Impacts of space weather on sea-level pressure over the auroral oval

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Solar energy that reaches the Earth consists mostly of electromagnetic (EM) radiation. The fluctuation of the intensity of its components in the course of the solar cycle is below a few percent. At the same time, however, there are considerable changes in the intensity of particle radiation emitted by the Sun. Furthermore, while the incoming energy of the EM radiation affects the whole illuminated hemisphere of the Earth, atmospheric absorption of incoming charged particle radiation occurs mainly within the polar regions of the geomagnetic field. Consequently, this particle radiation can produce various inhomogeneities in the upper atmosphere that may indirectly influence the subjacent meteorological processes as well. This can be investigated by observation of the upper atmosphere through the ultraviolet light or X-rays generated by energetic electrons, which precipitate into the atmosphere and interact with its components. Due to their higher energy the X-rays yield more compact observed areas. Therefore, in the present work an attempt is made to trace relationships between solar-induced ionospheric disturbances detectable in X-rays and the trends of changes of sea-level pressure (SLP) under these excited areas.

Introduction

The quiet solar wind is a flow of ionised solar plasma with a velocity of 400 km s^{-1} and a remnant of the solar magnetic field that pervades interplanetary space. It is the result of the significant difference in gas pressure between the solar corona and the interstellar space, which drives the plasma outward, despite the restraining force of solar gravity.

This wind interacts with the Earth's magnetosphere and modifies its shape, by pushing it in on the dayside and creating a long magnetotail on the nightside. However, the Sun is an active star with a roughly 11-year periodicity of storminess and quietness. This activity originates from the solar magnetic regions marked by the sunspots in the photosphere, which are the locations of an enormous magnetic stir of twisted field lines. When these fields short circuit, powerful solar flares send floods of X-rays into space and accelerate protons and electrons to near-light speed. This emission of billions of tonnes of plasma and its magnetic field, called coronal mass ejection (Fig. 1), can travel outward at more than 1000 km s^{-1} and can reach the Earth in only a few days' time. When the Earth lies in the path of the tide of these charged particles, which carry magnetic fields, they excite the Earth's magnetosphere and influence its balances of trapped particles and waves. When an energetic burst of solar-wind particles, which carry magnetic fields, reaches the Earth the magnetospheric shield is temporarily weakened and energetic plasma can

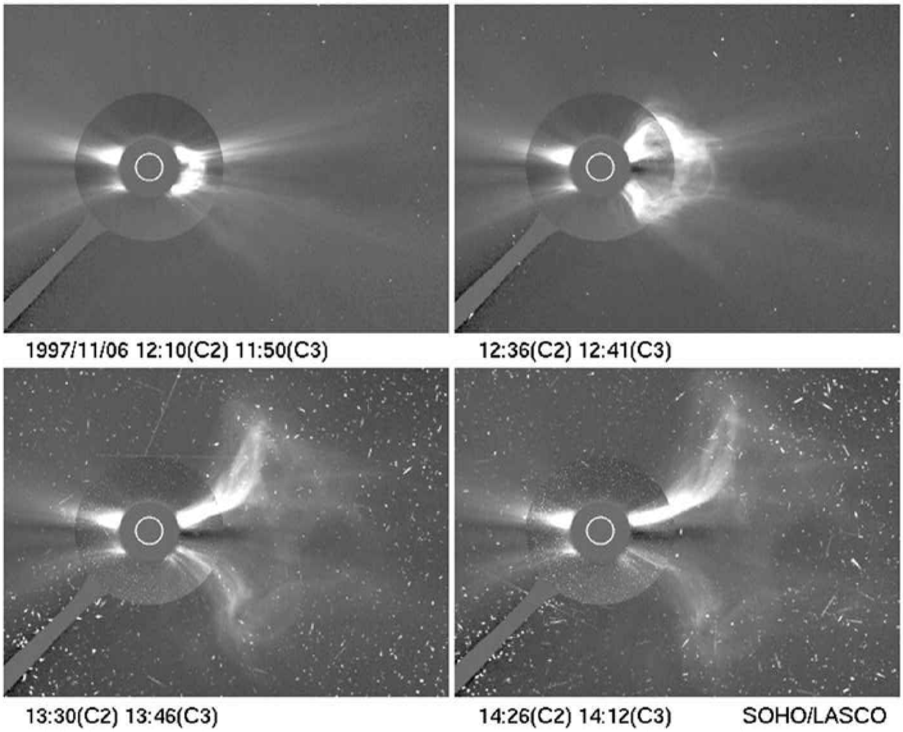

Fig. 1 Spectacular composite image of the progress of a coronal mass ejection following a solar flare; observed in the visible region by the C2 and C3 coronagraphs of the Large Angle and Spectrometric Coronagraph instrument of the Solar and Heliospheric Observatory spacecraft (http://sohowww.nascom.nasa.gov/). The various discs are the signs of the shading sheets of these two different coronagraphs, which cover the direct glaring light of the Sun. The inner white circle signifies the covered solar disc.

