Have Camera - Will Travel

Over 40 Years of Quantifying Dynamics and Impacts of Mesospheric Gravity Waves Around the World

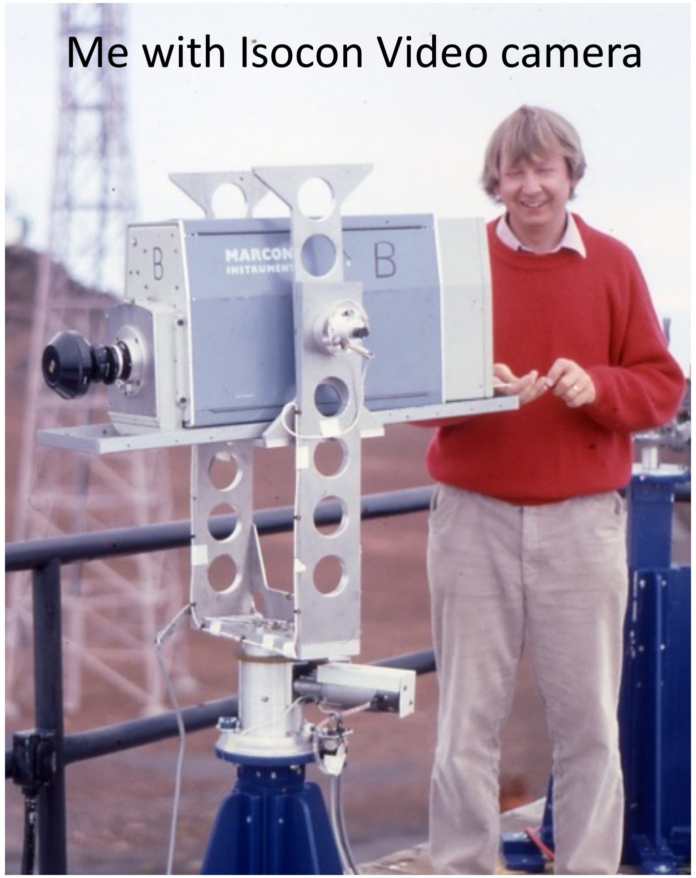
Prof. Mike Taylor
Utah State University

Credit:
NASA

CEDAR Workshop 2023, Distinguished Lecture

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

Prof. Pam Rothwell & Dr. Mike Hapgood

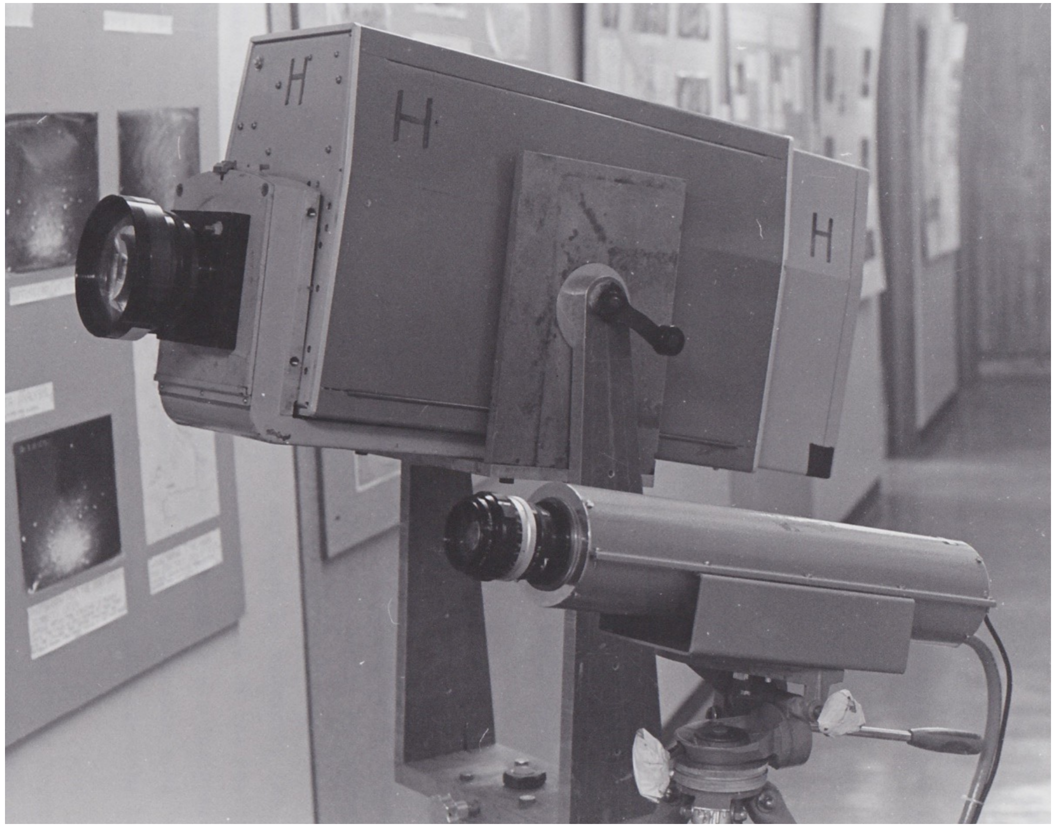


Me with Isocon Video camera

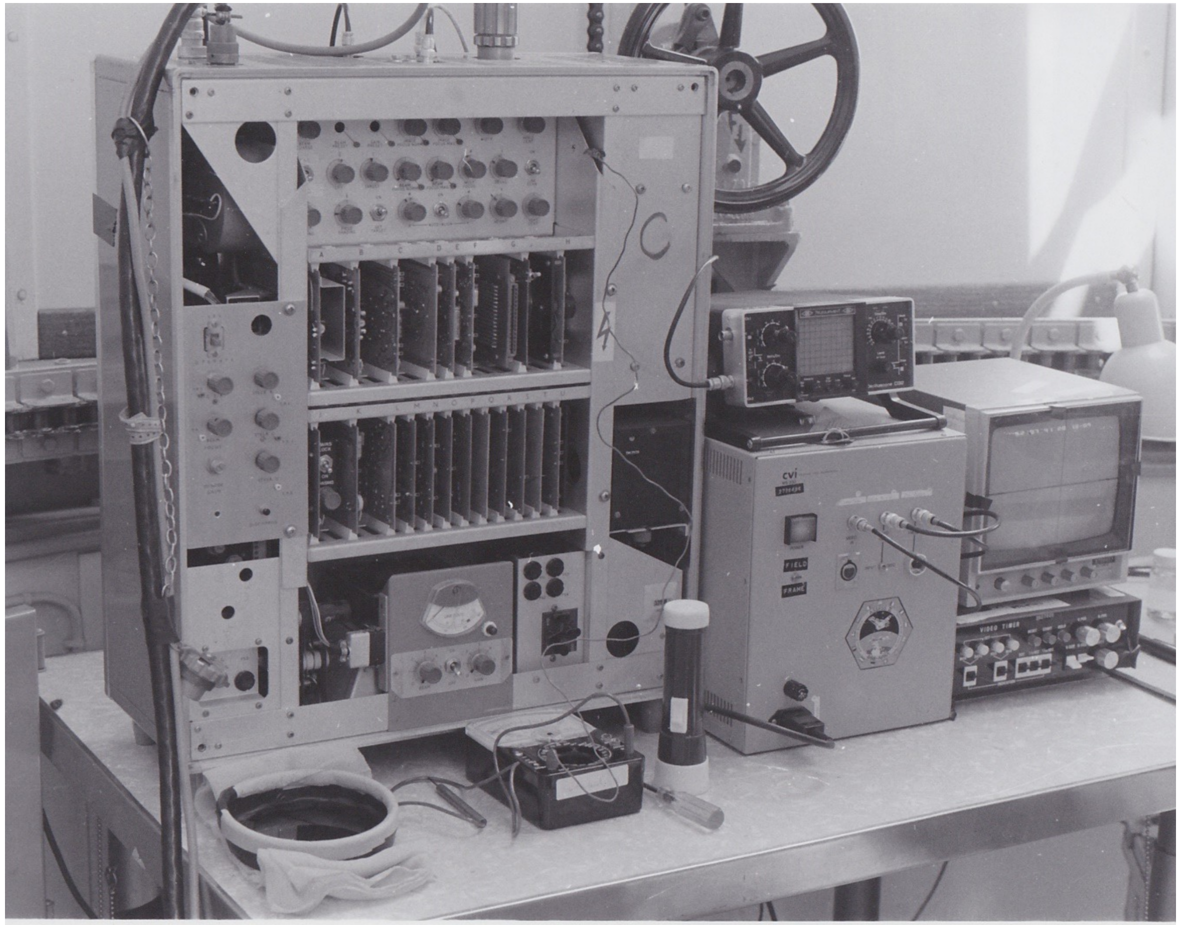
Maui, during the ALOHA-90 campaign

Prof. Mike Gadsden
Aberdeen University

Isocon Video Camera



Camera control unit

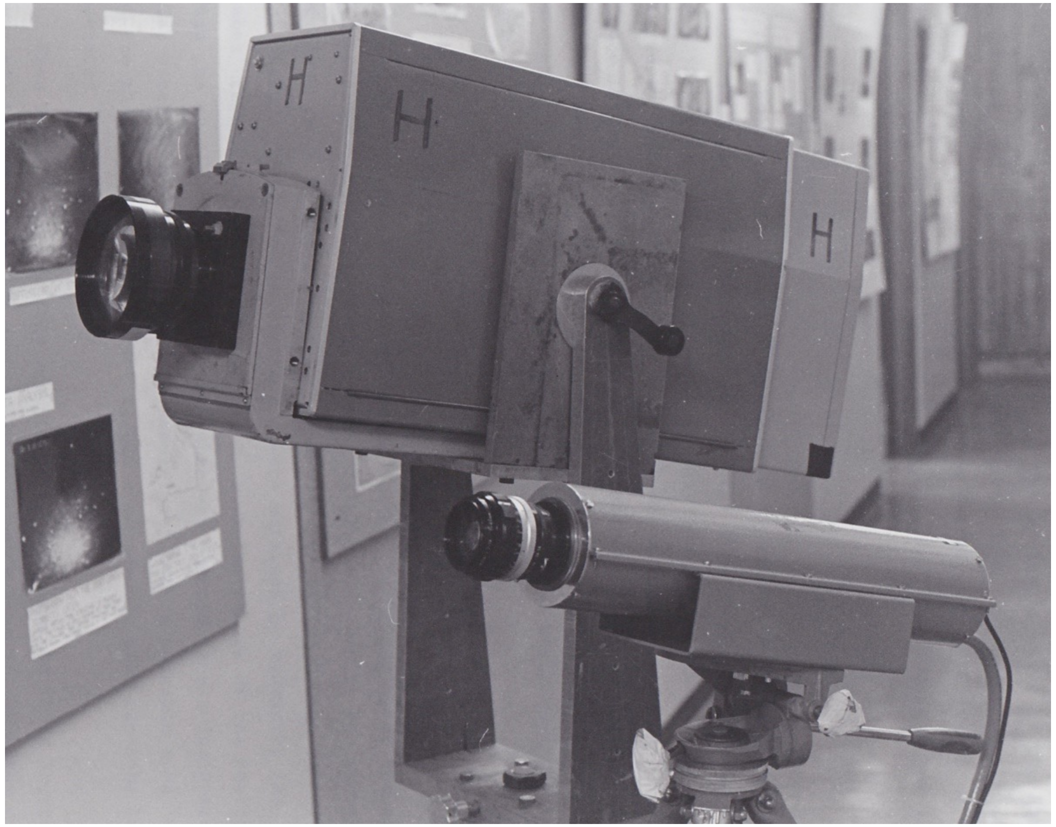


Marconi Instruments TF1709 camera:

- Designed for low intensity X-ray fluoroscopic screens
- with a 4.5 inch Image Isocon camera tube byP850X 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:



Marconi Instruments TF1709 camera:

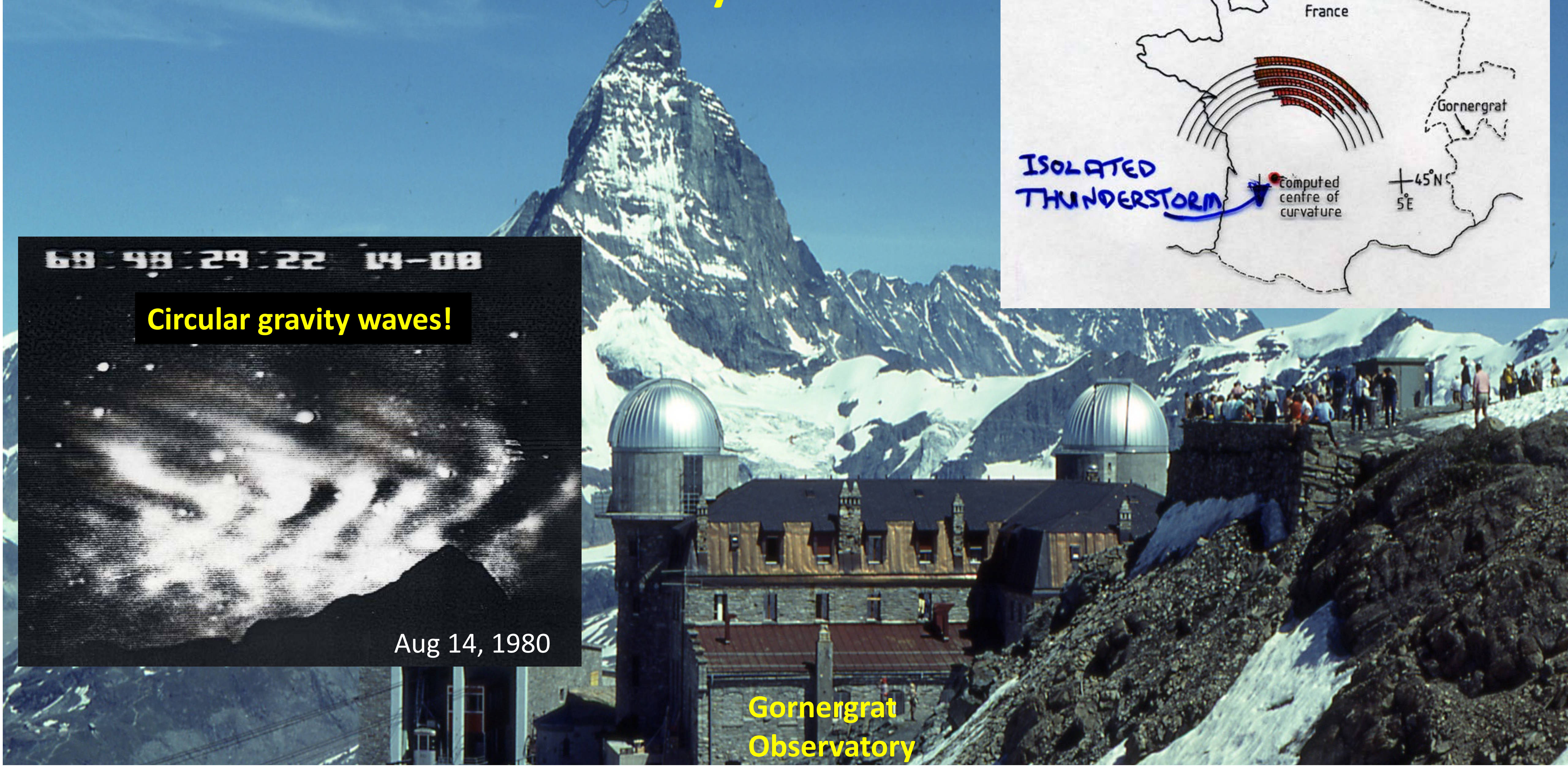
- Designed for low intensity X-ray fluoroscopic screens
- with a 4.5 inch Image Isocon camera tube byP850X by English Electric Valve Co. Ltd
- Donated to our group by a London hospital

Also the P4177 Miniature Isocon camera acquired later on

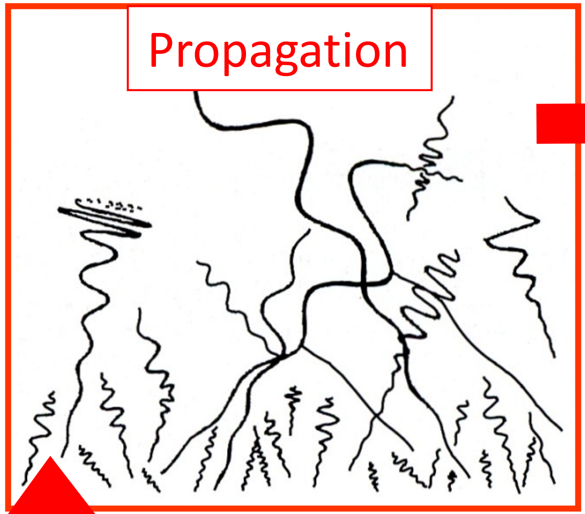
www.tvcameramuseum.org

Switzerland (1980):

