The Advanced Mesospheric Temperature Mapper: Remote Sensing of the Nighttime OH Layer During the DEEPWAVE Campaign

Pattilyn McLaughlin
Utah State University - Center for Atmospheric and Space Sciences

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THE ADVANCED MESOSPHERIC TEMPERATURE MAPPER: REMOTE SENSING OF THE NIGHTTIME OH LAYER DURING THE DEEPWAVE AND SUPER SOAKER CAMPAIGNS.

by

Pattilyn F. McLaughlin

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Physics

Approved:

Mike Taylor, PhD.  
Major Professor

Ludger Scherliess, PhD.  
Committee Member

Charles Torre, PhD.  
Committee Member

Mark R. McLellan, Ph.D.  
Vice President for Research and Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

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Abstract

The Advanced Mesospheric Temperature Mapper [AMTM] is a remote sensing instrument developed at Utah State University to map temperature structures in the hydroxyl airglow emission at ~87 km. These maps can then be used to quantify wave field characteristics and to observe general climatology trends. Two recent campaigns that it has been involved with are the DEEPWAVE campaign in Lauder, New Zealand and the Super Soaker campaign in Fairbanks, Alaska.

The Deep Propagating Gravity Wave Experiment, “DEEPWAVE” was an international measurement and modeling program intended to characterize the generation and propagation of a broad range of atmospheric gravity waves with measurements extending from the ground to ~100 km altitude. A suite of aircraft-borne and ground-based aeronomic and weather measurements was deployed from New Zealand during a two-month period in June-July of 2014 to investigate wintertime gravity wave [GW] events as well as to study their climatology. Data used in this study were obtained by a collection of ground-based instrumentation operated at the Lauder Station of the National Institute of Water and Atmospheric Research [NIWA] in New Zealand (45.0°S). Instruments included an AMTM, a Rayleigh lidar and an all-sky imager. Analysis of image data obtained by the AMTM revealed a rich spectrum of GWs with 19 unprecedented quasi-stationary mountain wave [MW] events generated by orographic forcing. This is the largest occurrence of MW activity recorded at heights of 80-100 km. This study will focus on four such events, illustrating their varying MW properties and in three cases determining their corresponding momentum flux.

The Super Soaker Sounding Rocket Mission was designed to study the transport, chemistry, and energetics of water in the mesosphere-lower thermosphere [MLT] region with the intent to create a Polar Mesospheric Cloud [PMC] through water deposition. Three sounding rockets were launched on January 26, 2018 into clear night-time skies over central Alaska with coincident ground-based AMTM, Rayleigh and Resonance lidar observations. In addition, the AMTM collected data for two months preceding and following the launch to establish typical GW characteristics and temperature variability during this period. This study will include an overview of PMC, a summary of the scientific goals and questions of the mission, results collected from the AMTM with an emphasis on the GWs, and an analysis of the wintertime climatology of the Fairbanks area at this time.

Introduction

A well-known example of gravity waves are the ripples in a pond after a stone is dropped into the water. The disturbance causes the water to be displaced but then due to gravity it adjusts in an attempt to return to equilibrium causing a ripple effect. Gravity waves occur only in stratified fluids. Since the atmosphere is nearly always close to geostrophic and hydrostatic balance if these balances are disturbed through heating or cooling, the atmosphere adjusts itself to get back into balance. This process is called geostrophic adjustment. Another example of a gravity wave is caused by airflow over a mountain. An air parcel expands as it climbs the slope because the atmospheric pressure falls with height. The adiabatic expansion causes the air to cool and fall once over the peak. The momentum it gained from its climb then causes the parcel to over correct and it travels passed its equilibrium point. The parcel then begins to oscillate. As
they propagate upwards their period is short and their frequency is high. Conversely if the wave is propagating outwards the period is long and the wavelength is large.

Potential sources for GW production are mountain ranges, thunderstorms through convection in the troposphere, weather fronts, the Jetstream and man-made explosions. Any perturbation on the ground that causes an air parcel to be pushed up can create gravity waves in the atmosphere. Even waves in the ocean are now being considered as a source.

A mountain wave is a particular type of gravity wave that is caused when stable air flow passes over an orographic feature. They were first discovered when On March 10, 1933, German glider pilot Hans Deutschmann was flying over the Riesen mountains in Silesia when an updraft lifted his plane by a kilometer. The event was observed, and correctly interpreted, by German engineer and glider pilot Wolf Hirth and has been an object of interest to scientists and pilots alike ever since.

There are two kinds of “Mountain Waves. “The first is vertically propagating waves that appear to have zero horizontal velocity with respect to the mountain but propagate to higher altitudes due to the upward force from the wind passing over the mountain. As the waves propagate they grow in amplitude due to decreasing density in the atmosphere. In this case the velocity of the wind and the leeward phase speed keep the wave from propagating horizontally. They typically have wavelengths of 10- 100s of km and as they extend upward they tilt upwind with height. As a MW propagates up through the atmosphere, two things can happen. Its amplitude will grow until it saturates and loses energy, or it will encounter a critical level, where the background wind gets close to 0 m/s. In both cases, the MW will break, creating turbulence and releasing their momentum into the background atmosphere, possibly generating secondary GWs.

Data is generally collected in the winter months due to the direction of the average global wind. In the summer the wind starts eastward but then moves westward at a low altitude so a critical level is reached. In the winter the wind moves generally eastward until about 100km which allows us to observe the propagation of MWs into the upper atmosphere. Fig. 1 shows the average wind for winter and summer.

![Fig. 1 - Typical summer (red) and winter (blue) zonal wind vertical profiles. (Evers and Dost, 2018)](image_url)
The study of GW is important because when a wave rises it eventually breaks which causes a large amount of momentum to be deposited into the atmosphere. This momentum can create severe turbulence affecting air traffic and can cause strong downslope winds which may be hazardous to people and property. The deposited momentum drives atmospheric circulation. GWs could have a potentially important role in climate and weather thereby affecting global weather predictions and climate models. In the ionosphere gravity waves could affect GPS communication, satellite tracking and future suborbital spaceflight.