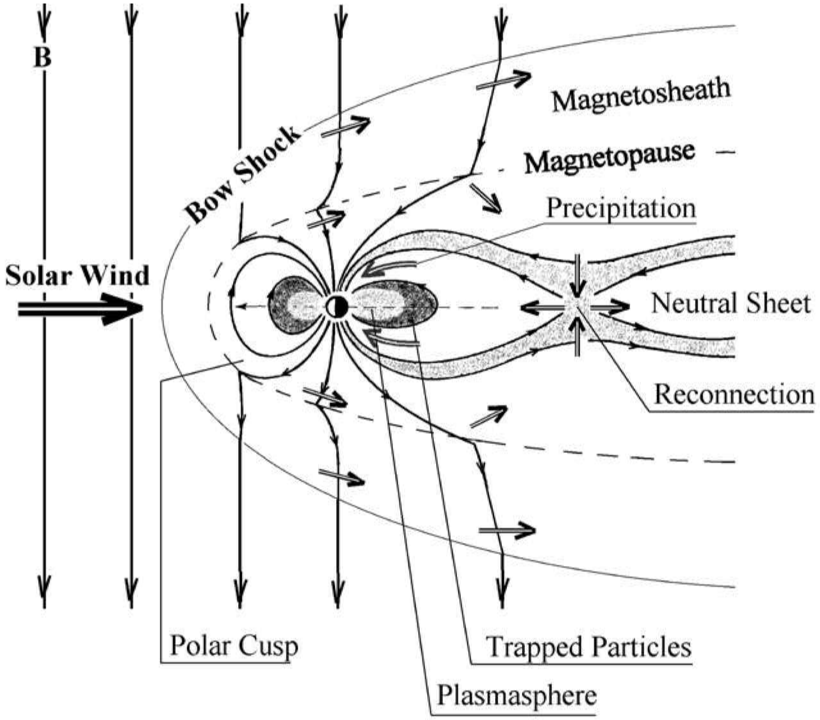

Fig. 2 Noon–midnight meridian cross-section of the interaction between solar wind and geomagnetic field and the resulting motions of the plasma (open arrows)

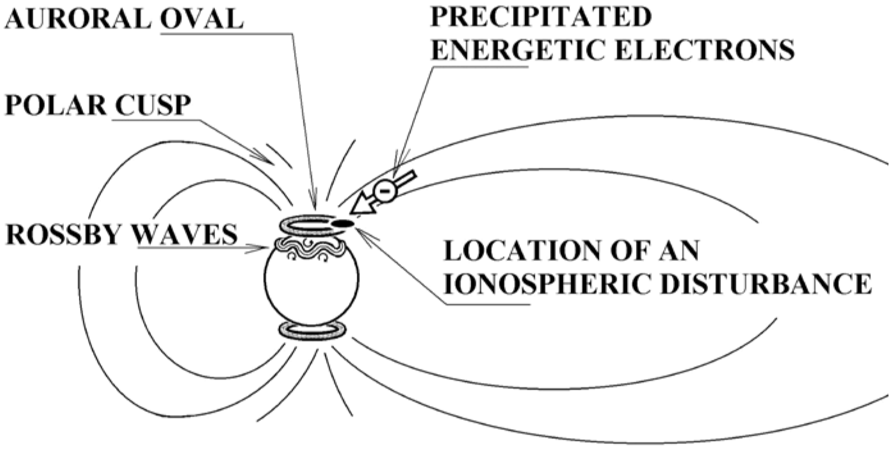

Fig. 3 Rough sketch of the processes, the auroral oval and its origin, and the subjacent atmospheric Rossby waves around the North Pole

enter the planet's magnetosphere. This is often followed by the reconnection of the nightside magnetic field lines (Fig. 2), an event which gathers some charged particles and precipitates others, with near-light velocity, earthward, mainly within the auroral oval (Fig. 3). It results in strong auroral activity (Fig. 4), ionospheric disturbances (Fig. 5), and geomagnetic storms (Fig. 6). All these effects are called 'space weather'.

During these geomagnetic disturbances caused by solar activities, considerable amounts of energy are absorbed in the upper atmosphere. The sources of this energy are the