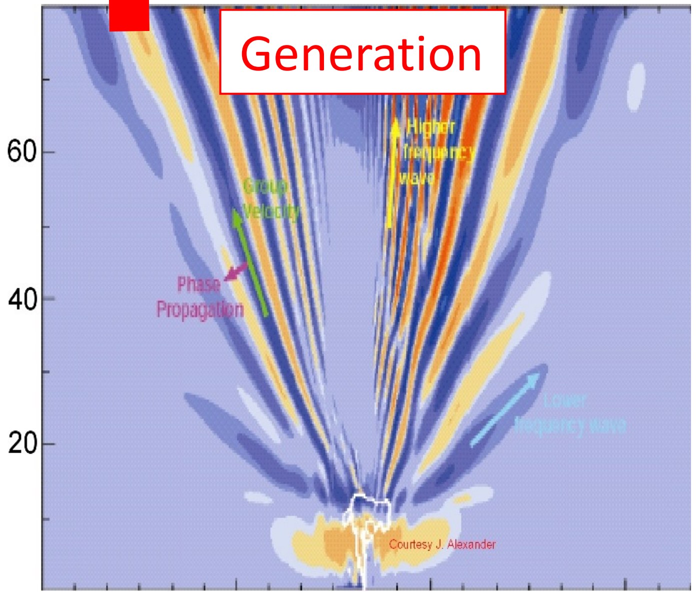
Switzerland (1980):
Thunderstorm Generated Gravity Waves



Atmospheric Gravity Waves



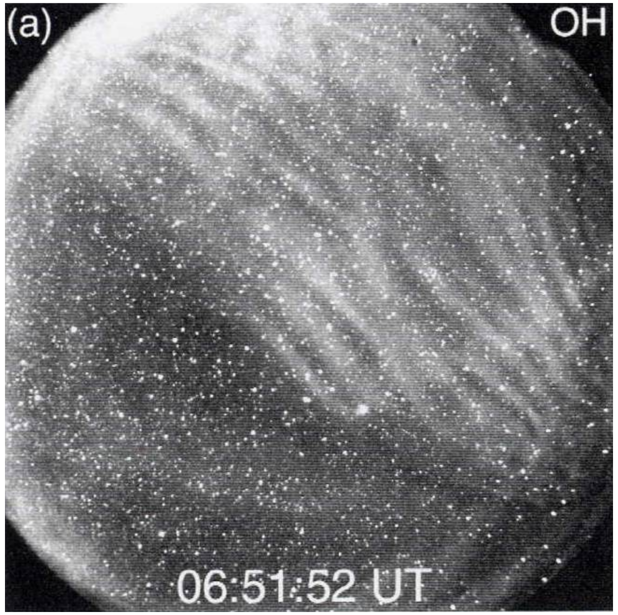
Hines, 1960



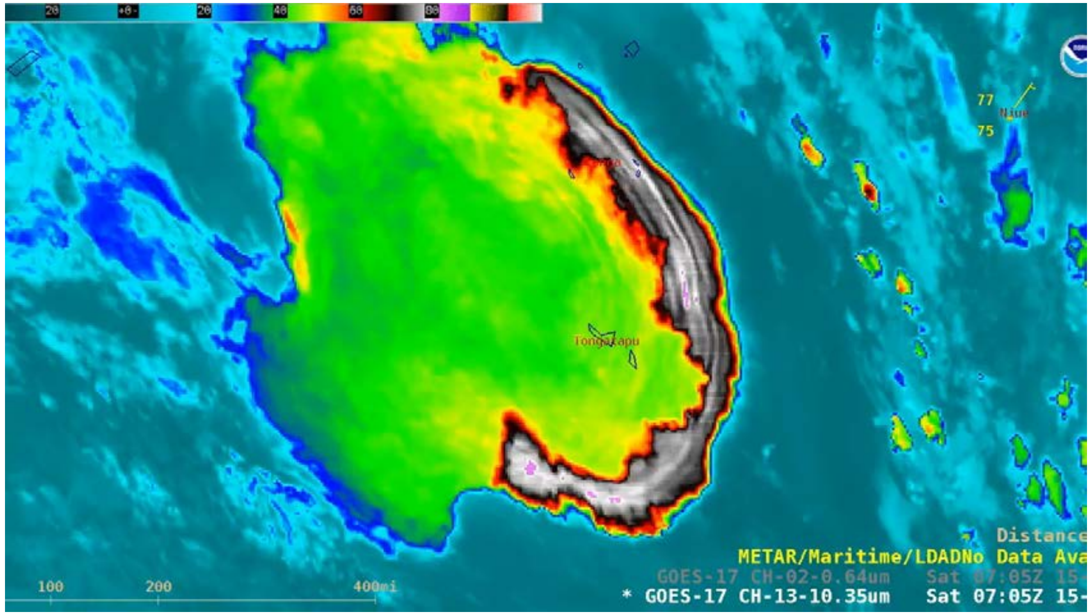
Courtesy J. Alexander

- 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



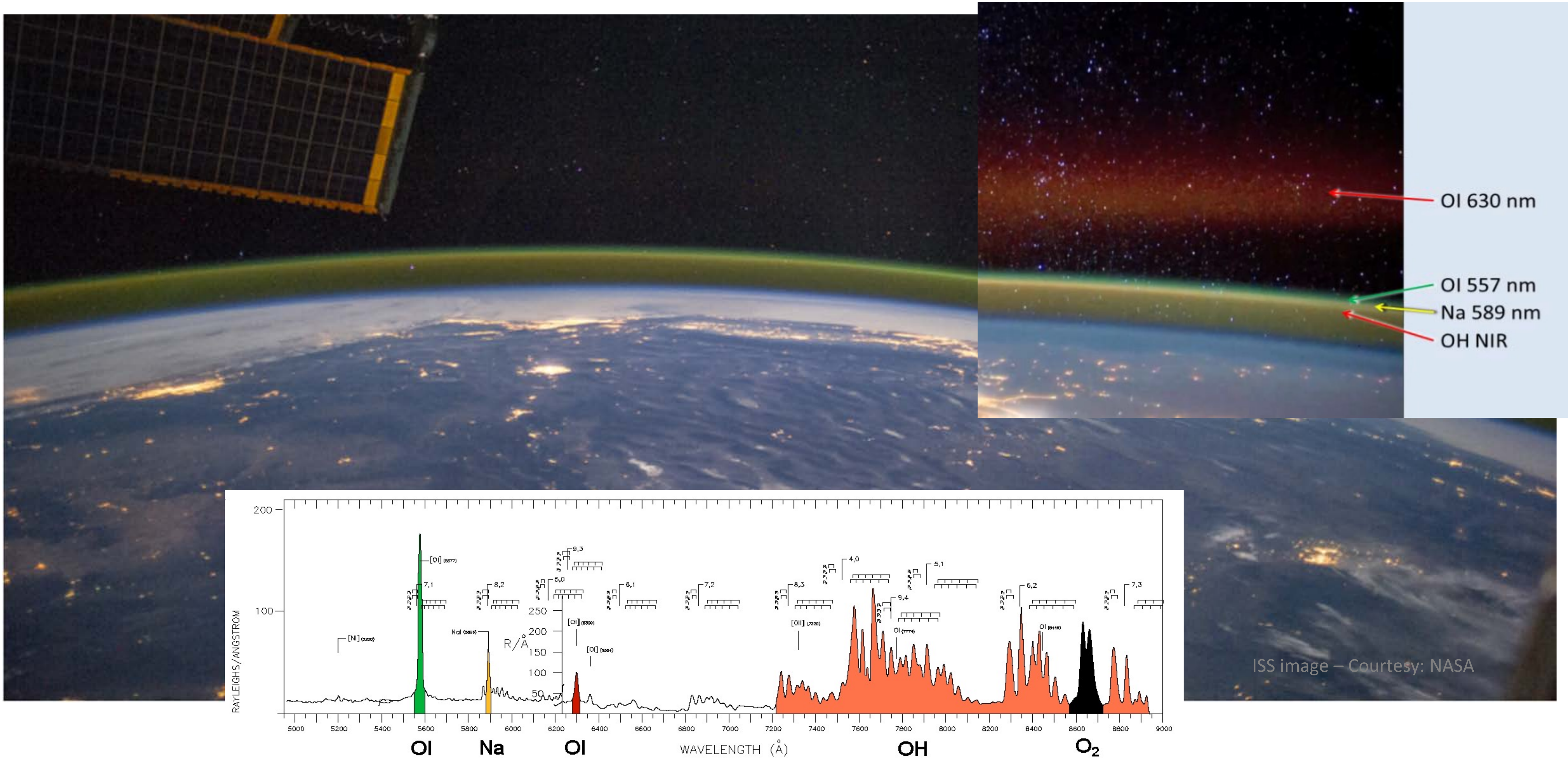
- Equatorial and mid-latitudes:
  - Deep convection
  - Orographic wind forcing
  - Jet stream instabilities
  - Frontal systems, hurricanes etc...
- High latitudes:
  - Orographic forcing and weather disturbances
  - Polar jet
  - Joule heating and particle heating during magnetic storms?
- Natural and man-made explosions!



Jan 15th 2022 Hunga Tonga volcanic eruption

Credit: NOAA

Earth’s Airglow Emission Spectrum



Sac Peak, NM (1983):
Coordinated Measurements with USU

Miniature Isocon camera aligned with SDL Interferometer (IRFWI)

Utah State University 1991 – date (ASI)

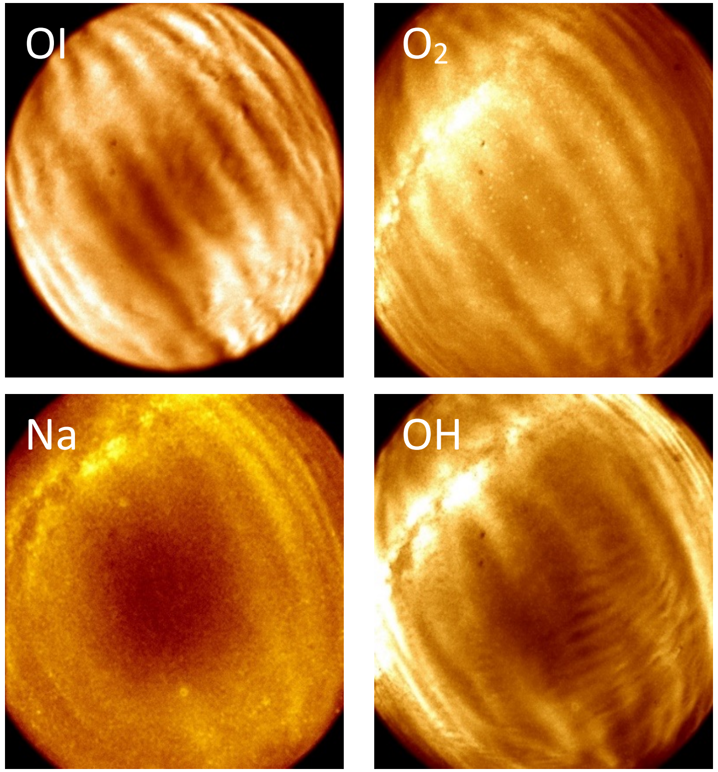
All-Sky Imagers

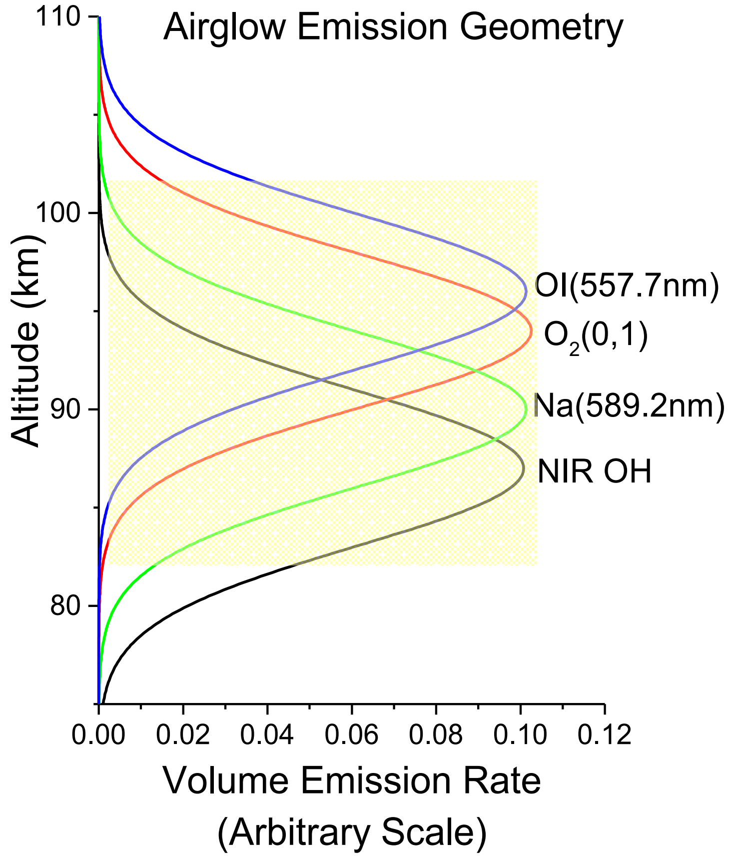
"10 Day Run" Arecibo Observatory Jan, 1993

Testing Photometrics CCD camera

Multi-wavelength CCD All-Sky Imager (ASI)

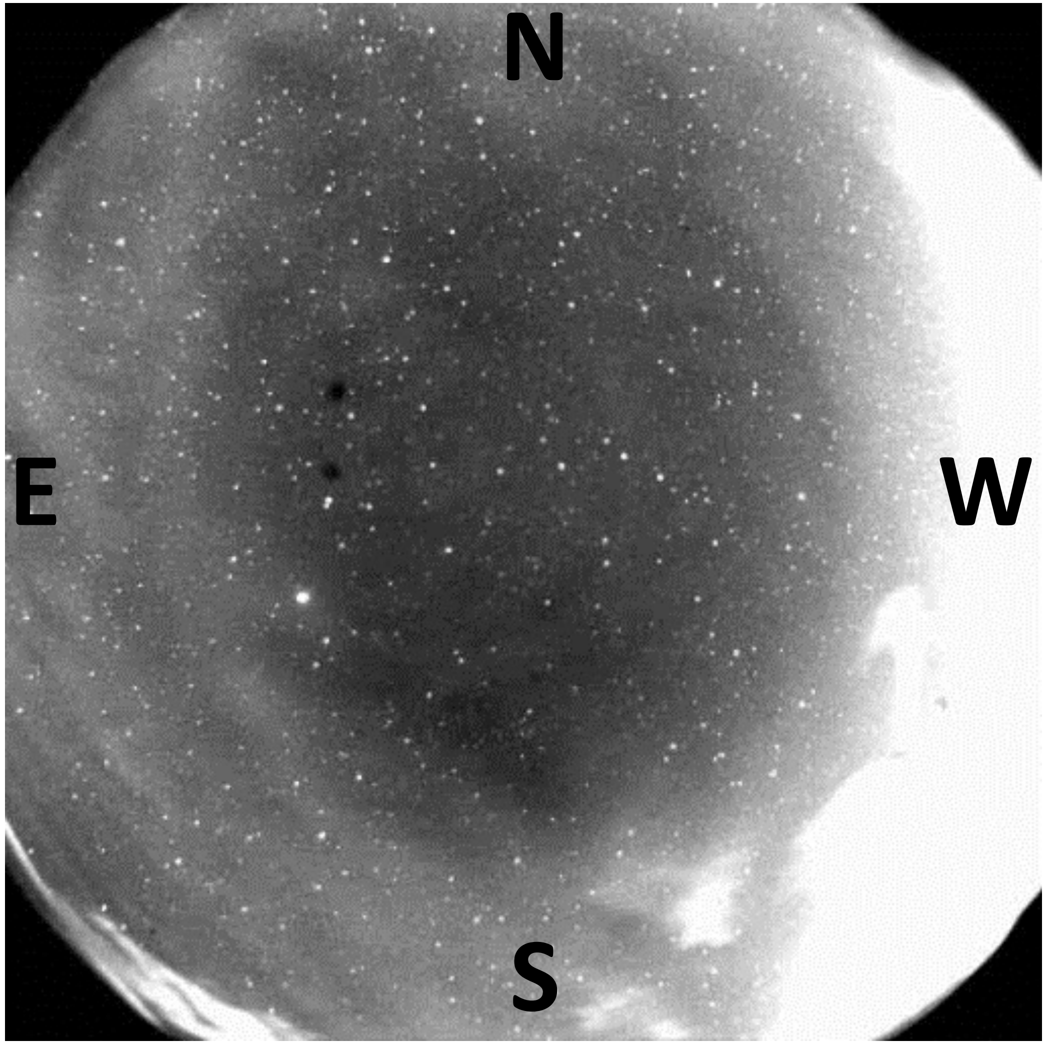
All-sky multi-wavelength new CCD imager 1993