**Advanced Mesospheric Temperature Mapper**

Ground-based remote sensing of the Earth’s atmosphere in the infrared portion of the electromagnetic spectrum can be used to better understand the processes and dynamics occurring in the MLT region (~80-100 km) and above. Measurements of the nighttime hydroxyl [OH] emission lines can be used to create intensity and temperature maps which show wave propagation and dissipation in the MLT. OH nocturnal emission typically originates in a well-defined layer centered at ~87km and exhibiting a layer full width half maximum [FWHM] of ~7km (Baker and Stair, 1988). The AMTM is an infrared digital imaging system developed at Utah State University in conjunction with the Space Dynamics Laboratory that is capable of measuring OH emission lines that originate at 87 km. This section describes the characteristics of the AMTM and its capabilities for the ground-based remote sensing of the upper mesospheric dynamics.

The AMTM collects signal for the OH M (3,1) rotational emission band. This band was selected as the primary target because it is a strong emitter in the upper mesosphere and is significantly less sensitive to contamination from auroral emissions and moonlight conditions than other bands. While auroral emissions rarely occur in the mid-latitudes they present a substantial impediment for airglow imaging observations at high-latitudes. This gives the AMTM a capability that few other instruments can match. In operation, signals from the OH (3,1) band, P1(2) and P1(4) emission lines are sequentially captured and then used to calculate the temperature of the region at ~87 km. The rotational temperature and derived intensity maps visualize MLT wave structure which can then be used to quantify the parameters of various wave parameters.

**Instrument Specifics**

The AMTM uses a fast (f:1) 120° field-of-view telecentric lens system designed and built at the Space Dynamics Laboratory [SDL]. Three 4” narrow band (2.5–3 nm) filters centered at 1.523 (P1(2)), and 1.542 μm (P1(4)) and a nearby background region filter are mounted in a temperature-controlled filter wheel and each have a 10s exposure time giving a 30s integration time capability. The detector is a 320x256 pixels InGaAs sensor, thermoelectrically cooled down to ~50°C. Its spectral range is 1.1 to 1.6 μm which includes the range of interest (1.5215-1.5435μm).

Table 1 lists various instrument and detector characteristics (Pautet et al., 2014).
<table>
<thead>
<tr>
<th><strong>Throughput</strong></th>
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</tr>
</thead>
<tbody>
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<td><strong>Pixel Size</strong></td>
<td>30μm</td>
</tr>
<tr>
<td><strong>Quantum Efficiency</strong></td>
<td>&gt;80%</td>
</tr>
<tr>
<td><strong>Detector Operating Temperature</strong></td>
<td>-50°C</td>
</tr>
<tr>
<td><strong>Optical Transmission</strong></td>
<td>50%</td>
</tr>
</tbody>
</table>

*Table 1 - AMTM instrument specifications.*
Part A

Mountain Waves

A mountain wave or MW is a type of gravity wave that is caused when stable air flow passes over an orographic feature. They were first discovered on March 10, 1933, as German glider pilot Hans Deutschmann was flying over the Riesen mountains in Silesia when an updraft lifted his plane by a kilometer. The event was observed, and correctly interpreted, by German engineer and glider pilot Wolf Hirth and has been an object of interest to scientists and pilots ever since (Tokgozlu et al., 2005).

There are two kinds of MW. The first is vertically propagating waves that appear to have zero horizontal velocity with respect to the mountain but propagate to higher altitudes due to the upward force from the wind passing over the mountain. As the waves propagate energy upwards they grow in amplitude due to decreasing density in the atmosphere (assuming no dissipation). In this case the velocity of the wind and the leeward phase speed are equal and opposite in direction. Thus a stationary wave with zero horizontal phase speed is created. They typically have wavelengths of 10 - 100s of km and as they extend upward they tilt upwind with height.

The second kind are trapped or lee waves (Fig. 2). These waves are also generated by stable air flow but they do not propagate upwards. They are trapped on the lee side of the orographic feature and can be made visible if clouds become trapped in the wave.

Keograms

A keogram is a visual representation of time-varying phenomena summarizing temporal-spatial data. They were first used to illustrate auroral morphology by Eather et al. in 1976 but have applications in other types of spatial data visualization such as OH temperature maps. The name keogram comes from the Inuit word “Koeeit,” meaning aurora (Mende et al., 1978) and the Greek suffix “–gram” meaning a drawing or something written or recorded. Keograms are in essence a time vs. latitude or longitude plot that represents a series of images taken over the course of one night (Eather, et al. 1976; Taylor et al. 2009). While small-scale structure in brightness and temperature are easily quantified in a series of individual AMTM images, larger-scale structure and general trends are nearly impossible to observe without a keogram.

Keograms are constructed temporally from left to right and consist of a compilation of image “slices” from a dataset. Each slice is a few pixels wide and taken either vertically or
horizontally depending on if the keogram intends to spatially represent North/South structure or East/West structure respectively. Each slice represents a moment in time so when they are combined into a composite image they show the time evolution of an observable. In the case of the AMTM the observable is OH airglow. The process of keogram creation is illustrated in Fig. 3.

Fig. 3 - Keograms are constructed with horizontal/vertical slices of a sequence of images to represent East/West and North/South structure vs. time. The horizontal slices are taken to form the East/West keogram (below) and the vertical slices form the North/South keogram (above). Image courtesy of P-D Pautet.