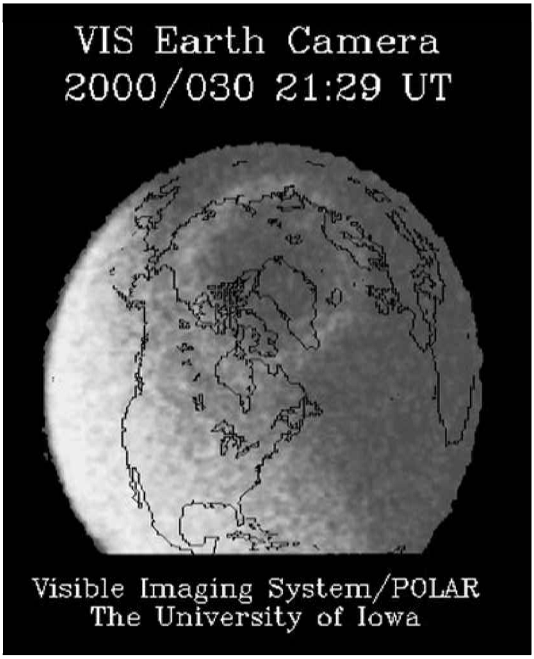

Fig. 4 The auroral oval observed in ultraviolet light by the Visible Imaging System (VIS) on the Polar space probe (http://www-pi.physics.uiowa.edu/vis/)

precipitated energetic electrons and the alternations of the terrestrial magnetic field.

At the present time the space probes detect only the few keV energy electrons (1 keV = 1.602×10^{-16} joules), while a significant part of the incoming particles are called relativistic electrons, with nearly MeV energy. Considering only the low-energy electrons we calculate that more than 10^{14} joules of energy can be absorbed in the atmosphere in the area of an event (this estimation is based on Wu *et al.* 1979 and Chenette *et al.* 1999). This approximately equals the energy of a thunderstorm but distributed over a larger area (Fig. 7). Thus this energy, and its density, is relatively small for any effect on meteorological processes. However, taking into account the large amounts of relativistic electrons as well, the energy absorbed in the atmosphere will be more by orders of magnitudes, which might be enough to influence the meteorological processes in the troposphere by means of several physical and chemical processes (McCormac and Seliga 1979; Hoyt and Schatten 1997; Bochnicek *et al.* 1999). The influence is signifi-

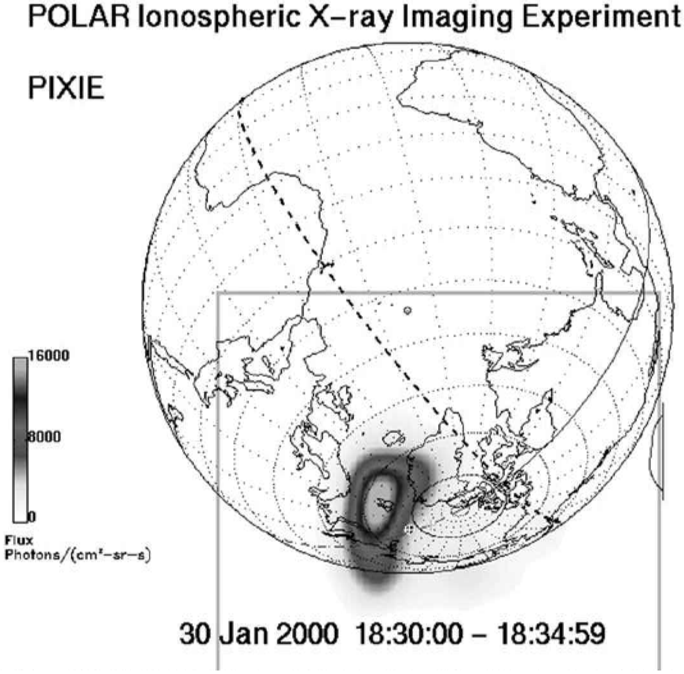

Fig. 5 Observation (the case of e_8, see Fig. 8(a)) of the Polar Ionospheric X-ray Imaging Experiment (PIXIE) on the Polar space probe. The dark area indicates the core of the energetic centre region of the location of energetic electron precipitation.

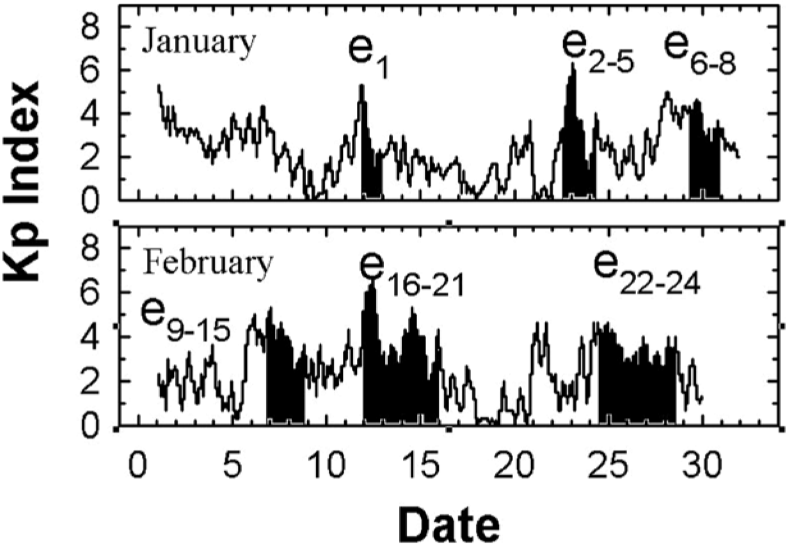

Fig. 6 Time pattern of the observed ionospheric X-ray events (indexes from e_1 to e_{24}, shaded areas) connected to the geomagnetic activity indices during January and February 2000 (National Oceanic and Atmospheric Administration 2000)

