NGGPS Physics: Integrating Unified Gravity Wave Physics into the Next Generation Global Prediction System: First Year Results in the Global Forecast System and Whole Atmosphere Model of NEMS

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Unified Gravity Wave Physics

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  **Collaborators:**  
  *J. Alpert (NCEP/EMC) and R. Akmaev (NWS/SWPC)*

- **Project Title:** Integrating Unified Gravity Wave Physics into the Next Generation Global Prediction System

- **Objectives:** Development of the vertically extended configurations of NOAA atmosphere models across the stratopause with realistic representations of sub-grid scale eddies by unified Gravity Waves (GW) schemes that improve the troposphere-stratosphere coupling, predictors of AO and NAO and propagation of atmospheric tides and planetary waves.

- **Deliverable(s):** A unified GW schemes in the vertically extended GFS and future NGGPS global atmosphere model configurations.

- **Deliverables of Yr-1:** The GFS-91L with GW physics were delivered to EMC GW group (J. C. Alpert); NEMS/WAM-150L simulations with GWs were used and evaluated by SWPC-WAM researchers (R. Akmaev and T.-W. Fang)
The R2O/NWS transforms and upgrades the operational GFS into the Unified Global Model within NEMS framework.

The first vert. extended GFS (from the current 64L to 91L) promises to improve the stratospheric forecasts and the trop-stratosphere coupling.

For vertically extended models, our current aim is to unify the GFS-91L (lid ~80km) and the 150L Whole Atmosphere Model (WAM-150L, ~500 km) under the Global Spectral Model (GSMe) of NEMS in 2016-17.

Unification and upgrades of GFS and WAM physics will streamline the interaction of analysis and forecast for terrestrial and space weather and climate predictions under NEMS/NGGPS framework.

Dynamics and physics of resolved and sub-grid quasi-stationary Orographic GWs (OGWs) and Non-stationary GWs (NGWs) represent the major uncertainties for extended models of NEMS. R2O/UGW project “unifies” GW physics.
Gravity Wave Hotspots/Sources from Satellites: AIRS, COSMIC, HIRDLS & SABER

Gong et al., 2012

Hindley et al., 2015

SH ORO-GW metrics

Ern et al., 2011

SABER, 30 km

AIRS-East

HIRDLS, Aug 2006

COSMIC

Oro-Andes Fronts/jets

Conv

Jan 35 km

Jan 55 km

Jul 35 km

Jul 55 km

HIRDLS, Aug 2006

SABER GW momentum flux [10^{-3} Pa]
Unified GW physics in the NCEP models: GFS, NEMS-GSM and NEMS-WAM

Specific R2O Goals:
(1) Perform “orchestration” of the GW solvers for all types of wave sources (orography, convections, front, jets, and other imbalanced dynamics); same breaking criteria and dissipation.

(2) Create portable and adaptable to the type of parameterization “GW-unified” module with 3 stages: Init - Advance - Diagnose.

(3) Allow both stochastic and deterministic performance of GW schemes (sources, spectra, and triggers).

(4) Explore novel observational GW metrics/constraints for “resolved” and sub-grid GWs

(5) Introduce GW effects (drag, heat & eddies) in the self-consistent, energy-balanced and resolution-aware formulations; orchestrate strengths of GW-drag, eddies and Rayleigh friction and “spectral” damping.

Unified GW Physics Module

INIT: GW_NML, choice of GW sources and solvers

ADVANCE: Drag, Heat, $K_{\text{eddy}}$ every time-step or 1-hr cadence

Data-driven Diagnostics: dominant wavelengths, energy, momentum and heat fluxes.

GW-sources: NRL, GMAO, ECMWF, NCEP and NCAR;
GW-solvers: operational weather and climate schemes with adapts for:
(a) energy-balanced formulations:
(b) eddy diffusion and mass fluxes and self-cons. heat-drag-$K$;
(c) resolution-sensitive specifications of parameters.
Diagnostics of GW-forcing: non-stationary GWs in July
NOAA-CIRES scheme, implemented in WAM-NEMS

GW wind rms

Eddy mixing, $K_{zz}$, due to GW instability

GW drag, momentum tendencies, m/s/day

Mean Zonal Wind, m/s

GW heating, K/s/day

Mean Temp-re, K, July

GW accelerations of zonal winds

GW spectrum In East-West directions of phase vel-
ties

20 modes In each direction

-50(E) $C_h$, m/s +50(W)
Resolving “GW-mesoscale” by Dycores: Kinetic Energy Spectra (KES) from Skamarock et al. (2014), MPAS with GFS-ICs, and KES from NOAA forecasts & analysis.

