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Advances in Space Research 48 (2011) 1–11

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

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24/7 Solar minimum polar cap and auroral ion temperature observations

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Received 23 December 2010; received in revised form 1 March 2011; accepted 7 March 2011
Available online 10 March 2011

Abstract

During the International Polar Year (IPY) two Incoherent Scatter Radars (ISRs) achieved close to 24/7 continuous observations. This presentation describes their data sets and specifically how they can provide the International Reference Ionosphere (IRI) a fiduciary *E*- and *F*-region ionosphere description for solar minimum conditions in both the auroral and polar cap regions. The ionospheric description being electron density, ion temperature and electron temperature profiles from as low as 90 km extending to several scale heights above the *F*-layer peak.

The auroral location is Poker Flat in Alaska at 65.1 °N latitude, 212.5 °E longitude where the NSF's new Poker Flat Incoherent Scatter Radar (PFISR) is located. This location during solar minimum conditions is in the auroral region for most of the day but is at mid-latitudes, equator ward of the cusp, for about 4–8 h per day dependent upon geomagnetic activity. In contrast the polar location is Svalbard, at 78.2 °N latitude, 16.0 °E longitude where the EISCAT Svalbard Radar (ESR) is located. For most of the day the ESR is in the Northern Polar Cap with a noon sector passage often through the dayside cusp.

Of unique relevance to IRI is that these extended observations have enabled the ionospheric morphology to be distinguished between quiet and disturbed geomagnetic conditions. During the IPY year, 1 March 2007 – 29 February 2008, about 50 solar wind Corotating Interaction Regions (CIRs) impacted geospace. Each CIR has a two to five day geomagnetic disturbance that is observed in the ESR and PFISR observations. Hence, this data set also enables the quiet-background ionospheric climatology to be established as a function of season and local time. These two separate climatologies for the ion temperature at an altitude of 300 km are presented and compared with IRI ion temperatures. The IRI ion temperatures are about 200–300 K hotter than the observed values. However, the MSIS neutral temperature at 300 km compares favorably with the quiet-background in temperature, both in magnitude and climatology.

Keywords: Ionosphere; High-latitudes; *F*-region temperatures; Climatology; Measurements

1. Introduction

This paper reports the high latitude climatology from a comprehensive data set of the ion temperature at 300 km during the entire International Polar Year (IPY). The observations are a very small subset of simultaneous measurement made at two high latitude locations. The first being in the polar cap-cusp at Svalbard being made by the Eiscat Svalbard Radar (ESR) and the second from Poker Flat by the Poker Flat Incoherent Scatter Radar (PFISR) (Sojka et al., 2007). These two radars began joint operations on 1 March 2007 on a 15 min, or better, cadence. The observation mode consisted of at least full altitude profiles of Ne, Ti, Te, and ion velocity along the magnetic field line through the *E*- and *F*-regions. On 29 February 2008, the end of IPY the ESR observations ended

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doi:10.1016/j.asr.2011.03.005

but PFISR continues this mode of operation. The selected observational parameter Ti at 300 km is studied to show that these two ISRs, captured both the quiet and disturbed climatologies of the high latitude ionosphere. That these measurements were made at the start of the extended solar minimum, period between solar cycles 23 and 24, makes these climatologies both new and provides an insight into the lowest energy levels that the ionosphere has been observed at. In this case, lowest level refers to the state of the ionosphere when driven by both low solar flux and negligible geomagnetic activity over an entire year.

In addition to the 24/7 ISR operations at PFISR and ESR ISR at Millstone Hill, Sondrestrom, EISCAT, and Irkutzk operated on a regular basis throughout the IPY period. Zhang et al. (2010) used ISR observations at four locations: Millstone Hill, Sondrestrom, PFISR, and ESR to examine the noon-time annual and semiannual variations. Their study showed clear morphological differences between the four locations, as well as showing that the *F*-layer ionospheric peak lay below 300 km during the IPY (see Zhang et al., 2010; Fig. 1). In addition they show that the average ion temperature noon morphology is very cold. In our study we extend their investigation of the ion temperature. Solomon et al. (2010) use the NCAR Thermosphere-Ionosphere-Electrodynamic General Circulation Model to investigate the thermosphere and ionosphere's response to the very low solar flux conditions between 2007 and 2009 (which includes the IPY) and contrasts these results to the prior solar minimum condition of 1996. They demonstrate that indeed the IPY thermosphere is, within the satellite era, the coldest observed.

The disturbed climatologies refer to periods when the ionosphere is driven by enhanced geomagnetic activity associated with the passage of corotating Interaction Regions (CIR) by the Earth. During the IPY year almost 50 such CIR passed the Earth (Sojka et al., 2009b). Each CIR was associated with a rapid increase in Ti at 300 km and then a gradual return to the lower temperature over 3–5 days. Both ISR observed the same CIR morphology and when both ISR were operating their Ti signatures would be synchronized (Sojka et al., 2009a). With this repeatable CIR disturbance morphology it is possible to identify days prior to a CIR onset as the quiet days and subsequent days as disturbed (Sojka et al., 2009a). Given that each solar rotation, 27 day period, had at least 2 CIRs each rotation has significant number of quiet and disturbed days. This provides the basis for generating independent quiet and disturbed seasonal climatologies.

Comparisons are made with the equivalent Ti at 300 km from the International Reference Ionosphere using the most recent IRI-2007 (Bilitza and Reinisch, 2008). The IRI model is an empirical representation of the global ionosphere and is used by scientists and engineers to forecast ionospheric climatological conditions. The IRI is under continuous development and as new observational data sets become available the model is revised. Hence the IRI-2007 is the revised version of IRI-2001 based on upgrades of the topside ionosphere as topside sounder profiles become available after the earlier models shortcomings were identified (Bilitza, 2004). In addition to upgrading and including new data sets the IRI is extensively validated, most recently this was done for the new IRI-2007 improvements (Bilitza, 2009). In presenting the IPY long ESR and PFISR data we believe they are observations worthy of considerations by the IRI team since they fully capture the high latitude ionosphere in density, ion temperature

