Rayleigh Scatter Lidar Observations of the Midlatitude Mesosphere's Response to Sudden Stratospheric Warmings

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Abstract-The original Rayleigh-scatter lidar that operated at the Atmospheric Lidar Observatory (ALO; 41.7°N, 111.8°W) in the Center for Atmospheric and Space Sciences (CASS) on the campus of Utah State University (USU) collected a very dense set of temperature data for 11 years, from 1993 through 2004. The temperatures derived from these data extended over the mesosphere, from 45 to 90 km. This work will focus on the extensive Rayleigh lidar observations made during the seven major SSW events that occurred between 1993 and 2004. In order to determine the characteristics of the midlatitude mesospheric temperatures during SSWs, comparisons were made between the temperature profile on an individual night during a SSW event and the climatological (11-year average) temperature profile for that night. An overall disturbance pattern was observed in the mesospheric temperatures during these SSWs. It included coolings (sometimes very significant) in the upper mesosphere and warmings in the lower mesosphere.

I. INTRODUCTION

Sudden Stratospheric Warmings (SSWs) are major disturbances in the polar region of the winter hemisphere that cause major changes in stratospheric temperature and circulation. SSWs are characterized by a temperature increase of tens of degrees Kelvin, averaged over 60°-90° N or S latitude, and a weakening of the polar vortex that persists for the order of a week at the 10 hPa level (roughly 32 km) [*Labitzke and Naujokat*, 2000]. The polar vortices are cyclones centered on both of the Earth's poles that are present from the upper troposphere to the upper stratosphere. Strong eastward zonal winds define the polar vortices in the winter. Increased planetary wave (PW) activity in the winter hemisphere leads to increased PW breaking in the polar stratosphere and the deposition of the PW's westward momentum in the polar vortex. This weakens the polar vortex, and in the case of major SSWs, can reverse the zonal wind direction to westward. The reversal of the stratospheric jet allows more eastward propagating gravity waves (GWs) to travel up into the mesosphere where, in normal winter conditions, westward propagating GWs dominate [*Liu and Roble*, 2002]. The atypical wintertime GW filtering and the resulting dominating westward GWs induce an equatorward circulation in the mesosphere, similar to what it is in summer, which leads to the cooling of the upper mesosphere. While these mesospheric coolings have been observed in the polar regions for several decades [*Labitzke*, 1972], they have only recently been observed at mid-latitudes [*Yuan et al.*, 2012].

II. MAJOR SSWs FROM 1993-2004

The types of SSW events described in *Labitzke and Naujokat* [2000] make up one of the most widely accepted SSW classification systems. This system defines four different types of SSWs as follows:

- ***Major.*** These events involve a stratospheric temperature increase averaged over the latitudes 60° and poleward at 10 hPa. They also must include a complete reversal of the zonal-mean zonal winds from eastward to westward at 60° at 10 hPa. This creates a complete change in the circulation, or a breakdown, of the polar vortex.
- ***Minor.*** These events are the same as major SSWs save for the zonal wind field reversal.

They often have smaller stratospheric temperature increases than major SSWs.

- ***Final*****.** These warmings mark the transition from winter to summer stratospheric circulation in that in the summer, the stratospheric polar vortex switches from an eastward direction to a westward direction. These warmings can either include or not include the zonal wind reversal, however if they do, they are almost immediately followed by the usual seasonal transition from eastward to westward zonal winds.
- ***Canadian*****.** These geographically localized events take place when the Aleutian anticyclone (rotates clockwise), which is located in the Northern Pacific, intensifies and moves poleward. These involve warmings over the Canadian Arctic Pole and sometimes, briefly, zonal wind reversals, but never a full breakdown of the polar vortex.

In this initial study of the mesosphere's response to SSWs above Logan, UT, we will focus on periods when there were major SSW events during the ALO Rayleigh-Scatter Lidar's (RSL's) original operational run, from 1993-2004. For the duration of this paper, the term "sudden stratospheric warming" will refer to the major events during this period. Table 1 gives a summary of the seven major SSW event periods that were captured by the RSL. The major SSW events were defined using the NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) database's zonal mean temperatures averaged over 60°-90° N and the 60° N zonal-mean zonal winds, both at 10 hPa [*NASA MERRA*]. Examples of the MERRA zonal temperatures and winds can be seen in Figure 1 for the January-February 2003 SSW. The vertical blue lines denote the peak date of the January 2003 major warming.