Fig. 4 illustrates an example of large-scale gravity wave structure, unable to be observed in a frame by frame analysis was detected in the temperature keogram from July 8th from Lauder, NZ during the 2014 DEEPWAVE campaign. It is easy to see a periodic warming in the keogram with a temporal period of about 2.5 hours. It is also apparent in the keogram that there are smaller-scale waves around 10:00 UT that appear to be moving in a southward direction and remaining stationary in the east/west direction. The downward slope of the structure in the N/S portion of the keogram (Fig. 4 top) indicates a southward movement, while the vertical structure in the east/west keogram (Fig. 4 bottom) indicates a quasi-stationary behavior in the east or west direction. The horizontal streak in the N/S keogram at 8:30 UT is due to the moon. It doesn’t appear in the E/W keogram because its elevation never goes past the vertical midpoint of the frame.

Fig. 4 - Temperature keogram from the night of July 8th at Lauder, NZ during the DEEPWAVE campaign. A large-scale wave with period ~2.5 hours is visible from 10:00 UT -20:00 UT with peaks at 13:30, 17:00 and 19:30 UT. Due to the scale of the periodic behavior this oscillation was undetectable in a frame by frame review of the dataset.

Keograms are a useful tool for summarizing a night’s worth of data succinctly. Large and small structure is easily seen in these graphs and they can provide information that individual
frames of data cannot. They can visualize trends in the climatology of a region as shown later with the Super Soaker campaign and display the quasi-stationary behavior of MW that may be overshadowed by brighter features in a frame as will be discussed in the DEEPWAVE campaign section.

**DEEPWAVE Overview**

The Deep Propagating Gravity Wave Experiment, “DEEPWAVE” was a program designed to characterize and predict the generation and propagation of a broad range of atmospheric GW with measurements extending from the ground to ~100 km in height. These waves typically arise from sources located at lower altitudes such as storms, frontal weather systems and winds interacting with mountain ranges. They dissipate at high altitudes in the MLT depositing large amounts of momentum into the upper atmosphere with regional and global impacts on the wind and temperature field (Fritts and Alexander, 2003).

A suite of aircraft-borne and ground-based aeronomic and weather measurements was deployed in New Zealand during a two-month period (June-July) in 2014 to investigate the wintertime GW climatology. New Zealand was chosen as it has been previously identified as a “hot spot” for GW activity in the stratosphere using several satellite studies (Fritts, Smith, et al., 2015), however little was known if this region of activity extended to higher altitudes with strong wave penetration into the overlying mesosphere and thermosphere.

Overarching goals of the DEEPWAVE program included:

- Detailed measurement and modelling of GW sources, propagation, and instabilities over New Zealand, Tasmania and the Southern Ocean.
- Predictability studies of GW sources, propagation, breaking and their influences on forecasting.
- Understanding the propagation of GWs throughout the stratosphere and their effects on the momentum budget.

During the campaign two Utah State University AMTM were deployed and operated for the DEEPWAVE mission. The primary goals were to measure the horizontal GW temperature structures in the OH airglow emission at ~87km to quantify the wave field characteristics and their amplitudes, and to help identify the dominant sources over New Zealand (especially mesospheric MW). One AMTM was deployed on the Gulfstream V aircraft and flew 25 missions over southern New Zealand and the surrounding oceans, while the second AMTM was set up and operated automatically from Lauder, New Zealand. Both instruments worked exceptionally well and collected data from May 31 to July 22, 2014.

In this study, data obtained by a suite of ground-based instrumentation operated at NIWA Lauder Station, NZ (45.0°S) are utilized to perform a detailed investigation of the generation and propagation of MW into the upper mesosphere and to quantify their impact on this area using novel measurements of momentum fluxes. The ensemble of instruments included the ground-based AMTM, a Rayleigh lidar and sodium lidar, and an All-Sky Imager. In our initial analyses of these image data obtained by the AMTM we have determined a rich spectrum of GWs. A remarkable 19 events were identified as strong signatures of mesospheric MW generated by orographic forcing from the nearby southern alps. This is by far the largest outflowing of MW activity ever recorded at MLT heights.
Introduction

The ground-based AMTM at Lauder collected data for 51 consecutive nights from May 30th to July 21st. As seen in Fig. 5, during the 51 days of operation the AMTM observed 372 hours of clouds, 223 hours of propagating waves and 141 hours of stationary waves. In total, 19 events with unmistakable evidence of generation from orographic forcing (MW) were observed. An example of one such event is shown in Fig. 6. The observed events were quasi-stationary, exhibited a variety of horizontal wavelengths and lasted for a few to several hours. Only one prior study has ever reported such waves. Smith, et. al. (2009) reported several MW events over the Andes mountains during July 2008. Events in this study are the first with unambiguous evidence of MW activity in the mesosphere meaning they were generated by orographic features and had subsequently propagated up into the MLT. Fig. 7 shows a representative intensity map of each similar event to occur during the DEEPWAVE campaign. This result is important because it provides evidence for frequent penetration of MW to high altitudes (>90 km).

This paper will discuss events that occurred on four of these nights, May 30th, June 21st, July 14th, and July 17th. I have analyzed these nights because they had longer lasting events than other nights and/or because of the availability of coincident lidar data enabling momentum flux estimates.

- On May 30th, 7 hours of propagating waves and 4+ hours of MW occurred.
- June 21st had the strongest example of a MW event.

Fig. 5 - The AMTM collected data a total of 736 hours. Of the total hours, three types of activity were observed, cloudy, propagating GWs, and quasi-stationary MWs. The plot above shows the hourly breakdown of events during the DEEPWAVE campaign. (P.-D. Pautet via private communication.)

Fig. 6 - OH intensity (left) and temperature (right) data from July 17-18 at 13:12:24 UT exemplifying a MW event. Temperature ranges from 190K to 232K. This event had wavelengths in the range of 15-25 km and lasted for ~6 hours.
July 14\textsuperscript{th} and July 17\textsuperscript{th} were clear nights where nearly all activity observed was quasi-stationary MW.