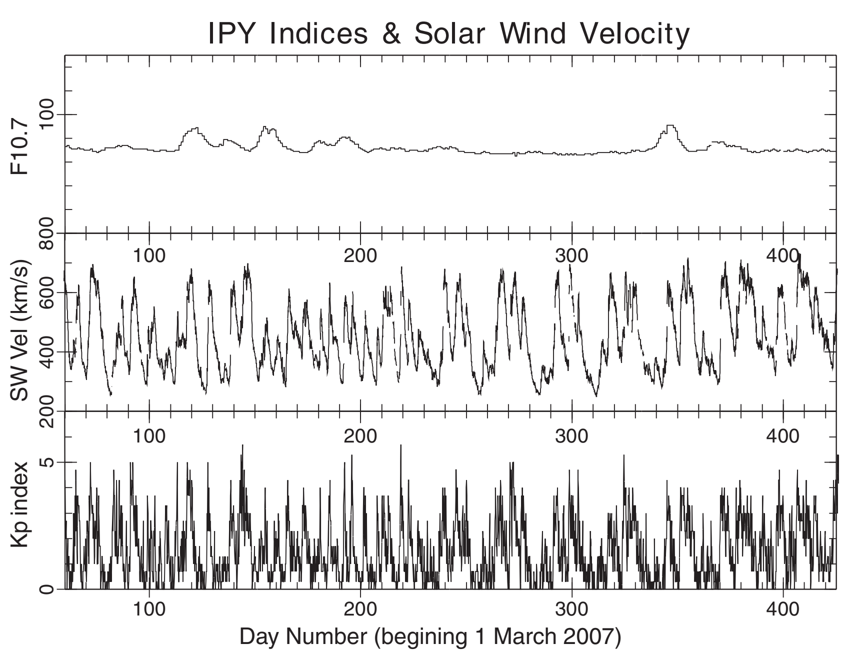

Fig. 1. The solar radio flux index F10.7, top panel, the ACE measured solar wind velocity at L1, middle panel, and the geomagnetic index Kp, bottom panel during the International Polar Year (IPY). The IPY began on 1 March 2007, day 60.

and electron temperature at two sites simultaneously and during exceptional solar minimum conditions. It is a region in which observations are relatively sparse, and hence, IRI has less success in this region. We will show using only one parameter, Ti, at one altitude, 300 km, that indeed the ESR and PFISR observations capture both the quiet and disturbed seasonal and UT climatology of the high latitude ionosphere. This is different from that of the IRI-2007.

2. Observations

2.1. EISCAT Svalbard Radar (ESR)

The EISCAT Svalbard Radar was commissioned in 1996 and is located at 78°09"11"N, 16°01'44"E, and 445 m above sea level. The Invariant Latitude is 75°11'N and the local dip angle is 82.06°. The radar is situated near the main Svalbard settlement, Longyearbyen, where it benefits not only from excellent supporting infrastructure, transport, and accommodation facilities. ESR is built around low maintenance television transmitter technology, combining eight transmitters to produce a peak output power of 1 MW at 25% duty cycle, and normally delivers in excess of 1500 h of data each year. For the IPY observations a large Cassegrain-fed parabolic antenna of 42 m diameter which is fixed to look parallel to the local geomagnetic field was used. The radar transmitter bandwidth is 4 MHZ, centered on 500 MHz while the receiver bandwidth is 30 MHz. Transmitter pulse lengths from 1 μs–2.0 ms can be used with a minimum inter-pulse period of 0.1 ms. The transmitted signal is circularly polarized and the effective receiver temperature is 65–75 K.

2.2. PFISR IPY operation

The Poker Flat Incoherent Scatter Radar (PFISR) is located at the Poker Flat Research Range (65.13 °N, 212.53 °E) near Fairbanks, Alaska. The phased array nature of PFISR allows it to steer on a pulse-to-pulse basis. The normal IPY mode is a single-look direction (up the local magnetic field line: azimuth −154.3°, elevation 77.5°), low duty-cycle mode (∼1%) that is designed for background characterization of the Poker Flat ionosphere. The IPY mode consists of 2 sets of interleaved pulses: a 480 μs (72 km) long pulse designed for *F*-region studies and a 30 μs baud (4.5 km), 16 baud strong alternating code (Lehtinen and Haggstrom, 1987) designed for E-region work. Data are integrated for 15 min prior to fitting. The returned power has been calibrated using measured up- and down-shifted long pulse plasma line cutoff data over the same observation period, and in general the data is calibrated using a system constant approach (e.g., Evans, 1969). For a typical daytime *F*-region ionosphere (long pulse measurements), and for PFISR operating in the low duty-cycle IPY mode with 15 min integrations, temperatures can be inferred to within ∼50–100 K, line-of-sight velocities can be inferred to within ∼10–15 m/s, and densities can be inferred to within a statistical precision of ∼2% (but are limited by the aforementioned source of calibration error). The range resolution of these measurements is limited by the pulse length (72 km), although products are computed every half pulse width after application of an appropriate summation rule.

3. IPY conditions

The two ISR data bases span the IPY period beginning on 1 March 2007 and ended on 29 February 2008. This period covers an entire year, hence all seasons. During this year the solar conditions were approaching the deep and extended solar minimum between cycles 23 and 24. The radio solar flux at 10.7 cm was mostly within 5 units of 70 on the standard radio flux scale for the F10.7 solar index. Fig. 1, top panel, shows this solar index variation over the IPY year. Note the sunspot number is not plotted since during this entire year 54% of the days had zero sunspots and 83% had 10 or fewer. However, during this period the Sun through its coronal hole fast streams did produce recurrent Corotating Interaction Regions (CIRs) that did generate significant geomagnetic activity. These events were monitored by both ISRs. The middle panel of Fig. 1 shows how the solar wind speed varied as measured by the NASA ACE satellite located close to the L1 point. As a result of these fast stream CIR events, periods of speeds larger than 500 km/s, the Kp index showed significant, recurrent, disturbances. This index is shown in the lower panel of Fig. 1.

From the perspective of the modeling procedures used by IRI to obtain monthly climatologies, i.e., average of middle quartiles, the IPY year poses a challenge since the effect of the enhanced geomagnetic activity is significant each month. These data can be parsed in ways such that non-disturbance climatology or specifically the disturbance climatology can be extracted. The standard procedures used to create the IRI core coefficients, i.e., the URSI *F*-region peak density coefficients was to use monthly averages of only the middle quartiles of the observations. Such a procedure can also be applied to the PFISR and ESR data sets. However, these new data sets offer more insightful alternative descriptions of the solar minimum climatology. This is the prime objective in presenting a subset of the PFISR and ESR climatology with comparisons to the IRI climatology at high latitudes.

Referring to Fig. 1 again, it is evident that the recurrence of the CIR disturbances on a 27 day period provides a method of separating the observations into quiet and CIR disturbed ionospheric conditions. Given that the solar rotation period of about 27 days is close to the monthly climatology window adopted for the original IRI development, this scheme of parsing observations is compatible to that used for IRI.

Hence, the PFISR and ESR observations will be separated into 27 day solar rotation periods in order to simplify the selection of quiet and disturbed days. Averages and averages over the middle quartiles to obtain monthly climatology is also tractable using this ordering of the data. Given that the ionosphere has a very marked diurnal cycle, i.e., day-night, which is predominantly controlled by the solar illumination-ionization the observations are also binned by Universal Time. Note, we have adopted UT rather than local time simply because the geomagnetic-solar wind driver is a UT dependent driver of the system and generates the strongest variability found in these data.