Table 1. List of major SSWs and RSL data from 1993-2004

SSW Event	Peak Date	Nights of RSL Data
Jan-Feb 1995	03 Feb 1995	18
Dec 1998- Jan 1999	15 Dec 1998	16
Feb-Mar 1999	03 Mar 1999	19
Mar-Apr 2000	15 Mar 2000	9
Jan-Mar 2001	15 Feb 2001	33
Feb-Mar 2002	15 Feb 2002	8
Jan-Feb 2003	14 Jan 2003	18

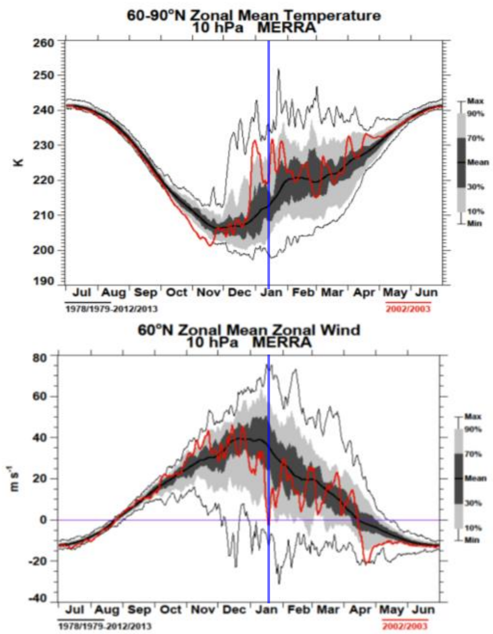

Figure 1. NASA MERRA temperature (top) and zonal wind (bottom) data for the 2002-2003 winter. The vertical blue lines mark the onset of wind reversal, also known as the "peak date", of the Jan 2003 major SSW [*NASA MERRA*].

III. ALO RSL CONFIGURATION 1993-2004

The original Rayleigh-scatter lidar system lidar that ran at the midlatitude site (41.7° N, 111.8° W), on the campus of Utah State University from 1993-2004 was comprised of a Nd:YAG laser operating at 30 Hz and either 18 or 24 W at a wavelength of 532 nm. The receiving telescope had a diameter of 44 cm and thus a receiving aperture of 0.15 m^2. Overall the system had a Power-Aperture Product (PAP) of 2.7 Wm^2 or 3.6 Wm^2, depending on which laser was being used.

The RSL measured relative densities that were then reduced using the Chanin-Hauchecorne method [*Hauchecorne and Chanin*, 1980], which uses hydrostatic equilibrium and the ideal gas law to give absolute temperatures. The initial temperature values for the downward integration came from the CSU climatology [*She et al.*, 2000].

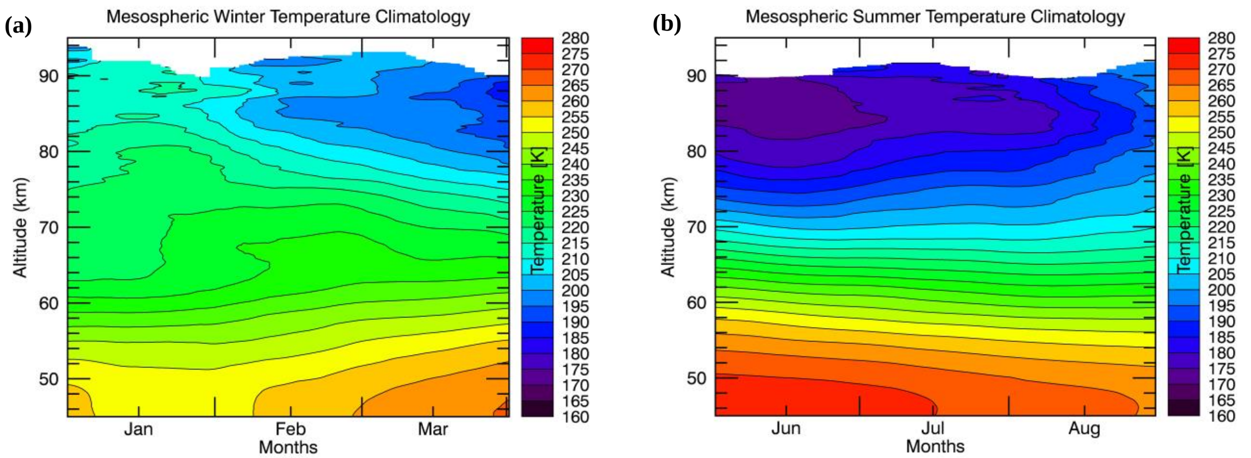

Figure 2. Winter (a) and summer (b) temperature climatologies from the 11-year ALO Rayleigh Lidar dataset

The composite year temperature climatology was created by averaging over a window 31 nights wide and 11 years deep, centered on each night. [*Herron*, 2007].

