Development toward NCEP's fully-coupled global forecast and data assimilation system: A coupled wave - ocean system
End Report

1. General Information

Project Title: Development toward NCEP's fully-coupled global forecast and data assimilation system: A coupled wave - ocean system
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Report Year (Final Report): FY18
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2. Main goals of the project, as detailed in the funded proposal

- Implementing the MOM6 ocean model in NCEP's coupled modeling framework
- Update the CVMix package in MOM6 to include wave induced Langmuir mixing processes
- Simulations of coupled wave - ocean dynamical processes using WAVEWATCH III and MOM6 to study the impact of wave induced mixing in sub-seasonal to seasonal scales
- Prepare the wave and ocean components as parts of the next generation operational seasonal forecast system that is being developed at EMC. This will include atmosphere - wave - ocean - ice - land coupled earth system
- Have the wave model implemented in GFDL's coupled modeling system

3. Results and accomplishments

MOM6 in the Unified Forecast System (UFS)

NCEP is building the Unified Forecast System (UFS) as part of its next generation forecast system, that uses the same framework from weather to sub seasonal and seasonal scales. The coupling architecture that is used in this framework is the NEMS/NUOPC framework. The UFS uses FV3GFS as its core atmospheric component. In this project the UFS framework was extended to include MOM6 as the ocean component, CICE5 as the sea ice component and WAVEWATCH III as the wave component.

Two coupled models in the UFS framework have been created - an FV3-MOM6-CICE5 system to simulate the impact of ocean and sea ice in S2S forecasts and an FV3-MOM6-CICE5-WW3 system to test the impact of wave induced Langmuir mixing. The two models have been tested with 35 day reforecast runs. Initializations for these simulations have come from operational analysis fields. Figure 1, shows the SST comparison between the coupled FV3-MOM6-CICE5 system and OI - SST analysis over a 35 day period. Overall the coupled models and the coupling infrastructure are working well with the ocean temperature showing very little drift over a 35 day run and comparing well with analysis.

