

Authors' response to comments on discussion paper acp-2015-326

Journal: ACP

Title: Neutral atmosphere temperature change at 90 km, 70°N, 19°E, 2003-2014

Author(s): S. E. Holmen et al.

MS No.: acp-2015-326

MS Type: Research Article

General response:

All feedback we got on this manuscript is highly appreciated, and we think that it has helped improve the manuscript a lot. Some of the comments from the reviewers we consider out of scope for this paper, and we hope that they acknowledge that, but in general we have tried to address most of the comments. In the updated version of the manuscript we have redone nearly all analyses and most of the figures, using Aura MLS temperature data at 90 km geometric altitude instead of at 0.001 hPa.

Response to comments from Referee #1:

Page 15291, lines 1-11:

Referee's comment: Another important aspect in this context is the shrinking of the atmosphere associated with a general cooling of the middle atmosphere. For this reason it makes a big differences, whether temperature trends are studied at constant pressure or at constant geometric altitude. Perhaps this can be mentioned briefly. This point was also discussed in detail in recent papers by Luebken, Berger et al.

Author's response/changes in manuscript: We have, in the updated version of the manuscript, done all analyses again using Aura MLS temperatures at 90 km geometric altitude instead of at 0.001 hPa. The Lübken et al. (2013) paper discusses the aspect of the shrinking atmosphere, and we have added a paragraph about this in page 15294, line 2 (updated version: page 5, line 1): "Because of a general cooling of most of the stratosphere and mesosphere the last decades due to e.g. increasing concentrations of CO₂ and O₃, the atmosphere has been shrinking, leading to a lowering of pressure surfaces at various altitudes. It is important to distinguish between trends on fixed pressure altitudes and fixed geometric altitudes, since trends on geometric altitudes include the effect of a shrinking atmosphere (Lübken et al., 2013). In this study, we have obtained Aura MLS temperature data (version 3.3) for latitude 69.7°N ± 5.0° and longitude 19.0°E ± 10.0° at 90 km geometric altitude."

Page 15293, lines 5-8:

Referee's comment: It is mentioned later in the paper, but I suggest mentioning here, that these density climatologies do not take potential long-term of solar cycle variations into account.

Author's response/changes in manuscript: Added text: "These densities do not take into account long-term solar cycle variations."

Page 15294, line 2:

Referee's comment: 'Version 03' This is not an official version number. It's probably vs. 3.4 or 3.4? The current version is 4.2, I think.

Author's response/changes in manuscript: This was a slip-up. The data used is from version 3.3. Changed 'version 03' → 'version 3.3'.

Page 15294, line 3:

Referee's comment: 'at pressure 0.001 hPa, corresponding to ~ 90 km.' I think you should use the temperatures at 90 km geometric altitude, and not at a fixed pressure level. The Aura files also contain geopotential height for each profile, which can easily be converted to geometric height.

Author's response/changes in manuscript: All analyses have now been conducted again using Aura MLS temperatures at 90 km geometric altitude instead of at pressure 0.001 hPa. Figures and trends have been updated. Changes in text: "...and longitude 19.0° E ± 10.0° at 90 km geometric altitude."

Page 15294, lines 12 – 15:

Referee's comment: 'This was done by super . . . during auroral particle precipitation' The first sentence deals with the issue of diurnal variations, the second sentence with an entirely different issue. The diurnal variations are taken up again a few sentences below, i.e. its discussion is interrupted by the issue of modified electron mobility. I suggested arranging the paragraphs in a different way to avoid this 'interruption'.

Author's response/changes in manuscript: We agree that the way we have written this may lead to confusion, and have therefore made this change to the text: "There is an ongoing investigation into the possibility that D_a derived by NTMR can be affected by modified electron mobility during auroral particle precipitation. According to Rees et al. (1972), neutral temperatures in the auroral zone show a positive correlation with geomagnetic activity. It is therefore a possibility that apparent D_a enhancements during strong auroral events do not necessarily depict neutral temperature increase."

Page 15297, line 23:

Referee's comment: 'The long-term linear temperature trend using monthly means is – 3.6 K +/- 1.1 K / decade' Please mention briefly what the uncertainty estimate is based on. Is it based on the propagated uncertainties of the monthly means or on the quality of the linear fit without considering the uncertainties of the monthly means. These values may be different. And if the uncertainties of the monthly means were propagated, what was used as an uncertainty estimate: The standard deviation or the standard error of the mean?

Author's response/changes in manuscript: The uncertainty is based on the quality of the linear fit (standard error). This has now been specified in the text.

Page 15301, line 23:

Referee's comment: 'the peak altitude of the OH airglow layer can range from 75 to > 90 km (Winick et al., 2009)' It's of course correct that the OH emission altitude is quite variable, particularly at high latitudes and during/after sudden stratospheric warmings. However, von Savigny (JASTP, 127, 120 –

128, 2015) has shown recently that the OH emission layer height is remarkably constant from 2003 to 2011, also at high latitudes (Table 3 in that paper).

Author's response/changes in manuscript: Changed to: "It must be noted that the peak altitude of the OH* airglow layer vary and thus affect the comparability of OH* airglow temperature trends and meteor radar temperature trends. Winick et al. 2009 report that the OH* airglow layer can range from 75 to > 90 km, while the newer study by von Savigny, 2015, indicates that the layer height at high latitudes is remarkably constant from 2003 to 2011." von Savigny's paper is added to the reference list.

Page 15302, lines 1 – 5:

Referee's comment: the pressure change issue: I think one could use the MLS data to investigate possible changes in pressure surface altitudes. The MLS temperature profiles come on a pressure grid, but the data also include geopotential height, which can be easily converted to geometric height. It should be fairly straightforward to determine changes in pressure surface altitudes from 2005 to 2014.

Author's response/changes in manuscript: All analyses have now been conducted again using Aura MLS temperatures at 90 km geometric altitude instead of at pressure 0.001 hPa.

Page 15302, line 8:

Referee's comment: 'and increased GW drag leads to cooling.' This is only true for the polar summer mesopause region, isn't it? Above the winter pole I would expect increased adiabatic heating.

Author's response/changes in manuscript: Thank you for pointing this out. This section (page 15302, lines 6-15) is referring to gravity waves and their effect on temperature trends in the mesosphere and thermosphere and not the mesopause alone. We have made this change to the manuscript: "It has been proposed that GWs may be a major cause of negative temperature trends in the mesosphere and thermosphere (Beig, 2011; Oliver et al., 2013). GWs effectively transport chemical species and heat in the region, and increased GW drag leads to a net effect of cooling above the turbopause (Yigit and Medvedev, 2009). GWs are shown to heat the atmosphere below about 110 km altitude, while they cool the atmosphere at higher altitudes by inducing a downward heat flux (Walterscheid, 1981). However, there are large regional differences regarding trends in GW activity. Hoffmann et al. (2011) ...". Two references are added to the reference list.

Response to comments from Referee #2:

1. *Referee's comment:* The altitude of your analysis (90 km) is near the upper limit of MLS temperature data, and the uncertainties are large there. There are several other satellite instruments that provide intermittent but extensive measurements of temperature at 90 km over the period of the observations (AIM/SOFIE, ACE-FTS, TIMED/SABER, Envisat/MIPAS). Given all the uncertainties in your temperature retrieval, it would be appropriate to take advantage of these data to improve the confidence in the results.

Author's response/changes in manuscript: We acknowledge that we could have used another dataset than Aura MLS to calibrate the NTMR temperatures. One argument for using MLS compared with e.g. SABER or SOFIE data is the temporal coverage. SABER does not yield daily temperature values over the relevant time period. We did consider incorporating SOFIE data into our analysis, but in order to get sufficient temporal coverage we would have to expand the area of interest (latitude, longitude) to such a high extent that we considered the temperatures not so representative for Tromsø anymore. Incorporating temperatures from other satellite instruments at this point would result in a major re-analysis. We are receptive towards incorporating temperatures from other instruments, but have refrained from this in the present submission.

2. *Referee's comment:* The technique for comparisons with MLS is not optimal. Rather than using monthly means to derive correction factors, I suggest that you start with observations that you can compare directly. This would mean first comparing the radar data at times of the MLS overpasses for comparison directly with the MLS temperatures. Finding individual coincident profiles would be the best but even using monthly means of similar variables (e.g. from a similar local time) is better than the comparison shown in Figure 1. The process described in the paper wraps several "corrections" (local time, bias) together is a way that comes across as arbitrary. It would be useful to the reader to see a separation of the local time correction and the bias correction.

Author's response/changes in manuscript: We have not used monthly means to derive correction factors, but daily values. (The old) Figure 1 shows the two datasets before any corrections are applied, which we thought would be useful to the reader. It is correct that Figure 1 contains daily means of first estimate NTMR temperatures, while the daily means of Aura MLS temperatures are from 01-03 UTC and 10-12 UTC. We could, as you propose, have used NTMR temperatures only from 01-03 UTC and 10-12 UTC, but since this paper is principally about the temperature change in NTMR temperatures (and not Aura MLS) we thought it would be most fruitful to use NTMR temperatures from 00-24 UTC as daily means. We agree that it would be useful to show how the local time correction and the cold bias correction affect the results separately, but we have refrained from doing this in the present submission.

3. *Referee's comment:* As a related comment, I was uneasy that you applied all the corrections to MLS, which is an extensively investigated and widely used dataset, rather than to your own retrieved temperatures. Did you look at MLS temperature validation papers for further guidance?

Author's response/changes in manuscript: The focus of this paper is not to correct Aura MLS temperatures, but to correct the NTMR temperatures relative to Aura MLS. The "only" corrections we have done to the Aura MLS dataset are the cold bias correction and the local-time correction. According to other papers (French and Mulligan, 2010; Garcia-Comas et al., 2014) Aura MLS exhibit a colder mesopause compared with other instruments. Regarding the local-time correction, the purpose was not to "correct" the MLS temperatures in itself, but since the diurnal variation shows that temperatures are in general lower in the forenoon (Fig.

2), which corresponds to when Aura MLS makes measurements over Tromsø, we thought it would be a good idea to compensate for this.

4. *Referee's comment:* Another advantage of using coincidences to compare with MLS would be the option to compare your pressure with the pressure from the MLS dataset. This would provide additional much-needed validation.

Author's response/changes in manuscript: To compare pressure values with Aura MLS pressure would result in a validation of the falling sphere measurements done by Lübken and von Zahn (1991) and Lübken (1999). We feel that this falls outside the scope of this paper. However, it would be very interesting to do this and it would be worth a separate study.

5. *Referee's comment:* The period of your data coverage presents difficult challenges for diagnosing trends and solar cycle. The period covers substantially less than one full solar cycle. Moreover, the net trend in the F10.7 radio flux over these 11 years is not negligible (for example see <http://www.swpc.noaa.gov/products/solar-cycle-progression>). It is premature to apply trend and solar cycle analysis to these or any observations for this time period.

Author's response/changes in manuscript: The data covers one solar cycle, and we agree that diagnosing trends over this time period presents challenges. We have used the term "change" instead of "trend" in the title of the paper, but we agree that we could have expressed ourselves differently throughout the paper to avoid misrepresentation. Therefore, we have made several corrections to the text regarding this.

6. *Referee's comment:* The discussion indicates that the trends are quite different for different seasons of the year. With this being the case, deseasonalizing the data and then calculating the trend using all months of the year will give a result that is very difficult to interpret.

Author's response/changes in manuscript: This is true. We have added an extra paragraph in the discussion to emphasize this. Page 13, line 13 (in updated version): "Our results indicate a cooling at 90 km altitude over Tromsø between 2003 and 2014 when deseasonalizing our dataset and calculating trend using all months of the year. At the same time we get quite different trends for winter and summer. We emphasize that this may give a result that may be somewhat difficult to interpret."

7. *Referee's comment:* Section 5.2 mentions that gravity wave activity could affect the temperature trend. Since you have radar wind data, this would be an important addition to the study. You could, at a minimum, determine whether there is a relationship between the interannual variability of gravity waves, mean winds, and temperature.

