 Integrating Unified Gravity Wave Physics into the Next Generation Global Prediction System:

Motivation and first results in an extended Global Forecast System (GFS-L91) and Whole Atmosphere Model (WAM-L150) in the NOAA Environmental Modeling System (NEMS)

T. J. Fuller-Rowell, V. A. Yudin, J. C. Alpert, R. A. Akmaev M. Iredell, and W. Yang

NGGPS NOAA meeting, College Park MD, July 15 2015
<table>
<thead>
<tr>
<th>System</th>
<th>Current</th>
<th>Q4FY14</th>
<th>FY18</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDAS</td>
<td>80 member @ T574 Eulerian (55 km)</td>
<td>80 member @ T574 SL (35 km)</td>
<td>4DHybrid 80 member @ T1148 SL (17 km)</td>
</tr>
<tr>
<td></td>
<td>Analysis @ T574 Eulerian (27 km) using T254 Eulerian ensembles</td>
<td>Analysis Increment @ T574 SL (35 km) using T574 SL ensembles</td>
<td>Analysis Increment @ T1148 SL (17 km) using T1148 SL ensembles</td>
</tr>
<tr>
<td></td>
<td>64 Vertical Levels</td>
<td>64 Vertical Levels</td>
<td>128 Vertical Levels</td>
</tr>
<tr>
<td></td>
<td>Uses GFS model below</td>
<td>Additional Obs., Improved radiative transfer, many smaller changes, uses GFS model below</td>
<td>Additional Obs., Cloudy Radiances, Improved QC and ob. Errors, Ensemble Hurricane relocation, uses GFS model below</td>
</tr>
<tr>
<td>GFS</td>
<td>T574 Eulerian (27 km) to 7.5 days</td>
<td>T1534 SemiLagrangian (13 km) to 10 days</td>
<td>T2000 SemiLagrangian (10 km) to 10 days</td>
</tr>
<tr>
<td></td>
<td>T254 Eulerian (55 km) days 7.5 to 16</td>
<td>T574 SL (35 km) days 10 to 16</td>
<td>T1148 SL (17 km) days 10 to 16</td>
</tr>
<tr>
<td></td>
<td>64 Vertical Levels</td>
<td>64 Vertical Levels</td>
<td>128 Vertical Levels</td>
</tr>
<tr>
<td></td>
<td>Enhanced Physics</td>
<td></td>
<td>Higher top, non-hydrostatic, NEMS, Coupled Ocean, enhanced physics</td>
</tr>
</tbody>
</table>

**Lapenta slide, Global Forecast System Evolution:**

- Additional Obs., Improved radiative transfer, many smaller changes, uses GFS model below
- Additional Obs., Cloudy Radiances, Improved QC and ob. Errors, Ensemble Hurricane relocation, uses GFS model below
- Higher top, non-hydrostatic, NEMS, Coupled Ocean, enhanced physics
Motivation of “extended” GFS model

- Remove artificial lid and reflections
- Downward influence of the middle atmosphere (stratosphere and mesosphere) on tropospheric dynamics
- Improve longer-range 1-4 week weather forecasts
Whole Atmosphere Model (WAM)

- Global seamless whole atmosphere model (WAM) 0-600 km, 0.25 scale height, 2° x 2° lat/long, hydrostatic, 10-fold extension of Global Forecasting System (GFS) US weather model.
- O₃ chemistry and transport
- Radiative heating and cooling
- Cloud physics and hydrology
- Sea surface temperature field and surface exchange processes
- Orographic gravity waves parameterization
- Eddy mixing and convection
- Diffusive separation of species
- Composition dependent \( C_p \)
- Height dependent \( g(z) \)
- EUV, UV, and non-LTE IR
- Ion drag and Joule heating

Coupled to an ionosphere/electrodynamics module (GIP/CTIPe)
The next generation global system will be:

- Non-hydrostatic
- Applicable and stable for all NWS applications currently using Global Spectral Model (GSM)
  - Global high resolution weather prediction
  - Whole Atmosphere Model
  - Multiple high resolution nests with moving capability for hurricane and severe weather forecasting
  - Aerosol forecasting
  - Seasonal climate modeling
  - Ensemble forecasting
  - Atmospheric composition forecasting (currently only ozone)
- Usable in NEMS infrastructure
- Usable within NWS data assimilation system
SW example: 50% increase in TEC in January 2009 when solar and geomagnetic activity were very low

Goncharenko et al. 2010

A response to changing tidal amplitudes during an SSW
Change in tidal propagation
Amplitude and phase change of SW2 vs zonal winds in 2009

SW2 amplitude

Stratospheric zonal winds

Zonal wind (m/s) 2009

15-16th July, 2015
NGGPS R2O PI Meeting
Predictability: WAM T62 compared with GFS

Initialized with operational data WAM forecasts the warming several days in advance

(a) Jan 12

(b) Jan 13

(c) Jan 15
Typical day-to-day changes of tidal variability
Tzu-Wei Fang et al. 2013 from WAM-GIP model simulation

Modulation of semi-diurnal tide SW2 correlates with increases in peak vertical plasma drift and $N_mF_2$

Tropical convection modulates DE3 and DE2 tidal amplitudes - correlates with number of longitude peaks of vertical plasma drift and density

NGGPS R2O PI Meeting
Current issues:

Jun-July Zonal mean zonal winds

(a) WAM-trunk has no non-orographic gravity wave drag – strongly over-estimated winter polar jet and no reversal of zonal mean zonal wind in mesosphere/lower thermosphere


(a) MERRA-GMAO reanalysis-I Jun/July of 2009.
WAM without GW physics: Zonal mean state

Other issues:

1) Cold pole and lower thermosphere bias

1) Delayed break-up of the polar vortex in both hemispheres can modulate seasonal variability of tides including ozone tidal forcing

1) Impact on transport/chemistry of Ozone and other related tracers
SUB-GRID SCALE GRAVITY WAVE DRAG AND MOUNTAIN BLOCKING
AT NCEP/GFS before June of 2015 (see J.C. Alpert et al., 2013)

The representation of orography and its influence in numerical weather prediction models are necessarily divided into resolvable scales of motion and treated by primitive equations, the remaining sub-grid scales to be treated by parameterization.

History of GW physics in GFS before Jun of 2015
Orographic Gravity wave Drag, 1987, 1997
Mountain Blocking, 2004
Upgrade including Vertical Diffusion, 2005
Convective Gravity Wave Drag stationary waves, 2014 (in operations since Jan of 2015)

Orographic GWD vs Convective GWD
Kim, Moorhi & Alpert’s vs Chun and Baik’s CGWD implemented by Ake
Both based on linear, 2-D non-rotating, stably stratified Homogenous vs non-Homogenous flow

- \( \tau = E \frac{m}{\Delta x} \left\{ \rho \frac{u^3}{N} G(F_r) \right\} \); Alpert’s version \( \hat{G} &a = 1 \), and \( E \frac{m}{\Delta x} \) constant but KMA

- \( G(F_r) = \frac{P_r}{(F_r + a^2)} \), \( F_r = Nh/U \); has \( E \frac{m}{\Delta x} \) and \( a \) from GW model stats.

- \( \tau = \rho \frac{u^3}{N} G(F_r) \); Ake’s (C&B) adds \( (gQ/cT_0) \) to the vertical GW equation

- \( G(F_r) = c_1 c_2^2 \mu^2 \); resulting in convection induced momentum flux.

- \( \mu = gQ_0 a_1 / (c_p T_0 NU^2) \); Where \( a_1 \) is related to structure of thermal forcing, \( c_2 \) to the basic-state wind and stability and the bottom and top heights of thermal forcing making up a nonlinearity factor of thermally induced gravity waves,