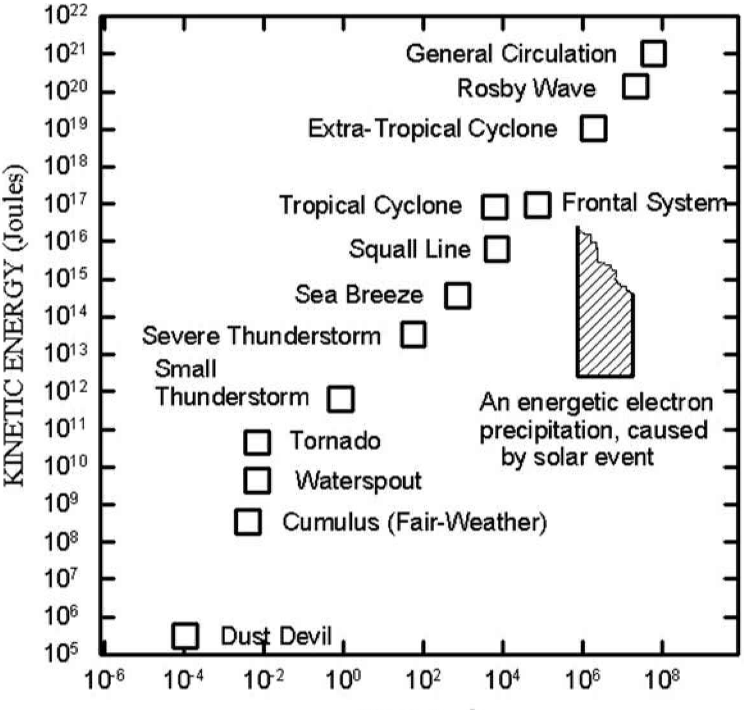

Fig. 7 Typical energy and size of the energetic electron precipitation events (hatched area) (on the basis of Wu et al. *1979 and Chenette* et al. *1999) compared with the kinetic energy and size of atmospheric phenomena (open squares) (on the basis of Wells 1997)*

cant, especially if the events follow each other frequently in space and time as is so around the maximum activity of the 11-year solar cycle.

One hypothesis is that when the charged particles due to solar activity penetrate into the atmosphere at the polar regions of the geomagnetic field, mainly within the auroral oval (Figs. 3, 4 and 5), they generate an electric jet current in the ionosphere. This current may induce a variable magnetic field that yields to the above-stated geomagnetic disturbances (Fig. 6) and produces further conductivity electric currents. These vortex currents are among the possible sources of the heating of the middle and upper atmosphere, which causes airmasses to expand, and this process may lead to the divergence of airmasses in the upper troposphere. This high-altitude divergence may contribute to the development of the convergence of airmasses near the surface, which is an important factor in the formation of surface low pressure systems, through the decrease of SLP (Ahrens 1988). Even if the air expansion occurs at higher altitudes the decreasing atmospheric pressure may cause observable changes in the SLP as well. These variations of the atmospheric pressure profile may cause a change in the zonal circulation.

This model has been supported by several investigations, which show slight changes in meteorological parameters connected to geomagnetic activities caused by solar events (Duell and Duell 1948; Mustel 1966, 1972; Schuurmans and Oort 1969; Roberts and Olson 1973; King 1974; Schuurmans 1979; Smirnov and Kononovich 1996; Bochnicek *et al.* 1999; Pudovkin and Morozova 1998; Olson 1975; Wilcox *et al.* 1975).

Here an attempt is made to find relationships between the locations of solar event-induced disturbances of the ionosphere and concomitant changes of SLP. Special interest lies in the fact that the incoming energetic electrons are mainly in the auroral oval. The auroral oval approximately coincides with the polar front and its stream of Rossby waves (Fig. 3).

Method of investigations

In the course of this study the changes of SLP under the centre of areas of the most intense 24 different ionospheric X-ray events between 11 January and 27 February 2000 (Fig. 6) were analysed. Of these, ten cases are presented here where the events were adequately separable in space and time (Table 1). We used SLP maps instead of 500 mbar geopotential height analysis charts because the pressure changes are observable also in the SLP charts, which in addition have a higher space and time resolution. The approximate time pattern of the observed 24 X-ray events (e_{1-24}) is shown in Fig. 6.

