Evaluation of WRF performance for depicting orographically-induced gravity waves in the stratosphere

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Outline

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Introduction

- **Internal Gravity (Buoyancy) Waves**
  - Means for transporting energy and momentum to upper atmosphere
  - Important in the formation of high altitude turbulence (Crooks, 1965)

- **Understanding Gravity Waves**
  - Boulder Windstorm, 11 January 1972 (Lilly & Zipser, 1972)
  - Several analytic and 2-D numerical simulations
  - Control of model dissipation and inclusion of an upper boundary condition (Klemp & Lilly, 1978)
  - Little effort beyond describing trapped lee waves and rotors (i.e. low levels)

- **High Resolution Simulations using prognostic models**
  - Colorado Windstorm, 9 January 1989 (Clark, et al., 1994)
  - Intercomparison of several prognostic models by Doyle, et al. (2000)
  - Need for increased vertical and horizontal resolutions to capture mountain generated gravity waves
  - Applying WRF to T-Rex cases (Koch, et al., 2006)
Case Study

• Field Campaign 22 November – 5 December 2004
  — Observatoire de Haute Provence (OHP), France (44º N, 5º 42’ E)
  — Special Observation Period: 23-24 November 2004
    • “Light” Mistral Conditions
    — Measurements by Thermosonde (Brown, et al., 1982) and SCIDAR (Fuchs, et al., 1998)
      • Indicated turbulence occurring near 13 km around 0000 UTC 24 November
    — No convection or strong wind shear present to account for gravity wave activity present
Model Simulations

WRF ARW Core Version 2.1.1 (November 2005)

• Model Set-up and Physical Parameterizations
  – Air Force Weather Agency (AFWA) Joint Operational Testbed (July 2005)
• AFWA Control version
  – Horizontal: 45 km with nests of 15 and 5 km
  – Vertical: 42 Eta levels (model top @ 50 hPa)
• Enhanced Resolution version
  – Horizontal: 36 km with nests of 12, 4 and 1.3 km
  – Vertical: 82 Eta levels (model top @ 10 hPa)
  – Inclusion of gravity wave absorbing upper boundary condition (UBC)
    • Tested with different damping coefficients
    – Tested without vertical velocity damping (w-damping)
• Horizontal grid/nests centered on observation area (OHP)
  – Runs initialized with 1° NCEP GFS data
  – 48 h simulation from 0000 UTC 23 November 2004
Model Simulations

Upper Boundary Condition

- Gravity Wave Absorbing (Diffusion/Sponge) Layer (Skamarock, et al., 2005)
  - Increase diffusion in horizontal/vertical by increasing eddy viscosities as the top of the model is approached (Klemp & Lilly, 1978)

Horizontal:

\[ K_{dh} = \frac{\Delta x^2}{\Delta t} \gamma_g \cos \left( \frac{z_{top} - z}{z_d} \frac{\pi}{2} \right) \]

Vertical:

\[ K_{dv} = \frac{\Delta z^2}{\Delta t} \gamma_g \cos \left( \frac{z_{top} - z}{z_d} \frac{\pi}{2} \right) \]

Typically,

\[ 0.01 \leq \gamma_g \leq 0.1 \]
Model Simulations

• Gravity wave absorbing layer tests for enhanced resolution WRF-ARW simulations
  – Damping layer depth ($z_d$) constant, 5 km
    • Deeper layer would intrude on a greater part of the domain in the stratosphere
  – Damping coefficients ($\gamma_g$) tested for 0.01, 0.04 and 0.08
    • Horizontal examples:
      \[
      \begin{align*}
      \gamma_g &= 0.01, \quad 0 \leq K_{dh} \leq 72000 \text{ m}^2\text{s}^{-1} \\
      \gamma_g &= 0.04, \quad 0 \leq K_{dh} \leq 288000 \text{ m}^2\text{s}^{-1} \\
      \gamma_g &= 0.08, \quad 0 \leq K_{dh} \leq 576000 \text{ m}^2\text{s}^{-1}
      \end{align*}
      \]
Vertical Velocity Damping (w-damping)

– Improves model robustness for operational and semi-operational applications

– Prevents strong updraft cores (when timesteps might be too large)

– Decreasing timestep should allow runs without w-damping

  • Typically only horizontal grid is used to determine timesteps (and avoid violating CFL criterion)

    – WRF-ARW documentation: $\Delta t = 6 \times \Delta x$ (in km)

  • Must also recognize impacts from increased vertical resolution

    – Tested by Koch, et. al. (2006)

– Smaller timesteps were chosen from beginning to test simulations with and without w-damping
Results
Grid Point Verification Statistics

RMSE of Potential Temperature

- 24 h Simulation vs. GFS Analysis valid 0000 UTC 24 November
- AFWA Control ARW (blue) and Enhanced Resolution ARW (red)
Results
Grid Point Verification Statistics

RMSE (left) and Mean Error (right) of Total Wind

- 24 h Simulation vs. GFS Analysis valid 0000 UTC 24 November
- AFWA Control ARW (blue) and Enhanced Resolution ARW (red)
Results
Comparison with Radiosonde

Temperature and Wind Speed Profiles

• Enhanced Resolution ARW model profiles (red) extracted from 36 km grid using balloon trajectories
Results
Enhanced Resolution ARW Cross Sections

• Domain of 1.3 km inner nest of enhanced resolution ARW model (left)
  – Line denotes vertical cross sections used for evaluation
  – Red dot marks location of OHP

• Cross section from surface to 10 km (right) indicating the presence of orographically generated gravity waves in the 24 h simulation valid 0000 UTC 24 November
  – Vertical line is location of OHP
Results
Enhanced Resolution ARW Cross Sections

- Horizontal Cross Sections at 13 km for 24 h simulation valid 0000 UTC 24 November
  - Dot indicates location of OHP

No UBC

UBC, $\gamma_g = 0.01$
Results
Enhanced Resolution ARW Cross Sections

γ_g = 0.01
• Comparison between gravity wave absorbing layer using damping coefficients (γ_g) of 0.01 and 0.04
  – Vertical line is location of OHP

γ_g = 0.04
Results
Enhanced Resolution ARW Cross Sections

\( \gamma_g = 0.04 \)

- Comparison between gravity wave absorbing layer using damping coefficients (\( \gamma_g \)) of 0.04 and 0.08
  - Vertical line is location of OHP

\( \gamma_g = 0.08 \)
Conclusions

• Mountain generated gravity (i.e. buoyancy) waves were simulated by the enhanced resolution ARW version
  — Not a particularly strong case over OHP where observations were made
• Unclear if increasing damping coefficient ($\gamma_g$) above 0.04 improves the effectiveness of the gravity wave absorbing layer and simulated wave structure.
  — Need more choices for UBC
• Elimination of w-damping led to small differences in simulated vertical velocity
  — Continue without w-damping in order to eliminate one source of model dissipation
• Forecasts would be difficult to operationally implement
  — Stratospheric Real-Time Turbulence Model (RTTM) (Kaplan, et al., 2006)
  — Dynamic Solution Adaptive Grid Algorithm (DSAGA) (Xiao, et al., 2005)