- 180° field-of-view
- Sequential observations of multiple airglow emissions:
  OH (~20s exposure), O_2 (90s), OI (90s), Na (120s)

Gravity Waves Over Bear Lake Observatory, Utah

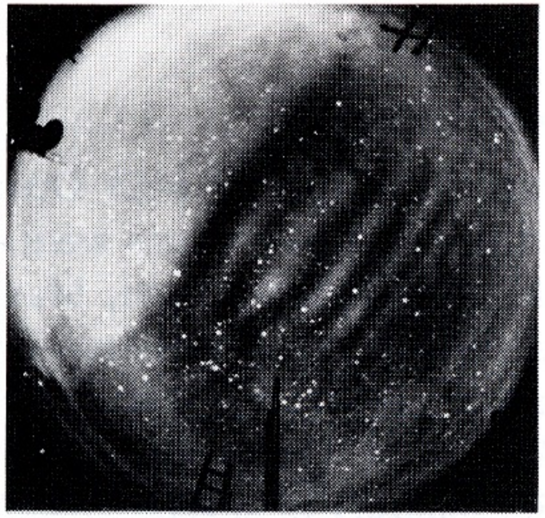


Movie: 3.6 hours
λ_h = 45 km
v_h = 45 m/s
τ = 15 min

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

ALOHA-93, Hawaii (1993) – Spectacular GW Event

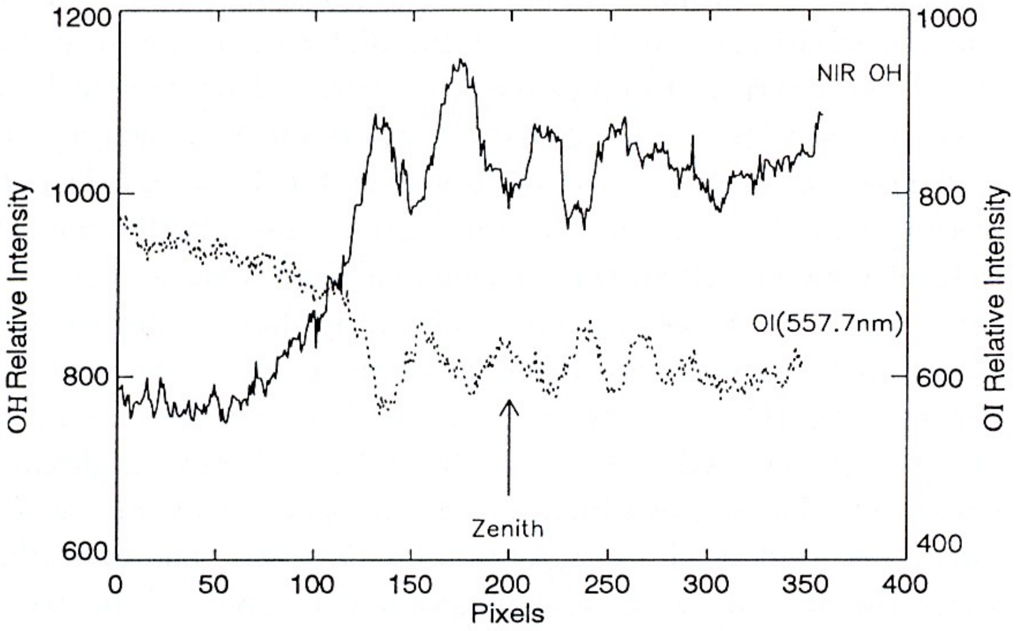
OI (557.7 nm)



10:57 UT

NIR OH

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

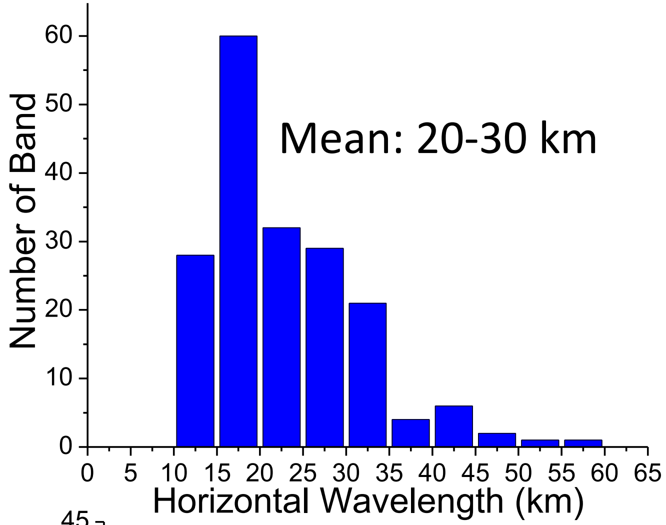


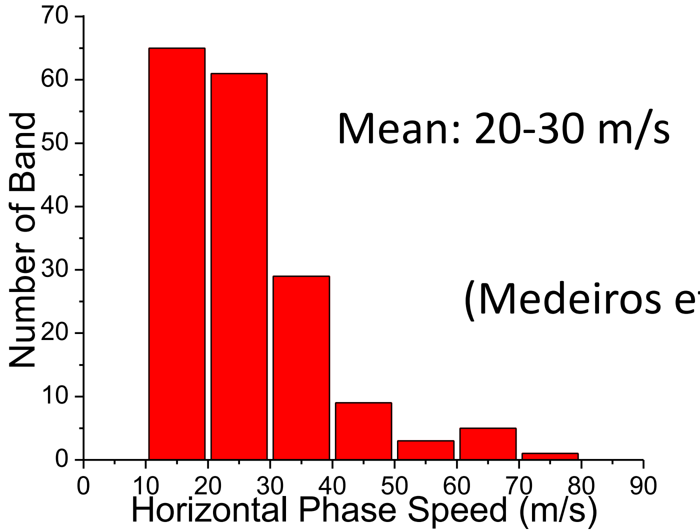
Scan of relative intensity showing an intensity reversal.

Taylor et al., 1995

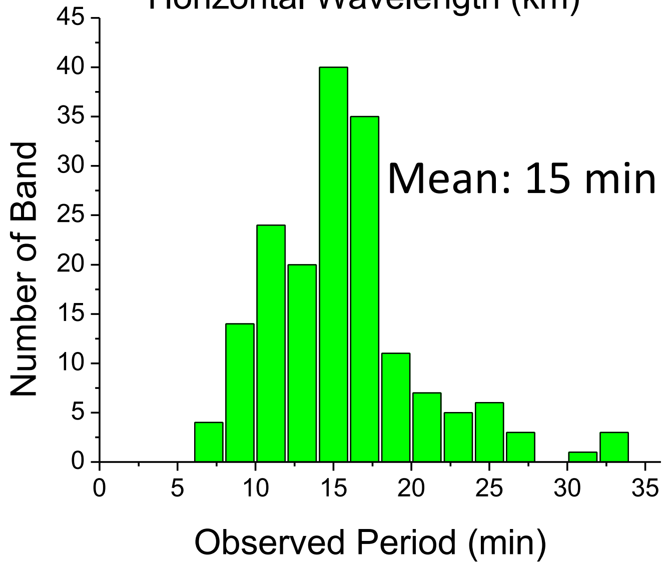
Typical Gravity Wave Characteristics at Low Latitude:

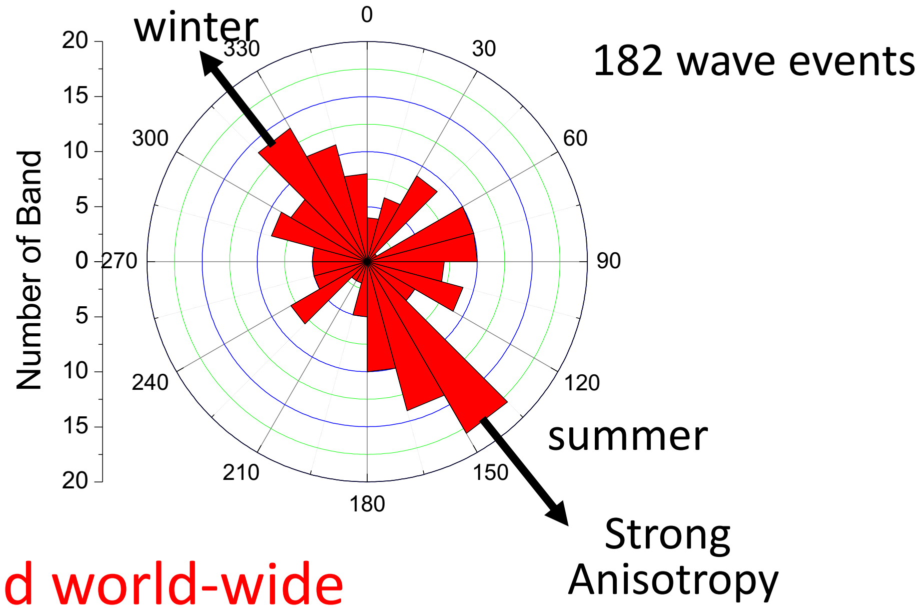
1998-99, Cachoeira Paulista, Brazil (23°S)





(Medeiros et al., 2003)





Many imagers now operated world-wide

First Collaboration with British Antarctic Survey (2000-2011)

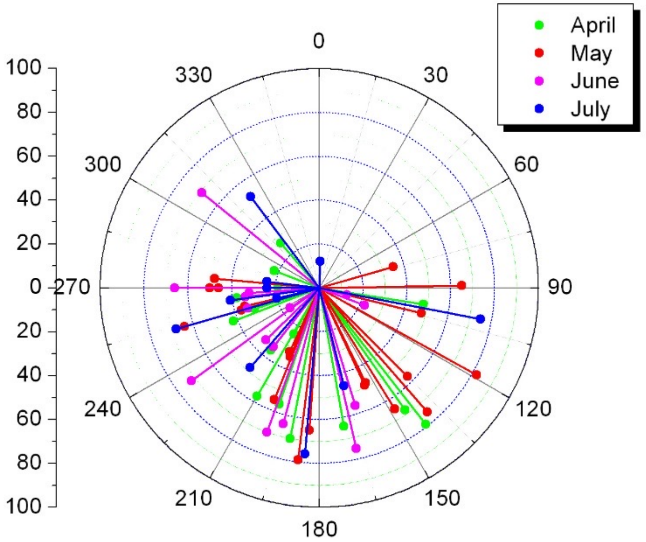
Self-service re-fueling

Halley Station (76^{o}S)

Ice cliffs

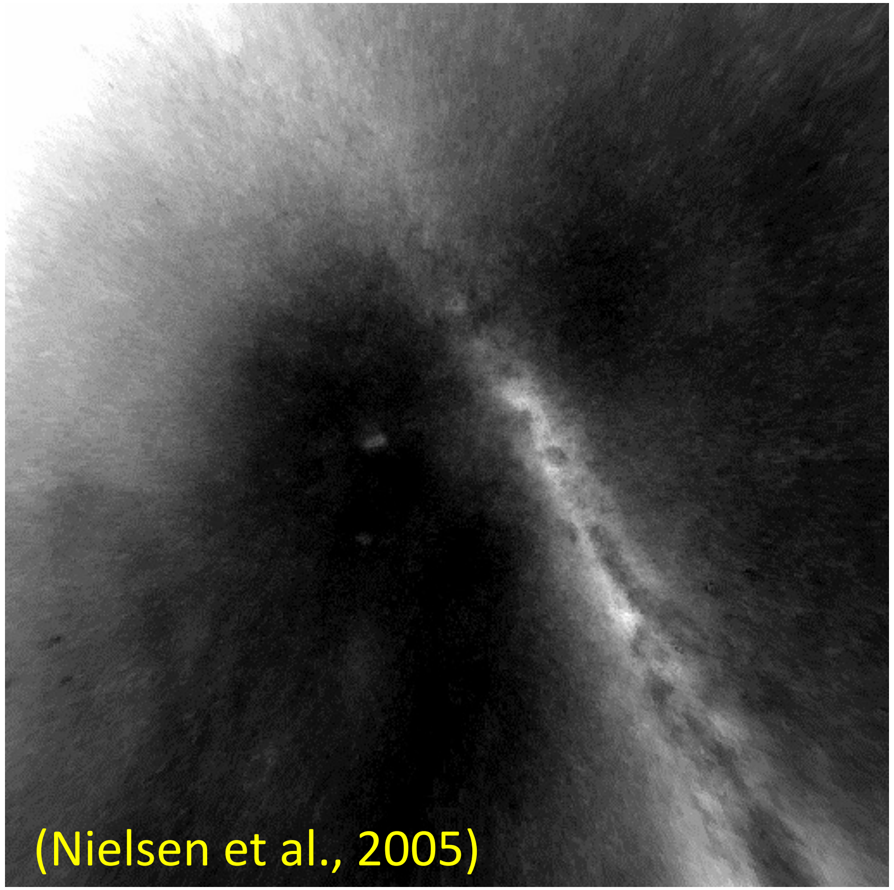
British Antarctic Survey

ASI: Halley Station, Antarctica



Phase Velocity, 2001

Nielsen et al., 2012



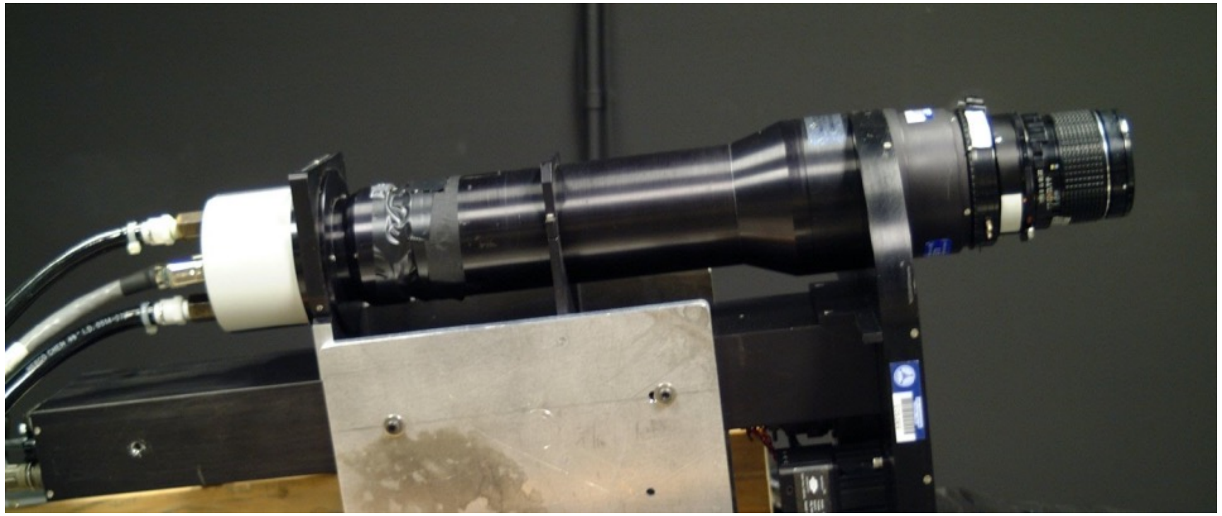
(Nielsen et al., 2005)

OH Gravity waves

May 27, 2001

… leaving Antarctica, 2000

CEDAR Mesospheric Temperature Mapper (**MTM**)

