Upgrading the CPC operational ocean monitoring to an eddy-permitting global ocean analysis using the Hybrid Global Ocean Data Assimilation System as a replacement for GODAS (NA16OAR4310140, 08/01/2016 - 07/31/2020)

1) General information

Project title: Upgrading the CPC operational ocean monitoring to an eddy-permitting global ocean analysis using the Hybrid Global Ocean Data Assimilation System as a replacement for GODAS

PI/coPI names and institutions: PI: James A. Carton(U.MD.), Stephen G. Penny (NOAA/CIRES), Yan Xue (NOAA)

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2) Major goals as outlined in the funded proposal

● Upgrade the Global Ocean Data Assimilation System (GODAS) ocean/sea ice model to the latest MOM6 ice/ocean numerics from GFDL including a shift from 1deg to 1/4-deg resolution.
● Increase the number and type of observations assimilated
● Improve GODAS Data assimilation (DA)
-- directly update salinity and sea level
-- upgrade the DA system to a hybrid system combining the Local Ensemble Transform Kalman Filter (LETKF) and 3DVar.

3) Results and Accomplishments

3.1) ocean/sea ice model upgrade

We have completed the upgrade the ocean/sea ice model from MOM4/SIS1 1° to MOM6/SIS2 OM4 1/4° resolution, retaining the z* (essentially iso-pressure) vertical coordinate. This upgraded model is now being adopted by the marine subsection of the new NOAA Unified Forecast System Research to Operations (SOCA) project being led by Guillaume Verniere.

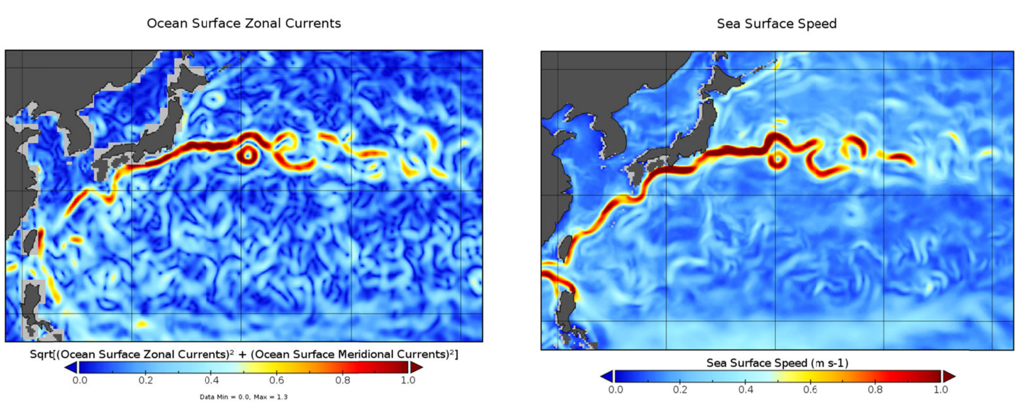

Figure 1 Comparison of the new MOM6/SIS2 OM4 1/4° resolution model surface currents with the independent OSCAR surface current estimate for a single day.

We have conducted studies examining the impact of bias in the surface fluxes (heat, freshwater, and momentum) provided by the atmospheric system by comparing results using a variety of different surface forcings such as CFS-RR, ERA-Int and ERA5. We have also examined the impact of alterations of the bulk formulas by which those fluxes are produces (e.g. COARE4). This examination shows that by changing these bulk formulas we change time mean net surface heat flux by 10 Wm^{-2} in high wind regions such as the Southern Ocean corresponding changes in net evaporation (greater changes to instantaneous values). If we interpret change as an estimate of the size of the flux error then such a flux error translates to a 0.1K error in a 100m deep mixed layer, as well as a 2cm error in evaporation when accumulated over 40dy. In effect this means that as many as 1/3 of the in situ profile observations are being wasted simply correcting for flux bias. Comparison of the full net surface fluxes from CFSR and ERA-Int shows even larger time mean net heat flux differences, as much as $30Wm^{-2}$, due to differences in the size of the state variables (SLP, U10m, T2m, and q2m) that enter the bulk formulae and in the cloud cover (area and cloud type). *All of this means that unbiased estimates of ocean variables, such as temperature or salinity, require that the DA be modified to account for surface flux bias at the* $10Wm^{-2}$ *level*.

