Long-term temperature trends in the ionosphere above Millstone Hill

J. M. Holt and S. R. Zhang

Received 27 June 2007; revised 6 December 2007; accepted 7 January 2008; published 13 March 2008.

[1] Increasing concentrations of greenhouse gases are expected on theoretical grounds to lead to a cooling of the upper atmosphere. Due to the close thermal coupling of the neutral and ionized components of the upper atmosphere the effects of this cooling are also expected to be seen in the ionospheric ion temperature. Long-term satellite observations of neutral density show a trend consistent with the expected cooling. Temperature data from the Millstone Hill incoherent scatter radar (46.2°N, 288.5°E) from 1978 to 2007 have been analyzed to provide a direct estimate of the temperature trend above the radar. The long-term trend in the directly measured ion temperature \( T_i \) at 375 km is found to be \(-4.7 \) K/year with a 95% confidence interval of \(-3.6 \) to \(-5.8 \) K. The estimated trend in the neutral temperature \( T_n \) is \(-5.0 \) K/year. These are significantly larger than predicted by theory. Citation: Holt, J. M., and S. R. Zhang (2008), Long-term temperature trends in the ionosphere above Millstone Hill, Geophys. Res. Lett., 35, L05813, doi:10.1029/2007GL031148.

1. Introduction

[2] Greenhouse gases such as \( \text{CO}_2 \) and \( \text{CH}_4 \) are well known to be increasing in the lower atmosphere. The effect of this on the upper atmosphere, in particular the ionosphere, has become an active topic of research since the publication of a theoretical modeling study by Roble and Dickinson [1989], suggesting a major greenhouse cooling in the thermosphere in response to increases in \( \text{CO}_2 \) and \( \text{CH}_4 \) concentration at 60 km. This cooling would lead to a global reduction in neutral densities including \( \text{O}, \text{N}_2 \) and total neutral mass density as the neutral temperature \( T_n \) decreases. If greenhouse gas concentrations are doubled, as predicted to happen by the end of the 21st century, they indicated that the decrease in thermospheric temperature would be as much as 50 K, and the decrease in thermospheric densities at a fixed height would be 40–50%. The ionospheric consequences of this thermal contraction would include a decrease in the F2 peak height, \( \text{hmF}_2 \), of 10–20 km [Rishbeth, 1990; Rishbeth and Roble, 1992], a decrease in the upper ionosphere electron density and an increase in the lower ionosphere electron density, with less change in the maximum density \( \text{NmF}_2 \).

[3] The above results, arising from theoretical considerations, have stimulated many investigations of long-term ionospheric change. More than 50 papers have been published in refereed journals. Most of these are based on long-term ionosonde observations which date to the early days of ionospheric studies and are readily accessible. Bremer [1992] published the first such ionospheric long-term trend observational results. Some, but not all, of these results concluded that \( \text{hmF}_2 \) indicated a decreasing trend in the electron density; other studies or the same studies but for different sites did not find a long-term trend or found a trend opposite to the sense predicted by Rishbeth and Roble. Recent results include: Ulich and Turunen [1997], Bremer [1998], Jarvis et al. [1998], Upadhyay and Mahajan [1998], Danilov and Mikhailov [1999], Marin et al. [2001], Mikhailov and Marin [2001], Xu et al. [2004], and Yue et al. [2006].

[4] Observations of thermospheric mass total density by satellites revealed a 2–5% decrease per decade [Keating et al., 2000; Emmert et al., 2004]. These have been considered to be evidence of thermospheric cooling, supporting the Roble and Dickinson [1989] theoretical calculations of the greenhouse effects. In fact, the greenhouse effect may not be the sole reason for the observed secular changes in the ionospheric parameters (especially \( \text{hmF}_2 \)). Long-term trends in solar and geomagnetic activity would have impacts on trends in the upper atmosphere [Mikhailov and Marin, 2001] and these have to be taken into account in any long-term trend study.

[5] There are a variety of factors that have prevented a consensus on long-term trends in the ionosphere and thermosphere, including questions about data quality and consistency and the appropriateness of different methods of analysis. Any ionospheric trends are probably the result of the thermospheric trends in temperature, composition, and winds. So far there has been no direct evidence for thermospheric cooling as indicated by measured temperatures.

2. Detecting Long-Term Trends With an Incoherent Scatter Radar

[6] Incoherent scatter radar (ISR) has the capability of directly monitoring the thermal status of the upper atmosphere in addition to electron density and plasma drifts. It directly provides ion temperature \( T_i \) and electron temperatures \( T_e \) over a large range of altitudes from 100 km to topside of the ionosphere. Based on a simplified energy equation for the ions, it is possible to deduce the neutral temperature \( T_n \) above 100 km, the exospheric temperature \( T_x \), and oxygen density [Bauer et al., 1970; Oliver, 1979; Alcaydé et al., 1982; Buonsanto and Pohlman, 1998]. Up to about 400 km, the ion temperature is relatively close to the neutral temperature. Typically a 50 K decrease in \( T_i \) corresponds to about a 46 K decrease in \( T_n \). So, even a rather large error in the energy balance calculation would not have a significant effect on the estimated \( T_n \) trend. Thus ISRs provide a direct measure of the thermal status of the...
ionosphere and thermosphere and ISR data, and in particular $T_i$ measurements, have a significant advantage for long-term trend studies.

