Southampton University, UK, Space Physics Group (1976-1991)

Me with Isocon Video camera

Maui, during the ALOHA-90 campaign

Prof. Pam Rothwell & Dr. Mike Hapgood

Prof. Mike Gadsden
Aberdeen University
Marconi Instruments TF1709 camera:
- Designed for low intensity X-ray fluoroscopic screens
- with a 4.5 inch Image Isocon camera tube by P850X by English Electric Valve Co. Ltd
- Donated to our group by a London hospital

Also the P4177 Miniature Isocon camera acquired later on
Video Camera:

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Switzerland (1980):

Gornergrat Observatory
Switzerland (1980): Thunderstorm Generated Gravity Waves

Taylor & Hapgood, 1988

Circular gravity waves!

Aug 14, 1980

Gornergrat Observatory
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)
Sources of Small-Scale Gravity Waves

• Equatorial and mid-latitudes:
  - Deep convection
  - Orographic wind forcing
  - Jet stream instabilities
  - Frontal systems, hurricanes etc...

• High latitudes:
  - Orographic forcing and weather disturbances
  - Polar jet
  - Joule heating and particle heating during magnetic storms?

• Natural and man-made explosions!

Jan 15th 2022 Hunga Tonga volcanic eruption
Credit: NOAA
Earth’s Airglow Emission Spectrum

Airglow Spectrum (Broadfoot and Kendal, 1968)

Airglow layer at ~87 km

ISS image – Courtesy: NASA
Sac Peak, NM (1983): Coordinated Measurements with USU

Miniature Isocon camera aligned with SDL Interferometer (IRFWI)
Utah State University 1991 – date
(ASI)
“10 Day Run” Arecibo Observatory Jan, 1993

All-Sky Imagers

Testing Photometrics CCD camera
Multi-wavelength CCD All-Sky Imager (ASI)

- 180° field-of-view
- Sequential observations of multiple airglow emissions:
  - OH (~20s exposure), O₂ (90s), OI (90s), Na (120s)
Gravity Waves Over Bear Lake Observatory, Utah

June 4-5, 2002, OH emission, altitude ~87 km

Movie: 3.6 hours

\( \lambda_h = 45 \text{ km} \)
\( v_h = 45 \text{ m/s} \)
\( \tau = 15 \text{ min} \)
ALOH A-93, Hawaii (1993) – Spectacular GW Event

Identified as a Mesospheric Bore (Dewan and Picard, 1998)

Scan of relative intensity showing an intensity reversal.

Taylor et al., 1995
Typical Gravity Wave Characteristics at Low Latitude:
1998-99, Cachoeira Paulista, Brazil (23°S)

Many imagers now operated world-wide
First Collaboration with British Antarctic Survey (2000-2011)

Halley Station (76°S)

Self-service re-fueling

Ice cliffs

British Antarctic Survey
ASI: Halley Station, Antarctica

Phase Velocity, 2001

Nielsen et al., 2012

OH Gravity waves
May 27, 2001

(Nielsen et al., 2005)
... leaving Antarctica, 2000

South Georgia

Shackleton’s Grave

Gritviken Whaling Station
CEDAR Mesospheric Temperature Mapper (MTM)

• Sensitive bare CCD Imager developed to measure mesospheric temperature variability using airglow emissions.
• Sequential observations (60 sec. exposure) of:
  - NIR OH (6, 2) Band ~ 87 km
  - O$_2$(0,1) A Band ~ 94 km
  - Background (~857.5 nm)
• Field of view ~90°, (180 x 180 km at 90 km altitude).
• Cycle time: ~ 3 min per OH/O$_2$ temperature determination (Precision ~2K).
OH and \( \text{O}_2 \) Temperature Analysis

\[
T_{\text{OH}} = \frac{228.45 \, K}{\ln[(2.600)(S_{1c} / S_{2c})]}
\]

\[
T_{\text{O}_2} = [248.9 (S_{2c} / S_{1c}) + 77.7] \, K
\]

- OH transition parameters from Goldman et al., 1998.
- Relative band intensity from \((S_{1c}+S_{2c})\) and \(T\) using simplified LTE calculation.