Author's response/changes in manuscript: Our main goal with this paper is to identify a temperature change over the 11 year time period from 2003 to 2014. We are suggesting hypothetical reasons for the change we see. It would be very interesting to do an analysis on the relationship between winds, temperatures and GW fluxes, but we consider this to be outside the scope of this study and something that would be worth a separate study. We have made an addition to the text in the discussion to emphasize this. Page 12, line 30: "It is

not the purpose of this study to analyse the contribution of dynamics to the temperature change we observe”.

Referee's comment: Editorial: There is an abrupt transition between the first and second paragraphs of Section 3 that is hard to follow.

Author's response/changes in manuscript: We agree that the way we have written this is confusing, and have therefore made this change to the text: “There is an ongoing investigation into the possibility that D_a derived by NTMR can be affected by modified electron mobility during auroral particle precipitation. According to Rees et al. (1972), neutral temperatures in the auroral zone show a positive correlation with geomagnetic activity. It is therefore a possibility that apparent D_a enhancements during strong auroral events do not necessarily depict neutral temperature increase.”

Response to comments from Referee #3:

Page 2., l. 18.

Referee's comment: I suggest to add reference(s) to this assertion.

Author's response/changes in manuscript: References added. The text is also slightly changed, since different model studies predict different results. Page 15291, lines 6-8 (page 2, line 16-20 in updated version): “Newer and more sophisticated models include important radiative and dynamical processes as well as interactive chemistries. Some model results indicate a cooling rate near the mesopause less than predicted by Akmaev and Fomichev (1998), while others maintain the negative signal (French and Klekociuk, 2011; Beig, 2011).”

Page 3, l. 19.

Referee's comment: It is not clear here if the radius of 50 km refers to horizontal space or to volume. I believe it refers to horizontal space. However, it is important to know at which altitudes the meteors (or better the echoes of them) take place. Also, I miss a figure showing the vertical distribution of them. It is mention that most of them occurs at 90 km with a height resolution and range resolution of 1 km. It would be useful to show the reader the actual vertical occurrence of the meteors. I point this out because the temperature trends tend to change significantly with altitude in this region, so it would be good to show it.

Author's response/changes in manuscript: 50 km refers to horizontal space. This has now been specified in the text. Also, we have added a figure showing the vertical distribution of meteor echoes from 2003 to 2014. (This is Figure 1 in the updated manuscript.)

Top of page 4 and further in the discussion:

Referee's comment: The effect of temperature. Both MLS and SABER measures the pressure. I think it would be very useful to repeat the study but with the "simultaneous" pressure measured by the satellite instruments.

Author's response/changes in manuscript: We feel that comparing pressure values falls outside the scope of this paper. However, it would be very interesting to do this and would be worth a separate study.

Page 4, lines 14 and ff.

Referee's comment: Is there a particular reason of why to change the "calibration" of radar temperatures from the OH rot. temperatures to MLS? MLS data have a very broad vertical resolution at this altitude, probably wider than the OH layer thickness.

Author's response/changes in manuscript: There are unfortunately no OH airglow temperatures available from Tromsø for the time period of interest. The nearest location for measuring OH temperatures is Andøya.

Page 5.

Referee's comment: Da rejection. Possible correlation of Da with geomagnetic activity. Have the authors looked at the correlation of Da with a geomagnetic index, Ap or Kp? That would be very useful. Not clear which Da values were rejected: "all half hourly Da values with a standard error larger than 7% of the estimated Da value were excluded from further analysis." Does this mean that Da outside +/-7% (plus and minus) were rejected? I would tend to reject only those with high values, but not the low values.

Author's response/changes in manuscript: We agree that looking at the correlation between Da and geomagnetic indices would be very useful and interesting. We have not calculated any correlation. However, we believe there is a clear relation between D enhancement and geomagnetic activity. Regarding the excluded values of Da: We rejected all individual D values (half hourly) whose estimation error was significantly large (standard error > 7 %). We calculated the standard errors, se, relative to the half hourly Da values, and the rejection procedure was as follows: if $se_t > Da_t * 0.07$ → reject Da_t .

Page 6, lines 8-11.

Referee's comment: The MLS bias of 10 K at 90 km does not seem to occur at all seasons. Garcia-Comas et al., 2014 have carried out a comprehensive validation/comparison of several satellite instruments and showed that although for polar summer/winter conditions the positive bias is large (close to 10 K) (Figs. 8 and 9, top left panels), for spring/fall conditions the bias is not so large, about 5 K (Figs. 6 and 7 top left panels).

Author's response/changes in manuscript: The calibration of the NTMR temperatures has been conducted again, using 5 K cold bias correction on the autumn and spring temperatures and 10 K correction on winter and summer temperatures. Changes in text: "Also, the Aura temperatures were corrected for "cold bias". French and Mulligan (2010) reported that Aura MLS temperatures exhibit a 10 K cold bias compared with OH*(6-2) nightly temperatures at Davis Station, Antarctica. A newer study by Garcia-Comas et al. (2014) shows that Aura MLS exhibits a bias compared with several satellite instruments which varies with season. According to their findings, a 10 K correction for cold bias was applied to the Aura summer and winter temperatures (Jun – Aug, Dec – Feb), while a 5 K correction was applied to autumn and spring temperatures (Sep – Nov, Mar - May)."

The updated Figure 4 (which is Figure 5 in the updated manuscript) shows now that a linear fit gives a just as good overall fit to the scatterplot of corrected Aura MLS temperatures and uncorrected NTMR temperatures compared to a quadratic, least-squares fit. Therefore, Equation 4 and the belonging text is changed: "Figure 5 shows a scatterplot of the corrected Aura temperatures against the "raw" NTMR temperatures. The red line represents the linear fit ($R^2 = 0.83$) and is described by: $T_{\text{NTMR}} = 0.84T_{\text{Aura}} + 32 \dots$ " The figure caption under Fig. 4 is changed correspondingly.

Page 6. Lines 20-21.

Referee's comment: "For calibration of the remaining NTMR temperatures ..." Could the authors clarify what are the "remaining NTMR temperatures"?

Author's response/changes in manuscript: The remaining NTMR temperatures are the NTMR temperatures for days of measurements not coinciding with Aura measurements. To clarify, we have made the following change to the sentence: "For calibration of NTMR temperatures from November 2003 to August 2004 (before the start of the Aura MLS dataset), the same equation (Eq. 4) was used, using NTMR Da-rejected temperatures from November 2003 to August 2004 as input instead of T_{Aura} ".

Page 6. Lines 23-24.

Referee's comment: Here and at other places it is not always clear when the meaning of the terms "corrected" and "raw". For example, in these lines, do the authors mean: "To estimate the calibration uncertainty, all LOCAL TIME-corrected Aura temperatures were subtracted from the MLS-CALIBRATED NTMR temperatures, and the differences were plotted in a histogram with 5 K bins."? Since there are several corrections: Darejected, local time correction and the "MLS-calibrated", I suggest to add an adjective about the correction when referring to the different corrected temperatures.

Author's response/changes in manuscript: We agree that the terminology can be confusing at times. To make it clearer, we have made several changes throughout the manuscript.

Page 5, line 9 (updated version): "Figure 2 shows daily NTMR temperatures.." Removed term "raw", since it should be obvious from the rest of the sentence what kind of temperatures we are talking about.

Page 6, line 1: Added sentence: "NTMR temperatures after application of the Da rejection procedure will henceforward be referred to as D_a -rejected NTMR temperatures".

Page 5, line 3: "Figure 3 shows monthly averages of the superposed values of D_a -rejected NTMR temperatures as a function.."

Page 6, line 22: Added sentence: "The corrected Aura temperatures will henceforward be referred to as local time and cold bias-corrected Aura MLS temperatures."

Page 6, line 25: "Figure 5 shows a scatterplot of the local time and cold bias-corrected Aura temperatures against the D_a -rejected NTMR temperatures."

Page 6, line 31: "NTMR temperatures were now corrected for the days of measurements coinciding with Aura measurements and are henceforward referred to as MLS-calibrated NTMR temperatures."

Page 7, line 6: "To estimate the calibration uncertainty, all local time and cold bias-corrected Aura temperatures were subtracted from MLS-calibrated NTMR temperatures, and the.."

Page 7, line 11: "Finally, Fig. 7 shows the MLS-calibrated NTMR temperatures with uncertainties plotted together with Aura MLS temperatures, corrected for cold and time-of-day measurement bias."

Page 7, line 15, line 18: "calibrated" → "MLS-calibrated"

Line 25.

Referee's comment: The uncertainty of the calibration is 8.9 K. This is large! How has this been taken into account when estimating the error in the trend? Assumed negligible because it is assumed to be constant in time?

Author's response/changes in manuscript: We have not taken the uncertainty of the calibration into account when estimating the error in the trend. As the referee mentions, the uncertainty is assumed to be constant in time. We are aware of that this uncertainty is high, but we are presenting it here as a caveat to the reader.

Line 29.

Referee's comment: I believe what you applied here is a "local time" correction (not tidal). It should be in general dominated by tidal (btw which is the tidal amplitude at 70N?) the correction was done in local time.

Author's response/changes in manuscript: We have replaced "tidal" with "local time", both in the text and in Fig. 6 (Fig. 7 in updated manuscript) (legend).

Page 7, line 17.

Referee's comment: The solar response coefficient obtained here is somehow smaller than the values obtained by Forbes et al. from SABER data of 5.9 K/sfu. at 80-90 km, 50-70N, and close to 10 K/sfu for 90-100 km at 50N-80N.

Author's response/changes in manuscript: In the updated version of the manuscript the solar response coefficient is $4.5 \text{ K} \pm 0.3 \text{ K}/100 \text{ SFU}$. It is true that our estimated solar response coefficient is smaller than what found by Forbes et al. (2014), but it is in line with results from other studies (Beig, 2011). Also, Forbes et al. write in the "Results in context of previous works" section that their values in general are larger compared with values obtained by others. We have included a short paragraph in the discussion regarding the solar response value. Page 12, line 6: "The estimated solar response coefficient of $4.5 \text{ K} \pm 0.3 \text{ K}/100 \text{ SFU}$ is somewhat smaller than values obtained by Forbes et al. (2014) using SABER data from 2002 through 2013. For latitudes 50°N - 80°N and altitudes 90-100 km solar response coefficients obtained by Forbes et al. are close to 10 K/100 SFU. However, Beig (2011) summarizes results from numerous studies on temperature variability due to solar activity and

reports that in general, temperature response is 4-5 K/100 SFU in the upper part of the mesopause. Our result is in line with this.”

Page 7, lines 22-23.

Referee’s comment: Could the authors mention the altitude range at which Ogawa et al. look at?

Author’s response/changes in manuscript: The altitude range they look at is 200-450 km. We have now pointed this out in the text.

Page 7, line 26

Referee’s comment: philosophy -> rationale? Also here, I am not sure about using the quadratic form. Figure 8 shows that at SFU larger than 180 units the quadratic fit is not really good. If applied the linear fit, would that change the trend?

Author’s response/changes in manuscript: If we apply the linear fit, the trend using monthly values would be $-4.7 \text{ K} \pm 1.4 \text{ K/decade}$. We have included also these numbers on page 8, line 26.

Page 7 bottom and ff. lines.

Referee’s comment: Since the AURA correction was done on the basis of monthly mean, I would then do the solar fit also using monthly mean values. Probably the results would be very similar but it seems to me more consistent.

Author’s response/changes in manuscript: The Aura MLS correction was not done on the basis of monthly means, but daily means.

Sec. 5.1 Page 9, bottom and first lines on page 10.

Referee’s comment: After this discussion, where those effects "... may lead to errors of several kilometres ..." do the authors still think that the errors in the altitude where they are looking at temperature trends is still 1 km, as asserted in page 3? It would be good to include a "realistic" error in this altitude and be included in the conclusion (remember the broad vertical resolution of MLS temperature around 90 km).

