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Neutral temperatures at 90 km altitude over Svalbard (78°N 16°E), 2002–2019, derived from meteor radar observations

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A R T I C L E I N F O

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A B S T R A C T

Neutral air temperatures at 90 km altitude over Svalbard (78°N, 16°E) for the period 2002 to 2019 inclusive have been estimated from observations by the Nippon/Norway Svalbard Meteor Radar (NSMR). The data are presented *per se* and we shall not attempt to identify contributions from extra-terrestrial or anthropogenic driving. On the other hand, comparison with the corresponding period of solar UV flux notably fails to exhibit similarities. Moreover, there is indeed evidence of systematic temporal changes, possibly with a breakpoint around 2012. Selecting winter and summer months and years before and after 2012 and fitting trend-lines, we see strong evidence for cooling during summer. An apparent winter cooling prior to 2012 lacks statistical significance. A suggestion of reversal to winter warming after 2012 is also very uncertain. The summer cooling is found to be 9.9 ± 2.9 K decade^{-1} between 2002 and 2012, and 4.3 ± 1.2 K decade^{-1} between 2002 and 2019. Importantly, there is a suggestion (although lacking statistical significance) that summer cooling alleviated after 2012, and even reversed in winter.

1. Introduction

A meteor detection system was installed in Adventdalen (78.17°N 15.99°E) on Svalbard in 2001 and since has provided an almost uninterrupted time-series of mesospheric/lower thermospheric winds and characteristic echo fading times centred on the peak meteor occurrence altitude of approximately 90 km. Here we employ the echo fading time data. The echo fading time may be thought of as the characteristic time for expansion of the meteor trail and therefore the ambipolar diffusion coefficient of ions in the neutral air. In turn, this gives information on ambient temperature. The physics, assumptions and derivation of neutral temperatures as presented here are given in a series of studies beginning with McKinley (1961), Chilson et al. (1996), Cervera and Reid (2000), Holdsworth et al. (2006) and Hocking (2011). Building on Holdsworth et al. (2006) and thereafter Hall et al. (2004, 2006, 2012), we adopt the approaches of Dyrland et al. (2010) and subsequently Holmen et al. (2015). In brief, the ambipolar diffusion coefficient, D is given by:

$$D = \frac{\lambda^2}{16\pi^2\tau} \tag{1}$$

where λ is the radar wavelength and τ is the echo fading time (usually the time for amplitude to attain e^{-1} of initial value). Thereafter an inital estimate for temperature, T, is determined:

$$T = \sqrt{\frac{D.P}{6.39 \times 10^{-2} K_0}} \tag{2}$$

where P is pressure and K_0 is the zero-field mobility factor. Due to the uncertainties in P and K_0, these temperatures are subsequently normalised to satellite measurements from a more limited time span. In this study, the focus will be on temporal development of temperatures over the 2002–2019 period and therefore the precision of the absolute values is not an issue; it is, rather, the interannual variation and its confidence that is of interest.

The meteor detection system, the Nippon-Norway Svalbard Meteor radar ("NSMR") is described in detail by Hall et al. (2002, 2004). It should be pointed out that while operations started in 2001, configuration changes were made such that only data from 2002 onwards are used to ensure compatibility. In short, NSMR, transmits at 31 MHz through crossed 3-element Yagi antennas and receives through a "Jones et al. cross" (Jones et al., 1998) of five 3-element Yagis. This configuration has a field of view (FoV) of 70° off zenith corresponding to an

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approximately circular region of radius 250 km at 90 km altitude such that the temperatures are representative of the entire Spitsbergen archipelago. The topology is illustrated in Fig. 1, the circle showing the FoV. The figure, apart from showing the reader the location of the observation, serves to accentuate that the results presented herewith are by no means representative of high latitudes and should be regarded as little more than a point measurement at 78°N, 16°E. Height resolution is 1 km, achieved using 4-bit complementary code, and time resolution 30-min; thereafter daily averages are determined (again as described by Dyrland et al. (2010) and references therein) to generate a basic time-series. As will be shown subsequently, this basic series will be used to generate monthly means whence trends will be identified together with comparison with solar activity. The latter are extracted from NASA/GSFC's OMNI data set through OMNIWeb.

