Mesospheric dynamics and temperature variance studies using satellite and ground-based instruments.

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Abstract
The Mesospheric Temperature Mapper located at Cerro Pachon, Chile (30.3° S, 70.7° W) has measured the mesospheric OH rotational temperature for over 5 years (2009-2015). The data, so far, show great day-to-day variability and begin to build a climatology of the mesosphere over the Andes. Increased temperature variance, an indication of increased gravity wave activity, during winter months is observed by both the ground-based imager and the space-based instrument SABER. SABER atmospheric temperature profiles are detrended to reveal small-scale gravity wave perturbations and this technique shows increased temperature variance during winter months as well as in other seasons. This technique has great potential for future case studies with other imager data sets. Gravity wave parameters of 400+ events from McMurdo Base, Antarctica are highlighted exhibiting a large spread of phase speeds, and anisotropic wave direction due to localized weather systems perhaps associated with the polar vortex.

1. Introduction
Wave phenomena are prevalent in planetary atmospheres and are a result of atmospheric disturbances. They are induced by both external and internal sources. Waves can be classified into two main groups based on the spatial scale length of the wave. There are large scale waves known as planetary waves and tides. They are both global in nature and exhibit coherent patterns in both latitude and longitude. On a smaller scale atmospheric gravity waves (AGWs) are generated by buoyancy forces in the atmosphere. AGWs propagate freely throughout the atmosphere transporting large amounts of momentum and energy from near the Earth’s surface to great altitudes where they dissipate. AGWs have a myriad of effects and are major contributors to atmospheric circulation, structure, and variability. Better understanding and parameterization of AGWs leads to better predictions of weather forecast and climate models. AGWs usually have local sources and propagate with a limited range of wavelengths. AGWs generally have sources in the troposphere and stratosphere such as thunderstorms, volcanoes, earthquakes, jet streams, and the flow of air over mountains. They can also be generated at high altitudes.

AGWs have been studied for the last 50 years starting with the pioneering work of Hines [1960] and the study continues to intensify with quantitative advances in our understanding of AGWs and advances in observational and computational techniques and capabilities. AGWs are arguably the most important process coupling all altitudes of the neutral atmosphere (0-100 km altitudes) [Fritts and Alexander, 2003]. The mesosphere and lower-
thermosphere (MLT) region (60-100 km) is a key region to study and to understand these coupling mechanisms. The Andes region in South America is of particular interest because during the winter, strong mountain forcing is expected to dominate in the creation of AGWs. This mountain forcing is caused by intense prevailing winds blowing eastward from the Pacific Ocean that suddenly encounter the towering Andes mountain range (average height 4000 m).

Large amplitude mountain waves (lee waves) have been measured penetrating into the stratosphere above a number of prominent mountain ranges [Eckermann and Preusse, 1999] but their effects have yet to be quantified in the mesosphere [Smith et al., 2009]. Mountain waves are characterized by a zero horizontal phase speed as observed from the ground. This is because they are generated by strong winds blowing over prominent mountains and so their phase speeds are equal to and in the opposite direction of the wind which is perpendicular to the mountain range. Mountain waves are prominent in the winter months because they are not filtered out by critical layer wind filtering. A critical layer is when the wind speed is equal to the phase speed of the wave causing the wave to break or saturate. In the winter months, the wind speed doesn’t change direction as a function of altitude. In the summer months it changes direction as its altitude increases and thus crosses the zero wind line.

In August 2009 the Andes Lidar Observatory (ALO), located near the Cerro Pachon astronomical observatory in Chile (30.3° S, 70.7° W), started observations of the MLT region (see Figure 1). ALO was specifically designed to investigate the dynamics of the MLT particularly the influence of mountain waves. It uses a suite of instruments including a Na wind-temperature lidar, a meteor-wind radar, an all-sky airglow imager and photometer suite, and a novel Mesospheric Temperature Mapper (MTM) camera developed at USU. The measurement of temperature is particularly important for understanding the dynamics of the MLT region. It provides information on the background structure of the atmosphere and the effects of wave perturbations. One of the longest and most established techniques for long-term measurements of mesospheric thermodynamics utilizes ground-based measurements of airglow emission rotational temperature. The most frequently used airglow emission is the near infrared OH Meinel band [Taylor and Garcia, 1995; Taylor et al., 1995, 1997].

