High-Latitude Short-Period Mesospheric Gravity Wave Dynamics and Winter Climatology

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Aeronomy Terms
Aeronomy Terms
The Atmosphere

- Exosphere
- Thermosphere
  - Mesopause
  - Mesosphere
  - Stratosphere
  - Tropopause
- Stratosphere
  - Supersonic plane
  - Radiosonde
- Troposphere
  - Commercial aircraft
  - Parachute jump
- Planetary boundary layer
- Sea level
- Temperature (°C)
  - -100
  - -60
  - -20
  - 0
  - 20
  - 40

- Ozone layer
- Polar lights
- Meteors
- Noctilucent clouds
- Nacreous clouds
Noctilucent Clouds
Consider a wave with wavelength \( l \) moving to the right with speed \( c \).

The wave crest moves from point \( a \) to point \( b \) in time \( \tau \), which is the period of oscillation of the wave as seen by a stationary observer.

[Nappo, 2002]
- Wavenumber: \( k = \frac{2\pi}{\ell} \)
- Wave frequency: \( \omega = \frac{2\pi}{\tau} \)
- Phase speed: \( c = \frac{\omega}{k} \)

[Nappo, 2002]
Importance of Gravity Waves

- Most gravity waves are assumed to originate in the troposphere and propagate up into the upper atmosphere.
- Gravity waves are an essential part of the dynamics of the atmosphere.
- An important property is their ability to transport energy.
- Transport energy away from the disturbances that generate them and act to distribute this energy throughout the atmosphere (Nappo, 2002).
Gravity Wave Sources
Gravity Wave Sources
Gravity Wave Sources
Gravity Wave Evident in Tropospheric Clouds

6 May, 2007 Tama, Iowa

[http://www.youtube.com/watch?v=yXnkzeCU3U]
The term gravity wave suggests that gravity is the restoring force acting on a fluid parcel which has been displaced from its equilibrium position (Nappo, 2002).

However, it is the fluid buoyancy rather than gravity that is acting.

[Knight, 2008]
Gravity Waves

- Can’t directly observe gravity waves.
- If it were possible to see gravity waves and to speed up their motions, we would see a wide variety of wave shapes moving in many directions (Nappo, 2002).

[Hines, 1974]
Gravity Waves

Since we cannot see gravity waves, we can only study their effects on the atmosphere.

We can observe their effects on the atmosphere, such as
- Temperature
- Density
- Wind field
Observations

Remote sensing measurements from satellites in space.

[www.crista.uni-wuppertal.de]
Observations

- Remote sensing measurements from satellites in space.
- Radiosonde.

[http://radiosondemuseum.org]
Observations

- Remote sensing measurements from satellites in space.
- Radiosonde.
- Rocket soundings.
Observations

- Remote sensing measurements from satellites in space.
- Radiosonde.
- Rocket soundings.
- Lidar.

[http://cass.usu.edu]
Observations

- Remote sensing measurements from satellites in space.
- Radiosonde
- Rocket soundings.
- Lidar.
- Radar.
Observations

- Remote sensing measurements from satellites in space.
- Radiosonde.
- Rocket soundings.
- Lidar.
- Radar.
- Optical Imagers.
The Mesospheric Airglow Imaging and Dynamics (MAID) project was initiated in January 2011

Main goals:
- Establish a long-term climatology of short-period gravity waves observed in the Arctic MLT region.
- Determine dominant source regions and potential sources.
- Investigate the impact of large-scale waves (tides and planetary waves) on the short-period wave field.
- Perform a quantitative comparison between Arctic and Antarctic winter-time dynamics.
The primary instruments used are a Keo Sentry airglow imager and the NICT Rayleigh lidar both located at Poker Flat Research Range (PFRR), Alaska.

Additional instruments are an MF radar and an incoherent scatter radar.
Airglow

Dayglow – During the day air molecules are excited by incoming solar radiation. As the molecules go back to the ground state they emit a photon.

Nightglow – During the night the molecules are excited by radiation being emitted from the earth.
Spectrometer shows peaks at:
- 630 nm (OI) at ~250 km
- 589.2 nm (Na) at ~90 km
- 715 to 930 nm (OH) at ~87 km
- 865.5 nm (O₂) at ~94 km
OH gives the brightest emission in the near infrared part of the spectrum.