(C&B, 1994).
GW wintertime hotspots diagnosed from AIRS, COSMIC and HIRDLS

Gong et al., 2012

Hindley et al., 2015
## Non-stationary (NST) sub-grid Gravity Wave Physics in Climate and Weather Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Climate/Weather</th>
<th>Levels &amp; Top Lid</th>
<th>GW-NST scheme</th>
<th>GW sources</th>
<th>GW-drag</th>
<th>GW-heat</th>
<th>GW-eddy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WACCM &amp; WACCM-X NCAR</strong></td>
<td></td>
<td>68 L (88L) ~140 km (500km)</td>
<td>Lin. Saturation (65 x 2 modes)</td>
<td>Physics-based triggers</td>
<td>Y</td>
<td>Y?</td>
<td>Y</td>
</tr>
<tr>
<td><strong>NAVGEM/NOG APS-NRL</strong></td>
<td></td>
<td>L70, 0.04 hPa, 70km; (0.001 hPa ~100 km)</td>
<td>Lin. Sat. with stochastic triggers (~1-4)</td>
<td>Lat-time depend.</td>
<td>Y</td>
<td>Y</td>
<td>Y?</td>
</tr>
<tr>
<td><strong>IFS-40R1/ECMWF</strong></td>
<td></td>
<td>91L (137L), 0.01hPa, 80 km</td>
<td>Univer. Lin. Sat. (25 x 4 modes)</td>
<td>Lat-depend.</td>
<td>Y</td>
<td>Y?</td>
<td>No</td>
</tr>
<tr>
<td><strong>GEOS-5/GMAO/GSFC</strong></td>
<td></td>
<td>72L, 0.01 hPa, ~80 km</td>
<td>NCAR scheme with reduced # of GW modes.</td>
<td>Lat-depend.</td>
<td>Y</td>
<td>Y</td>
<td>No</td>
</tr>
<tr>
<td><strong>GFS/NCEP-91L</strong></td>
<td></td>
<td>91L, 0.01 hPa, ~80 km</td>
<td>Lin. Sat (25 x 4 modes)</td>
<td>Lat-depend.</td>
<td>Y</td>
<td>Y</td>
<td>No</td>
</tr>
<tr>
<td><strong>WAM/NCEP-CU</strong></td>
<td></td>
<td>150L (T62) ~500 km</td>
<td>Lin. Sat (25 x 4 modes)</td>
<td>Lat-depend.</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>
1. Vertical levels and top lid of GFS-91L resemble IFS-91L of ECMWF and GEOS5-72L of GMAO

1. Decreased (3-times, 1/15 days) Rayleigh damping above ~70 km.

1. Previous (IFS, NOGAPS, NCAR) choices for GW intensity at ~ 700 hPa to replicate latitudinal and seasonal variations of GW activity from tropical convection and polar jets

2. GW solvers: (a) Linear saturation of modified Lindzen-81; (b) Hines’-97 with dissipation and nonlinear saturation (Doppler Spread Theory)

3. GW physics acts every time-step: non-stationary, horiz. phase speeds +/-60 m/s, 4 azimuths; 10-25 modes in each azimuth; horiz. wavelength \( \lambda_x \) 200 km, GFS runs at T62, T254, T382, T574, & T670 for ~ 1 month

NGGPS R2O PI Meeting
Diagnostics of GW-forcing of non-stationary GWs, NOAA-CIRES scheme, implemented in WAM-NEMS

GW wind rms

GW vertical eddy mixing

GW wind drag, m/s/day

GW heating, K/day

July UARS zonal wind clim,

Temperature clim, MSIS-00

GW E-wd & W-wd momentum fluxes

GW Phase velocities -60/60 m/s
Jun-July Zonal mean zonal winds

(a) WAM-trunk no nst-GWa

(b) WAM-GWP, Lindzen linear saturation (100 modes), launched at 700 hPa pressure layer;

(c) UARS zonal wind reference atmosphere based on the UKMO and HRDI wind measurements, 1992-1997.