- LTE rotational distribution with Schlapp (1936) line strengths.
- Relative band intensity from LTE model using fraction of \((S_{1c}+S_{2c})\) at rotational temperature \(T\).
MTM: Gravity Wave Momentum Flux ($F_M$) Calculation

\[ \frac{\Delta I}{I} = 6.4\% \]

(Phase $\phi = 60 \pm 5^\circ$)

\[ \frac{\Delta T}{T} = 2.0\% \]

$\lambda_H = 36 \text{ km},$

$\nu_H = 36 \text{ m/s},$

$T = 17 \text{ min}$

\[ F_M = \frac{k}{2} \cdot \frac{m}{m^2 + \frac{1}{4N^2}} \cdot \frac{g^2}{N^2} \left( \frac{\Delta T}{T} \right)^2 = 30 \pm 10 \text{ m}^2/\text{s}^2 \]
MTM: Collaborative Measurements with Na lidars

Starfire, NM, 1998-2000

AMOS
Maui-MALT, 2002-2007

ALO, Chile, 2009-to date
Mesospheric Mountain Wave Event as seen from 2 sites

Small colored image is MTM temperature map from ALO, Chile

Large BW image is ASI data from El Leoncito, Argentina (courtesy S. Smith)
Advanced Mesospheric Temperature Mapper (AMTM)

- Large format (120° FOV) fast (f/1) telecentric optics
- IR InGaAs detector (1.5-1.65 μm) OH (3,1) band measurements
- Sequential measurements of OH rotational temperature. Precision 1-2 K in ~30 sec
- High-latitude capability as emission lines avoid most of the auroral contamination

Scientific Goals
- Quantify characteristics and effects of gravity waves on mesopause region
- Coordinated measurements with lidar, radar and rocket soundings

Courtesy Roy Esplin and Dave McLain (SDL)

AMTM at South Pole Station (2010)
- 200x160 km temperature and intensity maps at 87km
AMTM Data Products

Long term temperature evolution of Planetary Waves

Keograms - 1-12hrs waves/tides

Temperature/Intensity maps
Short-period GWs/Wave breaking
AMTM: Gravity Wave Breaking Event - Brightness
Jun 06\textsuperscript{th}, 2013, Logan, Utah (41.7\degree N)

$P_1(2)$ line of the OH (3,1) emission – Exposure time 10s – 1 image every 30s
AMTM: Gravity Wave Breaking Event - Temperature
Jun 06th, 2013, Logan, Utah (41.7°N)

OH (3,1) rotational temperature – 1 map every ~30s
AMTM: South Pole Atmospheric Research
Antarctic Atmospheric Waves Research

• First collaborative project with British Antarctic Survey (2000-2011)
• South Pole AMTM (2010-to date)
• ANtarctic Gravity Waves Instrument Network (ANGWIN, 2012-to date)
Non-Stop AMTM Temperature Measurements at South Pole

1 month: May 2011

- Continuous large oscillations (>10K) due to tidal and/or planetary wave perturbations
- Estimated error ~1K
South Pole 2014: Large Amplitude Planetary Wave

- Large coherent oscillations starting in June (~day 150)
- ~4.5 cycles observed
- Max amplitude ~12K
- Rossby PW (1,4)

Zhao et al., 2019
ANtarctic Gravity Wave Instruments Network (ANGWIN)

In 2011, researchers from USU (USA), BAS (UK), NIPR (Japan), AAD (Australia), INPE (Brazil), and more recently KOPRI (South Korea since 2018) “joined forces” to enhance collaborative GW research across Antarctica on a continental scale

- Data sharing
- Normalization of analysis techniques
- Student exchange
- Regular (~2 years) scientific workshops
ANGWIN Workshops

NIPR, Japan, 2013
USU, USA, 2014
BAS, UK, 2016
INPE, Brazil, 2018
KOPRI, South Korea, 2022
Example of ANGWIN Collaboration: M-Transform AMTM Data

- Analysis technique developed at NIPR, Japan
- 96 hours of continuous clear-sky observations over McMurdo, Antarctica (June 26-29, 2017)
- Left: Merra-2 (every 3 hours) wind profiles interpolated to each window
- Right: Phase velocity PSD and resulting wind blocking region in pink
- Bottom: Total power with marker denoting current figure position.

