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Ionospheric measurements during the CRISTA/MAHRSI campaign: their implications and comparison with previous campaigns

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Abstract. The CRISTA/MAHRSI experiment on board a space shuttle was accompanied by a broad campaign of rocket, balloon and ground-based measurements. Supporting lower ionospheric ground-based measurements were run in Europe and Eastern Asia between 1 October–30 November, 1994. Results of comparisons with long ionospheric data series together with short-term comparisons inside the interval October–November, 1994, showed that the upper middle atmosphere (h = 80–100 km) at middle latitudes of the Northern Hemisphere in the interval of the CRISTA/MAHRSI experiment (4–12 November, 1994) was very close to its expected climatological state. In other words, the average results of the experiment can be used as climatological data, at least for the given area/altitudes. The role of solar/geomagnetic and "meteorological" control of the lower ionosphere is investigated and compared with the results of MAP/WINE, MAC/SINE and DYANA campaigns. The effects of both solar/geomagnetic and global meteorological factors on the lower ionosphere are found to be weak during autumn 1994 compared to those in MAP/WINE and DYANA winters, and they are even slightly weaker than those in MAP/SINE summer. The comparison of the four campaigns suggests the following overall pattern: in winter the lower ionosphere at northern middle latitudes appears to be fairly well "meteorologically" controlled with a very weak solar influence. In summer, solar influence is somewhat stronger and dominates the weak "meteorological" influence, but the overall solar/meteorological control is weaker than in winter. In autumn we find the weakest overall solar/meteorological control, local effects evidently dominate.

Key words. Ionosphere (ionosphere – atmosphere interactions; mid-latitude ionosphere)

1 Introduction

The CRISTA/MAHRSI (CRyogenic Infrared Spectrometers and Telescopes for the Atmosphere/Middle Atmosphere High Resolution Spectrometer Instrument) experiment/campaign has been described by Offermann *et al.* (1998), Conway *et al.* (1998) and several other papers in a special section of the Journal of Geophysical Research, series D – Atmospheric Chemistry. The supporting campaign of ground-based ionospheric measurements was run on 1 October–30 November 1994. Measurements in the lower ionosphere (h < 100 km) were made at middle latitudes of the Northern Hemisphere. Information on planetary wave activity obtained from ionospheric measurements has been described by Pancheva and Laštovička (1998). Low frequency (LF) radio wave absorption data from central Europe, including inferred gravity wave activity, were analyzed by Laštovička *et al.* (1997). The following important results were obtained in these two papers:

1. According to the LF absorptions, the CRISTA interval of 3–12 November, 1994, appears to be representative (i.e. very close to the climatological

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state) for autumn, low-to-moderate solar activity and the declining phase of solar cycle.

2. The planetary wave-type oscillations (T = 3–25 days), inferred from radio wave absorption, are much more intense in November than in October in Europe and vice versa in Eastern Asia. They prevailingly propagate eastward.

The lower ionosphere is the altitude region where the solar and meteorological influences are competing, while higher layers are dominated by solar activity and lower layers by meteorological effects. The lower ionosphere is controlled by the Sun e.g. during solar flares, and by "meteorology" (i.e. processes of neutral atmosphere origin) e.g. during winter anomalous days. In previous campaigns DYANA, MAP/WINE and MAC/SINE (Laštovička *et al.*, 1994; Laštovička *et al.*, 1990; Williams *et al.*, 1987; Laštovička *et al.*, 1989), the response of the lower ionosphere to solar and meteorological forcing was studied. This problem is also addressed in this study.

Section 2 contains a brief description of data. Probably the most important contribution of ground-based ionospheric measurements to the CRISTA/MAHRSI project is the use of very long data series to answer the question whether the CRISTA/MAHRSI campaign/experiment was run under typical (climatological) conditions or under anomalous conditions. This is done in Sect. 3 together with a brief description of the development of the lower ionosphere in October–November 1994, particular attention being paid to the interval of the CRISTA/MAHRSI experiment itself. Section 3 also deals briefly with electron density measurements in the lower ionosphere during the campaign. The response of the lower ionosphere to solar and meteorological forcing during the campaign is studied in Sect. 4 with a special emphasis paid to possible dependence of the response on altitude, latitude and longitude. The results are compared with the results from previous campaigns DYANA, MAP/WINE and MAC/SINE (Laštovička *et al.*, 1994; Laštovička *et al.*, 1990; Williams *et al.*, 1987; Laštovička *et al.*, 1989). A brief discussion of lower ionospheric measurements and conclusion close the work.

2 Data

The A3 absorption of radio waves (oblique incidence on the ionosphere), IPHA (indirect phase reflection height analysis) and $f_{\min}$ data, reduced to a constant solar zenith angle, χ, are used to describe the behaviour of the lower ionosphere over Europe and Eastern Asia based on data provided by "ionospheric" participants of the project CRISTA/MAHRSI. The data at a constant χ (75° or $\cos\chi = 0.2$) are average values from morning and afternoon values. The LF A3 absorption data are used for night ($\chi > 100°$). The IPHA method is applied to determine the LF phase reflection height (i.e. level of a constant electron density; Lauter *et al.*, 1984). An increase of the reflection height at a fixed solar zenith angle ($\cos\chi = 0.2$ is used) implies a decrease of the electron concentration at a fixed height. The parameter $f_{\min}$ is used as a rough measure of absorption as done e.g. by Sato (1981) or Laštovička *et al.* (1994) to obtain a larger spatial coverage (A3 absorption measurements are available only in a limited part of Europe). $f_{\min}$ is less accurate and less sensitive, because accuracy/resolution of $f_{\min}$ determination is 0.1 MHz, or under very optimum conditions 0.05 MHz. We can compare only relative variations of $f_{\min}$, not its absolute values, which depend on ionosonde characteristics and noise level. Single data gaps are replaced by interpolated data. Data are generally of good quality with a few gaps only. However, A3 270 kHz absorptions from Průhonice and Nagycenk and $f_{\min}$ from Grocka and Moscow are excluded from the analysis due to a more than acceptable number of data gaps. Values of $f_{\min}$ from Kaliningrad are omitted due to peculiar morning maximum coinciding with morning rush hours (probably artificial increase of $f_{\min}$ due to traffic or industrial noise). Values of $f_{\min}$ from Juliusruh are not used because almost 80% of values are at the lowest instrumental limit, 1.5 MHz, thus they do not allow to detect ionospheric variability.

Geographic coordinates of stations and parameters of A3 and IPHA radio circuits are given in Tables 1 and 2. Stations participating in the campaign covered Europe and Eastern Asia, and two stations, Irkutsk and Sverdlovsk, represented eastern and western Siberia. The available ionospheric data described the lower ionosphere at middle latitudes of the Northern Hemisphere at altitudes of about 85–100 km (except for

Table 1. Parameters of A3 absorption and IPHA (162 kHz) radio circuits used, name or location of station, frequency, latitude (φ) and longitude (λ) of the reflection point (a region of the ionosphere described by the data), the constant solar zenith angle used

Station	f (kHz)	φ (°N)	λ (°E)	χ/cos χ
Panská Ves	6090	50.1	10.3	75°
El Arenosillo	2830	38.5	−5.3	0.2
Průhonice	1539	50.3	11.8	75°
Kühlungsborn	243	54.9	11.4	Night
Kühlungsborn	177	53.5	12.6	Night
Kühlungsborn	162	50.7	6.6	0.2

Table 2. List of $f_{\min}$ measurements used, name of station, latitude (φ) and longitude (λ), the constant solar zenith angle (cos χ)

Station	φ (°N)	λ (°E)	cos χ
Beijing	39.9	116.4	0.2
Ebro	40.8	0.3	0.2
Irkutsk	52.5	104.0	0.2
Kokobunji	35.7	139.5	0.2
Okinawa	26.3	127.8	0.2
Roma	41.9	12.5	0.2
Slough	51.5	−0.6	0.2
Sofia	42.6	23.4	0.2
Sverdlovsk	56.7	51.1	0.2
Wakkanai	45.5	141.7	0.2
Yamagawa	31.2	130.6	0.2

IPHA near 80–81 km). The A3 absorption and IPHA measurements were run continuously only in Europe, all existing measurements are used.

The only electron density profile measurements made during the CRISTA/MAHRSI campaign are those obtained by a partial reflection radar at Nizhni Novgorod, Russia.

