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Impact of natural variability in the 11-year mesopause region temperature observation over Fort Collins, CO (41°N, 105°W)

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Abstract

The Colorado State University Sodium Lidar has measured temperatures in the mesopause region (80–105 km) for over 11 years. Based on 7 years' observation, an episodic change with a warming of 11.8 K in 1993 at the mean mesopause altitude of 98 km, attributable to Mt. Pinatubo eruptions, was reported. In this paper, we focus on the solar cycle effects. With 11 years of data, we observed a maximum solar response of 0.06 K/SFU at 99 km, which decreases at lower and higher altitudes to nearly zero and appears to change sign at ~82 and ~104 km. The phase changes are consistent with earlier midlatitude observation with incoherent scatter radar above and Rayleigh lidar below the altitudes reported here, providing clear experimental evidence of dynamical influences throughout different layers of Earth's atmosphere. We discuss the altitude dependence of response amplitudes and the effect of volcanic and solar flux variability have on the mesopause region temperatures, as well as long-term temperature trends.

Keywords: Lidar measurements; Mesopause temperture; Volcanic and solar cycle effects

1. Introduction

Around 1990, it became evident from satellite observation and model calculation that enhanced green house gases in the atmosphere would produce a cooling trend in the stratosphere and mesosphere. From temperature measurements based on passive sensing of natural OH emission and on rocket flights, there was considerable difficulty in determining long-term temperature change for the entire mesopause region (80–105 km). Coincidentally, the concept of remotely observing temperatures by probing laser-induced fluorescence from naturally occurring sodium atoms in the mesopause region became mature about this time. A unique ground based lidar for measuring nocturnal temperatures was deployed at Fort Collins, CO (41°N, 105°W) in 1989 (She et al., 1990), enabling the investigation of long-term temperature changes, with the potential of assessing anthropogenic effects. An 11-year data set with natural variability is still too short to assess the sign of the trend, but it is long enough for the investigation of long-term changes attributable to both volcanic eruption and solar flux variability.

By 1997, we had observed an episodic warming which peaked in 1993, attributable to Mt. Pinatubo eruption (She et al., 1998; Krueger and She, 1999), starting investigations of long-term changes. Recently comparisons of temperatures observed between April 1999 and December 2000 to the 8-year climatological mean (data between 1990 and March 1999) (She et al., 2000), yielded evidence of a solar cycle effect (She et al., 2002). Although these naturally occurring external perturbations to Earth's atmosphere are clear, their quantification is much more difficult, due to large geophysical variability and the lack of a physical model to describe the atmospheric responses. We fit nightly mean temperatures to an empirical model which is similar to that used by others (Keckhut et al., 1995). Here we focus on the atmospheric behavior over an 11-year solar cycle, in terms of the altitude dependent temperature change per solar flux unit (SFU). Limitations of the simple model are reflected upon the potential cross-talk between volcanic

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and solar effects as well as their impact on trend determination due to the geophysical noise in the data set. Trend determinations are limited by the marginal length of the data set, as well as subtle indirect effects of time-dependent forcing terms resulting from lack of physical understanding.

2. Data set and qualitative observation of naturally occurring perturbation

After four and five nights of initial observations, respectively, in springs of 1990 and 1991, quality regular temperature measurements, were made over Fort Collins, CO (41°N, 105°W) starting May 29, 1991. A temperature profile is computed for each night from photo-count profiles vertically smoothed using a FWHM Harnning window of 3.7 km giving a typical measurement precision of ~0.6 and ~5 K near the peak (92 km) and edges (81 and 107 km) of the Na layer, respectively. Observations through 1999 (2001) yielded a total of 455 (591) nightly mean temperature profiles.

