Investigating mesospheric gravity wave dynamics and temperature variability over the Andes

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Abstract−Observations of mesospheric OH(6,2) temperatures by the Utah State University Mesospheric Temperature Mapper located at Cerro Pachon, Chile (30.3°S, 70.7°S) reveal a large range of nightly variations induced by atmospheric gravity waves and tides, as well as strong seasonal oscillations. Comparative studies with other data sets including the satellite-borne SABER instrument show good agreement on nightly, as well as seasonal, temperature measurements.

1. INTRODUCTION

The Andes Mountain Range in South America is an excellent natural laboratory for investigating the effects of atmospheric gravity waves (AGW) on the upper atmospheric wind and temperature fields. AGW propagate freely throughout the atmosphere transporting large amounts of momentum and energy from near the Earth's surface to great altitudes where they dissipate. AGW 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 summer months the dominant gravity wave forcing is expected to be due to severe weather (e.g. thunderstorms) over the continent to the East. While, during the winter season strong mountain forcing is expected to dominate due to 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 [e.g. Eckerman and Preusse, 1999] but their effects have yet to be quantified in the mesosphere [Smith et al., 2009].

Figure 1. The Andes LIDAR Observatory located in the Andes Mountains near the Cerro Pachon astronomical observatory in Chile.

In August 2009 the Andes Lidar Observatory (ALO), located close to 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 using 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 CEDAR Mesospheric

Figure 2. Picture of all-sky imaging system. Fish eye lens at top, followed by filter wheel. CCD imager and cooling system are positioned at bottom.

Temperature Mapper (MTM) camera developed at Utah State University (USU) (Figure 2). 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 dynamics utilizes ground-based measurements of airglow emission rotational temperatures. The most frequently used nocturnal emissions which originate in well-defined layers (approximately 8-10 km wide), are the near infrared OH Meinel (6,2) bands (mean altitude ~87 km) and the O_2 (0,1) Atmospheric band (mean altitude ~94 km).

2. BACKGROUND

2.1. Mesospheric Temperature Mapper

The CEDAR MTM is a high performance imaging system capable of precise measurement of the intensity and rotational temperatures of the near infrared OH and O_2 nightglow emission layers. 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 3. Sequential measurements were made using a set of narrow band filters centered on selected emission lines, eg. the OH(6,2) $P_1(2)$ and $P_1(4)$ rotational emission lines 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 on computer disk and are downloaded at regular intervals to USU for analysis. To date, over 750 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.

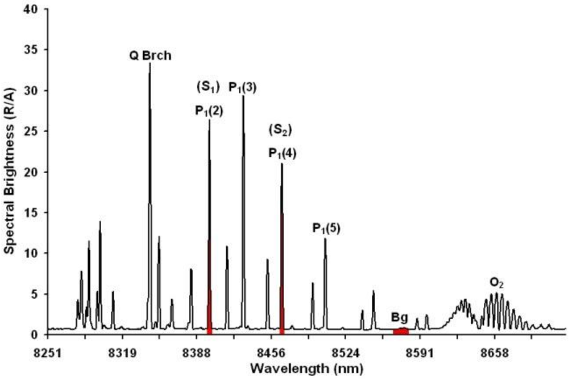

Figure 3. Emissions given by different OH vibrational mode transitions. The ratio of the $P_1(2)$ to $P_1(4)$ emissions (highlighted in red) is used to measure OH rotational temperature.

Relative intensity measurements of the selected OH emission lines are used to determine absolute rotational temperatures with high precision ~1-2 K using the well-established ratio method [e.g. Meriwether, 1984, Goldman et al., 1998]. Based on typical OH emission levels measured at Cerro Pachon, the precision of the measurements were determined to be <1-2 K (in 2 min) for the derived OH rotational temperatures. A previous comparison of the