\textbf{May 30\textsuperscript{th}}

May 30\textsuperscript{th} was the first night of observations for the ground-based AMTM during DEEPWAVE. It was also a night with a large variety of GW activity (Fig. 8). Six distinct events occurred during the night. The first five exhibiting different wave characteristics associated with freely propagating waves while the last event of the night showed clear stationary behavior indicative of MW. A visual breakdown of the night is shown in Fig. 9 with a frame from each distinct event. The night started with rapidly progressing, large-scale, large-amplitude GWs moving northeast with imbedded smaller-scale wave/instability features. These waves typically had velocities greater than 100 m/s, wavelengths of about 50 km and a 10 K temperature amplitude (Fig. 9a). As the night progressed this event continued but a smaller scale GW event moved through the larger-scale waves from the southeast. This heralded strong instability development along the wave crests of the larger features (Fig. 9b). At 10:30 UT the rapid, large-scale waves dispersed and were replaced with a coherent smaller-scale, low velocity (<20 m/s), northwest propagating event (Fig. 9c). At 12:05 UT there is evidence of clear counter-clockwise rotational wave genesis with strong temperature perturbations (Fig. 9d). The penultimate stage of activity was an ensemble of structures creating a chaotic state. There is a solitary stationary band of brightness in the NE corner of the frame (Fig. 9e). Finally, MW begin to develop. North-south aligned bands are visible which are indicative of MWs. They are quasi-stationary with a very
slow westward propagation (Fig. 9f). Table 2 contains the characteristics of the nights notable events.

Fig. 8 - OH (3,1) band intensity (top) and rotational temperature (bottom) keograms demonstrating a variety of propagating and standing GWs on May 30th. (McLaughlin et al., 2015)

Fig. 9 - Sequence of intensity and temperature frames from May 30th exemplifying wave events that occurred. The times for each event are as follows. A – 8:52 UT, B – 9:54 UT, C – 10:30 UT, D – 12:05 UT, E – 15:48 UT, F – 18:02 UT
### Table 2 - Summary of results from May 30th, 2014. ΔT is a peak-to-peak measurement.

<table>
<thead>
<tr>
<th>Event</th>
<th>Time</th>
<th>Wavelength [km]</th>
<th>Period [min]</th>
<th>ΔT [K]</th>
<th>Phase Velocity [m/s]</th>
<th>Θ [from North]</th>
<th>Duration [hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>08:52 UT</td>
<td>46</td>
<td>6</td>
<td>~20</td>
<td>135 ± 3</td>
<td>52°</td>
<td>1.5</td>
</tr>
<tr>
<td>B</td>
<td>09:54 UT</td>
<td>57</td>
<td>9</td>
<td>~30</td>
<td>108 ± 2</td>
<td>49°</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>10:30 UT</td>
<td>23</td>
<td>27</td>
<td>~20</td>
<td>14 ± 1</td>
<td>319°</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>12:05 UT</td>
<td>18</td>
<td>28</td>
<td>~25</td>
<td>11 ± 1</td>
<td>304°</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
<td>13:19 UT</td>
<td>21</td>
<td>26</td>
<td>~25</td>
<td>13 ± 1</td>
<td>300°</td>
<td>1</td>
</tr>
<tr>
<td>F</td>
<td>15:48 UT</td>
<td>13</td>
<td>45</td>
<td>~20</td>
<td>5 ± 1</td>
<td>225°</td>
<td>1.5</td>
</tr>
<tr>
<td>G</td>
<td>18:02 UT</td>
<td>50</td>
<td>-----</td>
<td>~20</td>
<td>~0</td>
<td>-----</td>
<td>&gt;4</td>
</tr>
</tbody>
</table>

**Momentum Flux**

Momentum flux [MF] can be used as a measure of how much energy a buoyancy wave may be depositing into the atmosphere. It is important to calculate the MF of MW because it can provide quantitative measure of the frequent forcing’s of wave events. Average MF deposition is vital for inclusion in DEEPWAVE modelling studies of MW impact on the MLT.

One way the MF for a wave can be calculated is by utilizing the following two equations from Fritts et al. 2014:

\[
< u_h' w' > = \frac{g^2 \omega_i}{2N^2} \sqrt{1 - \frac{\omega_i^2}{N^2} \left( \frac{<T'>}{T_0} \right)^2} \frac{1}{C^2} \tag{1}
\]

In this equation \( g \) is the acceleration due to gravity, \( N \) is the buoyancy frequency, \( \omega_i \) is the intrinsic frequency of the GW, \( <T'> \) is the measured temperature perturbation amplitude, \( T_0 \) is the mean temperature and \( C \) is a factor to compensate for the phase averaging over the finite thickness of the OH layer and is called the “cancellation factor”:

\[
C = \frac{<T'>}{T'(z_0)} = e^{-3.56 \frac{z_{FWHM}}{\lambda^2}} \tag{2}
\]

Specifically, for wave events during the DEEPWAVE campaign, the frequencies, \( \omega_i \) and \( N \) are calculated using the background wind data provided by the Navy Global Environmental Model [NAVGEM] (Eckermann et al., 2014; Pautet et al. 2016). The temperature terms in equation 1 are measured using lidar data that were collected at the same location as the AMTM and/or by using the AMTM data directly. The cancellation factor can be found using near-coincident SABER measurements of the thickness of the OH layer \( z_{FWHM} \) but these measurements are not always available.