Nightly means were computed from photocounts integrated 4–13 h. As such, most gravity wave, and terdiurnal and semidiurnal tidal perturbations were averaged out and annual and semi-annual perturbations dominate the main temperature variations at most altitudes. Fig. 1 shows the temperature at 98.5 km (squares) and the 81 day smoothed F10.7 solar flux (line) used as the proxy for solar forcing. Though over-simplified, the lidar data show a warming episode, peaking in 1993, riding on a cooling background for data before the solar minimum at 6.49 years. Between the solar minimum and the 7.25 years, the end of data used in our previous 7-year study, the temperature at 98.5 km appears to be constant. After that point, the background temperatures turned into a warming phase with expected temperature increase to the end of 1999. Then, at the second half of 2000, the temperatures showed abnormally high values, which appears to occur with an approximate 0.5-year delay from the solar flux maximum at the first half of 2000. Remsberg et al. (2002) have detected a 1-year delay in solar response from 9.5 years of HALOE data. The unusual manner of the mesopause temperatures responding to the solar max suggests that in addition to a 0.5-year delay, the functional dependence of temperature on solar flux proxy near solar max may be more complex and nonlinear. These empirical facts and the effect of geophysical variability in data on the delineation between volcanic and solar responses will be discussed and be used to guide our strategy for data analysis as described below.

3. Data analysis and least-square fit to an empirical model

Due to the periodic nature of the annual and semi-annual variations, their amplitudes and phases can be extracted reliably from the time series. The observed temperature at an altitude, $T(z,t)$, is fit to

$$\begin{aligned} T(t) = {} & \alpha(z) + \beta(z)t + A_1(z)\cos(2\pi t) + B_1(z) \\ & \times \sin(2\pi t) + A_2(z)\cos(4\pi t) + B_2(z)\sin(4\pi t) \\ & + \gamma(Z)P(z,t) + \delta(z)Q(t), \end{aligned} \tag{1}$$

where t is time in years since January 1, 1990, the Pinatubo impact function (and amplitude) is $P(z,t) = 2/\{\exp[-(t-t_0)/t_1] + \exp[(t-t_0)/t_2]\}$ (and $\gamma(z)$) with the z-dependent fit parameters t_0, t_1, and t_2. (She et al., 1998), implicating delay, rise and fall times, respectively, and $\delta(z)$ depicts the solar response in K/SFU. The solar flux unit (SFU) is 10^{-22} W m^{-2} Hz^{-1} and $Q(t)$ is the 81-day smoothed F10.7 solar flux. The constant $\alpha(z)$ is the annual nocturnal mean with the long-term average perturbations removed, and the rate constant, $\beta(z)$, then represents linear trend in K/years, presumably due to anthropogenic effects.

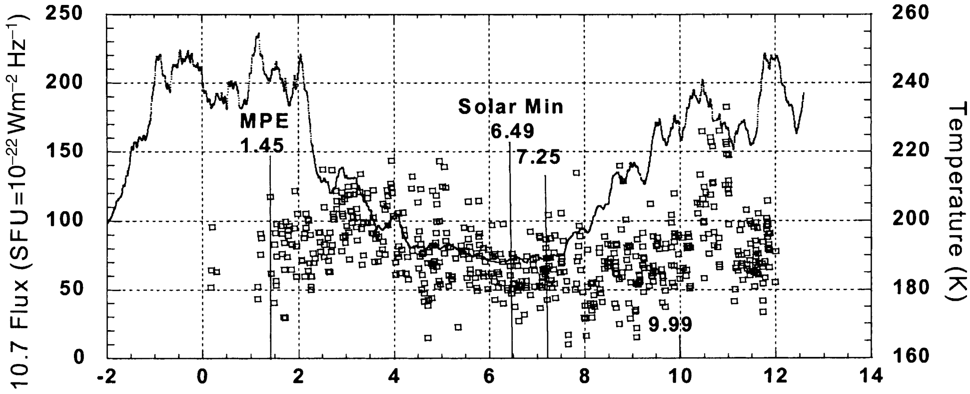

Fig. 1. Time series of solar flux (81-day mean, 88-02) and Na lidar temperatures (98.5 km; 90-01), showing their apparent correlation. The time of Mt. Pinatubo eruption is marked as MPE.

