How to Use Airglow Measurements in Atmospheric Wave Activity Studies

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Introduction

- Tides, planetary waves, gravity waves and seasonal oscillations dominate the Mesosphere and Lower Thermosphere (MLT) environment (~80-100 km).
- The large scale perturbations have traditionally been studied using instruments such as meteor wind radars, airglow photometers, spectrometers, interferometers and more recently using lidar soundings.
- Temporal/spatial ambiguity (especially in shorter period gravity wave studies) has naturally led to the development of two-dimensional imaging techniques using airglow emissions.
Atmospheric Gravity Waves

- Generated by disturbances in the troposphere (e.g. weather)
- Amplitudes grow as energy propagates upwards through the middle atmosphere
- Waves break at high altitudes depositing their energy and momentum
- Profound influence on the background mesospheric winds (reversal) and temperatures (cold summer mesopause)

Hines, 1960

Courtesy J. Alexander
Airglow Detection of Gravity Waves

Airglow Spectrum (Broadfoot and Kendal, 1968)

Gravity Wave Viewing Geometry

Airglow Emission Chemistry

H + O₃ → OH⁺ (v' ≤ 9) + O₂ (Bates and Nicolet, 1950)

OH⁺ (v') → OH⁺ (v'') + hv

Vis-NIR light (0.4 - 4 μm)

OH + O → H + O₂

O + O₂ + M → O₃ + M
Imaging Mesospheric Gravity Waves

"Ionospheric structure" (Gotz, 1941)

Bear Lake, 2003

NIR airglow photograph (15 min exp) (Petersen and Kieffaber, 1973)

Example all-sky CCD image showing short period (< 1 hour) mesospheric gravity waves imaged in the NIR OH emission (10 sec exp).
Evolution of Airglow Cameras

Hawaii 1990

Xmas Is., 1995

Stardust, 2006

Temperature Mapper 1997
USU All-Sky CCD Airglow Imager, Bear Lake Observatory

- High resolution imager:
- Cooled to -40º C
- Field of view: 180º circular
- Telecentric lens system for narrowband imaging (<2 nm)
Ex: Short-Period Gravity Wave Event

Movie: 3.6 hr

$\lambda = 45 \, \text{km}$

$V = 45 \, \text{m/s}$

$\tau = 15 \, \text{min}$

Bear Lake Observatory, UT (41.6 °N, 111.6 °W), June 4-5, 2002

OH emission, altitude ~87 km
Multi-Emission Imaging Capability

Airglow Emission Geometry

$\lambda Z > \sim 10 \text{ km}$

Bear Lake Obs. June 4-5, 2002
Airglow Image Processing

- Star + noise filtering
- Flat fielding
- Calibration + unwarping

Assumed height: 87 km

Dimensions:
- 512 pixels x 512 pixels
- 250 km x 250 km

Directions:
- E (East)
- S (South)
What can we measure?

- Wave occurrence and seasonal/geographic variability.
- Gravity wave event characteristics (observed horizontal wavelength, speed and dominant direction of motion).
- Effects of middle atmospheric winds on wave propagation (filtering and wave ducting).
- Dominant sources.
- Unusual events—bores
  - Breaking waves
  - Momentum flux
  - Wave-like instabilities
- Larger scale tides and seasonal oscillations using long-term intensity and temperature data.
3D-FFT Spectral Analysis

Series of unwarped images:
Select a region of interest.

(Coble et al., 1998)

Mean direction = 211°
Mean • horiz = 21.9 km

Unambiguous spectrum
Typical short-Period Wave Characteristics
1988-1989, Cachoeira-Paulista, Brazil (23°S)

Mean: 20-30 km
Mean: 20-30 m/s
Mean: 15 min

182 wave events

(Medeiros et al., 2003)

winter

summer

Strong Anisotropy
Comparison: Equatorial and Polar Waves

- Similar short-period wave characteristics at all latitudes

Antarctica
Causes of Anisotropy in Horizontal Gravity Wave Headings

- Anisotropy in geographic or seasonal source distribution.
- Preferential wave propagation due to source function.
- Wave filtering by background winds in the intervening middle atmosphere (critical layer filtering).
- Preferential ducting of waves at mesospheric heights.