OH production:

\[ H + O_3 \rightarrow OH^* + O_2 \]

Atomic hydrogen is recycled by:

\[ OH + O \rightarrow O_2 + H \]
MAID Imager

The imager is designed to remotely sense several faint airglow emissions primarily in the mesosphere lower thermosphere (MLT) region.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Filter Wavelength (nm)</th>
<th>Mean Layer Height (km)</th>
<th>Exposure Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OI</td>
<td>630.0</td>
<td>~250</td>
<td>120</td>
</tr>
<tr>
<td>Na</td>
<td>589.2</td>
<td>~90</td>
<td>90</td>
</tr>
<tr>
<td>NIR OH</td>
<td>715-930α</td>
<td>~87</td>
<td>15</td>
</tr>
<tr>
<td>O₂ (0,1)</td>
<td>865.5</td>
<td>~94</td>
<td>120</td>
</tr>
</tbody>
</table>
Field of View
MTM in Norway
The Rayleigh lidar has operated at PFRR since 1997.

Raw signal profiles are acquired every 50 seconds.
The Rayleigh lidar has operated at PFRR since 1997.

Raw signal profiles are acquired every 50 seconds.

The data are integrated to yield 15 minute profiles for density fluctuations and 30 minute temperature profiles over the altitude range ~40-90 km (Thurairajah et al., 2010).
Imager and Lidar

- The all-sky imager permits accurate measurements of the horizontal wave parameters.
- The lidar provides essential temperature profiles.
- Together, these two instruments can measure several of the key parameters needed to characterize the wave motions as well as investigate their propagation nature.
- Additional radar measurements of the background wind field enables the true motion of the gravity wave such as its intrinsic period, phase speed, and angle of ascent/descent (Taylor et al., 1995).
Characteristics of All-Sky Images

- (a) Image projection on to the CCD.
- (b) The effect of projecting a pixel in the all-sky image onto a geographic coordinate system.

[Garcia et al., 1997]
Before we can perform a quantitative analysis of the image data, it is necessary to use coordinate systems that relate distances between pixels in the image to physical distances in the airglow layer (Garcia et al. 1997).
All-Sky Spatial Calibration

- Stars in each image are used as reference points.
- Spatial calibration provides coefficients for mapping the original image to standard coordinates.
(a) Raw OH image.
Image Data Processing

(a) Raw OH image.
(b) Calibrated and rotated image.
(a) Raw OH image.
(b) Calibrated and rotated image.
(c) Star field removed.
Image Data Processing

- (a) Raw OH image.
- (b) Calibrated and rotated image.
- (c) Star field removed.
- (d) Unwarped (geometrically corrected for lens distortion and mapped onto geographic coordinates) image.
A region of interest containing wave structure is selected from sequential images.
Traditional spectral analysis techniques give an inherent $180^\circ$ ambiguity in the derived wave propagation (Coble et al., 1998).
Image Data Analysis

- Ambiguity can be resolved by using images obtained sequentially in time to determine the unambiguous 3-D horizontal wavenumber spectrum.

- The 3-D spectrum is computed as follows:
  - Calculate the \((\omega, k, l)\) spectrum from the processed images (where \(\omega\) is the temporal frequency, \(k\) is the zonal wavenumber, and \(l\) is the meridional wave number).
  - Then integrate over the negative frequencies (Gardner et al., 1996).
What you obtain is a single peak in the 3-D spectrum corresponding to the horizontal wavelength and direction of propagation.

\[ \lambda_H = 22.2 \pm 0.3 \text{ km} \]
\[ \theta_{\text{obs}} = 90.0 \pm 0.9^\circ \]
### Example of Results

