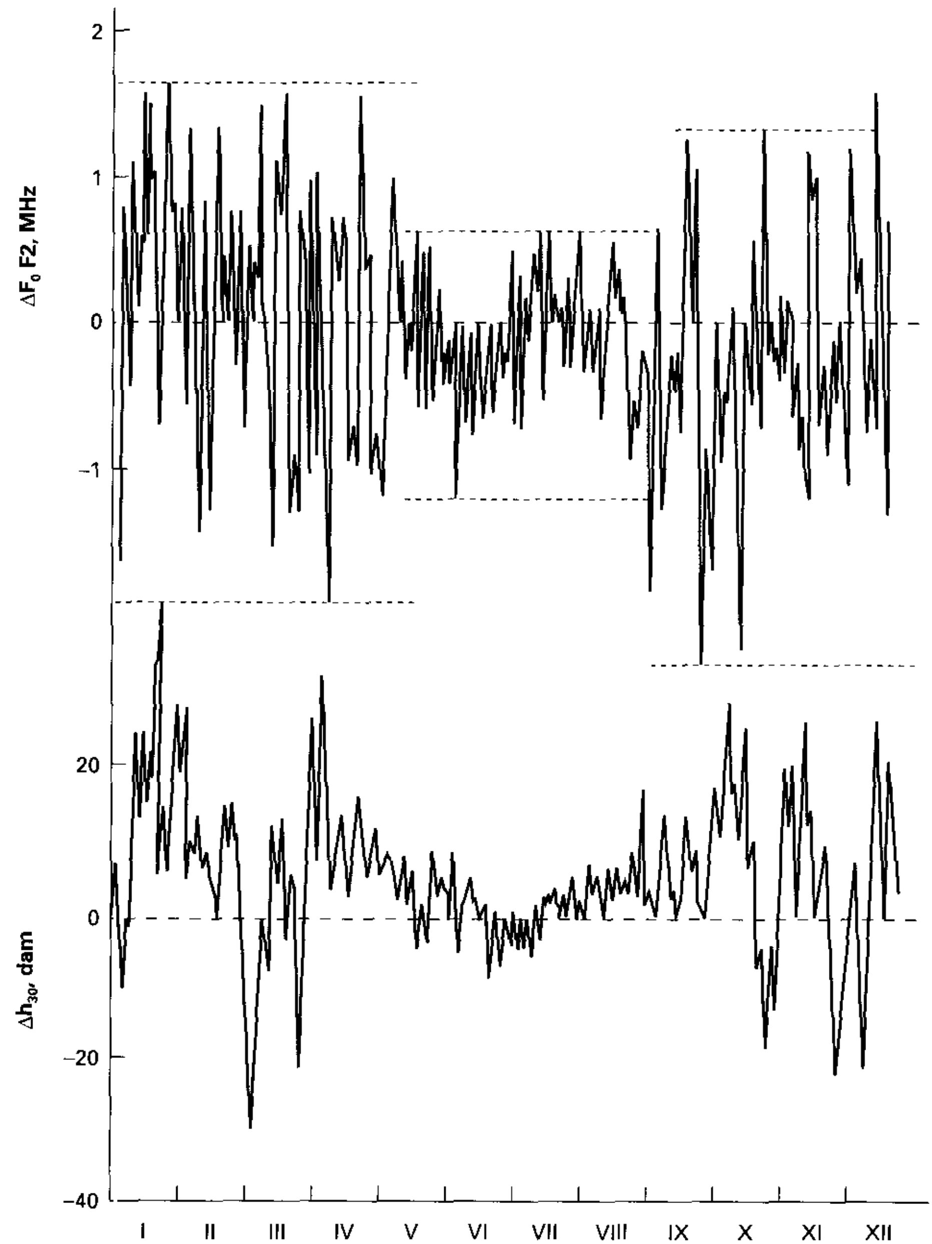

Figure 6. Stratospheric effects on the ionospheric F2 region. Daily values of the difference in noon values of f_0F2 and in heights of an isobaric surface at 30 hPa for two stations-Moscow (East Europe) and Sverdlovsk (Ural Mountains), located almost at the same latitude (~56°N). I...XII-months, 1969.