(a) MERRA-GMAO reanalysis-I Jun/July of 2009.
June -2014: GFS-91L 20-day forecasts with Rayleigh Friction (left), GW-physics (middle) and GEOS5 analysis (right, 2014-06-21)

RF with GW GEOS-5

15-16th July, 2015

NGGPS R2O PI Meeting
Zonal wind reversal and break-up of polar vortex now more realistic

will influence the downward control and the tidal variability in WAM

New: daily zonal mean flow
WAM-GW at 45 N & S

15-16th July, 2015

NGGPS R2O PI Meeting

NEMS WAM - no NST GW
GFS forecasts in L91 model with different GW sources: January and June

Sensitivity of GFS-91L to specification of GW-sources: e.g., constant, latitude and/or seasonal dependent

15-16th July, 2015
NGGPS R2O PI Meeting
Tracing the origin of one of the many source of waves – unbalance flow of stratospheric jets –

Scaled in altitude by \( \exp\left(-\frac{z-40}{2H}\right) \)

Instabilities in strong stratospheric jets in winter high latitudes at 50 km growing in amplitude into the lower thermosphere (100 km)
Sensitivity GFS-91GW to horizontal resolutions

T670 (30km)  T574 (35km)  T382 (50km)  T254 (75km)

15-16th July, 2015
NGGPS R2O PI Meeting
Sensitivity of U-winds GFS-91l/GW to horizontal resolutions

15-16th July, 2015
NGGPS R2O PI Meeting
Tides
- impact of upward propagation on SW -

Day-to-day, seasonal, and year-to-year variability of tides in WAM with GW schemes vs control WAM-NEMS
Migrating semi-diurnal tide: SW2

Previous study WAM SW2 with no GWs compared with SABER

GWs in WAM: leads to improved seasonal/latitude structure of SW2 temperature

GWs in WAM: impact on seasonal/latitude structure of SW2 meridional and zonal winds
Diurnal migrating tide: DW1

Above: Previous WAM compared with SABER 60 day mean Forbes et al., (2008)

RHS: WAM vertical structure and day-to-day tidal variations at equator and 20N and 20 S, compared with SABER
Non-migrating diurnal tide: DE3

Day-to-day and year-to-year variability of DE3 amplitudes at 116 km

Driven by:
(1) convective latent heat diurnal variations
(2) Tropical winds

WAM-DE3 is closer to DE3-2008

Previous comparison with SABER
Conclusions and Next Steps

1. Initial results from extended GFS-L91 the WAM-L150 experiments incorporating various GW schemes

2. Including physics of non-stationary GWs displayed clear improvements of the simulated zonal mean flows and temperature structure

3. The observed annual cycles and day-to-day variations of the main tidal modes are relatively well reproduced by WAM-GW simulations well into the thermosphere

4. Results did not appear to be overly sensitivity to resolution

5. Next steps: tune GW source; determine sensitivity to GW solvers; experiment with deterministic (wave sources and spectra) and stochastic (randomly triggered waves) formulations; compare with observations and define metrics; examine QBO in WAM; incorporate data assimilation GSI and IAU and validate forecasts
**Unified Gravity Wave Physics**

- **Name and Organization:** Tim Fuller-Rowell, University of Colorado

- **Project Title:** Integrating unified gravity wave physics into the next generation global prediction system

- **Objectives:** Vertically extended configurations of GFS models across the stratopause have the potential to improve longer range 1-4 week terrestrial and space weather predictions; the stratosphere and upper level domains need more sophisticated representation of sub-grid scale physics of unresolved waves to match climatology and observations; non-orographic gravity wave (GW) schemes will improve dynamics, mixing and transport, and as expected they can affect the troposphere-stratosphere coupling and improve predictors of AO and NAO; GW-controlled middle atmosphere circulation also impacts propagation of tides into the thermosphere impacting space weather forecasts.

- **Deliverables:** A unified gravity wave parameterization that can be applied to a range of extended GFS models and future NGGPS configurations (including the whole atmosphere L150); a resolution sensitive and adaptable GW scheme. The outcome will be improved model dynamics, transport and mixing for global terrestrial and space weather forecasts.

- **Co-Is and Collaborators:** V. Yudin, H. Wang, J. Alpert and R. Akmaev.
CTIPe simulations with WAM winds (lower panel) appear to reproduce the main features in the observed vertical plasma drift (upper panel) during a SSW, including the stronger upward drift early in the morning and reversal to downward in the afternoon.

- Largest tidal changes during interval are in SW2 and TW3.
Predictability: Polar cap T @ 10 hPa

Initialized with operational data WAM forecasts the warming several days in advance

15-16th July, 2015