

Comments on "Long-term variations of exospheric temperature inferred from foF1 observations: A comparison to ISR T_i trend estimates" by Perrone and Mikhailov

Shun-Rong Zhang, John M. Holt, Philip J. Erickson, and Larisa P. Goncharenko

MIT Haystack Observatory, 99 Millstone Road, Westford, MA 01886, USA

Key Points:

- Determination of T_{ex} , [O], [N₂], [O₂] and EUV flux from a single ionospheric parameter foF1 is not possible without significant ambiguity.
- Such derivations are very problematic for long-term trend studies.
- Large ISR data sets remain a consistent and statistically robust method for determining long term secular plasma temperature trends.

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Corresponding author: Shunrong Zhang, shunrong@mit.edu

Abstract

Perrone and Mikhailov [2017] and *Mikhailov and Perrone* [2017] have recently examined thermospheric and ionospheric long-term trends using a dataset of 4 thermospheric parameters (T_{ex} , [O], [N₂], [O₂]) and solar EUV flux. These data were derived from one single ionospheric parameter, foF1, using a non-linear fitting procedure involving a photochemical model for the F1-peak. The F1 peak is assumed at the transition height h_t with the linear recombination for atomic oxygen ions being equal to the quadratic recombination for molecular ions. This procedure has a number of obvious problems that are not addressed or not sufficiently justified. The potentially large ambiguities and biases in derived parameters make them unsuitable for precise quantitative ionospheric and thermospheric long term trend studies. Furthermore, we assert that *Perrone and Mikhailov* [2017] conclusions regarding incoherent scatter radar (ISR) ion temperature analysis for long-term trend studies are incorrect, and in particular are based on a misunderstanding of the nature of the incoherent scatter radar measurement process. Large ISR data sets remain a consistent and statistically robust method for determining long term secular plasma temperature trends.

Recent studies by *Perrone and Mikhailov* [2017] (hereafter designated PM17) and *Mikhailov and Perrone* [2017] used a single ionospheric measurement parameter, foF1, to derive a set of four neutral atmospheric parameters (exospheric temperature T_{ex} , neutral concentrations [O], [O₂], and [N₂]) and one solar EUV flux factor (f). They used these results to analyze long-term trends in the thermosphere and ionosphere. In particular, PM17 studied T_{ex} over multiple solar cycles and compared them to existing temperature trends from multiple observation sets using incoherent scatter radars (ISRs). The study states that “routine ISR observations based on a fixed model of ion composition may be not appropriate for long-term trend analyses”. These authors have also published separate studies [*Mikhailov and Perrone*, 2016a,b, 2017] examining long-term trends in the ionosphere and thermosphere using results from the same derivation technique. We assert in this commentary that several aspects of the technique as described introduce large analysis difficulties, and that the resulting ambiguities in derived parameters make them unsuitable for precise quantitative ionospheric and thermospheric long term trend studies. Furthermore, we assert that PM17 study conclusions regarding ISR ion temperature data are incorrect, and in particular are based on a misunderstanding of the nature of the incoherent scatter radar measurement process.

1 The method using a single ionospheric parameter foF1 for calculation of four thermospheric parameters and EUV flux

To allow calculation of T_{ex} , [O], [O₂], [N₂], and EUV flux from a single foF1 ionospheric parameter, PM17 and their other similar studies used a photochemistry model for the F1 region. Furthermore, since the analysis procedure attempts to generate five output values, at least five foF1 input values are required to avoid an under-determined situation. In the photochemical model, neutral temperature, composition and solar EUV flux are variable parameters that are adjusted to bring the photochemical model produced foF1 into agreement with observations. The MSIS model [*Hedin*, 1987; *Picone et al.*, 2002] is used to provide initial guesses of neutral atmospheric parameters (and may be used as well to specify some important height and time variations).

This overall procedure creates significant problems for the PM17 study results as follows:

(1) The five foF1 data used for each calculated result set are from different times (10-14 LT), and their use as a group for each output variable set must by definition introduce additional time variations in results for the five unknown parameters. These variations may occur in the base assumed neutral temperature and composition, but PM17 does not discuss these patterns, and therefore we assume that the default MSIS temporal variation

behavior was used. The authors must therefore assume that tidal harmonics in the MSIS model were specified with correct amplitudes and phases information to calculate reasonable foF1 values, including their variation in 5 hours around noon. PM17 does not address any of these time variation considerations nor justify the “hidden” assumptions which define the time variation of individual output parameters and, to a large degree, their final results.