Depending on the length of the data set and physical insight, some of the constants may be set to zero. In analyzing the previous 7-year data set up to 7.25 years, we set $\delta(z) = 0$. This is because the data set covers only falling phase of the solar flux which is approximately linear so both solar response and non-solar trend are lumped together into the $\beta(z)t$ term. However, the impulse response to volcanic eruption is well captured in the 7-year data set (She et al., 1998). Since the background temperature change appears to have opposite signs in data before and after the solar minimum ($t = 6.49$ yeras) as can be seen in Fig. 1, it would be problematic to use this model ($\delta(z) = 0$) for a data set much beyond solar minimum.

For a data set longer than 7 years, we include the solar forcing, i.e., allow nonzero $\delta(z)$. However, if the data set is much longer than 7 years, a different problem arises. If we try to fit the 11-year data set to Eq. (1), the time series may be too long, so that the statistical fluctuations in the data coupled with the rising solar forcing would tend to prolong the fall time, t_2, and extend the volcanic impact function longer than it should be. This in turn may contaminate the solar response as well. Thus, to avoid this contamination when analyzing an 11-year data set, we should ignore the detailed time dependence of the episodic response by setting $\gamma(z) = 0$. Thus the volcanic response between 1991 and 1994 will be averaged and the associated episodic warming will be included in the background annual mean, $\alpha(z)$. Though the 11-year data set includes solar max, the suspected nonlinear response mentioned earlier may not be as important as the apparent 0.5-year delay in solar response. Since the anomalous temperature response appeared only in half year duration, it should not affect the mean solar response $\delta(z)$ much. Guided by these observational physical insights, we follow others' lead and keep the solar response simple, i.e., linear in solar activity, but impose a 0.5 year delay. We then perform analysis with two different data sets. (A) A shorter data setup to the end of 1999 is least-square fit to Eq. (1) with all terms retained. (B) A data set with all available data to the end of 2001 is least-square fit to Eq. (1) by removing the explicit volcanic response, i.e., setting $\gamma(z) = 0$.

3.1. Temperature response to solar activity

We compare the solar responses from these analyses by showing their altitude dependence in Fig. 2. Both (A) and (B) analyses give essentially the same result. The error-bars indicate 1σ uncertainty. The results are, however, statistically significant as the mean values between 87 and 102 km from the 11-year data set are about 6σ from zero. The maximum solar response from Fig. 2 is 0.06 K/SFU at 99 km; this corresponds to ~11 K per solar cycle, a reasonable amplitude (Huang and Brasseur, 1993).

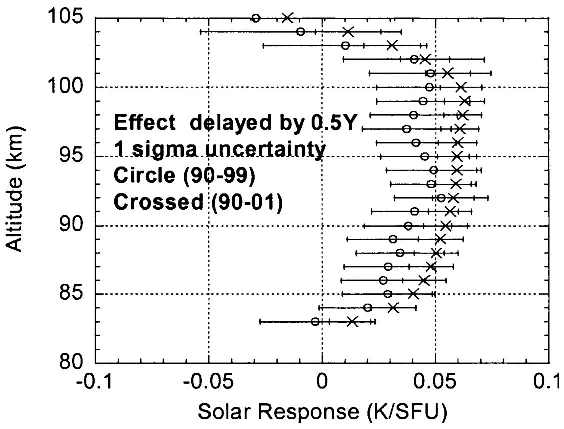

Fig. 2. Linear solar response in K/SFU.

