High Arctic observations of mesospheric inversion layers

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[1] Rayleigh lidar measurements of middle atmospheric temperatures obtained in the High Arctic at Eureka (80°N, 86°W) are examined for evidence of mesospheric inversion layers with overlying nearly-adiabatic lapse rates. Inversion layers are identified in 5.4 ± 0.5% of the measurements, a rate considerably lower than is observed at midlatitudes. The altitude distribution for the Arctic inversions is similar to that found at midlatitudes. No phase progression or relationship with stratospheric gravity wave activity was found. The observations have important consequences for theories of the mesospheric inversion layer. *INDEX TERMS:* 3332 Meteorology and Atmospheric Dynamics: Mesospheric dynamics; 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3384 Meteorology and Atmospheric Dynamics: Waves and tides. **Citation:** Duck, T. J., and M. D. Greene (2004), High Arctic observations of mesospheric inversion layers, *Geophys. Res. Lett.*, *31*, L02105, doi:10.1029/2003GL018481.

1. Introduction

[2] Thermal inversion layers are frequently observed in mesospheric temperature profiles measured at midlatitudes by ground-based lidars. The inversions occur predominantly in bands between 60–70 and 90–100 km in altitude, and have amplitudes up to about 30 K [*Meriwether and Gardner*, 2000]. Although the existence of mesospheric inversion layers has long been recognized [*Schmidlin*, 1976], the mechanisms responsible for their generation are still not well understood. Mesospheric inversion layers remain of continued interest because their understanding should provide insight into wave dynamics.

[3] Contrasting phenomenologies are observed for inversion layers occurring in the upper and lower altitude bands. Inversions between 90–100 km in altitude are a persistent feature of the mesopause region, and have a regular diurnal variation and downward phase progression [*States and Gardner*, 2000]; it is likely that the diurnal tide plays a key role in their generation. In contrast, inversions in the lower mesospheric band at midlatitudes show downward phase progression infrequently [*Meriwether and Gardner*, 2000], and so the role played by tides is uncertain. At lower latitudes the downward phase progression is seen more regularly [*Leblanc et al.*, 1999].

[4] A characteristic of many lower mesospheric inversion layers is an overlying nearly-adiabatic lapse rate, due perhaps to a well-mixed turbulent layer [*Whiteway et al.*, 1995]. Using a one-dimensional model with parameterized eddy diffusion, *Whiteway et al.* [1995] successfully reproduced the characteristic mesospheric inversion layer shape. Overlying nearly-adiabatic lapse rates are taken to be an important identifying feature in this study.

[5] The statistics of lower mesospheric inversion layers observed by lidars at midlatitudes are given by *Hauchecorne et al.* [1987] and *Whiteway et al.* [1995]. Depending upon the detection metric used, inversions are identified in upwards of 70 percent of the wintertime profiles and in about 20 percent of the profiles during summer. These studies show a seasonal height variation, with wintertime inversions observed between 60–70 km, and summertime inversions observed between 70–80 km.

[6] In contrast, wintertime measurements by *Cutler et al.* [2001] in the Arctic at Poker Flat, Alaska (65°N, 147°W), show that inversion layers occur relatively infrequently at high latitudes. They detected inversion layers on only five occasions in 27 nights of wintertime measurements. *Cutler et al.* [2001] noted that although extensive measurements had been made at other Arctic sites, none other had yet reported observations of mesospheric inversion layers.

[7] In this study, 422 measurements of wintertime mesospheric temperatures obtained with a Rayleigh lidar in the High Arctic at Eureka (80°N, 86°W) during 1993–1998 are examined for evidence of mesospheric inversion layers. The highly variable stratospheric thermal structure apparent in the measurements is explained by *Duck et al.* [1998, 2000a, 2000b, 2001]. The data were reanalyzed, and mesospheric inversion layers with overlying nearly-adiabatic lapse rates are found to occur at Eureka in 5.4 ± 0.5% of the measurements. The altitude distribution for Arctic inversion layers is similar to that at midlatitudes. No evidence was found for downward phase progression, or of a relationship to simultaneous measurements of stratospheric gravity wave activity. The observations highlight a number of unresolved problems that need to be explained for a comprehensive understanding of the lower mesospheric inversion layer.