A preferred method of MF calculation uses AMTM and coincident lidar data to bypass reliance on the cancellation factor. This is shown in equation 3 which is derived from equation 1. (Ern et al., 2004).
\[ <u_h'w' > \geq \frac{1}{2} g^2 \frac{\lambda_z}{N^2 \lambda_x} \left( \frac{\tau'}{T_0} \right)^2 \]

AMTM data are again used to find the horizontal wavelength and also the background temperature. Lidar data were used to find vertical wavelength and temperature perturbation. The buoyancy frequency or the Brunt–Vaisala frequency which is the angular frequency at which a vertically displaced parcel will oscillate within a statically stable environment was found using a sodium lidar during the campaign. It is taken as a constant \(0.018 \, \text{s}^{-1}\) for all calculations in this study.

TELMA or the Temperature Lidar for Middle Atmosphere research – is designed for measurements of atmospheric GW parameters in the middle atmosphere. The lidar system comprises a sodium resonance lidar and a powerful Rayleigh lidar. This portable lidar system was operated during the DEEPWAVE campaign by Dr. Bernd Kaifler of DLR in Germany. On clear nights it was able to collect temperature profiles that were later used in the MF calculations discussed previously.

**June 21-22**

On June 21, 2014 an exceptional MW event was observed from 10:15 UT to 13:00 UT. This MW exhibited large horizontal wavelengths (55–90 km) and temperature perturbations of 20–30 K. Signatures of the event lasted well into the night but with weaker characteristics. Fig. 10 shows the growing horizontal temperature amplitude with altitude. This event had large vertical wavelengths (~17km) which contributed to large calculated MF. The north-south alignment of the wave crests indicates that this event is caused by prevailing north-south wind over the southern alps of New Zealand on this night. The saw tooth temperature profile shown in Fig. 11 is unique to this event. MF calculations were performed by P-D. Pautet and are soon to be published in joint by Taylor et al. 2018 and an accompanying paper focusing on the related instabilities in Fritts et al. 2017 (Fig. 12). Magnitudes for MF are comparable with the largest events here-to-fore recorded. Error calculations for MF are large in nature due to the combined errors when measuring horizontal wavelengths and temperature perturbations. Using the USU AMTM and the high performance lidar helps minimize these errors.
Fig. 10. Left column: TELMA data showing MW growth with altitude (vertical wavelength ~17 km). Right column: Corresponding AMTM temperature maps showing horizontal structure.

Fig. 11. Above: Temperature map showing MW breaking and instabilities at 11:36 UT. Below: Temperature Profile also at 11:36 UT. Exemplifies periodic, sawtooth nature of event.
Fig. 12. Time evolution of MF on June 21-22, using a $\lambda_z$ obtained from ground-based lidar data and $\lambda_x$ from the AMTM temperature and OH intensity maps.

**July 14-15**

A summary of the highlights from this night are shown in Fig. 14. July 14th started with vertical wave fronts that quickly disappear (Fig. 14 – 06:24 UT). Later in the evening, large, tilted, quasi-stationary MWs were observed with larger horizontal wavelengths ranging from 33 to 37 km and a temperature perturbation (peak-to-peak) of 13K (Fig. 14–15:03 UT). Smaller-scale waves developed within the larger pattern exhibiting wavelengths ranging from 11-13 km with temperature perturbations up to 10K. A horizontal temperature scan at 15:03 UT in Fig. 13, shows large, variable amplitude waves. The event lasted less than 2.5 hours with lingering instability structures.

Fig. 13. 3 pt. averaged temperature scan centered on the 136th row from the top of the temperature map.

July 17-18

The events on July 17th were characterized by short horizontal wavelengths of 19-26 km (Fig. 6 & Fig. 15). Stationary waves were coherent with greater than 10 wave crests in a frame and large temperature perturbations of ~22K. The event lasted about 6 hours. Vertical wavelengths measured with the Rayleigh lidar this night were small (Fig. 16). Two MFs were calculated with reasonable certainty (12:20, 11:45 UT).

![Temperature and Intensity Maps](image)

Fig. 15 - Examples of intensity and temperature maps from July 17. The night was characterized by short horizontal wavelengths that lasted for a large portion of the night.

![Lidar Temperature Profiles](image)

Fig. 16 - Lidar temperature profiles from July 17th. Vertical wavelengths in this data were <5 km.

Table 3 shows the associated MF from July 14th and July 17th and the values used to calculate MF.
Table 3. Summary of MF from July 14 and July 17.

<table>
<thead>
<tr>
<th>July 14 [UT]</th>
<th>$T_0$</th>
<th>$\Delta T$</th>
<th>$\lambda_x$</th>
<th>$\lambda_z$</th>
<th>MF</th>
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<tr>
<td>06:24</td>
<td>213 K</td>
<td>26.5 K</td>
<td>124 km</td>
<td>12 km</td>
<td>210 m²/s²</td>
</tr>
<tr>
<td>14:09</td>
<td>205 K</td>
<td>17 K</td>
<td>44 km</td>
<td>8 km</td>
<td>176 m²/s²</td>
</tr>
<tr>
<td>14:19</td>
<td>209 K</td>
<td>19 K</td>
<td>43 km</td>
<td>7 km</td>
<td>189 m²/s²</td>
</tr>
<tr>
<td>15:04</td>
<td>216 K</td>
<td>10.5 K</td>
<td>37 km</td>
<td>5 km</td>
<td>69 m²/s²</td>
</tr>
<tr>
<td>16:34</td>
<td>224 K</td>
<td>15 K</td>
<td>46.5 km</td>
<td>5 km</td>
<td>67 m²/s²</td>
</tr>
<tr>
<td>18:14</td>
<td>223 K</td>
<td>23 K</td>
<td>44 km</td>
<td>8 km</td>
<td>272 m²/s²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>July 17 [UT]</th>
<th>$T_0$</th>
<th>$\Delta T$</th>
<th>$\lambda_x$</th>
<th>$\lambda_z$</th>
<th>MF</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:20</td>
<td>211 K</td>
<td>16 K</td>
<td>73 km</td>
<td>5 Km</td>
<td>54 m²/s²</td>
</tr>
<tr>
<td>12:45</td>
<td>213 K</td>
<td>12.5 K</td>
<td>15 km</td>
<td>6.5 km</td>
<td>209 m²/s²</td>
</tr>
</tbody>
</table>