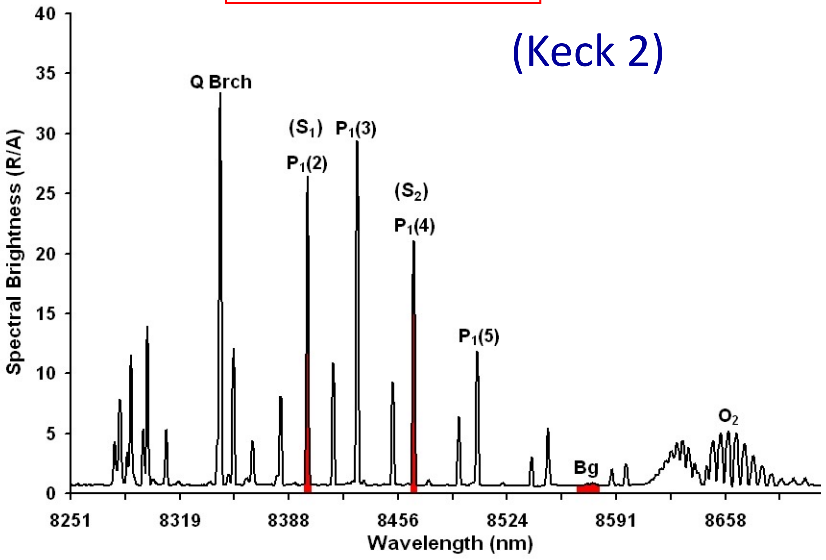


Mesospheric Temperature Mapper 1997

- 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 O_2 Temperature Analysis

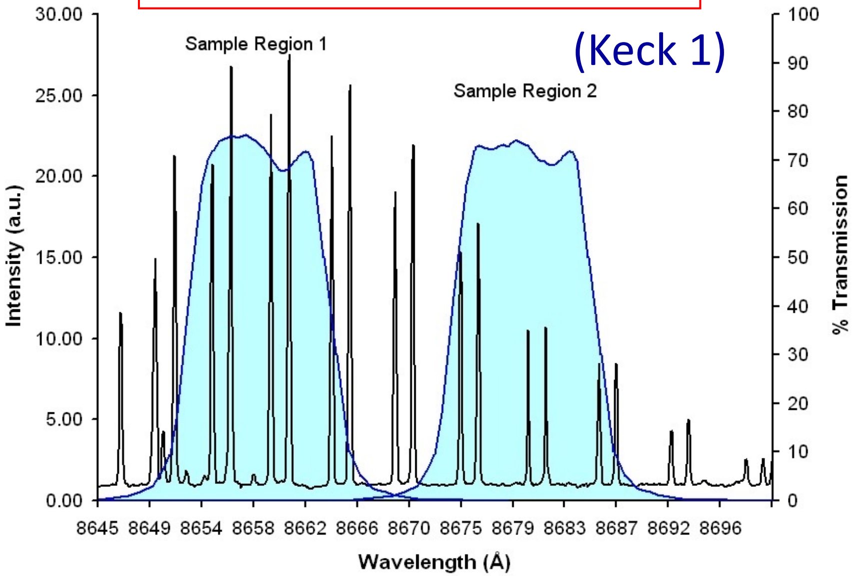
OH (6,2) Band



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

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

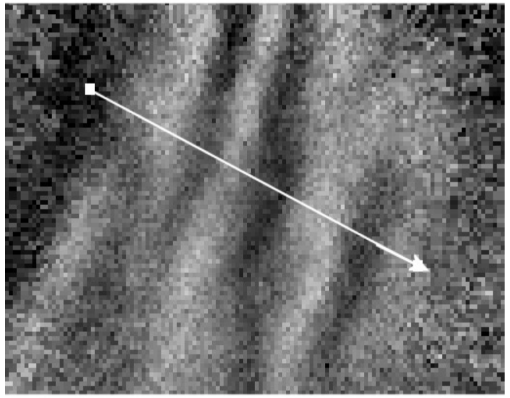
O_2 (0,1) Atmospheric Band

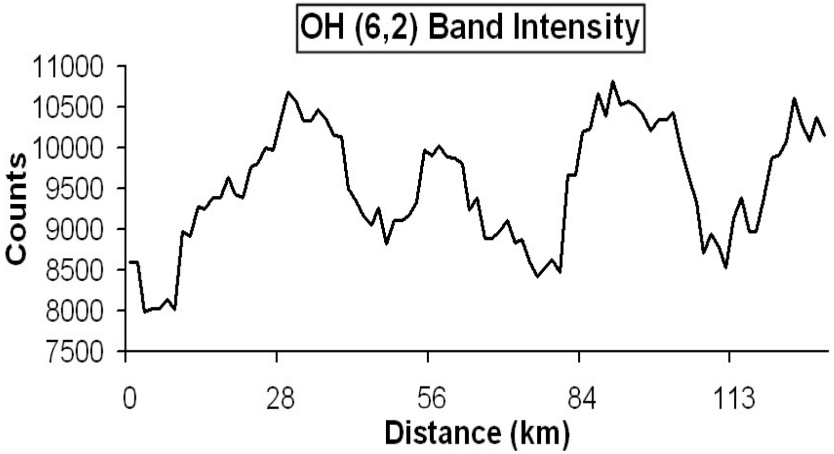


$$T_{O_2} = [248.9(S_{2c}/S_{1c}) + 77.7]K$$

- 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.

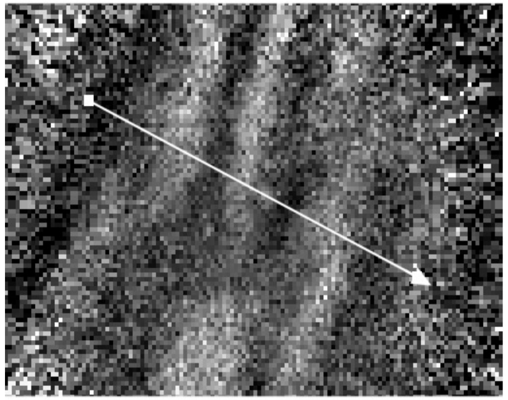
MTM: Gravity Wave Momentum Flux (F_M) Calculation

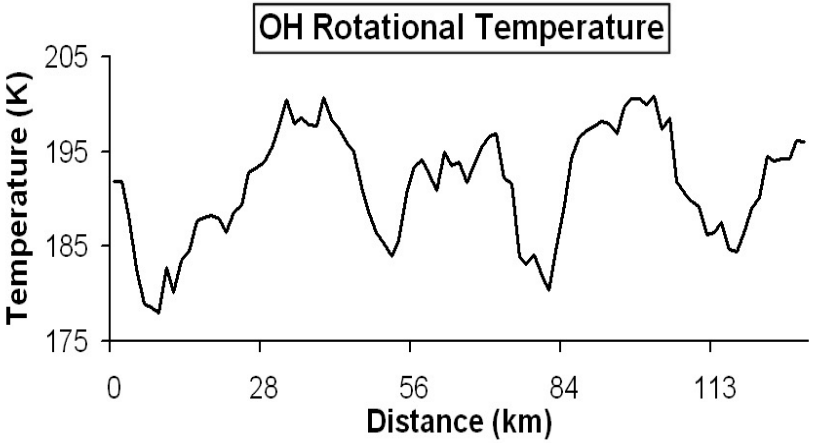




$$\frac{\Delta I}{I} = 6.4\%$$

(Phase ϕ =60 ± 5°)





$$\frac{\Delta T}{T} = 2.0\%$$

λ_H = 36 km,

v_H = 36 m/s,

T =17 min

$$F_M = \frac{k}{2} \cdot \frac{m}{m^2 + \frac{1}{4H^2}} \cdot \frac{g^2}{N^2} \left(\frac{\Delta T}{\bar{T}} \right)^2 = 30 \pm 10\, m^2/s^2$$

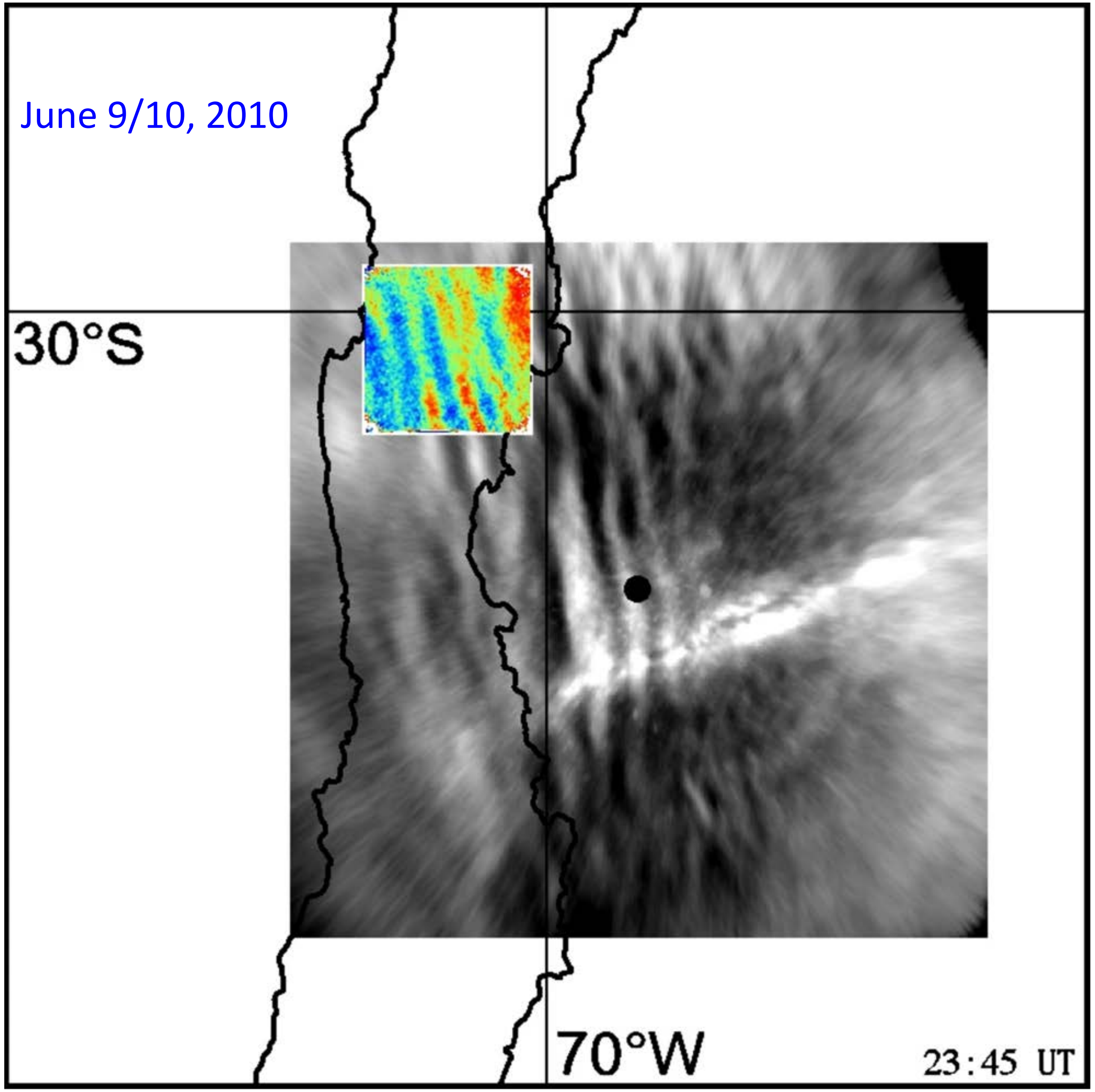
MTM: Collaborative Measurements with **Na lidars**

Photo/AFRL

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)

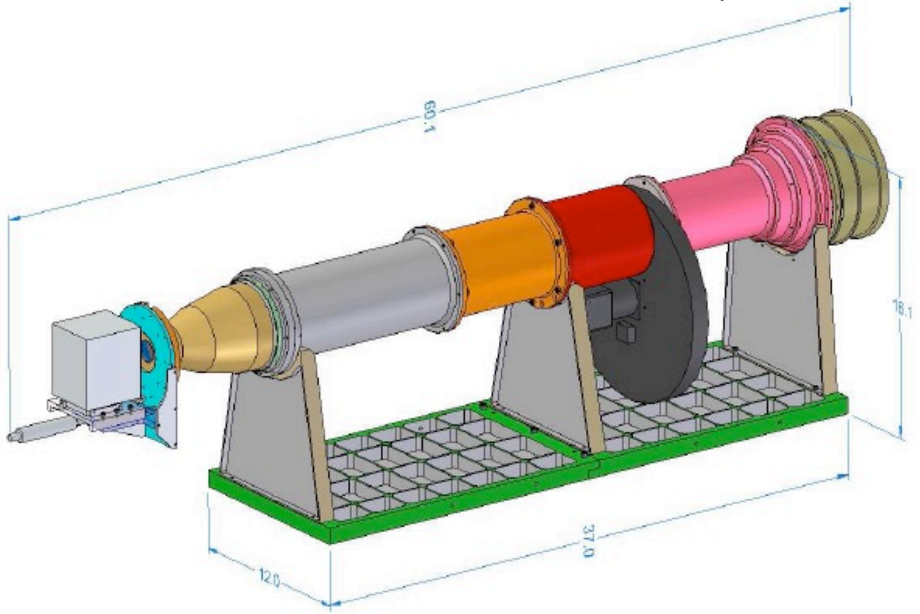


Advanved Mesospheric Temperature Mapper (AMTM)

- 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

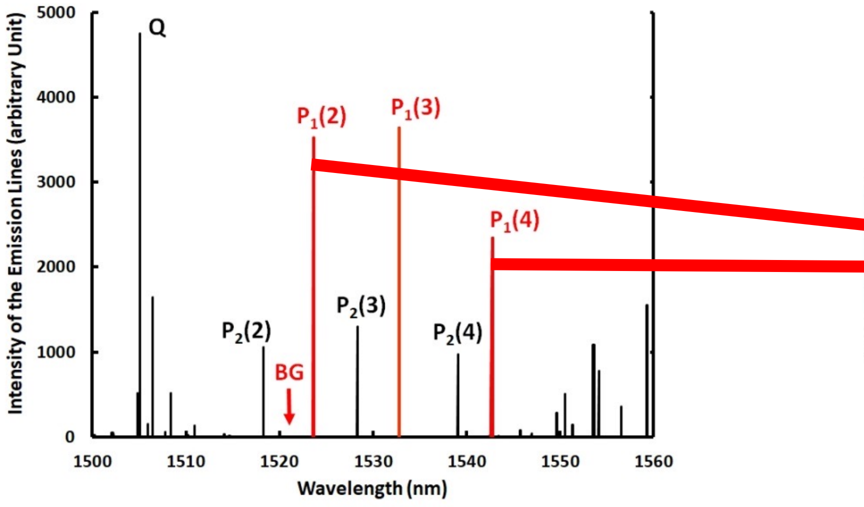
- Quantify characteristics and effects of gravity waves on mesopause region
- Coordinated measurements with lidar, radar and rocket soundings

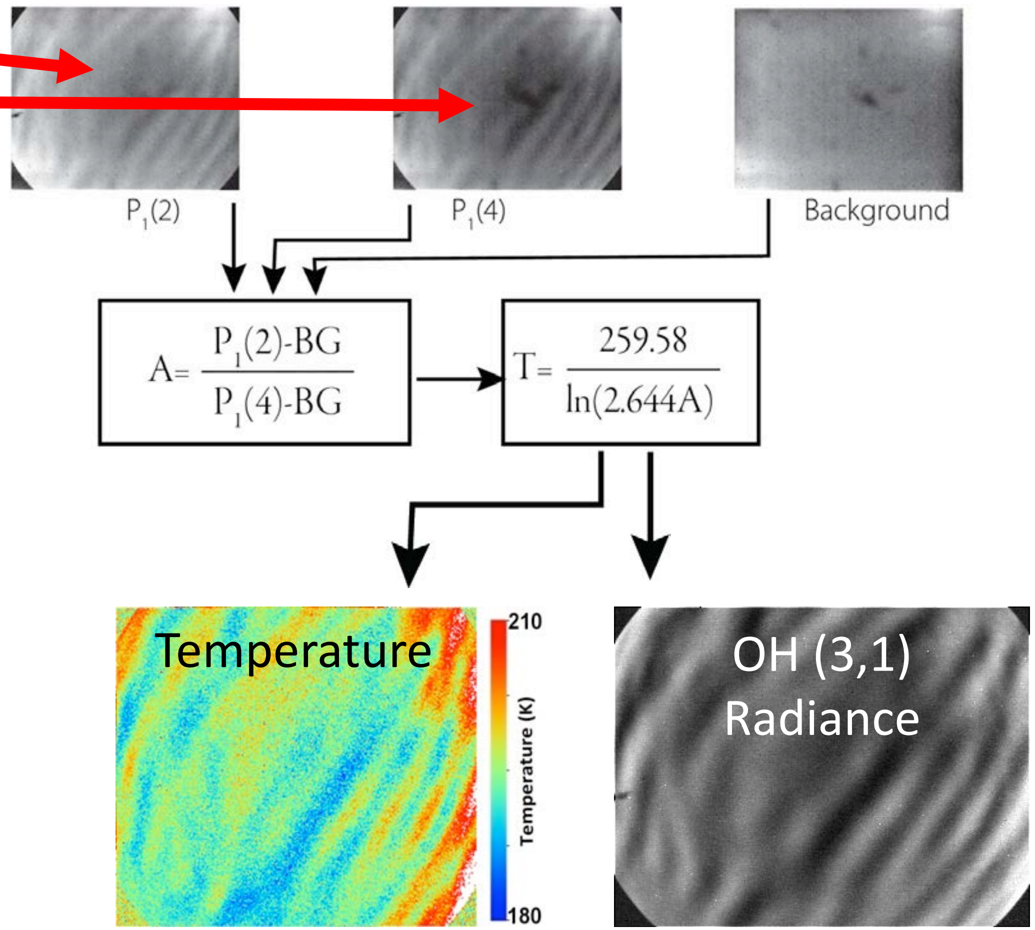


Courtesy Roy Esplin and Dave McLain (SDL)

