Report of the Gravity Wave (GW) Physics Sub-Group
(NGGPS Physics Workshop, Nov 8-9, 2016, College Park)

During the 2-day Physics Workshop the GW Physics Sub-Group (GWPSG) with the NGPPS science sub-group co-leads, Jordan Alpert (NCEP/EMC) and Stephen Eckermann (NRL), discussed and reviewed the suggested topics and timeline for upgrades of the sub-grid scale GW schemes in the global atmosphere models of NOAA Environmental Model System. On the second day, the participants of workshop from NCEP/EMC (Jordan Alpert and Fanglin Yang), CU-CIRES (Valery Yudin) and DTC/NCAR (Louisa Nance) discussed and suggested development plans, timeline, selection criteria, metrics, verifications and diagnostics tools related to the unified GW physics, Resolved and Sub-grid Orography. This report represents summary of the "Gravity Wave and Large-scale Orographic (and non-Orographic) Drag" sub-group discussions.

1. Timeline and selection criteria
Phase 1 (Nov 2016– Oct 2017)
Nov 2016 -May 2017

1. Upgrade NEMS/WAM physics with the non-stationary GW physics at the reduced resolutions of WAM (EMC-SWPC-CU/CIRES); *selection criteria:* observed annual variations of the zonal mean temperature and winds, and major tidal modes (12-hr & 24-hr).
2. Prepare transition and tests of the non-stationary GW physics from NEMS/GSM-91L to NEMS-128L (or other available configuration), orchestrating various components of damping (Rayleigh friction, spectral dissipation or divergent damping, and GW dissipation); *selection criteria:* capability of the 5, 15, and 30-day forecasts to represent observed features of dynamics in the upper stratosphere and mesosphere.
3. Propose and design algorithms to introduce the resolution-aware formulation of GW physics for variable resolutions; *selection criteria*: predictions of observed annual and sub-seasonal variations of the zonal mean fields, Planetary Waves (PWs) and tides.

Jun-Oct 2017

4. Develop diagnostics for mesoscale waves resolved by the default dynamical core of NEMS (FV3 or GSM) and sub-grid waves, parameterized by GW physics (energy spectra, Eliassen-Palm fluxes, wind and temperature rms); *selection criteria:* capability of GW diagnostics to reproduce observational constraints.
5. Determine the targeted months/seasons of 2014-2017 for tests of GW physics in NEMS/WAM and novel NEMS/FV3 (128L with top lid at ~80 km); *selection criteria*: availability of the space-borne determination of GW parameters along with their diagnostics from the high-resolution NWP analyses.
6. Perform the analysis-forecast (A-F) experiments for the NEMS/WAM-150L with the parallel scripts (workflow of Q3FY2017 for GFS-V14 planned for operations in May of 2017) and upgraded GW physics; *selection and verification:* evaluate

results with the research satellite MLS and SABER data, as well as against the operational analyses (GDAS, GEOS-5 and IFS).

Phase 2 (Nov 2017– Oct 2020)

2017/2018

1. Perform comparative tests of four selected GW solvers in NEMS/WAM; prepare and submit the final report for the R2O GW project with recommendations of GW solvers; *selection criteria:* computational efficiency and observed zonal mean climate predictions, seasonal variability of mean flow, tides and planetary waves.
2. Perform the high-resolution NEMS atmosphere forecasts with the Unified GWP in the novel vertically extended NEMS configurations (coordination with EMC for NEMS/FV3); *selection and verification criteria*: comparisons of 5-day, 15-day, and 30 day forecasts with corresponding analyses and independent data.
3. The resolution-aware tune-up of GW physics in NEMS/FV3 to better reproduce the stratospheric reanalysis and middle atmosphere data (MLS and SABER).
4. Create the WAM-IAU configuration for analysis of SABER or/and MLS data; *selection and verification criteria:* reproduction of operational analyses below 50 km, and available MLT (mesosphere and lower thermosphere) observations.
5. Prepare and write the renewal R2O GW physics proposal for 2018-2020.

2018/2019

1. Explore sensitivity of NEMS/WAM and NEMS/FV3 to the increase of the vertical resolutions (150L => 200L, 128L => 150L); evaluate role of the consistency between vertical and horizontal resolutions in NEMS forecasts;
2. Evaluate role of the vertical resolution and GW physics tune-up for the reproduction and support of the equatorial (QBO, SAO) and extra-tropical dynamics (SSW, polar vortex formation and break-down); *verification criteria*: stratospheric reanalysis data and Middle Atmosphere (MA) observations.
3. Perform similar experiments for NEMS/WAM at the reduced resolutions; *verification criteria:* evaluate waves and diurnal cycles with the MA data.
4. Start testing of GWP in NEMS/FV3 and check the balance between resolved and parameterized waves to adapt the resolution-aware formulations of GWP.

2019/2020

1. Perform forecasts with the non-hydrostatic NEMS/FV3 dynamical core; explore needed adaptations for GW physics for non-hydrostatic equations.
2. Perform NEMS/WAM forecasts with the hydrostatic and non-hydrostatic FV3 dynamical cores considering adaptation of GW physics for predictions of the tidal and planetary wave dynamics in the mesosphere and thermosphere.
3. Underline the role of stochastic and spontaneous launches of GWs in the stochastic physics of GFS in the free troposphere, stratosphere and mesosphere.
4. Compare the "persistent" missing momentum forcing, estimated in the GFS-V15 from the analysis tendencies and GW momentum depositions produced by GWP; elaborate possible use of the analysis tendencies of GFS-V15 in the tune-up of the sub-grid scale GW physics.
5. Finalize GWP schemes for GFS-V15 and use them in NEMS/WAM forecasts.