(2) The method requires a T_n altitude profile function in order to determine the exospheric temperature T_{ex} . Assuming the procedure adopts a Bates function height profile model as does the MSIS model (although it is not discussed in PM17), the T_n profile is parameterized by the thermobase temperature T_b , the exospheric temperature T_{ex} , and the shape factor s that determines how fast T_n changes in height from T_b to T_{ex} . Given this parameterization, we emphasize strongly that s is a very important and highly sensitive parameter, because it directly controls the relationship between F1 region information and the exosphere temperature. The MSIS model provides s and T_b values, and these are likely used in PM17, although once again this is not discussed. However, MSIS also provides quantitative estimates of T_{ex} . The study however ignores this value and rather trusts a derivation of T_{ex} from their procedure, with no justification of why MSIS s and T_b are to be trusted but MSIS T_{ex} is not. PM17, and previous cited studies by the same authors, do not discuss the sensitivity of their results to the nature of this parameterization, nor do these studies justify the use of default s and T_b values (given the well known uncertainty in the MSIS model). Therefore, serious doubt exists as to the validity of the stated approach for T_{ex} .

(3) The study’s treatment fundamentally assumes a photochemical mechanism. Since the study focuses exclusively on making use of the ionospheric F1 peak information, the altitude of the peak is critically important because it is known that the thermosphere temperature changes dramatically from a few hundred K to ~1000 K between 100 - 200 km (and neutral composition undergoes dramatic exponential changes). PM17 uses the transition height h_t as hmF1 where the linear recombination for atomic oxygen ions and the quadratic recombination for molecular ions are equal. The justification stated for using h_t as hmF1 in PM17 and earlier articles was two-fold: (1) no observational hmF1 was available and (2) Ratcliffe [1972]’s earlier F1-region theory used this altitude to describe the transition between linear recombination and square-law recombination. This approach raises multiple issues which are not accounted for in the PM17 analysis. In particular, the Ratcliffe [1972] F1-region theory has not one but two characteristic altitudes: (1) the transition height h_t , which corresponds to essentially the height of $[O^+]=[M^+]$ (molecular ion density) or the transition between recombination which is linear in electron density and square-law in electron density; and (2) h_m which is the height of maximum production rate. When $h_t > h_m$, the F1 region electron density profile exhibits a maximum density (the F1-peak) at h_m , and thus $h_m = \text{hmF1}$ (see P45 in Ratcliffe [1972]). However, when $h_t < h_m$, there is no clear F1-ledge. PM17 used foF1 data in summer when the F1-peak is well developed, and therefore, the first scenario where $h_t > h_m$ and $h_m = \text{hmF1}$ is the appropriate one to use. Over a solar cycle, h_m can vary by ~30 km and h_t by various amounts according to multiple observational and modeling studies [Zhang *et al.*, 1996; Lei *et al.*, 2004]. The difference $h_t - h_m$ changes over solar cycle [Ratcliffe, 1972], so apparently solar cycle variations in hmF1 / h_m and h_t are not consistent. In summary, these discussions suggest the foF1 peak height is strongly influenced by the electron peak production rate and hmF1 is not simply at the transition height h_t . Assuming hmF1 = h_t in summer time for the purpose of dealing with variations in solar cycles and beyond needs clearly justification. Finally, use of a purely photochemical model for all ion species is likely insufficient to describe accurately F1-peak behavior. In particular, Taieb *et al.* [1978] and Zhang and Huang [1995] indicated that transport of molecular ions can affect the F1-ledge evolution in a time-dependent manner.

(4) Secondary ionization is important for the F1-region and its contribution to the total F1 region production rate can be as high as 100% [Richards and Torr, 1988; Titheridge,

1996]. There is no indication in PM17 whether this important factor was considered. Further, the F1 region production rate, with both primary and secondary ionization considered, will be a rather complicated non-linear function involving all the unknowns that PM17 attempts to derive, and no discussion of this complicating factor is included.

Taken in aggregate, these factors have significant implications. Items (1) and (4) above suggest that solving for the 5 desired unknowns faces a very complicated multiple variable non-linear problem. However, PM17 do not state clearly how the study handles classic analysis challenges for problems of this class regarding robust finding of local minima in the model-data fit, inherent cross-coupling ambiguity (or lack thereof) between the 5 unknowns, range of typical uncertainties on output parameters and their relation to input uncertainties, and how these factors impact the resulting trend study. Similar attempts at deriving T_{ex} , EUV and other parameters from the ionospheric measurements were made in previous studies, and these works (e.g. *Zhang et al.* [2002]) reported significant ambiguities in T_{ex} , EUV and other parameters, all of which contributed to electron density variations. *Zhang et al.* [2002] proposed the use of full Ne altitude profiles to resolve some of the ambiguity, but no such awareness of this difficulty appears to have been realized by PM17. In general, it is quite difficult to understand how a single ionospheric parameter foF1 can allow for simultaneous and unambiguous quantification of the stated 5 unknowns (plus their temporal variations) without a detailed discussion or awareness of these issues and without proper calculation of the magnitude of covariances between output parameters.