AMTM at South Pole Station (2010)

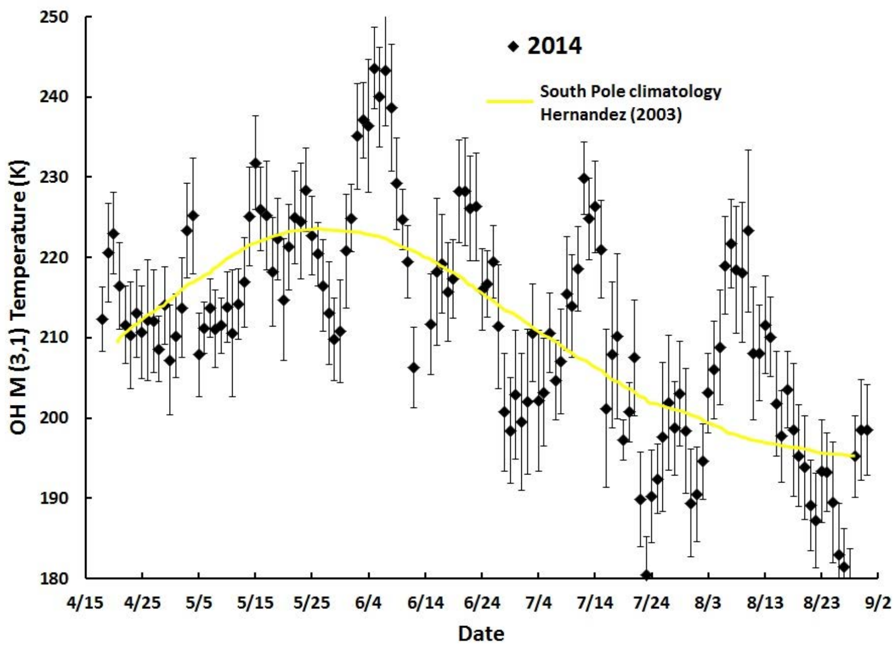
AMTM Rotational Temperature Processing



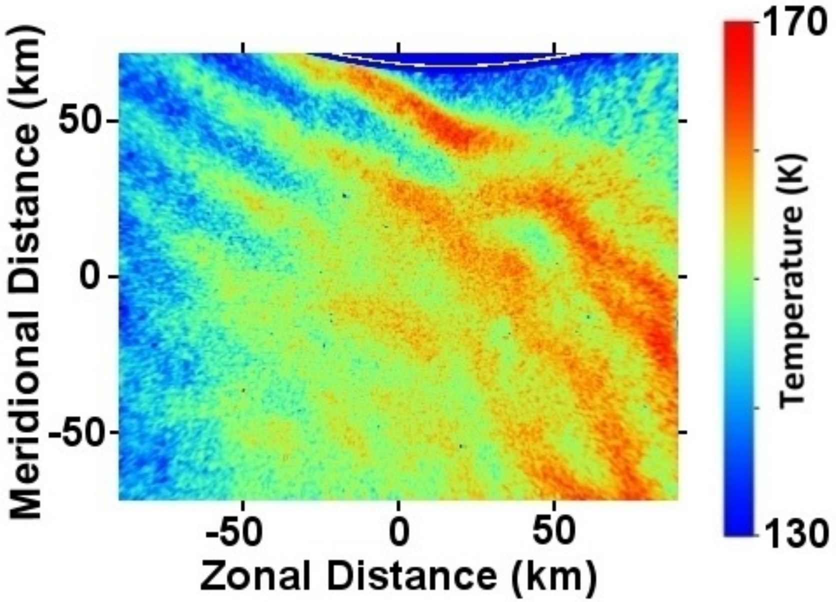


- 200x160 km temperature and intensity maps at 87km

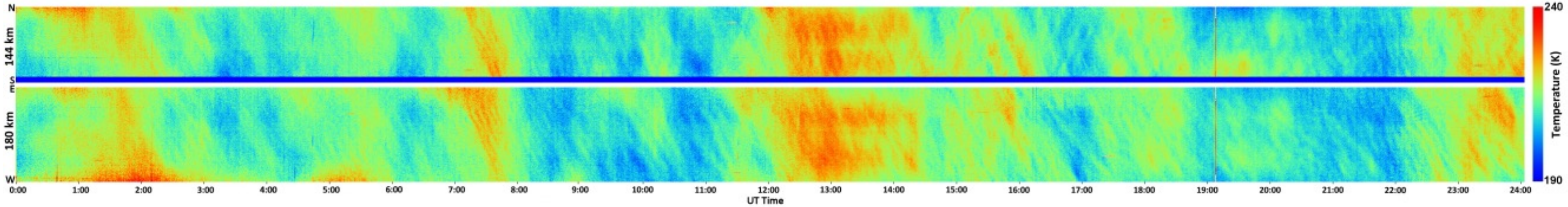
AMTM Data Products



Long term temperature evolution of Planetary Waves

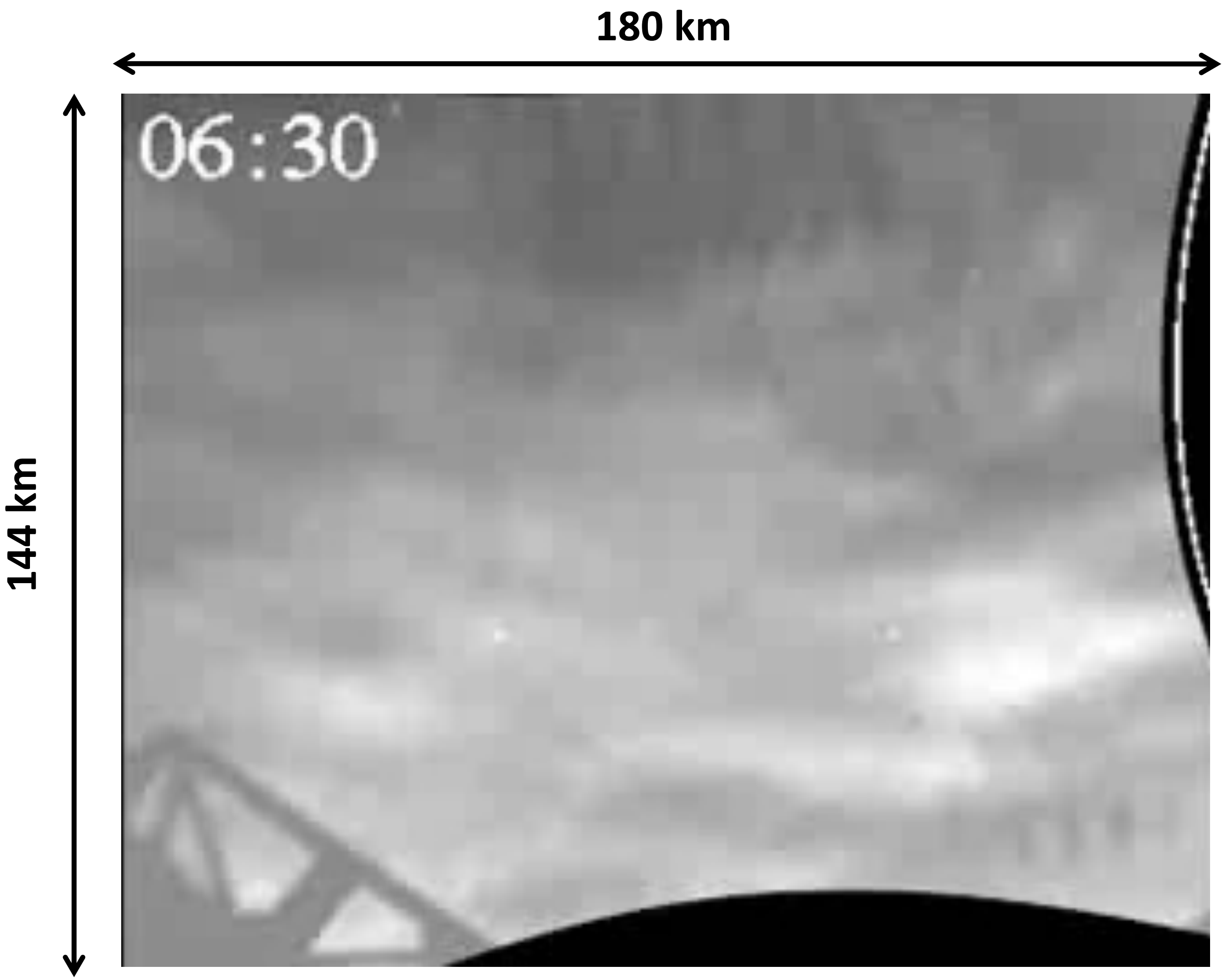


Temperature/Intensity maps
Short-period GWs/Wave breaking



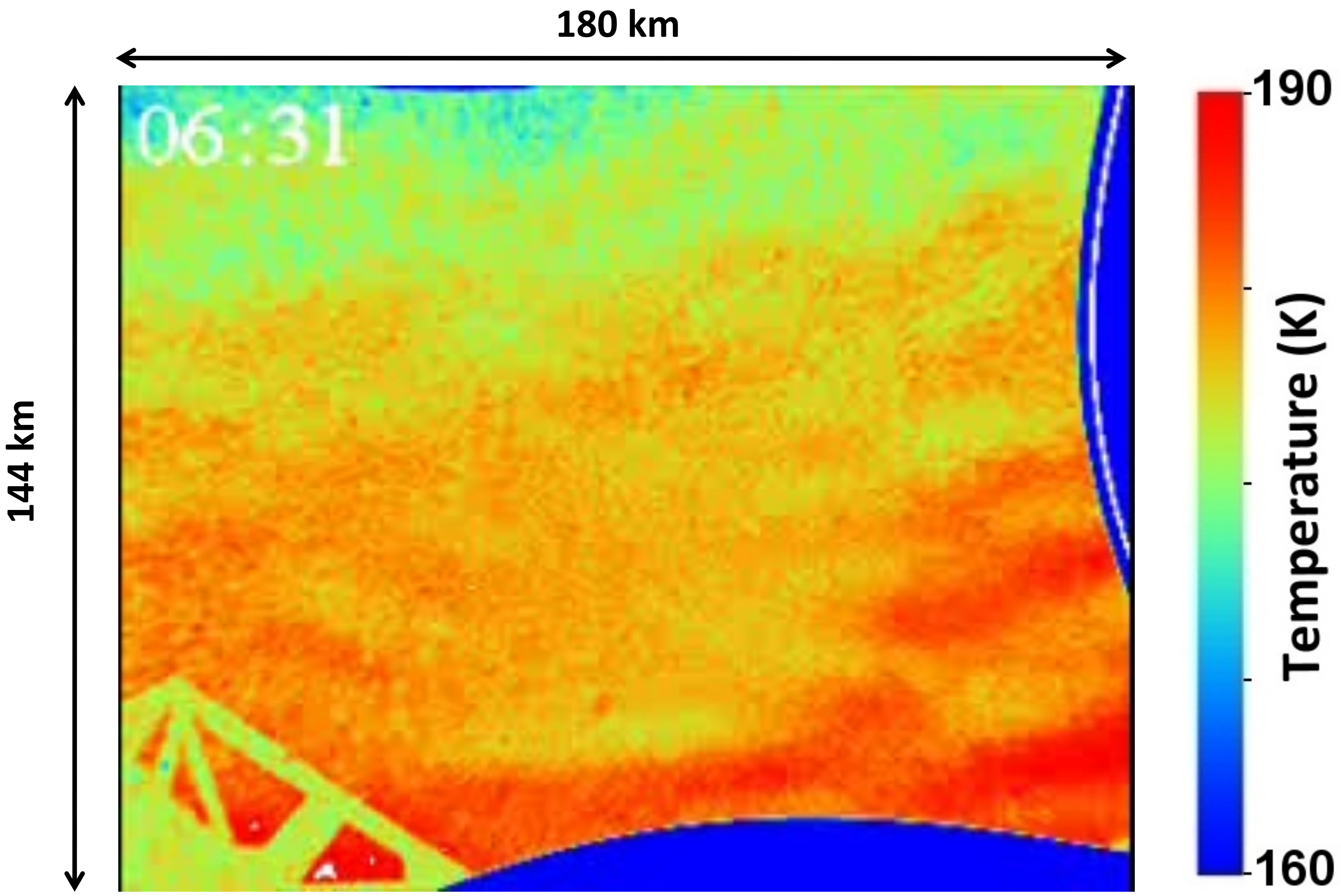
Keograms - 1-12hrs waves/tides

AMTM: Gravity Wave Breaking Event - Brightness
Jun 06th, 2013, Logan, Utah (41.7°N)



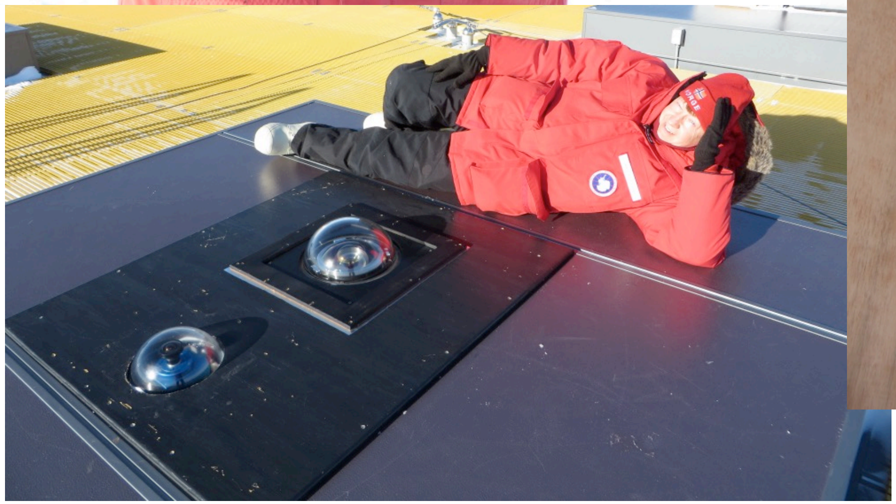
$P_1(2)$ line of the OH (3,1) emission – Exposure time 10s – 1 image every 30 s