Fig. 2 extracts from Fig. 1(a) 27 day period and adds to these two parameters from the ISR data sets. These two parameters are the PFISR ion temperature at 300 km and the ESR ion temperature at 300 km. During the IPY year at both the auroral PFISR and polar cap ESR locations the *F*-region peak was located below 300 km. Hence, the Ti being plotted in Fig. 2 represents the atomic oxygen ion temperature. The Ti observations show a number of features: a diurnal variation, data gaps, and correlated higher temperatures during CIRs. The CIRs in Fig. 2 occur between day 127 and day 130 and again between day 135 and day 148. In both CIR events the Ti is enhanced for several days with increases in the coldest diurnal temperatures of more than 100 K and "spike" like heating episodes of over 500 K. Also evident in these two temperature records

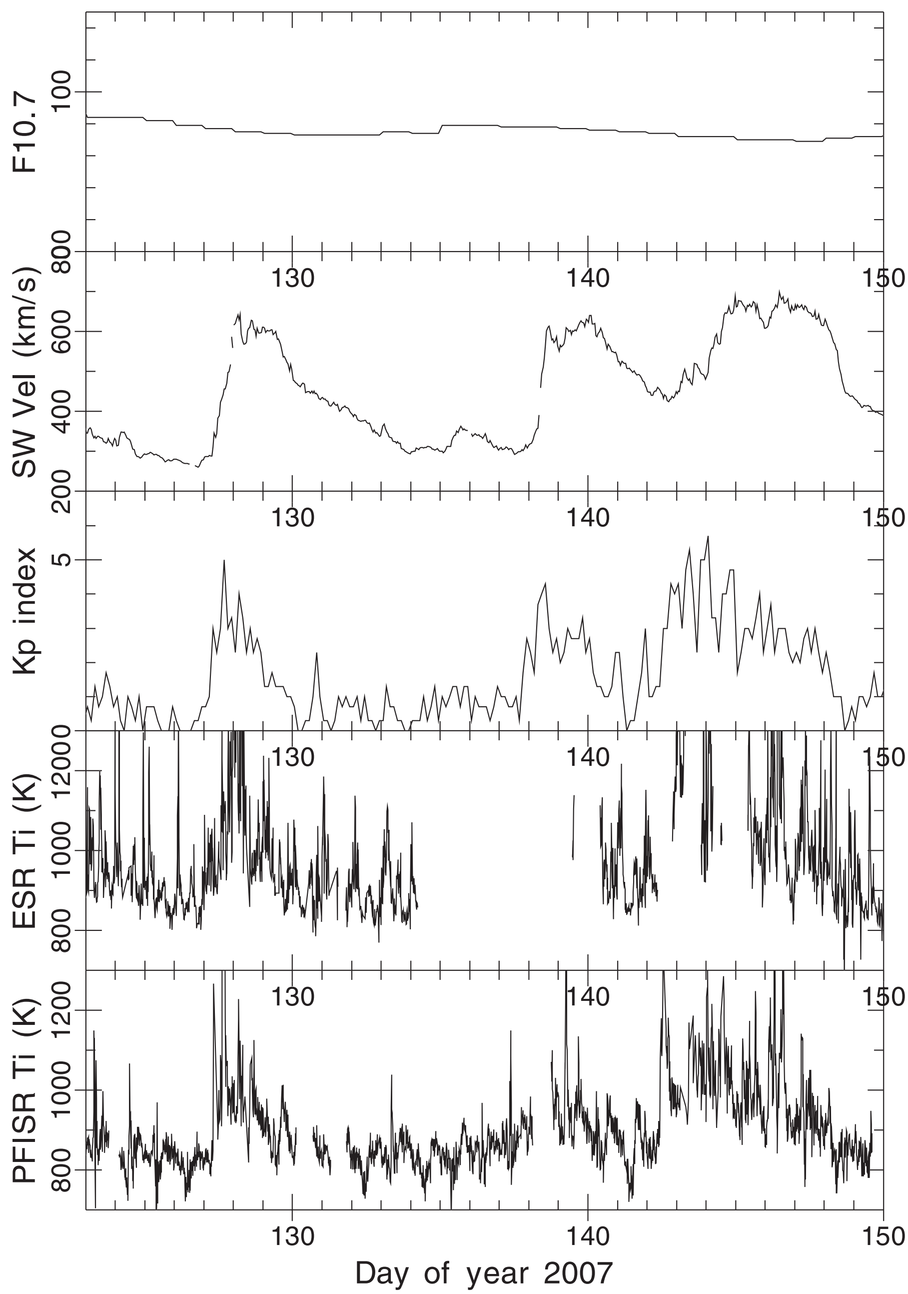

Fig. 2. A 27 day period during the IPY, beginning on 3 May 2007, day 123 showing the same three parameters F10.7, solar wind speed, and Kp as Fig. 1 with the PFISR Ti at 300 km, bottom panel, and the ESR Ti at 300 km in the second from bottom panel.

is the fact that the Ti decreases to its lowest temperature just prior to the onset of the CIR. Days 126 and 134 represent these two coldest days.

Data gaps are present, both ISRs had periods of non-operations. The largest outage for ESR occurred in October 2007 when the power station at Svalbard went offline for almost one month. For PFISR the longest outage occurred during November 2007 when the final 15% of the radar panels were being installed, again a data gap of almost a month. Statistically using one hour binning, the IPY year had 8784 h. PFISR had data for 5189 h (59.1%) while ESR had data for 5813 h (66.2%).

4. Various forms of PFISR and ESR IPY Climatology

For the IPY, PFISR and ESR observations not only span 14 solar rotations and all UTs, but span various ionospheric parameters and these are over a range of *E*- and *F*-region altitudes. Quantitatively the size of this new 24/7 ionospheric data set has the following dimensions:

(1) 14 solar rotations, equivalent to 12 months
(2) 48 half-hour UT bins
(3) 3 main parameters Ne, Te, and Ti
(4) 50, ten km altitude range gates from 100 to 500 km

The specific individual radar modes provided altitude profiles on a cadence of slightly less than 15 min, rather than the half-hour used in sorting the data. Similarly each radar had different range gate modes to sample the altitude profiles. Using the above (1) through (4) quantification the IPY ionosphere over PFISR and ESR is represented by 100,800 data bins. The most significant reduction in size of this data base is in reducing the year-long data set into only 14 solar rotations. In the following three subsections the climatology of Ti at 300 km will be presented for different selection criteria. This is done to show how the ionosphere responds to different driver conditions.

4.1. The Quiet IPY ionosphere

The data selection to identify the ionosphere's "coldest" state can be inferred from Fig. 2. Before each CIR the ionosphere reaches its coldest condition. This Ti criterion is adopted to represent the case when geomagnetic activity has been decreasing since the prior CIR and hence represents the quietest ionosphere-thermosphere condition from the perspective of external solar and magnetospheric drivers. Note this makes no inference on possible coupling to the lower atmosphere.

