Recent Improvements to Resolved and Parameterized Gravity-Wave Dynamics in NAVGEM, the Navy’s Global Numerical Weather Prediction System

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DEEPWAVE Research Flight 23
14 July 2014

Outbound RF23 Flight Leg
Linear Three-Dimensional Fourier-Ray Gravity-Wave Model

\[ \hat{\omega}(k, l, z) = -kU(z) - lV(z) \quad k_h^2 = k^2 + l^2 \quad s(k, l) = -\text{sgn}[\hat{\omega}(k, l, 0)] \]

\[ m(k, l, z) = s \left[ \frac{(k^2 + l^2)(N^2 - \epsilon_n \hat{\omega}^2)}{\hat{\omega}^2 - \epsilon_r f^2} \right]^{1/2} \quad \epsilon_n = 1: \text{nonhydrostatic solutions} \]
\[ \epsilon_n = 0: \text{hydrostatic solutions} \]

\[ X(x, y, z) = \int\int_{-\infty}^{\infty} S(k, l, z) \hat{\tilde{X}}(k, l, z) e^{i(kx + ly)} \, dk \, dl . \]

\[ \hat{\eta}(k, l, z) = \hat{h}(k, l) \left[ \frac{c_{gz}(k, l, 0)\hat{\omega}(k, l, z)\rho(0)\mathcal{P}(0)N^2(0)}{c_{gz}(k, l, z)\hat{\omega}(k, l, 0)\rho(z)\mathcal{P}(z)N^2(z)} \right]^{1/2} e^{i\int_{0}^{z} m(k, l, \tilde{z}) d\tilde{z}} \]

\[ c_{gz}(k, l, z) = \frac{\partial \hat{\omega}}{\partial m} = \frac{-m(\hat{\omega}^2 - \epsilon_r f^2)}{\hat{\omega}[\epsilon_n (k^2 + l^2) + m^2]} \]

\[ t_{\text{prop}}(k, l, z) = \int_{0}^{z} c_{gz}^{-1}(k, l, z') dz' \]

\[ S_{\text{prop}}(k, l, z, t) = \begin{cases} 
1 & z \leq z_c(k, l, t) \ [t_{\text{prop}}(k, l, z) \leq t], \\
0 & z > z_c(k, l, t) \ [t_{\text{prop}}(k, l, z) > t], 
\end{cases} \]
NAVGEM Reanalyses for DEEPWAVE Austral Winter (T119L74 & T425L74)

- Top Data Level Assimilated Operationally
- MLS Water Vapor
- MLS Ozone
- Version 2.0 SABER Temperature
- SSMIS UAS Radiances
- The NGV Dropwindsonde Data Were Also Assimilated
- Reanalysis Upper Boundary $p_{\text{top}} = 6 \times 10^{-5}$ hPa
- Both Pure 4DVAR & Hybrid Ensemble 4DVAR Reanalyses
- Current Operational Upper Boundary

Graph showing pressure altitude (km) vs. pressure (hPa) with data levels and reanalysis components.
Modeled Wavefield Response in MLT Airglow 0700 UTC

\[ T_{AG}'(x, y) = \frac{\int I(z')T'(x, y, z')dz'}{\int I(z')dz'} \]

Airglow Temperature 0700 UTC: \( z = 78 \) km

165°E 170°E

\( z \sim 83.5 \) km

\( \sigma_z \sim 7.5 \) km

50°S

6:50-7:10
Maximum Wavefield Steepness in Fourier-Ray “Hindcasts”

(a) Maximum Steepness 2014071406 V2
Linear Model Succeeds

(a) Maximum Steepness Locations 0600 UTC

1  ○ ○  \( z = 76-79 \text{ km} \)

(b) Cutoff time (hours)

2  ▲ ▲ ▲  \( z = 66-68 \text{ km} \)

Terrain Elevation
Inbound RF23 Flight Legs
Inbound AMTM Imagery

(a) 165°E 170°E
50°S
9:45-10:10

(b) 165°E 170°E
50°S
10:15-10:50

(c) 165°E 170°E
50°S
11:05-11:25

(d) 165°E
50°S

(e) 165°E
50°S

(f) 165°E
50°S

temperature (K)
190 220
Upstream Reanalysis Winds

(a) Horizontal Wind Vectors

(b) Zonal Winds
Large Migrating Semidiurnal Tide in MLT Reanalysis at 51°S

NAVGEM Reanalysis Wind on $6.41 \times 10^{-3}$ hPa (~82km)

(a) Zonal Wind

(b) Meridional Wind
FR Modeled Breaking Heights

Fourier Solution Breaking Heights

Mean

height (km)

85
80
75
70
65

hours (UTC)

4
6
8
10

t = 2.5 hr

t = 3.0 hr

t = 4.0 hr

t = 5.0 hr

...
Time Evolution of Wavefields

(a) 0400 UTC: $z=78$ km

(b) 0600 UTC: $z=78$ km

(c) 0800 UTC: $z=78$ km

(d) 1000 UTC: $z=78$ km

(h) 0400 UTC: $z=78$ km

(i) 0600 UTC: $z=78$ km

(j) 0800 UTC: $z=78$ km

(k) 1000 UTC: $z=78$ km

$T(x,y,z,t_c)$, $t_c = 4$ hours

$u'w'(x,y,z,t_c)$, $t_c = 4$ hours
Huge MLT Driving Effects

- Offline calculation using linear saturation theory
- Layer-averaged mean flow accelerations $\sim -350 \text{ m s}^{-1} \text{ hour}^{-1}$
- Layer-averaged dynamical heating rates $\sim 8 \text{ K hour}^{-1}$
Conclusions