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Duration (UT)</th>
<th>$\lambda_h$ (km)</th>
<th>$C_{obs}$ (m/s)</th>
<th>$\theta_{obs}$ (deg)</th>
<th>$T_{obs}$ (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2/05/11</td>
<td>03:46–4:27</td>
<td>28.8 ± 0.5</td>
<td>41.1 ± 3</td>
<td>35.1 ± 1</td>
<td>11.8 ± 1</td>
</tr>
<tr>
<td>2</td>
<td>2/7/11</td>
<td>5:05–6:35</td>
<td>34.1 ± 0.6</td>
<td>58.4 ± 4</td>
<td>13.5 ± 1</td>
<td>10.1 ± 1</td>
</tr>
<tr>
<td>3</td>
<td>2/7/11</td>
<td>6:05–7:16</td>
<td>37.6 ± 3</td>
<td>59.4 ± 4</td>
<td>13.4 ± 3</td>
<td>10.6 ± 1</td>
</tr>
<tr>
<td>4</td>
<td>2/7/11</td>
<td>6:39–8:46</td>
<td>28.4 ± 1</td>
<td>52.5 ± 4</td>
<td>14.2 ± 1</td>
<td>9.4 ± 1</td>
</tr>
<tr>
<td>5</td>
<td>2/7/11</td>
<td>12:12–14:00</td>
<td>29.5 ± 0.4</td>
<td>37.7 ± 5</td>
<td>17.4 ± 1</td>
<td>13.4 ± 2</td>
</tr>
<tr>
<td>7</td>
<td>2/23/11</td>
<td>4:37–7:57</td>
<td>37.0 ± 1</td>
<td>64.5 ± 5</td>
<td>134.6 ± 2</td>
<td>9.4 ± 1</td>
</tr>
</tbody>
</table>
Propagation Nature

- 14 wave events coincident with lidar for 2011.
- 7 wave events coincident with lidar for 2012.
- Use an event (#4 on previous slide) on 7 February 2011 for an example.
Wave Characteristics

- Wavelength (km)
- Direction (deg)
- Speed (m/s)

Time (UT hour)
Ducted Gravity Waves

- Under certain conditions, a gravity wave can become trapped.

- A trapped wave is said to be ducted and is capable of horizontally transporting energy over long distances with little attenuation.

- In effect, the wave duct is a wave guide.

[Nappo, 2002]
Wave Ducting

There are two kinds of wave ducting which can occur:

- Doppler ducting – which is created by a jet in the background wind in the direction of wave propagation.
- Temperature duct – which is caused by a discontinuity in the temperature lapse rate (temperature gradient) (Nappo, 2002).
Wave Ducting

- The vertical wavenumber squared $m^2$ profile is used to investigate a potentially ducted wave.

- A ducted region is characterized by a positive $m^2$ region bounded above and below by negative $m^2$ regions.

- $m^2 < 0$ get an evanescent wave.

- $m^2 > 0$ get a freely propagating wave.
Wave Ducting

- The $m^2$ profile is calculated using the following dispersion relation

$$m^2 = \frac{N^2}{(c-u_0)^2} - k^2 - \frac{1}{4H^2}$$

- Where $c$ is the observed phase speed, $u_0$ is the background wind in the direction of the wave propagation, $k$ is the horizontal wavenumber, and $H$ is the scale height.
Wave Ducting

- $N$ is the Brunt-Vaisala frequency given by
  \[ N^2 = \frac{g}{T} \left( \frac{dT}{dz} + \frac{g}{c_p} \right) \]

- Where $g$ is the acceleration due to gravity, $T$ is the temperature, $dT/dz$ is the lapse rate, and $c_p$ is the specific heat at constant pressure.
Lidar Temperature Profiles

PFRR Rayleigh Lidar 2/7/11 630 to 900 UT

PFRR Rayleigh Lidar 2/7/11

Altitude (km)

Temperature (K)

Altitude (km)

Temperature (K)
Wind Data

No wind observations were available, however, the horizontal wind model 2007 (HWM07) was used to get the horizontal wind field.

HWM07 is an empherical model.
$m^2$ profiles
Climatology

Climatology in this context refers to the geographical and temporal variations in gravity wave activity, and variations in gravity wave characteristics (wavelengths, phase speeds, etc..) (Fritts and Alexander, 2003).

The MAID imager runs continuously during the winter months to gain maximum data.