To characterize "meteorological" conditions of the middle atmosphere, we use polar temperatures at 10 and 30 hPa provided by the Stratospheric Group of the Free University, Berlin, as characteristics of development of the polar vortex, and winds in the upper middle atmosphere near 95 km as measured at Collm (R. Schminder and D. Kürschner, Results of high-atmosphere wind observations at Collm, October 1994 and November 1994). Unfortunately, other wind measurements in the region of interest from Shigaraki/Kyoto, Irkutsk and Obninsk have an unacceptably high number of days of no measurements for analyses made in the study.

Solar and geomagnetic activity during the period studied is described by general indices, sunspot number R, $F_{10.7}$ and A_p, and by the composite solar Lyman-alpha flux (Tobiska *et al.*, 1997), which for October-November 1994 is identical with the SOLSTICE/UARS Lyman-alpha flux.

3 CRISTA/MAHRSI campaign

3.1 Long-term comparisons

The purpose of long-term comparisons is to answer the question whether the CRISTA/MAHRSI campaign was run under normal/climatological conditions or under anomalous conditions. The available data allow us to answer this question reliably for heights of about 80–100 km (upper middle atmosphere) for Europe and Eastern Asia. For this purpose we use long series of measurements of absorption and partly of $f_{\min}$. The data series must be longer than 20–25 y, homogeneous, and reliable. Not all data series fulfill these conditions.

The October and November 1994 values of absorption and $f_{\min}$ are compared with values of these parameters from Octobers and Novembers of previous years under similar solar activity conditions: declining phase of solar cycle, $10 < R < 60$, $70 < F_{10.7} < 100$, R and $F_{10.7}$ being monthly averages. Such a comparison for the LF nighttime absorptions from central Europe was presented by Laštovička *et al.* (1997). Based on three data sets, which covered the period of the 1960s to the 1990s, they concluded that the LF absorption in October–November 1994 was close to the values expected on the basis of LF absorptions from previous years observed under similar conditions. In order to characterize better the area studied, we add here the results of long-term comparisons of $f_{\min}$ from Slough (England) and from three Japanese stations, Wakkanai, Kokobunji and Okinawa. The $f_{\min}$ data used for long-term comparisons are noon-time medians (10–14 LT). They generally cover the 1970s to 1990s.

Table 3 presents the results of long-term comparisons. These results illustrate problems with long-term analyses of lower ionosphere measurements. The 243 kHz absorption and Slough data display a positive trend. It is not our purpose to deal with long-term trends in the lower ionosphere and upper middle atmosphere. Information about results and related problems may be found e.g. in Bremer (1997), Danilov (1997) or Laštovička (1997). The 270 kHz absorption is too high in early 1980s, but this was a period with low measurement quality. The 177 kHz absorption shows a drop from 1983 to 1984, which can be attributed to change of transmitted frequency from 185 to 177 kHz. Nevertheless, when taking this all into account, absorptions and $f_{\min}$ from Slough provide consistent values for 1994,

Table 3. Long-term development of the nighttime LF radio wave absorption in Central Europe at three frequencies and of $f_{\min}$ in Western Europe (Slough) and Japan (Wakkanai, Kokobunji and Okinawa) under solar activity conditions similar to those of October–November 1994

		243 kHz	177 kHz	270 kHz	Slough	Wakkanai	Kokobunji	Okinawa
1972	October		$R > 60$					
	November	21.0	21.0	16.4	1.6	1.3	1.5	1.6
1973	October	19.0	19.0	15.3	1.6	1.5	1.5	2.0
	November	21.0	22.0	14.0	1.6	1.5	1.5	1.8
1974	October	19.0	21.0	15.2	1.40	1.6	1.6	2.0
	November	21.0	22.0	16.5	1.6	1.6	1.6	1.7
1983	October		$F_{10.7} > 100$					
	November	21.5	23.5	23.1	1.7	1.6	1.5	1.7
1984	October	21.0	19.0	20.0	1.7	1.8	1.5	1.9
	November	23.0	19.0	23.0	1.7	1.6	1.5	1.7
1985	October	21.0	18.0	17.0	1.6	1.6	1.5	1.8
	November	21.0	18.0	19.0	1.6	1.6	1.5	1.6
1993	October	23.0	18.0	16.1	1.8	very	high	values
	November	24.0	19.0	17.0	1.8	very	high	values
1994	October	24.0	19.0	15.9	1.8	1.55 1.6[a]	1.35	1.6 2.7[a]
	November	24.5	19.0	16.4	1.8	1.5 1.6[a]	1.3	1.6 1.8[a]
	Expected	24	18–19	16	1.75	1.6	1.5	1.7–1.8

Expected – values expected for 1994 as deduced from previous years [a] Automatic scaling of ionograms.

which are very close to what can be expected based on values from previous years. No other European data contradict this result. Thus in Europe the period October–November 1994 showed an average behaviour very close to the climatological one.

The Japanese data must be handled carefully. In the 1970s and the first half of the 1980s, ionograms were scaled manually. On the other hand, in the 1990s the basic scaling was automated except for Kokobunji, where the results of both automatic and manual scaling have been reported. There is a surprisingly large, systematic difference between the Kokobunji $f_{\min}$ from automatic and manual scaling. The former was 20–45% higher than the latter in October–November 1993 and 1994. Therefore the manual Kokobunji 1994 data are lower than expected, while the automatic scaling data of two other stations are apparently higher than expected. To help to resolve the problem with automatic scaling, the data from Wakkanai and Okinawa for 1994 were re-scaled manually. The results of re-scaling, shown in Table 3, confirm the difference between automatic and manual scaling, even though it is small for Wakkanai and large for Okinawa. Taking into account only the results of manual scaling, which are generally considered to be more reliable, we obtain for all three Japanese stations values lower than expected for 1994. This means that the lower ionosphere above Japan in October–November 1994 appears to be quieter than expected, i.e. it corresponds rather to the extreme minimum of the solar cycle. Values for 1993 were substantially higher than they should be. Since we do not know why (since solar/geomagnetic activity is not the reason due to absence of such an increase in Europe), the Japanese data of 1993 (automatic scaling) have not been considered.

A multicomponent regression analysis has been applied to another long ionospheric data series (25 y, 1971–1996), absorption at 6090 kHz. The analysis has been performed separately for monthly median values from October and from November with input parameters: $F_{10.7}$, A_p, time (for trend), QBO50 hPa, QBO30 h Pa and ENSO. The model describes 65% of variance for November and slightly less for October. $F_{10.7}$ is by far the most important input factor (through the effect of solar cycle), which itself describes 57% of variance for November. The model values for October and November 1994 are slightly lower than the observed values but the difference is within 1σ of observations. Thus these data confirm the basic "normality" of the period October–November 1994 in Europe.

It should be mentioned that the magnitude of planetary wave activity, inferred for October–November 1994 from daytime radio wave absorption measurements in Europe, was also very close to expected values (Pancheva and Laštovička, 1998). The gravity wave activity, inferred from the nighttime 270 kHz absorption measurements in Central Europe, reached expected values, as well (Laštovička *et al.*, 1997). These results complete the pattern of an almost "climatological" state of the upper middle atmosphere over Europe in October–November 1994.

3.2 Lower Ionosphere during the Campaign

To describe the lower ionosphere during the CRISTA/MAHRSI campaign, let us start with ionospheric effects of solar flares, sudden ionospheric disturbances (SIDs), and with information about geomagnetic activity. The list of all important SIDs (importance >1, widespread index >2) taken from Solar-Geophysical Data (NGDC/NOAA, Boulder) is given in Table 4. The solar flare/SID activity was moderate to low, particularly if considering that the last two events with WSI $=3$ were reported only as SEAs, i.e. their reliability is highly questionable. There was no important SID during the CRISTA/MAHRSI Shuttle experiment.

The lower ionosphere may be substantially affected by geomagnetic storms (e.g. brief review by Laštovička, 1996), even though there is a poor correlation of ionospheric variability with geomagnetic activity in October–November 1994 with exception of the 243 kHz and partly 177 kHz absorption. To this end, geomagnetic storms were examined. There were several geomagnetic storms with maximum $K_p > 5$. A double-peak event with maxima $K_p = 7$ on October 3 and 5+ on October 5 occurred in early October, another one with high activity on 22–24 October peaked on 22 October, $K_p = 6+$. The largest storm of this period occurred on 29–31 October with maximum on 29 October of $K_p = 7$. In November only short storms occurred with maxima on 4 November (5+), 6 November (6−), 20 November (5) and 26 November (6+). Thus the period October–November 1994 exhibited higher geomagnetic than solar activity and the interval of the CRISTA/MAHRSI experiment itself was not geomagnetically quiet in its early part.