The selection criterion is to identify within a half-hour UT bin during a 27 day solar rotation period the coldest Ti. Only Ti values that have been flagged with ISR "bad data" flags are excluded.

Fig. 3a shows the results of this selection for PFISR and Fig. 3b the ESR selection. There has been no smoothing and no averaging of observations. These distributions are composed of independent Ti values at 300 km. These figures use a color, or gray scale, key that linearly spans the 500–1200 K range. The temperatures shown in these two panels however, only extends over the 500–900 K range. Our reason for the extended temperature range is that in the subsequent sections that will include the IRI climatology, this expanded scale is needed. Hence, this scale will expedite the comparison between different climatology selections. The PFISR Ti in Fig. 3a has both a well defined seasonal and diurnal variation. Solar rotation one corresponds to the period 1 March to 27 March of 2007 and rotation 5 is July, summer. During summer the Ti values are at their seasonal high all day long since Poker Flat is sunlit all day. Mid-winter occurs between solar rotation 10 and 12, a time when Poker Flat is dark all day. Hence, the temperatures are at their lowest. At the Poker Flat location local noon occurs at 2200 UT which corresponds to bin 44 in the UT half-hour bins. The cold climatology has a well defined diurnal climatology which maximizes

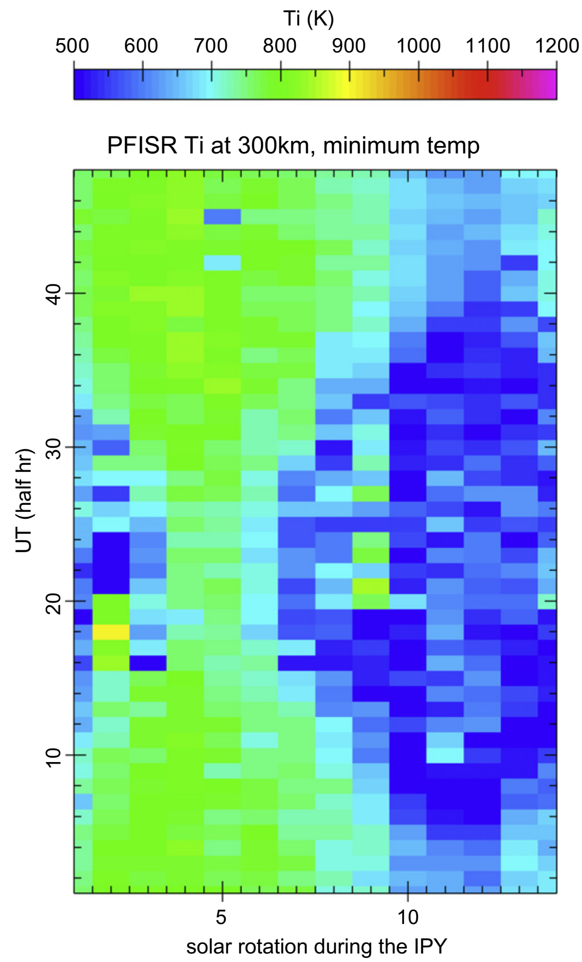

Fig. 3a. The IPY season and UT climatology of the coldest Ti at 300 km observed by PFISR. Season is shown as 14 solar rotations of 27 days each beginning on 1 March 2007 and UT is shown as 48 half-hour UT bins beginning at 00:00 UT. The climatology temperature is color or gray scale coded linearly between 500 and 1200 K. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

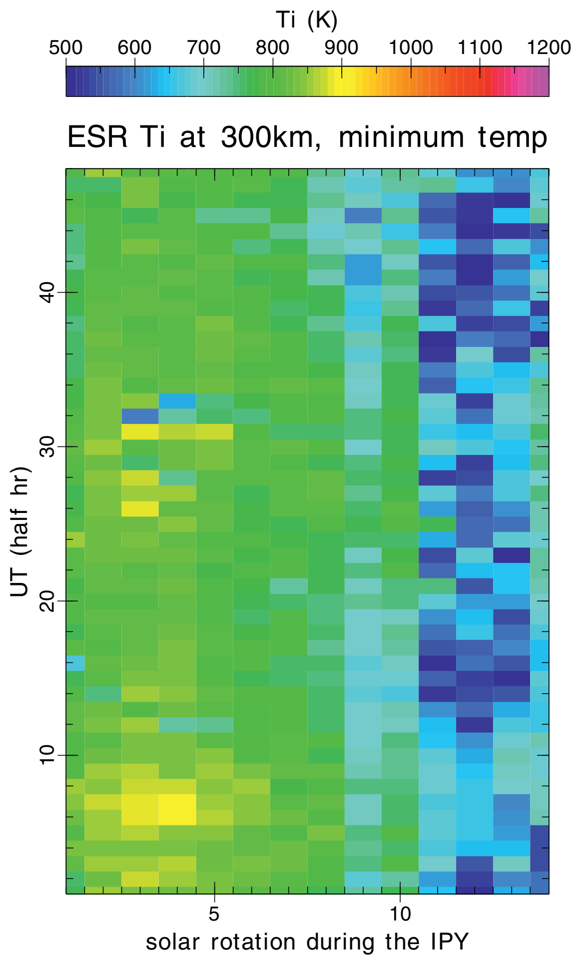

Fig. 3b. The IPY season and UT climatology of the coldest Ti at 300 km observed by ESR. The format is the same as used in Fig. 3a.

around local noon and has its lowest values in the night sector. On solar rotation 2, for UT half-hour bin 18, there is an anomalously high cold temperature which reaches 900 K. This value is the lowest for this bin, but it is a bin with very few entries due to a sequence of radar issues. AT ESR, Fig. 3b, the seasonal variation is quite similar, but the diurnal variation is relatively flat. At ESR, the Svalbard location, which is deeper into the polar cap the solar illumination conditions are quite different from these at Poker Flat. The polar cap is illuminated for a long summer and then dark for an equivalently long winter. The Ti values in summer, solar rotations 3–6 show values extending almost to 900 K which is slightly higher than those observed by PFISR. There are a few bins which have anomalous Ti values, i.e., solar rotation 4, UT half-hour bin 33 is too cold, again, these are anomalous coldest temperatures which only became apparent in the full climatology plot.