In this study, only temperature changes over the 2002 to 2019 period will be presented. No attempt will be made to determine an analytic relationship between mesospheric temperatures and solar activity with a view to identifying anthropogenic contributions to temperature change (e.g. as was done by *inter alia* Ulich and Turunen, 1997). We thus refrain from entering the "climate change battlefield" and merely wish to report observations based on proven scientific methods. Even so, there are certain assumptions in the derivation of temperatures from characteristic echo fading times, and these are well described by the references given. That we limit the investigation to the altitude of maximum echo occurrence is because at adjacent altitude intervals, there will be a weighting of echoes towards the maximum occurrence height such that the results will not be representative of the centre of the given interval. Furthermore, at height regions somewhat above and below the nominal maximum at 90 km, other processes influence the diffusivity (Dyrud et al., 2001; Hall et al., 2005; Ballinger et al., 2008). These aspects are reiterated in the penultimate section.

Even though identification of anthropogenic forcing is not an aim of this study, it remains a motivation (e.g. Thomas, 1996). Increases in greenhouse gas concentration responsible for warming in the lower atmosphere are proposed as a mechanism for cooling the middle atmosphere, particularly in the high-latitude mesopause region, whereby infrared emission to space is unhindered. The principle is described by Roble and Dickinson (1989), Rishbeth (1990) and Akmaev and Formichev (1998) for example. Beig et al. (2003) inform that despite evidence for negative trends, significant cooling during recent decades (i.e. prior to 2003) has not been reported by other research. Schmidt et al. (2006) have modelled these results and suggest that increasing CO_2 may cause seasonal differences in the temperature response in the mesopause region: notably, an enhancement of the summer cooling trend and reduction of the trend during winter.

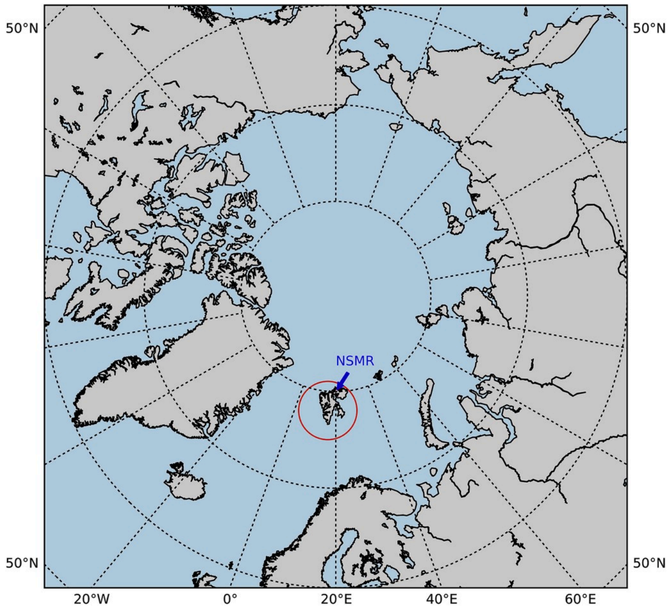

Fig. 1. Measurement topology. The map is centred on the geographic North Pole. The "NSMR" pointer indicates the approximate position of the radar, and the surrounding red circle the approximate field of view. Resulting temperatures are derived for echoes distributed over this circle. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

2. Results: neutral temperatures at 90 km altitude and detectable trends

Daily mean neutral temperatures smoothed using both 30- and 365 point (i.e. 1-month and 1-year wide respectively) running means, at 90 km altitude above the above the radar (78°N, 16°E), are shown in Fig. 2. The figure also includes the monthly mean f10.7 solar fluxes as described in the introduction. The need for a regression analysis is quite evidently superfluous: there is no indication whatsoever that these datasets are correlated. Based on this figure alone we therefore dismiss any hypothesis that the neutral temperatures are driven by the solar flux as determined by surface measurements, at least over the decadal timescales in focus here and at the geographical point of observation. Nevertheless, Gan et al. (2016) have studied mesospheric temperature observations and model predictions establishing a solar cycle signature in general, i a global perspective and at various altitudes. Thus, we do not dismiss solar forcing of temperatures at 90 km, merely report we fail to see the signature in the dataset presented here. Furthermore, Gan et al. (2016) provide a plethora of references to relevant literature.

