“Gravity Wave Diagnostics and Characteristics in Mesoscale Fields”

Christopher G. Kruse and Ronald B. Smith
Accepted to JAS with major revisions

• Describes nearly the same method to compute energy fluxes used in forecasts during DEEPWAVE

• Includes method verification and analysis of four gravity wave events:
  – Deep propagating (40+ km) mountain waves
  – Attenuated mountain waves
  – Southern Ocean jet generated gravity waves
  – Tasman Sea convection generated gravity waves

• Will gladly share a copy of the current manuscript
New Zealand Mountain Waves and Attenuation Within WRF

Christopher Kruse
and
Ronald Smith
Outline

1. 6-km WRF “Long Run” Verification

2. Dominant Wave Scales in RF04, RF09 According to 2-km WRF

3. Mountain Wave Attenuation/GWD in 6-km WRF
   – Compared with MERRA reanalysis param GWD

Future Work: Effects of Lower Stratospheric GWD
WRF Setup

• Long Run
  – 6-km Resolution, 110 vertical levels, top at ~45 km
  – 24 May – 31 July 2014
  – Continuous Simulation: only initialized twice within that period
  – Only forced through boundary conditions (BCs)
  – BCs provided by ECMWF analysis grids every three hours
  – Output frequency: 3 hr

• Event Runs
  – 6-km domain forced by ECMWF, 2-km nest
  – 150 vertical levels, top at ~45 km
  – 30 hour simulations
  – Output frequency: 1 hr
Wind Profiler/Long Run Comparison

\[ z = 1 \text{ km} \]

- 3 hour running avg smoothed profiler measurements (solid)
- Instantaneous WRF Long Run winds at same \( x, y, z \) (dashed)
Hokitika Sounding/Long Run Comparison

- WRF horizontally averaged over 60x60 km area (blue)
- ISS sounding measurements vertically averaged over 2 km depth (circles)
Hokitika Soundings: Long Run vs. Obs

- WRF horizontally averaged over 60x60 km area (blue)
- ISS sounding measurements vertically averaged over 2 km depth (circles)
ISS Soundings: Z vs. $R^2$

- Linear fit $R^2$ value as a function of height

- Why poor agreement between 15-20 km?
  Poor representation of frequent wave breaking there?
Aircraft/Long Run Comparisons

• Interpolated 6-km Long Run parameters to every aircraft measurement in space and time
  – Via 4-D linear interpolation
  – “Flight through the model” for all RFs

• Allows “apples to apples” comparisons
Leg Comparisons: Good

RF13, Leg 19
6-km WRF

RF16, Leg 3
Leg Comparisons: Bad

NGV
6-km WRF

RF05, Leg 15

RF12, Leg 10
Leg Comparisons: Phase Shifted

NGV

6-km WRF

RF05, Leg 4

RF05, Leg 5
Aircraft/Long Run Wind Comparison

Leg Averaged Quantities

- $y = 1.029 \times R = 0.966$
- $y = 1.028 \times R = 0.982$
- $y = 1.034 \times R = 0.958$
Aircraft/Long Run Run EFz Comparison

Leg Averaged Quantities

Leg Average EFz [W m^-2]

NGV 6-km WRF

May24 Jun01 Jun10 Jun20 Jul01 Jul10 Jul20 Jul31
Aircraft/Long Run EFz Comparison

Leg Averaged Quantities

\[ y = 0.946 \times \]
\[ R = 0.701 \]
Long Run Verification Summary

• Background winds are well represented within the Long Run
  – Probably do not change quickly

• Leg avg $EF_z$ quite variable within events (observations even more so)
  – Not be predictable

• WRF has some skill in predicting event mean leg avg $EF_z$

• Long Run is currently available in the DEEPWAVE data archive
2. Dominant Wave Scales

- What are the dominant flux carrying wavelengths according to 2-km WRF?
- Are there important long wavelengths not resolvable with the ~400 km DEEPWAVE legs

Method:
- Calculate $EF_z$ wavelet co-spectra east-west over model domain (~1000 km)
Observed Scales

$z = 12 \text{ km}$
Simulated Scales: RF04 Snapshot

12 km

PW Wavelet Cospectrum at 2014061412

2-km WRF
Avg $\text{EF}_z$ Cospectrum: RF04

12 km Avg PW Wavelet Cospectrum on 20140614

Wavelength [km]

Terrain [km]

Distance [km]

2-km WRF
RF09 Snapshot

12 km Mt. Cook PW Wavelet Co Spectrum at 2014062406

Distance [km]