The correlation of ionospheric parameters with solar and "meteorological" parameters is poor on average for October–November 1994 (Sect. 4). Nevertheless, a few

Table 4. List of important SIDs in October–November 1997. WSI, widespread index (maximum 5), importance indicates importance of SID (maximum 3+)

Date	Start	Maximum	End	Importance	WSI	Comment
5.10	07:10	07:22	08:10	2	5	
6.10	19:02	19:13	19:52	2−	5	
7.10	09:38	09:51	10:02	1+	3	X-ray flare
19.10	20:51	21:32	01:06	2	5	
28.10	09:32	09:49	10:13	2−	3	No flare
14.11	09:00	09:05	09:30	2−	3	No flare

ionospheric parameters are affected by "meteorological" variables. Therefore the course of T10 hPa is shown in Fig. 1. The low temperatures reached on early days of November 1994 indicate establishment of polar vortex. Some increase of temperature in mid-November together with correlation of T10 hPa with Irkutsk $f_{\min}$ as the only correlating ionospheric parameter (Table 7) indicate possible shift of vortex centre towards eastern Siberia.

Figures 2–5 show behaviour of various ionospheric parameters, arranged according to geographic regions and type of measurements, during October–November 1994. Figure 2 displays an evidently different pattern of Irkutsk $f_{\min}$ variability compared to other ionospheric data. No other station but Irkutsk (eastern Siberia) reveals a strong increase from October to November. Moreover, Irkutsk is the only station correlating with T10 hPa and the only station with a well-pronounced ~10-day wave in the spectrum of planetary wave-type oscillations (Pancheva and Laštovička, 1998), see e.g. four ~10-day waves between days 20–61.

Figure 3 reveals a substantially different behaviour of the lower ionosphere over northern (Wakkanai) and southern (Okinawa) Japan, particularly in terms of day-to-day variations and a very poor correlation ($r = -0.1$, Table 5). Also mutual correlations among other Japanese data are very poor (Table 5). In terms of somewhat smoothed behaviour, there are some features observed both in Wakkanai and Beijing, but in terms of day-to-day variability there is again no correlation ($r = 0$, Table 5 – however, for November replacement of Wakkanai automatic-scaled data by manually-scaled data improves the correlation substantially).

During the CRISTA/MAHRSI experiment itself (November 4–12, days 35–43 in Figs. 1–5), the average level of $f_{\min}$ was close to the mean level of the whole October-November 1994 period for Beijing, Wakkanai, Roma(Rome), Ebro, 6090 kHz absorption and night-time LF absorptions in central Europe (Laštovička *et al.*, 1997), slightly higher for Slough, 2830 kHz absorption and 1539 kHz absorption, and somewhat higher for the southernmost station Okinawa (by more than 0.1 MHz compared to the rest of November),

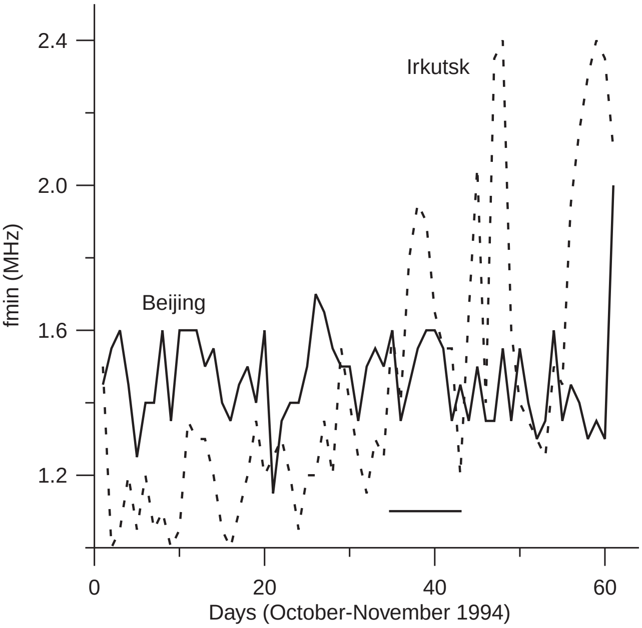

Fig. 2. Parameter $f_{\min}$ from Beijing (*solid line*) and Irkutsk (*dashed line*) during October–November, 1994 (days 1–61). *Short horizontal line*, interval of the CRISTA/MAHRSI experiment

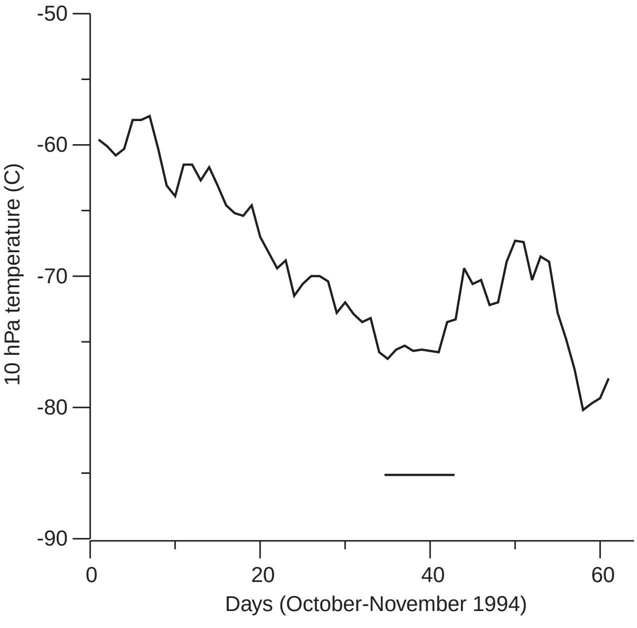

Fig. 1. Development of the North Pole stratospheric temperature at 10 hPa during October–November, 1994 (days 1–61). *Short horizontal line* indicates interval of the CRISTA/MAHRSI experiment

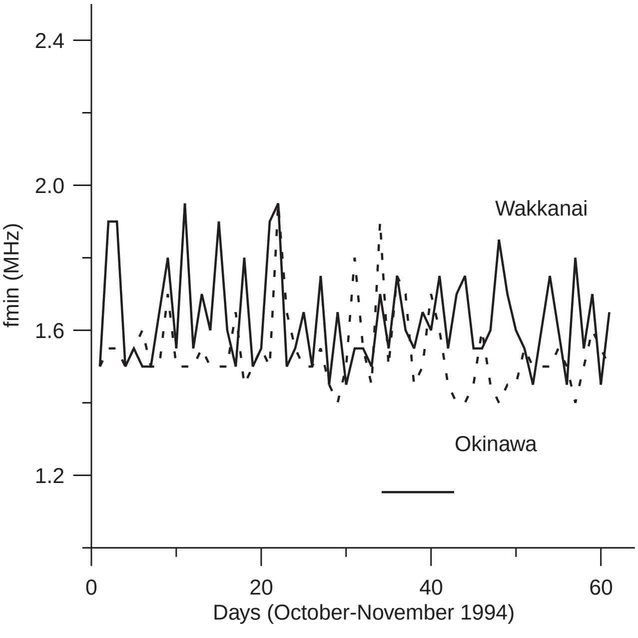

Fig. 3. Parameter $f_{\min}$ from Wakkanai (*solid line*) and Okinawa (*dashed line*) during October–November, 1994 (days 1–61). Short horizontal line, interval of the CRISTA/MAHRSI experiment

