Ionospheric signatures of Global Change

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Abstract: The increase of anthropogenic greenhouse gas emissions in the atmosphere is expected to cause an increase of the global temperature in the lower atmosphere and the oceans while a decrease is expected in the middle atmosphere and ionosphere (Ulich *et al.*, 2007). For instance, Brasseur and Hitchman (1988) anticipate a cooling of the stratosphere by 8 - 15 K, whereas Roble and Dickinson (1989) predict the mesosphere and thermosphere to cool by 10 and 50 K, respectively, for double concentrations of carbon dioxide and methane. These changes are much larger than the changes in the upper atmosphere, and possibly some of its consequences, should be easier to detect. Among others, changes in the electron concentration distribution are expected (Rishbeth, 1990) that can be parameterized by the values of maximum plasma frequency in the E and F regions (foE and foF2) and the height of foF2, hmF2. Earlier work on this topic is reviewed. The possibilities, and others, are assessed as to what and how EISCAT 3D can contribute to studies on Global Change by exploiting its capabilities to measure ionospheric parameters that are expected to change employing the existing EISCAT database expanding the available long time series results of WP 10 to the subject of Global Change.

An important issue in the context of the signatures of Global Change in the ionosphere is the understanding of the coupling between the different layers in the Earth's atmosphere leading to a transfer of energy.

Dr. Vasyl Belyey at the University of Tromsø has developed a database containing all 'raw' data as obtained from the Madrigal database up to January 1, 2007. In order to gain easier access, the data has been integrated during three hours per day for three months, e.g., four seasons. Using this routine, data from the EISCAT Svalbard Radar (ESR) is presented. It is concluded that EISCAT_3D can play an important role for improving our understanding of long-term ionospheric change in context of Global Climate Change.

1 Introduction

Temperature changes influence both heights and critical frequencies of ionospheric layers, however for different reasons. The E and F1 layers can be described as 'photochemical' layers which are produced by ionizing radiations in locations where these radiations reach unit optical depth. This depends on solar zenith angle, absorption cross-sections for these radiations as well as atmospheric pressure. The F2 peak, which normally is the level of highest electron density, is dependent on a balance between photochemical and transport processes which is present at some give pressure level (Rishbeth and Edwards, 1989). According to the hydrostatic equation, the variation of air pressure with height p(h) depends on how the scale height H varies with height:

$$z = \ln \frac{p_0}{p} = \int \frac{\mathrm{d}h}{H(h)}. \tag{1}$$

As greenhouse gas concentrations increase, the thermosphere cools whereas the lower atmosphere warms. An 'isopycnic' level exist in the middle atmosphere where the pressure stays constant. As the E layer is situated only a few scale heights above that level, its height will not decrease much as greenhouse gas concentrations rise. In contrast, the F2 layer is placed many scales heights above the isopycnic level. Thus, its peak height hmF2 should decrease due to the cumulative effects of the decreases of H below it.

The flux of ionozing photons and the chemical composition of the atmosphere (on which the radiation acts) determines the total number of electrons and ions produced along a slant path from the Sun through the ionosphere. Then the thickness of any layer dependes on the local scale height which in its turn is dependent on the temperature. Thus, the peak electron density should be related to the temperature such as $N\mathrm{m} \propto 1/T$. Additional changes due to 'greenhouse cooling' relate to how the rate coefficients of the chemical and transport processes vary with temperature. Global Change could also influence the chemical composition of the thermosphere, e.g., by altering the level of turbulence in the turbopause region, affecting both layer height and peak electron density.

2 Selected previous studies

This section gives an overview of selected previous work highligthning the different and partly conflicting results in connection with different trend analysis procedures. Studies often include the F2-peak height and the F2- and E-layer critical frequencies (foF2 and foE). In addition, studies of radio path reflection and ionospheric absorption have also been performed. Laštovička *et al.* (2008) presented a review of observations in the context of global change.

2.1 Trends in F2-layer peak height (hmF2)

Shimazaki (1955) showed that hmF2 can be approximated by the equation

$$A + \frac{B}{M(3000)\mathrm{F2}} \tag{2}$$

containing the maximum usable frequency factor $M(3000)$F2 for a 3000-km radio path and the numerical constants A and B. This equation has subsequently been empirically