Three main considerations were kept in view in the selection of the time period observed:

Table 1 Well separated X-ray events observed by the Polar Ionospheric X-ray Imaging Experiment during January and February 2000

Event	Date and time (GMT) (mmdd.hhmm)			Geographical location	
	Start	Max.	End	Latitude	Longitude
1	0111.2133	0111.2142	0112.2238	59.2°N	49.0°W
2	0122.1833	0122.1942	0122.2018	73.0°N	87.0°E
3	0122.1923	0122.1942	0122.2018	68.2°N	33.0°W
7	0130.0408	0130.0653	0130.0902	64.2°N	115.0°W
8	0130.1718	0130.1833	0130.2233	76.8°N	16.0°E
10	0206.1748	0206.1957	0206.2038	72.8°N	71.0°E
14	0207.1343	0207.1353	0207.1413	84.0°N	48.0°E
15	0207.2333	–	0208.0138	–	–
	0208.2023	0208.2023	0208.2027	70.0°N	41.0°W
	0209.0153	–	0209.0157	–	–
18	0211.2357	0212.0032	0212.0103	78.0°N	114.0°E
22	0224.1147	–	–	–	–
	0224.1612	0224.1723	0224.1823	76.0°N	76.0°E

(i) To identify the ionospheric disturbances, images of the Polar Ionospheric X-ray Imaging Experiment (PIXIE) (Fig. 5) were used.* In the selection of the time period studied a determinant restriction was that PIXIE has only been working since 1996.

(ii) A period was chosen that is close to the solar activity maximum.

(iii) The winter period is favourable because during that time the Arctic and the Rossby waves along the edge of the auroral oval (Fig. 3) are relatively free of disturbances caused by direct solar electromagnetic radiation. Furthermore, in winter the directions of large-scale streams do not differ too much from the lower part of the thermosphere to ground level (Wells 1997); thus the downward spreading of the studied effect is relatively undisturbed.

The changes of SLP over the north polar areas were analysed using the surface atmospheric pressure analysis charts of the Canadian Meteorological Centre.† First the geographical coordinates of the geometric centres of ionospheric disturbances (areas radiating most intensely in the X-ray) projected on to the surface of the Earth (Fig. 5.) were determined. Then the changes of atmospheric pressure at those geographical coordinates under the areas of ionospheric disturbances and the time derivatives of them were calculated by interpolation of the surface isobar charts.

Results

The observed changes of pressure at the surface of the Earth are similar to those that were expected. Namely, the heating of the atmosphere beneath the places of solar particle radiation-induced ionospheric disturbances usually caused observable decreases or a deceleration of the increase of SLP. Examples are shown in Fig. 8, especially where the negative peaks of the derivatives indicate the changes effectively.

Although in many cases the ionospheric X-ray events are shorter in time than the duration of the SLP changes and they are not in phase exactly, this can be explained. Because of the high energy of X-rays the satellite detects only the highest energy peaks of the ionospheric events in space and time. Consequently, the real length of the energy transmission, which can have an influence on the atmosphere, is wider in time than it is possible to observe in the X-ray band. It can be seen well in Fig. 8 where the geomagnetic Kp index indicates the real duration of the energy transfer that is already in line with the period of the changes of the SLP.

Furthermore, in Fig. 8 it is demonstrated clearly that the changes of cloud cover or the alternations of night and day periods could not cause the variation of SLP in our cases. It is best shown in the case of event e_{18} where there had been night and there were no changes in the cloud cover during the period observed. Moreover, the definitely characteristic decrease of the SLP is in phase with the increase of the geomagnetic Kp index and the minimum of SLP is in line with the ionospheric event detected in the X-rays. These facts prove that the observed changes of the SLP are caused indirectly by the showers of solar wind-induced energetic electrons precipitated into the atmosphere from the magnetotail of the Earth.

Events e_2 and e_{15} also support this model. They show the effect almost as clearly as event e_{18}. Moreover, this phenomenon is observable in the case of other events (e_1, e_3, e_7, e_8 and e_{22}) and to a lesser degree this is still detectable in those cases that are not presented here as well.

Our results (Fig. 8) are in agreement with those of Loon and Labitzke (2000) and partially support their findings. They have found correlation between the 10.7 cm solar flux and the annual mean 30 mbar heights over midlatitude regions in addition to anti-correlation over the Arctic and equatorial regions of the Earth. Because anti-correlation means the sinking of the 30 mbar heights, this is consistent with decrease of the SLP over a given area of the Arctic coinciding with the solar radio flux, which is in agreement with our work (Fig. 8).