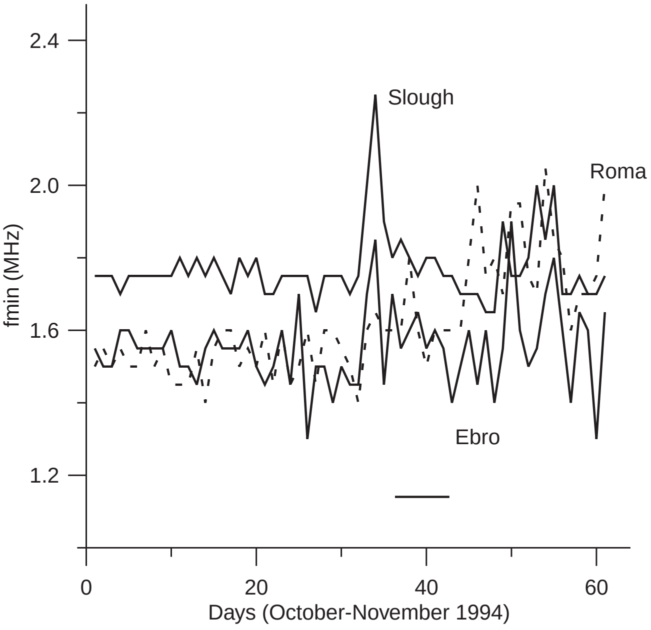

Fig. 4. Parameter $f_{\min}$ from Slough (*solid line*), Ebro (*solid line*) and Roma (Rome) (*dashed line*) during October–November 1994 (days 1–61). *Short horizontal line*, interval of the CRISTA/MAHRSI experiment

which was an essentially consistent pattern. However, on the day-to-day scale there was little similarity and correlation. The lower ionosphere appears to be dominated by local factors. The most remarkable feature on the day-to-day scale is the strong peak observed on November 3, just before the beginning of experiment, by the two most westerly located ionosondes at Slough and Ebro (Fig. 4).

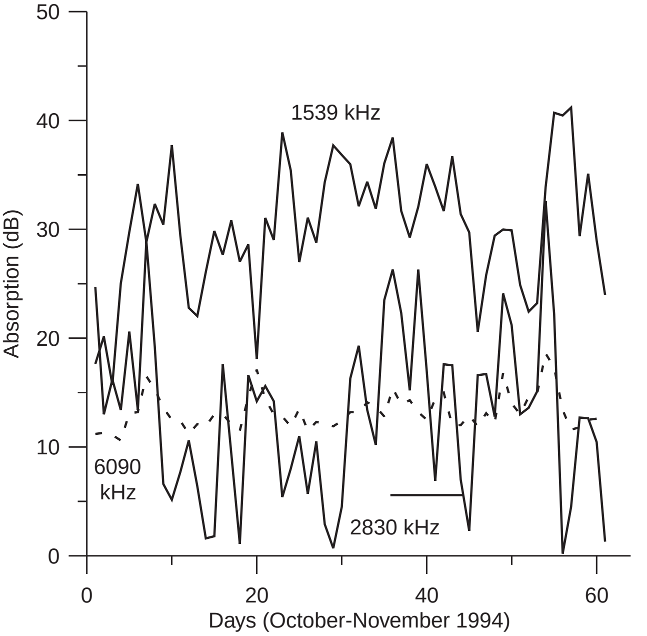

Fig. 5. Absorption at 1539 kHz (*solid line*), 2830 kHz (*solid line*) and 6090 kHz (*dashed line*) during October–November 1994 (days 1–61). Short horizontal line, interval of the CRISTA/MAHRSI experiment

In Europe, the lower ionospheric parameters during the interval of the CRISTA/MAHRSI experiment were predominantly close to average values of the period October–November 1994, which were close to values expected from long-term comparisons. Consequently, in Europe the interval of the CRISTA/MAHRSI experiment appears to describe by its average values the upper middle atmosphere in an essentially climatological state. In Japan the situation is not so evident. The $f_{\min}$ during the CRISTA/MAHRSI experiment was close to average value of the period October–November 1994 for Wakkanai, slightly higher for Kokobunji and Yamagawa, and somewhat higher for Okinawa. On the other hand, long-term comparisons seem to show that the values observed in October–November 1994 were lower than expected. As a consequence of these two opposite tendencies, the lower ionosphere over Japan again seems to be relatively close to the climatological state in its average values during the CRISTA/MAHRSI experiment.

European $f_{\min}$ values reveal more variability in November (e.g. Fig. 4), while Eastern Asian values show greater variability in October (e.g. Fig. 3). This is consistent with the pattern of planetary wave activity inferred from ionospheric data (Pancheva and Laštovička, 1998).

The dominant feature of absorption data (Fig. 5) is a large day-to-day variability, which does not seem to correlate much between various radio paths; we again see a rather local pattern of variability. However, the partly smoothed variations of the 2830 kHz El Arenosillo absorption and the 6090 kHz Panská Ves absorption reveal basic similarity in spite of a large distance between reflection points ($d > 1000$ km), which results in a fairly good correlation between them (Tables 5 and 6). They both describe the bottomside E-layer of the ionosphere.

Taking into account the timing of the observed geomagnetic storms versus the development of absorption and $f_{\min}$ for more northern radio paths/stations and correlations with geomagnetic activity, we may conclude that the observed geomagnetic storms did not affect the midlatitudinal ionosphere significantly except for the two nighttime radio paths, located at the highest geomagnetic latitudes among the analyzed ionospheric data.

3.3 Electron density measurements

The only electron density measurement campaign for CRISTA/MAHRSI was run at Nizhni Novgorod, Russia (56.2°N, 44.3°E) from 26 October to 11 November 1994, using a partial reflection radar working at a frequency of 2.95 MHz. Measurements are available on days October 26–31, November 1–3 and November 10–11 at altitudes between 60 and 90 km.

Figure 6 shows the development of the electron density profile over the period of measurements at a

Table 5. Matrix of correlation coefficients for all analyzed ionospheric parameters, October–November 1994. Correlation coefficients significant at the 0.01 level are underlined. Negative correlations with IPHA are due to the fact that an increase of electron density causes an increase of absorption and $f_{\min}$ but a decrease of IPHA reflection height

	Be	Eb	Ir	Ko	Ok	Ro	Sl	So	Sv	Wa	Ya	609	IPH	153	177	243	283
Beijing	1	0.1	0	−0.2	0	0	0.1	0.1	−0.2	0.1	−0.2	−0.2	0	−0.1	0.1	0	−0.2
Ebro	0.1	1	0	0.2	0	0.3	0.5	0.2	0.1	−0.1	0	0.4	−0.2	0.1	0.2	−0.1	0.2
Irkutsk	0	0	1	−0.2	0.3	0.5	−0.2	0.4	−0.1	−0.2	−0.1	−0.1	−0.3	0.1	−0.1	0	0
Kokobunji	−0.2	0.2	−0.2	1	0.1	−0.2	0.2	−0.1	0.1	0.2	0	0.1	0	0.1	0	0	0.1
Okinawa	0	0	0.3	0.1	1	−0.1	0	0.1	0.3	0.2	0	0	0.1	0	0	−0.2	0.3
Roma	0	0.3	0.5	−0.2	−0.1	1	0.1	0.5	−0.1	−0.2	−0.1	0.3	−0.4	0	0	0.1	0.2
Slough	0.1	0.5	−0.2	0.2	0	0.1	1	0.4	−0.2	0	0	0.4	−0.4	0.1	0.4	−0.2	0.2
Sofia	0.1	0.2	0.4	−0.1	0.1	0.5	0.4	1	−0.2	0.1	0	0.3	−0.6	0.1	0	−0.1	0.3
Sverdlovsk	−0.2	0.1	−0.1	0.1	0.3	−0.1	−0.2	−0.2	1	0.1	−0.1	0.1	0.2	−0.2	0	0	0.3
Wakkanai	0.1	−0.1	−0.2	0.2	0.2	−0.2	0	0.1	0.1	1	0.1	−0.1	0	0	−0.2	−0.2	0
Yamagawa	−0.2	0	−0.1	0	0	−0.1	0	0	−0.1	0.1	1	0.2	0	0.1	0	−0.1	0.2
6090 kHz	−0.2	0.4	−0.1	0.1	0	0.3	0.4	0.3	0.1	−0.1	0.2	1	−0.4	0.2	0.3	0	0.5
IPHA	0	−0.2	−0.3	0	0.1	−0.4	−0.4	−0.6	0.2	0	0	−0.4	1	−0.4	−0.2	−0.2	−0.1
1539 kHz	−0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	−0.2	0	0.1	0.2	−0.4	1	0	0.2	−0.1
177 kHz	0.1	0.2	−0.1	0	0	0	0.4	0	0	−0.2	0	0.3	−0.2	0	1	0.1	0.2
243 kHz	0	−0.1	0	0	−0.2	0.1	−0.2	−0.1	0	−0.2	−0.1	0	−0.2	0.2	0.1	1	0
2830 kHz	−0.2	0.2	0	0.1	0.3	0.2	0.2	0.3	0.3	0	0.2	0.5	−0.1	−0.1	0.2	0	1

quasi-constant solar zenith angle of about 71°. Electron densities measured during the CRISTA/MAHRSI experiment (November 3 and 11) are remarkably higher than those measured before the experiment (October 26 – November 1). The maximum electron densities on November 3 coincide with the sharp peak of $f_{\min}$ at Slough and Ebro (Fig. 4), but such a peak does not occur in the area between these two regions.