An independent (i.e. not influenced by *a priori* conceptions of climate change as was mentioned in the Introduction, viz. Beig et al. (2003) and Schmidt et al. (2006), for example) regression analysis was performed to identify possible change-points in temperature evolution. The method is developed, implemented and described by Muggeo (2003, 2008, 2016, 2017) in which multiple linear fits are applied to the measurements. In this analysis, monthly averages for July and December have been used to represent summer and winter conditions respectively. Although to some degree arbitrary, July being the month subsequent to the solstice, they are qualitatively representative for the lower atmosphere. The selection of months to represent winter is important because January, in particular is characterised by sudden stratospheric warmings (SSWs) (Butler et al., 2017) which often have dramatic cooling effects on mesospheric temperatures. Pedatella et al. (2018) provides an accessible introduction to SSWs and associated vertical coupling, accompanied by a good reference list; SSWs are not the focus of this study but suffice to note that short-term (~days) temperature variations are likely to exceed the solar and anthropogenic forcing. Although it can be discussed whether it is correct to exclude or include SSWs as intrinsic features of climate change (akin to tropospheric extreme weather events) (Kang and Tziperman, 2017) we have chosen to represent winter by December, thus avoiding the issue. For winter, the implementation by Muggeo (2008) identified a change-point in 2012 (±1 year). For summer, a change-point was indicated at 2005, but poor confidence (specifically at 95%) in the slope of the segment encompassing years 2002–2004 inclusive, characterised by little data and end-point uncertainty, leads us to disregard this. Our acceptance of the winter change-point of 2012 and rejection of the summer change-point of 2005 are supported by Tiao et al. (1990): the 2-σ uncertainty in the slope of the summer 2002–2005 segment exceeds the value of the slope itself, whereas for the winter 2002–2012 segment it does not. The aim of this study is not to compare methods of change-point detection, of course. Furthermore, the Muggeo (2008) algorithm assumes a "hinge-point" in 2012, where in reality there is a considerable spread in values and not least undiscovered errors in radar operation.

Having identified a winter change-point in 2012, but no significant one in summer, we now proceed to investigate these segments using

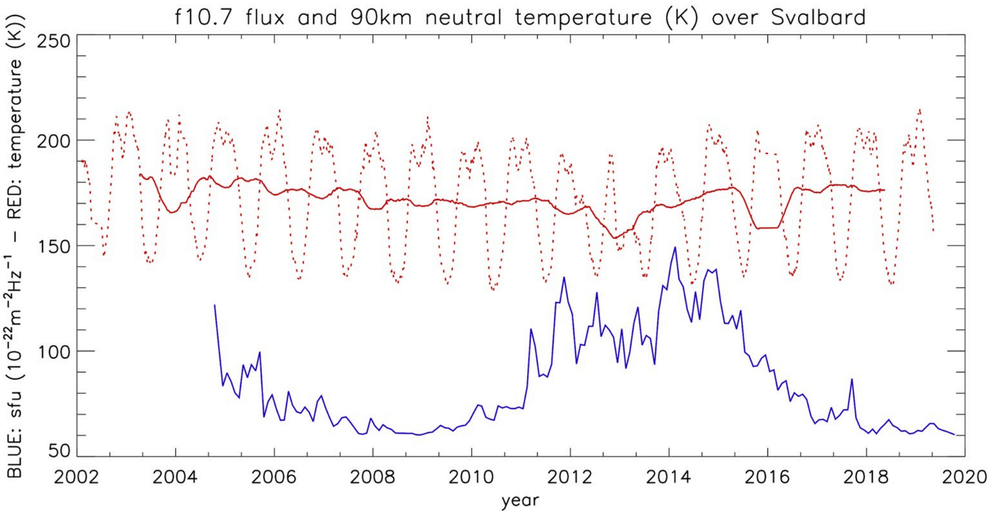

Fig. 2. Daily mean neutral temperatures smoothed using a 30-point (i.e. 1-month wide) running mean, at 90 km altitude and 78°N, 16°E) (red dotted line). The solid red line shows a 1-year wide running mean. Monthly means of the solar f10.7 flux are depicted by the blue line, which in turn illustrates the end of solar cycle 23 and thereafter cycle 24. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

least-squares fit analyses of the subsets of the time-series. These analyses are illustrated in Fig. 3. Here, summer values are represented by June and July, and winter by November and December (again avoiding inclusion of SSWs), in order to improve statistics. Based on the findings identifying the winter change-point, regression lines (least-squares) are fitted to the periods 2002–2011 inclusive and 2013–2019 inclusive. For summer, both these periods and the entire dataset are used. For clarity, uncertainties (1-σ) are indicated by text rather than plotted (Taylor, 1997).

