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Rayleigh lidar observations of a mesospheric inversion layer during night and day

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Abstract. A narrow field of view Rayleigh lidar has been constructed at Millstone Hill / MIT Haystack Observatory (42.6°N, 71.5°W) for observations of middle atmospheric temperatures throughout the diurnal cycle. During a 31.5 h measurement on 19-21 March 2001 a mesospheric thermal inversion layer was observed in both the night and day. It developed near 60 km in altitude, progressed downward at 0.40 ± 0.06 km/h, and had an overlying adiabatic lapse rate. The inversion amplitude correlated with the evolution of stratospheric gravity wave activity, although the mesospheric perturbations were too large to be due to conservative gravity-wave growth alone. The 24 h mean temperature profile shows no evidence of a residual inversion layer.

Introduction

Thermal inversion layers are regularly observed in the mesosphere and mesopause regions [*Meriwether and Gardner*, 2000]. Mesospheric inversion layers are seen most frequently during winter, have a pronounced altitude variation with season, and often have overlying adiabatic lapse rates [*Whiteway et al.*, 1995]. They are commonly detected at midlatitudes, but are seen infrequently at higher latitude sites [*Cutler et al.*, 2001].

While chemical and tidal processes are likely important in the production of mesopause inversion layers [*Meriwether and Gardner*, 2000], the formation mechanisms for inversions at lower altitudes are less certain. It has been proposed that mesospheric inversion layers may be the result of gravity-wave drag induced compressions [*Hauchecorne and Maillard*, 1990], turbulent mixing [*Whiteway et al.*, 1995], enhanced tidal modes [*Leblanc et al.*, 1999], and gravity wave / tidal interactions [*Meriwether et al.*, 1998; *Liu et al.*, 2000]. Phase progression with the diurnal tide has been observed [*Dao et al.*, 1995], although this is not always the case. *Meriwether and Gardner* [2000] have suggested that measurements throughout the diurnal cycle could help identify the important processes.

A Rayleigh lidar with a 24 h observational capability has been constructed at Millstone Hill / MIT Haystack Observatory (42.6°N, 71.5°W). It has been in operation since September 2000, and several long data sets have been collected. During a 31.5 h measurement on 19-21 March 2001 a mesospheric inversion layer was observed in both the night and day. In what follows the characteristics of that inversion layer and its relationship to stratospheric gravity wave activity will be detailed.

Instrumentation and Data Analysis

A description of the lidar is given by *Duck et al.* [2001a]. It uses a 30 Hz pulsed 24 W injection-seeded doubled Nd:YAG laser (532 nm wavelength) coupled through the Coudé path of a 1.2 m f/200 steerable Cassegrain telescope transceiver. During the day the receiver's field of view is set to 0.067 mrad which lowers the solar background by a factor of more than 200 compared to typical (1 mrad) nighttime-only systems. The background is further reduced through the use of a Fabry-Perot etalon (10 GHz passband) and a broadband interference filter. The daytime data presented here have been corrected for changes in the transmitted beam's focus due to thermal expansion of the telescope; ground level temperature measurements from a nearby weather station were used for the calibration.

Signal profiles are acquired in 1-min intervals and at 37.5 m vertical resolution and later integrated to the required resolutions. 1-min profiles with signal-to-noise ratios less than 5 at 30 km in altitude were rejected in this study. Because

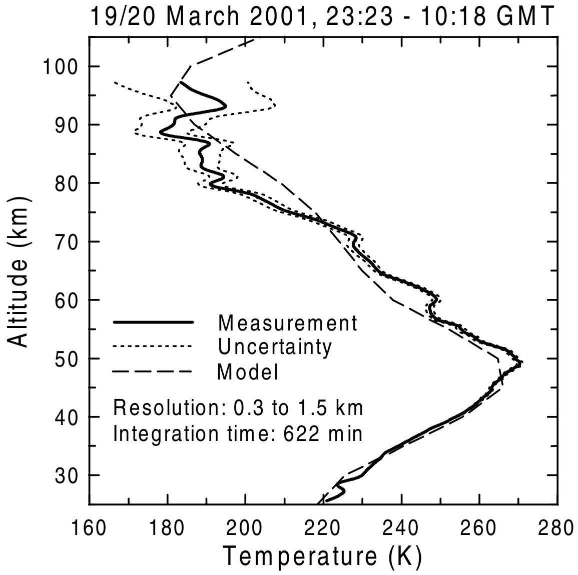

Figure 1. A night-mean temperature profile with the climatological model of *Fleming et al.* [1990] given for reference. Small thermal inversion layers are seen at 60 and 70.5 km in altitude.