Wavelength [km]

Terrain [km]

2-km WRF
RF09 Snapshot

12 km Mt. Cook PW Wavelet Cospectrum at 2014062407

2-km WRF
RF09 Snapshot

12 km Mt. Cook PW Wavelet Cospectrum at 2014062409

Distance [km]
Avg $\text{EF}_z$ Cospectrum: RF09

12 km Mt. Cook Avg PW Wavelet Cospectrum on 20140624
Avg $E_{F_z}$ Co-spectrum: RF09

20 km Mt. Cook Avg PW Wavelet Co-spectrum on 20140624

Distance [km]

Terrain [km]

Wavelength [km]

2-km WRF
Scale Summary

• Important flux carrying wavelengths within 2-km WRF range from 20-250 km
  – Depends on event (and maybe transect location)
  – Long wavelengths in aircraft wavelets also in WRF

• Longer aircraft legs would not reveal longer wavelength fluxes according to WRF

• Wave fluxes above attenuation regions seem random, do not resemble waves below
  – Will better quantify spectral changes through attenuation layers
3. Mountain Wave Attenuation

Attenuation and GWD

Gravity Wave “Valve Layer”?

-0.03 N m$^{-2}$

MF$_x$ Isosurface
South Island Avg MF$_x$ Divergence

6-km WRF

d(MFx)/dz [N/m2/km]

- Fluxes computed using 2-D filtering method proposed by Kruse and Smith 2015 (Accepted with revisions to JAS)
South Island Avg GWD Acceleration

6-km WRF

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

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

RF04
RF09
“Valve” Events
Deep Events

Valve Layer

Time Avg Profile

May 24, Jun 1, Jun 10, Jun 20, Jul 1, Jul 10, Jul 20, Jul 31

-40 -30 -20 -12 -10 -8 -4 -2 0 2 4 8 12 15 20 30 40
6-km WRF/MERRA GWD Comparison

6-km WRF

MERRA GWD

McFarlane 1987 OGW Param
Valve Layer Summary

• Enhanced attenuation frequent in 15-20 km region during 2014 winter
  – In both units of force and deceleration
  – “Valve Layer”

• MERRA parameterized GWD structure agrees well with 6-km WRF resolved GWD, though significantly underestimated
Future Work

• Lower stratospheric attenuation

Questions

• What is the mechanism of attenuation?
• How do wave spectra change through “valve layer”?
• Is PV conservation invalidated in attenuation regions?
Gravity Waves and PV

• Ertel PV conserved in linear gravity waves
  \[ PV = \frac{\vec{\omega} \cdot \nabla \theta}{\rho} \quad \frac{dPV}{dt} = 0 \]

• PV conservation invalidated in attenuation regions?
  \[ \frac{dPV}{dt} = f(Turbulent \ Heat, \ Momentum \ Fluxes) \]

• Are PV banners generated?
  – I.e., PV generated via local GW attenuation, advected conservatively from there?
RF09 x-GWD Deceleration

RF09 SI Average x-GWD (du/dt) [m/s/day]

Height

18 21 0 3 6 9 12 15 18 21 0

15 12 9 6 3 0

5

28 24 20 16 12 8 4 0 2 4 8 12 16 20 24 28

2-km WRF
RF09 x-GWD Deceleration
WRF/Obs Leg Avg EFz Comparison

Area Average EFz [W m$^{-2}$]

Leg Average EFz [W m$^{-2}$]

May24  Jun01  Jun10  Jun20  Jul01  Jul10  Jul20  Jul31

Legend:
- Blue: 30 km
- Red: 12 km
- Black: 4 km
Extra: RF04 WRF/AIRS Comparison

2 hPa Satellite Observed $T'$
13:19 UTC

2014.06.14 Descending 2 hPa

Steve Eckermann, NRL

2 hPa Simulated $T'$
(High-Passed $T$, L = 500 km)
13:00 UTC

Height Contours: 39600 to 41600 by 200

Temperature High-Passed at L = 500 km (K)
EF$_z$ Transience?

Leg Average EF$_z$

Terrain
Method Verification

- Energy and momentum fluxes quantitatively satisfy the Eliassen-Palm theorem:

\[ EF_z = -\overline{U} \cdot MF \]

(Eliassen and Palm 1961)
Method Verification

- Can also compute perturbation quantities by subtracting fields from a simulation with terrain from one without.
- Compared the two methods via the following ratio:
  \[ R = \frac{EF_{z_{filt}}}{EF_{z_{diff}}}, \]
- The two very different methods typically agree within 10%.