Intrinsic phase speed \( = \frac{c-U}{c} \)

\( c = \) observed wave speed
\( U = \) background wind in wave direction

Layer filtering: \( (c-u) = 0 \).
GW-Critical Level Interaction (Wind Filtering)

Wave momentum is transferred to background wind.
Effects of Critical Layer Wind Filtering (Seasonal and Latitudinal Variation)

**Wind Climatology (July, 40°N)**

- **Equator**
- **Low**
- **Mid**
- **High Latitude**

**Critical layer:**
Intrinsic phase speed (c-U) = 0

**Airglow layer**

**Summer (westward blocking)**

**Winter (eastward blocking)**
Mid-Latitude Seasonal Gravity Wave Propagation Characteristics

Stockwell and Lowe (2001)

Summer

Winter

Maui, Hawaii (20.6°N) 2004
Bear Lake (41.6°N) 2002

Blocked areas for wave propagation CL filtering
Comparison of Anisotropy in Antarctic Wave Headings

Different dominant wave propagation directions from Rothera and Halley during winter months.

(Nielsen Ph.D, 2006)
Goal: To measure and understand large scale gravity wave climatology and effects over the Antarctic Continent
Sources of Short Period Gravity Waves

- Equatorial and mid-latitudes:
  - Deep convection (storms)
  - Orographic forcing by strong wind
  - Jet stream instabilities
  - Frontal systems, hurricanes etc...

- High latitudes:
  - Orographic forcing and weather disturbances
  - Heating by strong aurora during Solar magnetic storms.
  - Natural and man-made explosions
Evidence for Convective Wave Generation


OH airglow

MSX Satellite-Stratospheric Waves (40 km)

(Yue et al., 2008)

DAWEX Campaign, 2001
Circular Mesospheric Gravity Waves

Sentman et al., 2006
New: Mountain Waves in the Mesosphere

New OH measurements in Argentina (31.8°S) show stationary waves in the mesosphere associated with orographic wind forcing over the Andes mountains (wavelength: 36 km)

Nightly averaged data illustrating the stationary of the wave pattern over 8 consecutive nights (1-8, July 2008) Horizontal wavelength: 36 km

Mountain waves can only be seen in the winter months when the zero wind line is at highest altitudes.

(Smith et al., GRL, 2009)
Doppler ducts can occur whenever the mean wind profile has a local maximum slightly less than the observed wave phase speed.

The increase of \((c-U)^2\) away from the local wind maximum leads to regions of evanescence \((m^2<0)\) on either side of the region of vertical propagation \((m^2>0)\) (Chimonas and Hines, 1986).

(Isler et al, 1997)
Evidence for Wave Ducting in MLT
Maui, Hawaii, July 5th, 2003

Simkhada et al., 2010

Event Duration: ~3 hours
By combining spatial information from the north-south and east-west keogram, we can determine the horizontal wavelength and velocity of medium-scale gravity waves.

SpreadFEx Campaign, Brazil, 2005
Example Results: Medium Scale Waves

Brasilia and Cariri Results

Taylor et al. (2009)
USU Mesospheric Temperature Mapper

- Sensitive bare CCD Imager developed to measure mesospheric temperature variability using OH and O2 airglow emissions.
- Field of view ~90°, (180 x 180 km).
- Sequential observations (60 sec. exp.) of
  - NIR OH (6, 2) Band ~ 87 km
  - O2(0,1) A Band ~ 94 km
  - Background (~857.5 nm)
- Cycle time: ~ 6 min per OH/O2 temperature measurement (precision 2K)

- Maui-MALT program, HI, 2000-2005
- Currently operating at Cerro Pachon, Chile, August, 2009 to date
OH and O2 Temperature Analysis

- OH transition parameters from Goldman et al., 1998.
- LTE rotational distribution with Schlapp (1936) line strengths.
- Relative band intensity from LTE model using fraction of (S1c+S2c) at rotational temperature T.
Example of MTM Measurements