Our results indicate a negative correlation above 143 km and below 82 km. Negative correlation has also been reported in the literature (Keckhut et al., 1995; Hernandez, 1976), suggesting that dynamics plays an essential role. Dynamical coupling and feedback effects (Labitzke, 1987) have been of considerable interest in the past two decades. Using incoherent scatter radar data between 100 and 140 km from Saint Santin (45°N, 2°W) and Rayleigh lidar data between 30 and 80 km from Observatory of Haute-Provence (OHP, 44°N, 6°E), Chanin et al. (1989) discussed the dynamical effects including quasi-biennial oscillation (QBO) on the temperature response to solar variability, yielding an altitude dependence with phase reversals. Since our Na lidar is located at mid-latitude and the range of our data set falls between 80 and 105 km, it would be instructive to re-visit the question of dynamical influence on solar response and investigate its altitude dependence from 30 to 140 km. For this purpose, we took the San Santin incoherent radar temperature response from Fig. 5 of Chanin et al. (1989), averaged over both QBO phases, and Rayleigh lidar temperature response from Fig. 5(a) of (Hauchecorne et al., 1991), and plot along with our 11-year Na lidar temperature response to solar activity in Fig. 3. The 1σ uncertainly of the response (same as in Fig. 2) is shown for Na lidar data, which is quite small in the scale plotted. It is intriguing to see that the altitude dependence of solar responses, including altitudes of phase reversal, measured from three different instruments, each covering a different altitude range, can be more-or-less continuously connected into a single curve between 30 and 140 km. The observation of several phase changes in solar response as shown in Fig. 3 is a strong statement of dynamical influences, showing that the atmospheric layers are dynamically coupled even at a decadal scale. We hope our result will stimulate theoretical discussion and model simulation aiming at the understanding of this interesting and significant effect.

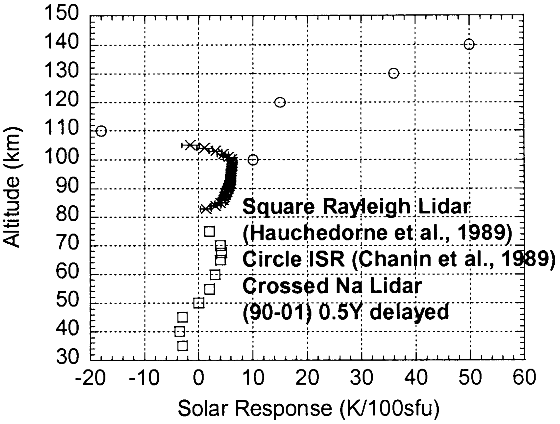

Fig. 3. Solar cycle effect as a function of altitude measured by Rayleigh lidar (OHP), Na lidar (CSU) and incoherent scatter radar (San Santin).

4. Response to volcanic eruption

We now discuss the volcanic response. The four parameters: amplitude, γ, time delay, t_0, rise time, t_1, and fall time, t_2, were determined by best fit of the 9-year data set to the model, Eq. (1). To evaluate the episodic effect, as before we plot the profiles of time of peak temperature change as well as of temperature change as shown in Fig. 4(a) and (b), respectively. Plotted in the same figures are the results deduced from the 7-year data set without expressing the solar response explicitly (Krueger and She, 1999). Depending on altitudes, the time delay of peak temperature change is about 2 years from eruption at $t = 1.45$ years below 90 km and 1.5 year above 93 km. There is good agreement between the two data sets. The relative altitude dependence of peak temperature change appear to be the same, though the 9-year data set show ~3 K warmer throughout the altitude range, giving, for example a 11.8 vs. 14.9 K warming at the annual mean mesopause of 98 km. This discrepancy is the result of different models used with the solar response explicitly included in the best fitting of the 9-year data set. Including the decreasing solar flux between 1990 and 1996, results in a larger volcanic response.

A similar difference in the annual nocturnal mean with long-term average perturbations removed, $\alpha(z)$, between the 9-year analysis and 11-year analysis as shown in Fig. 5, can also be understood. When episodic warming is included explicitly in the 9-year analysis, this warming is not included in $\alpha(z)$, leading to a episodic warming removed temperatures, cooler by ~5 K (She et al., 2000). Indirectly, this difference demonstrates the existence of a volcanic response in the observed temperatures whether this response is explicitly included in the fit-model or not. On the other hand, it also suggests that when a longer data set is available, one can use a model that contains no explicit volcanic response to avoid contamination in solar response, yet its effect can be absorbed into the annual mean at least in the average sense. For the solar response, using the 11-year analysis and ignoring the detailed time dependence of volcanic response, should produce more correct and a less contaminated response amplitude.