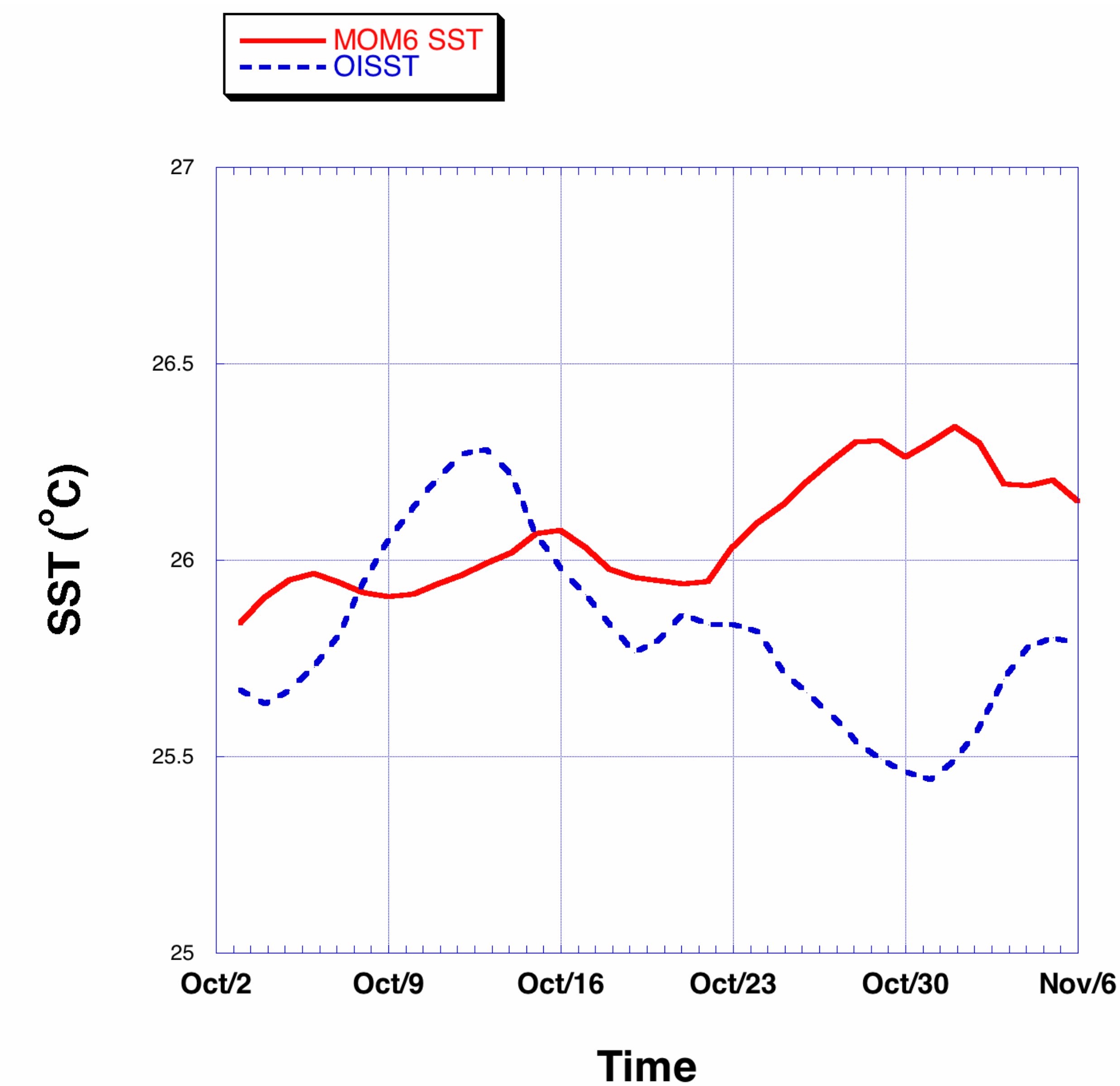

Figure 1: Average SST over the NINO 3.4 region (170 W - 120 W; 5 S - 5 N) for a 35 day coupled model forecast. Red is SST from the ocean model and blue is OI SST analysis. Initial conditions for this coupled run come from the operational CFSR analysis.

Tripolar grid wave propagation in WAVEWATCH III

WAVEWATCH III is a third generation spectral wave model that propagates wave solutions in physical space as well as spectral and directional space. The wave model allows for multiple grid options (rectilinear, curvilinear, tripolar, unstructured etc.). In directional space, the wave propagation solution has a singularity at the north and south poles. At the South Pole this singularity is not an issue as it is over land. The North Pole, however, can be a problem when it is ice free. Since an ice-free summer Arctic is becoming a strong possibility with melting polar caps, a solution for wave propagation across the North Pole is critical for the utility of WAVEWATCH III for global prediction and climate modeling.

There are two things that happen when waves go over the North Pole -- a change in direction and the singularity in directional space. This can be addressed by use of a tripolar grid. In the tripolar grid the North Pole singularity is split into two singularities that are moved over land, and the wave solution is then developed over the grid relative direction. This grid change means that in the wave propagation equation a correction term needs to be developed that accounts for the difference between “Grid North” and “True North”. A mathematical term has been derived and has been tested in the wave model. Figure 2 shows the propagation of an ocean swell field across the North Pole using the tripolar grid. The new solution avoids the singularity at the North Pole as well as changes the direction of the wave field appropriately as the waves cross the North Pole. This allows for developing waves to propagate through the North Pole without having to mask out the North Pole (as was done earlier).