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* Available online at http://pixie.spasci.com/

† Available online at http://www.cmc.ec.gc.ca/cmc/htmls/analysis.html

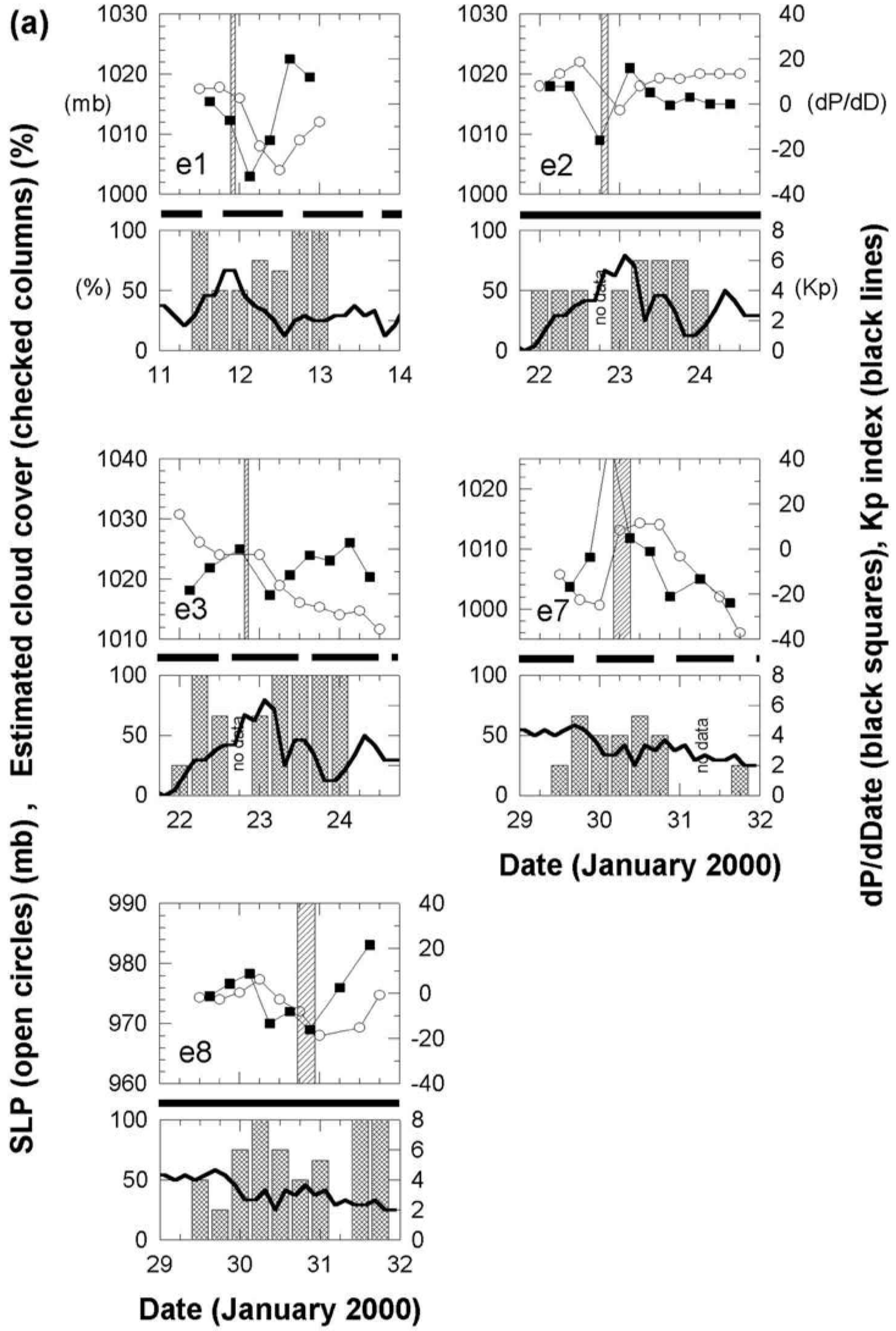

Fig. 8 Changes of sea-level pressure (SLP) as a function of time (GMT) (open circles, measured at the left vertical axes) and the time derivatives of them (dP/dD) (black squares, measured at the right vertical axes) under the location of the studied ionospheric disturbances. The duration of the given ionospheric disturbance event ($e_{1,\ldots 22}$) observed in X-rays is shown by hatched columns. Under every figure of SLP is one with the estimated ratios of cloud cover at the given geographical location (checked columns, measured at the left vertical axes) and the variation of the geomagnetic Kp index (black lines, measured at the right, vertical axes). The horizontal black stripes between every pair of figures show the duration of the night periods for the investigated term at the given geographical locations.