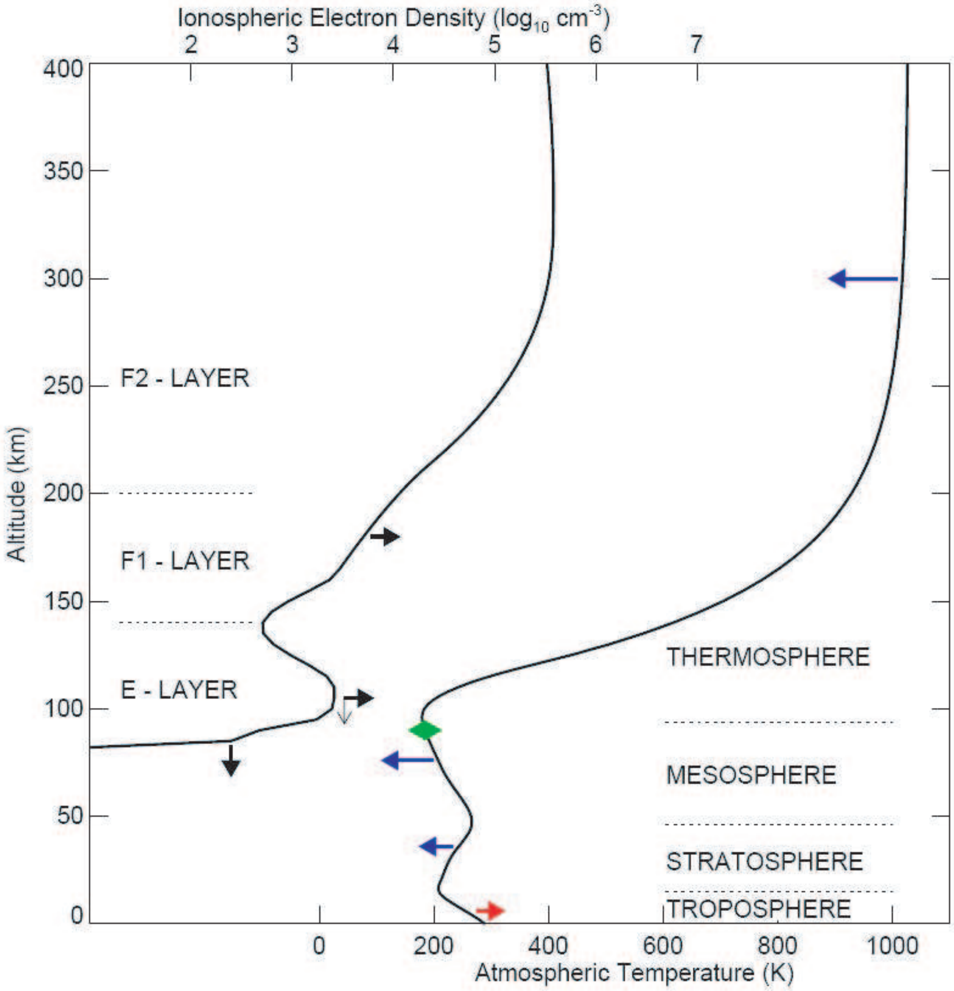

Figure 1: Trends in the Earth's atmosphere. Atmospheric layers are defined by the temperature profile. Ionospheric layers are defined by the electron density profile. The direction of change for the respective layers are indicated by arrows: red - warming, blue - cooling, green - no change of temperature, black - changes in electron density (horizontal) and heights of ionospheric layers (vertical). Adapted from Laštovička *et al.* (2008).

modified mostly by adding a correction term ΔM to $M(3000)$F2. This allows for ionisation effects below F2 (Dudeney, 1983). Jarvis (2002) reported that the choice of some formulae may even reverse the sign of the observed trend which shows the necessity to validate the equation for any given ionosonde (Ulich, 2000).

Bremer (1992) was the first to report on trends obtained from ionosonde data from Juliusruh, Germany, yielding a trend of -0.24 km/yr. Rishbeth and Roble (1992) showed that in most places hmF2 drops by 10 - 20 km if atmospheric CO_2 and CH_4 are doubled. Observations performed by Ulich and Turunen (1997) revealed a trend of -0.39 km/yr for Sodankylä. Jarvis *et al.* (1998) presented data from the southern hemisphere (Argentine Island, Antarctica, and Port Stanley, Falkland Islands) indicating that the - mostly negative (between (-0.1 km/yr) and (-0.4 km/yr) - trends depend on season and time of day. Measurements by Bremer (1998) yielded negative trends west and positive trends east of 30° E. Upadhyay and Mahajan (1998) were the first to present global results which were, however, inconclusive (seven positive and seven negative trends) with some being in contrast with Bremer's results. Negative trends have also been reported by Ortiz de Adler *et al.* (2002) and Clilverd *et al.* (2003). Several trend models were tested against data from Kokubunji, Japan, by Xu *et al.* (2004) yielding negative trends. Ulich (2000) presented observations from 66 stations worldwide providing both negative and positive trends without any geographic consistency. A review was presented by Laštovička *et al.* (2006a).

