MLT cooling during stratospheric warming events

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Received 21 January 2004; revised 8 March 2004; accepted 30 April 2004; published 25 May 2004.

[1] MLT (Mesosphere and Lower Thermosphere) airglow emission rates and temperatures have been monitored with a Spectral Airglow Temperature Imager (SATI), operated at Resolute Bay (74.68°N, 94.90°W). The 2001/2002 winter season data exhibits a major cooling event for both the O_2 and OH emissions near the end of December, a mild event in mid February and a final cooling in early March. These temperature perturbations are compared with the UKMO stratospheric assimilated data for the Resolute Bay location and for zonally averaged data at 75°N, at two pressure levels, 3.16 hPa and 0.316 hPa. For the major event the 3.16 hPa zonally averaged temperature coincides in time with the MLT cooling. The O_2 temperatures increase slightly, prior to the stratospheric warming, but after onset both emissions exhibit cooling; this is consistent with the TIME-GCM/CCM3 predictions for the meridional circulation at high latitudes. *INDEX TERMS:* 0310 Atmospheric Composition and Structure: Airglow and aurora; 0341 Atmospheric Composition and Structure: Middle atmosphere—constituent transport and chemistry (3334); 0342 Atmospheric Composition and Structure: Middle atmosphere—energy deposition; 0350 Atmospheric Composition and Structure: Pressure, density, and temperature; 1694 Global Change: Instruments and techniques. **Citation:** Cho, Y.-M., G. G. Shepherd, Y.-I. Won, S. Sargoytchev, S. Brown, and B. Solheim (2004), MLT cooling during stratospheric warming events, *Geophys. Res. Lett.*, *31*, L10104, doi:10.1029/2004GL019552.

1. Introduction

[2] The MLT regions are known for breaking waves that propagate upward from below; tidal waves, planetary waves, and gravity waves. Their interaction with the middle atmosphere controls the large scale circulation, which in turn determines the upwelling and downwelling of the polar atmosphere. These vertical motions have a strong influence on the mesospheric temperature, and the atomic oxygen concentration. During some winters in the Northern Hemisphere, polar MLT coolings were shown to be related to stratospheric sudden warmings (SSW) [*Walterscheid et al.*, 2000; *Myrabø and Deehr*, 1984; *Holton*, 1983]. *Matsuno* [1971] suggested that the main mechanism of the SSW is induced by the interaction of planetary waves and the mean flow, and this is still accepted as the primary mechanism. Recently, *Liu and Roble* [2002] examined the SSW using the coupled TIME-GCM/CCM3 (National Center for Atmospheric Research Thermosphere, Ionosphere, Mesosphere, and Electrodynamics General Circulation Model/Climate Community Model version 3). They confirm that planetary wave 1 and mean flow interaction play a dominant role in the warming event and show that the deceleration of the stratospheric jet accompanying its reversal allows more eastward gravity waves to propagate into the MLT, forcing an equatorward and upward meridional circulation that is responsible for upper mesospheric cooling.

[3] The SATI was developed to measure the temperature and emission rate of the MLT region, and the instrument has been operated at Resolute Bay (74.68°N, 94.90°W) since November, 2001. MLT cooling was observed in association with a major stratospheric warming event at the end of December, 2001, with a mild event in mid-February, 2002, and with what appears to be a final winter warming in early March. These coolings are compared to the UKMO stratospheric assimilated data provided by the British Atmospheric Data Centre (BADC) and the relationship is different for each event, although all three indicate similar MLT precursor behavior. The results are interpreted using the predictions of *Liu and Roble* [2002], which show excellent agreement in the main features.

2. Measurements

[4] The SATI instrument, a spatial scanning Fabry-Perot spectrometer, is able to measure the column emission rate and vertically averaged rotational temperature of both the P branch of the O_2 Atmospheric (0–1) band from ~94 km and the Q branch of the OH Meinel (6–2) band from ~87 km [*Sargoytchev et al.*, 2004]. The Q branch transition probabilities have been corrected as described by *French et al.* [2000] so the absolute temperature values are realistic. The multi-emission observations also allow the vertical structure of the wave to be examined. The SATI consists of a conical mirror, Fresnel lens, a CCD detector, cooling system for the CCD detector, and two narrow band interference filters. The conical mirror projects the field of view onto the sky as an annulus of radius 30 degree centered on the zenith. The annular image is focused on the CCD plane through the Fresnel lens, preventing spatial non-uniformities. The SATI detector, a Kodak KDF260 CCD, is used at a temperature of −30°C. The binning of the CCD is 2 × 2 pixels, and it has an exposure time of 120 s. The sequence

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of observations is scheduled from York University by operations software that changes filters, takes dark images, checks sun and moon conditions, and records the temperature of the CCD and filter.