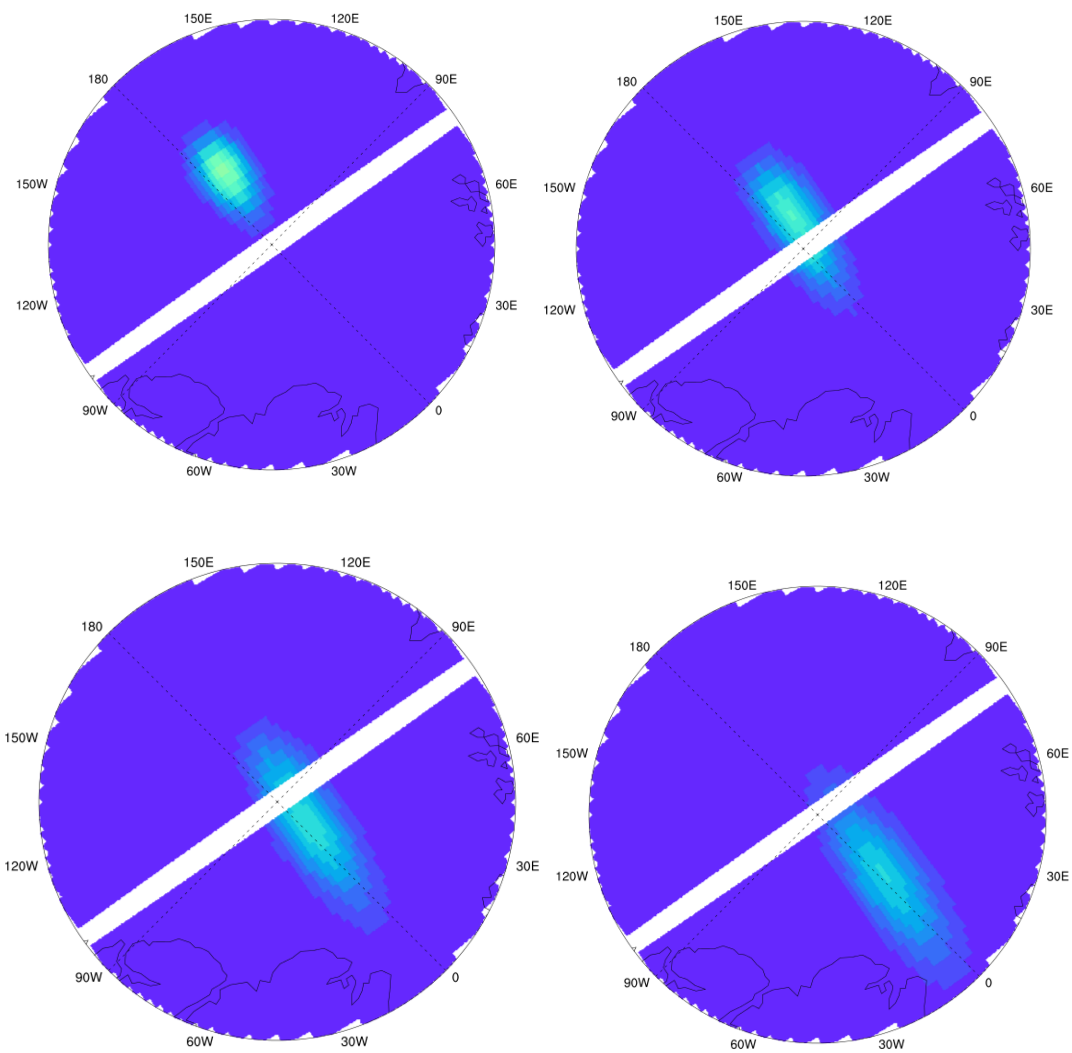

Figure 2: Propagation of a swell field across the North Pole in WAVEWATCH III using a tripolar grid

Stokes Drift profile from WAVEWATCH III to MOM6

To account for wave induced mixing, the Stokes drift (wave induced drift) profile needs to be passed from the wave model to the ocean model. In principle, we need to transfer the full wave spectra from the wave model to the ocean model. This transfer would correspond to passing fields of order Nx * Ny * Nf * Nd, with (Nx,Ny) the number of space grid points and (Nf,Nd) the number of frequency and wavenumber bands. This transfer incurs a significant computational cost for the coupling infrastructure.