2.2 Trends in F2-layer critical frequency (foF2)

Little changes in foF2 should be expected from a cooling thermosphere as calculations by Rishbeth and Roble (1992) showed (mainly decreases of no more than 0.5 MHz for doubled CO_2). No significant changes could be reported from observations at Juliusruh (Bremer, 1992). Upadhyay and Mahajan (1998) suggested that a global trend could not be derived from ionospheric observations - they found 17 negative and 14 positive trends. As for trends in hmF2, Bremer (1998) found negative trends west and positive trends east of 30° E. A strong negative trend (-40 kHz/yr) obtained from measurements at Ahmedabad, India, was reported by Sharma *et al.* (1999) Danilov and Mikhailov (1999) presented results from 22 stations all of them showing negative trends. Mikhailov and Marin (2000) proposed a 'geomagnetic control concept' after showing that measurements at 30 stations in the northern hemisphere depend on geomagnetic latitude. Alfonsi *et al.* (2001) showed that their observations from high latitude stations in the Southern Hemisphere were in accordance with model calculations. Alfonsi *et al.* (2002) reported on observations from two high-latitude stations (Lycksele and Mawson) resulting in negative trends. Ulich *et al.* (2007) use 48 years of F2-layer critical frequency data from Sodänkylä, Finland, in order to demonstrate how the sign and amplitude of the detected trends depend upon choice of model which is fitted to the data. A comparison of various methods in determining long-term trends in foF2 was presented by Laštovička *et al.* (2006b). These authors find all trends to be either negative or insignificant. In addition, it is noted that data correction with sunspot number R, F10.7 adjusted to 1 AU, observed F10.7, adjusted E10.7 and observed E10.7 result in different trends. The observed F10.7 and E10.7 are reported to represent the best correcting factors. Furthermore, the observed trends are small, of the order of (-10 kHz/yr), which is much smaller than the solar cycle effect. This shows that accurate solar activity corrections are of great necessity. In addition, Laštovička *et al.* (2006b) point out a number of issues which should be addressed by future studies.

2.3 Trends in E-layer critical frequency (foE)

Rishbeth (1990) suggested that trends in the E layer are practically non-detectable. However, Bremer (1998) attempted to measure trends at 25 stations yielding only 11 trends to be significant at 90% confidence level. Typical trend levels were around a few kHz/yr. Mikhailov and de La Morena (2003) reported that the geomagnetic control concept is valid for (foE), too. They also report on an anti-correlation of long-term changes of geomagnetic activity (Ap index) with (foE) long-term trends, however only before the early 1970s. Later this relation is not valid anymore which is suggested to be caused by anthropogenic effects, e.g., chemical pollution.

2.4 Additional work

The International Space Science Institute (ISSI) in Bern, Switzerland, coordinates the work of international teams of experts. The two active or recently finished teams at ISSI are as follows: **Team (1):** '*Towards more effective physics-based and statistical models of the polar ionosphere*' (team leader: Prof. Tony van Eyken). **Team (2):** '*Bridging the gap between middle and upper atmosphere: coupling processes due to winds and waves over an extended altitude range*' (team leader: Dr. Peter Hoffmann). Information concerning each team can be found under (1) http://www.issibern.ch/teams/effective-physics and (2) http://www.issibern.ch/teams/middleupperatmosphere, respectively.

3 Problems of trend determination

General problems which are faced when addressing long-term trends include the following:

1. resolution of the data,
2. use of smoothing filters,
3. quality and consistency of time series (change of hardware, location or personnel),
4. if and how known variations have been removed from the time series.

In addition, operational accuracy of the instruments is often greater than the observed trends. Thus, an evaluation of the significance of the trends and error bars should be included in the plots. See Ulich *et al.* (2003) or Ulich *et al.* (2007) for principal problems with trend studies.

4 Additional factors that may influence trend signals

4.1 Choice of the model

In order to reveal the unknown components which make up the variation of the residual, known components have to be removed from the time series. In addition to 'natural' variations such as the atmospheric chemical composition, the geomagnetic field, thermospheric winds or atmospheric dynamics in general, the residuals also include measurement errors and possibly elements which thus far have not been paid attention to at all.

