The Deep-Propagating Gravity Wave Experiment (DEEPWAVE): A Comprehensive Airborne and Ground-Based Measurement Program Based in New Zealand in 2014

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A long history of airborne mountain wave studies

The earliest MW studies employed balloons and gliders in N. Africa and Europe (Queney, 1936a,b; Küttner, 1938, 1939; Manley, 1945)

The Sierra Wave Project (1951-2 and 1955)

- 1951-2 phase used only gliders, 1955 phase also employed powered aircraft
- led to key theoretical advances (Queney, 1947; Scorer, 1949; Long, 1953, 1955)

Mountain wave studies over the Rockies – (Lilly, Kuettner, and colleagues, 1968-1982)

- NCAR, other aircraft, new in-situ instrumentation, vertical profiling

Many more recent studies used research and commercial aircraft (ALPEX, FASTEX, GASP, MAP, PYREX, SOLVE, T-REX, others)
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But new satellite & ground-based data also revealed MW penetration to much higher altitudes

Eckermann and Preusse (1999), Smith et al. (2009)
DEEPWAVE plan – characterize Gravity Wave propagation and dynamics from their sources to regions of dissipation - airborne & ground-based measurements over major source "hotspot"
GV sodium and UV lidars

Na lidar: ~0.2 W & 9.8 W beams
- $\rho_{\text{Na}}(z)$ and $T(z)$ ~75-105 km
UV lidar: ~5 W pulsed
- densities & temperatures ~20-60 km

Advanced Mesosphere Temperature Mapper & "Wing" cameras

- AMTM: vertical viewing, $T'(x,y)$ along track
- IR Wing cameras to achieve ~900 km cross-track imaging of GWs at ~85 km
DEEPWAVE also employed extensive GB instrumentation

primary instrumentation on NZ South Island

also new Rayleigh lidar and meteor radar on Tasmania specifically to support DEEPWAVE

- 449 MHz BL radar (NCAR)
- Radiosondes (NCAR, DLR)
- MLT airglow imagers (BU)
- MLT FPI (UW)
- MLT AMTM (USU)
- Na Rayleigh lidar (DLR)

Rayleigh lidar, meteor radar, and radiosondes at Kingston, Tasmania (AAD, ATRAD)
DEEPWAVE measurement capabilities

GV sodium lidar $\rho_{Na}'(x,z) & T'(x,z)$ $\sim$75-100 km

GV AMTM $T'(x,y)$ $\sim$87 km

Rayleigh lidars (Lauder/NZ & Tasmania)

GV Rayleigh lidar $\rho'(x,z), T'(x,z)$ $\sim$20-60+ km

radiosondes

GV sodium lidar $w(x,z) \sim$15-30 km

GV in-situ V,T

MTP $T'(x,z)$ $\sim$8-20 km

drops sondes

DLR Falcon in-situ V,T & Doppler wind lidar

S. Alps
DEEPWAVE Flight Tracks

- multiple GV and Falcon flights targeted mountain waves over NZ, Tasmania, and Southern Ocean islands

- other flights targeted jet stream, frontal, and convective sources
South Island average GWD – 6-km WRF model

6-km WRF forecast of OGWD

\[ GWD = -\frac{1}{\rho} \frac{\Delta M F_x}{\Delta z} \]

SI average x-GWD (\(du/dt\)) [m/s/day]

-40 0 40

altitude (km)

May 24 June 01 June 10 June 20 July 01 July 10 July 20 July 30

"deep" events

RF12, 16, RF22

(very weak MW forcing – VERY strong responses in the MLT)

(Stratospheric MW breaking events)

airborne measurements

GB 21 June
Two flight legs over Mt. Aspiring:

- Leg 14: $z = 12.2$ km
- Leg 22: $z = 13.7$ km

RF12 (29 June) – strong cross-mountain flow - weak stratospheric flow, breaking at GV flight altitudes

WRF 6-km model:
- strong tropospheric response,
- MW breaking in lower stratosphere

$\lambda_h \approx 70$ km
$\lambda_h \approx 5-15$ km

$u' > -U$, => overturning
RF12 – MWs seen at flight level extend into the thermosphere

- apparent propagating MWs at \( \lambda_h \approx 20-70 \) km over terrain
- trapped lee waves at \( \lambda_h \approx 5-15 \) km over and leeward of terrain
- breaking in stratosphere reduces MW amplitudes
- further breaking in the mesosphere
- influences extend into the thermosphere