Author’s response/changes in manuscript: In Section 5.1. we discuss the suitability of a meteor radar for estimation of temperatures at 90 km height. Using our method, adopted from Holdsworth et al. (2006), we assume that ambipolar diffusion alone determines the decay of underdense echoes. According to Hall et al. (2005) this is only the case between ~85 km and ~95 km. Above ~95 km anomalous fading times of the echoes can be attributed to Farley-Buneman instability, which can lead to errors in the temperature estimation (e.g. Dyrud et al., 2001). We only use echoes around 90 km height, and therefore do not have to be concerned about the “errors of several kilometres” due to Farley-Buneman instability. Since we are looking at 90 km height, we believe that the height resolution and the range resolution are both 1 km. To make this clearer, we have made a small change to the instrument section.

Page 3, line 27: “The height resolution and the range resolution are both 1 km, when looking at altitudes around the peak occurrence height.”

Page 10. lines 20 and ff.

Referee's comment: See point before. Why not use pressure from MLS? Or use p-T from SABER?

Author's response/changes in manuscript: We feel that comparing pressure values falls outside the scope of this paper. We could have used pressure from Aura MLS, but we chose to use pressure from Lübken and von Zahn (1991) and Lübken (1999) when calculating the NTMR temperatures, for consistency with Dyrland et al. (2010).

Sec. 5.2

Referee's comment: Do the authors have any explanation of why the trend derived from OH at near 87 km differs so much (it is nearly zero vs. -3.6K/dec) from the results of this work?

Author's response/changes in manuscript: The two trends differ, that is true. The OH* airglow temperature trend is from Longyearbyen, Svalbard, ~8° further north. Also, the OH* temperature series is much longer, dating back to 1983. Another difference is that the meteor radar temperatures are recorded all year round, while the OH* temperatures are only recorded during winter.

Lines 16-17.

Referee's comment: I think the result of Winick et al. is overstated here. The changes in the OH layer from 75 to > 90 km actually only occurs when there are extreme stratospheric warmings, such as that of 2009, occurring, as most, during only a few weeks. In general it is very stable (except for the tidal effects). There are several studies showing this. I think this is not a convincent argument for explaining the discrepancy.

Author's response/changes in manuscript: We have added another reference in addition to Winick et al. (2009) and changed the text: "It must be noted that the peak altitude of the OH* airglow layer can vary and thus affect the comparability of OH* airglow temperature trends and meteor radar temperature trends. Winick et al., 2009 report that the OH* airglow layer can range from 75 to >90 km, while the newer study by von Savigny, 2015, indicates that the layer height at high latitudes is remarkably constant from 2003 to 2011. "

Page 11, line 30.

Referee's comment: I understand that GW could lead to cooling but also to heating (breaking of GWs should deposit their kinetic energy). Could the authors give a reference to the assertion about the cooling?

Author's response/changes in manuscript: We have made this change to the manuscript: "It has been proposed that GWs may be a major cause of negative temperature trends in the mesosphere and thermosphere (Beig, 2011; Oliver et al., 2013). GWs effectively transport chemical species and heat in the region, and increased GW drag leads to a net effect of cooling above the turbopause (Yigit and Medvedev, 2009). GWs are shown to heat the atmosphere below about 110 km altitude, while they cool the atmosphere at higher altitudes by inducing a downward heat flux (Walterscheid, 1981). However, there are large regional differences regarding trends in GW activity. Hoffmann et al. (2011) ...". Two references are added to the reference list.

Fig.1

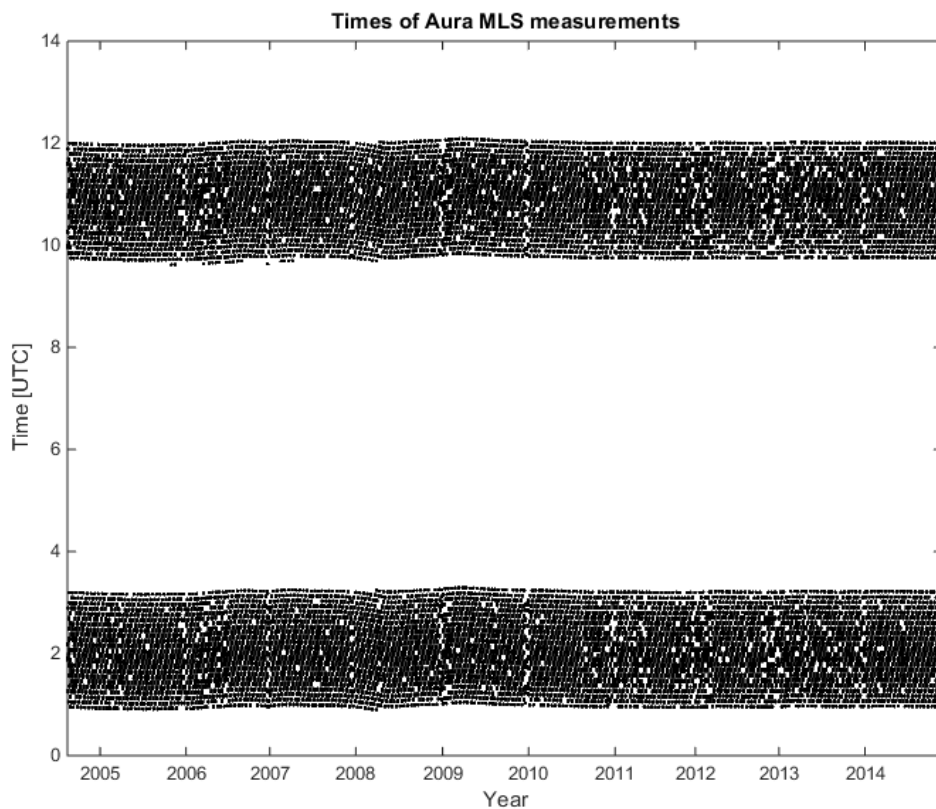
Referee's comment: Are daily, monthly values? Does Aura (uncorrected) mean "not local-time corrected", e.g, as measured by AURA? Are the "raw" NTMR already corrected for high D_a ?

Author's response/changes in manuscript: We realize that the figure caption lacks some vital information and have made these changes: "Daily values of NTMR temperatures derived from Eqs. (1) and (2), before correction for high D_a , plotted together with Aura MLS temperatures, before applying any corrections."

Fig. 2.

Referee's comment: Are the NTMR T corrected for high D_a here? One question about the variability of the local time of MLS measurements with years: are the local times fixed in the 10 years period? In other words, are the different local times in Fig. 2 (highlighted) for each of the two mean times spread more or less evenly over each year or do they have any trend with year?

Author's response/changes in manuscript: Yes, the NTMR temperatures are corrected for high D_a in this figure. We have made changes to the text and the figure caption. Regarding the local times of Aura MLS measurements, we have plotted the times (all individual data points, approximately 17 data points per day) in a figure:



The figure is not a part of the manuscript. It is only to show the reviewer that we consider the local times fairly fixed during the 10-year period.

Fig. 4.

Referee's comment: Are the NTMR "raw" temperatures corrected for Da high values? If yes (as I guess), why then call them "raw"? Do you mean "uncalibrated"?

Author's response/changes in manuscript: Figure caption changed to: "Scatterplot of Aura temperatures corrected for cold and time-of-day bias against NTMR Da-rejected temperatures. The red line.." Label on y axis changed to "NTMR derived 90 km temperature, uncalibrated".

Fig. 5.

Referee's comment: and ... LOCAL-TIME-corrected Aura MLS temperatures?

Author's response/changes in manuscript: Figure caption changed to: "Histogram of the differences between MLS-calibrated NTMR temperatures and local time and cold bias-corrected Aura MLS temperatures. The red curve..."

Fig. 6

Referee's comment: Daily? Monthly?

Author's response/changes in manuscript: Daily values. Figure caption changed to: "Daily values of MLS-calibrated NTMR temperatures plotted together with Aura MLS temperatures corrected for cold and time-of-day bias. The overall..."

Fig. 7.

Referee's comment: I think this figure is not necessary. The seasonal cycle is quite well know.

Author's response/changes in manuscript: We have now skipped this figure and made a small change to the text (page 7, line 3): "The seasonal variation is not shown here but reveals a summer minimum of around 150-160 K and ..."



Neutral atmosphere
temperature change
at 90 km, 70° N, 19° E,
2003–2014

S. E. Holmen et al.

This discussion paper is/has been under review for the journal Atmospheric Chemistry and Physics (ACP). Please refer to the corresponding final paper in ACP if available.

Neutral atmosphere temperature change at 90 km, 70° N, 19° E, 2003–2014

S. E. Holmen^{1,2,3}, C. M. Hall², and M. Tsutsumi^{4,5}

¹The University Centre in Svalbard, Longyearbyen, Norway

²Tromsø Geophysical Observatory, UiT – The Arctic University of Norway, Tromsø, Norway

³Birkeland Centre for Space Science, Bergen, Norway

⁴National Institute of Polar Research, Tokyo, Japan

⁵The Graduate University for Advanced Studies (SOKENDAI), Department of Polar Science, Hayama, Japan

Received: 28 April 2015 – Accepted: 12 May 2015 – Published: 5 June 2015

Correspondence to: S. E. Holmen (siljeh@unis.no)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

Neutral temperatures for 90 km height above Tromsø, Norway, have been determined using ambipolar diffusion coefficients calculated from meteor echo fading times using the Nippon/Norway Tromsø Meteor Radar (NTMR). Daily temperature averages have been calculated from November 2003 to October 2014 and calibrated against temperature measurements from the Microwave Limb Sounder (MLS) on board Aura. The long-term trend of temperatures from the NTMR radar is investigated, and winter and summer seasons are looked at separately. Seasonal variation has been accounted for, as well as solar response, using the F10.7 cm flux as a proxy for solar activity. The long-term temperature trend from 2003 to 2014 is $-3.2 \pm 1.1 \text{ K decade}^{-1}$, with summer and winter trends $-0.8 \pm 2.9 \text{ K decade}^{-1}$ and $-8.1 \pm 2.5 \text{ K decade}^{-1}$, respectively. How well suited a meteor radar is for estimating neutral temperatures at 90 km using meteor trail echoes is discussed, and physical explanations behind a cooling trend are proposed.

1 Introduction

Temperature changes in the mesosphere and lower thermosphere (MLT) region due to both natural and anthropogenic variations cannot be assessed without understanding the dynamical, radiative and chemical couplings between the different atmospheric layers. Processes responsible for heating and cooling in the MLT region are many. Absorption of UV by O_3 and O_2 causes heating, while CO_2 causes strong radiative cooling. Planetary waves (PWs) and gravity waves (GWs) break and deposit heat and momentum into the middle atmosphere and influence the mesospheric residual circulation, which is the summer-to-winter circulation in the mesosphere. Also, heat is transported through advection and adiabatic processes.

For decades, it has been generally accepted that increased anthropogenic emissions of greenhouse gases are responsible for warming of the lower atmosphere (e.g.

ACPD

15, 15289–15317, 2015

Neutral atmosphere
temperature change
at 90 km, 70° N, 19° E,
2003–2014

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Neutral atmosphere
temperature change
at 90 km, 70° N, 19° E,
2003–2014**

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Manabe and Wetherald, 1975), and that these emissions are causing the mesosphere and thermosphere to cool (Akmaev and Fomichev, 2000; Roble and Dickinson, 1989). Akmaev and Fomichev (1998) reported, using a middle atmospheric model, that if CO₂ concentrations are doubled, temperatures will decrease by about 14 K at the stratopause, by about 10 K in the upper mesosphere and by 40–50 K in the thermosphere. ~~Newer and more sophisticated models include important radiative and dynamical processes as well as interactive chemistries, and they predict that the cooling rate near the mesopause is less than previously expected.~~ The thermal response in this region is strongly influenced by changes in dynamics, and some dynamical processes contribute to a warming which counteracts the cooling expected from greenhouse gas emissions (Schmidt et al., 2006).