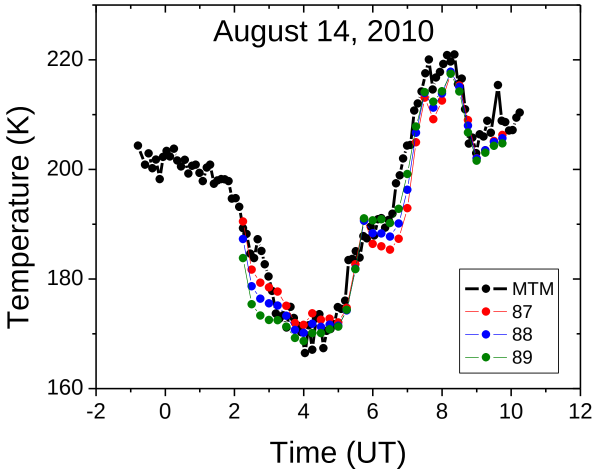

Figure 4. MTM temperature data plotted with Na Lidar temperature data for three altitudes centered on ~87 km measured on the night of August 14, 2010.

MTM OH rotational temperature with other well calibrated instruments, including Na lidar and spectrometer, has shown that our nocturnal mean temperatures, referenced to 87 km, are accurate to ± 5K [Pendleton Jr., et al, 2000]. Measurements of the OH rotational temperature as measured by the MTM at ALO are in good agreement with measurements of the on-site Na lidar. Figure 4 shows MTM OH temperature data for one night (black line) and temperature measurements from the Na lidar sampled at 87, 88, and 89 km (red, blue and green lines, respectively).

2.2. SABER

NASA's space-borne instrument SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) allows researchers to investigate the upper atmosphere by helping produce the first comprehensive global measurements of this region. SABER, built by USU'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 the atmosphere has never before been used to study the MLT region in such detail. SABER version 1.07 uses a 10-channel broadband limb scanning infrared radiometer covering the spectral range from 1.27 μm to 17 μm. These limb scans view radiation emitted by the atmosphere such as in the form of airglow and provide vertical profile measurements of temperature of the atmosphere between 10 and 180 km in altitude. Temperature measurements are derived from CO_2 channel radiances in the stratosphere and mesosphere [Remsberg, et al., 2008]. The instrument provides fundamental information on the energy balance, chemistry, dynamics and transport of the MLT region.

3. DATA ANALYSIS

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 OH rotational temperatures are derived from these intensity measurements using the above mentioned ratio method. This process is shown in Figure 5. In Figure 5a, the OH emission intensities (shown in black and grey), the background (green) and the dark (blue) intensities are recorded every 3 minutes for one night, September 13-14, 2012 shown from sunset (vertical lines near 0:00 UT time) to sunrise (near vertical lines near 10:00 UT). In Figure 5b, the OH band intensity (red) and derived OH rotational temperature (blue) are shown for the same night. The mean OH temperature for the night is 188 ± 8 K (where the uncertainty is a measure of the temporal variability). Nocturnal OH temperature variability shows effects of both small-scale gravity wave activity and larger diurnal tide activity.