Zia, 2022
DEEPWAVE Campaign - New Zealand (2014)

Gulfstream V (GV) Upper Atmosphere Instruments

Advanced Mesospheric Temperature Mapper (AMTM):
- 120x80 km temperature and intensity maps of the OH layer (~87 km), centered at the zenith, every ~15 s (Pautet et al., 2014)

Rayleigh and Na lidars:
Density and temperature 20-60 km and 75-100 km

Two IR wide field-of-view side looking cameras:
OH brightness over a large region (up to 450 km on each side of the GV), every 3-4 s
Orographic Waves over Auckland Islands

Pautet et al., 2016; Eckermann et al., 2016
Ground-Based AMTM Measurements
Lauder Observatory (45.0°S)

One zenith-looking mesospheric temperature mapper
• FOV 120°
• 1 temperature map every ~30s
Mountain Wave and Momentum Flux Variability
June 21-22, 2014

MF oscillation with a ~30-min period

Taylor et al., 2019
Atmospheric Waves Experiment (AWE)

AWE is the first dedicated NASA mission to investigate global gravity wave properties in the upper atmosphere and their impacts on the ionosphere-thermosphere-mesosphere (ITM)

How does tropospheric weather influence space weather?
AWE AMTM - Glamour Shots
Global GW Sources

All source types in both hemispheres

Global 4-day night-time coverage (+/-55° latitude), ~30 days full Local Time coverage.

~85% global coverage
40+ Years of Studying Atmospheric Phenomena

Projects related to gravity waves
- Switzerland, 1980 (circular GW)
- Coordinated measurements with USU, 1983
- Arecibo, Puerto Rico, 1993
- ALOHA-93, Hawaii, 1993 (Front/bore)
- NASA Guará campaign, Brazil, 1994
- MU Radar, Japan, 1995
- INPE, Brazil, 1998
- Fort Collins, Colorado, 1998
- Starfire, New Mexico, 1999 (MTM/Na lidar)
- BAS, Antarctica, 2000 - to date (GW over Antarctica)
- DAWEX, Australia, 2001 (Convective sources)
- MacWAVE, Sweden, 2003 (High latitude GW)
- NASA TIMED coordination at BLO, Utah, 2002 - 2005
- Maui-MALT program, Hawaii, 2002 - 2007 (Tides, SAO, critical level filtering)
- SpreadFEx, Brazil, 2005, 2009-10 (Plasma bubbles seeding by GW)
- Andes Lidar Observatory, Chile, 2009-to date
- AMTM: ALOMAR, Norway, 2010-2017, 2023; South Pole, 2010 - to date
- ANGWIN, 2012 - to date
- DEEPWAVE, New Zealand, 2014 (Mountain waves)
- GW_LCYCLE 2, Norway, Sweden, Finland, 2015-16
- VortEx rocket campaign, Norway, 2023
- AWE

Projects not related to gravity waves
- Scotland, 1979 (NLC)
- Christmas Island, Pacific Ocean, 1995 (Plasma bubbles)
- Leonid MAC, 1999 (meteor shower)
- Brazil Balloon Sprite campaign, 2002-2003
- Leonid MAC, 2002 (meteor shower)
- Genesis re-entry, California, 2004
- Yucca Ridge sprite campaign, Colorado, 2005
- SpreadFEx, Brazil, 2005, 2009-10 (Plasma bubbles seeding by GW)
- 2nd Brazil Balloon Sprite campaign, 2006
- Stardust re-entry, 2006
- Jules Verne ATV re-entry, Tahiti, 2008
- Hayabusa re-entry, Australia, 2010
- Draconids mission, 2011 (meteor shower)
- Supersoaker, Alaska, 2017 (NLC)
All Around the World!