Furthermore, Item (3) implies PM17's results could be biased as a result of assuming $\text{hmF1} = h_i$. Unfortunately, PM17 does not present or refer to observational evidence verifying the insensitivity of their neutral parameter analysis to actual hmF1 variations, which can be significant. For example, we examined daily ionosonde data at Millstone Hill during recent (June-September 2017) months with solar F10.7 being 70-90 sfu. These data showed that noon-time hmF1 (derived from routine electron density profile inversion) was consistently close to (or slightly less than) 150 km, lower than h_i reported earlier [*Zhang et al.*, 1996; *Lei et al.*, 2004] by ~ 30 km at solar minimum. In aggregate, these factors therefore raise concerns on whether PM17 derived values are reliable consistently for detecting weak long-term ionospheric temperature trends.

In fact, PM17's results already contain signatures of major problems with derived T_{ex} results. A comparison between PM17's T_{ex} and corresponding MSIS T_{ex} (Figure 2) indicates PM17's T_{ex} is persistently 100-200 K higher in medium to high solar activity years, and we note in particular that Figure 2 in PM17 deals with yearly means. A 100-200 K yearly bias is a very serious problem for trend and climatological studies, as MSIS monthly T_{ex} is usually very accurate and therefore the yearly PM17 to MSIS discrepancy should not be this large. For example, *Zhang et al.* [2015] indicates Millstone Hill incoherent scatter radar observed T_{ex} was typically different from MSIS model values by less than 10 K (or 1%) during daytime hours on a monthly (not yearly) median basis for October 2002 (with F10.7 between 155-185 sfu corresponding to medium to high solar activity). Arecibo ISR T_{ex} also agrees very well with the MSIS model, both in the seasonal averages and on a day-to-day basis [*Nicolls et al.*, 2006].

Using two sets of small samples, *Mikhailov and Perrone* [2016a] made comparisons between their derived neutral density and CHAMP data. The ~ 70 sample set came from the years 2003, 2006, 2007, and 2008; the later 3 years had very low solar activity where the deviations between the MSIS model and their derivations are small (Figure 2 in PM17). For 2003, the deviations are still modest. However, the representative case of more severe deviations as should occur at high solar activity (Figure 2 in PM17) were not considered in the study. Also, the sample set included high magnetic activity cases, and this raises additional concerns on the feasibility of their technique for high magnetic activity conditions. As described, the PM17 comparison for selected samples indicates that the mean relative deviations between neutral densities from CHAMP and their technique are still at least 10% for approximately 45 out of 70 (64%) samples (compared to 15% deviations between

the MSIS model and CHAMP). These large deviations make it unclear in general whether the PM17 results, even with a 10% uncertainty for 64% data points, are suitable for long-term trend studies. *Mikhailov and Perrone* [2016b] also presented T_{ex} comparisons (among other parameters) between the MSIS model and their technique (in their Figure 1). We have just discussed a persistent large result offset compared to climatology at >1100 K (or medium and high solar activity). Additionally, the statistics listed in PM17's Table 1 can be misleading because of the dramatic difference in the deviations across solar cycles. In particular, at solar medium and maximum, all the deviations are likely doubled or nearly so from the numbers listed in Table 1. Also, T_{ex} shift for Rome should be a positive number, not -54 as listed (see Figure 2 in PM17). There are very likely problems (or typos) for other numbers. Taken in aggregate, these comparative studies do not provide convincing evidence to support the use of these data for detecting weak long-term trends in the ionosphere and thermosphere.

In summary, the approach described in PM17 and earlier referenced papers by the same author team suffers complex non-linear and ambiguity problems, has an inappropriate constant height hmF1 problem, T_n profile concerns, and a not universally valid photochemical assumption, does not state fair observational verification of their approach, and gives problematic neutral T_{ex} results. We assert that this raises serious questions about any long-term trend derivations based on this type of foF1 analysis yielding T_{ex} , [O], [N2], [O2] and solar EUV flux results.