2. Measurement and Analysis Technique

[8] The measurements were obtained with an ozone-DIAL lidar as described by *Duck et al.* [2000a]. Temperature profiles were determined from the 353 nm laser backscatter using the Rayleigh lidar technique [*Hauchecorne and Chanin*, 1980]. The profiles were initialized at the top altitude using a climatology. A vertical resolution of 1.2 km was used to reduce the measurement uncertainties in the mesosphere to acceptable levels. The top ten kilometers of each profile, where the solution converges and the uncertainties are high, were discarded from the analysis. No smoothing was applied to the data.

[9] Of the 422 nightly averaged profiles in the data set, only those with measurement durations over four hours long were considered in order to eliminate transient gravity wave

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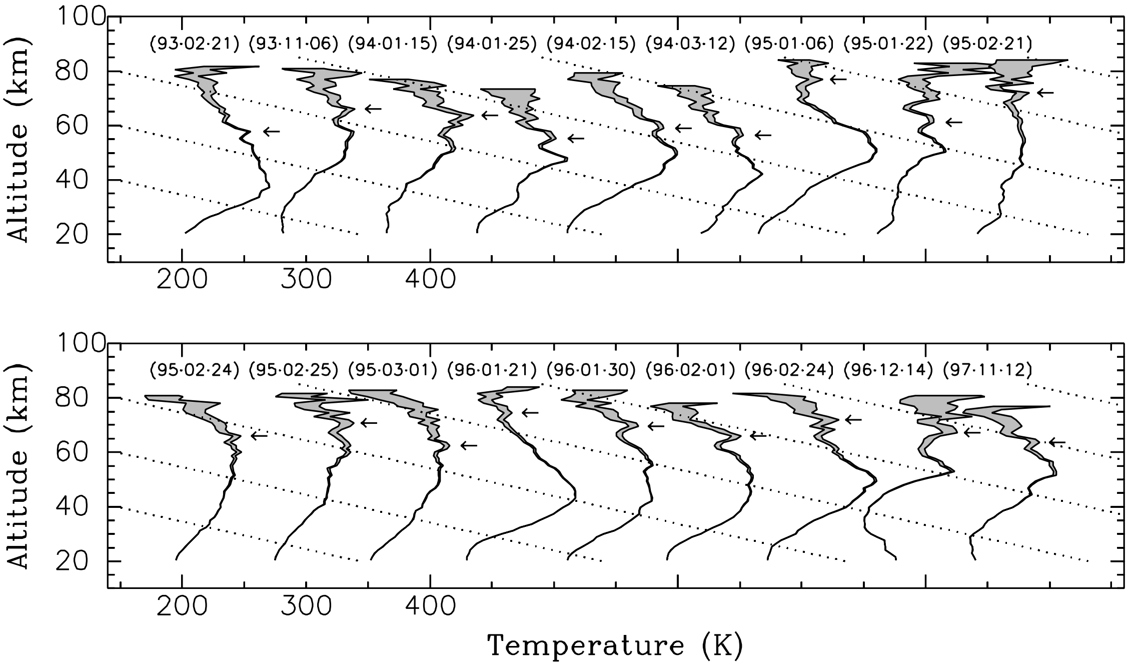

Figure 1. Night-mean temperature profiles for each inversion layer detected during winter at Eureka from 1993–1998. Successive profiles are shifted by 80 K, and the end date for each measurement is given. Shading indicates one standard deviation of uncertainty, and the slope of the dotted lines is the adiabatic lapse rate (−9.8 K/km). Arrows mark the altitude of maximum temperature for each inversion layer.

packets and other short-term phenomena from the analysis. Furthermore, only profiles initialized above 74 km in altitude were considered. These criteria reduced the data set to the best 302 nights of observation.