IV. ALO RSL SSW OBSERVATIONS 1993-2004

During a SSW event, the polar stratosphere switches from typical winter conditions to summer conditions for the order of a week. At approximately the same time, we will show that the midlatitude mesosphere undergoes a similar season-like transformation. The winter (January-March) and summer (June-August) ALO climatologies are seen in Figures 2a and 2b, respectively. In Figure 3 (a-g), the ALO RSL temperatures for each of the seven SSW event periods are shown with red vertical lines denoting the peak of the SSW event. For most of these event periods, the RSL temperatures have a range closer to the temperature range characteristic of the climatological summer (~165-280 K) rather than that of the climatological winter (~190-270 K). In fact, of all the SSW event temperatures, the temperature minimum is approximately 134 K, which is over 30 K cooler than the climatological temperature minimum of 165 K. The RSL temperatures during the SSW periods show the coldest temperatures between 70-93 km and the warmest temperatures from 45-55 km, which is similar to the summer climatological values. The coldest temperatures in the upper mesosphere occur before, during, and/or after the peak date of the SSW, depending on the particular event, in these time series plots.

To gain a better understanding of the time evolution of the mesospheric coolings at mid-latitudes, temperature difference plots were created and can be seen in Figure 4 (a-g). The temperature differences were calculated by subtracting the climatological night's temperatures from the night-time average's. This way, coolings are represented by negative temperature difference values and warmings are represented by positive values. Temperature difference values of ± 5 K are taken to be the noise level in these plots. Night zero is the peak date of the corresponding SSW event, negative night values are prior to the peak of the event and positive night values are after the peak of the event. In Figure 4, a time evolution "rise-and-fall" pattern emerges from five of the six plots that includes a cooling, between 70-80 km that precedes night zero, that then intensifies and moves up (rises) in altitude near night zero and dissipates and lowers (falls) in altitude after night zero. The magnitude of these coolings range from -6 to -45 K. This puts them on par with the coolings