2. Background

2.1. Mesospheric Temperature Mapper

The MTM is a high performance imaging system capable of precise measurement of the intensity and rotational temperatures of the near infrared OH nightglow emission layer which occur at peak altitude of ∼87 km [Taori et al., 2005; Taylor et al., 2001]. The MTM uses a high quantum efficiency CCD array coupled to a wide-angle telecentric lens system (90° field of view centered on the zenith) to observe selected emission lines in the OH (6,2) Meinel band as shown in Figure 2. Sequential measurements were made using a set of narrow band filters centered on the OH P_1(2) and P_1(4) emissions at 840 and 846.5 nm respectively. Each emission is observed for 30 sec followed by a background sky measurement at 857 nm, resulting in a cycle time of ∼2 min. The camera operates automatically from dusk to dawn (for solar depression angles <12°) for approximately 23 nights each month (centered on the new moon period). Data are stored locally.

Figure 2. Emissions given by different OH vibrational mode transitions. The ratio of the P_1(2) to P_1(4) emissions (highlighted in red) is used to measure OH rotational temperature.
on a computer drive and are downloaded at regular intervals to USU for analysis. To date, over 1100 nights of quality data have been obtained, providing detailed information on the nocturnal and seasonal behavior of mesospheric temperature and its variability at the OH emission height.

Relative intensity measurements of the selected OH emission lines are used to determine absolute rotational temperatures with high precision $\sim 1-2$ K using the well-established ratio method [Goldman et al., 1998; Meriwether Jr, 1984]. Based on typical OH emission levels measured at ALO, the precision of the measurements were determined to be $<1-2$ K (in 3 min) for the derived OH rotational temperatures. A previous comparison of the MTM OH rotational temperature with other well calibrated instruments has shown that our nocturnal mean temperatures, referenced to 87 km, are accurate to $\pm 5$ K [Pendleton et al., 2000].

### 2.2. SABER

NASA’s spaceborne instrument called SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) allows researchers to learn more about the upper atmosphere by helping produce the first comprehensive global measurements of this region. SABER, built by Utah State University’s Space Dynamics Laboratory and managed by NASA Langley Research Center, is one of four instruments on the TIMED (Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics) spacecraft launched in late 2001. The technique that SABER uses to sound, or make measurements in the atmosphere, has never before been used to study the MLT region in such detail. SABER uses a 10-channel broadband limb-scanning infrared radiometer covering the spectral range from 1.27 $\mu$m to 17 $\mu$m. These limb scans view radiation emitted by the atmosphere, such as in the form of airglow, and provide vertical profile measurements of temperature, pressure, geopotential height and chemical structures of the atmosphere between 10 and 180 km in altitude. The instrument provides fundamental information on the energy balance, chemistry, dynamics and transport of the MLT region [Russell III et al., 1999]. SABER temperature profiles (V2.0) used for this experiment have an altitude range 15-100 km and the data was averaged vertically over 1 km to reduce statistical uncertainty.
3. Data Analysis

3.1. MTM Data

The MTM data are stored as images and processed using software developed at USU. The background stars are first removed from the images. The intensity of the center pixels (zenith) of each of the \(P_1(2), P_1(4),\) background and dark images are next recorded. The \(\text{OH}\) rotational temperatures are derived as a function of time from these intensity measurements using the above mentioned ratio method.