[10] Anticipating that mesospheric inversion layers occur infrequently in the Arctic, it is important to precisely define the inversion layer form in order to separate out the measurement noise artifacts. Thermal inversion layers were identified using the following metric: The region of increasing temperatures was expected to be at least 2.4 km deep (i.e., 2 range bins), with the maximum and minimum temperatures differing by at least two standard deviations. Furthermore, a region of near-adiabatic lapse rate (gradients <−8.0 K/km calculated using a two-point formula) was required within 4.2 km above the inversion layer peak, with an adjacent region of decreasing temperatures. Note that this definition is consistent with the representative inversion layer profiles given by *Whiteway et al.* [1995].

[11] Simulated temperature profiles were prepared in order to determine the utility of the detection metric in eliminating noise as a spurious source of inversion layers. One hundred simulated profiles were constructed for each night of observations, with each simulation following the measured background temperature profile. The background profile was estimated for each night using a cubic polynomial fit to the data above 30 km in altitude, which removes inversion layers and other sources of small-scale variability. Noise was added to each simulated profile with parameters corresponding to the actual lidar measurement uncertainties. The creation of simulated profiles in this way is described by *Duck et al.* [2001]. The inversion layer identification algorithm was applied to the simulated data set in order to determine the rate of false detections. The simulations

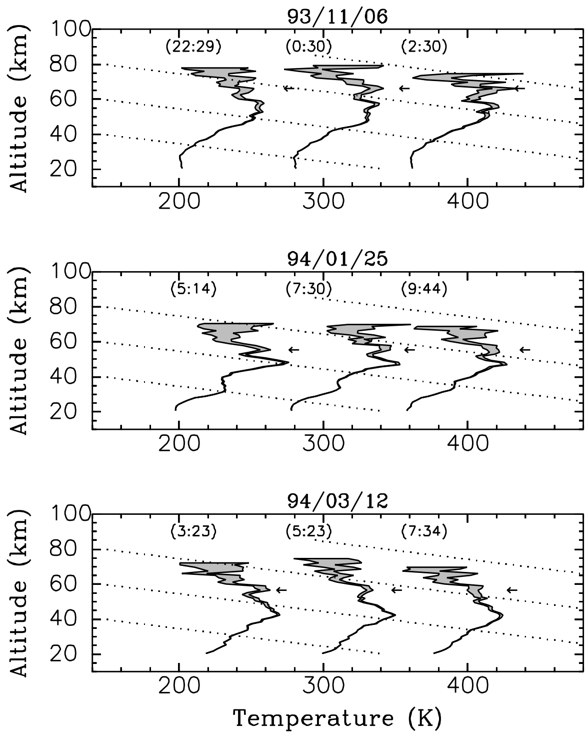

Figure 2. Two-hour average profiles for three cases from Figure 1. The start time (GMT) for each profile is given. Arrows mark the same altitude as the corresponding profile in Figure 1.

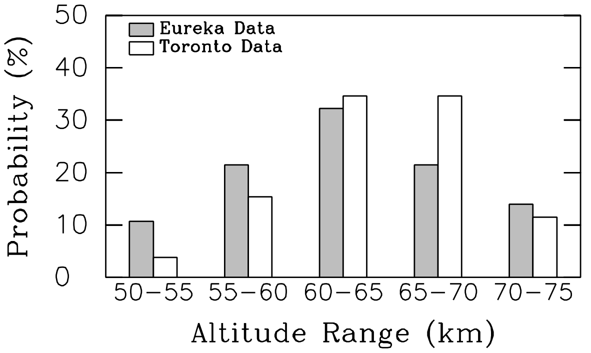

Figure 3. The altitude distribution for temperature inversions measured at Eureka and Toronto. The altitude for each inversion is measured at the inversion's base (i.e., where the temperatures first begin increasing with altitude).

showed that relaxation of the inversion layer definition results in an unacceptable increase in false detections.