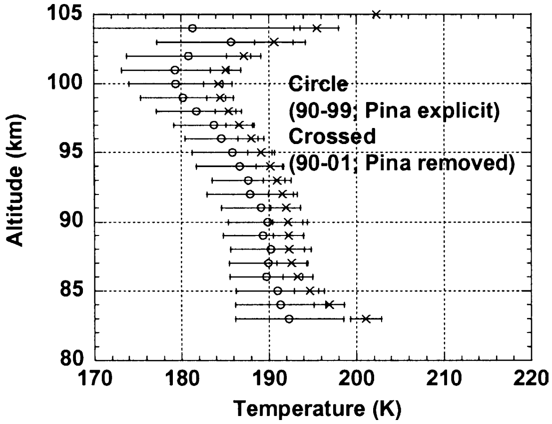

Fig. 5. Long-term annual mean with and without Pinatubo term in fitting.

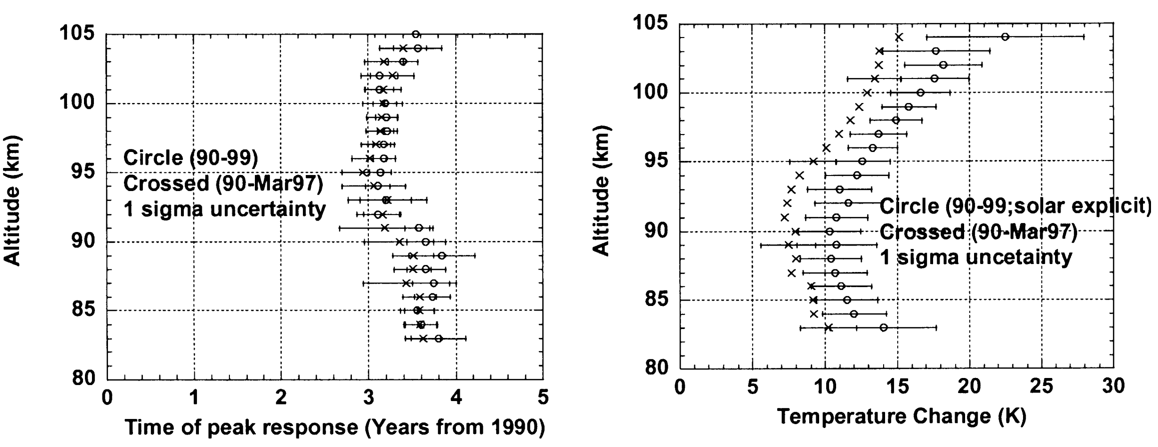

Fig. 4. Episodic response to Mt. Pinatubo eruption, (a) time of peak response, and (b) peak temperature change.

5. Trend analysis

Data sets longer than a decade contain signature of both, the solar cycle effect and long-term trend. The occurrence of noctilucent clouds has steadily increased in the past 30 years with a superimposed modulation of 10.5 year period (Gadsden, 1997). Reflection height of radiowaves over the past 30 years has shown a steady subsidence modulated by quasi 11-year oscillation due to solar variability (Taubenheim et al., 1997). Similarly, the centroid height of the atmospheric sodium layer showed a gradual decline with the existence of a 10-year solar cycle related oscillation (Clemesha et al., 1997). In addition to the solar cycle effect, each of these observations revealed a long-term temperature trend. Though with a different (smaller but more controlled) data set, Kirkwood and Stebel (2003) found solar cycle signal but no long term trend from NLC observation, the subsidence of radiowave reflection still stands and continues to be studied (Bremer and Berger, 2002). Upon further analysis of atmospheric Na signal, Clemesha et al. (2003) now find no trend. However, improved statistics on satellite orbit subsidence now appear to provide a creditable evidence of upper atmosphere cooling and anthropogenic effects (Keating et al., 2000).