In summer, there is evidence for a trend of -4 ± 1 Kdecade^{-1} and satisfying the 95% confidence condition. Prior to 2012 there is an indication of somewhat steeper cooling (viz. 10 ± 3 Kdecade^{-1}) although after 2012 the uncertainty is too large to trust the 0 ± 6 Kdecade^{-1} (i.e. constant) estimate. In winter, there is considerably more variability in the temperatures in general and therefore the trends obtained cannot be relied on with 95% confidence due to the uncertainties. Prior to 2012, there is an indication of cooling at 9 ± 8 Kdecade^{-1} and thereafter a warming, at 6 ± 8 Kdecade^{-1} Taking into account the uncertainties in the trend-lines and considering in particular the variability in winter temperature values (some of which may be real and some may be instrumental) we hypothesize, as opposed to determine, that an overall cooling of the upper mesosphere took place prior to 2012, but since then this has reduced or even reversed. Again, it must be stressed that these observations are from a specific geographical location. It is also worthy to note that the summer mesopause is on average a few kilometres below 90 km, whereas in winter the mesopause is well above 90 km, such that the respective temperatures are characterised by very different gravity wave modulation. Even so, in summer, the circulation is well defined and centred on the geographic pole such that the results we present may well be representative of a zonal mean. In winter, with opposite circulation, planetary wave activity demands that meridional as well as zonal coverage is desirable. Vincent (2015) gives a modern review and a plethora of references. Furthermore, although tempting to do so, our results must not be construed as any indication of global change, or even more dangerously, any alleviation of anthropogenic forcing. By comparison, Hall et al. (2012) reported a 4 Kdecade^{-1} overall cooling for the period up to 2011, in other words in (not surprisingly) exact agreement with the current finding, except that study did not discriminate between seasons. Similarly Holmen et al. (2015) performed the same analyses for 70°N 22°E for the period 2003–2014, finding an overall cooling of 4 Kdecade^{-1} with 8 Kdecade^{-1} in summer and 1 Kdecade^{-1} in winter. As in this study, the variability in winter generates a considerable uncertainty and not fulfilling the condition for 95% confidence; the overall cooling for the entire period, however, *does*

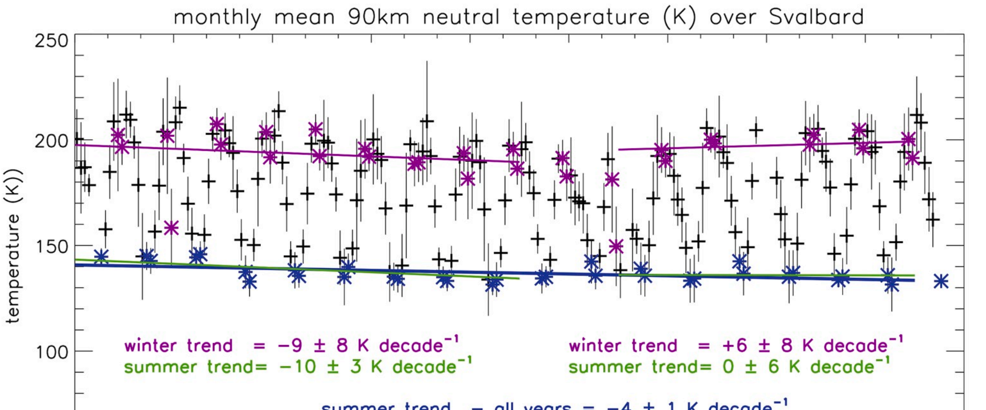

Fig. 3. Neutral temperatures from 90 km altitude and 78°N, 16°E. Black: monthly mean values and associated standard deviations; magenta asterisks: November and December highlighted monthly means; blue asterisks: June and July highlighted monthly means. The magenta line segments show the linear fits to the November and December and (i.e. winter) months, before and after 2012. Similarly, the green line segments show the linear fits to the June and July (i.e. summer) months, before and after 2012. The blue line shows the linear fit to all summer months from 2002 to 2019. Confidence limits are not shown graphically for clarity, but the 1-σ deviations in the fits are given in the annotation together with the slopes of the trend-lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

fulfil the condition. Again, while not presenting results as representative of any geographical area other than the FoV above Adventdalen, the similarity with the FoV above Tromsø (i.e. 70°N 22°E) is reassuring. It is important at this point to be aware of assumptions and caveats made in arriving at these results. All envisaged pitfalls are described in detail by Holmen et al. (2015) but are summarised here:

(a) In the temperature derivation (Hall et al., 2012), a seasonally dependent pressure model is used, which cannot account for possible climate change. The already negative trend in temperature would increase if both pressure and temperature decrease at the fixed altitude of 90 km (and vice versa). Thus, if we could obtain a pressure model that incorporated climate change, the trends we report here would increase in magnitude.
(b) Again, following the method of (Hall et al., 2012), it is also assumed that the normalisation to independent measurements (as opposed to the independent measurements themselves) does not vary during the observation-period.
(c) It is known that the maximum altitude for echo occurrence varies slightly (at least seasonally). Immediately above and below this peak, the meteor trail detections decay rapidly, even over a 1 km range gate. This means that obtained diffusivities might not be representative of the nominal altitude of the range gate.
(d) Our choice to restrict the study to the nominal meteor occurrence peak at 90 km is justified on two grounds. First, a few km above 90 km, diffusion of the meteor trail becomes influenced by electrodynamics (Dyrud et al., 2001). Second, at lower altitudes (e.g. below ~80 km) apparent diffusivity can become approximately altitude independent Hall et al. (2005); Ballinger et al. (2008).

It is difficult to make comparisons with similar observations due to the location of NSMR. Shorter - campaign-based – temperature observations exist (e.g. Höffner and Lübken, 2007) as do hydroxyl emission measurements. Hydroxyl observations in particular, although comprising a longer time-series, are restricted to clear skies and in winter (during darkness at 78°N) (Sigernes et al., 2003; Mulligan et al., 2009; Holmen et al., 2014). Earlier, measurements were made regularly from Heiss Island (80°N, 58°E), and thus a similar latitude to NSMR (Kokin and Lysenko, 1994) but were discontinued long before the observations reported here. The reviews by Danilov (1997) (a pioneering study), Beig (2011), Blum and Fricke (2008) and more recently by Vincent (2015) are good sources, but very high latitude results are sparse. Preceding the observation period in this study, increasing occurrence of noctilucent clouds, proposed by Thomas (1996) to be a consequence of cooling near the mesopause, corresponds to ~2–4 K decade^{-1} cooling (Gadsden, 1990) and similar to our result. Recent research is illustrated by Vincent et al. (2019) (albeit for summer only in the southern hemisphere) for example where the vertical wind component is examined (upwelling and therefore adiabatic cooling contributing to temperature variation).

To summarise, it is common knowledge that increasing concentrations of greenhouse gasses such as CO_2 and methane are responsible for the increasing temperatures in the troposphere and it is accepted that the same constituents result in cooling of the middle atmosphere (i.e. above ~20 km altitude) (e.g. Roble and Dickinson, 1989; Rishbeth, 1990). This cooling in the middle atmosphere results in a net shrinking and thus a corresponding lowering of upper mesospheric pressure surfaces. The scenario is supported by our findings, while the 2012 change-point will need to be validated by further observations of temperatures and explained by observations of underlying aeronomy.

3. Summary

By using echo fading time data from the Nippon/Norway Svalbard Meteor Radar (NSMR), it has been possible to determine estimates of ambipolar diffusion and, thereafter estimates of daily mean temperatures. These estimates were then calibrated using independent observations following the method of Dyrland et al. (2010) thus yielding a little-interrupted time-series of neutral temperatures at 90 km altitude for 78°N, 16°E between 2002 and 2019 inclusive. We fail to perceive (as opposed to disprove) any correlation with the corresponding solar cycles (determined by the f10.7 solar flux) and therefore conclude the variations we detect are independent of solar forcing. There is an indication of a change-point in observed trends in 2012, primarily in winter. Prior to 2012, we detect a cooling in winter followed by a warming after 2012, albeit with low degrees of confidence due to high variability, data-gaps and shortness of the time-series segments. On the other hand, during summer we can report a cooling over the entire 2002–2019 period of 4 ± 1 K decade^{-1}. We refrain from attributing the summer cooling, and especially the apparent change-point in winter trends to any particular mechanism, although cooling is commensurable with increasing concentrations of greenhouse gases in the underlying middle atmosphere.

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