This procedure is repeated for each clear, moonless night. The mean temperature values for each night are then recorded and plotted along with the standard deviation \((\sigma)\)—shown as the vertical error bars in Figure 3—in order to reveal the nightly variations for the entire run of data from August 12, 2009 until April 1, 2015. Each night the temperature amplitude can range from \(\pm 5 \text{ K}\) up to \(\pm 20 \text{ K}\). A 15 night average smoothing curve is applied to the data; this is shown in Figure 3. Average nightly \(\text{OH}\) rotational temperature for each year is shown, separated by a vertical dashed line. There is a positive linear trend of \(\sim 1 \text{ K per year}\). The average \(\text{OH}\) temperature for the 64 months is \(199 \pm 9 \text{ K}\).

The increase of mountain wave activity in the winter months can be inferred by observing the temperature variance \((\sigma^2\text{ measured in units } \text{K}^2)\) as modeled by the Mountain Wave Forecast Model developed by the Naval Research Laboratory [Jiang et al., 2002]. Variance measurements are often used as a substitute for wave activity because satellites can only obtain instantaneous profiles at any given location. Thus, satellites cannot observe the wave activity visible to a stationary camera over the course of a night. In Figure 4, temperature variances are recorded for 2 years due to simulated mountain waves. Similar results have also been found at ALO. In Figure 5, the 64 months of MTM data have been averaged into one year with the winter in the southern hemisphere centered on UT day 180. While the tides (large-scale wave features) have not yet been removed, the increased temperature variation during the winter months is still visible at ALO. Note the similarities of Figures 4 and 5.

3.2. SABER Temperature Profiles

AGW perturbations can be extracted from SABER temperature profiles [Remsberg et al., 2008] by removing the zonal mean temperature (zonal wave number 0) and the large-scale tides and planetary waves with zonal wave number 1-6 (similar methods were used by Preusse et al. [2002] and John and Kumar [2012]). These large-scale waves add substantially to the variability and need to be removed to make accurate measurements of only the small-scale AGWs. The daily temperature profiles are gridded into \(5^\circ \) latitude zones with increasing
longitudes to construct longitude-height plots. This is done separately for the ascending and descending orbits of the satellite to account for diurnal tides. The zonal mean temperature and wave numbers’ amplitudes and phases are estimated and subtracted from the temperature profile as the background. The temperature perturbations are then visible and assumed to comprise of AGWs. Once the fluctuations due to AGWs are extracted, further analysis can be carried out.

In order to study the mountain waves over the Andes Mountains, detrended temperature profiles recorded within a 5° box around ALO are included to measure variance as a function of altitude throughout the year. As shown in Figure 7, temperature variance is plotted for the year 2010. The black line shows the 15 day smoothing of the measured variance at the altitude of 87 km, the red line at 67 km, and the green line at 42 km. The variance increases with altitude which shows that the waves are propagating upwards and growing in amplitude. There is also increased variance in the winter months. An interesting feature of the SABER data is the spike in temperature variance observed in the mesosphere in the spring and fall. This does not appear in the MTM temperature measurements or other ground-based measurements and may be due to the difference in the spectrum of AGWs that are observable using one technique opposed to the other. While mountain waves are only expected to propagate into the mesosphere during the winter months, AGWs with other sources can propagate throughout the year. In spring and fall, this propagation is driven by convection and storms located near the Andes Mountains.

4. McMurdo Data

As part of a project to better understand AGW activity over Antarctica, Utah State University’s Atmospheric Imaging Lab also operates all-sky cameras and a MTM camera at several research sta-
Figure 8. Wave parameters observed during 2012 at McMurdo Station. Their (a) average wavelength was 22 km, (b) average observed phase speed was 42 m/s, while their (c) direction of propagation has many asymmetries suggesting localized sources.

Rations around the perimeter of Antarctica and at the South Pole. An all-sky CCD camera at McMurdo Station (77° S, 166° E) on Ross Island, off the coast of Antarctica, has operated during the dark winter months from March to September for the past three years. Two initial primary goals are to quantify the properties of small- and medium-scale mesospheric AGW climatology over this region of Antarctica, and combine results with similar measurements from other Antarctic stations to investigate continental-wide AGW dynamics.