The development of electron density profiles in the D-region with the course of day is shown in Fig. 7. Almost all profiles reveal an indication of the existence of the C-layer, a layer peaking between 65–70 km. Otherwise the profiles essentially confirm the strong solar zenith angle control of electron density in the D-region with some exception at the C-layer heights, where between 60–67.5 km the profile measured at 10:45 LT appears to dominate. The dominant role of cosmic rays in ionization at the C-layer heights may explain the missing solar zenith angle control.

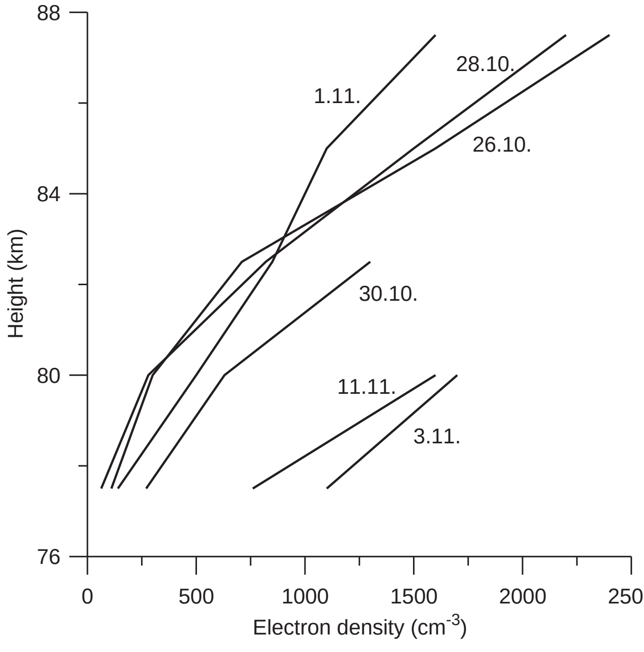

Fig. 6. Development of the electron density profile over Nizhni Novgorod at $\chi = 71°$ during 26 October–11 November 1994

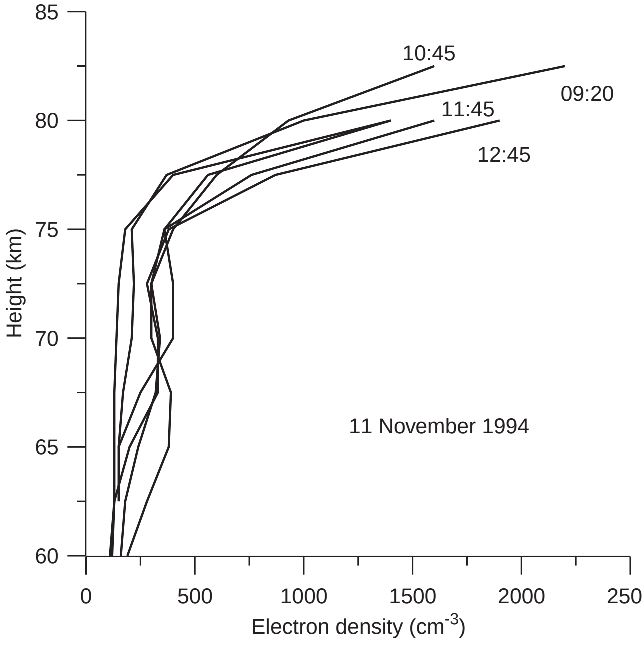

Fig. 7. Development of the electron density profile over Nizhni Novgorod during 11 November, 1994. Two profiles without time information were measured at 13:45 and 14:45 (all times are local times). The latter provides the lowest electron densities in 65–75 km. The corresponding solar zenith angles vary between 74° (11:45) and 81° (09:20 and 14:45)

4 Response of the lower ionosphere to solar and meteorological forcing

The response of the lower ionosphere at (higher) middle latitudes to solar and meteorological forcing depends on season; it is different in winter with shorter daytime period and an influence of polar vortex on the lower ionosphere (e.g. Laštovička *et al.*, 1990), and in summer. The CRISTA/MAHRSI period represents an intermediate period of change at autumn, with formation of the polar vortex, change of winds in the stratosphere and mesosphere etc.

First, matrices of correlation coefficients of all available daily ionospheric (17 stations/radio circuits, see Tables 1 and 2), solar (4 parameters) and meteorological (4 parameters) data were calculated for the whole interval studied, and separately for October and for November 1994. This division is not artificial, because the wintertime polar vortex seems to be established approximately with the beginning of November 1994, geomagnetic activity was substantially lower in November, and planetary wave activity inferred from absorption was also evidently different in October and November (Pancheva and Laštovička, 1998). The correlation between geomagnetic activity (A_p) and solar indices/parameters R, $F_{10.7}$ and Lyman-alpha flux was quite insignificant, $r = 0.06$, 0.13 and −0.03, respectively. This made separation of solar ionizing radiation and geomagnetic activity effects reasonable. The correlation between daily values of R and $F_{10.7}$ was close, $r = 0.90$, but this was not the case as regards their correlation with the solar Lyman-alpha flux, where $r = 0.57$ and 0.36. This illustrates the known, but not always accepted, fact that the day-to-day changes of solar indices do not describe sufficiently well the day-to-day changes of solar ionizing radiation. The general level of solar activity in October–November 1994 was moderate to low, thus the Lyman-alpha flux dominated in ionizing the lower ionosphere over solar X-rays both in absolute values and in ionospheric variability; the latter was controlled prevailingly by solar X-rays under high solar activity conditions, e.g. Laštovička and Boška (1982).

The mutual correlations between "meteorological" parameters were also different. There was a close correlation between daily values of the North Pole 10 hPa and 30 hPa temperatures, $r = 0.92$, 0.86 and 0.85 for the whole period, October and November, respectively. The correlation between zonal and meridional wind from Collm was only moderate, $r = 0.49$, 0.66 and 0.42, respectively. Correlations of the North Pole 10 hPa and 30 hPa temperatures with meridional wind from Collm are negligible, about $r = 0.1$, and with zonal wind again negligible, about $r = -0.1$. However, correlations of both wind components with temperatures are more positive in October, about $r = 0.45$ and 0.20 for 10 and 30 hPa temperatures, respectively, and are close to zero in November (Table 6). Thus Collm winds near 95 km are almost independent of North Pole stratospheric temperatures.

Table 5 shows the matrix of correlation coefficients of all ionospheric parameters studied for the whole CRISTA/MAHRSI campaign. Correlations are generally weak and mostly statistically insignificant. This is the case particularly for Eastern Asia (Beijing, Irkutsk, Wakkanai, Kokobunji, Yamagawa, Okinawa), where no correlation is statistically significant. Thus the behaviour of f_{min} at various stations seems to be basically independent of each other. However, it should be mentioned that it might be partly an artifact of a relatively quiet situation combined with low resolution of f_{min} determination, which both enhance the role of random errors and local variations/influences. Another reason might be a rather large latitudinal span covered

Table 6. Matrix of correlation coefficients for European ionospheric parameters, solar parameters and meteorological parameters, November 1994. Correlation coefficients significant at the 0.01 level are underlined. Negative correlations of ionospheric parameters with IPHA are due to the fact that an increase of electron density causes an increase of absorption and f_{min} but a decrease of IPHA reflection height