MPAS and FV3 are two dycores selected for NGGPS and final decision...in Aug of 2016.

Analysis (GDAS) shows enhanced mesoscale variations of divergence, noise or data signal?
“Placing” non-st. GW schemes in the chain of NEMS (NUOPC) physics of Global Atmosphere Models (WAM & GSM)

NUOPC Physics Driver Schematic

Dynamics
- Dynamical equations, advection, horizontal mixing, diffusion.

Call of WAM Sub-grid GW Physics

Call of GSM/GFS Sub-grid GW Physics

Atmospheric Physics Driver
- (init, run, finalize modes)

Modified Kalnay Rules Layer
- Radiation
- Deep and Shallow Cumulus
- Surface Layer
- PBL and Vertical Mixing
- Microphysics Sat. adjust

NUOPC Layer
- Wave
- LSM
- Ocean

LSM, Ocean, Wave, Chemistry, Aerosol, Ice Driver

NGGPS Physics Team Plan

Long Term Goals

4. Gravity Waves and Large-scale Orogric (and non-Orogric) Drag
   A. Purpose
   Improve representation of gravity wave drag and orographic drag
   B. Development Activities
   a. Improve model performance in upper stratosphere and mesosphere (will also improve data assimilation in entire vertical column)
   b. Develop non-orographic and non-stationary gravity wave drag
   c. Scale-aware orographic drag formulation
   d. Gravity wave physics that is adaptable to variable horizontal and vertical resolutions
Specifics of Vertically Extended Configuration of NEMS, GFS/GSM-91L: GW Physics in the Strato-Mesosphere

- Vertical levels of GFS/GSM-91L follow IFS-91L of ECMWF and resemble GEOS-5 (72L) of GMAO (TL ~80 km); Decreased (~3-times) Rayleigh friction above ~70 km with inv. scale 15 days.

- Previous (IFS, NOGAPS, GMAO) choices for GW intensity at ~ 700 hPa (or at ~500 hPa) to replicate latitudinal and seasonal GW activity from data.

- Adapted GW solvers: (a) Linear saturation with dis-n; (b) IFS-2000 with dis-n; (c) DSP-Hines’ with dis-n and nonlinear saturation; (d) Alexander & Dunkerton-99 with dissipation.

- GW physics acts every time-step: four azimuths and tested for T62 ..->..T670

- In progress: online diagnostics and eddy mixing; other GW “candidates”; adding non-LTE radiation of WAM for GSM; tests for oper. res-n at T1574 (~ 13km)
Non-stationary sub-grid Gravity Wave (NGW) Physics in Climate and Weather Models

<table>
<thead>
<tr>
<th>Model 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>WACCM &amp; WACCM-X NCAR</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>NAVGEM/NOGAPS-NRL</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>IFS-40R1/ECMWF</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>GEOS-5/GMAO/GSFC</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>GFS/NCEP-91L</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>WAM/NCEP-CU</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>
June 2014: GFS-forecast in 64L & 91L models with Rayleigh Frictions (RF) and physics of NGWs

Role of RF (wind damping), it attempts to resolve 2 issues:

1. The top lid model effects, sponge layer to suppress resolved wave reflections; (GFS-64L); extra-heating;

2. The winter-summer zonal wind drag in the strato-mesosphere.

Issues with RF-schemes:
- erroneous reflections of PWs;
- absence of the U-wind reversals above ~70-80 km;
- warm mesosphere relative to EOS-Aura MLS and TIMED-SABER multi-year observations.

Advantage of GW-physics:
handle “above-listed” GFS-biases; consistency with the data.

20-day GFS forecasts from June 1 of 2014 vs MLS-Aura 2014-06-30 (mean temperatures)
2014 GFS-T574 forecasts in 91L model with GW sources: Jan (15 day, right) and Jun (25 day, left)

GFS-91L with GW physics and GEOS-5 analysis

Sensitivity of GFS-91L runs to specification of GW-sources: constant, time-lat dependent & latitude-only dep-nt
GFS-91L (T670) 10-20-30 day forecasts vs MLS-Aura and GEOS-5

GFS-91L 800-hr forecast
WT: 4 hr 48 min RF
WT: 5 hr 57 min GW-40

EOS-Aura MLS-V4.3
June 2014

GEOS-5 Analysis,
June 2014
The 10 hPa (~30 km) Forecasts of the South Ocean Winds by GFS-64L, GFS-91L and GDAS-analysis, June 2014

GFS-64L

GFS-91L

GDAS

June 2014

5-day fst

20-day fst

Zonal Wind, m/s

Meridional Wind, m/s
Enhanced resolution of GFS-91L (75 km => 34 km) may better fit GDAS Vorticity and the filament shapes after 20-days over the South Ocean and Antarctica at ~24 km (50 hPa).