Summary

The DEEPWAVE campaign enabled the observation of many GW events. It seems that GWs continuously bombard the upper atmosphere in this location and confirms that New Zealand has a hot spot for GW in the MLT region (as well as in the stratosphere). MWs here varied in horizontal wavelength and in duration with most lasting for a few to several hours. These MW events have expanded current knowledge about typical characteristics. No other campaign has observed more than a handful of MW events. DEEPWAVE saw 19 with the ground-based AMTM. The high occurrence of MW breaking under variable forcing conditions caused MF deposition in this region to be highly variable and significant.
Part B

Noctilucent Clouds

Noctilucent clouds [NLC] are a crepuscular phenomenon that occur at mid to high-latitudes (65° - 75°) (Gadsden 1982). The term noctilucent literally means “night-shining.” NLC are white/silver/blue glowing ice clouds that form at high altitudes in the mesopause region where atmospheric temperatures reach a minimum. They occur almost exclusively during the summertime since that is when the mesopause is coldest due to upward cooling over the summer polar regions. NLC consist of ice-water which nucleates and grows under these extreme cold conditions. When the sun has set relative to an observer, sunlight can still hit the ice due to its high-altitude location causing the ice cloud to scatter sunlight. This causes an NLC to appear brighter than its surroundings.

The MLT is a notoriously difficult region in the atmosphere to gather in-situ measurements. Balloons cannot go high enough to collect data here. Any satellite launched at this altitude would fall before finishing a single orbit. Sounding rockets can effectively reach MLT heights but only have the opportunity for two measurements during the trajectory’s up leg and down leg. This is part of the reason that so little is known about the transport, chemistry, and energetics of water in the MLT. Observing NLC gives insight into these topics because they provide a means to watch the behavior of the atmosphere allowing the estimation of wind speeds and wave phenomenon. (Gadsden 1989). As the gateway to the ionosphere, phenomena in the MLT can affect radar detection, air transportation and navigation and can interrupt satellite communications.

NLC have been observed from the ground since 1884 and have since been observed from space. When detected by satellite these clouds are known as Polar Mesospheric Clouds [PMC] (Thomas, 1984).

Super Soaker Intro

The Super Soaker sounding rocket mission was designed with the intent to create a polar mesospheric cloud through artificial water deposition in the MLT at arctic latitudes. The motivation for this study partially comes from several studies that discuss PMC formation from space shuttle exhaust. Stevens et al. (2012) and Kelley et al. (2010) showed that Arctic PMCs can form within one day of a shuttle launch. A single shuttle launch can contribute 20% to the PMC ice mass in a season (Stevens 2005). PMCs can be a controversial topic due to the attribution of their increasing occurrence to climate change. The potential formation of PMCs is very sensitive to small changes in temperature. Due to this it has been speculated that PMCs are the proverbial canary in the coal mine, a forewarning of events to come. It is possible that this is not the case and that their increase in occurrence with time is due to an increase in space traffic in recent decades. To address this issue, the super soaker mission proposed to study the transport, chemistry and energetics of the water in the MLT and how this affects PMC formation which no previous study has undertaken.

The three proposed science questions were:

1. What is the energetic and chemical response of the upper mesosphere and lower thermosphere to water in the Mesosphere and Lower Thermosphere?
2. How does the injection of large amounts of water vapor change the thermodynamics and impact the PMC microphysics?

3. How is the water vapor that gets injected into the lower thermosphere, redistributed vertically to the PMC region near 82 km?

To answer these questions an experiment was designed to artificially release water into the MLT via rocket launch. This rocket along with two others containing TMA to be released and meant to track the local winds was launched on January 26th, 2018 from Poker Flat Research Range [PFRR] in Chatanika, AK (Fig. 17).

![Image of rocket launch](image)

*Fig. 17 - The Super Soaker Sounding Rocket was launched from PFRR on January 26th, 2018. Image courtesy of the Super Soaker Science Team.*

**Instruments and Institutions**

Several institutions were involved in this experiment, each providing their own instruments or expertise. A list of those participating follows.

**Trimethylaluminum**

Rockets 41.119 and 41.120 both carried a TMA payload that would be released during the up-leg and down-leg trajectory of the carrying rockets. Ground-based wind observation would be conducted using the TMA trails and footage from three white-light cameras triangulated in order to identify the path of the TMA. Three cameras were operated to observe the TMA; One each in Coldfoot, AK, the Neal Davis Science Operations Center at PFRR and in the air on a NASA-8 aircraft flying near the launch. TMA was to be released between 85 and 150 km in altitude. The two payloads were launched roughly 37 minutes apart. The second payload launched approximately 1.5 minutes before the water payload launched. The TMA canisters were designed and built by Clemson University.

**Water-release canister**

The water-release canister carried by rocket 41.121 is a hollow cylinder filled with liquid water. The water payload consisted of four canisters each filled with 30 kg of liquid water for a
total of 120 kg of water to be released at 85 km altitude during the up-leg segment of the rocket trajectory. “Black powder” was included in the payload in order to propel the water out of the canister at the appropriate altitude and to turn the water into an aerosol as it entered the atmosphere.

**Lidar**

Three ground-based lidars from the Geophysical Institute at the University of Alaska, Fairbanks were part of the mission’s instrument suite. This included a Rayleigh lidar, an iron lidar, and a sodium lidar. The Rayleigh lidar was pointed toward the predicted water deposition site to potentially observe conditions during the rocket-release and to measure cloud formation. The iron and sodium lidars were zenith-pointing. These instruments were all operated at the Lidar Facility on the PFRR. The Rayleigh lidar system employed a horizontally-oriented 1-m telescope and a 1-m steerable flat mirror (Mizutani et al., 2007) with a 40-100 km altitude range of temperature measurement (Fig. 18).