A variety of models have been used in literature. Some authors chose to remove known variabilities in separate steps. This procedure makes it difficult to estimate an error for the resulting trend. In contrast, a linear combination of base functions $f_k(t)$ to model the data, replicates models that have been used in published trend analyses. These models contain a constant x_1 and a linear trend x_2t. The parameters x_k can then be fitted to the data set, e.g., foF2 for Ulich *et al.* (2007), in the least-square sense by means of singular value decomposition. The advantage of this procedure is that it fits all model components in a single step. This gives the most probable solution for the unknown x_k and their standard error Any of these models is given by

$$M(t_i) = x_1 + x_2 t_i + \sum_{k=3}^{N} x_k f_k(t_i), \tag{3}$$

where t_i are the sampling times and N is the number of functions included. Note also that the inclusion of the samling times yields another advantage of this method, since it removes the need for interpolating gaps. Interpolation is connected with the risk of introducing pseudo data into the time series. Furthermore, a basic version of the model would only contain the two first terms.

4.2 Long-term changes in solar activity

Firstly, the strong impact of solar variations on ionospheric data should be noted. It has been shown in the literature that it is essential to remove solar activity variations from the data prior to trend determination (Jarvis, 2002; Clilverd *et al.*, 2003). The trend depends on the phase of the solar cycle at the beginning and end of the data set, e.g., if the data set begins at solar maximum and ends at solar minimum, then a strongly negative trends is likely in foF2 and hmF2 which correlate positively with solar activity. In that context it should be noted that most ionosondes were started during the International Geophysical Year (IGY) in 1957, which stood for the highest solar activity in the 20th century. Thus, every time series that is strongly modulated by solar activity and started during that period will show a negative trend.

Secondly, a variety of ways can be used to express solar activity. In the simplest approach, a sinusoidal wave with a period of 11 years would be utilized as a proxy. However, solar cycles are not symmetrical, thus this would be a too crude approximation. A more appropriate description of solar cycles can be obtained by making use of, e.g., Zürich sunspot numbers or Royal Greenwich Observatory (RGO) sunspot group numbers. However, sunspot numbers are often considered 'unphysical' measurements. In contrast, observations of solar 10.7-cm radio fluxes are available in the form of 'adjusted' values normalised to the distance between Earth and Sun of 1 AU (Astronomical Unit) and as 'observed' values containing the 3.3 % distance variation. Ulich *et al.* (2007)

uses for example monthly means of fluxes and Zürich sunspot numbers. It should also be mentioned, that other proxies, e.g., the E10.7 index, are possible, since the ionosphere is mainly created by UV and X solar radiation.

Laštovička (2005) showed that the role of solar activity for retrieving long-term trends decreases with decreasing altitude from the F-region down to the troposphere and decreases from the beginning of the 20th century during its end. Concerning the response of the lower ionosphere to external solar forcing, Laštovička (2009) presented a review.

4.3 Change of the atmosphere's chemical composition

This point is only mentioned, but due to simplicity reasons no further information is given here. See, e.g., Roble and Dickinson (1989) for ionospheric behaviour resulting from changes in chemical composition.

4.4 Long-term changes in the geomagnetic field and seasonal variations

Clilverd *et al.* (1998) concluded that long-term changes in the geomagnetic field affect the ionosphere which can be described by a variety of geomagnetic indices. Ulich *et al.* (2007) states that the logarithmic Kp index is not suitable. In contrast, the linear Ap index can directly be used for trend studies. In addition, local Ak indices from an ionosondes could be used. Ulich *et al.* (2007) used monthly means of both Ap and Sodankylä Ak indices. Note that also secular changes in the geomagnetic field may also have a great impact on ionospheric features. At middle and high latitudes, the daily variations of the F2-layer are partly controlled by thermospheric winds which depends on the orientation of the terrestrial magnetic field (King *et al.*, 1968).

Furthermore, Rishbeth *et al.* (2000) reported that ionospheric foF2 is modulated by annual and semi-annual variations. Alfonsi *et al.* (2002) could not find a dependence of their observed trends on the long-term behaviour of geomagnetic behaviour. Laštovička (2005) showed that the role of geomagnetic activity for retrieving long-term trends decreases with decreasing altitude from the F-region down to the troposphere and decreases from the beginning of the 20th century during its end.

Mikhailov (2006) considered long-term trends in the F2-layer in the light of geomagnetic control and the greenhouse hypotheses and concluded the necessity to remove geomagnetic effects from the observations in order to retrieve a trend.

4.5 Other causes of long-term change

Ozone depletion might lead to changes in tidal forcing in the middle atmosphere and subsequently to dynamical changes in the thermosphere (Ross and Walterscheid, 1991). These effects would be especially prominent in the equatorial region. Serafimov and Serafimova (1992) suggested that temperature changes in the lower ionosphere might be detectable by their effect on radio-wave absorption.