4.2. Middle quartile climatology of IPY

The selection algorithm for this climatology begins with all Ti observations within a specific half-hour UT-solar rotation bin. Often this number exceeds 60 values. These are then put into an ascending order to enable the bottom and top quartiles to be removed. In so doing the observations that constituted Figs. 3a and 3b are removed. The remaining Ti values are then averaged. Figs. 4a and 4b show the PFISR and ESR Ti middle quartile averages in the same format as Figs. 3a and 3b. Figs. 3a and 3b and 4a and 4b are decidedly different, the Ti values are higher and at ESR the Ti increase is significantly more than at PFISR. The PFISR climatology, Fig. 4a, does compare well with the cold Ti climatology Fig. 3a. The Ti increase ranges from 100 to 150 K. On inspection the ESR climatology in Fig. 4b appears slightly different from its cold Ti climatology, Fig. 3b. This difference appears not as a diurnal variation but as a semi-diurnal variation that is consistently present over almost 10 solar rotations. At the ESR location local noon corresponds to half-hour UT bin 22. Neither of the two Ti enhancements correspond well with this solar local noon. Rather the two enhanced periods are centered about magnetic noon and midnight. In Fig. 4b the very low temperatures between solar rotation 10 and 12 and

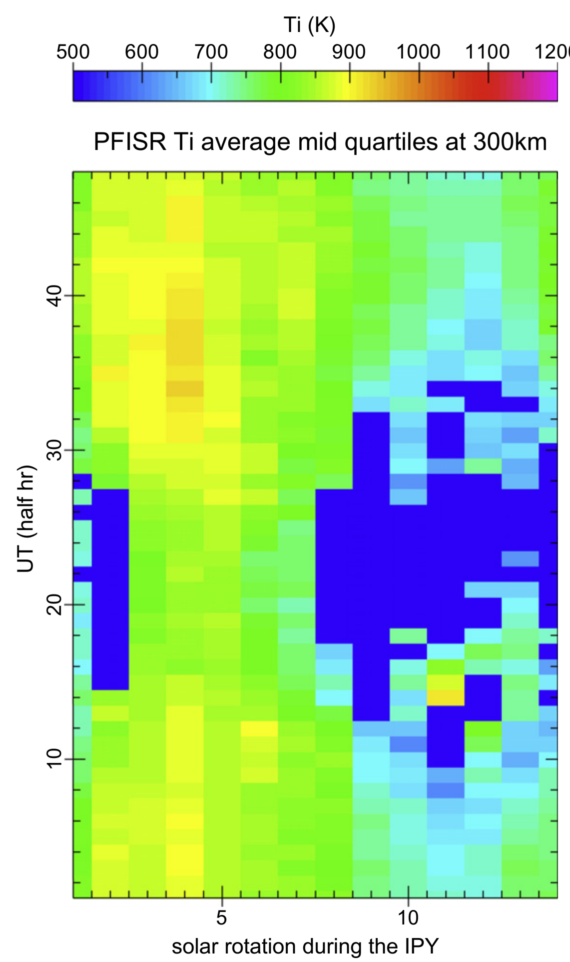

Fig. 4a. The IPY season and UT climatology of the middle quartile average of Ti at 300 km for the PFISR observations. The format is the same as used in Fig. 3a.

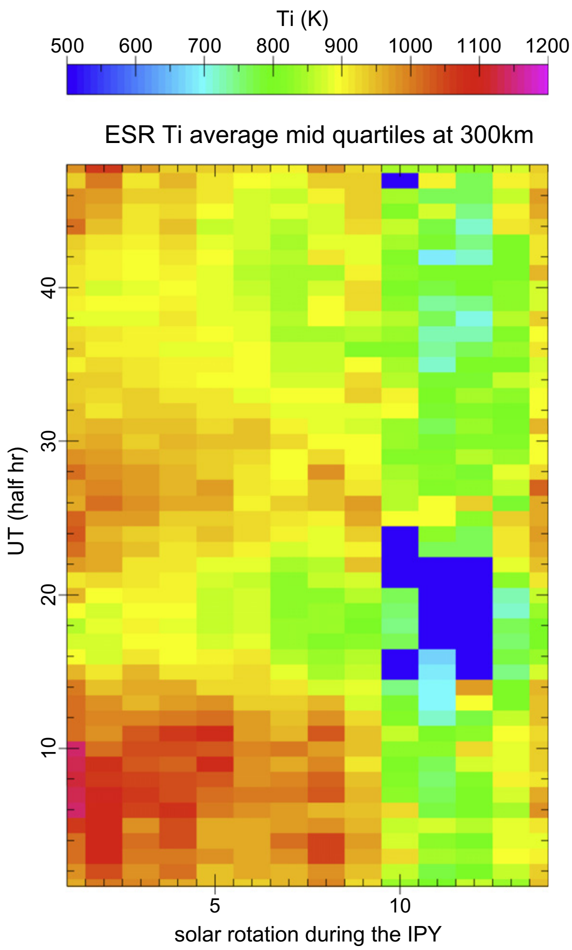

Fig. 4b. The IPY season and UT climatology of the middle quartile average of Ti at 300 km for the ESR observations. The format is the same as used in Fig. 3a.

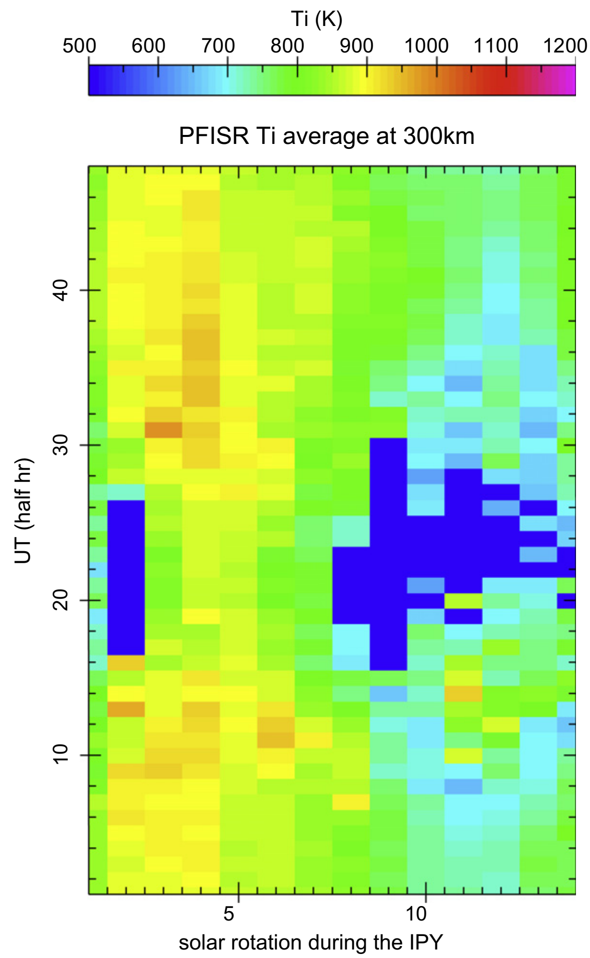

Fig. 5a. The IPY season and UT climatology of the average Ti at 300 km for the PFISR observations. The format is the same as used in Fig. 3a.

between half-hour UT bins 16 and 24 correspond to bins with insufficient observations to carry out the analysis and have defaulted to the 500 K lower values. At Svalbard ESR the Ti increases from Fig. 3b to Fig. 4b is almost 200 K which is somewhat higher than seen at Poker Flat.