6. Continue multi-year NEMS/WAM and NEMS/FV3 simulations to reproduce the seasonal and year-to-year variability in the equatorial and extra-tropical dynamics; evaluate the role of the vertical resolutions and GWP in the QBO, SAO and mid-winter Sudden Stratospheric Warming (SSW) events.
7. Prepare suite of the unified GW physics schemes for CCPP of NGGPS, including documentation.
8. Finalize upgraded GWP for GFS-V16/17 with FV3 non-hydrostatic dynamical core. Recommend the computationally effective and promising GWP schemes for the NOAA seasonal forecasts and reanalysis projects.
9. Evaluate and explore possible links of GW physics with other CCPP physics (PBL, convection, turbulence, eddy diffusion) and data assimilation.

2. Metrics

We discussed the need for NEMS/GSM and NEMS/WAM evaluation/verification metrics to be responsive to the strategic NGGPS goal toward unified weather-climate modeling and applications, as reflected in the proposed timeline. In addition to the current set of primary EMC weather metrics that form the EMC Verification Package for the current GFS-64L with the top lid at ~55 km we suggested the following metrics for global weather and climate models that may largely be controlled by GWs (both sub-grid physics and resolved dynamics).

(1) *Zonal mean temperature, winds, water vapor and ozone* from the surface to the model top lid as verified by GDAS/NCEP, GEOS-5/GMAO and IFS/ECMWF analyses, modern reanalyses and the middle atmosphere data (2000-present).
(2) *Zonal mean "eddies"* as deviations from the zonal mean state and Elliassen-Palm fluxes verified by NWP analyses and non-assimilated middle atmosphere data.
(3) *Transport or/and residual circulation for NEMS tracers.*
(4) *Diurnal cycles for NEMS model extended above the stratopause*: 24-hr and 12-hr tides, diurnal variations of temperature, winds and ozone verified by the MA data; later consider results of NRL and NOAA/R2O projects for DA in the MA.
(5) *Capability to support and maintain the equatorial QBO and SAO signatures* in the winds, temperature and ozone during sub-seasonal and seasonal forecasts initialized from the operational analyses.
(6) *Capability to generate "climatological" frequencies of the SSW events*, *timeliness of formation and break-up of the stratospheric polar vortex.*

3. Diagnostics to facilitate GW physics development and tune-up

Based on these additional metrics we also discussed and considered the following diagnostics to facilitate the scale-aware development of Unified GWP, its verification and evaluation.

Standalone Physics

We plan to use diagnostics for GW physics under the standalone physics with the different dimensions under vertical (single) column physics framework; it will be performed for the zonal mean and 4D NEMS fields (with longitudinal and diurnal variations). Diagnostics for 12 months with the zonal mean momentum and heat GW depositions, momentum fluxes and eddy diffusivities. GW energies can be verified against available estimates of the reported GW characteristics deduced from SABER, MLS, HIRDLS and radio occultation data. The 4D-type of the standalone GW diagnostics will be necessary to gain information on the GW-PW and GW-tidal interactions for selected types of GW solvers and various specifications of GW sources.

Diagnostics of GW physics from NEMS forecasts and NOAA analyses

The similar type of diagnostics planned for the Standalone Physics will be transformed to the NEMS models performing forecasts and analysis-forecast cycling. We plan to add the GW physics-oriented history files that output the main GW diagnostics: momentum and heat tendencies, GW fluxes and eddy diffusivities.

Current Gaps and Limitations

During the break-out session, several issues and problems with the current operational versions of GFS, NEMS/GSM and NEMS/WAM were discussed:

a) Failures of GFS/GSM to reproduce the '-5/3' tail of the kinetic energy spectra at mesoscales; this limitation of GSM precludes adequate formulation of the scale-aware (resolution-sensitive) formulation of GW physics.
b) Current GW schemes for stationary orographic and convective waves do not consider non-stationary oscillations and formulated without background dissipation (crude approximation for NEMS/WAM)
c) Current schemes do not consider turbulent/eddy mixing and its relations with wave heating and eddy heat conductivity.
d) As shown by the recent climate-weather model evaluations studies, there is potential connection between climatological biases that could be addressed by missing physics, in particular by physics of non-stationary GWs and tune-up of orographic GW source and wave breaking mechanisms.
e) Possible improvements and calibration of GW physics can stimulate the modeling of equatorial climate oscillations such as QBO and SAO and their wintertime teleconnections

Brief Summary and Priorities

The purpose of this report was to represent the planned (2017-2020) developments for *Gravity Wave Physics, Resolved and Sub-grid Orography* in the NEMS global atmosphere models, and formulate the Research-to-Operation (R2O) activity of GWP sub-group, coordinated with the transitional implementation of FV3 dynamical core in the forthcoming GFS versions (V15-V17, see diagram for planned timeline).

In 2017-2020, the work of GWP sub-group will be closely related to tests and implementations of the suite of the Unified GW schemes in the NEMS/WAM (Whole Atmosphere Model extended into the thermosphere) with GSM and FV3 dynamical cores and NEMS-FV3 extended into the mesosphere. The work will also continue to test and implement the suite of the Unified GWP schemes for advanced upgrades in the NGGPS physics in GFS-V17 (May of 2020) with Common Community Physics Package.