Even though the increasing concentration of greenhouse gases is generally accepted to be the main driver, also other drivers of long-term changes and temperature trends exist, namely stratospheric ozone depletion, long-term changes of solar and geomagnetic activity, secular changes of the Earth's magnetic field, long-term changes of atmospheric circulation and mesospheric water vapour concentration (Laštovička et al., 2012). The complexity of temperature trends in the MLT region and their causes act as motivation for studying these matters further.

In this paper, we investigate long-term trends of temperatures obtained from the NTMR radar, and we also look at summer and winter seasons separately. In Sect. 2, specifications of the NTMR radar are given, and the theory behind the retrieval of temperatures using ambipolar diffusion coefficients from meteor trail echoes is explained. In Sect. 3, the method behind the calibration of NTMR temperatures against Aura MLS temperatures is explained. Section 4 treats the temperature trend analysis, including the correction for seasonal variation and solar response. The theory and underlying assumptions for the method of determining neutral temperatures from meteor trail echoes and thus how well suited a meteor radar is for estimating such temperatures is discussed in Sect. 5. Also, physical explanations behind the trend are discussed, as well as comparison with other reports on trends.

2 Instrumentation and data

The Nippon/Tromsø Meteor Radar (NTMR) is located at Ramfjordmoen near Tromsø, at 69.58° N, 19.22° E. It is operated 24 h a day, all year round. Measurements are available for more than 90 % of all days since the radar was first operative in November 2003. The meteor radar consists of one transmitter antenna and five receivers and is operating at 30.25 MHz. It detects echoes from ionized trails from meteors, which appear when meteors enter and interact with the Earth's neutral atmosphere in the MLT region. The ionized atoms from the meteors are thermalized, and the resulting trails expand in the radial direction mainly due to ambipolar diffusion, which is diffusion in plasma due to interaction with the electric field. Underdense meteors, which are the ones used in this study, have a plasma frequency that is lower than the frequency of the radar, which makes it possible for the radio wave from the radar to penetrate into the meteor trail and be scattered by each electron.

Echoes are detected from a region with a radius of approximately 50 km. The radar typically detects around 10 000 echoes day⁻¹, of which around 200–600 echoes are detected per hour at the peak occurrence height of 90 km. The number of echoes detected per day allows for a 30 min resolution of temperature values. The intra-day periodicity in meteor detections by the NTMR radar is less pronounced than that of lower latitude stations and we do not anticipate tidally-induced bias regarding echo rates at specific tidal phases for daily averages. The height resolution and the range resolution are both 1 km. From the decay time of the radar signal we can derive ambipolar diffusion coefficients, D_a :

$$D_a = \frac{\lambda^2}{16\pi^2\tau} \quad (1)$$

where λ is the radar wavelength and τ is the radar echo decay time. It has been shown that this coefficient also can be expressed in terms of atmospheric temperature and

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc


Printer-friendly Version

Interactive Discussion



pressure:

$$D_a = 6.39 \times 10^{-2} K_0 \frac{T^2}{p} \quad (2)$$

where p is pressure, T is temperature, and K_0 is the zero-field reduced mobility factor of the ions in the trail. In this study we use the value for K_0 of $2.4 \times 10^{-4} \text{ m}^2 \text{ s}^{-1} \text{ V}^{-1}$, in accordance with e.g. Holdsworth et al. (2006). Pressure values are derived from atmospheric densities obtained from falling sphere measurements appropriate for 70° N , combining those of Lübken and von Zahn (1991) and Lübken (1999), previously used by e.g. Holdsworth (2006) and Dyrland et al. (2010). 

The NTMR radar is essentially identical to the Nippon/Norway Svalbard Meteor Radar (NSMR) located in Adventdalen on Spitsbergen at 78.33° N , 16.00° E . Further explanation of the radar and explanation of theories can be found in e.g. Hall et al. (2002, 2012), Cervera and Reid (2000) and McKinley (1961).

Calibration of temperatures derived from meteor echoes with an independent, coinciding temperature series is necessary, according to previous studies (e.g. Hocking, 1999). Temperatures from the NSMR radar have been derived most recently by Dyrland et al. (2010), employing a new calibration approach for the meteor radar temperatures, wherein temperature measurements from the Microwave Limb Sounder (MLS) on the Aura satellite were used instead of the previously used rotational hydroxyl and potassium lidar temperatures from ground-based optical instruments (Hall et al., 2006). Neither ground-based optical observations nor lidar soundings are available for the time period of interest or the location of the NTMR. In this study we therefore employ the same approach as Dyrland et al. (2010), using Aura MLS temperatures to calibrate the NTMR temperatures.

NASA's EOS Aura satellite was launched 15 July 2004 and gives daily global coverage (between 82° S and 82° N) with about 14.5 orbits per day. The MLS instrument is one of four instruments on Aura and samples viewing forward along the spacecraft's flight direction, scanning its view from the ground to $\sim 90 \text{ km}$ every $\sim 25 \text{ s}$, making

measurements of atmospheric temperature, among others (NASA Jet Propulsion Laboratory). ~~Aura MLS temperature data (version 3.2) were obtained for latitude 69.7° N ± 5.0° and longitude 19.0° E ± 10.0° at pressure 0.001 hPa, corresponding to ~ 90 km.~~

3 Calibration of NTMR temperatures

Figure 1 shows NTMR “raw” temperatures from November 2003 to October 2014, derived from Eqs. (1) and (2), plotted together with Aura MLS temperatures. The Aura satellite overpasses Tromsø at 01:00–03:00 and 10:00–12:00 UTC, which means that the Aura daily averages are representative for these time windows. It was therefore necessary to investigate any bias arising from Aura not measuring throughout the whole day. A way to do this is to assume that Aura temperatures and NTMR temperatures follow the same diurnal variation and thus investigate the diurnal variation of NTMR temperatures. This was done by superposing all NTMR temperatures by time of day, obtaining 48 values for each day, since the radar allows for a 30 min resolution.

There is an ongoing investigation into the possibility that D_a derived by NTMR can be affected by modified electron mobility during auroral particle precipitation. According to Rees et al. (1972), neutral temperatures in the auroral zone show a positive correlation with geomagnetic activity. It is therefore a possibility that ~~the diurnal variation of NTMR neutral temperatures is in fact influenced by aurora, and that~~ apparent D_a enhancements during strong auroral events do not necessarily depict neutral temperature increase. This matter requires further attention.

Investigation of possible unrealistic D_a enhancements was carried out by calculating standard errors of estimated half hourly D_a values:

$$se = \frac{\sigma}{\sqrt{ne}} \quad (3)$$

where σ is standard deviation and ne is the number of echoes detected by the radar. By inspection and comparison of results between one of the authors (M. Tsutsumi) and

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Neutral atmosphere temperature change at 90 km, 70° N, 19° E, 2003–2014

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



S. Nozawa (personal communication, 2015), all half hourly D_a values with a standard error larger than 7% of the estimated D_a value were excluded from further analysis. This rejection criterion led to that 5.4% of the D_a values were rejected.

Figure 2 shows monthly averages of the superposed values of NTMR temperatures, after application of the D_a rejection procedure, as a function of time of day for days coinciding with Aura measurements. It is evident from the figure that the lowest temperatures are in general achieved in the forenoon, which coincides with one of the periods per day when Aura MLS makes measurements over Tromsø.

Subtracting the monthly averages of the 00:00–24:00 UTC temperatures from the 01:00–03:00 and 10:00–12:00 UTC temperatures gave the estimated biases in Aura daily means due to only sampling during some hours of the day and are given in Fig. 3. The figure shows that by judging by the measurement windows, Aura underestimates the daily mean (00:00–24:00 UTC) more during winter than during spring and summer. Note the higher standard deviations in spring and summer compared to winter.

The initially obtained Aura temperatures were corrected by adding the biases from Fig. 3 in order to arrive at daily mean temperatures that are representative for the entire day. Also, a 10 K correction for cold bias was applied to the Aura temperatures, following a suggestion from French and Mulligan (2010) from their comparison with other independent temperature measurements.

Figure 4 shows a scatterplot of the corrected Aura temperatures against the “raw” NTMR temperatures. By observing the two datasets, a seasonally dependent relationship is discernible. A 2nd degree polynomial provided the best overall fit ($R^2 = 0.87$) compared with a linear fit. The blue line represents the quadratic, least squares fit and is described by:

$$T_{\text{NTMR}} = 0.0035T_{\text{Aura}}^2 - 0.32T_{\text{Aura}} + 126 \quad (4)$$

where T_{NTMR} is the “raw” temperature obtained from NTMR, and T_{Aura} is the corrected temperature from Aura MLS. Inverting Eq. (4) enabled us to estimate NTMR temperatures calibrated with respect to Aura MLS temperatures. NTMR temperatures were

now corrected for the days of measurements coinciding with Aura measurements. For calibration of the remaining NTMP temperatures the same equation (Eq. 4) was used with NTMP “raw” temperatures not coinciding with Aura measurements as input.

To estimate the calibration uncertainty, corrected Aura temperatures were subtracted from the NTMR temperatures, and the differences were plotted in a histogram with 5 K bins. A Gaussian was fitted to the distribution. The standard deviation of the Gaussian was 1 K, which is then considered the overall uncertainty of the calibration. Figure 5 shows the histogram and the fitted Gaussian curve. Finally, Fig. 6 shows the calibrated NTMR temperatures with uncertainties plotted together with Aura MLS temperatures, corrected for tidal and cold bias.

4 Trend analysis

A monthly climatology of the calibrated NTMR temperatures was obtained by averaging all January, February, etc. values. The seasonal variation is shown in Fig. 7 and reveals a summer minimum of around 150–160 K and a winter maximum of around 200–210 K. The monthly values were then subtracted from the daily calibrated temperatures, obtaining daily residuals independent of seasonal variation.

There are several measures of solar variability available, e.g. the F10.7 cm solar radio flux, the sunspot number (SSN), total solar irradiance (TSI), Mg II 280 nm core-to-wing ratio UV-index and the flare index (FI). These indices are considered proxies for solar radiation formed on different altitudes of the solar atmosphere and are highly correlated (Bruevich et al., 2014). In this study we use the F10.7 cm flux as a proxy for solar activity, which is the most commonly used index in middle/upper atmospheric temperature trend studies (e.g. Laštovička et al., 2008; Hall et al., 2012).

A 30 day running mean filter was applied to the daily residual temperatures. Figure 8 shows the residuals plotted against corresponding F10.7 cm values. The straight, red line in the figure gave the best linear fit to the daily residuals with a 30 day running mean

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



applied and gave a solar response coefficient of $4.2\text{K} \pm 0.3\text{K} (100\text{SFU})^{-1}$ (1 SFU = 1 solar flux unit = $10^{-22}\text{Wm}^{-2}\text{Hz}^{-1}$).

From Fig. 8 there appears to be a somewhat non-linear relationship between the temperatures at 90 km height and the F10.7 cm index. There seems to be a tendency of a less steep increase in temperatures toward higher F10.7 values. Ogawa et al. (2014) also found a non-linear relationship between upper atmospheric temperatures and solar activity using EISCAT UHF radar observations from Tromsø, even though it must be noted that the altitude range they looked at differs from ours. In Fig. 8 we have therefore also plotted the quadratic, least-squares fit to the running mean values. Lacking any objective scientific basis to do otherwise, we chose to fit a 2nd degree polynomial following the philosophy of Ogawa et al. (2014), although it is conceivable that other functions could be more suitable. The 2nd degree polynomial gave us a better fit to the residuals ($R^2 = 0.17$) compared to the straight line ($R^2 = 0.07$). We subtracted the solar response from the dataset of daily, seasonally corrected residuals using this relation:

$$T' = T - (a \cdot f10.7^2 + b \cdot f10.7 + c) \quad (5)$$

where T' is the new set of residual temperatures with seasonal and solar response subtracted, T is the residual temperatures with only seasonal variation subtracted, $f10.7$ is the daily F10.7 cm flux corresponding to T , and a , b and c are coefficients of the 2nd degree polynomial ($a = -0.0015$, $b = 0.37$, $c = -21$).