4.3. Average Ti climatology

This third ISR climatology is an average overall Ti observations within its solar rotation and half-hour UT bin. Figs. 5a and b show these Ti averages for PFISR and ESR, respectively. These plots are only slightly hotter than the middle quartile Ti averages of Figs. 4a and 4b. PFISR Ti values may be about 50 K higher and those at ESR slightly more than 50 K. In both cases the morphology in Figs. 5a and 5b corresponds to that found in Figs. 4a and 4b.

4.4. Climatology summary

The three climatologies enable the ionospheres behavior under two different geomagnetic conditions to be distinguished. In Fig. 2 the ionospheric Ti at 300 km demonstrates how after a CIR event the temperature, all day, decreases. It then rapidly increases when a CIR occurs. During the IPY there were about 50 CIRs and since they were locked to the solar rotation period of 27 days they are evenly distributed over the year. The cold climatology, Figs. 3a and 3b, is a very systematic coldest state of the high latitude ionosphere experienced during the IPY. That these patterns are reasonably coherent with no averaging or smoothing speaks to the fact that this coldest state was indeed well captured by the two ISRs. During CIR events the temperature at all UTs increases and from Fig. 2 there is an overall increase of up to 200 K with additional spiked temperature increases of over 500 K. The middle quartile climatology has rejected both the very cold temperatures (Figs. 3a and 3b) as well as the spiked temperatures. Hence, Figs. 4a and 4b, middle quartile, climatology is capturing the ionospheric consequences of the bulk heating associated with the CIR. Finally the overall average climatology, Figs. 5a and 5b, includes the cold Ti values about 200 K lower and the spiked enhancements of over 500 K, hence generating averages somewhat hotter than that of Figs. 4a and 4b.

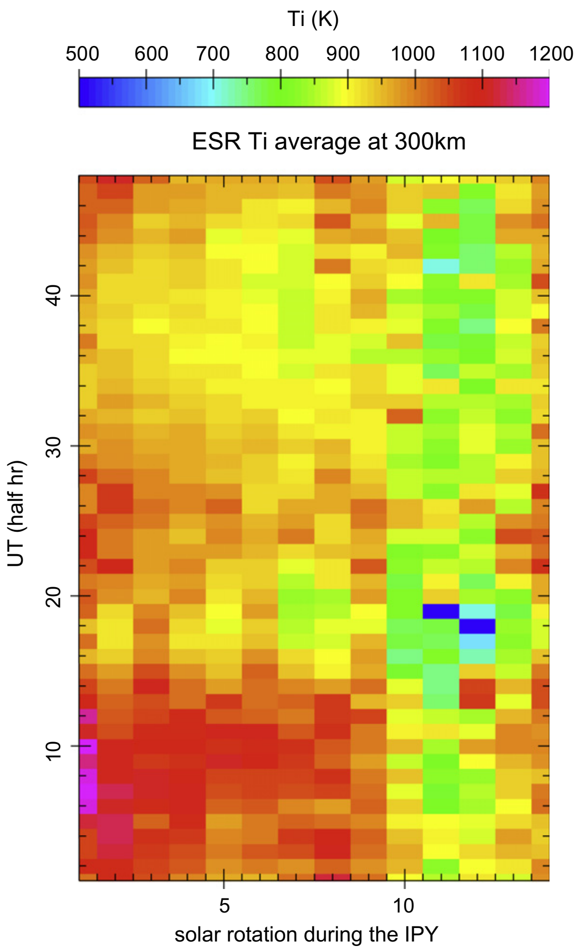

Fig. 5b. The IPY season and UT climatology of the average Ti at 300 km for the ESR observations. The format is the same as used in Fig. 3a.

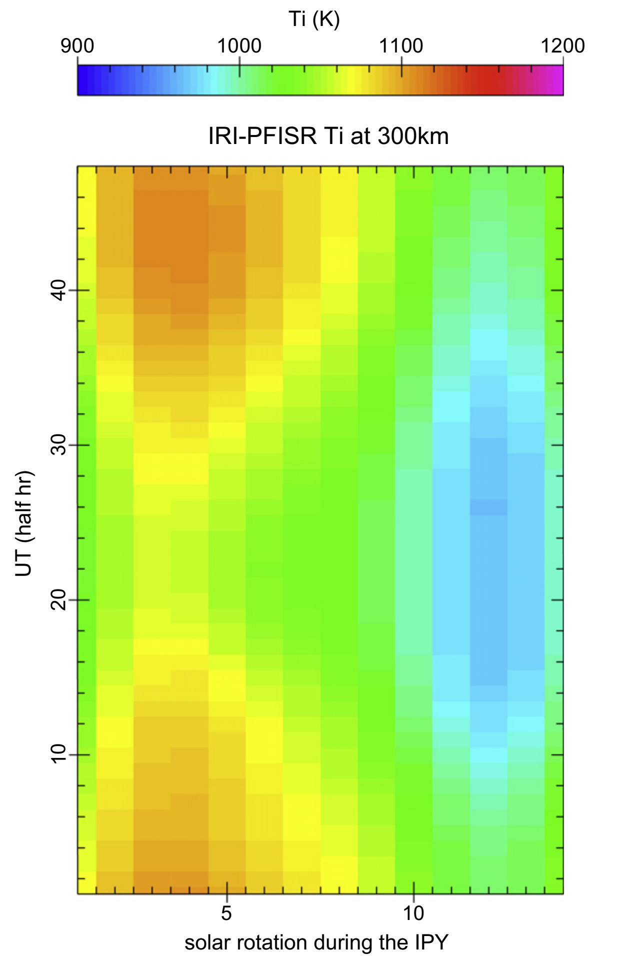

Fig. 6a. The IPY season and UT climatology of the IRI-2007 Ti at 300 km for the Poker Flat (PFISR) location. The format is the same as used in Fig. 3a, but a color key range of 900–1200 K.

5. IRI climatology

The 2007 release of the IRI model (Bilitza, 2009) has been used to compute the IRI Ti at 300 km distributions for both the Poker Flat and Svalbard locations. In 2010 the most updated coefficient data sets, i.e. IRI indices files, etc. were uploaded to ensure IRI was correctly computing the IPY period, 1 March 2007 – 29 February 2008. Figs. 6a and 6b show the IRI Ti at 300 km climatology at the Poker Flat and Svalbard locations respectively. There is clearly a significant difference between these IRI plots and the PFISR and ESR climatologies. These IRI Ti values range from about 950 to 1150 K. Where as the PFISR climatology has the highest temperature approach, 950 K. The ESR middle quartile and overall averages, Figs. 4b and 5b do have Ti values that reach the IRI highest values of 1150 K, however, these ESR lower temperatures in all cases drop below 800 K.