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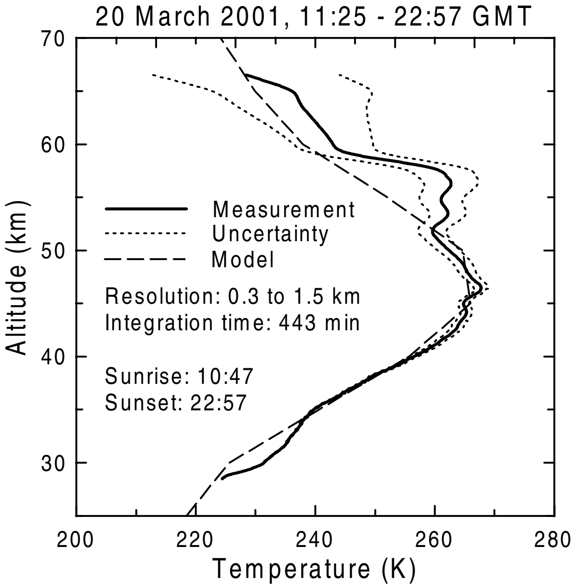

Figure 2. A day-mean temperature profile showing a mesospheric inversion layer at 56 km in altitude.

midday cirrus cloud activity caused the background levels to increase and fluctuate, fewer profiles were available at those times for integration. Longer integrations in both time and space usually allow measurements to higher altitudes.

Temperature profiles are determined by using the Rayleigh lidar technique [*Hauchecorne and Chanin*, 1980]. The temperature retrieval is initialized at the top altitude with the climatology of *Fleming et al.* [1990] and integrated downward. Profiles are plotted up to the top altitude unless noted otherwise; while systematic errors may exist in the first scale height below the top, relative variations that exceed the uncertainties are expected to be geophysical.

Perturbations induced by gravity waves and thermal inversions were extracted from 15-min average temperature profiles by approximating the mean state as a series of overlapping cubic polynomial fits of 25 km in length. *Duck et al.* [2001b] have shown that this technique extracts perturbations with vertical wavelengths between 2 and 15 km. Mean variance profiles are determined and the noise variance is subtracted to yield the average fractional temperature variance.

Observations

Figure 1 shows the mean temperature profile obtained during the night of 19/20 March 2001. The profile extends up to 97 km in altitude and is generally in good agreement with the climatological profile. Two small mesospheric inversion layers with peak temperatures at 60 and 70.5 km in altitude are apparent.

Figure 2 shows the mean profile obtained during the day of 20 March 2001. The profile extends up to 66.5 km in altitude and there is evidence for a mesospheric inversion layer with peak temperatures at 56 km in altitude. We believe this to be the first daytime observation of a mesospheric inversion layer with a Rayleigh lidar. 24 h measurements of