[5] The standard deviation of the measurements was determined from the Nov. 12, 2001 observations between 2 and 9 hr UT by calculating the root-mean-square difference between the data and the fit to the 4-hr wave present on this day; this wave feature has been described by *Won et al.* [2003]. The derived standard deviation of 1.7 K includes both the instrumental noise and the atmospheric perturbations incremental to the 4-hr wave.

3. MLT Precursors

[6] The rotational temperatures from the O_2 and OH emissions are shown in Figure 1 in three sections during the 2001/2002 winter season; prior to, during, and after the December stratospheric warming event. The diamonds represent the OH temperature and the crosses are for O_2; the latter temperatures are lower than for OH, indicating the high altitude of the winter mesopause. Data gaps result from full-moon periods.

[7] In Figure 1a, two types of variability are evident. The rapid variation during each nightly "burst" of data corresponds to the semi-diurnal tide, although there are discussions about the nature of this 10–12 hour feature [*Fisher et al.*, 2002]. The O_2 temperature tidal amplitude, averaged over day 317 to day 322, is 4.8 K and 6.4 K for OH. The second variability has a longer period and has been fitted with combined 3 and 4.5 day waves separately for the OH and O_2 temperatures.

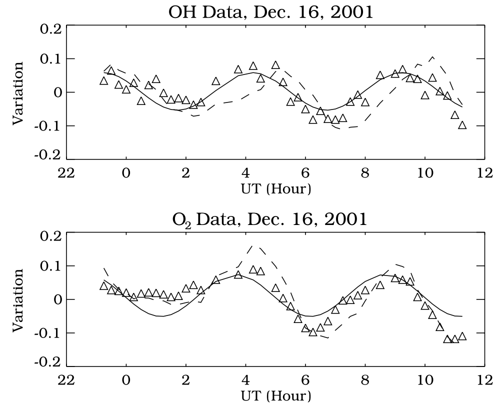

Figure 2. Variations of rotational temperatures and emission rates of OH and O_2 at Resolute Bay, December 16, 2001. The triangles represent the rotational temperature variation ($\Delta T/\bar{T}$), and the dashed line indicates the emission rate variation ($\Delta I/4\bar{I}$).The solid curve is a 5-hour sinusoidal fit superimposed on the temperature data.

[8] In Figure 1b, from day 348 (Dec. 14) to day 350, two different things happen. First, the amplitude of the daily variations markedly increases and the 12 hour variations are replaced by short-period variations. Second, the average daily temperature increases for OH but decreases for O_2, closely consistent with the residual circulation prediction by *Liu and Roble* [2002] (their Figure 13) that prior to a warming the level dividing upward and downward flows is located near 94 km. The short-period variations are shown in detail in Figure 2, where the data triangles are closely fitted with a solid line of 5-hour period. The dashed lines indicate the emission rate variations, which are nearly in phase, but have a fractional amplitude variation about 4 times larger than that for the temperatures. Thus the enhanced short-period variations compared with that of the semi-diurnal tide and the divergent temperature trends appear to be precursors of the major warming which began on day 355 (Dec. 21) of 2001 and continued to day 5 of 2002.

[9] In Figure 1c, from days 62 to 67, weakly divergent MLT temperatures are discernable preceding the final warming that begins on day 67. The rise in OH temperature from 232 to 235 K accompanied by the O_2 temperature cooling from 182 to 179 K is consistent with the predictions of *Liu and Roble* [2002] discussed earlier, and both changes are greater than the measurement standard deviation of 1.7 K.

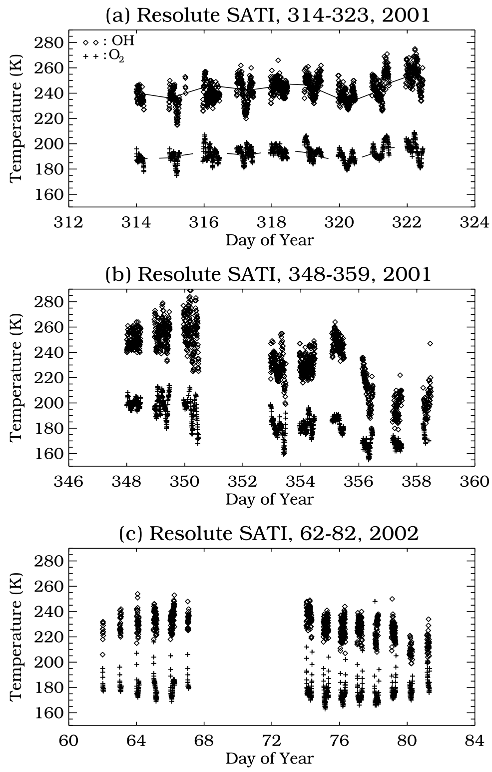

Figure 1. The rotational temperature variations of O_2 and OH at Resolute bay for different time periods. (a) From November 10, 2001 (day 314) to November 20, 2001 (day 324) (b) From December 14, 2001 (day 348) to December 24, 2001 (day 358) (c) From March 3, 2002 (day 42) to March 23, 2002 (day 82).