Direct temperature measurements have also been used to assess trends, noticeably, data taken from routine rocket launches between mid-1960s and early 1990s, covering altitudes up to 70 km, at different latitudes (Golitsyn et al., 1987), at Ryori (39°N, 141°E) (Keckhut and Kodera, 1999), and in low latitudes (8°S–34°N) (Keckhut et al., 1999), respectively. Generally, they find negative trends in the stratosphere and lower mesosphere. Between 30 and 80 km, regular nighttime Rayleigh lidar observation at Observatory of Haute-Provence (OHP, 44°N, 6°E) since 1979 (Hauchecorne et al., 1991) have provided evidence for ~−0.4 K/years between 60 and 70 km.

In the mesopause region, one has passive observations of species layer temperatures from OI emission at 97 km, Na emission at 92 km and OH emission at 87 km, and sounding of ionosphere for 105–110 km. For these Lagrangian measurements, the mean altitude of the tracer, OI or OH, may be influenced by atmospheric dynamical and photochemical perturbations during the measurement (Melo et al., 2001). Semenov et al. (2002) have recently incorporated these measurements with rocket sounding and reported monthly mean trends at mid-latitudes with annual mean trend being negative in the stratosphere and lower mesosphere, peaked at 80 km with a rate of −1 K/years, and then decreasing to zero at 95 km, beyond which the trend becomes positive and increasing steadily to 1.5 K/years at 110 km. On the other hand, by comparing weekly mean temperatures measured from 89 rocket-falling spheres since 1987 to 21 rocket-grenades measurement between 1963, Lübken (2000) deduced a zero trend at 82 km in polar summer mesosphere. Obviously, considerably more of the direct measurements of temperatures are needed.

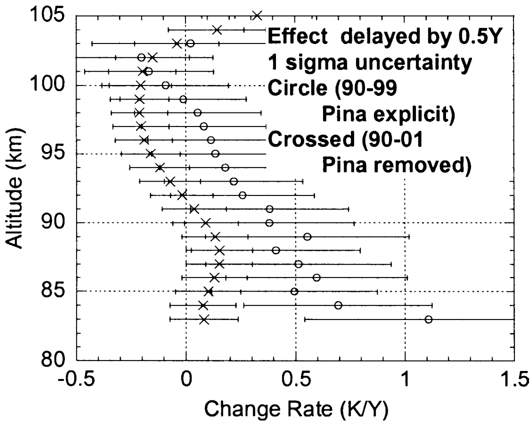

Fig. 6. Linear temperature trends derived from 9-year data set with Pinatubo forcing term and 11-year data set without it.

It is in this light that we turn to the trend determined from 11-year Na lidar observation at a single mid-latitude site despite its short length. As plotted in Fig. 6, the trend deduced from 9-year analysis has larger uncertainty and larger variability because a shorter data set is fit to a function with more parameters. Further, the inclusion of the volcanic response explicitly in the 9-year analysis makes it a nonlinear least-square fit. The 11-year analysis (with the Pinatubo term removed), which has fewer fit parameters is a linear least-square fit, leading to a unique determination of the fit parameters, thus a smoother profile with smaller 1σ uncertainty. Though both results are within each other's error-bars, we prefer the trend deduced from the 11-year analysis.

For the 11-year results, the trend overlaps zero within 2σ uncertainty (or 95% confidence), so the sign is not determined. However the best estimate of the trend is ~0.2 K/years between 83 and 90 km, goes to zero at 92 km, and becomes negative up to 102 km and nearly constant about −0.2 K/years between 96 and 101 km. The trend turns positive above 103 km and steadily increases to 0.35 K/years at 105 km. Though a positive trend between 83 and 90 km is in disagreement with Semenov (2002), it is consistent with Keckhut et al. (1995). That the trend becomes positive again beyond 103 km is in agreement with Semenov and a recent modeling result (Akmaev, 2002).