F-spread on ionograms is often connected with wave-like structures of F-region irregularities induced by upward propagating AGW's of meteorological origin. It is especially true for equatorial F-spread. For instance, spread-F occurence in the African area was investigated by means of non great-circle radiowave propagation on the transequatorial path. The distribution of the horizontal velocity, the horizontal wavelength of the quasi-periodical structures, and the tilt of the irregularity patches led to the assumption that these structures of the equatorial F-spread are connected with AGW in the equatorial region (*references in Gershman et al., 1984*).

The variations of the Total Electron Content (TEC) over low-latitude stations sometimes also show wave-like structures at the moment of 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 gives evidence that the AGW were generated by a singular tropospheric event and propagated to ionospheric heights without significant changes of period (*e.g. Shodel et al., 1973*).

3.5. A possible greenhouse effect in the ionosphere

Releases of trace gases from human activity have a potential for causing a major change in the climate of the Earth. But there is no doubt that the subject of global climate warming due to so called «greenhouse effect» has led to controversy, speculation and confusion. Despite the many uncertainties that remain, the consensus of 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 expected to warm, the stratosphere —to cool, ozone content— to decrease, the consequences of these processes on the atmosphere above 60 km are considered at present and overall results indicate that global change resulting from trace gas variations (e.g. CO_2 and CH_4 doubling) is not confined only to the lower atmosphere but also extends well into the mesosphere, thermosphere and ionosphere regions. 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 in a thin layer of sodium vapour, about 90 km above the Earth, could be revealing the far-reaching effects of greenhouse gases (since 1972 up to 1987 its mean height had fallen nearly a kilometre). Although it is not possible to state with absolute certainty that the decrease in the altitude of the sodium layer is an indication of global cooling in the middle atmosphere, the behaviour of the layer clearly bears systematic watching 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 of water vapour concentration or by changes of 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 the mesosphere, where they can change the aeronomy. Polar Mesosphere Summer Echoes (Incoherent Scatter Radar) 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 possibly anthropogenic origin, have extensively been studied with the use of almost 30 years of absorption measurements along various radiopaths in Europe. Trends are more pronounced in daytime than in night time (*e.g. Lastovicka, 1997*).

According to model predictions, doubling of the greenhouse gases concentration should lead to a significant cooling of the upper atmosphere and resulting changes in F2-region parameters - a decrease of h_mF2 by about 15 km with only small changes of f_oF2 and probably 2.5 - 3.5 % increase of M(3000)F2. The longterm changes of h_mF2 and f_oF2 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. Further studies are necessary together with testing homogeneity of data (*e.g. Rishbeth, 1997; Ulich and Turunen, 1997; Bremer, 1998; Jarvis et al., 1998*).

4. CONCLUSION

The ionosphere, embedded in and tightly coupled to the thermosphere, is strongly influenced by couplings to other geophysical regions. In addition to ionizing energetic solar irradiation above the ionosphere both the magnetosphere and plasmasphere greatly affect the ionosphere by the precipitation of soft and energetic particles, by heat conduction, and by fluxes of thermal particles. Below, the middle atmosphere affects it with 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 in realm of science fiction. Hopefully, progress will be even more rapid in the decades to come. Studies of the meteorological effects in the ionosphere are actively under way and the main aim of this review paper was to stimulate these investigations.

We must look forward to a further breakdown of the traditional isolation of the ionosphere from the lower atmosphere. 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-weather effect.

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 these relationships 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 contribution in the fields of meteorology, climatology, aeronomy, ionospheric physics, atmospheric electricity, and plasma physics. Further regional, national and international cooperative efforts are needed to organize a global monitoring system of atmospheric oscillations with various new techniques. Continuous observations from these networks permit resolution of planetary waves, atmospheric tides and gravity waves and hypothesis that such motions propagate upward from the lower atmosphere or are generated in situ could be examined critically with observational data.

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

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