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

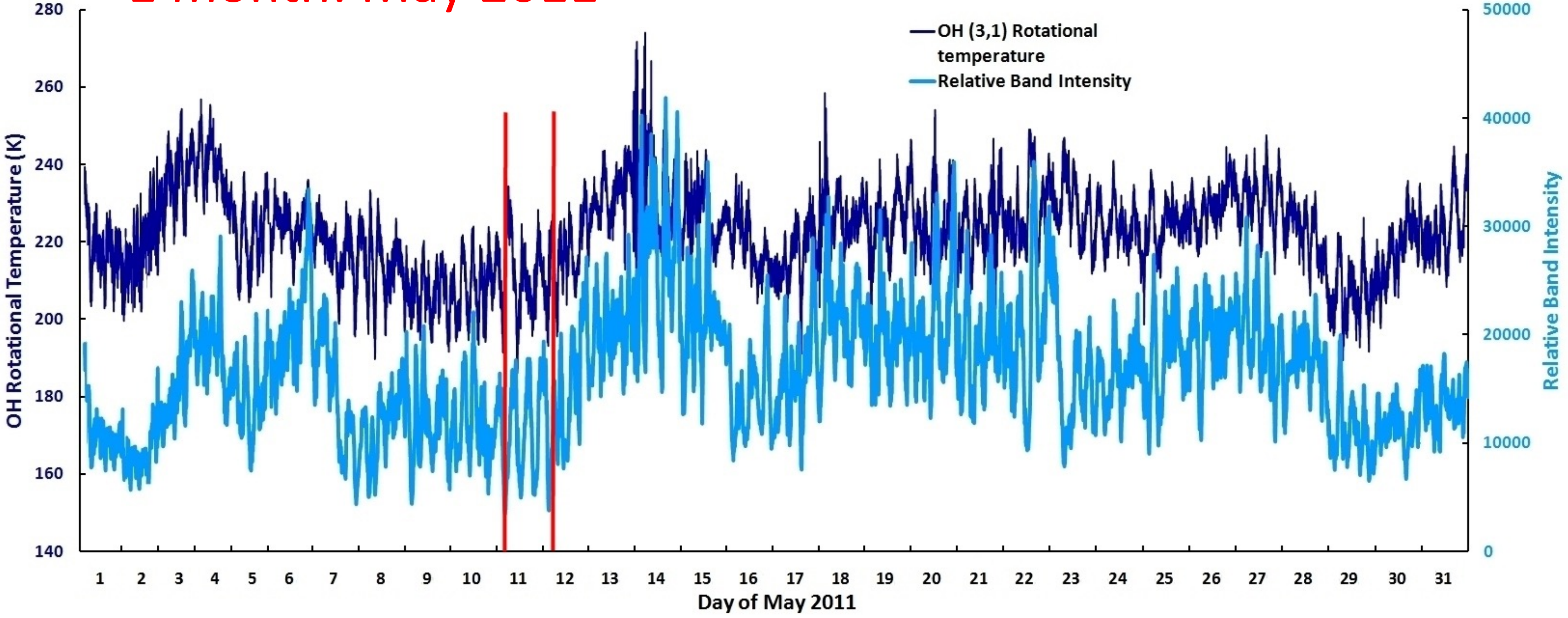


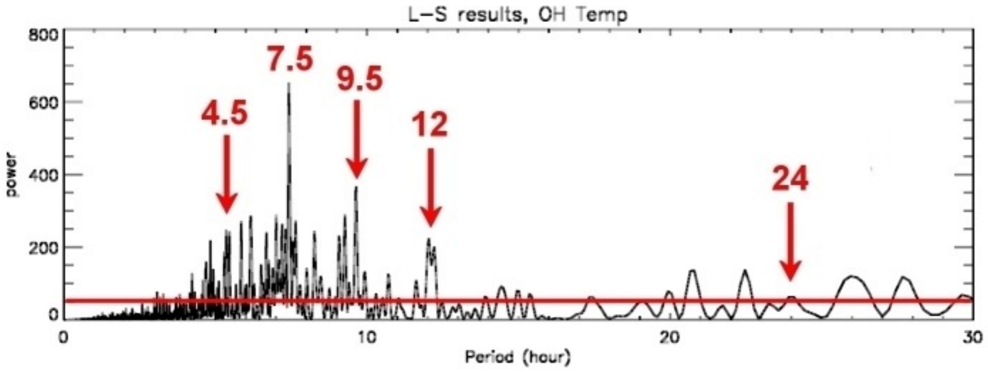
Antarctic Atmospheric Waves Research

- First collaborative project with British Antarctic Survey (2000-2011)
- South Pole AMTM (2010-to date)
- **AN**tarctic **G**ravity **W**aves **I**nstrument **N**etwork (**ANGWIN**, 2012-to date)

Non-Stop AMTM Temperature Measurements at South Pole

1 month: May 2011

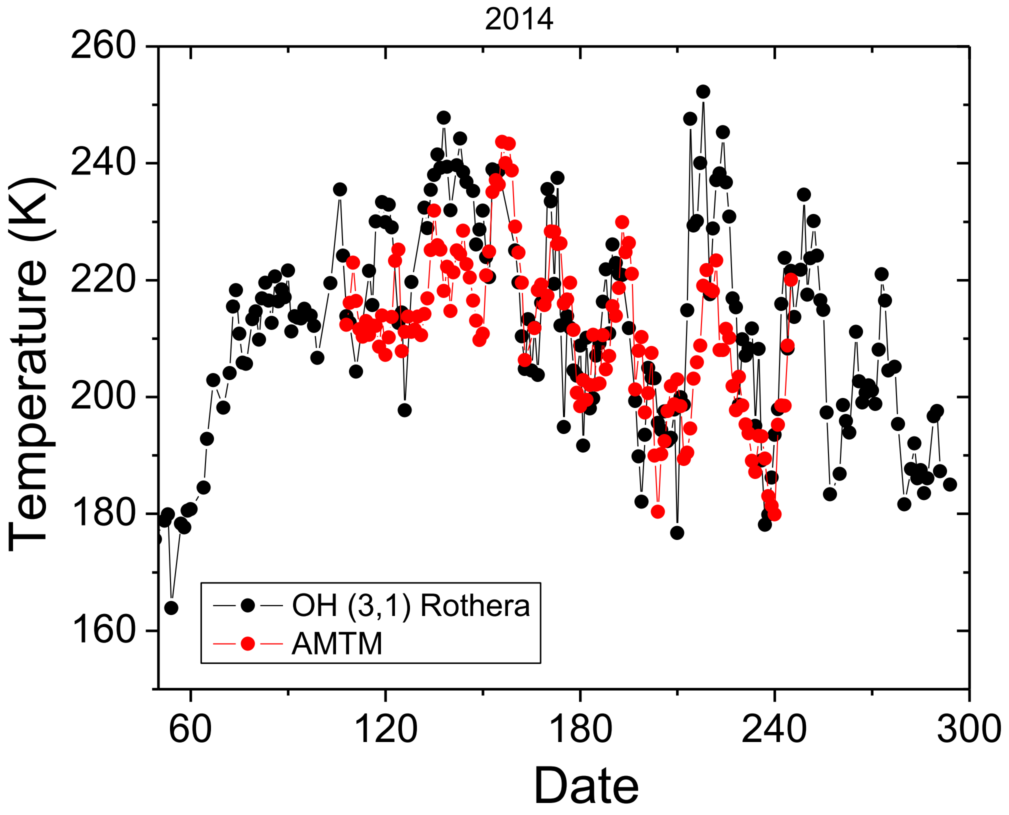


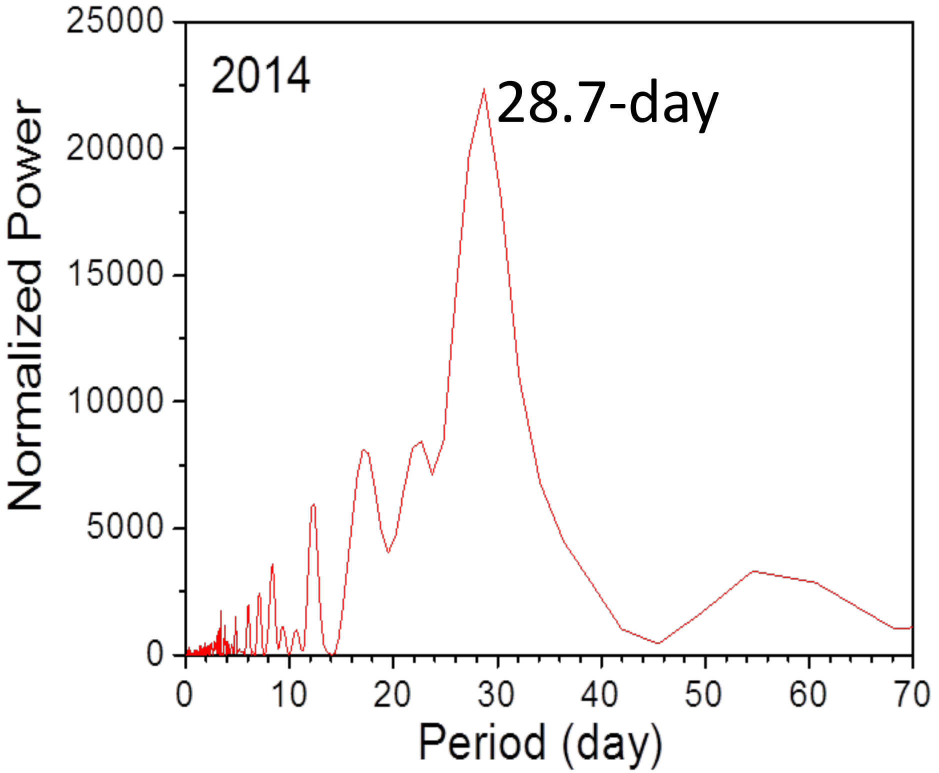


- Continuous large oscillations (>10K) due to tidal and/or planetary wave perturbations
- Estimated error ~1K

South Pole 2014: Large Amplitude Planetary Wave

24-hr average temperatures





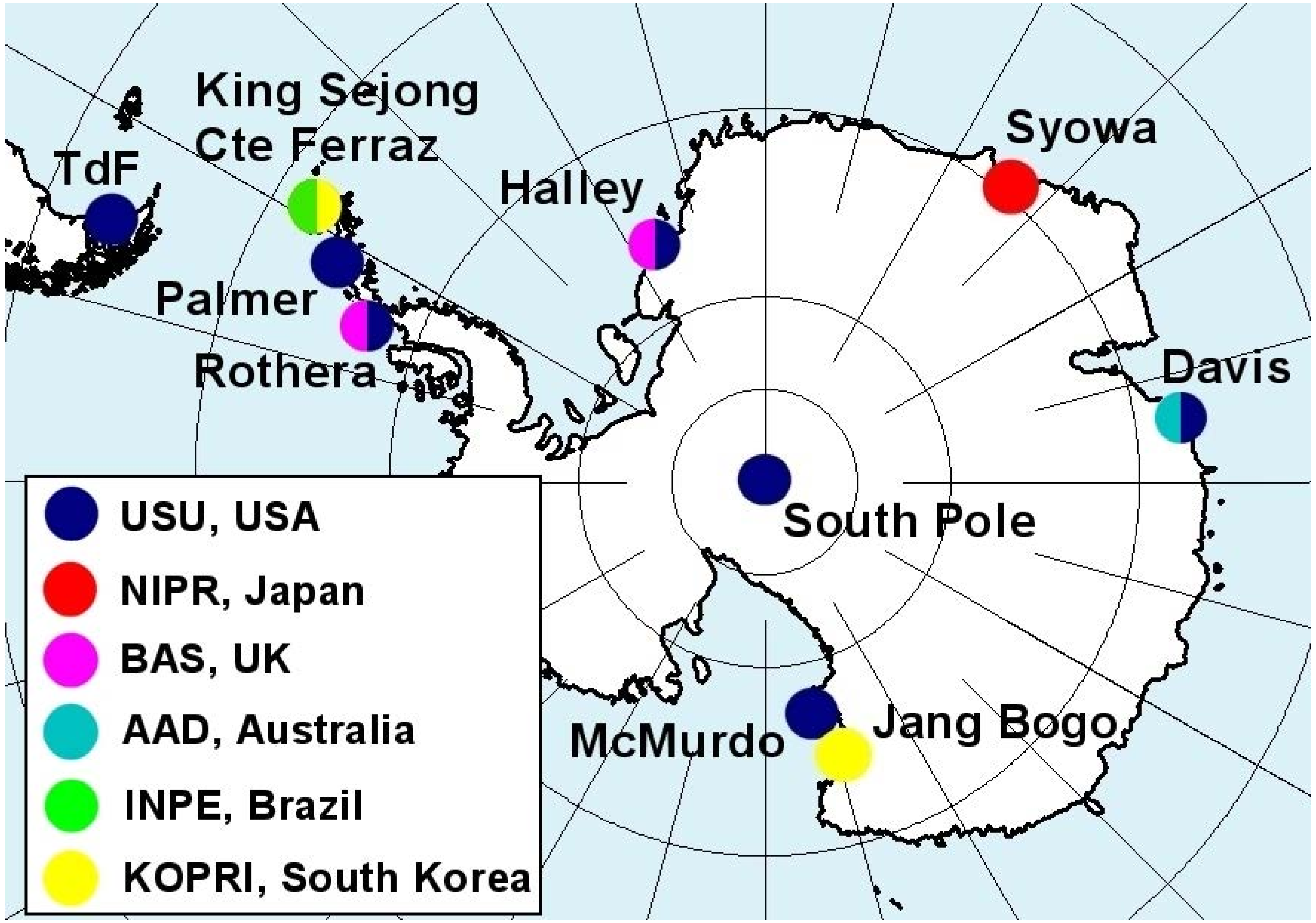
- Large coherent oscillations starting in June (~day 150)
- ~ 4.5 cycles observed
- Max amplitude ~12K
- Rossby PW (1,4)

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 Stations

ANGWIN Workshops

NIPR, Japan, 2013

USU, USA, 2014

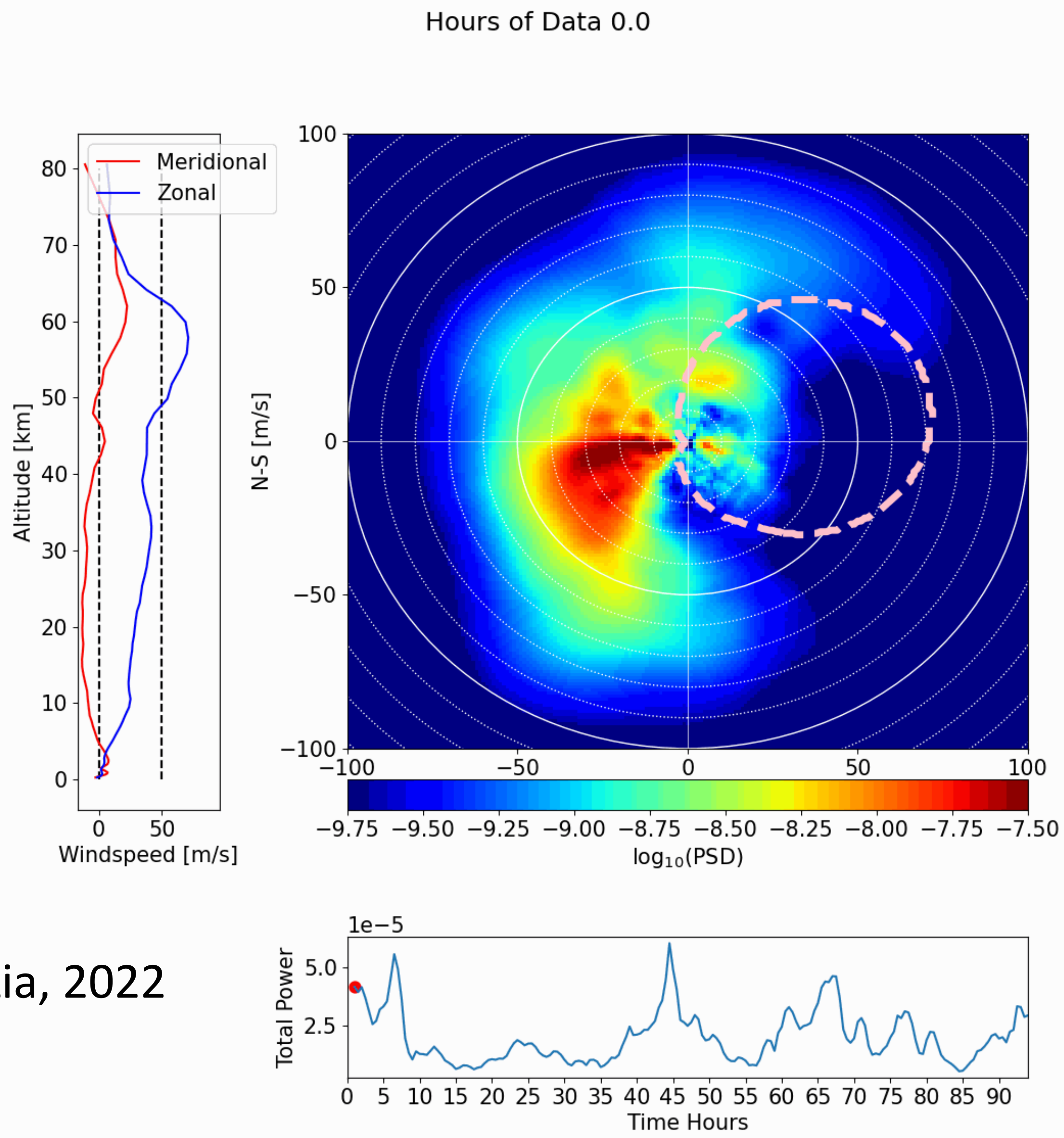
BAS, UK, 2016

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)

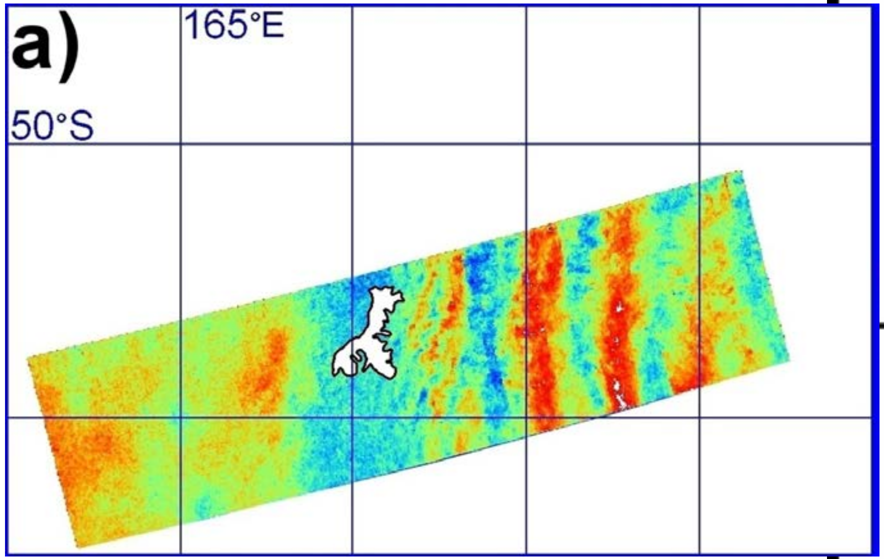
Rayleigh and Na lidars:

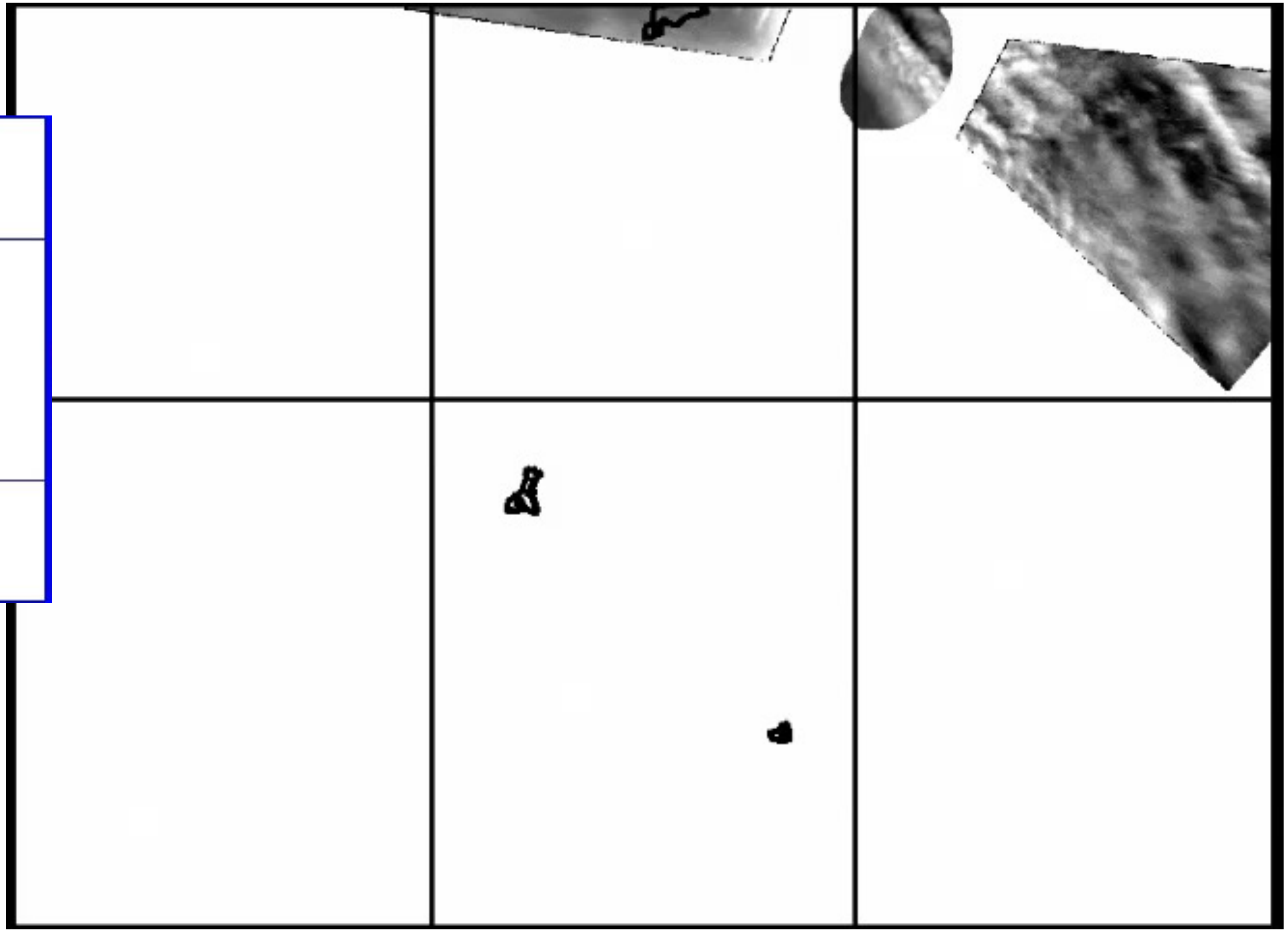
Density and temperature
20-60 km and 75-100 km

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

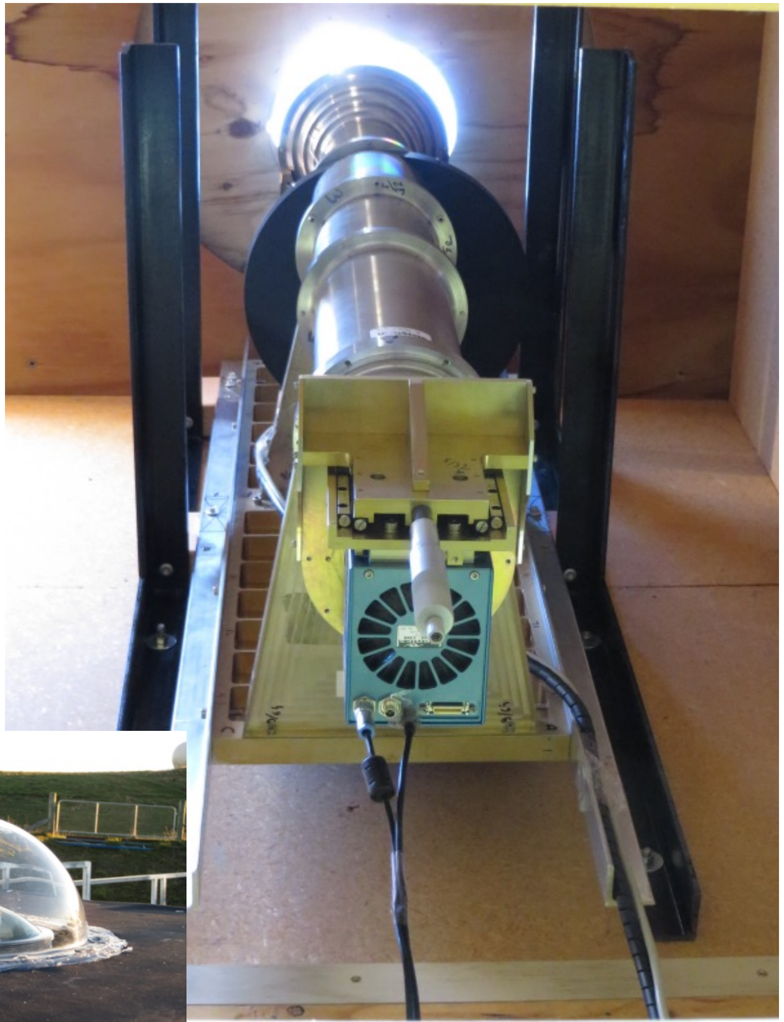




Auckland Islands
Maximum altitude 660 m

Pautet et al., 2016; Eckermann et al., 2016

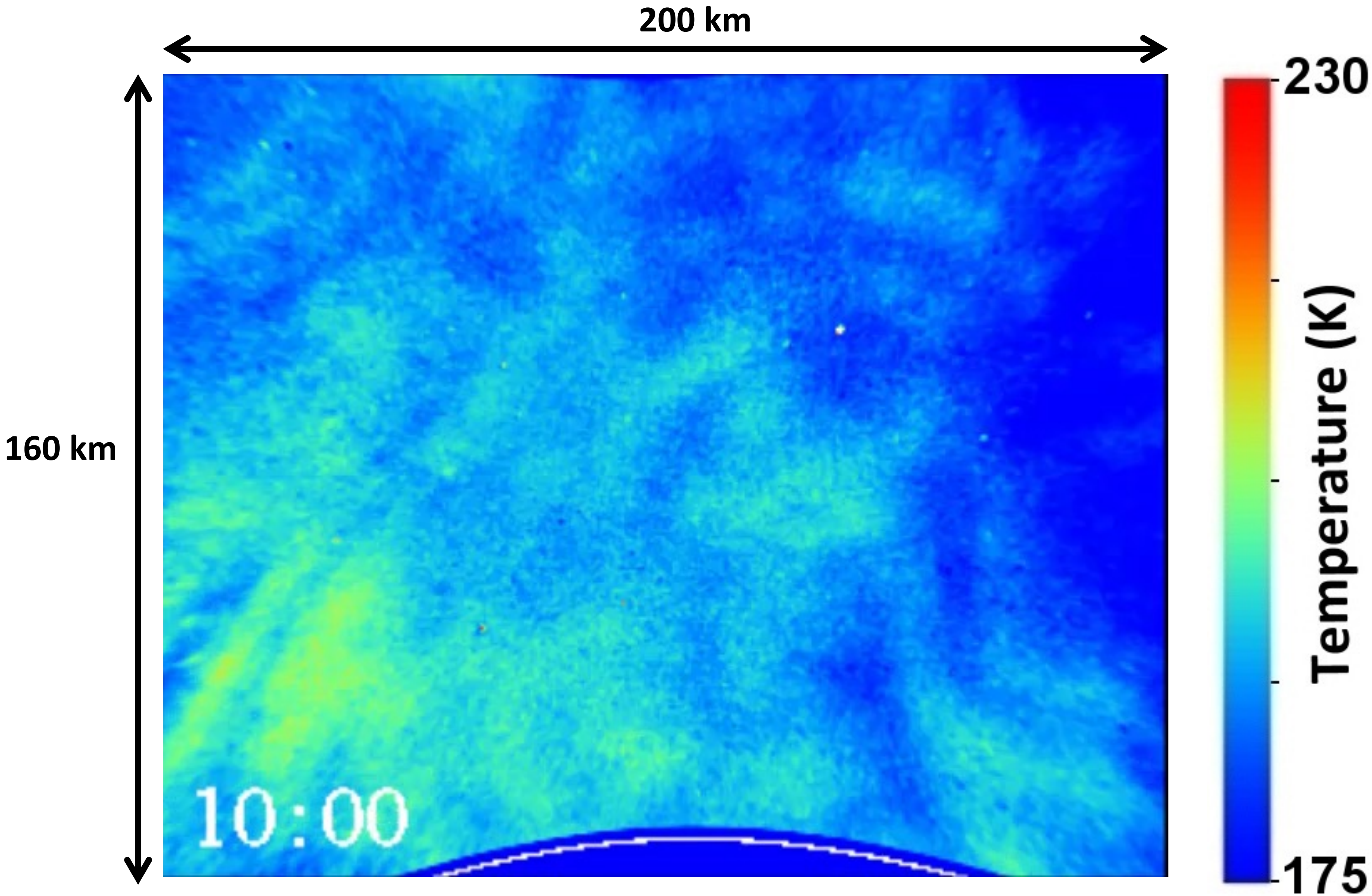
Ground-Based AMTM Measurements Lauder Observatory (45.0°S)



One zenith-looking mesospheric temperature mapper

- **FOV 120°**
- **1 temperature map every ~30s**

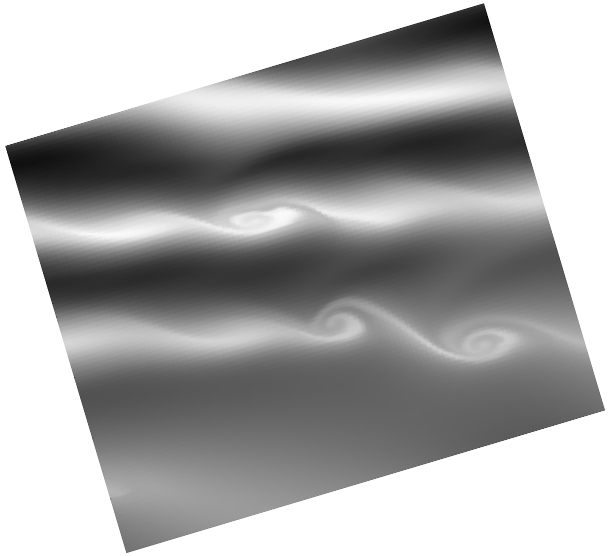
AMTM Mountain Wave Temperature Movie, Jun 21-22, 2014 (5hrs)



Taylor et al., 2019

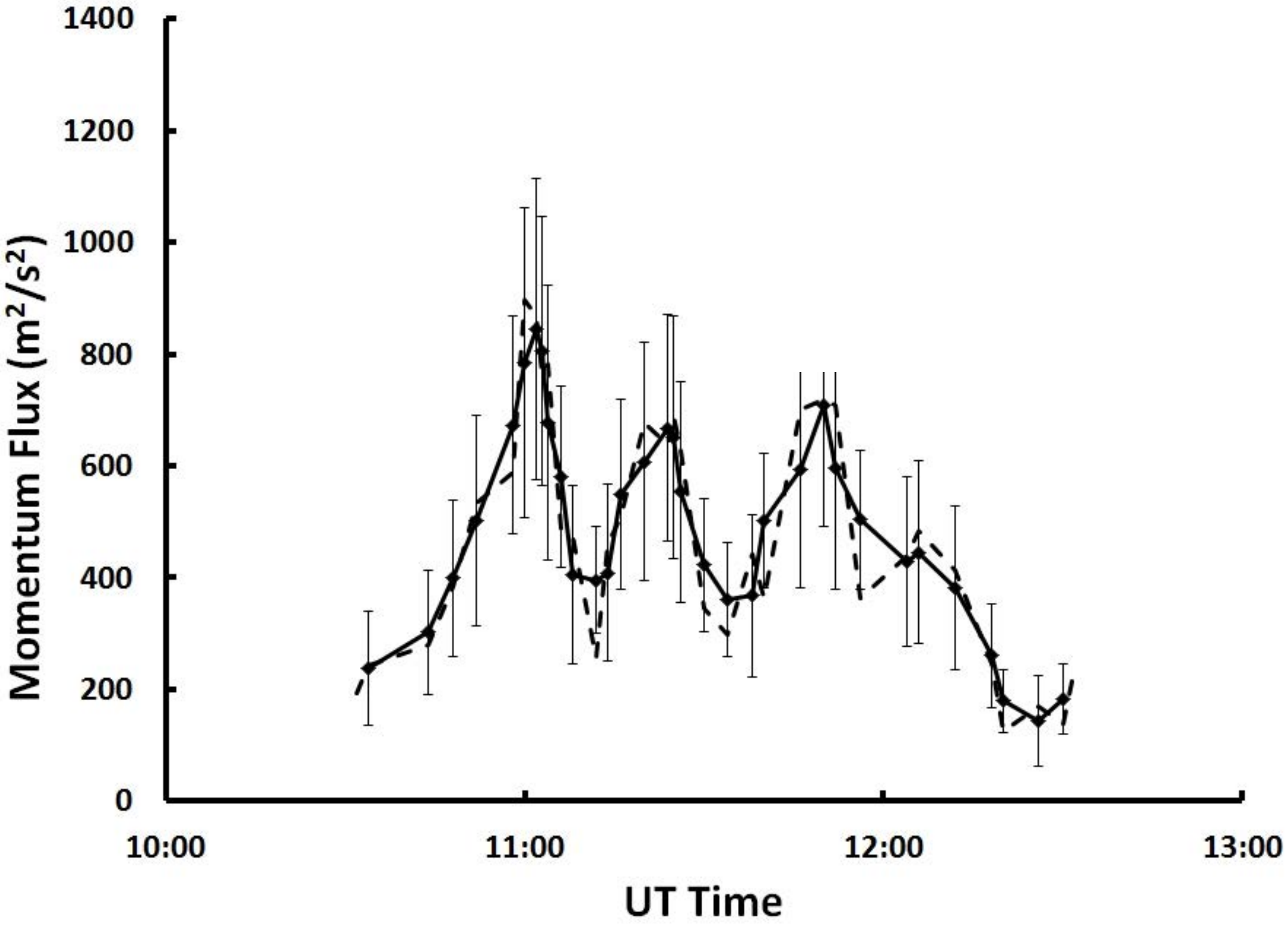
$\langle u'_h w' \rangle > 300\ m^2/s^2$