A more efficient alternative to the above transfer is to pass spectral integrated bands across the coupler. Doing so reduces the dimension of the transferred information to Nx * Ny * Nb, where Nb is the number of bands. The aim then is to make the number of bands (Nb) small, yet accurate enough (see Figure 3) that they reproduce most of the Stokes drift vertical profile. A prototype for this more efficient transfer has been completed and is in the process of being tested.

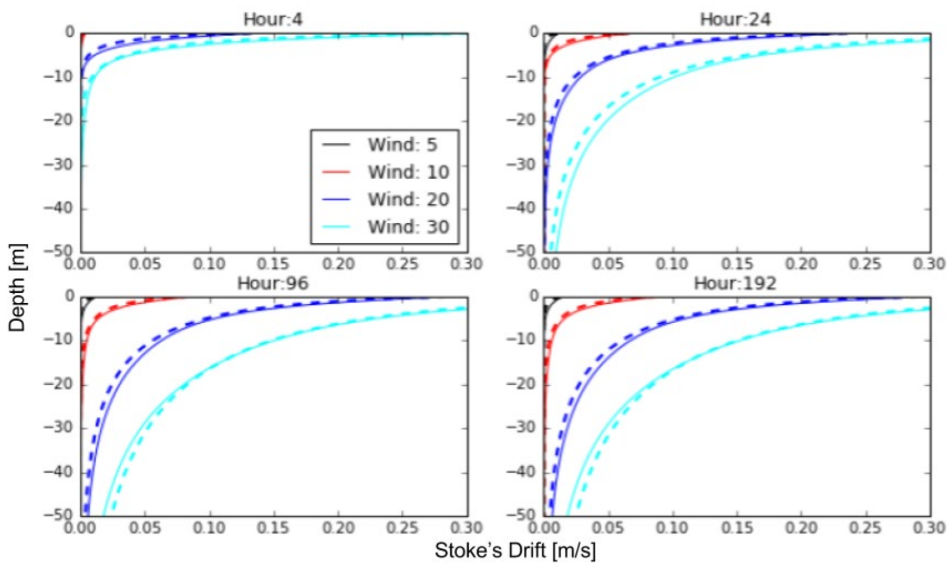

Figure 3: Stoke's drift profile at various times where the dashed line is solved directly from the full spectrum and the solid line is solved using three bands. Note the relatively accurate profiles resulting from the three-band approximation, thus motivating the use of this approach for coupling WWIII to MOM6

Improved Mechanical and Buoyancy Forced Mixing in MOM6/ePBL

The standard vertical mixing parameterization within MOM6 is the energetic Planetary Boundary Layer (ePBL) scheme (Reichl and Hallberg, 2018). The mixing parameterization has been improved by constraining results of surface temperature and integrated turbulent kinetic energy against simulations using a well-tested (but computationally more expensive than ePBL) two-equation turbulent closure called *k*-*ε*. The resulting ePBL parameterization leads to improved results of surface temperature and mixed layer depth in GFDL's CM4 coupled climate model, relative to observed climatological values. However, the improved results have a significant shallow bias for Summer mixed layer depth. This bias is hypothesized to be related to missing surface wave (Langmuir turbulence) effects within the model framework (see Fan and Griffies, 2015; Li et al, 2016).

Addition of Langmuir Turbulence to ePBL

To improve the Summer mixed layer depths for ocean simulations a new Langmuir turbulence parameterization was developed for the MOM6 ePBL boundary layer scheme. The new parameterization was constrained against Large Eddy Simulation (LES) of the boundary layer under conditions with varying wind speed (5-10 m/s), surface buoyancy forcing (-300 to 50 W/m^2), and wave conditions (wave-age ranging from 0.6, or young seas, to 1.2, which are well-developed seas). The three-dimensional, high resolution Large Eddy Simulations are chosen for a baseline because they are skilled at resolving a majority of the turbulent fluxes and have been modified to include the effect of Langmuir turbulence.

To emphasize the role of surface waves we show the results of the ePBL parameterization without Langmuir turbulence compared to the LES, including cases with and without Langmuir turbulence (Figure 2). Clearly, the total mixing (shown here as a vertical integral of the stabilizing turbulent buoyancy flux) is significantly underestimated for the blue shaded symbols, which are the cases where the surface wave effect is expected to be significant. When the surface wave effect is either absent or insignificant, the model performs as expected (Figure 4, red symbols).