• RF23 supports important role of small subantarctic mountains to middle atmosphere momentum (and heat!) budget in austral winter (Alexander et al. 2009; McLandress et al. 2012; Alexander and Grimsdell, 2013)

• How does wavefield stay linear up to ~78 km before breaking?
  1. Spectral filtering of wavefield content (turning points & directional critical levels)
  2. Horizontal geometrical spreading of wavefields
  3. Nonhydrostatic downstream dispersion/spreading

=> Only nonhydrostatic solutions accurate: corresponding hydrostatic solutions are grossly inaccurate (parameterization implications)

• Huge MLT drag and heating rates (consistent with AMTM “warm up” in final overpass) with strong semidiurnal tidal modulation

• The “right” linear gravity-wave models CAN be accurate up to high altitudes right up to point of incipient wave breaking

BACKUP SLIDES
Model MLT Wavefields 0700 UTC

(a) Temperature 0700 UTC: $z=78$ km

(b) Airglow Temperature 0700 UTC: $z=78$ km
Inbound AMTM Imagery
Fr$^{-1} = N h_{max}/U_{tot} \sim 0.3$
14 July 2014 0600 UTC, $t_c = 4.0$ hours, $z = 78.0$ km

(a) Zonal Momentum Flux per unit Mass

$$\frac{u'w'(x,y,z,t_c)}{t_c = 4 \text{ hours}}$$

(b) Meridional Momentum Flux per unit Mass

$$\frac{v'w'(x,y,z,t_c)}{t_c = 4 \text{ hours}}$$
Model MLT Wavefields 1000 UTC

(a) Temperature 1000 UTC: z=78 km

(b) Airglow Temperature 1000 UTC: z=78 km
Linear Solution Approximations

\( \eta \quad z = 67 \text{ km} \quad t = 4 \text{ hr} \)
DEEPWAVE Model Measurement Comparison

RF25 GV Raleigh Lidar, MTP, and GV insitu Temperature Measurement

NAVGEM (t425l74m3) Vertical Profile along RF25 flight track

ECMWF Vertical Profile along RF25 flight track

UT (hrs) on July 18, 2014
NAVGEM
Navy Global Environmental Model
Navy’s bridge to a future ESPC

Global SLSI Forecast Model

6-hourly update cycle

6 hourly global analysis fields

Data Assimilation System
NAVDAS-AR 4DVAR

0-10 Day Forecasts
0-9 Hour Forecasts
Global observations over next 0-6 hours

ATMOSPHERIC BACKGROUNDS:

NAVGEM 0-100 km Reanalysis for DEEPWAVE Austral Winter
Global Model Physics Modules Needed for Upper Levels

• Shortwave heating due to UV $O_2$ and $O_3$ photolysis
• Non-LTE $CO_2$ longwave cooling to space
• Exothermic Chemical Heating
• **Gravity-Wave Drag** (Momentum Deposition)
  – Orographic Sources of Gravity Wave Drag
  – Nonorographic Sources of Gravity Wave Drag
  – Frictional Heating (KE Dissipation)
  – Momentum/Heat Mixing due to GW-Induced Turbulence
The Deep Propagating Gravity Wave Experiment
Climatological Winds vs. Height

(a) Zonal Winds: July 2007-2009 140-190°E

(b) Remote Sensing from NGV
- AMTM
- Rayleigh Lidar
- Sodium Lidar
- MTP
- Dropsondes

**Pressure Height (km)**
- 0
- 20
- 40
- 60
- 80

**Zonal Wind (m s⁻¹)**
- -50
- 0
- 50
- 100

**Pressure (hPa)**
- 0.001
- 0.01
- 0.1
- 1
- 10
- 100
- 1000

**Latitude**
- 70°S
- 60°S
- 50°S
- 40°S
- 30°S
- 20°S

**Location**: Christchurch
AIRS 7hPa RMS GW Radiances:
2002-2011

SAANGRIA

DEEPWAVE
Profiling Instruments on NSF/NCAR Gulfstream V during DEEPWAVE

- Airglow AMTM
- Sodium Lidar
- Rayleigh Lidar
- Microwave Temperature Profiler
- Dropsondes (AVAPS)

Temperatures

- 120 km Thermosphere
- 110 km Mesopause
- 100 km Mesosphere
- 90 km Stratosphere
- 80 km Tropopause
- 70 km Troposphere

- 150K
- 200K
- 250K
- 300K
- 350K
- 400K
- >500K

RMS AIRS Brightness Temperature: June-July 2003-2011 2.5 hPa

DEEPWAVE Research Flights

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

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

Hokitika
Mt. Cook
Mt. John
Mt. Aspiring
Lauder

Sydney
Melbourne
Auckland
Christchurch
Hobart
Auckland Island
Macquarie Island

Elevation

0 50 100 200 300 400 Km

0.470 0.595 0.720 0.845 0.970 1.09 1.22
DEEPWAVE Model Measurement Comparison

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NAVGEM (t425174m) Vertical Profile along RF25 flight track

ECMWF Vertical Profile along RF25 flight track

UT (hrs) on July 18, 2014