Temperature Jun29 RF12

Sodium Mixing \( \times 10^{-14} \) RF12
RF16 (4 July) – strong MW forcing, weak stratospheric winds

WRF forecast:
- strong MW forcing at scales ~30+ km scales
- MW breaking in weak stratospheric flow
- significant secondary GWs ~25-30 km

Rayleigh lidar reveals:
- weak GWs at ~20-30 km
- both westward and eastward-propagation over terrain > 25 km
- amplitudes increase rapidly above ~30 km
RF16 – strong strat. winds enable penetration to high alts. - \( \lambda_h \sim 30-100 \text{ km} \) MWs with large-amps./MFs in the MLT.
RF22 (13 July) – weak forcing

- predicted very weak MWs in WRF and other models at lower altitudes
- flight-level measurements reveal \( \lambda_h \sim 30-60, 120-250 \text{ km} \)
- Rayleigh lidar shows \( \sim 240 \)-km MW growing strongly in altitude, \( \lambda_z \) increasing as \( U(z) \) increases, addit. GWs >50 km
- ECMWF captures \( \lambda_h \sim 240 \) km MW, under-estimates \( T' \) by \( \sim 2-3 \) times
RF22 – MLT responses
- AMTM/IR Cam Keogram show $T' \sim 10-25$ K, $\lambda_h \sim 30-240$ km
- $\rho_{Na}/\rho$ show
  - MWs have $\delta z \sim 1-3$ km, $\Rightarrow \lambda_z \sim 15-20$ km
  - secondary GWs above breaking region

- $\lambda_h \sim 25-80$ km dominant in MLT

(apparent MW breaking $\Delta z > 8$ km)

MW critical level $\sim 90$ km
RF22 – UKMO UM 2-km mesoscale simulation to 80 km (S. Vosper)

- MWs at 58 km have
  - \( u' \sim 25 \text{ m/s} \), \( w' \sim 2-10 \text{ m/s} \),
  - \( T' \sim 10-25 \text{ K} \),
  - \( \lambda_h \sim 25-240 \text{ km} \),
  - \( \lambda_z \sim 15-30 \text{ km} \)

- momentum flux varies as \(<u'w'> \sim u'T'\) (so peaks at intermediate scales)
RF23 (14 July) – Auckland Is. MW event
- moderate forcing over a small island

- first observation ~7 UT
- evolved and decayed over ~4 hr
- $dz \sim 2-3$ km, $T' \sim 20-30$ K
- peak $\langle u'w' \rangle \sim 300$ m$^2$/s$^2$
21 June – Large-Amplitude MWs

- apparently transient event ~1 hr
- scales vary from ~12 to 80 km
- "sawtooth" $T(x) \Rightarrow$ strong overturning at ~87 km
- dominant MWs at ~85 km have $\delta z > 2 \text{km}$, $T' \sim 20 \text{K}$, $T \sim 210 \text{K}$, $N \sim 0.02 \text{s}^{-1}$, $\lambda_h \sim 65 \text{km}$, $\lambda_z \sim 20\text{–}32 \text{km}$
  $\Rightarrow <u'w'> \sim 400 \text{ m}^2\text{s}^{-2}$ or greater
- MWs seen by AIRS for ~4 days
- MW response is larger than NZ
Summary

- MWs achieved large amplitudes and fluxes in the stratosphere and MLT:
  - weak forcing enables "linear" propagation, very large amplitudes in the MLT
  - large MW amplitudes and/or weak winds yield breaking in the stratosphere, but continue propagating with smaller amplitudes
  - MW breaking (stratosphere or MLT) yields strong 2ndary GW generation

- the largest momentum fluxes accompany smaller horizontal scales
  - $\lambda_h < 100$ km dominate MLT fluxes during DEEPWAVE
  - local fluxes are often ~10-100 times mean values
    => stratospheric "hotspots" also extend much higher

- GWs from jet streams & fronts have larger $\lambda_h$, also penetrate to high altitudes

- larger-scale GWs modulate the propagation of smaller-scale GWs

- high-resolution global and regional models often do a good job of predicting the gross features of the observed responses, under-estimate amplitudes

- our field team of >100 researchers and support staff did a great job!
DEEPWAVE papers to date


Eckermann et al. (2016), Dynamics of orographic gravity waves observed in the mesosphere over the Auckland Islands during the Deep Propagating Gravity Wave Experiment (DEEPWAVE), J. Atmos. Sci., in press.


- others in progress …