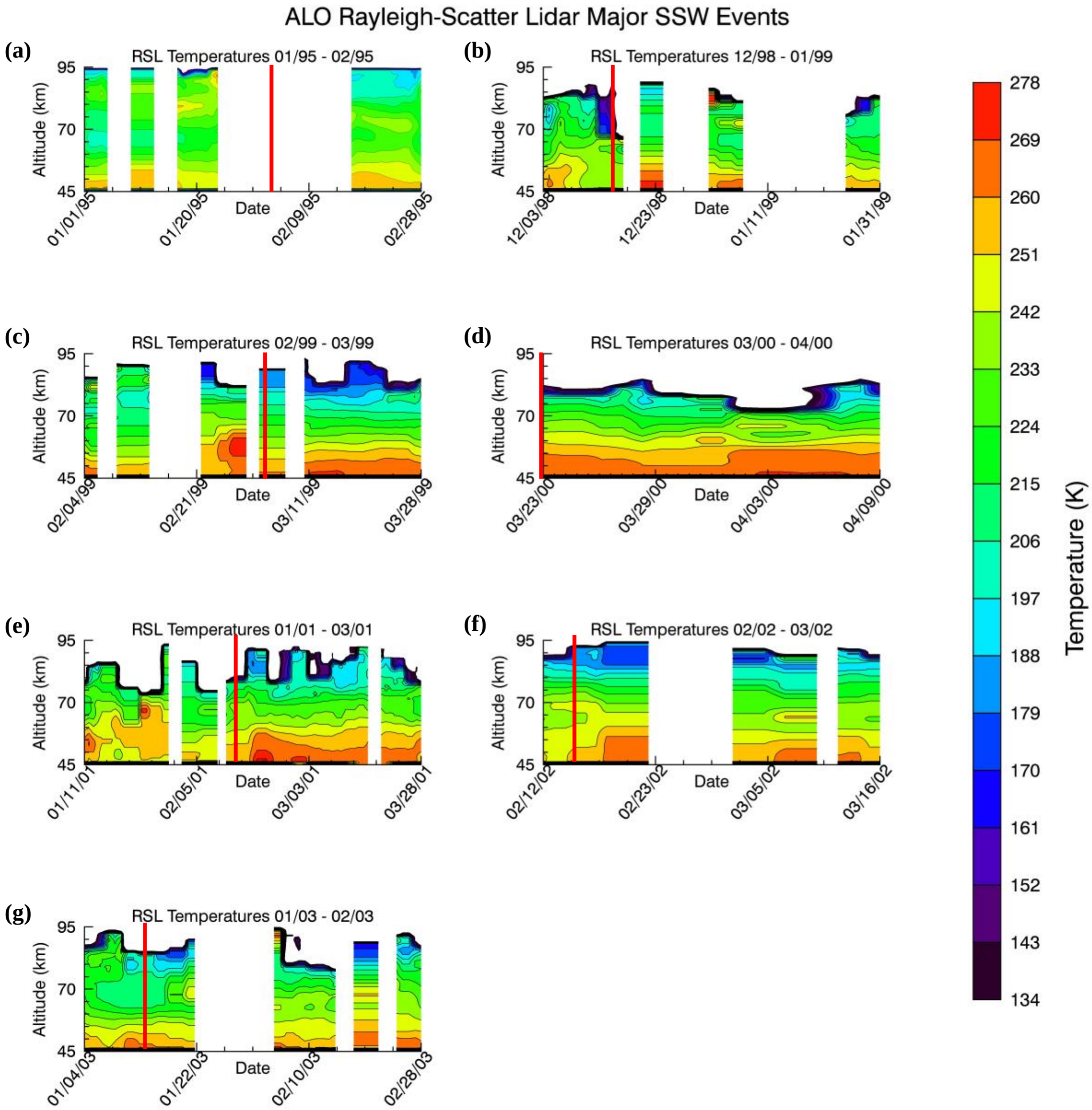

Figure 3. ALO Rayleigh-scatter lidar mesospheric temperatures for the seven major stratospheric warming event periods from 1993-2004

that are seen in the polar mesosphere and makes them much stronger than what was predicted for the midlatitude mesosphere [*Liu and Roble*, 2002]. Additionally, two of the seven events in Figure 4 show warmings below approximately 70 km of 10-45 K magnitude. Again, these are much stronger than what has been predicted for the midlatitude mesosphere.

V. CONCLUSIONS

In this study, we have shown that the mesospheric coolings in the upper mesosphere, associated with sudden stratospheric warmings, extend down to mid-latitudes for almost every major SSW event between 1993 and 2004. These coolings were shown to have significant magnitudes of up to -45 K, which is much higher than what had been predicted at midlatitudes. Mesospheric warmings of significant magnitude were also