	Ebro	Rom	Slou	Sofi	609	IPH	153	177	243	283	R	F_{10}	Lyα	T10	T30	mer	zon
Ebro	1	0.3	$\underline{0.5}$	0.2	$\underline{0.5}$	−0.1	0.1	0.3	−0.1	0.2	0	0.1	0	0.1	0.1	−0.1	−0.2
Roma	0.3	1	−0.1	0.2	0.2	0.1	−0.4	0	0.2	0	−$\underline{0.6}$	−$\underline{0.6}$	−0.2	0.4	0.3	−0.2	0.2
Slough	$\underline{0.5}$	−0.1	1	0.3	$\underline{0.5}$	−$\underline{0.5}$	0.1	$\underline{0.5}$	−0.4	0.2	0.4	0.4	0.2	0.1	0.2	−0.2	−0.2
Sofia	0.2	0.2	0.3	1	0.4	−0.3	0	0.3	−0.1	0.4	−0.2	0	−0.2	0	0	0	0.2
6090 kHz	$\underline{0.5}$	0.2	$\underline{0.5}$	0.4	1	−$\underline{0.6}$	0.2	$\underline{0.7}$	−0.1	$\underline{0.6}$	−0.1	0	−0.2	0.4	0.4	−0.2	−0.2
IPHA	−0.1	0.1	−$\underline{0.5}$	−0.3	−$\underline{0.6}$	1	−0.3	−$\underline{0.6}$	−0.1	−0.2	0.1	0.1	0.1	−0.1	−0.1	0.3	0
1539 kHz	0.1	−0.4	0.1	0	0.2	−0.3	1	0.3	−0.1	0.1	0.3	0.4	0	−0.4	−0.4	0.1	−0.2
177 kHz	0.3	0	$\underline{0.5}$	0.3	$\underline{0.7}$	−$\underline{0.6}$	0.3	1	−0.1	0.2	0.1	0.1	−0.2	0	0	−$\underline{0.5}$	−0.4
243 kHz	−0.1	0.2	−0.4	−0.1	−0.1	−0.1	−0.1	−0.1	1	−0.1	−0.3	−0.3	−0.1	−0.1	0	−0.2	0
2830 kHz	0.2	0	0.2	0.4	$\underline{0.6}$	−0.2	0.1	0.2	−0.1	1	0	0.1	−0.2	0.2	0.2	0.1	0.1
R	0	−$\underline{0.6}$	0.4	−0.2	−0.1	0.1	0.3	0.1	−0.3	0	1	$\underline{0.9}$	$\underline{0.5}$	−0.2	−0.2	0	−0.4
$F_{10.7}$	0.1	−$\underline{0.6}$	0.4	0	0	0.1	0.4	0.1	−0.3	0.1	$\underline{0.9}$	1	0.4	−0.4	−0.3	0	−0.4
Lyman-α	0	−0.2	0.2	−0.2	−0.2	0.1	0	−0.2	−0.1	−0.2	$\underline{0.5}$	0.4	1	−0.1	0.1	−0.1	−0.4
T10 hPa	0.1	0.4	0.1	0	0.4	−0.1	−0.4	0	−0.1	0.2	−0.2	−0.4	−0.1	1	$\underline{0.9}$	0	0.2
T30 hPa	0.1	0.3	0.2	0	0.4	−0.1	−0.4	0	0	0.2	−0.2	−0.3	0.1	$\underline{0.9}$	1	−0.1	0
Collm-me	−0.1	−0.2	−0.2	0	−0.2	0.3	0.1	−$\underline{0.5}$	−0.2	0.1	0	0	−0.1	0	−0.1	1	0.4
Collm-zo	−0.2	0.2	−0.2	0.2	−0.2	0	−0.2	−0.4	0	0.1	−0.4	−0.4	−0.4	0.2	0	0.4	1

by data from Eastern Asia. Sverdlovsk data (western Siberia) appear to be uncorrelated with all other ionospheric data, as well.

A better situation is found for Europe. IPHA and the 6090 kHz absorption have the "right" sign of correlation (+ for 6090 kHz, − for IPHA) with all European ionospheric data and statistically significant correlations with five and six of them out of nine. Also Slough reveals a statistically significant correlation with five and Sofia with four European data sets. It might be of some interest that Irkutsk correlates better with European data than Sverdlovsk. Somewhat poorer correlation of the 243 kHz absorption is due to its correlation with the geomagnetic activity index A_p ($r = 0.5$) as a consequence of its highest geomagnetic latitude and use of nighttime data. For all other ionospheric data the correlation with A_p is weak, if any, not better than about $r = 0.2$ (except for $r = 0.28$ for the 177 kHz nighttime absorption).

Mutual correlations among ionospheric data in autumn (October–November 1994) are evidently much poorer than in winter, as shown by MAP/WINE (Laštovička *et al.*, 1990) and DYANA (Laštovička *et al.*, 1994) campaign data.

Correlations among ionospheric parameters in October were even slightly worse than those shown in Table 5. However, this is not the case for November. For Eastern Asia and western Siberia (Sverdlovsk), correlations are improved very little and remain essentially as poor as they are for the whole interval. Replacement of automatically scaled $f_{\min}$ of Wakkanai and Okinawa by manually scaled values improves considerably the correlation between Wakkanai and Beijing, but all other correlations remain as poor as they were before this replacement. For Europe, however, we find some improvement of correlations, as shown in Table 6. The 6090 kHz absorption now correlates fairly well with most of European ionospheric data ($r = 0.5$–0.7). Also majority of other stations/circuits display a visible improvement of mutual correlations. Nevertheless, they remain lower than wintertime correlations from campaigns MAP/WINE and DYANA.

Table 6 reveals no detectable solar activity control of the European lower ionosphere, particularly when considering the Lyman-alpha flux. The same is valid for the whole period October–November 1994 and also for data from Eastern Asia.

During MAP/WINE, ionospheric data were predominantly organized according to altitude, not latitude or longitude (Laštovička *et al.*, 1990). This does not seem to be the case for CRISTA/MAHRSI. Table 6 does not indicate a dependence on altitude, e.g. because of a relatively good correlation of European $f_{\min}$ data with IPHA, which describes the lowest height of the height interval studied.

Table 6 displays some correlation of ionospheric parameters with the lower thermospheric winds only for 177 kHz but this correlation is of opposite sign to that observed in winter (e.g. Laštovička *et al.*, 1994). Data for the whole interval do not provide any statistically significant correlation of ionospheric parameters with winds from Collm, which was a representative wind for majority of the analyzed European ionospheric data in the MAP/WINE winter (e.g. Laštovička *et al.*, 1990). As for correlations of ionospheric parameters with the North Pole temperatures, T10 and T30, the best and of right sign correlations are found for Irkutsk, −0.3 for October, −0.5 for November and −0.7 for the October–November period, which indicates that the coincidence is mainly in long-term development of temperatures and $f_{\min}$ from Irkutsk. Other ionospheric parameters display rather poor relationships to T10 and T30.

Table 5 shows that Irkutsk does not correlate much with other ionospheric parameters and for November itself it is even worse, because Irkutsk reveals negative correlations with most of ionospheric parameters. Together with its highest correlation with T10 and T30 and evidently better correlation in November than in October it all could indicate a displacement of a newly created polar vortex in November towards Irkutsk (eastern Siberia).

To obtain a deeper insight into the results of correlation analysis, principal component analysis (PCA, sometimes called factorial analysis; e.g., Joreskog *et al.*, 1976) without and with axis rotation has been applied to all parameters studied over the whole period and for November separately. October data do not fulfill the Kaiser-Meyer-Olkin measure of sampling adequacy criterion, therefore the PCA is not applied to these data. Out of 25 parameters studied, 9/8 factors (whole period/November) describe more than 75% of variability and 14/12 factors more than 90% of variability for the whole interval and for November, respectively, for the PCA without axis rotation. The general pattern provided by the PCA analysis is similar for both data sets, so we will present here only the results for the whole October–November interval shown in Table 7 for the first nine factors. Unfortunately, the first two factors represent a mixed influence of solar activity and temperatures, and $f4$ of A_p and winds. Factors $f6$–$f9$ reflect only relations between some ionospheric parameters. Consequently, only factor $f3$, which shows a positive effect of solar activity on $f_{\min}$ from Slough and the 6090 kHz absorption, and $f5$, which shows a positive effect of geomagnetic activity on the 177 kHz absorption, may be, with some limitations used for grouping of data and physical interpretation of the results. Therefore we applied the varimax axis rotation and transformation (commercial software SPSS) to obtain scores shown in Table 8. These scores allow a better grouping of data. Only the first five factors reflect the influence of solar and meteorological parameters on ionospheric parameters, therefore only the first five factors are shown in Table 8. The first factor reflects the influence of the north polar stratospheric temperatures solely on Irkutsk $f_{\min}$, probably due to a displacement of the newly created polar vortex towards eastern Siberia. The second factor includes only solar activity parameters (measures) and, thus, confirms no detectable influence of solar activity on the midlatitudinal lower ionosphere in October–November 1994. The third factor describes some intraionospheric