6. Discussion and conclusion

The time dependence of temperature profiles in the mesopause region (83–105 km) over Fort Collins, CO, were fit to a simple model capable of capturing the response of volcanic and solar forcing as well as a linear trend. In addition to the 9-year (with explicit volcanic forcing) and 11-year (without explicit volcanic forcing) analyses discussed above, we have also analyzed the same data set with other alternatives. Fitting 11-year data set to Eq. (1) with explicit volcanic forcing term leads to a larger solar response and it decreased to zero at a higher altitude. The associated linear trends are between 0.5 and 1.5 K/years, unacceptably large. On the other hand, fitting the first 9-year data set without explicit volcanic forcing leads to a solar response with similar altitude dependence, but 40% smaller in amplitude. The associated linear trends now have opposite sign and are between −0.5 and −2.0 K/years, again unacceptably large. We have also considered the cases without imposing a solar delay. For the 11-year analysis, we found the same solar response and a reasonable trend of ~0 between 83 and 88 km, and turns negative between 89 and 103 km with max absolute value of 0.4 K/years. Like the case with 0.5 years delay, the trend becomes positive between 103 and 105 km. For the 9-year data, we find that the trend is essentially the same (with perhaps 0.1 K/years more negative compared to the case with 0.5-year delay). The solar response is identical between 80 and 92 km, and 20% larger between 93 and 100 km; unlike the case with delay, the solar response increases to 0.14 K/SFU. Since the solar response $\delta(z)$ is the only solar parameter for each altitude, we would expect the same amplitude whether one uses 9-year data set or 11-year data set. We thus prefer the use of a 0.5 years delay. For the solar response and linear trend, we believe that the simpler model with 0.5 years delay and 11-year data gives the most creditable results. Within the simpler model, the result of 11-year data set without assuming delayed solar response is similar and also credible. What is presented here represents the first step in a systematic analysis of solar response. We hope to examine these and possibly more options more carefully with one more year of data in the future. With a longer data set, we will group our data according to QBO and season and attempting to examine the difference in solar response between different QBO phases and between winter and summer.

In conclusion, our 11-year Na lidar data clearly revealed the fact that both Mt. Pinatubo eruption and solar flux variability affect mesopause region temperatures. The volcanic response is found to agree with early results using the 7-year data set, except the peak episodic change should be increased by ~3 K, when the solar effect is properly and explicitly accounted for. The solar response increases from zero at ~82 km to 0.05 K/SFU at ~90 km, and it stays there until 101 km with the peak of 0.06 K/SFU at 99 km. It then decreases quickly to zero at 104 km and becomes negative at 105 km. The solar response amplitude changes with altitude suggest that dynamics plays an important part even in perturbation of a long period of 5–10 years. This dynamical coupling becomes more clear when the solar response of Rayleigh lidar covering 30–80 km, of Na lidar covering 80–105 km and that of incoherent scatter radar, covering 100–140 km are plotted in one graph to form a single continuous curve.

Though our 11-year data set is not long enough to deduce the sign of the trend, our unique data set from a single observational station nonetheless can be used to aid analysis strategy and for information and discussion purpose. That our deduced trend falls in the range of −0.2 to 0.2 K/years, and the altitude dependence are consistent with other observational and model results reported in the literature is intriguing and by no means coincidental. Of course, only continued careful observation for another solar cycle can test its validity and improve its results.

Note added in proof

We have discovered 21 problematic high temperature data points among the 41 points acquired during the period between May 10, 2000, and January 9, 2001. After removing these 21 points, the remaining 570 observed temperatures still captured the solar max well; it however eliminated the argument for a 0.5Y delay in solar response. Re-analysis of this data without delaying the solar response yields a nearly constant solar response of 0.04K/SFU between 92 and 99 km, which decreases to nearly zero at ~84 km and ~103 km. The temperature trends are shifted lower by 0.45K/Y, giving a trend which varies from 0.3K/Y at 84 km to 0.7K/Y at 100 km, and then goes positive to 0.1 K/Y at 105 km. The observed cooling trend between 90 and 100 km is now statistically significant.

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