![Fig. 18 - The beam from the Rayleigh lidar hitting the 1-m steerable flat mirror in the lidar facility at PFRR. Courtesy of Vanessa Chambers.](image)

**AMTM**

The Atmospheric Imaging Lab at USU operated an AMTM for several months before and after the launch window. The camera was zenith-pointing and managed to capture the water release. It was based at the Neal Davis Science Operations Center (PFRR) (Fig. 19).
**PFISR**

The Poker Flat Incoherent Scatter Radar was included in the mission to measure electron densities near PFRR for several hours before and after the launch. It was predicted that electron densities would respond to a water deposition and this response could indicate formation of a noctilucent cloud.

**Intensified CCD cameras**

Two electronically gated intensified CCD video cameras were operated by Utah State University personnel, Pattilyn McLaughlin and Vanessa Chambers during the Super Soaker launch in order capture time record of the experiment. Manufactured by Xybion Electronic Systems Corporation these model ISG-780s ran with two different fields of view (wide and narrow) from the Neal Davis Science Operations Center at PFRR (65°N) 2.77 km from the launch pads. Both cameras captured the night’s events from 14 UT to 15:15 UT. A list of those participating follows.

**Visual Data**

The two USU intensified CCD cameras took visual footage of the TMA releases and the water dispersal. Below is a timeline of events as seen from the small FOV camera system.

14:01:02 – Footage on System 2, tape 1 starts
14:11.20 – The rocket carrying TMA 1 is launched.
14:12.25 - TMA 1 is released
14:16.05 – Down-leg puffing
14:22.14 – Footage on system 2, tape 1 ends
14:38.51 – Footage on system 2, tape 2 starts
14:48:00 – The rocket carrying TMA 2 is launched.
14:49.10 – TMA 2 is released
14:49.27 – The final rocket, which carries the water payload is launched.
14:51.11 – The water is expelled from the third rocket causing a small bright flash.
14:52.52 – Down-leg puffing
15:15.28 – Footage on system 2, tape 2 ends

Fig. 20 - Infrared camera system 2 (narrow field) freeze frame showing the trail from the second TMA release and the water expulsion (circled in red).

Fig. 20 shows the second TMA trail and the explosion from the water canister release. After the water was released into the mesosphere a bright artificial aurora appeared near where the water canister was unloaded. It was originally thought to be an indication that water ice had formed but it is now thought to be a reaction between the water and kerosene from the TMA reentry bag. There have been previous observations of similar artificial aurora that coincide with TMA releases during a launch (Gelinas et al., 2006). The generation of “artificial aurora” masked some of the observing field and was not taken into account during the planning of the Super Soaker mission.

AMTM DATA

The AMTM collected OH intensity data for several months before and after the launch window. Appendix A includes 20 keograms, one from each clear night a week before and a week after the launch and including the launch on January 26th. Four of the total fifteen nights were cloudy or mostly cloudy. One night was unable to be observed due to snow accumulation on the camera dome. Nights for which there is no data shown in the two-week time period are Jan. 20, Jan. 22, Jan. 23, Jan. 25, and Jan. 27. Nine nights had significant wave activity with most having large period warming cycles throughout the night. The AMTM took 10s exposures throughout each night except for the night of the 26th when it took 4s exposures during the Super Soaker launch as discussed in the section on January 26th that follows. Below is a description of each night’s events.

Nightly Observations

January 21 – There is a clear cyclic warming apparent in the temperature keogram from this evening. The cycle has a 7-hour period and starts at 2:30 UT. Extensive small-scale ripples appear in the southwest corner of the field of view at 10:56 UT and last until 12:00 UT (Fig. 21). They are small-scale (~5km) and have a velocity of ~14 m/s at 154° (SE). They recur intermittently throughout the night but return at 13:15 UT. These ripples are also small-scale but clusters of the ripples are moving in different directions simultaneously as if there are multiple coincident sources.
Figure 21 - Jan 21. 11:05 UT. Ripples are apparent in the OH intensity map but not the rotational temperature map. Weird texture occurs in the left-hand portion of both images. Snow appears in the upper right hand corner of the frame.

January 24 – Observations available in OH intensity from 2:30 UT to 7:30 UT. Temperature data is 4s exposure test-mode from 7:30 UT onward. Evening starts off with breaking signatures in SE corner of frame @ 2:28 UT. Large wave front from 3 UT to 4:15 moving northeastward (Fig. 22). The waves have a 34 km wavelength and are moving at 25 km/s at 70°. The night is characterized by small-scale waves moving across each other. This is observable in the night’s keogram as a cross-hatch pattern from 4 -7:30 UT.

Figure 22 - Jan 24. 3:07 UT. Large wave feature enters the AMTM field of view from the southwest.

January 26 – The Super Soaker rocket and the two rockets carrying the TMA payloads were launched between 14 UT and 15:15 UT (Fig. 24). A crosshatch pattern occurs and is present nearly the entire observing period. The night has some clouds from 7-8 UT as seen in the keogram. There is a larger-scale 2.5-hour periodic warming from 10 UT to 18 UT. At 5:40 a diagonal, stationary feature appears and stays for 20 minutes then fades (Fig. 23).

The night has a lot of small wave activity with some instances of smaller waves travelling through the bigger waves perpendicularly.

The AMTM took 10s integrations until 07:02 when data collection was switched to 4s integrations until 17:19 UT when 10s integrations were resumed (i.e. an image was produced every 15s instead of 30s).
Fig. 23 - Diagonal stationary feature on January 26th, 2018 at 05:49. The feature is bordered by two bright bands with a trough in-between. This feature is nearly imperceptible in the corresponding temperature map.