Table 7. PCA loadings (no axis rotation) for October–November 1994, all parameters studied. The first nine factors, which cover 76.5% of the total variance, are shown. Important loadings are underlined

Factor	$f1$	$f2$	$f3$	$f4$	$f5$	$f6$	$f7$	$f8$	$f9$
Percentage	20.2	11.6	10.4	8.7	6.7	5.5	4.7	4.5	4.2
Cumulative Percentage	20.2	31.8	42.2	50.9	57.7	63.2	67.8	72.3	76.5
Beijing	0	−0.1	0	−0.3	0.4	$\underline{0.5}$	−0.1	0.3	0.3
Ebro	−0.3	0.4	0.3	0.1	0.2	−0.1	−0.4	−0.1	0.1
Irkutsk	$\underline{-0.7}$	−0.2	−0.4	−0.3	−0.1	−0.1	0.1	0	−0.3
Kokobunji	0	0	0.2	$\underline{0.5}$	0	0.2	$\underline{-0.6}$	−0.1	−0.4
Okinawa	−0.2	−0.1	0.4	0	−0.3	$\underline{0.5}$	0.2	$\underline{0.5}$	−0.2
Roma	$\underline{-0.7}$	0.2	−0.2	−0.1	0	−0.1	0	0	0.3
Slough	−0.3	0.2	$\underline{0.7}$	0.1	0.3	0.2	−0.1	−0.1	0
Sofia	$\underline{-0.8}$	0	0.2	−0.2	−0.1	0.1	0	0	0.1
Sverdlovsk	0.2	0.4	0	0.1	−0.4	−0.3	−0.3	0.4	−0.2
Wakkanai	0.1	0.1	−0.1	0.2	0.1	0.4	0	$\underline{-0.6}$	−0.2
Yamagawa	0	−0.1	0.3	0.2	−0.4	0	$\underline{0.6}$	−0.2	−0.1
6090 kHz	−0.4	0.4	$\underline{0.5}$	0.3	−0.2	−0.1	0.1	0	0.3
2830 kHz	−0.3	$\underline{0.6}$	0.1	0.3	−0.3	−0.1	0.2	0.2	−0.1
1539 kHz	−0.3	$\underline{-0.5}$	0.3	0.3	0.1	0.4	0	−0.2	0
IPHA	$\underline{0.8}$	0.2	−0.2	−0.2	−0.1	0	0	0.1	−0.2
177 kHz	−0.1	0.3	0.3	0.2	$\underline{0.6}$	0	0.3	0.2	−0.2
243 kHz	−0.1	−0.2	−0.4	$\underline{0.5}$	0.3	−0.2	0.1	0.2	0.1
R	$\underline{0.6}$	$\underline{-0.5}$	$\underline{0.5}$	−0.1	0	−0.1	0	0	0.1
$F_{10.7}$	$\underline{0.7}$	−0.3	$\underline{0.5}$	0	0	0	0	0	0.1
Lyman-α	0.1	$\underline{-0.6}$	0.4	−0.1	0	−0.2	0	0.1	0.1
A_p	0.3	−0.1	−0.2	$\underline{0.5}$	$\underline{0.6}$	−0.1	0.2	0.3	−0.2
T10 hPa	$\underline{0.8}$	$\underline{0.6}$	0	0	0	0	0.1	−0.1	0.2
T30 hPa	$\underline{0.8}$	$\underline{0.5}$	0	0.1	0	0	0.1	−0.1	0.3
Collm-me	0.3	−0.3	−0.2	$\underline{0.6}$	−0.3	0.2	−0.1	0.1	0.3
Collm-zo	−0.3	−0.2	−0.3	$\underline{0.6}$	−0.2	0.3	0	0	0.3

Table 8. PCA factor scores after varimax axis rotation and transformation for October–November 1994, all parameters studied, the first five factors. Important scores are underlined

Factor	$f1$	$f2$	$f3$	$f4$	$f5$
Beijing	0.1	0	0.1	0.1	0
Ebro	0	0	$\underline{0.3}$	0	−0.1
Irkutsk	$\underline{-0.2}$	−0.1	$\underline{-0.2}$	−0.1	0
Kokobunji	−0.1	0	0	0	0
Okinawa	0	0	−0.1	0	0
Roma	−0.1	−0.1	0.1	0.1	−0.1
Slough	0	0.1	$\underline{0.3}$	−0.1	0
Sofia	−0.1	0	0.1	0	−0.1
Sverdlovsk	0	−0.1	−0.1	0	0
Wakkanai	0	−0.1	−0.1	0	−0.1
Yamagawa	0	0	0	0	0
6090 kHz	0.1	0	$\underline{0.3}$	0.1	0
2830 kHz	0	−0.1	0.1	0	0.1
1539 kHz	−0.1	0.2	0.1	0	0.1
IPHA	0.1	−0.1	−0.2	−0.1	0
177 kHz	0	0	0.1	$\underline{-0.3}$	$\underline{0.4}$
243 kHz	0	0	0	0.2	$\underline{0.4}$
R	0	$\underline{0.3}$	0	0	0
$F_{10.7}$	0.1	$\underline{0.3}$	0	0	0
Lyman-α	−0.1	$\underline{0.3}$	0	0	0
A_p	0	0	−0.1	−0.1	$\underline{0.5}$
T10 hPa	$\underline{0.3}$	−0.1	0.1	0	0
T30 hPa	$\underline{0.3}$	0	0.1	0.1	0
Collm-me	0.1	0	0	$\underline{0.5}$	0
Collm-zo	0	−0.1	0.1	$\underline{0.5}$	0

relations. The fourth factor reveals a limited influence of the lower thermospheric wind on the lower ionosphere, only the 177 kHz absorption and in part, the 243 kHz absorption are affected. For these two radio circuits the Collm wind may be geographically considered to be the local wind. Again solely these two absorption data sets are significantly influenced by geomagnetic activity, as shown by the fifth factor. This is due to the fact that both absorptions are nighttime data (more sensitive to geomagnetic activity) and that their reflection points have the highest geomagnetic latitudes among the investigated ionospheric data. However, Table 8 clearly shows that the majority of ionospheric parameters are not significantly affected by solar/geomagnetic and meteorological factors, used in this analysis.

We can conclude that there is generally no detectable solar or geomagnetic (except for nighttime absorptions at the highest geomagnetic latitudes) control of and a rather poor global meteorological influence on the midlatitude lower ionosphere over Europe and Eastern Asia during October–November 1994. Much stronger meteorological control has been observed in winter, as shown by MAP/WINE (Laštovička *et al.*, 1990) and DYANA (Laštovička *et al.*, 1994) campaign results. Mutual correlations among ionospheric parameters and with solar and meteorological parameters have been slightly better even during summertime campaign MAC/SINE (June–August 1987; Laštovička *et al.*, 1989).

The meteorological control of the day-to-day variability appears to be best-developed in winter. During the MAP/WINE winter, 1 December 1983–31 March 1984, the controlling meteorological factor was neither local stratospheric temperature, nor wind near 95 km (even local wind), but the North Pole 10 hPa temperature (Laštovička *et al.*, 1990). The dominant role of the polar stratospheric temperature means the decisive role of the global state of the polar stratospheric vortex. Correlation coefficients between ionospheric parameters and T10 hPa were typically around $r = -0.6$ in the MAP/WINE winter (Laštovička *et al.*, 1990). The DYANA winter, 1 January–31 March 1990, revealed a similar pattern with the dominant role of the North Pole 10 hPa temperature and correlation coefficients typically around $r = -0.5$ (Laštovička *et al.*, 1994). In both winters, the solar variability effect was substantially weaker than the effect of meteorological parameters. During the MAC/SINE summer, 1 June–31 August 1987, the correlation with meteorological parameters is very different for different ionospheric data and in average very weak, $r = -0.2$. Solar indices appear to correlate better with ionospheric parameters (Laštovička *et al.*, 1989). The correlation of ionospheric parameters with meteorological parameters is even slightly worse in the CRISTA/MAHRSI autumn (e.g. Table 6) than in the MAC/SINE summer, except for one station Irkutsk. The same statement is valid also for the correlation with solar indices and even the solar Lyman-alpha flux.