Morphologically the IRI seasonal trend of hot in summer and coldest in winter is consistent with the observations at both Poker Flat and Svalbard. The difference between summer and winter is about 200 K for both the IRI and observations. Comparing the IRI with the middle quartile climatologies of both PFISR and ESR, Figs. 4a and 4b with Figs. 6a and 6b, provides the following insights:

(1) The PFISR observations are approximately 150 K colder in summer, but in winter this difference increases to over 250 K.
(2) The ESR observations are between 0 and 150 K colder in summer, while in winter the difference increases up to 200 K.
(3) The IRI temperatures are similar at both locations, while PFISR observations are colder than the ESR middle quartile values by 100–200 K.

Note this last difference between the PFISR and ESR middle quartile average temperatures does not reflect an instrument/analysis bias or offset for the following reason. In Figs. 3a and 3b the coldest Ti climatology has an identical Ti seasonal dynamic range between ESR and PFISR. Hence, assuming under the least disturbed conditions the whole high latitude ionosphere-thermosphere system is in

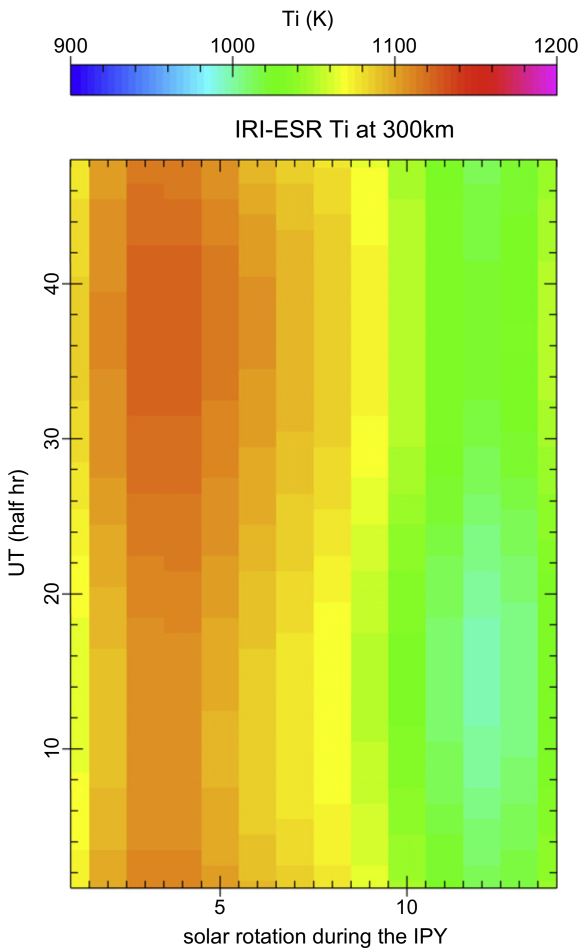

Fig. 6b. The IPY season and UT climatology of the IRI-2007 Ti at 300 km for the Svalbard (ESR) location. The format is the same as used in Fig. 3a, but a color key range of 900–1200 K. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

near thermal equilibrium the Figs. 3a and 3b comparison would imply that the two instrument/analysis are self-consistent. Given this to is a very probable case, then the differences seen in the middle quartile Figs. 4a and 4b climatologies suggest that CIR heating at Svalbard in the polar region is more effective than at Poker Flat. In fact, the ESR Ti at 300 km in summer shows the strongest heating in the magnetic midnight sector, see Figs. 4b and 5b where Ti is largest around half-hour UT bins 2 to 8. The deduction being that the CIR energy deposition is stronger at the polar cap than at the auroral ISR location.

6. Neutral temperature at 300 km

In addition to its ionospheric products, IRI provides the user other parameters such as the thermospheric neutral density and temperature (Tn). IRI does this by making a suitable call to a MSIS neutral atmosphere model. Given that the 300 km height is located between 10 and 100 km above the *F*-region peak and that levels of geomagnetic activity are negligible for the cold Ti study of Section 1 (Figs. 3a and 3b) there is an expectation that this cold Ti should be similar to Tn. Under such conditions Tn at this altitude would be the exospheric temperature $T\infty$. In order to evaluate this hypothesis the most recent MSIS model, NRL-MSIS (Picone et al., 2002) has been used to obtain Tn. Figs. 7a and 7b show the NRL-MSIS Tn at 300 km for the Poker Flat and Svalbard locations respectively for the study IPY conditions. Figs. 7a and 7b is to be compared to Figs. 3a and 3b. At both locations the comparison of season and UT are excellent. The absolute temperatures are even in near agreement. At PFISR the agreement is such that the daytime summer values are the same with PFISR night-winter values being perhaps 25 K colder. The ESR comparison is somewhat different with the winter values being the same while the ESR daytime values being slightly higher by about 20–50 K. In addition, in summer ESR identifies between 0000 and 1000 UT a second local time ion temperature maximum not present in NRL-MSIS. This is a small effect and possibly due to a data selection limitation.

Overall the very positive comparison is indicative that indeed the thermosphere and ionosphere are approaching

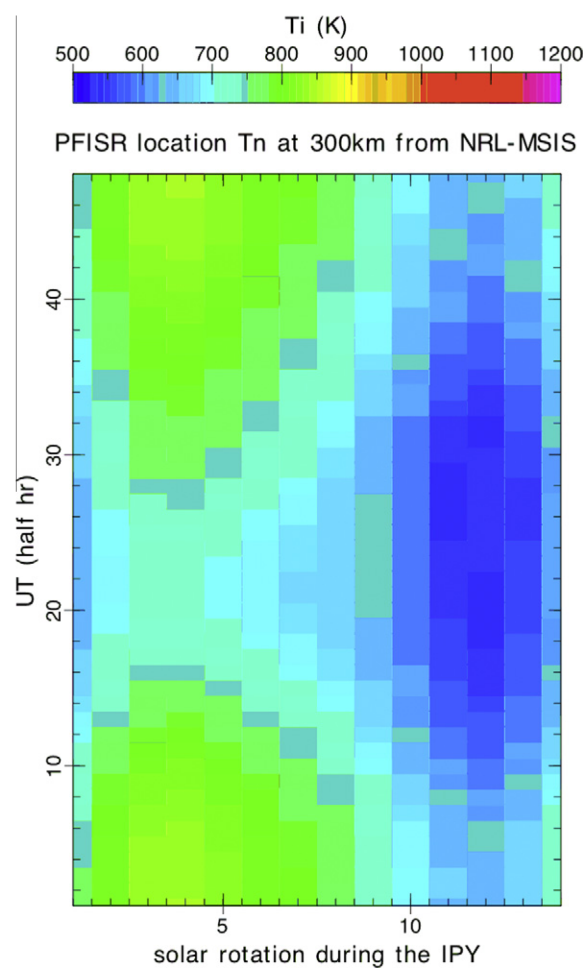

Fig. 7a. The IPY season and UT climatology of the NRL-MSIS Tn at 300 km for the Poker Flat (PFISR) location. The format is the same as used in Fig. 3a.