Motivated by similar parameterizations of the Langmuir turbulence effect in KPP (an alternative vertical mixing parameterization, see Reichl et al. 2016, Li et al. 2016 and van Roekel et al 2018), the Langmuir turbulence contribution to ePBL is parameterized based on the Langmuir number (ratio of wind to wave forcing). By explicitly constraining the parameterization to fit the LES results we can skillfully capture the enhanced mixing due to surface waves (see Figure 5). The resulting ePBL modifications show significant improvement in prototype CM4 simulations including improvement of the bias in Summer mixed layer depths relative to observed climatological values. The next step of this work will be to conduct comparisons with a coupled wave-ocean model to fully understand the impact of surface waves on vertical ocean mixing and potential changes in future climate scenarios.

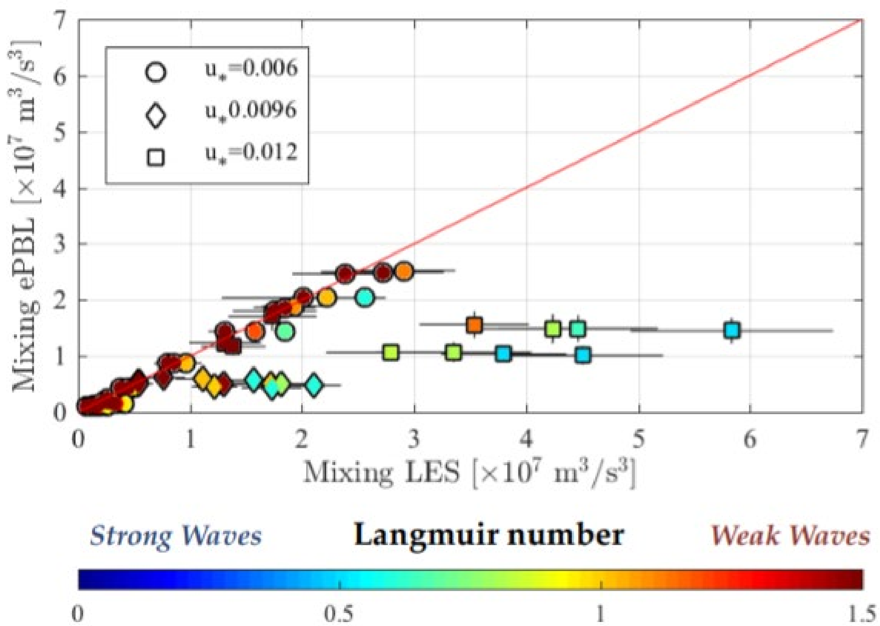

Figure 4: Integral of turbulent vertical buoyancy flux in regions of gravitationally stable stratification using ePBL embedded in MOM6, with comparison to LES. Values where there is significant departure from LES using ePBL indicate the missing effect of Langmuir turbulence.