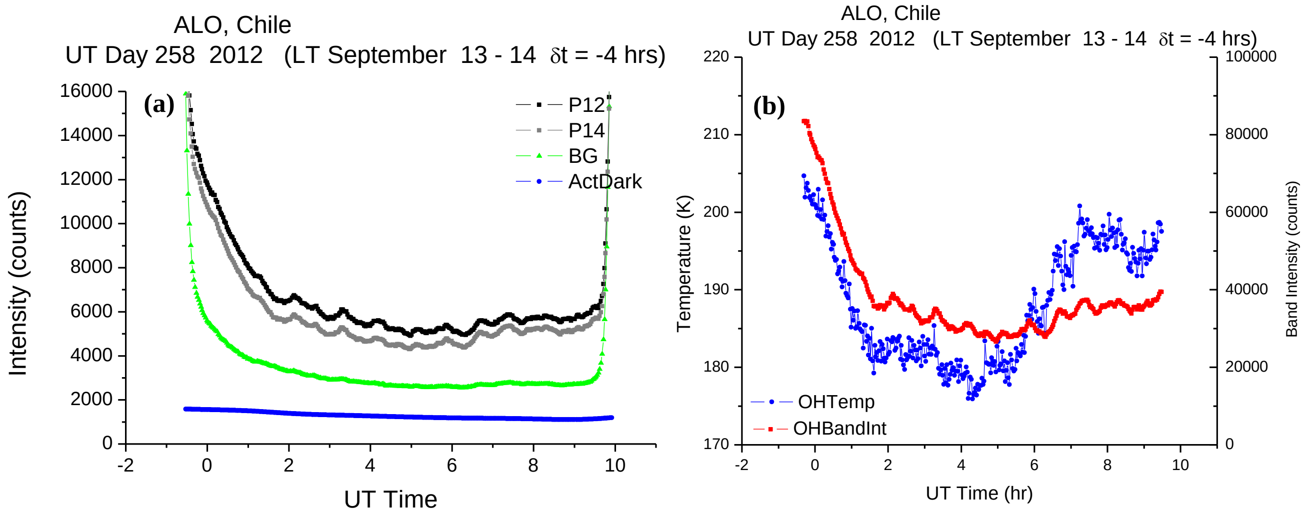

Figure 5. MTM temperature data for September 13-14, 2012. (a) plots the OH emissions (shown in black and grey), the background (green) and the dark (blue) intensities. (b) plots the OH band intensity(red) and the derived OH temperature (blue).

This procedure is repeated for each clear, moonless night. The mean temperature values for each night are recorded and plotted along with the standard deviation shown as the vertical error bars in order to show the nightly possible variations for the entire run of data from August 12, 2009 until December 31, 2012. Each night the temperature variation can range from ± 5 K up to ± 20 K. A 15 night running average smoothing curve is applied to the data, this is shown in Figure 6. Each year in the plot is separated by a vertical dashed line and average nightly OH rotational temperature