PV-filaments, desirable feature for forecasts of the ozone transport and polar stratospheric chemistry.
NEMS-GSM, 64L & 91L during SSW pulsations of 2016 (01/25 –02/20) vs GDAS-NCEP & GEOS-5/GMAO analyses

The 6-hr separated polar (75-85N) zonal mean temperatures and the high latitude (55-65N) zonal mean winds during the minor Sudden Stratospheric Warming (SSW) pulsations, Feb 2; GFS-91L with GWP tends to predict the wind reversals in upper layers and temperature-wind variations.

The top rows (a-b) display temporal variations deduced from GDAS (64L, T1534) and GEOS-5 (72L, 1/8 deg); The bottom (c-d): GSM/GFS forecasts at T670 with 64L (c) and 91L (d).
Integrating Unified Gravity Wave Physics into the Next Generation Global Prediction System

- **Summary of the 1-year results**
  GW physics in NEMS-WAM improved zonal mean flows, planetary waves and tides.
  GW physics in GFS-91L brought a realism in the stratospheric dynamics during winters and winter-to-spring transitions comparing to the Rayleigh Friction simulations.

**Transition to NOAA operations, climate tests, and future plans**

a) **Analysis-Forecast Cycling with GFS-90L** (~80 km top) with “parallel” operational scripts; tests during SSW events (2009, 2013, & 2016).

b) **NEMS-WAM multi-year climate runs** for self-generated equatorial oscillations (QBO and SAO).

c) **New related projects**: Assimilation of middle atmosphere O₃, H₂O and T-re profiles (MLS & SABER) to properly initialize NGGPS forecasts.

Jan-Feb 2016: GFS-91L 25-day polar temperature forecasts (d), SABER (e) & MLS (f) data (left), and NWP analyses (right column): GDAS-NCEP (a), GEOS5-GMAO (b) and IFS-ECMWF (c).
WAM-trunk, no NGW Physics in the Strato-Mesosphere and Thermosphere, vs NOGAPS, UARS and MERRA

WAM Trunk Run: WAM-NEMS, January (left, top) no NGW physics

NOGAPS-Alpha, Jan 2009 with DA of SABER and MLS (right, top)

UARS-SPARC wind climatology (1992-97) (HRDI-WINDII) +UKMO

MERRA-V1/GMAO Jan 2009 (right, bottom).

Biases above 40 km:
- No MLT wind reversals
- Cold T-bias at 90-110 km.
- Strong strato-meso winds.
- Errors in PWs and Tides.
WAM-150L as Vertically Extended Atm-re Model of NEMS: specifics of Physics in the Mesosphere and Thermosphere

- WAM, 150 vertical levels with top lid at ~500-600 km; “Zero” Rayleigh damping with molecular visc./cond and 4-th order spectral diffusion.
- EUV and non-LTE radiation, ion drag, Joule heating, molecular processes, major tracer (O-O₂N₂) transport-diffusion-chem, & variable “g-C_p-R” (enthalpy).
- WAM-T62 as development runs with Eulerian dynamical core enhanced res-ns T254,T382; uniform NGW triggers,~700 hPa.
- GW solvers with molecular dis-n: GW drag, heat & mixing: 4-8 azimuths; stochastic (random draw of single wave) and deterministic spectra (10-20 modes per azimuth) for the linear saturation schemes.
Role of Realistic Zonal Mean Flows in SW2 Tidal Predictions for “JJA” by NEMS-WAM with GW Physics (GWP)

Akmaev et al., 2008, WAM no GWP

Forbes et al., 2008

40-50°S
Towards Assimilation of the Space-Borne MLT winds: Outlook for Analysis of WINDII/UARS Data in NEMS-WAM

**UARS, V-wind, 1993-94**

**NEMS-WAM, T254, Mar 8**

Dominant structures of the 24-hr tide in the tropical MLT, $l_z \sim 25$ km seen in UARS data and WAM.
Integrating Unified Gravity Wave Physics into the Next Generation Global Prediction System

Timothy Fuller-Rowell and Valery Yudin, CU-CIRES

- **As R2O NGGPS effort**, this project implemented the non-stationary Gravity Wave (GW) schemes in NOAA weather and climate predictions system, GFS and NEMS to extend them above ~50 km and improve vertical atmosphere coupling, annual and sub-seasonal variations.
- **Expected outcome**: improvement of forecast skills from the surface to the thermosphere for time windows from ~2 weeks to ~1mth by adding physics of GWs for unresolved momentum, heat and energy depositions. **Deliverables**: GFS-91L, WAM-150L with GW physics