From the new set of temperature residuals we calculated monthly means. This was done to remove any high-frequency deterministic component, such as that resulting from multi-day period waves. Finally, the linear trend was found by performing linear regression using a least-squares fit. The long-term linear temperature trend using monthly means is $-3.6\text{K} \pm 1.1\text{Kdecade}^{-1}$. This trend can be considered statistically significant (i.e. significantly non-zero at the 5% level), since the uncertainty ($2\sigma = 2.2\text{Kdecade}^{-1}$) is less than the trend itself (Tiao et al., 1990). Figure 9 shows the linear trend of the monthly values for the whole dataset, from November 2003 through

**Neutral atmosphere
temperature change
at 90 km, 70° N, 19° E,
2003–2014**

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



October 2014. For comparison, the long-term trend using daily temperature values is $-3.4\text{ K} \pm 0.5\text{ K decade}^{-1}$.

In addition to the average temperature change, we also treated summer and winter seasons separately. First, trends for each month were investigated using the same approach as for the average regardless of month. Figure 10 shows the result. Then, averages of November, December and January, and of May, June and July were made. They were defined as ‘‘winter’’ and ‘‘summer’’, respectively. The long-term linear winter trend is $-8.1\text{ K} \pm 2.5\text{ K decade}^{-1}$, and the long-term summer trend is $-0.8\text{ K} \pm 2.9\text{ K decade}^{-1}$.

The trend analysis was also performed without carrying out the D_a rejection procedure explained in Sect. 3. Final results with and without data rejection do not differ significantly considering the calculated uncertainties.

5 Discussion

5.1 Suitability of a meteor radar for estimation of neutral temperatures at 90 km height

As explained in Sect. 2, neutral air temperatures derived from meteor trail echoes depend on pressure, p , the zero-field reduced mobility of the ions in the trail, K_0 , and ambipolar diffusion coefficients, D_a . K_0 will depend on the ion composition in the meteor trail, as well as the chemical composition of the atmosphere. The chemical composition of the atmosphere is assumed to not change significantly with season (Hocking, 2004). Unfortunately, the exact content of a meteor trail is unknown. Usually, a value for K_0 between 1.9×10^{-4} and $2.9 \times 10^{-4} \text{ m}^2 \text{ s}^{-1} \text{ V}^{-1}$ is chosen, depending on what ion one assumes to be the main ion of the trail (Hocking et al., 1997). Even though we in this study have chosen a constant value for K_0 of $2.4 \times 10^{-4} \text{ m}^2 \text{ s}^{-1} \text{ V}^{-1}$, some variability in K_0 is expected. According to Hocking (2004) variability can occur due to fragmentation of the incoming meteoroid, anisotropy in the diffusion rate, plasma instabilities and vari-

ations in the composition of the meteor trail. Using computer simulations, they reported a typical variability in K_0 from meteor to meteor of 27 % and that the variability is most dominant at higher temperatures. Based on this, we cannot rule out sources of error due to the choice of K_0 as a constant, but since we have no possibility to analyse the composition of all meteor trails detected by the radar we have no other choice than to choose a constant value for K_0 .

How well ambipolar diffusion coefficients obtained for 90 km altitude are suited for calculating neutral temperatures has previously been widely discussed, e.g. by Hall et al. (2012) for the trend analysis of the Svalbard meteor radar data, but will be shortly repeated here. For calculations of temperatures using meteor radar, ambipolar diffusion alone is assumed to determine the decay of the underdense echoes. Diffusivities are expected to increase exponentially with height through the region from which meteor echoes are obtained (Ballinger et al., 2008; Chilson et al., 1996). Hall et al. (2005) found that this is only the case between ~ 85 and ~ 95 km altitude, using diffusion coefficients delivered by NTMR from 2004. They found diffusivities less than expected above ~ 95 km and diffusivities higher than expected below ~ 85 km. Ballinger et al. (2008) got a similar result using meteor observations over northern Sweden. It has been proposed that processes other than ambipolar diffusion influence meteor decay times. If this is the case it may have consequences for the estimation of temperatures, and therefore it is important to investigate this further.

Departures of the anticipated exponential increase with height of molecular diffusion above ~ 95 km have in previous studies been attributed to gradient-drift Farley–Buneman instability. Farley–Buneman instability occurs where the trail density gradient and electric field are largest. Due to frequent collisions with neutral particles, electrons are magnetised while ions are left unmagnetised, causing electrons and ions to differ in velocity. Electrons then create an electric field perpendicular to the meteor trail, leading to anomalous fading times that can be an order of magnitude higher than those expected from ambipolar diffusion. The minimum altitude at which this occurs depends on the trail altitude, density gradient and latitude, and at high latitudes this altitude is

**Neutral atmosphere
temperature change
at 90 km, 70° N, 19° E,
2003–2014**

S. E. Holmen et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

~ 95 km. Therefore, using ambipolar diffusion rates to calculate trail altitudes above this minimum altitude may lead to errors of several kilometres, due to that the diffusion coefficients derived from the measurements are underestimated (Ballinger et al., 2008; Dyrud et al., 2001; Kovalev et al., 2008).

Reasons for the higher diffusivities than expected according to theory below ~ 85 km are not completely understood. Hall (2002) proposed that neutral turbulence may be responsible for overestimates of molecular diffusivity in the region ~ 70–85 km, but this hypothesis was rejected by Hall et al. (2005) due to a lacking correlation between neutral air turbulent intensity and diffusion coefficients delivered by the NTMR radar. Other mechanisms for overestimates of molecular diffusivity include incorrect determination of echo altitude and fading times due to limitations of the radar (Hall et al., 2005).

Since the peak echo occurrence height is 90 km and this is also the height at which a minimum of disturbing effects occur, 90 km height is therefore considered the optimal height for temperature measurements using meteor radar. Ballinger et al. (2008) report that meteor radars in general deliver reliable daily temperature estimates near the mesopause using the method outlined in this study, but emphasize that one should exercise caution when assuming that observed meteor echo fading times are primarily governed by ambipolar diffusion. They proposed, after Havnes and Sigernes (2005), that electron-ion recombination can impact meteor echo decay times. Especially can this affect the weaker echoes, and hence can this effect lead to underestimation of temperatures.

Determination of temperatures from meteor radar echo times is a non-trivial task, mainly because the calculation of ambipolar diffusion coefficients depends on the ambient atmospheric pressure. By using radar echo decay times to calculate ambipolar diffusion coefficients from Eq. (1), we can from Eq. (2) get an estimate for T^2/ρ . Input of pressure values into the equation will thus provide atmospheric temperatures. However, measurements of pressure are rare and difficult to achieve at 90 km height, and often one has to rely on model values. Traditionally, pressure values at 90 km have been calculated using the ideal gas law, taking total mass density from atmospheric models,

Neutral atmosphere temperature change at 90 km, 70° N, 19° E, 2003–2014

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Neutral atmosphere temperature change at 90 km, 70° N, 19° E, 2003–2014

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



e.g. the MSISE models, where the newest version is NRLMSIS-00. It is hard to verify the pressure values derived from the models because of lack of measurements to compare the model to, and hence using the pressure values may result in uncertainties of estimated atmospheric temperatures. In this study, we obtained pressure values from measurements of mass densities obtained from falling spheres combined with sodium lidar from Andøya (69° N, 15.5° E) (Lübken, 1999; Lübken and von Zahn, 1991). All measurements have been combined to give a yearly climatology, that is, one pressure value for each day of the year. Since Andøya is located in close proximity to Tromsø (approximately 120 km), the pressure values are considered appropriate for our calculations of neutral temperatures. One disadvantage with using pressure values obtained from the falling sphere measurements is that no day-to-day variations are taken into account, only the average climatology.

5.2 Physical explanations for cooling and comparison with other studies

Other studies on long-term mesospheric temperature trends from mid and high latitudes yield mostly negative or near-zero trends. Few studies cover the same time period as ours, and few are from locations close to Tromsø. Hall et al. (2012) reported a negative trend of $-4\text{ K} \pm 2\text{ K decade}^{-1}$ for temperatures derived from the meteor radar from Longyearbyen, Svalbard (78° N, 16° E) at 90 km height over the time period 2001 to 2011, while Holmen et al. (2014) found a near-zero trend for OH* airglow temperatures at ~ 87 km height over Longyearbyen over the longer time period 1983 to 2013. Offermann et al. (2010) reported a trend of $-2.3\text{ K} \pm 0.6\text{ K decade}^{-1}$ for ~ 87 km height using OH* airglow measurements from Wuppertal (51° N, 7° E). It must be noted that the peak altitude of the OH* airglow layer can range from 75 to > 90 km (Winick et al., 2009) and thus affect the comparability of OH* airglow temperature trends and meteor radar temperature trends. Beig (2011) reported that most recent studies on mesopause region temperature trends show weak negative trends, which is in line with our results.

Our results indicate a cooling at 90 km altitude over Tromsø. A general cooling of the middle atmosphere will cause a contraction of the atmospheric column and hence

**Neutral atmosphere
temperature change
at 90 km, 70° N, 19° E,
2003–2014**

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



a lowering of upper mesospheric pressure surfaces. The pressure model used as input to Eq. (2) is only seasonally dependent, so a possible trend in pressure at 90 km must be addressed. By looking at Eq. (2), it is evident that if pressure decreases, temperature will decrease even more. By incorporating a decreasing trend in the pressure model will then serve to further strengthen the negative temperature trend we observe.

It has been proposed that GWs may be a major cause of negative temperature trends in the mesosphere and thermosphere (Beig, 2011; Oliver et al., 2013). GWs effectively transport chemical species and heat in the region, and increased GW drag leads to cooling. However, there are large regional differences regarding trends in GW activity. Hoffmann et al. (2011) found an increasing GW activity in the mesosphere in summer for selected locations, but Jacobi (2014) found larger GW amplitudes during solar maximum and related this to a stronger mesospheric jet during solar maximum, both for winter and summer. Since we have not conducted any gravity wave trend assessment in this study, we cannot conclude that GW activity is responsible for the negative temperature trend, but we cannot rule out its role either.

The stronger cooling trend for winter compared to summer is consistent with model studies. Schmidt et al. (2006) and Fomichev et al. (2007) show, using the HAMMONIA and CMAM models, respectively, that a doubling of the CO₂ concentration will lead to a general cooling of the middle atmosphere, but that the high-latitude summer mesopause will experience insignificant change or even slight warming. They propose that this is the result of both radiative and dynamical effects. In summer, the CO₂ radiative forcing is positive due to heat exchange between the cold polar mesopause and the warmer, underlying layers. Also, CO₂ doubling alters the mesospheric residual circulation. This change is caused by a warming in the tropical troposphere and cooling in the extratropical tropopause, leading to a stronger equator-to-pole temperature gradient and hence stronger midlatitude tropospheric westerlies. This causes the westerly gravity wave drag to weaken, resulting in decreased adiabatic cooling from a slower ascent of the upper mesospheric circulation.



6 Conclusions

The long-term trend of neutral temperatures at 90 km height derived from the NTMR radar in Ramfjordmoen, Tromsø, with seasonality and solar response subtracted, is $-3.6\text{K} \pm 1.1\text{K decade}^{-1}$. The linear fit between the smoothed daily residuals and corresponding F10.7 cm values gave a solar response coefficient of $4.2\text{K} \pm 0.3\text{K}(100\text{SFU})^{-1}$. However, a 2nd degree polynomial gave the best fit to the data and was thus used for correcting the dataset of solar response. When looking at summer and winter seasons separately, the trends are $-0.8\text{K} \pm 2.9\text{K decade}^{-1}$ for summer and $-8.1\text{K} \pm 2.5\text{K decade}^{-1}$ for winter.