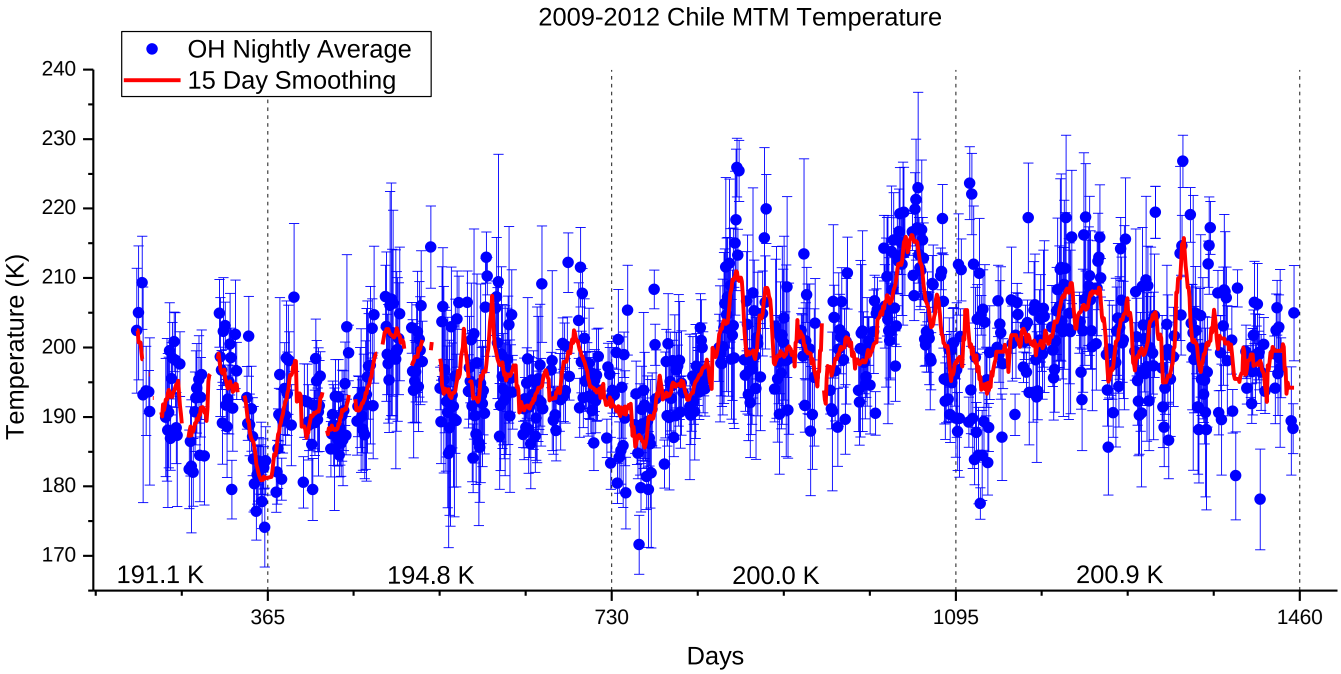

Figure 6. MTM nightly averaged OH temperature measurements from August 12, 2009 until December 31, 2012. Days are counted from January 1, 2009, where years are separated by black vertical lines. The blue points are the mean temperature for each night and the error bars represent the standard deviation in temperate each night. A 15 day running average smoothing fit (red line) is applied to the data.

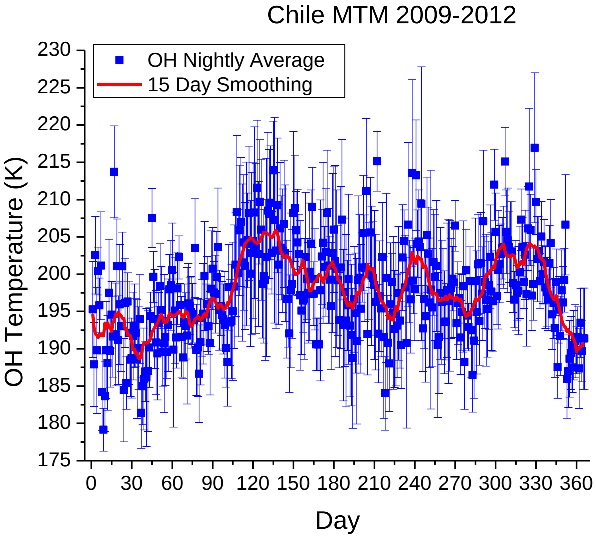

Figure 7. MTM nightly average OH temperature from August 2009 to December 2012 folded into one year. As in Figure 8, error bars represent the standard deviation each night and the red line is a 15 day running average smoothing fit.

for each is shown. The averaged OH temperature for the 40 months is 197.7 ± 0.2 K with a standard deviation of 4.2 K. This measurement is in good agreement with data from the Maui-MALT program, where five years of MTM were previously obtained (2001-2006) from the Air Force facility at the summit of Haleakala Crater, Maui, Hawaii (20.8° N, 156.2° W ~3000 m) [Zhao et al., 2005].

In order investigate yearly trends the data plotted in Figure 4 can be folded into one year's worth of data by averaging all temperature measurements from the same UT day number. This folded plot is shown in Figure 7. A 15 day running average smoothing curve is also fitted to the data. A harmonic analysis shows that the three years of data exhibit an annual and semi-annual oscillation. To show this, a sine wave is fitted to the 15 day smoothing curve data with a period of 365 days and an amplitude of 2.9 K (Figure 8a). The annual oscillation sine wave is then subtracted from the data in order to find the semi-annual oscillation with a period of 183 days and an amplitude of 3.8 K (Figure 8b). The semi-annual