In addition, volcanic explosions can contaminate the upper atmosphere. However, their atmospheric effects may average out in the long term, since they have occurred throughout geological time. In terms of man-made contamination, rocket launches could

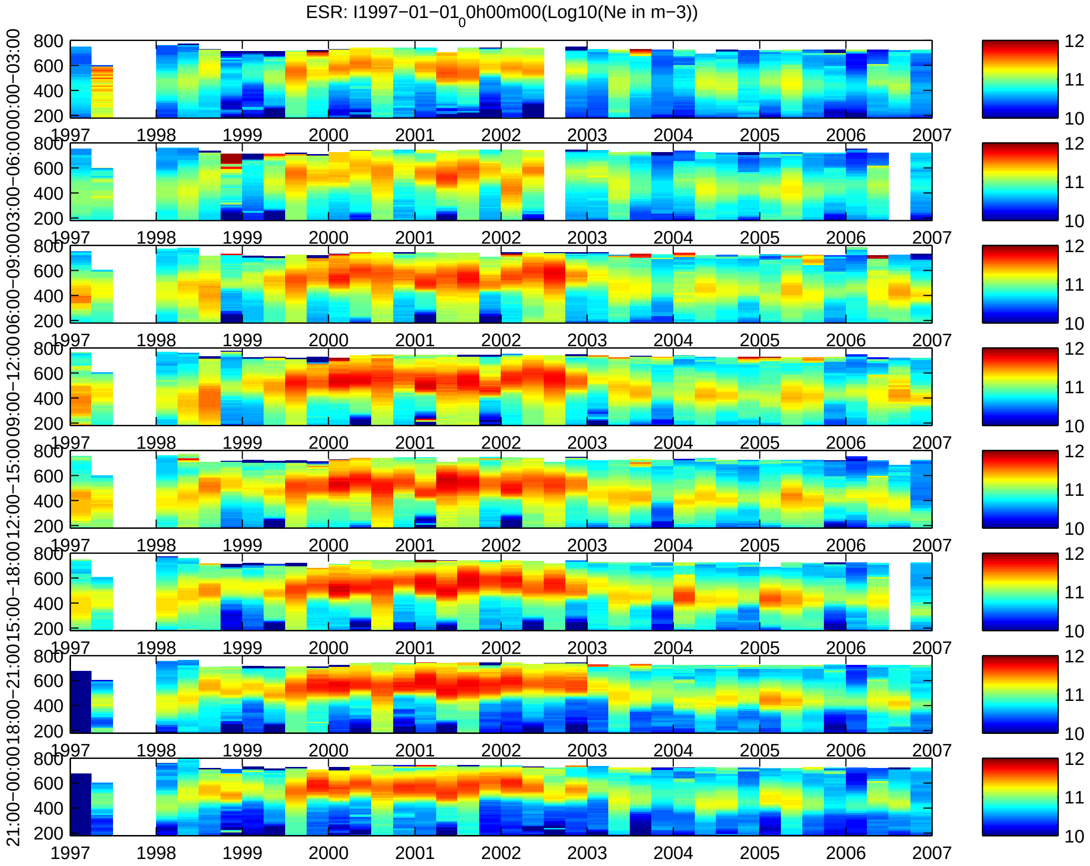

Figure 2: Density profiles over ESR showing variations during the day during the period 1997 - 2007. The panels (from above) show the results for UT 00-03, 03-06, 06-09, 09-12, 12-15, 15-18, 18-21 and 21-24.

change the chemistry of the upper atmosphere. On a speculative basis, this could lead to an increasing occurrence of sporadic E layers and noctilucent clouds.

5 EISCAT observations

Dr. Vasyl Belyey at the University of Tromsø has developed a database containing all ’raw’ data as obtained from the Madrigal database up to January 1, 2007. In order to gain easier access, the data has been integrated during three hours per day for three months, e.g., four seasons. Figures 2 and 3 show the output of the routine plotted in different ways emphasizing daily and seasonal variations, respectively.