3.2) Expansion of the numbers and types of observations being assimilated

The most dramatic increases are of salinity and sea level through the inclusion of the salinity profiles from Argo and altimeter sea level (https://www.star.nesdis.noaa.gov/sod/lsa/RADS.php). The annual report for Year 3 summarizes the remotely sensed and in situ observations now entering GODAS and their sources, but the list is fairly comprehensive. We have also developed a full set of quality control checks: duplicate checks, depth checks, gross error checks, climatological checks, density inversion checks, time averaging, and BUFR compatibility (https://github.com/UMD-AOSC/OceanObsQC). One lingering problem is that SST updating relies on the bias-corrected along track night-time satellite SST data (L2) from the Advanced Clear Sky Processor for Ocean (ACSPO). At polar latitudes this SST data set is sparse or absent due to sea ice cover, low cloud decks, low air humidity, and an inability to separate water and ice in the marginal ice zone. *In those locations GODAS SST defaults to WOD climatological values which are themselves based on a limited observation set. This lack of constraining data is highlighted by the fact that the regular data stream such as is accumulated in the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) is also missing temperature observations under sea ice*.

3.3) Improve the data assimilation (DA)

We have upgraded the GODAS 3DVAR of Behringer (2007) with a new 3Dvar solver, which shifts from model to observation space using the preconditioned conjugate gradient solver, similar to Navy's NCODA system (https://github.com/UMD-AOSC/godas-3dvar). We have incorporated this new solver into the Hybrid-GODAS developed from Penny et al (2015) (https://github.com/travissluka/UMD-LETKF). For the new Hybrid-GODAS, 20 ensemble members were used. The horizontal localization scale was defined as 1 standard deviation of a Gaussian, linearly interpolated based on observation type and latitude. Profiles: 550km at equator, 300km at 10N/S, 100km poleward of 50N/S; SST/ADT: 200km at equator, 50km poleward of 10 N/S. The new system workflow is diagramed in **Fig. 2**.

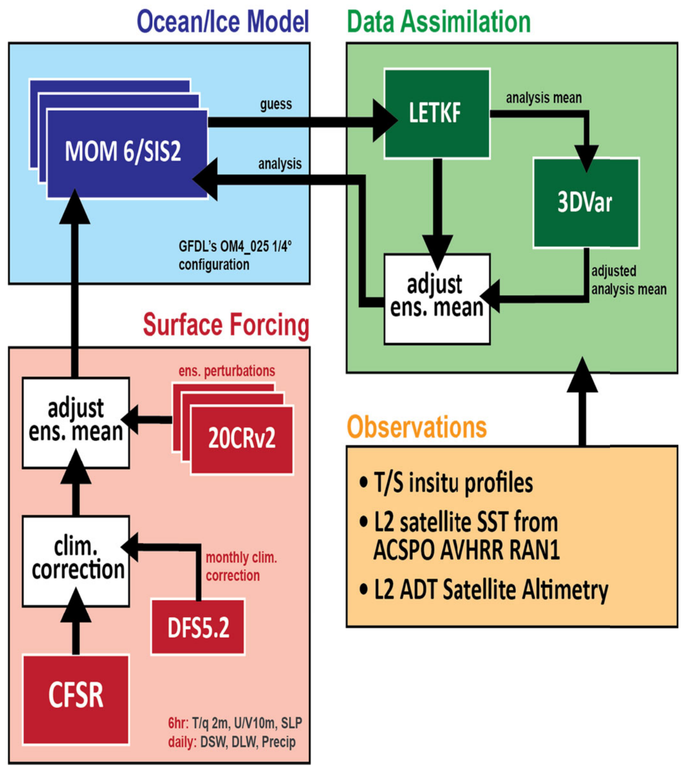

Figure 2 Schematic diagram of the Hybrid-GODAS.