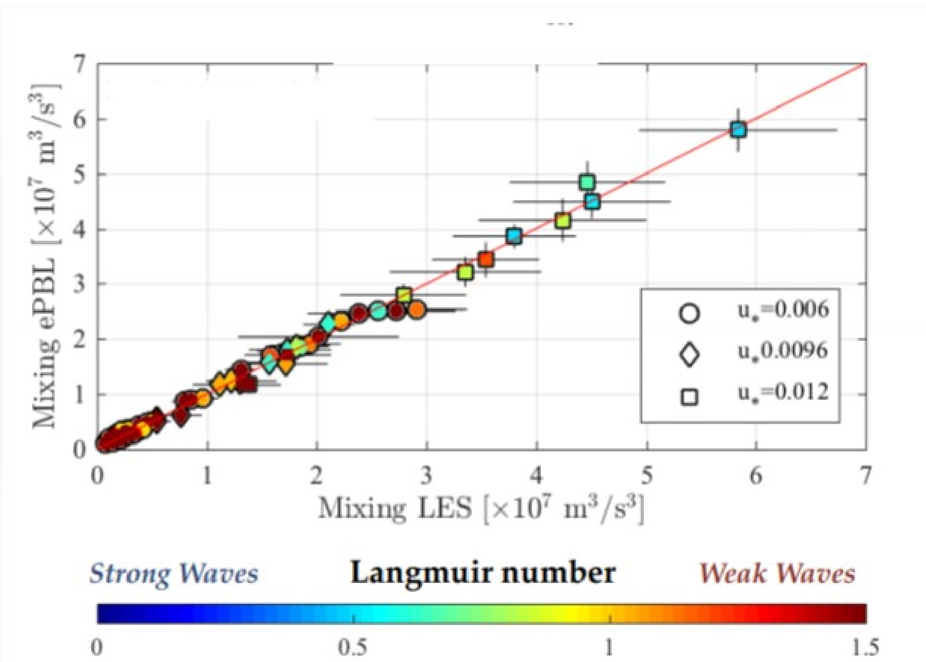

Figure 5: Similar to Figure 4, but now including the surface wave (Langmuir turbulence) parameterization within ePBL. Note the significant improvement in the agreement for the cases with strong waves, as compared to results in Figure 4.

4. Coupled model results

This modeling system is being developed with the aim of enhancing the next generation Global Ensemble Forecast System (GEFS) to provide environmental forecasts out to 35 days, and the next generation Seasonal Forecast System (SFS) to provide environmental forecasts out to 9 months. Both modeling systems are applications of NCEP’s Unified Forecast System (UFS).

With that in mind, initial testing of the coupled model has been done by carrying out 35 day reforecast runs. Since full Data Assimilation packages for MOM6, CICE5 and WAVEWATCH III are being developed in parallel, the focus on the tests here have been on the impact of the coupled physical processes during the model forecast. Initial conditions have been taken from current operational systems, (GDAS for the atmosphere and CFSR for the oceans and ice).

The grid configurations for these initial runs are as follows

- For the FV3 atmospheric model : A cube sphere grid at C96 (~100 km resolution)
- For the ocean and ice : A tripolar grid at ¼ degrees (~25 km resolution)
- For the waves : A regular lat - lon grid at ½ degrees (~50 km resolution)

Note, these grids are initial configurations to test the feasibility of the coupling. Work is currently undergoing to improve the efficiency of the wave model using a tripolar grid as well as using a higher resolution C384 grid (~ 25 km resolution) for the atmosphere. Results from these configurations will be reported when available.

Figure 6, shows the mixed layer depth at the end of the 35 day simulation, both with and without wave - ocean mixing in the coupled model. The mixed layer depth shows significant deepening in the Southern hemisphere where there is higher wave action.