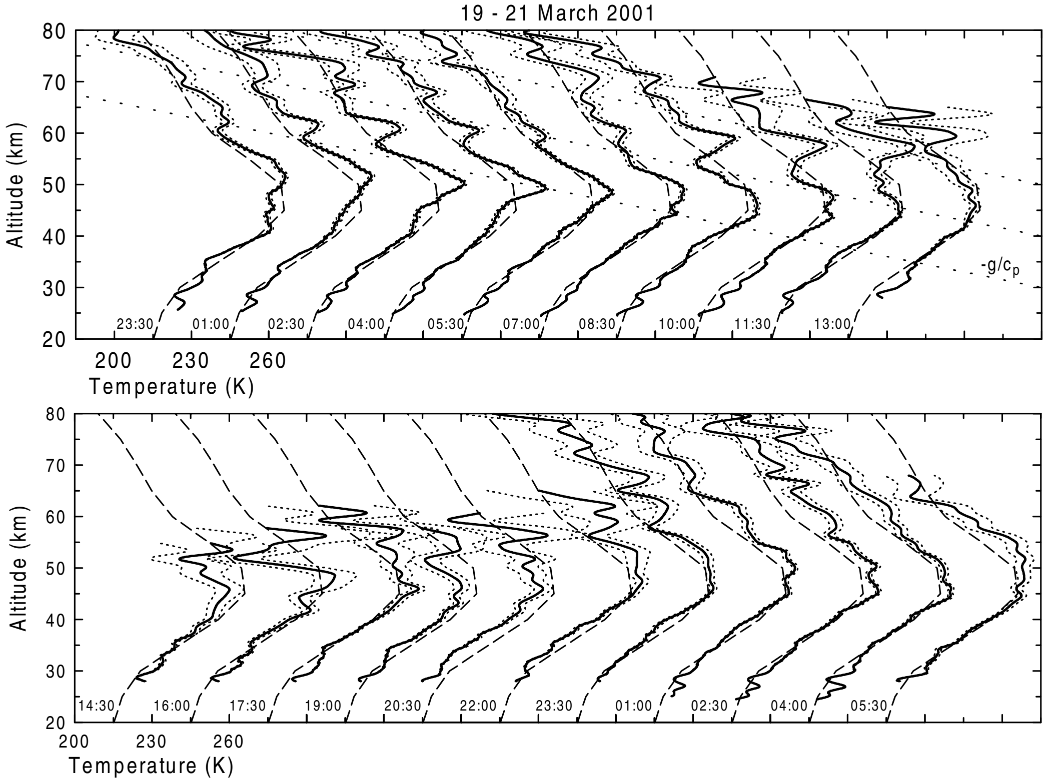

Figure 3. A time series of 1.5 h average temperature measurements. Successive profiles in time are separated by 30 K, and the time stamps indicate the start of each integration. The adiabatic lapse rate ($-g/c_p$) is given by the dotted lines for reference. The nighttime profiles have been truncated at the top for this plot. Sunrise was at 10:47 GMT, and civil twilight began about half an hour earlier. Note that local time lags GMT by five hours.

tides with a Rayleigh lidar were taken previously by *Gille et al.* [1991].

A progression of temperature profiles obtained during 19-21 March 2001 is given in Figure 3. As is shown in Figure 3, a mesospheric inversion layer developed near 60 km in altitude and had an overlying adiabatic lapse rate for much of the night. The descent rate of the inversion peak on March 20 from 01:00 to 12:59 GMT was determined to be 0.40 ± 0.06 km/h using a least squares fit. The inversion layer was clear for the first few hours of measurements during the day. At later times, cirrus clouds prevented the acquisition of enough data to reach the higher altitudes for 1.5 h integrations (but an inversion is seen for data integrated between 14:30 and 21:59 GMT, not shown). The inversion near 70 km was not persistent, but a co-descending perturbation (as witnessed by the descending stratopause) can be identified near 50 km in altitude.

The mean fractional temperature variance between 01:00 and 12:59 GMT is given in Figure 4. The interval was chosen to coincide with times when the inversion layer had an overlying adiabatic lapse rate and was therefore well developed. Also plotted in Figure 4 is the approximate growth rate for gravity waves in a shearless isothermal flow. Figure 4 shows that the high-altitude perturbations associated with the inversion layer have larger amplitudes than would be expected for the conservative growth of upward propagating gravity waves.

Figure 5 presents a time series of both the mesospheric inversion layer amplitude and the variance associated with gravity waves in the stratosphere. The amplitude of the temperature inversion was low for much of the night and then increased dramatically after 07:00 GMT. The inversion amplitude correlated strongly with changes in the stratospheric gravity wave variance.

Figure 6 shows the 24 h mean temperature profile, calculated by averaging the profiles from two separate twelve-hour integrations. The two-segment approach was taken to ensure equal representation between night and day, which was not possible in a single 24 h integration because of the weaker signals and lower data density obtained during the day. Figure 6 reveals that although a temperature inversion was seen during both night and day, no residual inversion layer appeared in the diurnal mean.

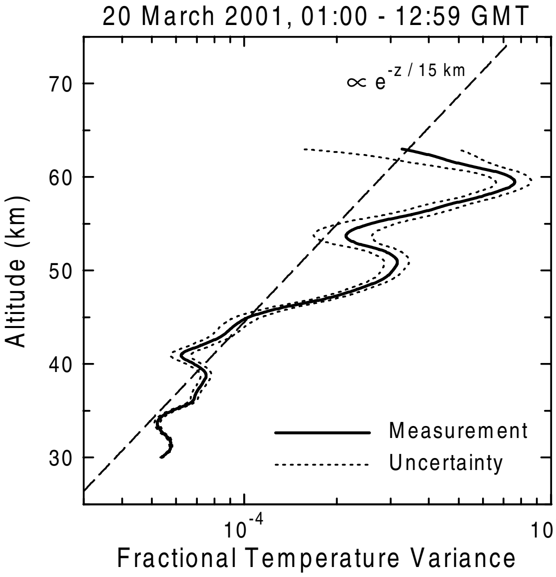

Figure 4. The average fractional temperature variance while the mesospheric inversion layer was observed. The approximate growth rate for conservative gravity wave propagation is given by the dashed line.