2 foF1 long-term trends

Regardless of the physical driver, thermospheric cooling reduces [O], [O₂] and [N₂] at fixed altitudes and therefore affects ionospheric photo-ionization and photo-absorption (optical depth). Heavier molecular gases [O₂] and [N₂] experience relatively larger changes, such that [O]/[M2] (where M2 is molecular gases) at fixed altitudes increases. Additional cooling effects include neutral temperature changes (e.g., apparent warming in the F1 and E regions at fixed altitudes) that affect chemical reaction rates and scale heights. At the transition height h_t ,

$$N_e = \beta / \alpha_{eff} = (k_1[N_2] / \alpha_1 + k_2[O_2] / \alpha_2)$$

and below h_t ,

$$N_e = \sqrt{q(O+) / \alpha_{eff}}$$

where $\alpha_{eff} = \beta / (k_1[N_2] / \alpha_1 + k_2[O_2] / \alpha_2)$ and $\beta = k_1[N_2] + k_2[O_2]$. Sophisticated model simulations suggest that long-term cooling leads to foF1 long-term increases [*Qian et al.*, 2008]. Observational analysis of F1-region long-term trends also show an increasing trend (*Bremer* [2008]; *Laštovička et al.* [2006]; *Zhang et al.* [2011]). However, PM17 shows a decreasing trend, in sharp contrast to these prior results. While it is no surprise that different observations can yield inconsistent and sometimes contradictory results, addressing and understanding the difference would have been an important task. For example, PM17 evaluated the trend of relative foF1 (ratio), or the residual foF1 (ratio) variation after solar cycle variations being removed. Geomagnetic activity influences, which may not correlate with the solar flux ones exactly in phase for different latitudes, are not involved in the trend analysis. Also do these trends in relative foF1 (ratio) mean the same as in absolute foF1 in *Bremer* [2008]? PM17 did not address these, and instead moved directly to using the derived T_{ex} , [O], [O₂], [N₂] and EUV flux to examine weak long-term trends in the ionosphere. *Perrone and Mikhailov* [2016]; *Mikhailov and Perrone* [2016a] ascribed the same foF1 decreasing trends to secular changes in geomagnetic activity. *Laštovička* [2017] has commented on the inconsistency of their foF1 trend analysis reported in *Mikhailov and Perrone* [2016a]. These F1-region trend controversies increase the uncertainty regarding the validity of trend study results in those derived parameters reported not only by PM17

but also by *Mikhailov and Perrone* [2016b, 2017], particularly with regard to whether the original foF1 data and/or the deriving method have led to any unrealistic trend determinations.

3 Incoherent scatter radar ionospheric long term trend data

The technique of incoherent scatter radar (ISR) relies on weak backscatter from thermal ionospheric electron density fluctuations, with the ion-acoustic resonance mode ("ion line") representing the primary diagnostic tool (see, e.g., *Evans* [1969]). For regular ISR ion line spectrum measurements, a primary F1 layer ion temperature and ion composition ambiguity is typical. This is because the ion-line spectrum is sensitive fundamentally to the T_i/m_i ratio, where m_i is the ion mass (we assume all ions have the same temperature for this discussion). In a purely $[O^+]$ ionosphere, $m_i = 16$ amu, and in a $[O^+]$ and $[NO^+]$ ionosphere, the ISR backscatter spectrum shows signatures of both $m_i = 16$ and $m_i = 30$ amu (although these signatures are not linearly additive due to the electrostatically coupled nature of the scattering process). Typically, model assumptions of ion composition percentage for O^+ relative to molecular ions (along with Poisson's law implying ion density = electron density) are used to fix m^+ at a particular altitude, allowing T_i to be determined. In general, the model composition approach introduces uncertainty in T_i reduction particularly for the F1-region and mildly for other regions, since any degree of uncertainty in relative ion composition maps through the ion-acoustic dispersion relation to a corresponding percentage of uncertainty in T_i . Therefore, depending on the specific scientific questions to be addressed and the altitude regime under consideration, a constant composition model may or may not have an impact on scientific conclusions using ISR plasma temperature measurements.

It is straightforward however to quantify this uncertainty. For Millstone Hill ISR F region measurements, a sensitivity study using standard incoherent scatter radar theory shows that increasing the molecular ratio $[M^+]/Ne$ from 0.0 to 0.01 (by 1%) increases the ion temperature by a factor of ~ 1.002 (0.2%). Increasing the molecular ratio from 0.0 to 0.1 (by 10%) increases the ion temperature by a factor of ~ 1.02 (by 2%). Finally, increasing the molecular ratio from 0.0 to 0.5 (by 50%) increases the ion temperature by a factor of ~ 1.2 (20%).