All DA codes have been migrated to the JEDI framework (https://github.com/travissluka/UMD-LETKF). The new DA code is forming the basis for the marine subsection of the NOAA Unified Forecast System Research to Operations project SOCA. *This project has represented one of the initial tests of the JEDI system, which we think has great potential for organizing much of NOAA's modelling, data assimilation and data handling software.*

3.4) Opportunities for training and professional development

The knowledge gained by the postdoc associated with this grant, Dr. Travis Sluka, is now being put to work as he heads the ocean/sea ice development portion of the NOAA Joint Effort for Data assimilation Integration (JEDI) project, and continues his interest in the new SOCA project.

4. Highlights of Accomplishments

- Implement new ocean/sea ice model with enhanced resolution
- Implement new data inputs
- Implement new/improved data assimilation
- Convert to the JEDI software framework

5/6) Transitions to Applications/Estimate of current technical readiness level of work
Much of the results of this project are being implemented operationally through the follow-on project.

7) Dissemination/Publications
Results from the grant have already been disseminated through a series of talks at meeting such as the AGU, Ocean Obs19, AMS, Ocean Sciences by Penny, Carton, and Sluka. Results of this project have entered a series of refereed publications (below). Finally, the project has helped set directions for the $12M marine subsection of the new NOAA Unified Forecast System Research to Operations project.

7.1) References acknowledging the award

Penny, S.G., 2017: Mathematical foundations of hybrid data assimilation from a synchronization perspective. *Chaos,* **27**, 126801; doi: http://dx.doi.org/10.1063/1.5001819

Sun, L., and **S.G. Penny**, 2019: Lagrangian Data Assimilation of Surface Drifters in a Double Gyre Ocean Model using the Local Ensemble Transform Kalman Filter. *Mon. Wea. Rev*., **147**, 4533-4551. https://journals.ametsoc.org/doi/full/10.1175/MWR-D-18-0406.1

Penny, S.G., E. Bach, K. Bhargava, C-C. Chang, C. Da, L. Sun, T. Yoshida, 2019: Strongly coupled data assimilation in multiscale media: experiments using a quasi-geostrophic coupled model. *Journal of Advances in Modeling Earth Systems*, 11. https://doi.org/10.1029/2019MS001652 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019MS001652

7.2) Separately funded references that benefitted from the award

Penny, S.G., S. Akella, M.A. Balmaseda, P. Browne, 2019: Observational Needs for Improving Ocean and Coupled Reanalysis, S2S Prediction, and Decadal Prediction, Front. Mar. Sci., 11| https://doi.org/10.3389/fmars.2019.00391

Fox-Kemper, B., A. Adcroft, C.W. Böning, et al. 2019: Challenges and Prospects in Ocean Circulation Models, Front. Mar. Sci., 26 February 2019 doi.org/10.3389/fmars.2019.00065

Carton, J.A., S.G. Penny, and E. Kalnay, 2019: Temperature and Salinity Variability in the SODA3, ECCO4r3, and ORAS5 Ocean Reanalyses, 1993–2015. J. Climate, 32, 2277–2293, https://doi.org/10.1175/JCLI-D-18-0605.1

7.3) Presentations related to the award

Sluka, T., and S. Penny, 2018: OS44A-02: NCEP's Hybrid-GODAS: A Path towards an Operational "Strongly Coupled" Ocean/Ice/Wave Data Assimilation System, Fall meeting of the AGU, https://agu.confex.com/agu/fm18/meetingapp.cgi/Paper/465697

Sluka, T., Y. Xue, S. Penny, J. Carton, and H.-C. Lee, 2018: Upgrading NCEP's operational ocean monitoring system with Hybrid-GODAS, Oceanpredict, http://oceanpredict19.org/splinter-session-d/#54

8. PI Contact Information

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Cumulative net outcomes and impacts of the project, as of the writing of the report
This grant was primarily focused on upgrading many aspects of the global ocean data assimilation system GODAS, which has remained essentially unchanged for 20 years.