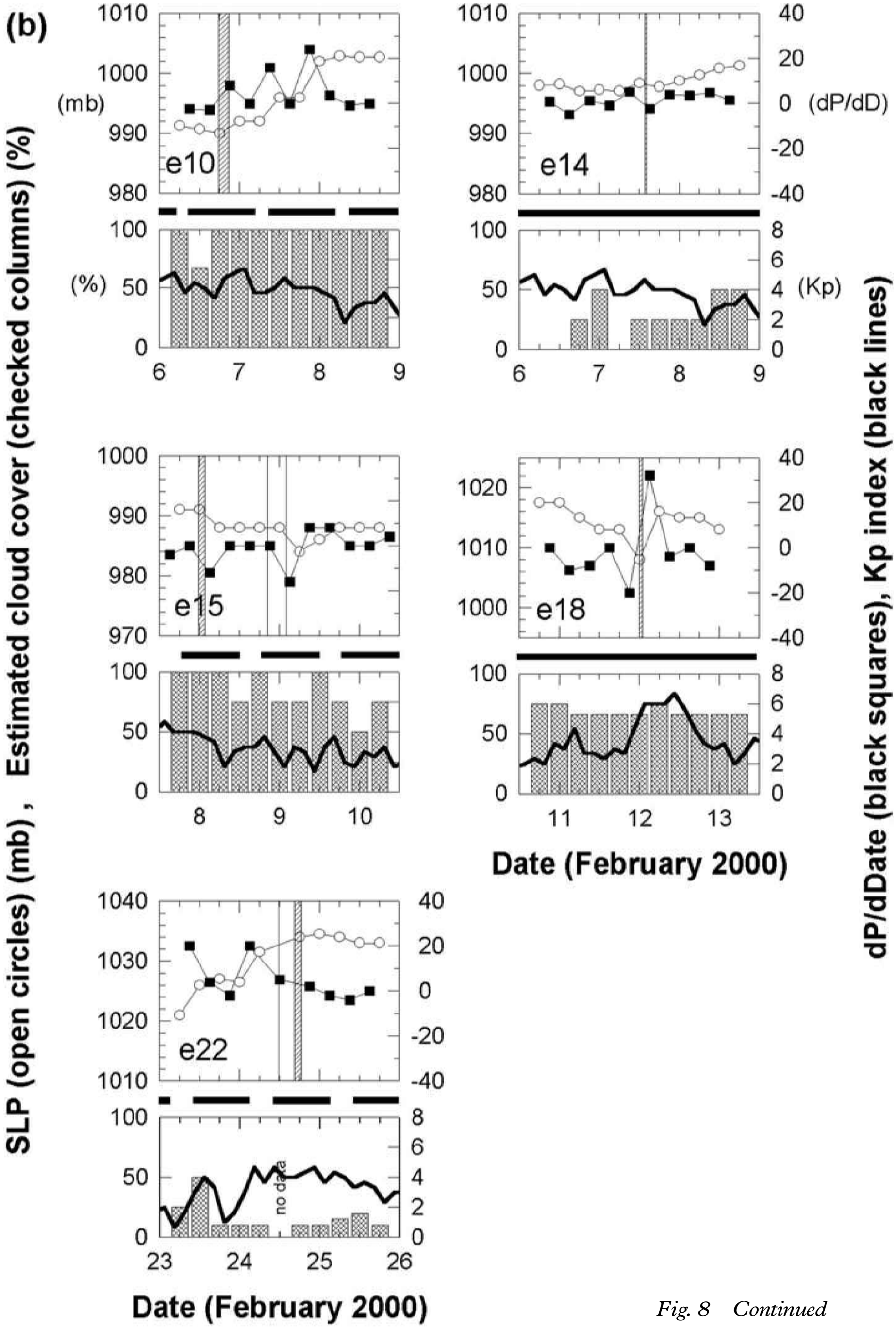

Fig. 8 Continued

Synoptic events such as cyclonic or anticyclonic development under the areas of ionospheric disturbances have been taken into consideration as well. On this basis it can be stated that under the areas of the ionospheric disturbances atmospheric low pressure systems (lows) may deepen when the SLP is stagnating or decreasing. Furthermore, they may slow down or turn back the increase of SLP when lows weaken or high pressure ridges develop.

When the events occur over areas of stable high or low pressure systems the results are quite different. Such cases in the course of our investigations were events e_{9-14} where two large and relatively stable low pressure systems with a high pressure ridge between them covered the Arctic. These systems were such large and stable formations that the processes connected to geomagnetic disturbances presumably were unable to produce considerable decreases in the SLP (e_{10} and e_{14} events in Fig. 8). However, an interesting effect was produced between these stagnating areas. The surface between the high and low pressure systems is like a wavy membrane and prone to cyclogenesis (Parker 2000). The heating of the atmosphere around that location during geomagnetic disturbances may modify the fluctuation of SLP there (e_{10} and e_{14} events in Fig. 8). The impacts of heating by energy absorbed in the atmosphere around this region are different depending on the initial conditions. If the change induced by geomagnetic disturbances in the atmospheric pressure is in phase with the trends of the 12-hour waves of SLP in the given area, it may strengthen those (case e_{10} in Fig. 8). If it is in anti-phase it may weaken or even extinguish those 12-hour waves (case e_{14} in Fig. 8).

Conclusions

In spite of the fact that there are not many investigated events, our results support the hypothesis that the lower atmosphere undergoes a change during ionospheric disturbances occurring at a higher altitude connected to solar activity. Namely, the absorbed energy affects the patterns of SLP, modifying dynamic processes in the troposphere:

(i) In areas of stagnating low or high pressure systems it may cause observable decreases of SLP.
(ii) In areas where SLP shows a decreasing trend it may accelerate this process.
(iii) In areas where SLP shows an increasing trend it may decelerate this process.