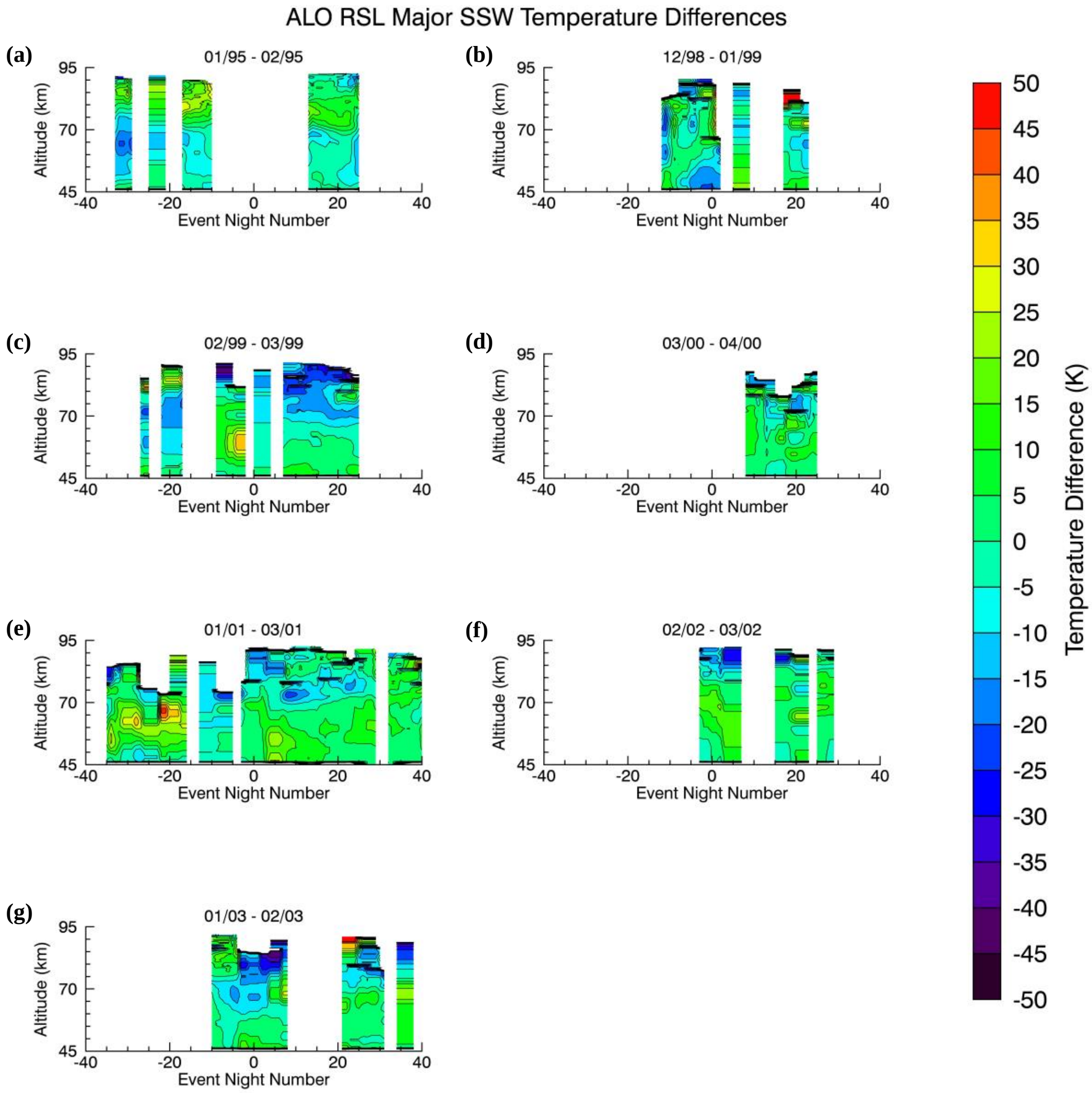

Figure 4. ALO Rayleigh-scatter lidar mesospheric temperature differences for the seven major stratospheric warming event periods from 1993-2004. Temperature differences were calculated by subtracting the temperatures from the corresponding day of the year of the climatology from the all-night averaged temperatures for a given night in an SSW event period.

observed in the lower mesosphere, at this midlatitude site, though less frequently than the coolings at higher altitudes. Finally, a rise-and-fall pattern in the time evolution of the upper mesospheric coolings was illustrated using the differences between the climatological temperatures and the night-time averaged temperatures.

VI. FUTURE WORK

To further this work, additional event periods, which correspond to the other types of SSWs (minor, final) can be examined. Additionally, future zonal wind and temperature measurements from the nearby meteor wind radar, Dynasonde and ALO Na lidar and the SABER instrument aboard the TIMED satellite can be combined with the temperatures from the soon-to-be-completed

Rayleigh-Mie-Raman Scatter (RMR) lidar at ALO, to provide a more comprehensive description of the midlatitude mesosphere during sudden stratospheric warmings.

The new, large aperture RMR lidar, that is currently being built at the ALO in place of the original Rayleigh-scatter lidar, will provide a much more complete picture of the latitudinal extent of sudden stratospheric warmings and their associated mesospheric coolings and lower thermospheric warmings. With an altitudinal observing range of 15-120 km, the new RMR lidar will capture temperatures from the midlatitude stratosphere, mesosphere and lower thermosphere. Thusly, with temperature measurements from the RMR lidar, this work can be extended to both the stratosphere and lower thermosphere in order to compare observations with the temperature anomalies that have already been predicted for these regions at midlatitudes.

VII. ACKNOWLEDGMENTS

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