- **Connection to NGGPS**: Development and implementation of Unified Sub-Grid scale Gravity Wave (GW) physics in the vertically extended global atmosphere models of NGGPS that resolve upper stratosphere and mesosphere for the terrestrial weather and climate predictions (**NEMS-GFS/GSM 90 level, ~80 km lid**) and space weather predictions (**NEMS-WAM, 150 levels, ~500 km top lid**).
1. **GW Sources**: Stochastic and physics-based mechanisms for GW-excitations in the lower atmosphere, calibrated by the high-res runs analyses, and observations (3 types of GW sources: orography, convection, fronts/jets).

2. **GW Propagation**: Unified solver for “propagation, dissipation and breaking” of waves excited from all type of GW sources.

3. **GW Effects**: Unified representation GW impacts on the ‘resolved-scale’ flow for all types of GWs (energy-balanced parameterizations of momentum, heat, depositions and eddy mixing).

4. **Resolution-awareness of sub-grid GW schemes** in all aspects of wave physics (sources, propagation, dissipation, effects on the resolved-scale flow).

**GW Momentum Flux**:
\[ F_{uw} = \langle U'W' \rangle = -L_z \frac{\langle U'^2 \rangle}{L_x} \]
\[ L_x \sim (1-3) \, dx \]
\[ dx \sim \text{typical size of the H-grid} \]
\[ F_{uw} \sim 1/ \, dx, \quad F_{uw} (T62) < F_{uw} (T670) \]
But...\[ \langle U'^2 (T62) \rangle \ll \langle U'^2 (T670) \rangle \]
Summary and what will be next in 2016-17 and... beyond

The unified GW physics package \textit{(momentum/drag, energy/heat, and mixing)} for OGW and NGW was developed. Its implementations in GFS-91L show better skills in the service windows 6-10 days and 2-4 weeks in the stratosphere. As expected, extended models may improve winter predictions of SSW, NAO and AO patterns.

For “dissipative” atmosphere four candidates for GW solvers are now adapted and evaluated in WAM. \textbf{WAM-GW simulations display improved dynamics above 40 km: MF, PWs and Tides.}

Next, select “primary” NGW scheme for NEMS/GSM-91L, commit it in Sep/Oct 2016 with GW physics extended for WAM-150L.

Sensitivity GFS-91GW to horizontal resolutions

T670 (30km)  T574 (35km)  T382 (50km)  T254 (75km)
Sensitivity U-winds GFS-91I/GW to horizontal resolutions

T670 (30km)  T574 (35km)  T382 (50km)  T254 (75km)
Merid. winds: 5- and 20-day GFS forecasts and analysis

V, m/s T574-RF91 at 32 km, 20d-fst

V, m/s T574-RF64 at 32 km, 5d-fst

V, m/s T574-GW91 at 32 km, 5d-fst

20140606: GDAS-64L,T574, at 32km

V, m/s T574-GW91 at 32 km, 20d-fst

20140621: GDAS-64L,T574, at 32km
Goals and Objectives of R2O for GW physics

CU-CIRES collaborative research with NOAA/NWS is to support upgrades and improvements of GW physics in the NEMS global atmosphere models, CFS, GFS and WAM. The planned improvements for the NEMS models are:

1) Calibration of model physics for higher vertical and horizontal resolution and an extended (from ~50 km to ~100 & 500 km) top lids of simulations;
2) Upgrades to GW schemes, including the turbulent heating and eddy mixing due wave dissipation and breaking, and
3) Tests of GW physics and understanding its role on weather dynamics (SSW, season-to-season transitions) and seasonal/climate oscillations (QBO, SAO, NAO, AO) with emphasis on impacts of non-orographic GWs.

Development and evaluation timeline

Year 2015/16: Porting and testing unified suite in the vertically extended models NEMS-WAM and GFS-90L to demonstrate role of GW physics of non-stationary and orographic waves (performed)

Year 2016/17: Evaluations of GW physics in updated atmosphere models: sub-seasonal predictability; experiments with NEMS GFS/GSM operational versions to quantify skill in the service windows 6-10 days and 2-4 weeks verifying with NAO-AO patterns; experiments with WAM multi-year runs (QBO and SAO) and WAM-IPE with space weather forecast indices (ongoing).

R2O/NGGPS PI meeting- Aug 2 2016