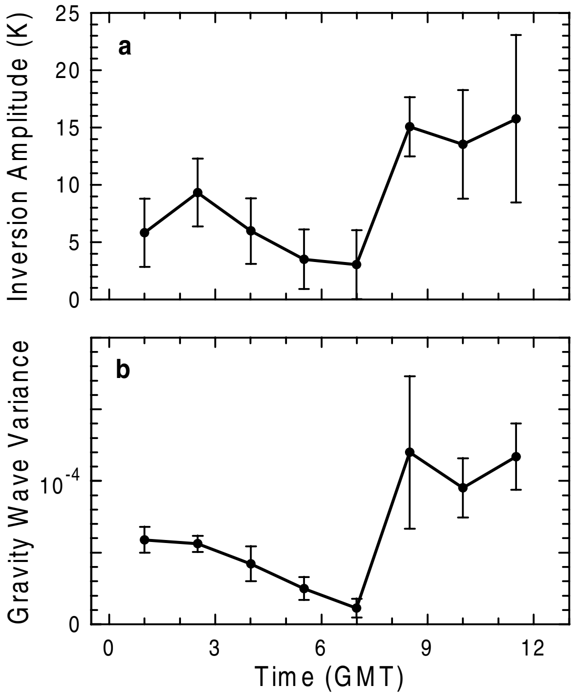

Figure 5. A time series showing **a**, the amplitude of the mesospheric inversion layer near 60 km in altitude (peak temperature - base temperature), and **b**, the mean fractional temperature variance due to stratospheric gravity waves (30 - 40 km mean). The error bars in **a** represent the amplitude uncertainties whereas in **b** they represent one standard deviation of the variance measurements.

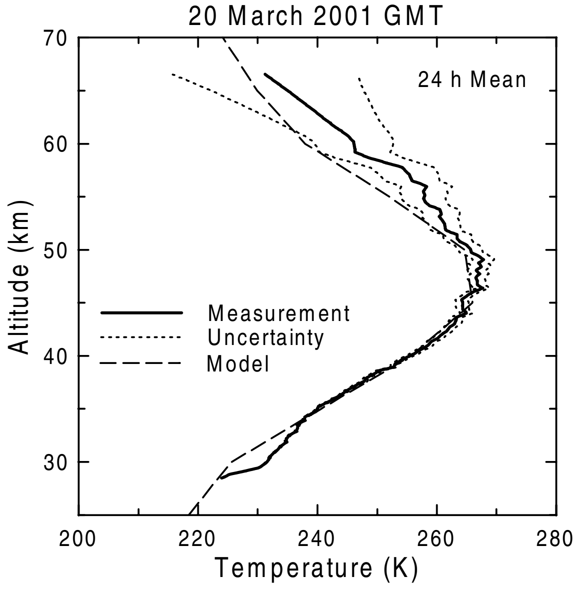

Figure 6. The mean 24 h temperature profile.

Discussion

Perturbations associated with mesospheric temperature inversions were observed with an approximately 10.5 ± 0.5 km spacing and descended at a rate of 0.40 ± 0.06 km/h, implying a period of 26 ± 4 h. Although this period is consistent with the diurnal tide, the observed inversions may only be associated with the higher order modes because of the small vertical wavelength [*Forbes*, 1995]. Local generation might be responsible for amplification of the higher order tidal modes.

The observations are suggestive of an upward propagating gravity wave; however, the mesospheric perturbation variances shown in Figure 4 are too large to be due to conservative gravity-wave growth alone unless the waves entered the measurement column obliquely. Notwithstanding, the mesospheric inversion amplitude correlated strongly with the evolution of stratospheric gravity wave activity. This suggests that gravity waves produced temperature inversions where instabilities developed, consistent with the theories of *Whiteway et al.* [1995] and *Liu et al.* [2000].

The model of *Liu et al.* [2000] showed further that below the levels where tides are important the inversion layer descent rate can be much slower than the tidal phase speed. In their model, inversion layers were first seeded at the lowest tide-induced gravity-wave breaking level and were maintained during a slow descent by gravity-wave drag induced wind shears. Thus it is possible that the near diurnal period observed in this study was forced by tidal seeding of the inversion layer, but that the descent was determined by other factors. Alternatively, the observations are also consistent with inversion generation by a long period gravity wave, for example, by an inertia-gravity wave excited by the jet stream [*Pavelin et al.*, 2001].

Further experiment is required to help understand the mesospheric inversion layer phenomenon. The daytime lidar capabilities at Millstone Hill / MIT Haystack Observatory will be enhanced to reduce the uncertainties; a Doppler-wind capability is also needed to measure shears in the inversion region. Finally, more data will need to be obtained to gain statistics on inversion layer periods and amplitudes, and to determine the relationship with gravity wave activity.

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