These two figures show that it is feasible to analyse and present long-term EISCAT data. However, some of the problems mentioned in Section 3 have to be addressed, e.g., resolution of the data and quality and consistency of the time series. See Section 6 for

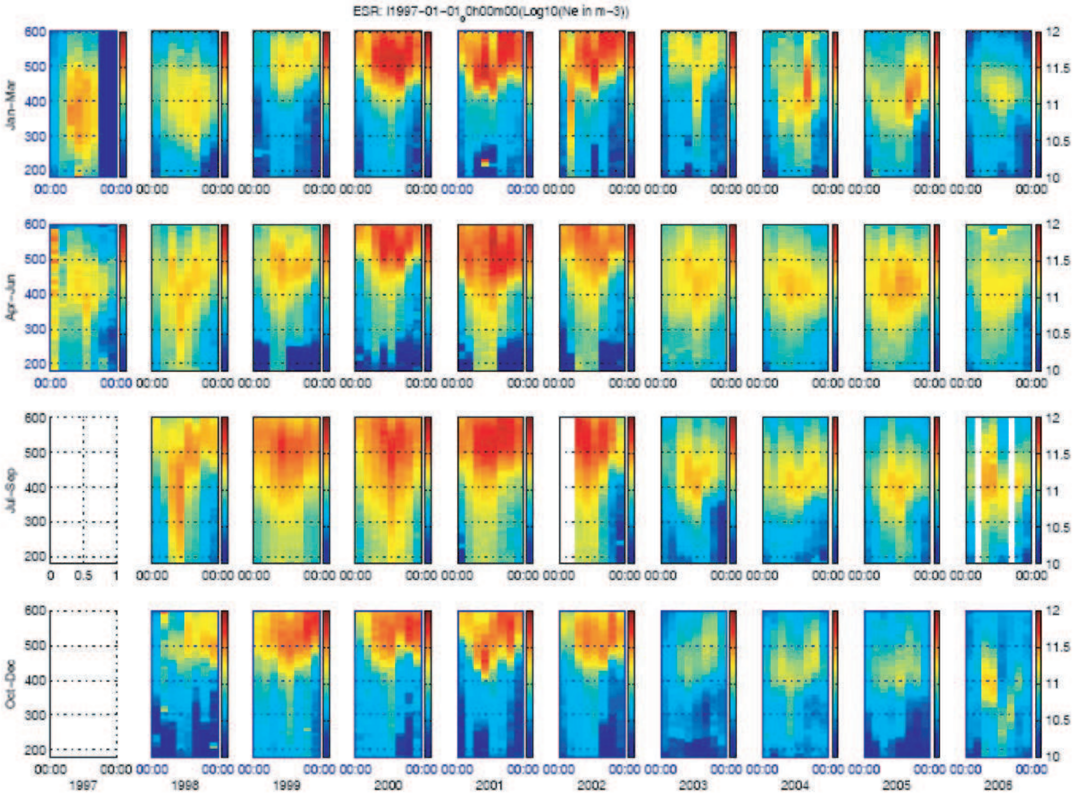

Figure 3: Density profiles over ESR integrated over 3 hours in a day for 3 months for the period 1997-2006. The panels (from above) show the seasonal variations within a year (January - March, April - June, July - September, October-December).

suggestions concerning future data analysis for EISCAT and comments on the feasibility for EISCAT_3D.

6 Summary, discussion and outlook

An overview of earlier work concerning determination of long-term trends in the ionosphere has been given. In addition, examples of long-term data obtained by the EISCAT Svalbard Radar (ESR) has been presented. Thus it is feasible to study long-term changes with incoherent scatter radars.

However, one should pay attention to a few important issues. Firstly, to ensure data quality, one needs to ensure that changes in equipment, codes etc. should be kept to a minimum. The data for ESR presented in Section 5 comprises a variety of different codes (Rishbeth and van Eyken, 1993). In addition, the instrumental setup has changed as well data analysis software. A long-term planning would minimize the impact of changes in the hardware or software on retrieved trends. Secondly, the resolution is also affected by the use of different codes.

A possible scenario for continous future studies could be cross-calibration of electron densities obtained by incoherent scatter radar measurements with TEC estimates from GPS-based or GPS radio occultation measurements. The feasibility of these procedures has been shown by Lilensten and Cander (2003) and Stolle *et al.* (2004). In this context, the review paper on observations of the high latitude ionosphere during the IPY by Alfonsi *et al.* (2008) should be mentioned.

With these comments in minds, we can suggest that EISCAT_3D can contribute to solve outstanding problems in the context of long-term changes in the ionosphere, thus providing a better understanding of the coupling between different layers in the atmosphere.

References

Alfonsi, L., De Franceschi, G., and Perrone, L. (2001). Long term trend in the high latitude ionosphere. *Phys. Chem. Earth*, **26**, 303–307. doi:10.1016/S1464-1917(01)00003-4.

Alfonsi, L., De Franceschi, G., Perrone, L., and Materassi, M. (2002). Long-term trends of the critical frequency of the F2 layer at northern and southern high latitude regions. *Phys. Chem. Earth*, **27**, 607–612. doi:10.1016/S1474-7065(02)00043-8.