4. Stratospheric Warmings/MLT Coolings

[10] The UKMO stratospheric assimilated data are sets of meteorological analysis comprising 3-D fields of temperature, geopotential height and wind components at 2.5° × 3.75° resolution from 1000 hPa to 0.316 hPa (approximately 0–55 km). Data were originally produced by the UK Met Office primarily to provide independent correlative data for

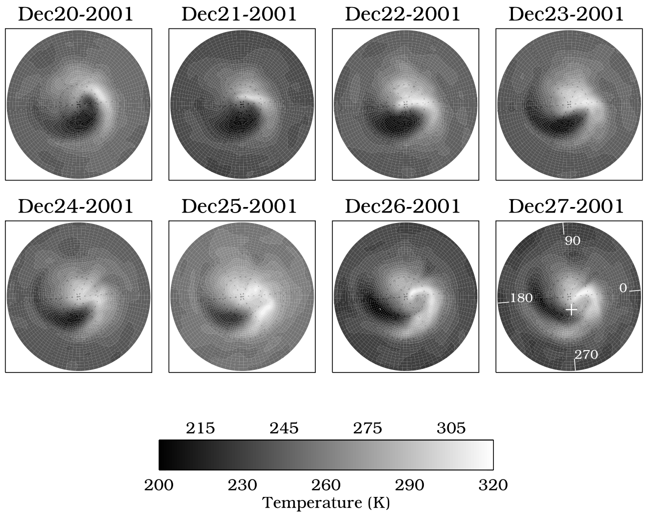

Figure 3. Polar view of the stratospheric assimilated UKMO data at 3.16 hPa, Dec. 20–27, 2001. The longitudes and location of Resolute Bay are shown for Dec. 27. The circumference corresponds to the equator.

instruments on the Upper Atmosphere Research Satellite (UARS) and are generated using temperatures from NOAA polar orbiting satellites (ATOVS). A 3D-Var system was implemented in Nov 2000. Further details are given by *Swinbank and O'Neill* [1994], and by *Swinbank et al.* [2002].

[11] Polar temperature maps at 3.16 hPa (about 40 km) for Dec. 20 to Dec. 27 are shown in Figure 3. The white cross on the Dec. 27 map shows the location of Resolute Bay; longitudes are also shown here. Strong warming is seen in an incomplete annular region passing near Resolute Bay. The observed temperature extremes are 192 K and 320 K.

[12] Daily MLT temperature averages are presented in Figure 4, with the stratospheric temperatures at 3.16 hPa for the Resolute Bay location shown with dash dot lines. The solid line represents the zonal mean temperature at 75°N for 3.16 hPa. Three warming events are identified in this data set, based on the 3.16 hPa temperatures over Resolute Bay. The "start day" is defined as the day in which the fast monotonic rise in temperature begins, the "peak day" is the day of the first peak following the rise and the "end day" is the last day of monotonic decrease.

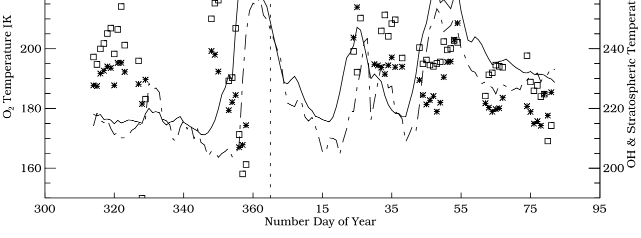

Figure 4. Comparison of the UKMO stratospheric temperatures with SATI O_2 and OH rotational temperatures at Resolute Bay, 74°N.

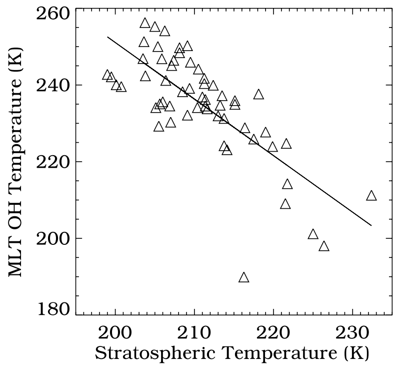

Figure 5. Correlation of stratospheric temperatures and mesospheric OH temperatures.

[13] The December major warming starts on day 355 (Dec. 21, 2001), peaks on day 358 and ends on day 5 of 2002. The 60 K of cooling for OH closely coincides in time with the 60 K zonally averaged warming, with the 50 K warming at Resolute Bay delayed by about 3 days.