Because of their relatively small energy, these impacts cannot trigger large-scale meteorological processes such as cyclogenesis alone, but locally they can strengthen or weaken the development of different tropospheric processes. However, since during strong solar activity the influence of solar-induced ionospheric events on the SLP beneath can be more significant, the possible effects of them on weather processes demand additional investigation.

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References

Ahrens, C. D. (1988) *Meteorology today*. West Publishing Co., St. Paul

Bochnicek, J., Hejda, P., Bucha, V. and Pycha, J. (1999) Possible geomagnetic activity effects on weather. *Ann. Geophys.*, **17**, pp. 925–932

Chenette, D. L., Imhof, W. L., Petrinec, S. M., Schulz, M., Mobilia, J., Pronko, J. G., Rinaldi, M. A., Cladis, J. B., Fenrich, F., Ostgaard, N. and McNab, M. C. (1999) Global energy-resolved X-ray images of northern aurora and their mappings to the equatorial magnetosphere. In: Burch, J. L., *et al.* (Eds.) *Sun–Earth plasma connections, Geophysical Monograph 109*, pp. 65–76

Duell, B. and Duell, G. (1948) The behavior of atmospheric pressure during and after solar particle invasions and solar ultraviolet invasions. *Smithsonian Misc. Collection*, **110**, No. 8

Hoyt, D. V. and Schatten, K. H. (1997) *The role of the Sun in climate change*. Oxford University Press

King, J. W. (1974) Weather and the Earth's magnetic field. *Nature*, **247**, pp. 131–134

Loon, H. and Labitzke, K. (2000) The influence of the 11-year solar cycle on the stratosphere below 30 km: A review. *Space Sci. Rev.*, **94**, pp. 259–278

McCormac, B. M. and Seliga, T. A. (1979) Symposium/workshop conclusions. In: McCormac, B. M. and Seliga, T. A. (Eds.) *Solar–Terrestrial Influences on Weather and Climate, Proceedings of a Symposium/Workshop, Ohio, 24–28 August, 1978*, pp. 1–24

Mustel, E. R. (1966) The influence of solar activity on the troposphere in the polar cap regions. *Astron. Zh.*, **10**, pp. 188–194

—— (1972) On the reality of the influence of solar corpuscular streams upon the lower layer of the earth's atmosphere. *USSR Acad. of Sci. Astron. Council, Moscow*, **24**, pp. 5–55

National Oceanic and Atmospheric Administration (2000) *Solar-Geophysical Data Prompt Reports No. 667* (p. 146) *and 668* (p. 162). National Oceanic and Atmospheric Administration of the US Department of Commerce

Olson, R. H. (1975) Short term relationships between solar flares, geomagnetic storms, and tropospheric vorticity patterns. *Nature*, **257**, pp. 113–114

Parker, D. J. (2000) Frontal theory. *Weather*, **55**, pp. 120–134

Pudovkin, M. I. and Morozova, A. L. (1998) Time variation of atmospheric pressure and circulation associated with temperature changes during solar proton events. *J. Atmos. Sol.–Terr. Phys.*, **60**, pp. 1729–1737

Roberts, W. O. and Olson, R. H. (1973) Geomagnetic storms and wintertime 300-mb trough development in the North Pacific–North America area. *J. Atmos. Sci.*, **30**, pp. 135–140

Schuurmans, C. J. E. (1979) Effects of solar flares on the atmospheric circulation. In: McCormac, B. M. and Seliga, T. A. (Eds.) *Solar–Terrestrial Influences on Weather and Climate, Proceedings of a Symposium/Workshop, Ohio, 24–28 August, 1978*, pp. 105–118

Schuurmans, C. J. E. and Oort, A. H. (1969) A statistical study of pressure changes in the troposphere and lower stratosphere after strong solar flares. *Pure Appl. Geophys.*, **75**, pp. 233–246

Smirnov, R. V. and Kononovich, E. V. (1996) The infuence of solar activity on Earth's weather. In: Balasubramaniam, K. S., Keil, S. L. and Smartt, R. N. (Eds.) *Solar Drivers of Interplanetary and Terrestrial Disturbances*, APS *Conference Series*, **95**, pp. 481–488

Wells, N. (1997) *The atmosphere and the ocean*. John Wiley and Sons, Chichester

Wilcox, J. M., Svalgaard, L. and Scherrer, P. H. (1975) Seasonal variation and magnitude of the solar sector structure-atmospheric vorticity effect. *Nature*, **255**, pp. 539–540

Wu, S. T., Kan, L. C., Tandberg-Hansen, E. and Dryer, M. (1979) Energy deposition in the Earth's atmosphere due to impact of solar activity-generated disturbances. In: McCormac, B. M. and Seliga, T. A. (Eds.) *Solar–Terrestrial Influences on Weather and Climate, Proceedings of a Symposium/Workshop, Ohio, 24–28 August, 1978*, pp. 119–124

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