[7] In addition to providing an excellent estimate of changes in $T_m$, $T_i$ follows variations in the solar activity rather well (linear for most values of $F_{10.7}$), an extremely important feature making it relatively easy to remove effects of the solar activity on long-term trends. The electron density in the F2-layer, however, exhibits a somewhat more complicated response to solar activity. Saturation effects [Balan et al., 1994; Richards, 2001] in the maximum electron density dependence on solar 10.7 cm flux, for example, add more complexity for mathematically representing the control of the solar flux, a needed procedure to detect the trends from solar cycle influences. While saturation sometimes appears in the response of $T_m$ to solar activity, the effect is significantly less important than for $N_e$. The value of hmF2 used for ionosonde-based long-term trend studies is based on an empirical function relating hmF2 to foF2, foE and the M3000F2 factor [see, e.g., Bradley and Dudenev, 1973; Bilitza et al., 1979]. Also, hmF2 is subject to complicated processes in the ionospheric dynamics and thermospheric conditions [see, e.g., Zhang et al., 1999] such that not only the neutral temperature, but also winds and electric fields can cause changes in it.

[8] As a rule, ISRs have been relatively well maintained and calibrated over the years. The theory relating ISR measurements to ionospheric parameters and the methods for deriving these parameters from the data is very well established. Rishbeth [1999] and Ulrich et al. [2003] have raised concerns about the quality of ionosonde data for the purpose of the long-term trend studies.

[9] Incoherent scatter radar measures the backscatter of incident radio waves by electrons in the ionosphere. The spectrum of the received signals exhibits a double-humped pattern due to ion-acoustic waves. The separation of the humps is a measure of the ion temperature for a given ion species. The observed ISR spectrum is fit to a theoretical spectrum yielding ionospheric parameters including $T_i$. Typically the experimental error of the $T_i$ measurement is on the order of a few tens of K. As mentioned earlier, Roble and Dickinson [1989] estimated a decrease in thermospheric $T_n$ of about 50K if greenhouse gases are doubled. If $T_n$ decreases by that amount or more over a period of decades, the corresponding change in $T_i$ should be detectable with an ISR.

[10] A series of empirical ionospheric models has previously been developed using data from the long-term Madrigal Database as described by Holt et al. [2002] and Zhang et al. [2005]. These models are functions of local time, altitude, season, solar activity represented by $F_{10.7}$ and geomagnetic activity represented by the 3-hour ap index. These models have been developed for most of the World's ISRs. Two of these radars, Saint Santin, which operated in France from 1966–1987, and Millstone Hill, which has operated since 1964, are best suited for long-term trend studies. In our initial attempt to detect a trend we simply added a trend term to the model and recomputed the model parameters [e.g., Zhang et al., 2005]. For most altitudes and seasons the computed temperature trend was negative [Lastovicka et al., 2006], but the confidence interval was rather large and we were unable to rule out a non-negative trend. Part of the problem lay in the large number of model parameters, all of which are correlated to some degree with the trend term. To simplify statistical calculations the analysis was simplified by binning the data by local time, altitude and month and then modeled the data in each bin as a linear function of four parameters — a constant term, year, $F_{10.7}$ and ap. We were then able to more easily deal with issues like outliers and data autocorrelation, but the parameter uncertainties were still too large to convincingly demonstrate a negative long-term temperature trend.

[11] The Millstone Hill empirical models and initial trend estimates were based on data collected through 2001. Since that time more recent data have been analyzed and calibrated. This data and details of the analysis are discussed in Section 3, and results are discussed in Section 4.

3. Data and Method

[12] The data used in this report were all available local (elevation $\geq 45^\circ$) Millstone Hill Radar measurements from 1978–2007, 1630–1730 UT (noon LT) and 350–400 km altitude. The raw data (spectra and autocorrelation functions) were all analyzed by an incoherent scatter analysis program (inscal), which has been in the standard Millstone Hill analysis program since 1976. Except for the receiver and data acquisition system the radar has remained mostly unchanged throughout this period. On the three occasions when the data acquisition system changed, careful comparisons of data from the old and new systems were carried out by one of the authors (Holt). Altogether there were 46779 measurements, each yielding values for $T_i$, $T_e$ and $N_e$. Our climatological models are less reliable during geomagnetically disturbed conditions and periods of high solar activity. Therefore measurements for which $F_{10.7} > 300$ or $ap > 80$ were eliminated, yielding 45769 measurements. Medians of the data were then computed for each individual month in the data set, yielding 278 median-filtered points. This serves three major purposes. First, most outliers are eliminated. Second, over-weighting of long-duration experiments is eliminated. This is particularly important in the case of the Millstone Hill data because during the early part of this dataset relatively few local measurements were made and in recent years there have been several long duration (~30 days) runs. Third, the need to correct for short-term autocorrelation (on the order of hours or days) in the data is eliminated [Weatherhead et al., 1998, 2002]. This use of monthly medians is justified by the final results which show that the scatter of the medians around the fit is almost constant with time. This indicates that the scatter is due to ionospheric weather (geophysical noise not captured by the statistical model) rather than to errors in the measurements. This also justifies using a constant data error when fitting the data. Finally, months for which there were fewer than six points were eliminated, leaving 259 monthly medians. This helps to insure that outliers are reliably eliminated by the median filter.