[14] A mild warming of 40 K starts on day 41, (Feb. 10, 2002), with the zonally averaged warming of the same amplitude closely in phase. The mesospheric cooling is about 15 K for both emissions. If the precursor period is extended back to day 30, OH warming accompanied by O_2 cooling is discernable, though not as clearly as for the major event. The final warming begins on day 67 (March 8, 2002); it is very gradual and is not seen in the zonally averaged data. The MLT observing period ends (with summer sunlight) before peak and end dates can be seen. This event also appears to have a precursor period as discussed earlier in relation to Figure 1c, followed by a cooling of 20 K for OH and 10 K for O_2. Otherwise the final event is quite different from the two earlier events, and may well be related to the transition to summer circulation.

[15] The close relationship of the OH and 0.316 hPa temperatures is demonstrated in the Figure 5 scatterplot for the entire 2001/2002 dataset. There is a consistent inverse relationship that is not limited to the periods of warming and cooling. Such a striking correlation is not seen with the 3.16 hPa data. The airglow emission rates, not shown here, decrease to minimum values during all of the MLT coolings, consistent with upward flow.

5. Summary and Conclusions

[16] For the 2001/2002 winter at Resolute Bay, three MLT coolings were observed in association with stratospheric warmings at 3.16 hPa and 0.316 hPa taken from the UKMO stratospheric assimilated dataset. The relationship between the two is different for each, and the results are summarized as follows, in the context of *Liu and Roble* [2002], herein abbreviated as LR2002:

[17] 1. One month before the major cooling, weak planetary waves with amplitudes of 3.0 and 4.8 K (coincidentally the same for the 3 and 4.5 day components) were observed for the OH and O_2 temperatures respectively. A semi-diurnal variation is superposed on this planetary wave feature, with an amplitude of about 4.8 K for O_2 and 6.4 K for OH.

[18] 2. Seven days before the start of major mesospheric cooling, the character of the short-term variation changes and a trend in mean temperature begins. The amplitude of the semi-diurnal tide is reduced in comparison with the 5-hr variations, while the daily mean OH temperature increases and the O_2 temperature decreases. This indicates that the altitude dividing upward from downward flow is located between 87 and 94 km, close to the 97 km prediction of LR2002.

[19] 3. During the warming/cooling event, both OH and O_2 temperatures fall, indicating that at the start of the stratospheric warming the altitude dividing upward from downward MLT flow falls below the OH layer; consistent with the LR2002 predicted altitude of 83 km.

[20] 4. The December MLT cooling coincides with a 60 K enhancement in the 3.16 hPa zonally averaged temperature, and in the 3.16 hPa temperature above Resolute Bay. Warming is also seen at 0.316 hPa, but this is localized to the region of Resolute Bay. This coincidence in time and location of the warming/cooling is consistent with the movement of planetary waves shown by LR2002, where the phases of wave 1 at different altitudes become the same at the time of strong stratospheric warming.

[21] 5. A weaker 15 K cooling is seen in mid-February, coinciding with the 40 K zonally averaged temperature enhancement at 3.16 hPa, and with that seen over Resolute Bay. A precursor divergence of O_2 and OH temperatures is discernable prior to the start of warming, though not so clearly as for the major warming.

[22] 6. In early March, a gradual MLT cooling of 20 K in OH and 10 K in O_2 coincides with a gradual warming of 10 K at 3.16 hPa over Resolute Bay, that is not seen at all in the zonally averaged 3.16 hPa temperatures. This may be a planetary wave MLT interaction without a full stratospheric warming, consistent with the analysis of LR2002, who show that longitudinal modulation occurs through heating mainly in the warm phase of wave 1.

[23] 7. The emission rate decreases are consistent with the LR2002 predicted decreased emission rate for the atomic oxygen emission $O(^1S)$ emission at 557.7 nm. The emission rates of OH and O_2 are observed to decrease by 78% and 83% respectively, compared to a prediction of about 70% for the $O(^1S)$ by LR2002.

[24] 8. A scatter plot of mesospheric OH and 0.316 hPa stratospheric temperatures shows a consistent inverse relationship for the entire period, Nov. 10, 2001 to March 22, 2002, indicating that the coupling between these regions is not limited to periods of stratospheric warmings. Despite reservations about the 0.316 hPa data which come from above the 1 hPa limit of assimilated temperatures, the excellent correlation suggests that these temperatures, and the correlation, are realistic.

[25] **Acknowledgments.** The SATI is partly provided by KORDI grant PP03105, and the analysis is supported by the Natural Sciences and Engineering Research Council of Canada. The authors are grateful to the British Atmospheric Data Centre for providing access to the Met Office Stratospheric Assimilated Data, and to the Met Office for making it available for this study. The authors wish to thank H.-L. Liu and R. Swinbank for helpful comments.

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