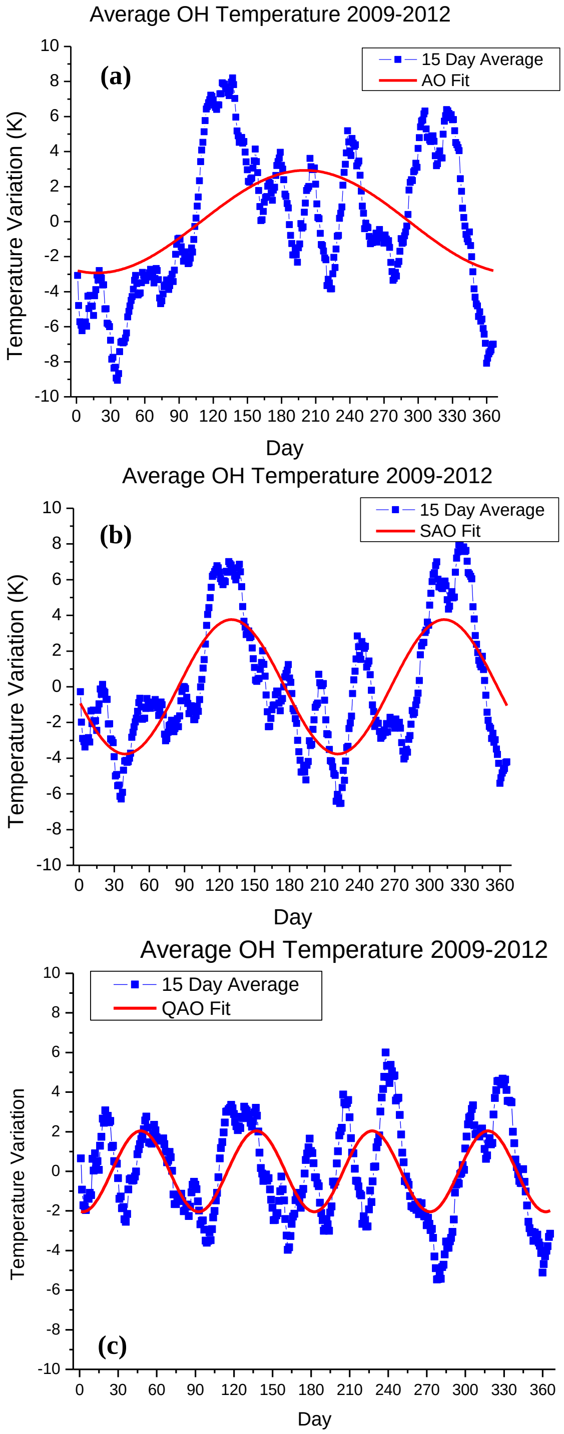

Figure 8. 15 day running averaged OH temperature data from August 2009 to December 2012 fit to (a) an annual oscillation, (b) a semi-annual oscillation and (c) a ~90 day oscillation (quarter-annual oscillation).