Fig. 24 - Sequence of Super Soaker events as observed by the AMTM at the Neil T Davis science center. A - 14:11:39. First rocket carrying TMA payload has launched. B - 14:11:54. Rocket about to release TMA. C - 14:12:57. TMA canister 1 has been released. D - 14:17:52. TMA Trail appears. E - 14:48:24. Second TMA rocket has launched. F - 14:49:26. TMA 2 has been released and the rocket carrying the water canister has launched. F - 14:51:15 - Artificial aurora has occurred.

January 28 – Night starts off cloudy. Crosshatch pattern begins at 5 UT and continues for the rest of the night. A prolonged warm event occurs from 10 UT to 17 UT. During that time there is a slight rippling effect at 13:30 indicative of wave breaking. The effect lasts for 1.5 hours (Fig. 25).

Fig. 25 - Bright ripples at 14:14 UT on Jan. 28.
January 29 – This night, too has a crosshatch pattern the entire night as observable in the keograms. There are some very clear nearly horizontal waves that take up the entire field of view at 5:01 UT and 15:26 UT with wavelengths ~10km and moving at 12 m/s north-northeast (Fig. 26). There is a faint north-south aligned band that is present the entire night. A warming takes place at 10 UT followed by a delayed brightening that peaks at 11 UT. At the end of the night there is a chaotic flurry of rippling activity in several directions.

![Image 1](image1.png)

![Image 2](image2.png)

*Fig. 26 – January 29th. Above – 5:01 UT. Below - 15:27 UT. Horizontal ripples cover the entire field of view.*

January 30 – Cloudy until 14 UT. Another crosshatch pattern is visible for the rest of the data until 18 UT. At 14:20 and again at 15:10 there is a cascading of small un-even ripples from the north to the southwest that lasts for about a half hour. The cascading is moving quite rapidly, entering the FOV at 15:30:04 and exiting at 15:36:13. After the second cascading clears horizontal ripples with stationary wave fronts and 5 km wavelengths become apparent (Fig. 27).

![Image 3](image3.png)

*Fig. 27 - OH Intensity map on January 30th at 15:41 UT. Ripples form after the “cascading” ceases.*

January 31 – Crosshatch ripples occur throughout most of January 31st with a general movement trend toward the south. Three distinct warm periods occur at 3:30, 11:00 and beginning at 13:00 and continuing on.
At 13:00 curved, large, rapidly-moving wave fronts begin to move from the north, directly south. These crests have a wavelength of 38km and a velocity of 101 m/s at 180° (South) (Fig. 28). These characteristics are indicative of a mesospheric bore. They are very bright for the first 15 minutes but then fade and last until 14:30 when they brighten again and continue to fade until 15:30. The temperature perturbation for this event is ~10K (Fig. 29).

**Fig. 28 - Southward moving wave fronts at 13:23. Crests are ~38 km apart with a temperature perturbation of 15K.**

**Fig. 29 - Vertical temperature profile from map at 13:23 UT. The largest peak to trough temperature difference is 10 K.**

**February 1** – This evening has a crosshatch pattern but unlike other nights the bands are significantly more frequent in the southeast direction and weaker in the northwest direction making the crosshatch uneven. There is a prolonged warm period from 9:30 UT – 13 UT in which the presence of the moon creates artificial wave bands in both the intensity and temperature keograms.

**February 2** – Small numerous vertical waves occur from 4 - 6 UT (~10 km). The nearly 20 wave fronts are nearly north-south aligned but then appear to rotate until 6 UT when they are aligned diagonally from northeast to southwest.

From 7– 9 UT there are 25 km waves moving to the southwest at 56 m/s.

There is an intense warming of ~20K from 8:30-11:15 UT. From 11 UT to 14 UT small stationary waves appear in the temperature keogram but are nearly imperceptible in the intensity keogram. This phenomenon seems to be an artifact of the instrument caused by the presence of
the moon in the FOV. A similar effect happens on January 31st and Feb 1st which both observed the moon followed by small stationary waves in the temperature data but not the intensity data.

**February 3** – From 11:30 to 13:00 UT there is a bright front that appears, moving at 34 m/s from the south northward that leaves a wake of smaller waves perpendicular to the large maximum. The smaller waves have a scale of 5km wavelength. The crosshatch pattern, similar to other nights occurs the entire night.

**Summary**

The Super Soaker Mission achieved launch despite several logistical setbacks including power outages, conflicts concerning the launch of the water-release with the Federal Flight Administration, and rocket malfunctions. During the two weeks preceding and following launch the AMTM observed a warming event each night from Jan 28th – Feb 3rd at ~ 10 UT. Wave structure was detected each clear night in the form of both large-scale and small-scale features. There was a crosshatch pattern in almost all of the nights’ keograms indicating numerous wave sources. The night of launch exhibited waves of similar morphology to other nights but was generally “quieter” concerning small-scale wave activity.

**Conclusion**

The AMTM is a powerful aeronomy tool that can provide science support for many different types of missions. It’s ability to collect data nearly unaffected by auroral emission and full moon light makes it a versatile instrument unlike any other in the field. The AMTM during the DEEPWAVE project was able to observe 19 mountain waves events with MF depositions of 50-500 m²/s². These results are much larger than previously observed.

During Super Soaker, the AMTM was operational for several months before and after the launch and observed a smattering of unique wave activity. A rich source of wave generation exists near PFRR causing many nights with similar characteristics. This could be the basis for future investigation as Super Soaker analysis continues.
Appendix A.

January 21

[Images of temperature data charts for January 21]

January 24

[Images of temperature data charts for January 24]

January 26

[Images of temperature data charts for January 26]
February 3
References


Evers, Läslo & Dost, Bernard. (2018). Infrasound and seismology in the Low Frequency Array LOFAR.