For the PM17 solar cycle scenario, the mean ion mass is $\sim 27 \pm 0.5$ amu corresponding to a molecular ion fraction $[M^+]/Ne \sim 0.8 \pm 0.03$. This 3% uncertainty for the PM17 F1 region (which, based on our previous discussions, appears to be significantly overestimated with excessive molecular ions) translates to a maximum 4 % T_i instrumentally induced uncertainty under a worst case scenario. However, as is well known, the true solar cycle geophysical variation in T_i ($\sim T_n$) at 175 km is $\sim 25\%$ at noon in summer at Millstone Hill (F107 $\sim 135 \pm 70$ sfu using an incoherent scatter radar ionospheric empirical model, ISRIM, see *Zhang et al.* [2005, 2007]). Therefore, the potential instrument uncertainty in ion temperature through an error in ion composition fraction remains much less than the geophysical signal.

Furthermore, for the F2-region, uncertainty in relative ion composition will be very small because $[M^+]$ there is under nearly all circumstances 1 to 2 orders of magnitude less than $[O^+]$. In particular, any potential long-term trends, solar cycle or seasonal changes on these minor species that give fractional $[M^+]$ changes would contribute only fractions of a few percentage changes in m^+ amu from the ISR standard composition model. Uncertainty in the ISR F2 region T_i analysis caused by these m^+ uncertainties would therefore cause only minor measurement error, as even a highly exaggerated 5% M^+ error translates using the previously mentioned sensitivity analysis to only a 1% T_i error in the F2 region. By contrast, true geophysically induced solar cycle changes in T_i are $\sim 40\%$ at 300 km and the summer-to-winter change in the noontime T_i is $\sim 10\%$ at 300 km and $\sim 5\%$ at 175 km, again much larger than any potential T_i measurement uncertainty induced by composition errors.

For ISR based long-term trend studies, if we assume that PM17 is correct and that a $< 0.2\%$ per decade trend in the F1-region m^+ exists, the constant composition model used by the ISR analysis would introduce only $< 0.08\%$ per decade additional instrumental uncertainty in the F1-region T_i , and an uncertainty much less than this for the F2 region because there [M+] are minor species being 1-2 orders of magnitude less than [O⁺]. However, the geophysical trend results in F1-region observations reported in *Zhang et al.* [2011, 2016] are $\sim +2\%$ per decade, and in the F2 region are $\sim -2\%$ per decade [*Zhang et al.*, 2011; *Zhang and Holt*, 2013; *Ogawa et al.*, 2014; *Zhang et al.*, 2016]. Once again, these trends are well beyond the constant composition model induced T_i uncertainty, and therefore the ISR technique's slight sensitivity to precise minor molecular ion percentage will not invalidate the ion temperature trend results.

The direction of the m^+ trend is also important. PM17 suggested a decreasing m^+ trend (because of decreasing foF1) in their analysis. However, as stated earlier, many ionospheric long term observations, including at Millstone Hill (Figure 10 in *Zhang et al.* [2011]), show an increasing trend in the F1-region electron density. Thus as *Zhang et al.* [2016] pointed out, "If m^+ does increase, the standard ion composition model underestimates m^+ , and therefore, the derived T_i underestimates the true T_i . This implies that the T_i observations would have shown an artificial long-term cooling. However, we see a dominant F1 layer warming. This suggests that the observed warming is not related to the F1 layer T_i ambiguity in the radar data but is rather a geophysical effect." In fact, the F1-region positive T_i was explained in terms of down-welling of the warm neutral atmosphere observed at a fixed altitude (rather than a constant pressure level) as a result of thermospheric cooling [*Akmaev et al.*, 2006; *Zhang et al.*, 2011, 2016]. Finally, it should be noted that *Oliver et al.* [2014]'s T_{ex} analysis based on Millstone Hill data has attempted to remove the small impacts described above which derive from using a fixed ion composition model.

4 Conclusions

For the detailed reasons stated above, we assert that PM17 analysis and conclusions on long term ionosphere/thermosphere temperature trends are flawed and quantitatively unlikely. The method is based on a technique with a number of obvious problems that are not addressed or not sufficiently justified. The PM17 extension of their F1-region study results to statements about the validity of ISR long-term T_i data in both F1 and F2 regions are furthermore highly questionable due to insufficient justification and verification and a significant misunderstanding of incoherent scatter radar physics. Published long-term trend analyses based on the datasets derived from the same method, as used in PM17, but not adequately justified raise similar questions. These conclusions are important for the geospace community in order to continue significant recent progress on quantification of ionospheric and thermospheric climatology and long term trends.

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