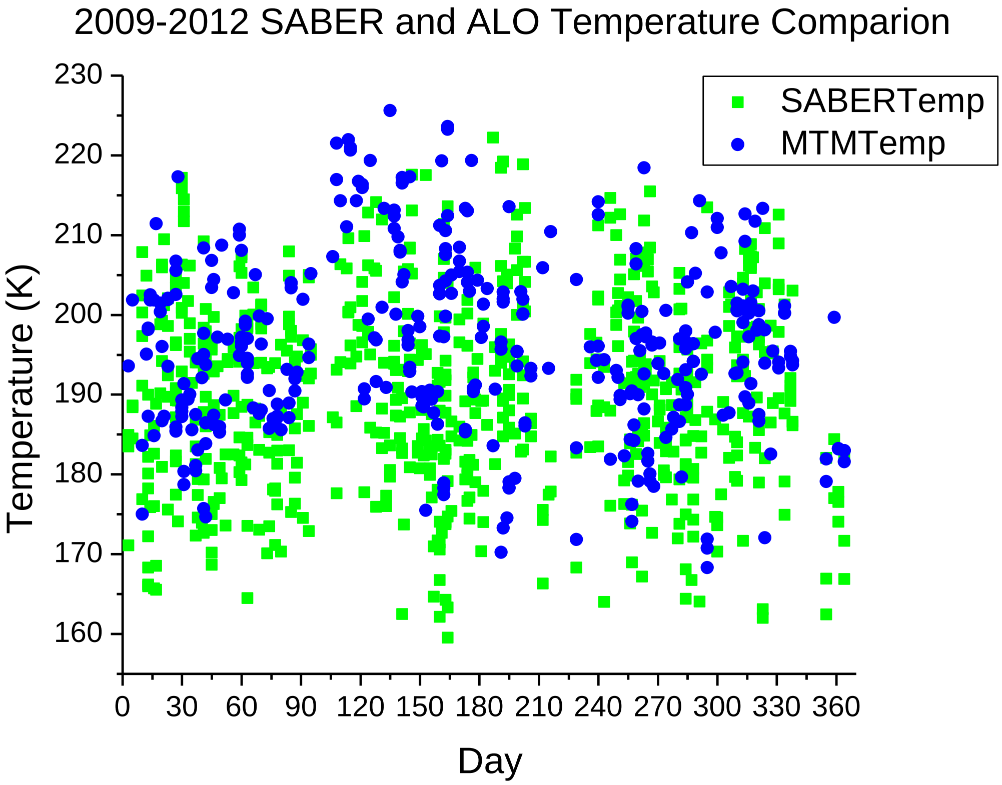

Figure 9. Coincident SABER temperature measurements and MTM OH temperature measurements for August 2009 to December 2012 folded into one year. SABER average temperature is 190.2 K and MTM OH average temperature is 195.9 K.

oscillation is also subtracted from the data and an oscillation of ~90 days has been found with an amplitude of 2.0 K (Figure 8c). Annual and semi-annual oscillations have been found in other locations, such as Maui [Zhao, et al., 2007], but the ~90 day, or quarter-annual oscillation, is unexpected and further investigation is required.

Once nocturnal OH temperature measurements are obtained by the MTM at ALO, a comparison with the SABER instrument can be made. As the TIMED satellite orbits earth, among other measurements, SABER makes temperature profile measurements every ~30 sec as a unique event in numbered orbit. Along with the temperature profile SABER records the time and location. First, all events that are recorded at night within a 10° x 10° box centered at ALO are selected by an IDL software program. The temperature is height weighted with a Gaussian profile in order to compare SABER and MTM OH temperatures at the nominal peak OH emission layer of 87 km. Often there will be two to four SABER events that will happen in the geographic box during one night. Each of the SABER temperature measurements is compared to the closest in time averaged MTM temperature measurement.

All SABER events that are within 30 min coincident with MTM temperature measurements from August 2009 to December 2012 are plotted in Figure 9. The multiple years of data are folded into one year for viewing purposes. The temperatures range from ~165-225 K and show good agreement over this range. SABER height weighted temperature measurements (green) average 190.2 ± 0.5 K and MTM OH temperature measurements (blue) average

195.9 ± 0.4 K for the 40 months of data with an offset of 5.7 ± 0.7 K (SABER lower) and a standard deviation of ±12 K. This compares very favorably with a previous study using SABER and MTM data from the Maui-MALT program where the offset was found to be 5.8 ± 0.2 K (SABER lower).

4. CONCLUSION

Nocturnal variations of temperature at the ALO are highly variable and at times can exhibit large amplitudes, exceeding 40 K during the course of a night observations probably driven by tidal harmonic oscillations (periods of 8 and 12 hrs). Other nights show evidence for smaller amplitude (several K) gravity waves in both intensity and temperature data with well-defined periods ranging from tens of minute to a few hours.

An initial harmonic analysis applied to the 40 months OH intensity and temperature data has been used to study the seasonal variations. The data show clear signature of an annual (AO) and semi-annual (SAO) signatures with similar amplitude to those observed at Maui. However, the ALO data reveal an unexpected 90 day oscillation that lasted for the first 1.5 years of the measurements and exhibited a significant amplitude. This result is under further investigation.

SABER temperature comparisons demonstrate the long-term stability and utility of ongoing MTM observations at ALO. These data are important for studying a broad range of wave phenomena extending from short period gravity waves to seasonal variations.

Ongoing work includes comparison with OH spectrometer data from nearby (200 km) El Leoncito, Argentina (courtesy J. Sheer). For the first two years of operation at ALO the MTM also measured O_2 temperatures. Phase differences between the O_2 and OH temperature waves in these two emissions will be measured to investigate gravity wave growth and dissipation over the Andes Mountains for comparison with Maui-MALT wave data over an oceanic site. These results will be used to study regional differences in gravity wave forcing in the MLT region.

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