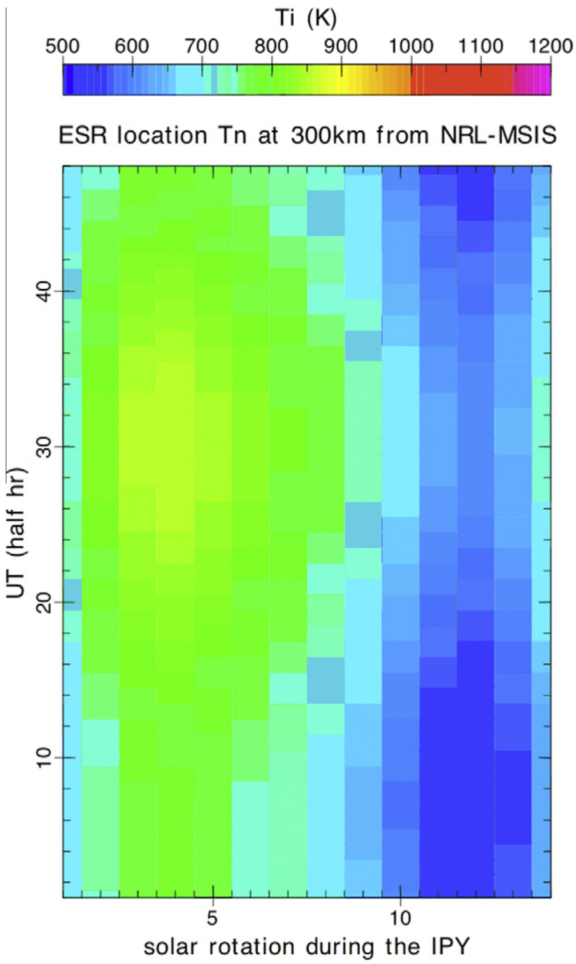

Fig. 7b. The IPY season and UT climatology of the NRL-MSIS Tn at 300 km for the Svalbard (ESR) location. The format is the same as used in Fig. 3a.

thermal equilibrium during the non-CIR periods. Only in winter at PFISR is the ion temperature slightly colder is perhaps an indication that during the IPY, the beginning of the extended solar minimum between solar cycles 23 and 24, the thermosphere-ionosphere temperatures are colder than the most recent NRL-MSIS expectation.

7. Discussion

The IRI model which provides climatology of the ionosphere captures the ionospheres latitude, longitude, seasonal, and solar cycle trends. At high latitudes especially in the dynamic auroral regions the season trends are masked by the large variability associated with both auroral precipitation and plasma convection. During solar minimum this geomagnetic auroral activity is minimized. Hence, to some extent the IPY and subsequent years of solar minimum are the best conditions for making comparisons of IRI with high latitude observations.

Both the PFISR and ESR observations have provided an entire year of ionospheric observations. Hence at these two locations a comprehensive full ionospheric observational data base exists. The significance of "full" being that the observations contain altitude profiles of the electron density, ion and electron temperatures, and plasma drifts. A caveat that also provides additional insight is that the ion temperature analysis from these two ISRs does require ion composition knowledge at altitudes below the *F*-region peak. Note at 300 km used in this study the assumed composition being atomic oxygen ions is very probably appropriate. From the ISR measurement analysis presented here two distinct climatologies are shown, the first being the coldest high latitude ionosphere, Figs. 3a and 3b, and the CIR disturbed ionospheres of Figs. 4a and 4b and 5a and 5b. IRI does not distinguish between these two, but arguments can be made that the original URSI coefficient data bases were obtained by a middle-quartile analysis would suggest an expectation that IRI, Figs. 6a and 6b, should be somewhat more akin to Figs. 4a and 4b and 5a and 5b averages. This is not particularly the case, but the trend is such especially at the ESR location. Arguably the use of only two locations, an auroral and a polar cap location, does not provide IRI sufficient information on latitude, longitude, and UT dependence. Rather the two locations establish what the full seasonal and UT, quiet time and CIR disturbed time, ionosphere actually was during the IPY solar minimum and that this is different than Ti at 300 km from IRI-2007. It must be noted that this study has only dealt comprehensively with one parameter at one altitude. More extensive studies are needed to generalize and quantify this latter statement.

The comparison with the neutral temperature, Tn, provides evidence that the ionosphere ions at the 300 km and below altitudes are in thermal equilibrium with the thermosphere during the quietest periods. Solomon et al. (2010) present model simulations for these same quiet conditions that further demonstrate this equilibrium (see Figs. 4a and 4b, Solomon et al., 2010). In their global study the very cold temperatures found in our analysis at PFISR and ESR (Figs. 3a and 3b) are modeled and shown to be a global property. The other aspect that needs further study is during CIRs in which Ti is heated, Figs. 4a and 4b and 5a and 5b, does the thermospheric Tn also get heated? If so, are the heated ions in the lower ionosphere in thermal equilibrium with the thermosphere?

8. Summary

The two incoherent scatter radars at the Poker Flat and Svalbard locations operated on a continuous basis during the IPY year. These data sets represent a comprehensive resource against which the IRI can be compared and to an extent provide a unique climatology data base that could be added to IRI. The key findings of this study are:

- During the IPY which occurred at the start of an extended solar minimum period the PFISR and ESR observations are readily separated into a cold and CIR disturbed climatology of Ti at 300 km.

- Neither of these two ion temperature climatologies coincides with that of IRI.
- The IRI Ti at 300 km is about 200 K hotter than the ISR CIR disturbed climatology and 400 K hotter than the ISR cold climatology.
- The NRL-MSIS Tn at 300 km climatology is morphologically almost identical to the cold Ti at 300 km.

This study has only addressed one parameter, Ti at 300 km, and only at one altitude 300 km. The choice of this parameter was made to specifically look at *F*-region energy and heating during the recurrent CIR heating events that occurred during the IPY year. Follow-up studies will address other parameters and altitudes.

Acknowledgements

This research was supported by NSF grant ATM-0533543 to Utah State University. PFISR is operated by SRI International under NSF cooperative agreement ATM-0608577. EISCAT is an international association supported by research organizations in China (CRIRP), Finland (SA), France (CNRS, until the end of 2006), Germany (DFG), Japan (NIPR and STEL), Norway (NFR), Sweden (VR), and the United Kingdom (PPARC). The solar wind data was obtained from the ACE satellite. The International Space Science Institute (ISSI) is gratefully acknowledged for its role in sponsoring IPY team meetings on this research topic.

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