Wave Overturning

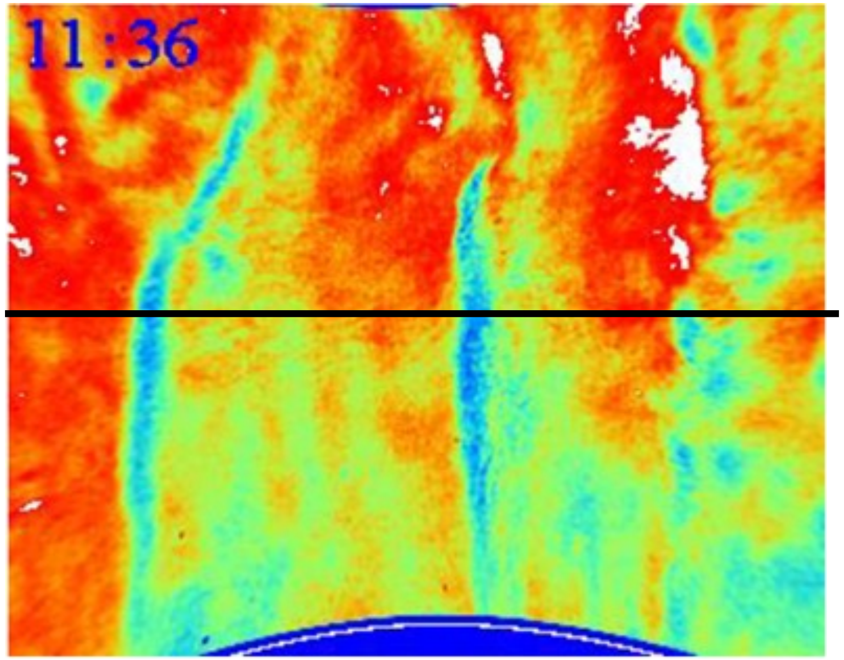


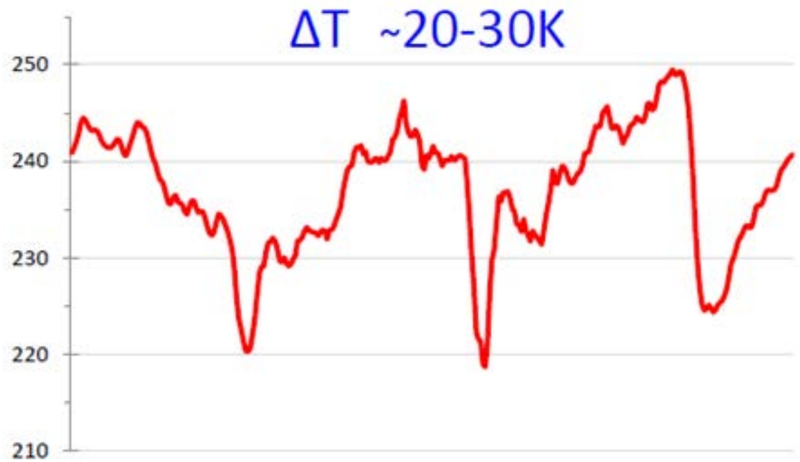
Courtesy J. Snively

Mountain Wave and Momentum Flux Variability
June 21-22, 2014



MF oscillation with a ~30-min period





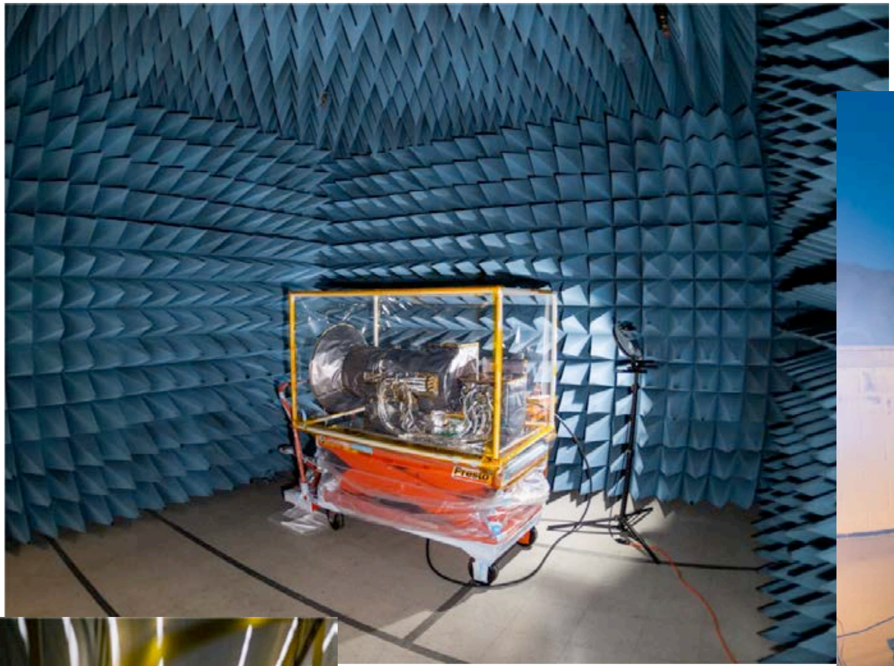
Taylor et al., 2019

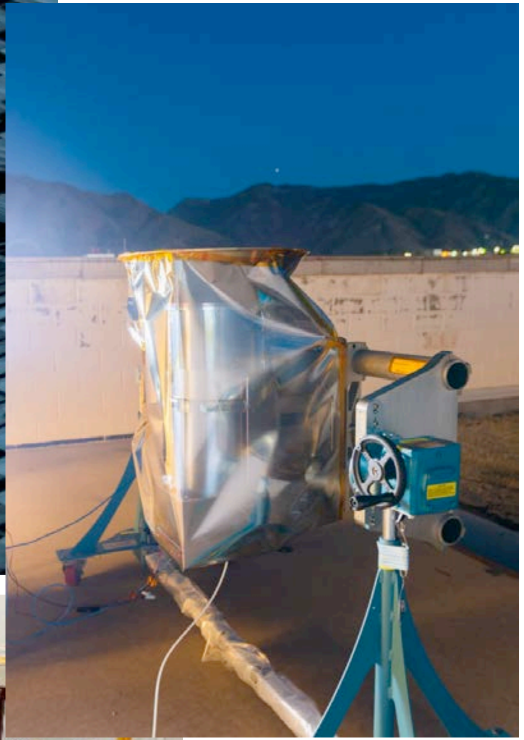
Atmospheric Waves Experiment (AWE)

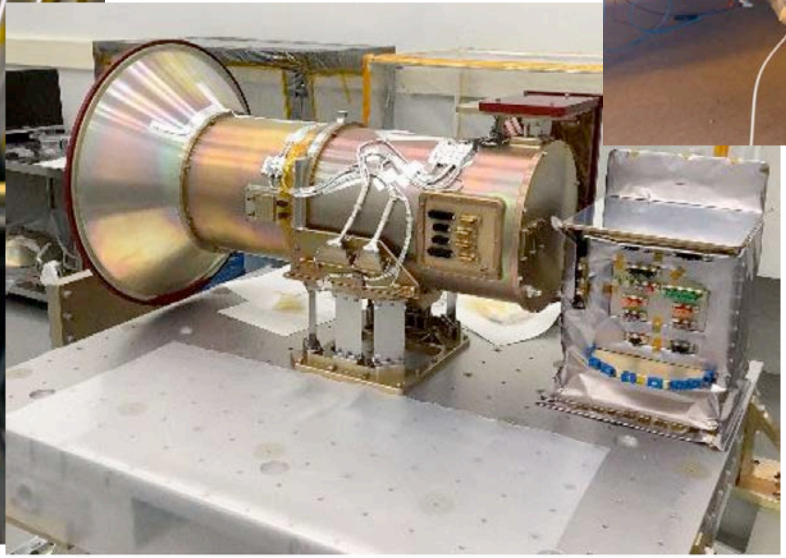
AWE is the first dedicated NASA mission to investigate global gravity wave properties in the upper atmosphere and their impacts on the ionosphere-thermosphere-mesosphere (ITM)

How does tropospheric weather influence space weather?

AWE AMTM - Glamour Shots

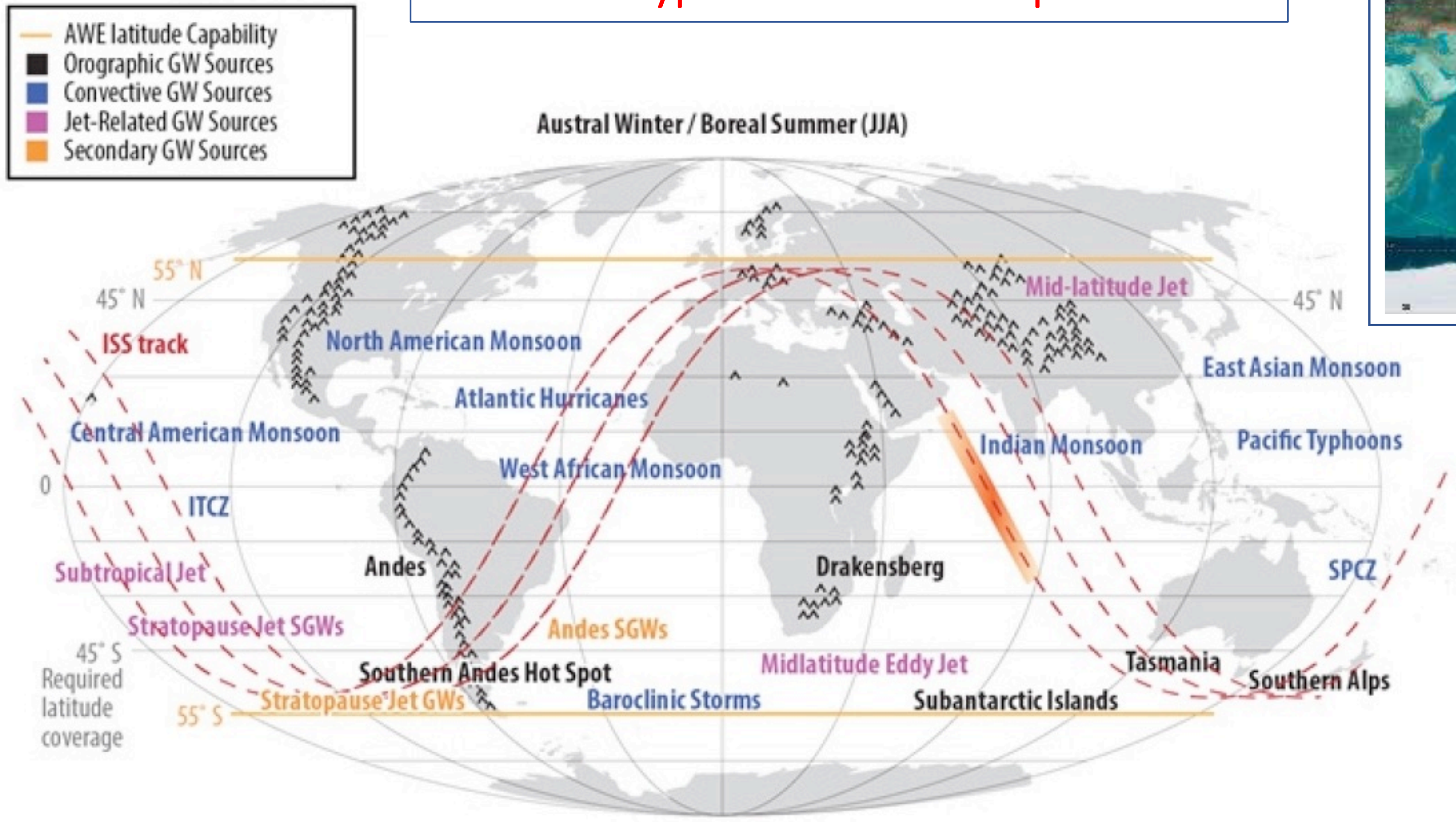




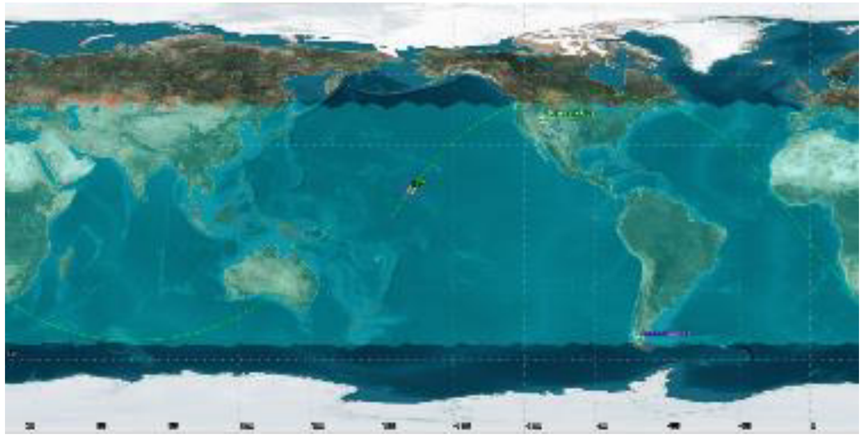


Global GW Sources

All source types in both hemispheres



~85% global coverage



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

40+ Years of Studying Atmospheric Phenomena

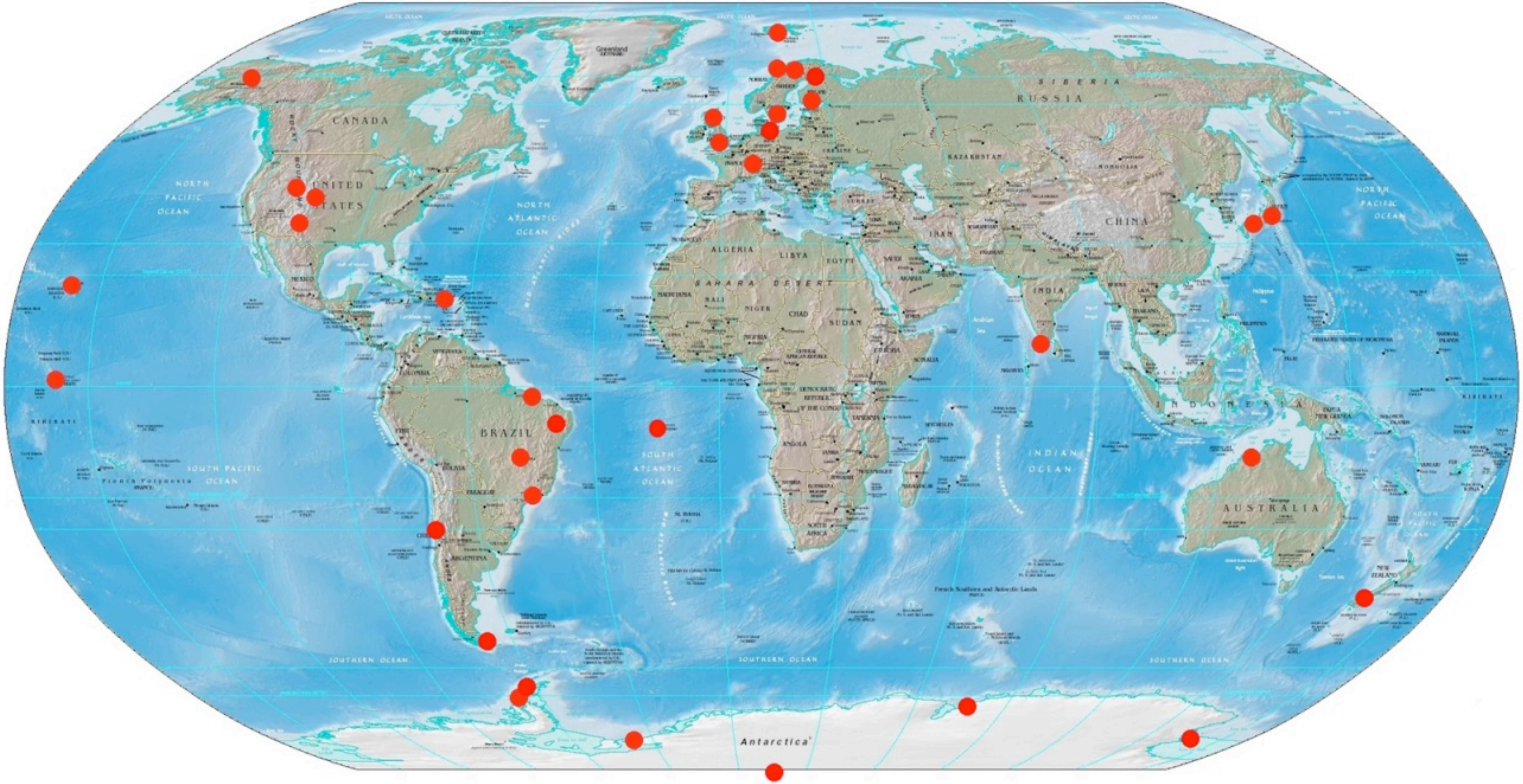
Projects related to gravity waves

- 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)
- Yucca Ridge sprite campaign, Colorado, 1995, 1997/98
- 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!




Utah State
UTAH ST