[13] Least squares fits to ion temperature ($T_i$), electron temperature ($T_e$), electron density ($N_e$) and neutral temperature ($T_n$) calculated as described in Section 2 were
then computed. Ne was not temperature corrected, that is, the ion and electron temperatures were assumed to be equal when computing the density from the directly measured returned power. The independent variables of the fits were year, including a fractional part corresponding to the day number of the experiment, $F_{10.7}$ and $ap$. Initially twelve fits were computed, one for each month of the year. These yielded similar estimates of the fit parameters and no seasonal variation of the trend parameter was evident. So all the data were combined and a single fit computed. Seasonal effects were ignored which is justifiable because for 30 years of data they will basically introduce high-frequency noise with no effect on the long-term trend. Some of the $F_{10.7}$ dependencies showed a clear saturation effect at high values of $F_{10.7}$ which was addressed by adding a quadratic term in the $F_{10.7}$ dependence of all parameters.

[14] In this report the uncertainty of trend estimates will be expressed in terms of confidence intervals rather than error bars. This is appropriate when asking questions such as “what is the probability that there is a negative trend?” It is also appropriate when using the bootstrap as discussed in Section 4, since the bootstrap probability distribution is not necessarily symmetric. We plan to apply the technique described in this report to different times and altitudes for which these considerations are likely to be more important than is the case for the results reported here.

4. Results

[15] Results for Ti are shown in Figure 1. The plots show the fits to each independent variable with the effects of the other two trends removed. The long-term trend in Ti is clearly visible with a computed least squares fit value of $-4.7$ K/year. The fit has a standard deviation of 73.7 K and the estimated variance of the trend parameter is 0.57 which corresponds to a 95% confidence interval of $-3.6$ to $-5.8$ K. The three dimensional covariance matrix with the exception of the small quadratic term in $F_{10.7}$ is shown in Figure 2. The error calculation assumes that the

Figure 1. Least squares fits to data (solid lines) and data with contribution of the other two parameters removed (dots) for (top) long-term trend, (middle) $F_{10.7}$, and (bottom) ap for 1630–1730 UT and 350–400 km altitude.
data have a Gaussian distribution and are homoscedastic and uncorrelated which seems reasonable in this case. An alternative approach is the bootstrap \[\text{Chernick, 1999; Efron and Tibshirani, 1993}\]. This relatively new and now widely accepted computer intensive technique makes no assumption about the distribution of the data. A large number of bootstrap data sets are generated from the actual data set or from the residuals of the fit by sampling with replacement. A least squares fit is computed for each of the bootstrap samples and the limits of the 95% bootstrap confidence interval are the points on the histogram of the resulting fit parameters such that 2.5% of the parameter values are less than and 2.5% greater than the limits. Results for 10000 bootstrap samples are shown in Figure 3. The 95% confidence levels are essentially identical to those from the trend variance computed from the fit.

Trend estimates and bootstrap 95% confidence intervals for the remaining three parameters are:

\[\begin{align*}
\text{T}_e &= +4.5(-1.6 + 10.4) \text{K/year} \\
\log_{10}(\text{Ne}) &= -0.004(-0.009 + 0.0003) \log_{10}(\text{m}^{-3})/\text{year} \\
\text{T}_n &= -5.0(-6.2 - 3.9) \text{K/year}.
\end{align*}\]

5. Discussion

The observed \(\text{T}_i\) and \(\text{T}_n\) trends are much larger than would be expected from the \textit{Roble and Dickinson [1989]} calculations. Nevertheless, standard statistical analysis and bootstrap analysis both support a large negative temperature trend with a high level of confidence. It seems unlikely that the theoretical calculations of the greenhouse gas effect are wrong by such a large factor, so the observed decrease may be caused in part by other factors. We are now extending the analysis to other altitudes and times with the goal of producing altitude profiles of the temperature trend for a range of daylight hours. These may provide clues to other causative factors and will further constrain future theoretical studies of the observed trends.
Acknowledgments. We thank the staff, and in particular Bill Rideout and Glenn Campbell, for assembling and maintaining the Madrigal Database. This work was supported by NSF Space Weather Grant ATM-0207748 and NSF Cooperative Agreement ATM 0417666. The Millstone Hill incoherent scatter radar is supported by the US National Science Foundation (NSF) as part of the Upper Atmosphere Facility Program.

References


J. M. Holt and S. R. Zhang, MIT Haystack Observatory, Westford, MA 01886, USA. (jmh@haystack.mit.edu)