3. Observations

[12] Mesospheric inversion layers with overlying nearly-adiabatic lapse rates were observed at Eureka on eighteen occasions, each of which is shown in Figure 1. The simulations produced a mean of 1.7 inversions for 302 observations, with a standard deviation of 1.5 for the 100 artificial data sets. Therefore only 5.4 ± 0.5% of the wintertime temperature profiles above Eureka have occurrences of mesospheric inversion layers.

[13] For each of the eighteen days, a series of two-hour average temperature profiles were constructed; three examples are given in Figure 2. The inversion layers are seen to be persistent phenomena in the two-hour averaged profiles. There is no clear evidence of phase progression, although progression is difficult to detect due to the elevated uncertainties at mesospheric altitudes in the two-hour profiles.

[14] The inversion layer distribution with altitude is given in Figure 3, and is compared with the midlatitude data from Toronto (44°N, 80°W) for November-March given by *Whiteway et al.* [1995]. For the Eureka dataset, the effect of the variable maximum altitude of night-averaged profiles was removed so that the distribution provided represents the true geophysical probabilities; it was assumed that all of the measurements at Toronto reached a sufficient height so that such adjustments were not necessary. Figure 3 shows that the inversion layers at Eureka occurred between 50 km and 75 km in altitude, with the peak occurrence rate in the 60 to 65 km range. The measurements of *Hauchecorne et al.* [1987] are not given in the comparison because they also reported inversion layers without overlying nearly-adiabatic lapse rates.

[15] The probability of detecting an inversion layer with a specific amplitude or greater is given in Figure 4. The amplitude is defined as the temperature at the top of the region of increasing temperatures minus the temperature at the bottom. The median amplitude for the inversion layers observed at Eureka was 11 K, and only one inversion layer with an amplitude greater than 15 K was found.

[16] The existence of inversion layers was compared to the stratospheric gravity wave energies (30–35 km average) measured simultaneously and given by *Duck et al.* [2001]. If one outlier is excluded (94/01/25), then the average gravity wave energy observed during inversion layer episodes is 6.6 J/kg with a standard deviation of 3.2 J/kg, which is consistent with the mean gravity wave energies presented by *Duck et al.* [2001] for the entire measurement ensemble.

4. Discussion and Conclusions

[17] The measurements from Eureka (80°N) show that mesospheric inversion layers occur infrequently during the High Arctic winter: only 5.4 ± 0.5% of the time. This is somewhat less than the detection frequency further south at Poker Flat (65°N), and is considerably lower than the 90% wintertime rate at Toronto (44°N).

[18] The inversion layer altitude distributions between Eureka and Toronto are very similar in form. Both data sets record over half of the inversion layer detections in the 60–70 km altitude range. About 55% of the observed inversion layers at Eureka had amplitudes in excess of 10 K. *Hauchecorne et al.* [1987] indicate that about 50% of wintertime profiles at midlatitudes have inversions with amplitudes in excess of 10 K (although they used a different detection criterion); if the *Whiteway et al.* [1995] occurrence rate of 90% (any amplitude) is used, then amplitudes in excess of 10 K should be expected for 56% of the detected inversions at midlatitudes, i.e., about the same rate as at Eureka. The data suggest that although the features of mesospheric inversion layers at midlatitudes and in the High Arctic are very similar, they occur at dramatically reduced rates in the Arctic. This fact has considerable implications for theories of the mesospheric inversion layer.