Alfonsi, L., Kavanagh, A. J., Amata, E., Cilliers, P., Correia, E., Freeman, M., Kauristie, K., Liu, R., Luntama, J.-P., Mitchell, C. N., and Zherebtsov, G. A. (2008). Probing the high latitude ionosphere from ground-based observations: The state of current knowledge and capabilities during IPY (2007 2009). *J. Atmos. Sol.Terr. Phys.*, **70**, 2293–2308. doi:10.1016/j.jastp.2008.06.013.

Brasseur, G. and Hitchman, M. H. (1988). Stratospheric Response to Trace Gas Perturbations: Changes in Ozone and Temperature Distributions. *Science*, **240**, 634–637.

Bremer, J. (1992). Ionospheric trends in mid-latitudes as a possible indicator of the atmospheric greenhouse effect. *J. Atmos. Terr. Phys.*, **54**, 1505–1511.

Bremer, J. (1998). Trends in the ionospheric E and F regions over Europe. *Ann. Geophys.*, **16**, 986–996. doi:10.1007/s005850050668.

Clilverd, M. A., Clark, T. D. G., Clarke, E., and Rishbeth, H. (1998). Increased magnetic storm activity from 1868 to 1995. *J. Atmos. Sol.Terr. Phys.*, **60**, 1047–1056.

Clilverd, M. A., Ulich, T., and Jarvis, M. J. (2003). Residual solar cycle influence on trends in ionospheric F2-layer peak height. *J. Geophys. Res.*, **108**, 1450–+. doi:10.1029/2003JA009838.

Danilov, A. D. and Mikhailov, A. V. (1999). Spatial and seasonal variations of the foF2 long-term trends. *Ann. Geophys.*, **17**, 1239–1243. doi:10.1007/s005850050849.

Dudeney, J. R. (1983). The accuracy of simple methods for determining the height of the maximum electron concentration of the F2-layer from scaled ionospheric characteristics. *J. Atmos. Terr. Phys.*, **45**, 629–640.

Jarvis, M. (2002). Methodological influences on F-region peak height trend analyses. *Phys. Chem. Earth*, **27**, 589–594. doi:10.1016/S1474-7065(02)00041-4.

Jarvis, M. J., Jenkins, B., and Rodgers, G. A. (1998). Southern hemisphere observations of a long-term decrease in F region altitude and thermospheric wind providing possible evidence for global thermospheric cooling. *J. Geophys. Res.*, **103**, 20775–+. doi:10.1029/98JA01629.

King, J. W., Kohl, H., Preece, D. M., and Seabrook, C. (1968). An explanation of phenomena occuring in the high latitude ionosphere at certain Universal Times. *J. Atmos. Terr. Phys.*, **30**, 11–23.

Laštovička, J. (2005). On the role of solar and geomagnetic activity in long-term trends in the atmosphere ionosphere system. *J. Atmos. Sol.Terr. Phys.*, **67**, 83–92. doi:10.1016/j.jastp.2004.07.019.

Laštovička, J. (2009). Lower ionosphere response to external forcing: A brief review. *Adv. Space Res.*, **43**, 1–14. doi:10.1016/j.asr.2008.10.001.

Laštovička, J., Mikhailov, A. V., Ulich, T., Bremer, J., Elias, A. G., Ortiz de Adler, N., Jara, V., Abarca Del Rio, R., Foppiano, A. J., Ovalle, E., and Danilov, A. D. (2006a). Long-term trends in foF2: A comparison of various methods. *J. Atmos. Sol.Terr. Phys.*, **68**, 1854–1870. doi:10.1016/j.jastp.2006.02.009.

Laštovička, J., Mikhailov, A. V., Ulich, T., Bremer, J., Elias, A. G., Ortiz de Adler, N., Jara, V., Abarca Del Rio, R., Foppiano, A. J., Ovalle, E., and Danilov, A. D. (2006b). Long-term trends in foF2: A comparison of various methods. *J. Atmos. Sol.Terr. Phys.*, **68**, 1854–1870. doi:10.1016/j.jastp.2006.02.009.

Laštovička, J., Akmaev, R. A., Beig, G., Bremer, J., Emmert, J. T., Jacobi, C., Jarvis, M. J., Nedoluha, G., Portnyagin, Y. I., and Ulich, T. (2008). Emerging pattern of global change in the upper atmosphere and ionosphere. *Ann. Geophys.*, **26**, 1255–1268.

Lilensten, J. and Cander, L. R. (2003). Calibration of the TEC derived from GPS measurements and from ionospheric models using the EISCAT radar. *J. Atmos. Sol.Terr. Phys.*, **65**, 833–842. doi:10.1016/S1364-6826(03)00087-7.