From Maui-MALT Program

Phase shift ~2 hr

semi-diurnal tide

OH Temperature (K)

<table>
<thead>
<tr>
<th>Year</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>192.5</td>
</tr>
<tr>
<td>2003</td>
<td>200.4</td>
</tr>
<tr>
<td>2004</td>
<td>198.3</td>
</tr>
</tbody>
</table>
Investigating AO and SAO Signatures
Maui-MALT (2002-2004)

Mean: 196.7 K
SAO: 3.6 K  AO: 3.3 K
Seasonal OH Temperature Variability at Cerro Pachon (30 °S)

Lomb-Scargle Periodogram

90 days?

SAO

AO
Breaking Waves and Momentum Flux (FM)

Unique event:
- Large intensity perturbation $\Delta I/I$: ~ 50%
- Horizontal wavelength $\lambda_H$: 27 km.
- High intrinsic phase speed: 80m/s
- Formation of turbulent-like features.
- Instability duration: 40 mins.

Momentum flux:

where $v'$, $w'$ are the horizontal and vertical wave perturbation velocities.

For a breaking wave, the momentum flux $FM$ can be estimated by:

Large amplitude Momentum flux: $\sim 900$ m2/s2
Mean-flow acceleration: ~ 80m/s in < 1 hr.

(Yamada, et al., 2001)
Temperature Mapping & Momentum Flux

\( \lambda H = 36 \text{ km} \),
\( vH = 36 \text{ m/s} \),
\( T = 17 \text{ min} \)

(Phase \( \phi = 60 \pm 5^\circ \))
**Advanced Mesospheric Temperature Mapper (AMTM) for High-Latitude Research**

**Scientific Goals:**
- Investigate gravity waves at high-latitudes and dissipation effects on the mesopause region.
- Investigate impact of auroral storms on D-region dynamics.
- Coordinated measurements with lidar, radar and rocket soundings of the high-latitude Mesosphere, Thermosphere and Ionosphere (MTI) system.
Coincident IR Image and Na Lidar Measurements at ALOMAR

Feb 18-19, 2010

$T = 8-10$ min at 85 to 90 km

(Courtesy B. Williams and D.C. Fritts, CoRA)

Horizontal wavelength $\sim 27$ km
Phase velocity $\sim 54$ m/s at $\sim 38$ E of N
Period: $\sim 8.3$ min
$\Delta I/I: \sim 9\%$
Small-Scale Instability Structures

Jan. 22-23, 2010
Horizontal Wavelength ~5 km.
Horizontal motion: ~stationary
Amundsen-Scott South Pole Station

New camera here

South Pole

USU South Pole 2010
USU Imaging Research at South Pole

- New Advanced Mesospheric Temperature Mapper (AMTM):
- Gravity wave intensity and temperature perturbations and phase relationship
- Infrared (1.5-1.65μm) OH (3,1) and (4,2) bands measurements
- Precision ~1 K in <30 sec.
- Emission lines avoid auroral contamination

- OH all-sky imager (180°):
- Near infrared deep depletion CCD (950nm, bandwidth 10nm)
One Month of OH (3,1) Rotational Temperature Measurements – May 2011

- Continuous large amplitude oscillations (>10K)
- Mixture of tidal, gravity waves and/or planetary waves
- Temperature error ~1K
Planned: Southern Andes ANtarctic GRavity wave InitiAtive (SAANGRIA)

Goal: Investigate gravity wave “hotspot” over the Drake Passage and the Antarctic Peninsula
Summary

- Wealth and diversity of wave phenomena to study in our atmosphere.
- Imaging instrumentation provide an essential component of new instrument clusters for quantifying atmospheric dynamics.
- Here we illustrated the importance of combining data sets to investigate the nature (and impact) of these waves on the MLT region.
- New programs (e.g. ANGWIN and SAANGRIA) focused on high-latitude MLT dynamics provide an excellent opportunities for collaborative research with strong student involvement.
Paljon kiitoksiä