Observations since January 2011 have yielded:

- 1249 hours of data.
- 609 hours of clear sky.
- 279 hours of good wave events.
Wave Characteristics

- Standard histogram plots of the observed phase speed, horizontal wavelength, and period for the two winter seasons combined together yielding 117 short-period events.
- Wavelengths ranging from 15-47 km.
- Phase speeds ranging from 10 to >70 m/s.
- Periods typically 10-15 minutes.
Directionality

- Plot of the observed direction of motion for the 117 band events in 30° bins.
- Shows dominate eastward motion.
Monthly/Yearly Directions

(a) Jan 2011: 15 Events
   Jan 2012: 22 Events

(b) Feb 2011: 21 Events
    Feb 2012: 11 Events

(c) Mar 2011: 28 Events
    Mar 2012: 11 Events

(d) 2011
    2012
Comparison Sites

Compared our results to other similar high-latitude measurements at:

- PFRR (65° N).
- Resolute Bay, Canada (74° N) \((\text{Suzuki et al., 2009})\).
- Svalbard (78° N) \((\text{Dyrlund et al., 2012})\).
- ALOMAR, in Norway (69° N).
- Rothera Station, Antarctica (68° S) \((\text{Nielsen, 2007})\).
Comparison of observed wave parameters at PFRR and four other high-latitude sites, illustrating the similarity of the wave characteristics.

These distributions are also similar to short-period events measured at mid- and low-latitude sites, indicating their global nature.
The reported measurements at the comparison sites are all dominated by westward wave propagation.

In stark contrast, ongoing measurements at PFRR show a clear preference for eastward propagation during the winter period.
Gravity waves propagating energy upward from the lower atmosphere are absorbed into the mean flow as the approach a critical layer where the intrinsic frequency \( (\omega - k_x V_{0x}) \) of the wave is Doppler shifted to zero.

This situation may occur at any height level when the local horizontal wind speed along the direction of propagation equals the observed horizontal phase speed of the gravity wave (Taylor et al., 1993).
Approach

- Still no wind data.
- Used the HWM07.
- Also used NASA’s Modern-Era Retrospective Analysis for Research and Applications (MERRA) to get the zonal and meridional winds above PFRR.
MERRA

- MERRA records winds every 3 hours.
- Variability during the day.
Lots of variability during a month.

Also shows how MERRA and HWM07 data don’t exactly match.
Critical Level Blocking Diagrams

- Used monthly averaged MERRA and HWM07 winds to build blocking diagrams for each month.

\[ \Omega = \omega - k_x V_{0x} \]

\[ \Omega = \omega \left(1 - \frac{V_{0x}}{v_x}\right) \]

\[ \Omega = \omega \left(1 - \frac{V_z \cos \phi + V_m \sin \phi}{v_x}\right) \]

- Forbidden regions, \( \Omega \leq 0 \) (Taylor et al., 1993).
Found that most of the observed events were outside the blocking region.

Some of the events were in the blocking region.
Used MERRA winds closest to an event and built blocking diagram for each event.

Also used MERRA wind to find the intrinsic phase speed of the wave.
Used MERRA winds closest to an event and built blocking diagram for each event.

Also used MERRA wind to find the intrinsic phase speed of the wave.
Our determination of strong eastward propagation during the winter is most intriguing as it differs strongly from previous results to date.

The reported westward wave propagation is attributed to critical level filtering of the upward propagating gravity waves by the background wind field.

The PFRR eastward propagating waves exhibited relatively high phase speeds suggesting they were not restricted by the critical level filtering.
Future Work

- Further investigation of these high phase speed events, their potential sources, and collaborative measurements with PFISR to study their penetration into the lower thermosphere.
Acknowledgments

This project is funded by the National Science Foundation, Office of Polar Programs grant OPP-1023265 entitled Collaborative Research: An Investigation of Wave Dynamics in the Arctic Mesosphere and Coupling Between the Lower and Upper Polar Atmosphere.

This material is based upon the work supported by the National Science Foundation Graduate Research Fellowship under Grant No. 1147384.
References


Nielsen, K. (2007), Climatology and case studies of mesospheric gravity waves observed at polar latitudes, Ph. D. Dissertation, USU, Logan, UT.