Hence the comparison of the four campaigns suggests the following overall pattern: In winter the lower ionosphere at northern middle latitudes appears to be fairly well "meteorologically" controlled with a very weak solar influence. In summer, solar influence is somewhat stronger and dominates the weak "meteorological" influence, but the overall solar/meteorological control is weaker than in winter. In autumn we find the weakest overall solar/meteorological control, local effects evidently dominate the behaviour of the lower ionosphere. These results are based on the analysis of the day-to-day variability of ionospheric data. The obtained seasonal pattern of the relative role of meteorological and solar parameters in the lower ionosphere does not contradict the current understanding of the lower ionosphere behaviour.

During the MAP/WINE winter, the European ionospheric data were divided into two groups according to altitude, not latitude or longitude in spite of a large latitudinal and longitudinal extent of ionospheric observations. These two groups responded with the opposite sign to the meridional wind near 95 km and the boundary between them (near 90 km) coincided with height of the change of sign of meridional wind (Laštovička *et al.*, 1990). A similar division of ionospheric data according to altitude, related to the change of sign of the meridional wind component, was found also in the DYANA winter (Laštovička *et al.*, 1994), even though the strength of this effect was weaker because the DYANA period included the whole of March. The meridional wind can play a central role through transport of a nitric oxide rich air from auroral to middle latitudes in winter, when the photochemical lifetime of NO is relatively large (days). On the contrary, the autumnal CRISTA/MAHRSI ionospheric data do not show such a division related to the meridional wind. They do not display a systematic relation to and/or correlation with the meridional wind and a division according to altitude (Tables 6 and 7). A shorter photochemical lifetime of NO probably contributes to the loss of the meridional wind effect. There were not enough data in the MAC/SINE summer to look for such a division.

5 The future of lower ionosphere monitoring

The data presented clearly show the limitations of lower ionospheric measurements. A remote satellite sounding of the neutral upper atmosphere is possible and at present it is made by UARS. However, the lower ionosphere itself (ionized component) is not accessible to satellite measurements. The only in situ measurements in the lower ionosphere are rocket measurements, which have been rare. The rocket monitoring made by the Russians has been terminated so that in the near future we can only expect a few rocket flights per year worldwide.

This work is based on the ground-based radio propagation measurements of the lower ionosphere. The best ground-based measurements are those by the partial reflection radars, which provide electron density profiles. Such measurements are, however, very scarce, during CRISTA/MAHRSI they were run only in Nizhni Novgorod. Moreover, they would be rather expensive for monitoring.

Another possibility is the use of a long-distance VLF radio paths. They have been used mainly for solar flare effects (SPA) monitoring and for investigations of short-time effects caused by particle precipitation (Trimpi effects etc.). However, they describe the lowermost part of the ionosphere and they are not suitable for investigations of slow, longer-term changes. Their LF analog, the IPHA measurements used in this work, are currently made and evaluated along one radio path in Europe and used only for solar flare effect monitoring with one more path, and that is all. In other words, the quantity of these continuous measurements is quite insufficient.

The worldwide network of ionosondes would in principle allow us to monitor the state of the lower ionosphere via the use of the $f_{\min}$ parameter. However, ionosondes have been designed and used for monitoring of the E- and F-layer ionosphere. Some ionosonde stations do not evaluate $f_{\min}$ at all. Some others evaluate this parameter routinely as a less important parameter without much quality control of $f_{\min}$ data. Another problem is with the current trend to introduce automatic scaling of ionograms. As was illustrated in Sect. 3, the automatically scaled $f_{\min}$ is of poor quality, particularly in disturbed periods. It may be used for a routine service and a "first-look" information, but is inadequate for investigations. The problem is not really in quality of the measurements, but lies in the algorithm of $f_{\min}$ evaluation, which has to be an expert system, replacing an experienced observer. Even the introduction of modern digisondes does not result in significant progress on this point. Another problem is the lowest sounding frequency of the ionosonde and resolution of the $f_{\min}$ determination from non-digital ionosondes. Nevertheless, some stations provide reasonably homogeneous and long data series to allow for studies of long-term changes, stronger effects and various large features.

The last but not least method are measurements of radio wave absorption in the lower ionosphere. The A1 measurements (vertical incidence sounding), popular in the past, has almost been stopped worldwide. These absorption values were instantaneous and they were formed in a relatively narrow height interval. However, there were some problems with height determination, with deviative absorption, and in some cases with calibration. The best long-term absorption data have been provided by the A3 method (oblique incidence on the ionosphere, continuous wave). The method exists in the LF and HF versions, which differ in "ionospheric" (or absolute) calibration. These measurements have been made predominantly in Europe. The longest homogeneous data series of such measurements is available at 243 kHz at Kuhlungsborn, Germany, almost 50 y of data. The A3 absorption is formed in an interval of altitudes, usually basically in the last 3–5 km below the reflection height. On one hand, it does not allow us to associate them with a single altitude, but on the other hand, it gives better information on the overall state of the lower ionosphere. The A3 absorption is suitable for studies of stronger events, of large features, and particularly of long-term trends and changes. The A3 method is very cheap, because it uses commercial radio transmitters (broadcasting etc.). This is, however, the weak point of the method, because the number of transmitters, working in the regime suitable for A3 absorption measurements, has been diminishing continuously and, thus, the number of A3 radio paths has slowly but continuously been reduced.

In summary we can say that current measurements have various described limitations. They provide good coverage in time (long, continuous data series) but insufficient coverage in space. If the present-day trends in the lower ionospheric measurements and a relatively weak interest in these data continue, we are afraid that for future campaigns the lower ionosphere support will not be sufficient. Taking into account the present-day interest in such measurements, and various technical, organizational and financial problems, we do not see a near-future solution of the problem of lower ionosphere measurements/monitoring.

6 Conclusion

Lower ionospheric ground-based measurements, run in Europe and Eastern Asia over the period of 1 October–30 November 1994 as a part of the CRISTA/MAHRSI campaign, were analyzed from two main points of view: (1) to decide whether the CRISTA/MAHRSI experiment was performed under normal or anomalous conditions, and (2) to investigate the role of solar and meteorological parameters in the variability of the lower ionosphere under autumn, moderate solar activity conditions. Data on the A3 radio wave absorption in the lower ionosphere, $f_{\min}$, IPHA and electron density profiles from 18 places were used.

For question (1), comparisons of the CRISTA/MAHRSI experiment period data (4–12 November, 1994) with various long (25–30 y) ionospheric data series and data over the interval October–November 1994 (supporting campaign of ionospheric measurements) show that the state of the lower ionosphere (h = 80–100 km) in the interval of the CRISTA/MAHRSI experiment is close to the expected average (typical) state in Europe and Japan. In other words, the CRISTA/MAHRSI experiment was run under conditions, which were in the upper middle atmosphere of the Northern Hemisphere middle latitudes close to climatological conditions in Europe and Japan. Thus the average results of the CRISTA/MAHRSI experiment can be used as climatological data, at least for the given area and altitudes (~80–100 km).

As for item (2), the role of solar/geomagnetic and "meteorological" control of the lower ionosphere was investigated and compared with the results of MAP/WINE, MAC/SINE and DYANA campaigns. The effects of solar and geomagnetic activity and global meteorological factors on the lower ionosphere at middle latitudes of the Northern Hemisphere were generally found to be weak during autumn 1994 compared to those in the MAP/WINE and DYANA winters, and they were even slightly weaker than those in the MAP/SINE summer. This means that the lower ionosphere varied predominantly on local, small scales. This statement is supported by certain correlations of the 243 and 177 kHz absorptions with "local" lower thermospheric wind from Collm. One of the reasons might be a rather moderate variability of solar activity (not large enough to overcome random noise variability). There were only a few exceptions, eastern Siberia (Irkutsk) was significantly affected by polar vortex (North Pole T10 hPa and T30 hPa) in November, and both nighttime absorptions (243 and 177 kHz), which were measured at the highest geomagnetic latitudes among the ionospheric data investigated, were affected by geomagnetic activity.

The comparison of the four campaigns suggests the following overall pattern: in winter the lower ionosphere at northern middle latitudes appears to be fairly well "meteorologically" controlled with a very weak solar influence. In summer, solar influence is somewhat stronger and dominates the weak "meteorological" influence, but the overall solar/meteorological control is weaker than in winter. In autumn we find the weakest overall solar/meteorological control, local effects evidently dominate the behaviour of the lower ionosphere.

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