Final results of the trend analysis, both when excluding and including rejection of D_a values due to hypothetical anomalous electrodynamic processes, do not differ significantly. It is reasonable to believe that strong geomagnetic conditions can affect derived temperatures on a short time scale. However, due to the considerable quantity of data employed in this study, it is inconceivable that this effect will change the conclusions regarding trends, as our results also show.

90 km is considered the optimal height for retrieval of neutral temperatures using ambipolar diffusion coefficients from NTMR, due to that the peak echo occurrence height detected by the radar is 90 km and that this is also the height at which a minimum of disturbing effects occur. Above ~ 95 km anomalous fading times that can be an order of magnitude higher than those expected from ambipolar diffusion may be measured, due to gradient-drift Farley–Buneman instability, causing the derived ambipolar diffusion to be underestimated. Below ~ 85 km higher diffusivities than expected according to theory in which the temperature estimation is based on may be encountered, due to reasons not fully understood.

A weak cooling trend is in line with other recent studies on mesopause region temperature trends. A cooling of the middle atmosphere will cause a lowering of upper mesospheric pressure surfaces. By implementing a negative trend in pressure at 90 km into the equation we use for estimating temperatures the negative temperature trend is

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Neutral atmosphere temperature change at 90 km, 70° N, 19° E, 2003–2014

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



enhanced, which reinforces our finding of a cooling trend. The most accepted theory behind a cooling of the middle atmosphere is increased greenhouse gas emissions, but also dynamics may play a significant role. Our results yield a more negative trend in winter compared to summer, which may be explained by both radiative and dynamical effects. In summer, a larger heat exchange takes place from atmospheric layers below the cold, polar mesopause. Weakening of gravity wave drag leads to weakening of the mesospheric residual circulation, which counteracts cooling. These effects occur due to increased CO₂ concentrations in the atmosphere, according to model studies.

Acknowledgements. The research for this article was financially supported by The Research Council of Norway through contract 223252/F50 (CoE). NTMR operation was supported by Research Project KP-0 of National Institute of Polar Research. The authors wish to thank Frank Mulligan at Maynooth University, Ireland, for providing the NASA EOS Aura MLS temperatures.

References

- Akmaev, R. A. and Fomichev, V. I.: Cooling of the mesosphere and lower thermosphere due to doubling of CO₂, *Ann. Geophys.*, 16, 1501–1512, doi:10.1007/s00585-998-1501-z, 1998.
- Akmaev, R. A. and Fomichev, V. I.: A model estimate of cooling in the mesosphere and lower thermosphere due to the CO₂ increase over the last 3–4 decades, *Geophys. Res. Lett.*, 27, 2113–2116, doi:10.1029/1999GL011333, 2000.
- Ballinger, A. P., Chilson, P. B., Palmer, R. D., and Mitchell, N. J.: On the validity of the ambipolar diffusion assumption in the polar mesopause region, *Ann. Geophys.*, 26, 3439–3443, doi:10.5194/angeo-26-3439-2008, 2008.
- Beig, G.: Long-term trends in the temperature of the mesosphere/lower thermosphere region: 1. Anthropogenic influences, *J. Geophys. Res.-Space*, 116, A00H11, doi:10.1029/2011JA016646, 2011.
- Bruevich, E. A., Bruevich, V. V., and Yakunina, G. V.: Changed relation between solar 10.7-cm radio flux and some activity indices which describe the radiation at different altitudes of atmosphere during cycles 21–23, *J. Astrophys. Astron.*, 35, 1–15, 2014.

Neutral atmosphere temperature change at 90 km, 70° N, 19° E, 2003–2014

S. E. Holmen et al.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


- Cervera, M. A. and Reid, I. M.: Comparison of atmospheric parameters derived from meteor observations with CIRA, *Radio Sci.*, 35, 833–843, doi:10.1029/1999RS002226, 2000.
- Chilson, P. B., Czechowsky, P., and Schmidt, G.: A comparison of ambipolar diffusion coefficients in meteor trains using VHF radar and UV lidar, *Geophys. Res. Lett.*, 23, 2745–2748, doi:10.1029/96gl02577, 1996.
- 5 Dyrland, M. E., Hall, C. M., Mulligan, F. J., Tsutsumi, M., and Sigernes, F.: Improved estimates for neutral air temperatures at 90 km and 78° N using satellite and meteor radar data, *Radio Sci.*, 45, RS4006, doi:10.1029/2009rs004344, 2010.
- Dyrud, L. P., Oppenheim, M. M., and vom Endt, A. F.: The anomalous diffusion of meteor trails, *Geophys. Res. Lett.*, 28, 2775–2778, 2001.
- 10 Fomichev, V. I., Jonsson, A. I., de Grandpré, J., Beagley, S. R., McLandress, C., Semeniuk, K., and Shepherd, T. G.: Response of the middle atmosphere to CO₂ doubling: results from the Canadian Middle Atmosphere Model, *J. Climate*, 20, 1121–1144, doi:10.1175/JCLI4030.1, 2007.
- 15 Ingh, W. J. R. and Mulligan, F. J.: Stability of temperatures from TIMED/SABER v1.07 (2002–2009) and Aura/MLS v2.2 (2004–2009) compared with OH(6-2) temperatures observed at Davis Station, Antarctica, *Atmos. Chem. Phys.*, 10, 11439–11446, doi:10.5194/acp-10-11439-2010, 2010.
- Hall, C. M.: On the influence of neutral turbulence on ambipolar diffusivities deduced from meteor trail expansion, *Ann. Geophys.*, 20, 1857–1862, doi:10.5194/angeo-20-1857-2002, 2002.
- 20 Hall, C. M., Aso, T., Tsutsumi, M., Nozawa, S., Manson, A. H., and Meek, C. E.: *Letter to the Editor* Testing the hypothesis of the influence of neutral turbulence on the deduction of ambipolar diffusivities from meteor trail expansion, *Ann. Geophys.*, 23, 1071–1073, doi:10.5194/angeo-23-1071-2005, 2005.
- 25 Hall, C. M., Aso, T., Tsutsumi, M., Höffner, J., Sigernes, F., and Holdsworth, D. A.: Neutral air temperatures at 90 km and 70° N and 78° N, *J. Geophys. Res.*, 11, D14105, doi:10.1029/2005JD006794, 2006.
- Hall, C. M., Dyrland, M. E., Tsutsumi, M., and Mulligan, F. J.: Temperature trends at 90 km over Svalbard, Norway (78° N 16° E), seen in one decade of meteor radar observations, *J. Geophys. Res.-Atmos.*, 117, D08104, doi:10.1029/2011JD017028, 2012.
- 30 Havnes, O. and Sigernes, F.: On the influence of background dust on radar scattering from meteor trails, *J. Atmos. Sol.-Terr. Phys.*, 67, 659–664, doi:10.1016/j.jastp.2004.12.009, 2005.

**Neutral atmosphere
temperature change
at 90 km, 70° N, 19° E,
2003–2014**

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Hocking, W. K.: Temperatures using radar-meteor decay times, *Geophys. Res. Lett.*, 26, 3297–3300, doi:10.1029/1999GL003618, 1999.
- Hocking, W. K.: Radar meteor decay rate variability and atmospheric consequences, *Ann. Geophys.*, 22, 3805–3814, doi:10.5194/angeo-22-3805-2004, 2004.
- 5 Hocking, W. K., Thayaparan, T., and Jones, J.: Meteor decay times and their use in determining a diagnostic mesospheric temperature-pressure parameter: methodology and one year of data, *Geophys. Res. Lett.*, 24, 2977–2980, doi:10.1029/97gl03048, 1997.
- Hoffmann, P., Rapp, M., Singer, W., and Keuer, D.: Trends of mesospheric gravity waves at northern middle latitudes during summer, *J. Geophys. Res.*, 116, D00P08, doi:10.1029/2011JD015717, 2011.
- 10 Holdsworth, D. A., Morris, R. J., Murphy, D. J., Reid, I. M., Burns, G. B., and French, W. J. R.: Antarctic mesospheric temperature estimation using the Davis mesosphere–stratosphere–troposphere radar, *J. Geophys. Res.-Atmos.*, 111, D05108, doi:10.1029/2005jd006589, 2006.
- 15 Holmen, S. E., Dyrland, M. E., and Sigernes, F.: Long-term trends and the effect of solar cycle variations on mesospheric winter temperatures over Longyearbyen, Svalbard (78° N), *J. Geophys. Res.-Atmos.*, 119, 6596–6608, doi:10.1002/2013jd021195, 2014.
- Jacobi, C.: Long-term trends and decadal variability of upper mesosphere/lower thermosphere gravity waves at midlatitudes, *J. Atmos. Sol.-Terr. Phys.*, 118, 90–95, doi:10.1016/j.jastp.2013.05.009, 2014.
- 20 Kovalev, D. V., Smirnov, A. P., and Dimant, Y. S.: Modeling of the Farley-Buneman instability in the E-region ionosphere: a new hybrid approach, *Ann. Geophys.*, 26, 2853–2870, doi:10.5194/angeo-26-2853-2008, 2008.
- Laštovička, J., Akmaev, R. A., Beig, G., Bremer, J., Emmert, J. T., Jacobi, C., Jarvis, M. J., Nedoluha, G., Portnyagin, Yu. I., and Ulich, T.: Emerging pattern of global change in the upper atmosphere and ionosphere, *Ann. Geophys.*, 26, 1255–1268, doi:10.5194/angeo-26-1255-2008, 2008.
- 25 Laštovička, J., Solomon, S. C., and Qian, L.: Trends in the neutral and ionized upper atmosphere, *Space Sci. Rev.*, 168, 113–145, doi:10.1007/s11214-011-9799-3, 2012.
- 30 Lübken, F.-J.: Thermal structure of the Arctic summer mesosphere, *J. Geophys. Res.-Atmos.*, 104, 9135–9149, 1999.
- Lübken, F.-J. and von Zahn, U.: Thermal structure of the mesopause region at polar latitudes, *J. Geophys. Res.-Atmos.*, 96, 20841–20857, doi:10.1029/91JD02018, 1991.



Neutral atmosphere temperature change at 90 km, 70° N, 19° E, 2003–2014

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Manabe, S. and Wetherald, R. T.: The effects of doubling the CO₂ concentration on the climate of a general circulation model, *J. Atmos. Sci.*, 32, 3–15, 1975.

McKinley, D. W. R.: *Meteor Science and Engineering*, McGraw-Hill, New York, 1961.

NASA Jet Propulsion Laboratory: EOS Microwave Limb Sounder, available at: <http://mls.jpl.nasa.gov/index-eos-mls.php>, last access: January 2015.

Offermann, D., Hoffmann, P., Knieling, P., Koppmann, R., Oberheide, J., and Steinbrecht, W.: Long-term trends and solar cycle variations of mesospheric temperatures and dynamics, *J. Geophys. Res.*, 115, D18127, doi:10.1029/2009JD013363, 2010.

Ogawa, Y., Motoba, T., Buchert, S. C., Häggström, I., and Nozawa, S.: Upper atmosphere cooling over the past 33 years, *Geophys. Res. Lett.*, 41, 5629–5635, doi:10.1002/2014GL060591, 2014.

Oliver, W. L., Zhang, S.-R., and Goncharenko, L. P.: Is thermospheric global cooling caused by gravity waves?, *J. Geophys. Res.-Space*, 118, 3898–3908, doi:10.1002/jgra.50370, 2013.

Rees, D., Rishbeth, H., and Kaiser, T. R.: Winds and temperatures in the auroral zone and their relations to geomagnetic activity, *Philos. T. R. Soc. S.-A*, 271, 563–575, 1972.

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

Schmidt, H., Brasseur, G. P., Charron, M., Manzini, E., Giorgetta, M. A., and Diehl, T.: The HAMMONIA Chemistry Climate Model: sensitivity of the mesopause region to the 11-year solar cycle and CO₂ doubling, *J. Climate*, 19, 3903–3931, doi:10.1175/JCLI3829.1, 2006.