[19] For example, a criticism of the theory of *Whiteway et al.* [1995] is that the high level of turbulent diffusivity used in their model to produce inversion layers is not supported by the rocket measurements of *Luebken* [1997] (see, for example, *Meriwether and Gardner* [2000]). However, the *Luebken* [1997] measurements were obtained in the Arctic, where inversion layers with overlying nearly-adiabatic lapse rates are seen infrequently. Using our measured frequency, the probability of serendipitously measuring an inversion layer during the 11 wintertime rocket flights provided is only 46%; note that no observations of inversions during the rocket flights were reported. An assessment of the theory by *Whiteway et al.* [1995] requires rocket turbulence measurements at midlatitudes coordinated with simultaneous lidar

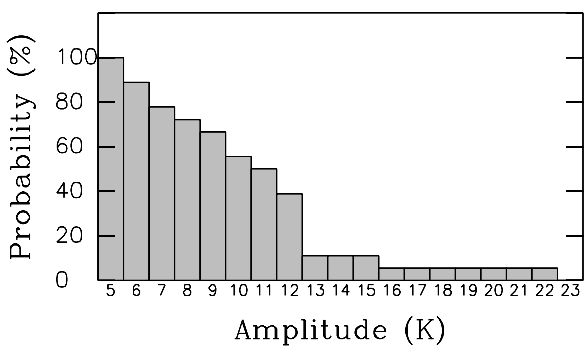

Figure 4. The probability distribution for a given inversion amplitude or greater.

observations of a mesospheric inversion layer with an overlying nearly-adiabatic lapse rate.

[20] The High Arctic data do, however, present a challenge for any theory involving atmospheric gravity waves. Measurements at Eureka show that gravity wave activity is highest in the vicinity of the stratospheric vortex jet [*Duck et al.*, 2001]. One might expect there to be many occurrences of mesospheric inversion layers in the Arctic due to gravity wave induced turbulent mixing, but this is not observed.

[21] Gravity wave-tide interactions may also be important for mesospheric inversion layer generation because tide-induced wind shears modulate the atmospheric stability [*Liu et al.*, 2000]. Tides are both observed and modeled to have significant amplitudes in the High Arctic [*Walterscheid and Sivjee*, 1996; *Hagan and Forbes*, 2002], and so might be expected to contribute to inversion layer formation. However, Global Scale Wave Model results [*Hagan and Forbes*, 2002] (available at http://www.hao.ucar.edu/public/research/tiso/gswm/gswm.html) for migrating and non-migrating tides show wind speed phases that are constant with height in the lower mesosphere above Eureka. It follows that the Arctic tides do not likely induce the wind shears needed for inversion layer generation, and so the *Liu et al.* [2000] mechanism is consistent with our measurements. Notwithstanding, gravity wave-tide interaction theories do not currently explain the general lack of downward progression for lower mesospheric inversion layers at mid-latitudes, and the eddy diffusion coefficient determined by *Liu et al.* [2000] for wave-induced turbulence is three times larger than the controversial value used by *Whiteway et al.* [1995]. The gravity wave-tide interaction theory appears promising, but some theoretical and experimental challenges remain.

[22] Another theory seeks to explain mesospheric inversion layers in terms of planetary wave breaking in a mesospheric surf zone. This mechanism was modeled by *Sassi et al.* [2002], and is found to generate strong inversion layers in the Arctic during winter, which does not agree with our measurements. However, the inversion examples given by *Sassi et al.* [2002] had overlying lapse rates that were far from adiabatic, and were much deeper in extent compared to those presented here. This suggests that the inversion layers modeled by *Sassi et al.* [2002] may be different in nature from the inversions with overlying nearly-adiabatic lapse rates measured by the ground-based lidar systems. Nevertheless, the strong seasonal variation in mesospheric inversion occurrences modeled by *Sassi et al.* [2002] at midlatitudes, together with a presumed lack of downward progression, suggests that some types of inversion layers may be well explained by the planetary wave breaking mechanism.

[23] Further understanding of mesospheric inversion layers will require developments in both experiment and theory. A single climatology of lidar observations at a variety of latitudes, analyzed in a consistent manner between datasets, would be a considerable asset. More observations over longer time intervals and at a greater range of northern and southern hemisphere latitudes and longitudes would also be helpful. A comprehensive understanding of the mesospheric inversion layer will likely require elements of each of the theories discussed here, and will need to explain the variety of observed phenomenology, including the dependencies on latitude, season, and height.

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