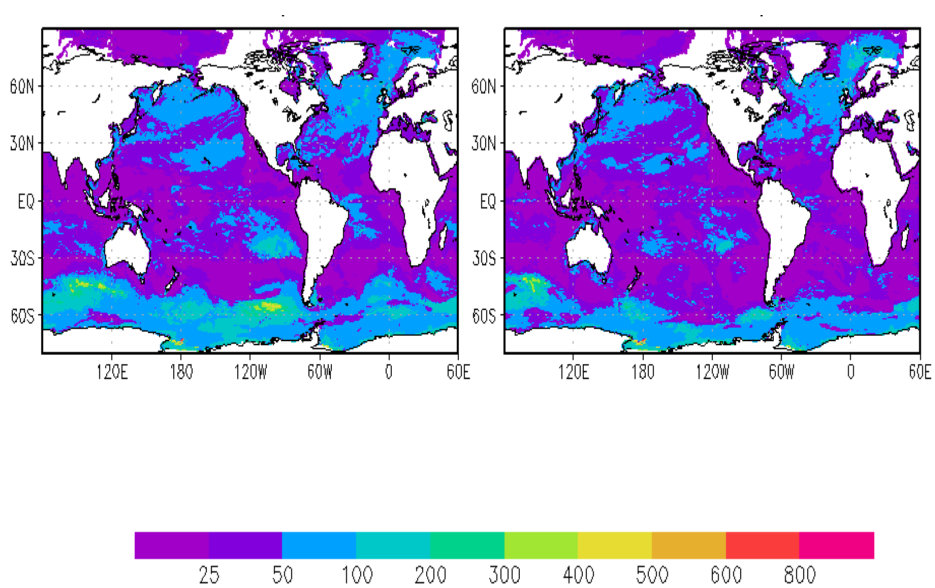

Figure 6: Mixed layer depth (in m) at the end of a 35 day simulation for a coupled system. Left panel: Including wave - ocean mixing; Right panel: Without wave - ocean mixing

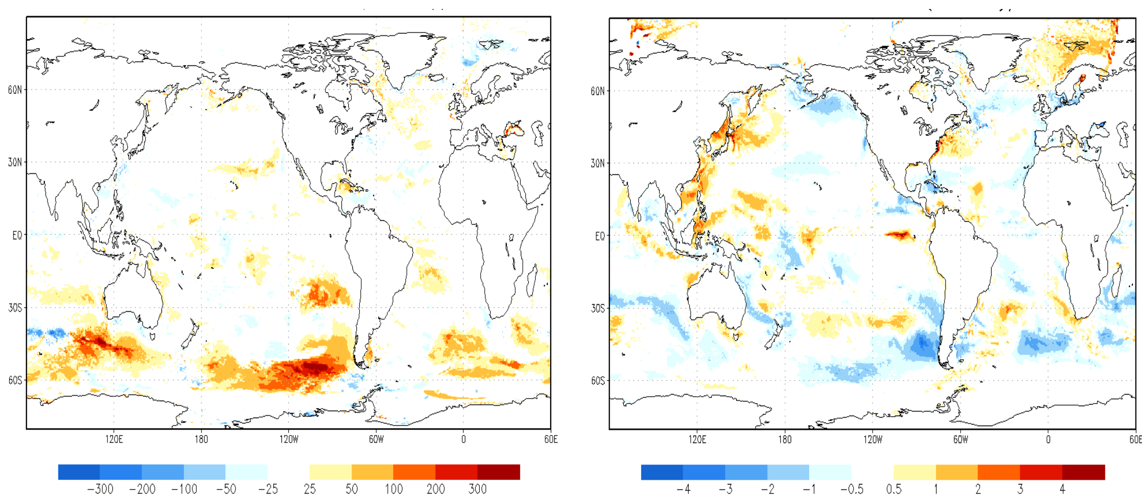

Figure 7: Impact of wave - ocean mixing on coupled model. Left panel: difference (with - without) in mixed layer depth (in m). Right panel: difference in SST (in C)

5. Highlights of Accomplishments

- A NUOPC cap for the MOM6 ocean model has been developed and tested as part of the Unified Forecast System (NCEP's next generation forecast modeling system)
- A fully coupled atmosphere - ocean - wave - ice modeling system has been developed that accounts for atmosphere - ocean, ocean - wave, atmosphere - ice and ice - ocean processes.
- The wave model was updated to account for singularities in wave propagation at the North Pole.
- Detailed testing of the fully coupled model has begun in preparation for transition to operations for S2S model guidance.

6. Issues remaining

A major issue that still remains (at the writing of this report) is that the solution for the tripolar grid propagation over the North Pole, while numerically accurate, is incomplete as it is not yet working in the wave model for parallel processing. While the coupled modeling system can be used for wave - ocean mixing process studies in regions away from the poles, for cases of wave propagation through ice free polar caps this is still a limitation. The solution to this is a technical one that we will be pursuing over the next month even though the project is coming to an end as this is a capability that is needed at both centers. We do not anticipate this to be a prolonged effort as we have a solution sketched out that will be implemented over the next few weeks.