In the images recorded every ∼10 seconds individual AGW events are observed in the OH emission layer although temperature measurements are not available. Using software developed at USU, the horizontal wavelength, observed phase speed and the direction of propagation of the waves are recorded. Over 400 AGW events during the 2012 observing season have been observed. The average horizontal wavelength of the AGW is 22 km, the average observed phase speed is 42 m/s, and the direction of propagation reveals East-West direction dominance (shown in Figure 8). McMurdo AGWs exhibit a large spread of phase speeds with a tendency for high phase speeds up to ∼120 m/s not seen at other high-latitude Antarctic sites. The data show evolution from NW propagation (107 events) in the fall which expands to NE and SW wave motions during mid-winter (110 events). The late winter was dominated by many waves (202 events) again exhibiting strong NE and SW motions but more isotropic than earlier. The strong asymmetries are suggestive of wave sources probably associated with strong localized weather systems caused by the polar vortex. This research is ongoing with more events needed to be processed in the 2013 and 2014 seasons.

5. Conclusion

Nocturnal variations of temperature at the ALO are highly variable and at times exceed 40 K during the course of the night. Other nights show evidence of smaller amplitude AGWs. Five years of MTM temperature data reveal an increasing linear trend in temperature; however, more years of data are needed to understand the long term climatology in the mesosphere above the Andes Mountains. These data are important for studying a broad range of wave phenomena extending from short period waves to seasonal variation.

Increased temperature variance in the winter months is a strong indication of the presence of mountain waves and results from the MTM and SABER temperature data sets are in agreement with models [Jiang et al., 2002] and other sites [Reisin and Scheer, 2004]. Comparisons with results from SABER show increased AGW activity over the Andes Mountains which, with our variance measurements, indicate that the prominent wave source is orographic forcing (created by mountains). Further research is needed to understand the increased variance observed in the SABER data during the spring and fall but not seen with ground-based measurements.
Optical observations of AGW activity over the Antarctic Continent is a new and ongoing study. Initial results are promising although further data reduction and analysis is needed. To date, one year of data from McMurdo Station, Antarctica has been analyzed. A large number (400+) of short-period AGWs observed over McMurdo, Antarctica enabling the wintertime mesosphere wave climatology to be investigated for the first time. McMurdo waves exhibits a large spread of phase speeds with a tendency for high phase speeds up to $\sim 120$ m/s. The sources of the wave events observed from McMurdo are probably associated with strong localized weather systems caused by the polar vortex. New analysis of McMurdo data from 2013 and 2014 data will further clarify the asymmetries in the wave propagation at this site for understanding the climatology of AGWs observed at McMurdo. Future work includes comparison with on-site Fe Boltzmann Lidar measurements and MF radar wind measurements.

Having showed that temperature variability increases in regions with enhanced mountain wave activity (see Figure 7) future research will focus on using SABER data to measure temperature variances at other locations where we have MTM temperature data sets (Hawaii [Zhao et al., 2007], New Zealand, and Logan, UT). With vertical temperature profiles available from SABER, AGW potential energy per unit mass measurements can be made for the first time at ALO and at future case study sites. AGW potential energy is an indicator of AGW intensity is widely used by the AGW community using lidars, radars, and other satellite instruments. Further understanding of mountain waves will improve parameterization of waves in weather, turbulence and climate forecast models.

Acknowledgement I would like to thank the Utah NASA Space Grant Consortium for supporting me for the past three years. A special thanks to my major professor Dr. Mike Taylor for his continued support. Also, this research could not be done without the help of Dr. Yucheng Zhao and Dr. Dominique Pautet. This research is supported under NSF grants AGS-1110215 and ANT-1045356.

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