Mikhailov, A. V. (2006). Ionospheric long-term trends: can the geomagnetic control and the greenhouse hypotheses be reconciled? *Ann. Geophys.*, **24**, 2533–2541.

Mikhailov, A. V. and de La Morena, B. A. (2003). ong-term trends of foE and geomagnetic activity variations. *Ann. Geophys.*, **21**, 751–760.

Mikhailov, A. V. and Marin, D. (2000). Geomagnetic control of the foF2 long-term trends. *Ann. Geophys.*, **18**, 653–665. doi:10.1007/s005850000232.

Ortiz de Adler, N., Elias, A. G., and Hereda, T. (2002). Long-term trend of the ionospheric F2-layer peak height at a southern low latitude station,. *Phys. Chem. Earth*, **27**, 613–615.

Rishbeth, H. (1990). A greenhouse effect in the ionosphere? *Planet. Space Sci.*, **38**, 945–948. doi:10.1016/0032-0633(90)90061-T.

Rishbeth, H. and Edwards, R. (1989). The isobaric F2-layer. *J. Atmos. Terr. Phys.*, **51**, 321–338.

Rishbeth, H. and Roble, R. G. (1992). Cooling of the upper atmosphere by enhanced greenhouse gases - Modelling of thermospheric and ionospheric effects. *Planet. Space Sci.*, **40**, 1011–1026. doi:10.1016/0032-0633(92)90141-A.

Rishbeth, H. and van Eyken, A. P. (1993). EISCAT - Early history and the first ten years of operation. *J. Atmos. Terr. Phys.*, **55**, 525–542.

Rishbeth, H., Sedgemore-Schulthess, K. J. F., and Ulich, T. (2000). Semiannual and annual variations in the height of the ionospheric F2-peak. *Ann. Geophys.*, **18**, 285–299. doi:10.1007/s005850050889.

Roble, R. G. and Dickinson, R. E. (1989). How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere? *Geophys. Res. Lett.*, **16**, 1441–1444.

Ross, M. N. and Walterscheid, R. L. (1991). Changes in the solar forced tides caused by stratospheric ozone depletion. *Geophys. Res. Lett.*, **18**, 420–423. doi:10.1029/90GL02786.

Serafimov, K. and Serafimova, M. (1992). Possible radioindications of anthropogenic influences on the mesosphere and lower thermosphere. *J. Atmos. Terr. Phys.*, **54**, 847–850.

Sharma, S., Chandra, H., and Vyas, G. D. (1999). Long term ionospheric trends over Ahmedabad. *Geophys. Res. Lett.*, **26**, 433–436. doi:10.1029/1998GL900303.

Shimazaki, T. (1955). World-wide variations in the height of the maximum electron density of the ionospheric F2-layer. *J. Radio Res. Labs Japan*, **2**, 85–97.

Stolle, C., Jakowski, N., Schlegel, K., and Rietveld, M. (2004). Comparison of high latitude electron density profiles obtained with the GPS radio occultation technique and EISCAT measurements. *Ann. Geophys.*, **22**, 2015–2028. SRef-ID: 1432-0576/ag/2004-22-2015.

Ulich, T. (2000). *Solar variability and long-term trends in the ionosphere*. Ph.D. thesis, Sodankylä Observatory, Sodankylä, Finland.

Ulich, T. and Turunen, E. (1997). Evidence for long-term cooling of the upper atmosphere in ionosonde data. *Geophys. Res. Lett.*, **24**, 1103–1106. doi:10.1029/97GL50896.

Ulich, T., Clilverd, M. A., and Rishbeth, H. (2003). Determining Long-Term Change in the Ionosphere. *EOS Trans.*, **84**, 581–585. doi:10.1029/2003EO520002.

Ulich, T., Cliverd, M. A., Jarvis, M. J., and Rishbeth, H. (2007). Unravelling Signs of Global Change in the Ionosphere. In J. Lilensten, editor, *Space Weather : Research Towards Applications in Europe 2nd European Space Weather Week (ESWW2)*, volume 344 of *Astrophys. and Space Sci. Lib.*, pages 95–+.

Upadhyay, H. O. and Mahajan, K. K. (1998). Atmospheric greenhouse effect and ionospheric trends. *Geophys. Res. Lett.*, **25**, 3375–3378. doi:10.1029/98GL02503.

Xu, Z.-W., Wu, J., Igarashi, K., Kato, H., and Wu, Z.-S. (2004). Long-term ionospheric trends based on ground-based ionosonde observations at Kokubunji, Japan. *J. Geophys. Res.*, **109**, 9307–+. doi:10.1029/2004JA010572.