In parallel, we shall begin benchmark testing of the mixing scheme and its impact on a fully coupled atmosphere - ocean - ice - wave model in sub seasonal (weeks 3 - 4) and seasonal range (up to 1 year) at EMC, and for longer time scales at GFDL.

7. Transitions to Applications

The coupled MOM6 - WAVEWATCH III system is being developed to be part of the next generation coupled seasonal forecast systems for the S2S range (GEFS and SFS) which will include fully coupled wave - atmosphere - ocean - sea ice - land systems. Adding the MOM6 NUOPC layer and refining the boundary mixing scheme as well as developing the coupling fields to exchange wave and ocean parameters through the NEMS mediator adds capability to the next generation seasonal forecast system.

A critical aspect of developing a coupled modeling system is a data assimilation process for each of the components. There is a parallel effort at EMC to develop a marine data assimilation system for MOM6, CICE5 and WAVEWATCH III. For the atmosphere, we will leverage the data assimilation capability of the atmospheric model that has been developed for operations. A prototype data assimilation system has been developed for WAVEWATCH III that is currently being tested, while those for MOM6 and CICE5 are in advanced stages of development.

The coupled modeling system is at an RL6 now. With the commencement of our benchmark runs, which is part of our development plans for the Next Generation Unified Forecast System (UFS), we will begin the transition to RL7. The whole system will move to RL8 with the inclusion of data assimilation. The model is slated for implementation in operations for sub seasonal forecasting (the GEFS model) in FY 2020/2021 and for seasonal forecasting (the SFS model) in FY 2022.

8. Publications

Reichl, B. G. and R. Hallberg, 2018 in review: A Simplified Energetics Based Planetary Boundary Layer (ePBL) Approach for Ocean Climate Simulations. Ocean Modelling, doi.org/10.1016/j.ocemod.2018.10.004

Reichl, B.G., and Q. Li, 2018 in prep: A parameterization with a constrained potential energy conversion rate of vertical mixing due to Langmuir turbulence

Reichl, B.G., S. Griffies, A. Adcroft, R. Hallberg: Addition of Langmuir Turbulence in a Hierarchy of Vertical Mixing Parameterizations for Ocean Climate Modeling. 20th Amer. Meteor. Soc. Conf. on Air-Sea Interaction. Madison, WI. Aug. 2016.

Reichl B.G.: An Energetic Model of the Upper Ocean Turbulent Boundary Layer Including Surface Wave Effects. GFDL Lunchtime Seminar Series. Princeton, NJ. Oct. 2016.

Reichl, B.G., S. Griffies, A. Adcroft, R. Hallberg: Ocean Surface Waves in Coupled Climate Modeling. 16th Annual Carbon Mitigation Initiative Meeting. Princeton, NJ. Apr. 2017.

Reichl, B.G., A. Adcroft, S. Griffies, R. Hallberg, Q. Li, and B. Fox-Kemper: An Energetically Constrained Ocean Surface Boundary Layer Parameterization including Surface Wave Effects for Climate Applications. 49th Liège Colloquium on Ocean Dynamics & 8th Warnemünde Turbulence Days. Liège, Belgium. May 2017.

Reichl, B. G., A. Adcroft, S. Griffies, R. Hallberg: Energetic Constraints for Vertical Mixing in the Ocean Surface Boundary Layer, AGU Ocean Sciences Meeting. Portland, OR. Feb 2018.

Van Roekel, L., A.J. Adcroft, G. Danabasoglu, S.M. Griffies, B. Kauffman, W. Large, M. Levy, B.G. Reichl, T. Ringler, M. Schmidt, 2018: KPP boundary layer scheme for the ocean: revisiting its formulation and benchmarking one-dimensional simulations relative to LES, Journal of Advances in Modeling the Earth System (JAMES), doi:10.1029/2018ms001336.

Meixner, J., B.G. Reichl, J. Wang, A. Chawla, S. Griffies, R. Hallberg, and A. Adcroft: Impact of a Langmuir Mixing Parameterization in a Coupled Climate System, AGU Ocean Sciences Meeting. Portland, OR. Feb 2018.

9. PI Contact Information

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