Tiao, G. C., Reinsel, G. C., Xu, D., Pedrick, J. H., Zhu, X., Miller, A. J., DeLuise, J. J., Matteer, C. L., and Wuebbles, D. J.: Effects of autocorrelation and temporal sampling schemes on estimates of trend and spatial correlation, *J. Geophys. Res.-Atmos.*, 95, 20507–20517, doi:10.1029/JD095iD12p20507, 1990.

Wick, J. R., Wintersteiner, P. P., Picard, R. H., Esplin, D., Mlynczak, M. G., Russell III, J. M., and Gordley, L. L.: OH layer characteristics during unusual boreal winters of 2004 and 2006, *J. Geophys. Res.*, 114, A02303, doi:10.1029/2008JA013688, 2009.



Neutral atmosphere temperature change at 90 km, 70° N, 19° E, 2003–2014

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

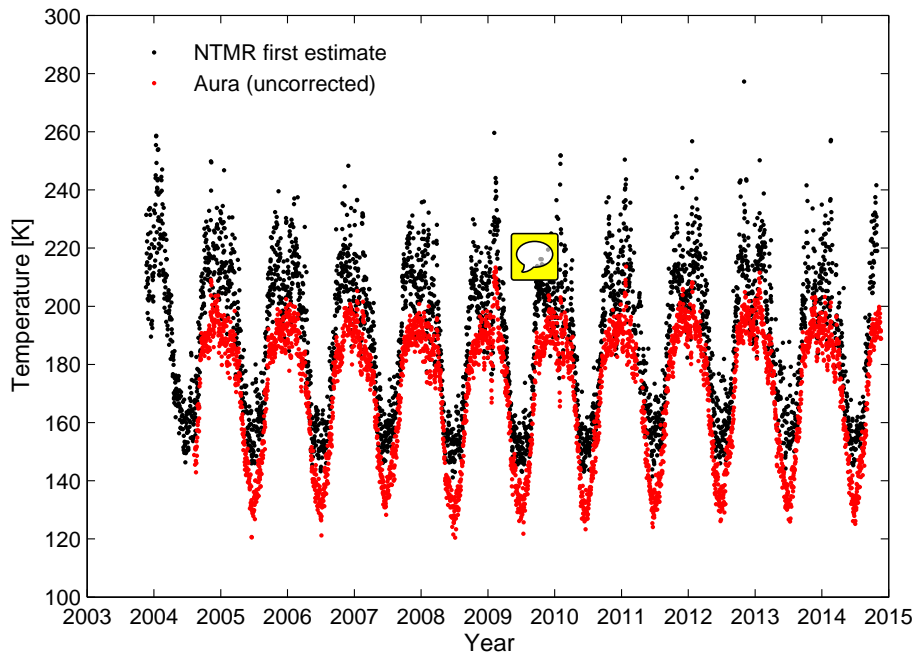


Figure 1. NTMR “raw” temperatures derived from Eqs. (1) and (2), plotted together with Aura MLS temperatures.

Neutral atmosphere temperature change at 90 km, 70° N, 19° E, 2003–2014

S. E. Holmen et al.

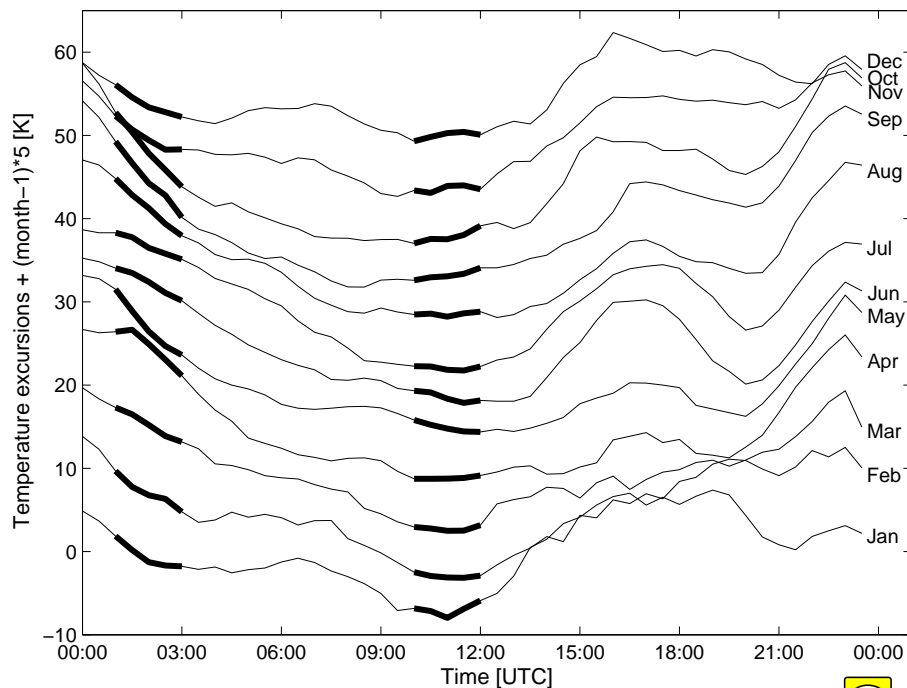


Figure 2. Monthly averages of diurnal temperature variation derived from NTMR at 90 km altitude. For clarity time series are displaced by 5 K month^{-1} subsequent to January. The time of day corresponding to when Aura makes measurements over Tromsø (01:00–03:00 and 10:00–12:00 UTC) is highlighted.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Neutral atmosphere temperature change at 90 km, 70° N, 19° E, 2003–2014

S. E. Holmen et al.

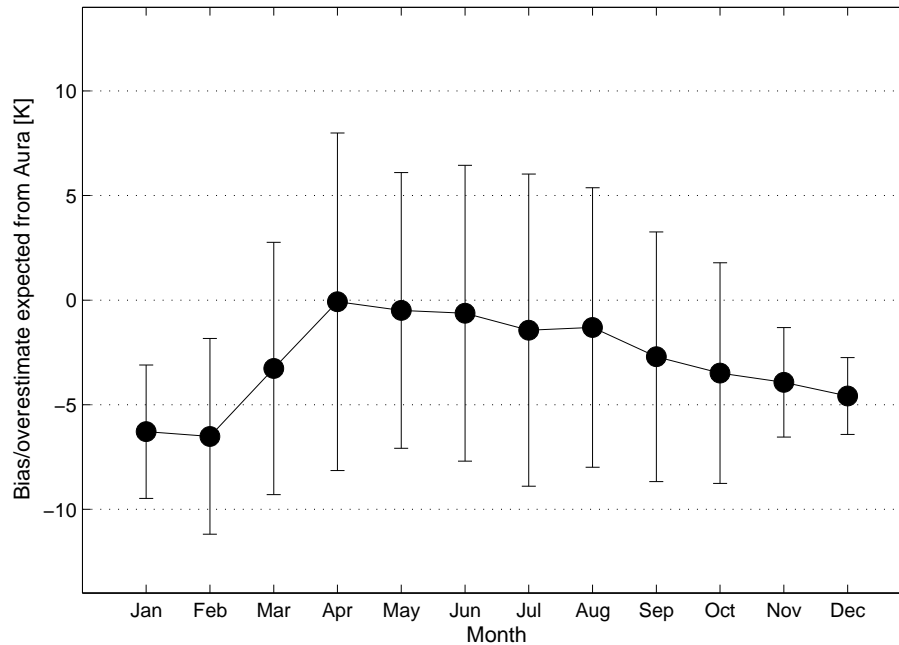
[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Figure 3. Bias in Aura monthly averages due to that Aura MLS only measures between 01:00 and 03:00 UTC, and between 10:00 and 12:00 UTC. Error bars represent standard deviations.

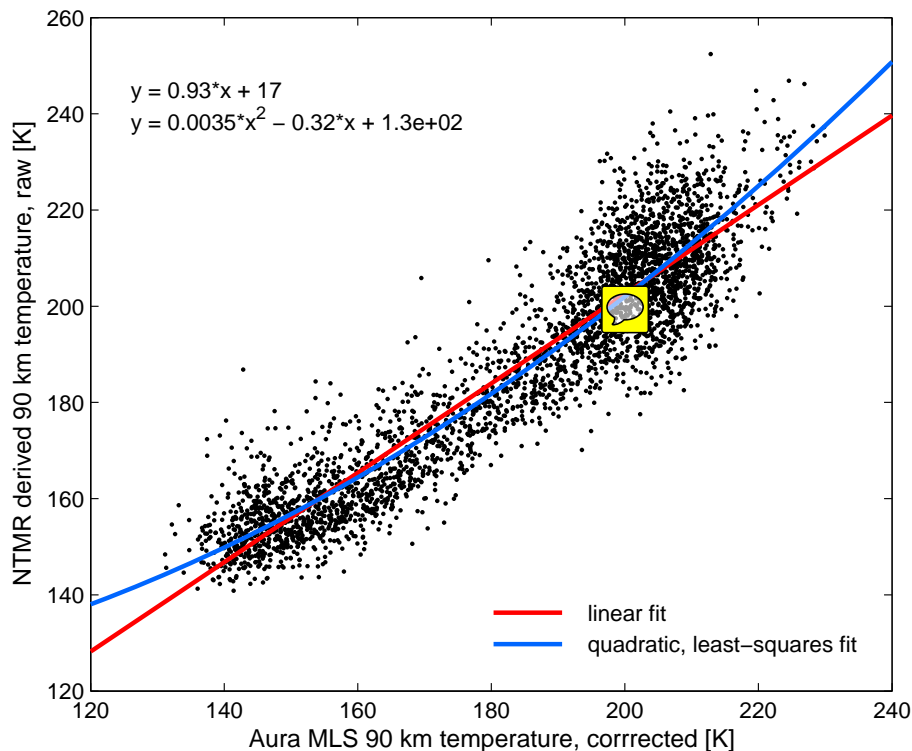


Figure 4. Scatterplot of Aura temperatures corrected for cold and time-of-day measurement bias against NTMR “raw” temperatures. The blue line represents the quadratic least-squares fit, which is the approach used in the further calibration of the NTMR temperatures. The red line represents the linear fit and is only shown for comparison.

| | |
|--------------------------|--------------|
| Title Page | |
| Abstract | Introduction |
| Conclusions | References |
| Tables | Figures |
| ◀ | ▶ |
| ◀ | ▶ |
| Back | Close |
| Full Screen / Esc | |
| Printer-friendly Version | |
| Interactive Discussion | |



**Neutral atmosphere
temperature change
at 90 km, 70° N, 19° E,
2003–2014**

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

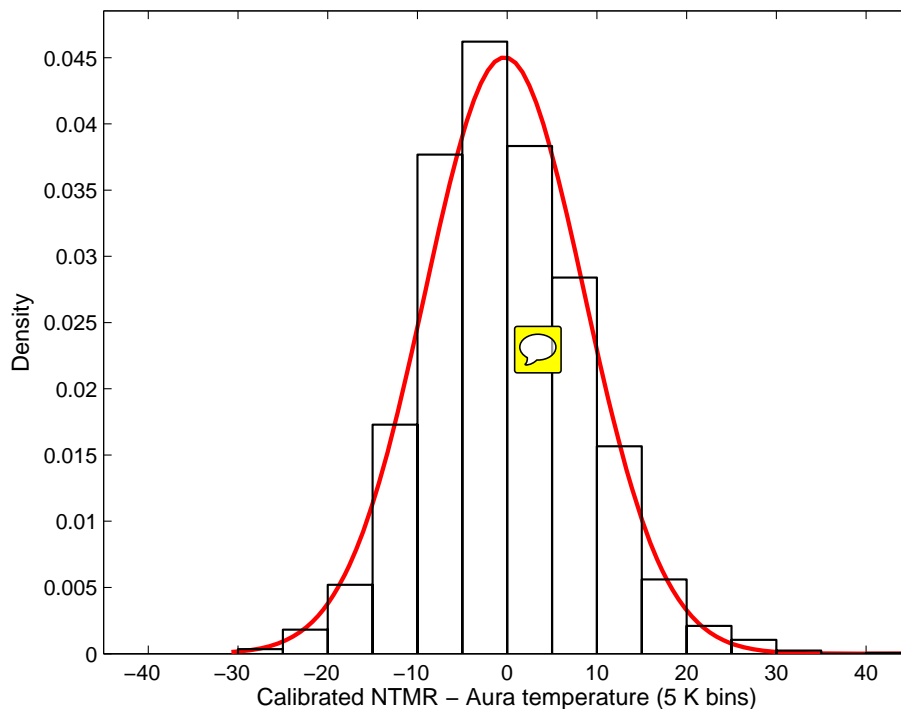


Figure 5. Histogram of the differences between calibrated NTMR temperatures and corrected Aura MLS temperatures. The red curve is a fitted Gaussian to the distribution.

Neutral atmosphere temperature change at 90 km, 70° N, 19° E, 2003–2014

S. E. Holmen et al.

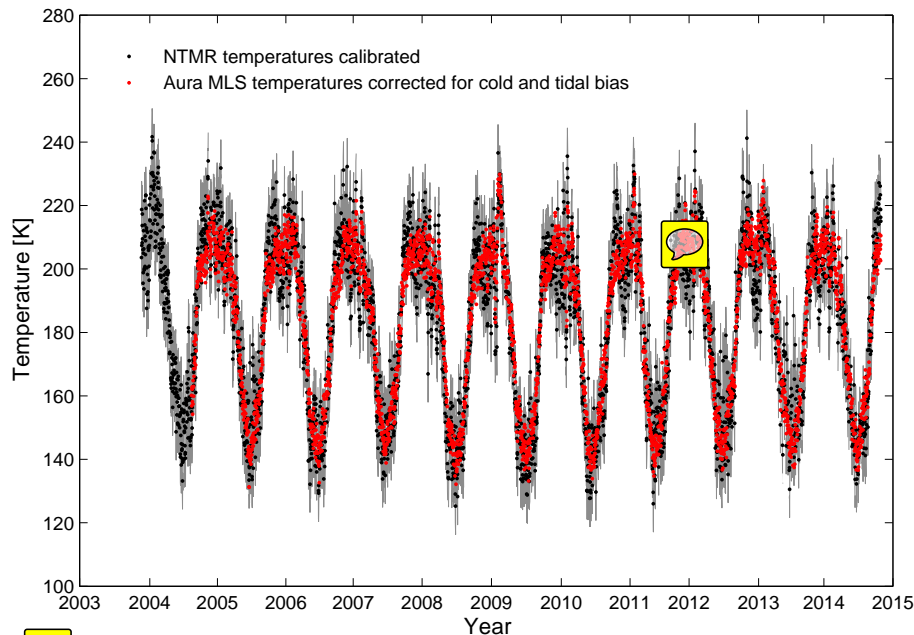
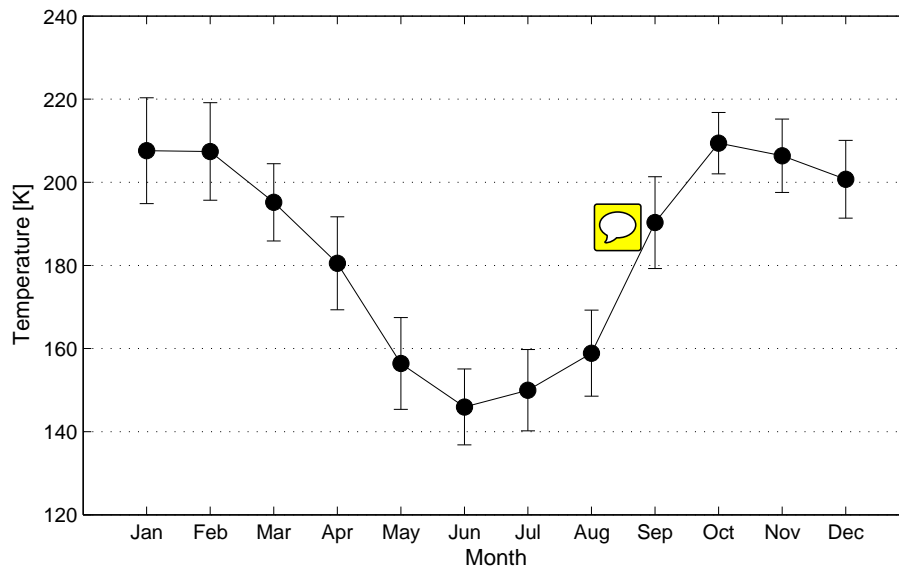



Figure 6. Calibrated NTMR temperatures plotted together with Aura MLS temperatures, corrected for tidal and cold bias. The overall calibration uncertainty is indicated by the grey shading.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



 **Figure 7.** Monthly climatology of the NTMR temperatures obtained for 90 km altitude, using calibrated temperatures from November 2003 through October 2014. Standard deviations are shown as error bars.

Neutral atmosphere
temperature change
at 90 km, 70° N, 19° E,
2003–2014

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



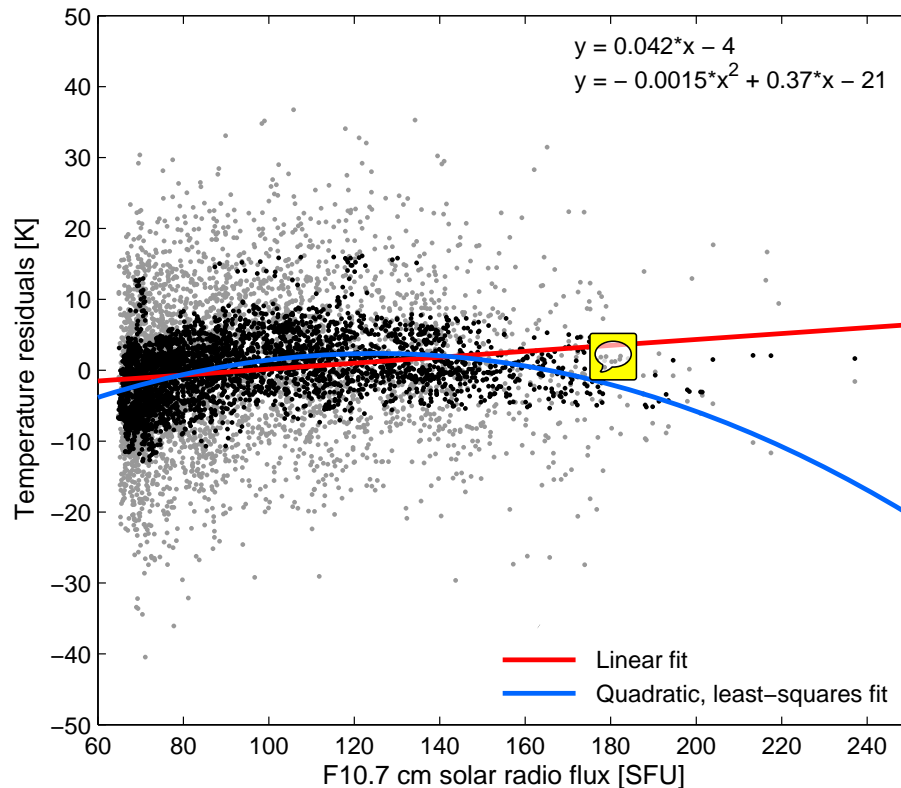


Figure 8. Scatterplot of daily averaged residuals against the corresponding F10.7 cm solar flux values. Grey dots are daily residuals, while black dots are the residuals with a 30 day running mean applied. The red line is the linear fit to the daily residuals with the 30 day running mean applied, while the blue line is the quadratic, least-squares fit.

Neutral atmosphere temperature change at 90 km, 70° N, 19° E, 2003–2014

S. E. Holmen et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Neutral atmosphere temperature change at 90 km, 70° N, 19° E, 2003–2014

S. E. Holmen et al.

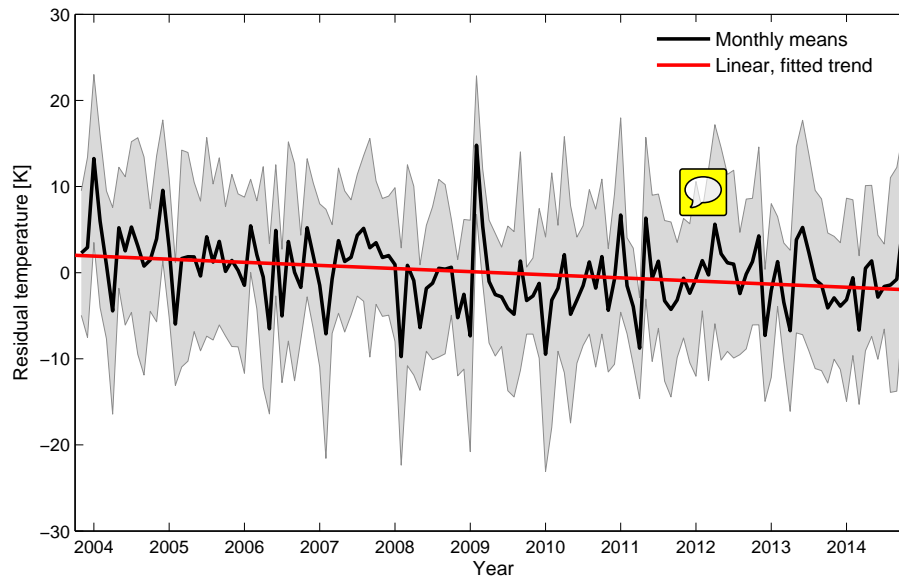


Figure 9. Monthly means of NTMR residual temperatures, corrected for climatology and solar response. The grey shading yields standard deviations.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Neutral atmosphere
temperature change
at 90 km, 70° N, 19° E,
2003–2014**

S. E. Holmen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

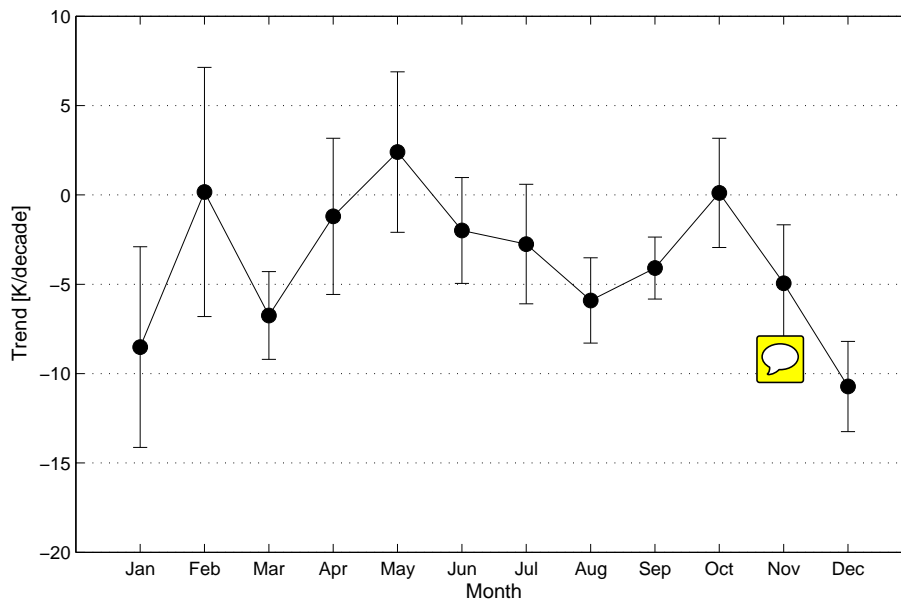


Figure 10. Monthly long-term temperature trends at 90 km altitude over Tromsø. Standard deviations are given as error bars.