Oceanic Energy Cascade to Global from Regional Predictive Models

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LONG-TERM GOALS

The long-term scientific goals of this research project are:

1. Examine how small-scale energy input (such as vorticity) may alter the predictability of global models
2. Examine the fluctuations in the NECC and its sensitivity to these small-scale inputs
3. Using advanced state-estimation techniques identify the energy inputs and how they propagate out to large-scale models
4. Examine the sensitivity of the state-estimate to observations at the island-scale

OBJECTIVES

The primary objectives of this project are: (i) produce a suite of high-resolution state-estimates of the Western Pacific and region around Palau (including Yap) that include tides and are constrained by observations collected as part of the Flow Encountering Abrupt Topography (FLEAT) program; (ii) Use these state-estimates to examine how small-scale energy injected into the ocean cascades to lower wavenumbers; (iii) Examine how the excitation of the lower wavenumbers by the local processes affects the predictive skill of global models; (iv) Examine how well the local observations constrain estimates of the local processes that are missed by global models; and, (v) transition the results and methodology to NRL for further examination and possible inclusion into NRL operations.

APPROACH

We are using a unique multi-model approach that is well integrated into the FLEAT program to examine how the energy cascade is influencing predictability in the Western Pacific. In particular, we are examining the meander and variability of the NECC to identify how and if local processes in the FLEAT region impact the NECC variability. Meanders of the NECC affect the predictability of global models across the entire Pacific basin, so small-scale variability in the Palau region that affects the NECC will impact global model predictions.

A pre-cursor to understanding energy transfer across scales is characterizing the variability in the circulation features and how they are forced. Sverdrup [1947] was the first to solve for the steady state circulation, and there has been recent progress in understanding the large scale controls on its variability. The Sverdrup balance comprises a series of large-scale alternating zonal currents across the Pacific basin including the South Equatorial Current (SEC), the North Equatorial Counter Current (NECC), and the North Equatorial Current (NEC). The currents are bounded to the west by the Philippines and New Guinea, and the circulaiton features are closed by the northwards and southwards flowing (respectively) geostrophically adjusted western boundary currents [Qu et al., 2012], the New Guinea Coastal Current (NGCC) and the Mindanao Current (MC). Just south of the Philippines, the southward flowing MC and northward flowing NGCC converge to feed the eastward flowing NECC. There are also a pair of quasi-permanent large-scale counter-rotating eddies just to the east of Mindanao (Mindanao Eddy; ME) and Indonesia (Halmahera Eddy; HE). In a 1.5 layer reduced-gravity model, Arruda and Nof [2003] showed that these eddies are necessary features to close the non-linear momentum budget on a β-plane.

A major goal of this proposal to provide useful techniques, ideas, and methodologies to the Navy that can be integrated into the operational context. While the work within this proposal is of basic research, results and experimental design will be shared with the NRL team throughout the period of this proposal.

ACCOMPLISHMENTS

- We have developed a 4D-Var ROMS model of the Western Pacific at 1/14 and performed a 4D-Var state estimate from 2014Oct., 2016 using a total 40,855,539 observations with an average of 284,000 observations for each 7-day period. Observations included: NAVO SST, Along-Track SSH from several satellites, Aquarius SSS, Argo (T, S), Spray Ocean Gliders (T, S) from Dan Rudnick/FLEAT, TAO moorings (velocity, T, S) (Figure 1). Model includes full tides (barotropic and baroclinic), and adjusts initial conditions, boundary forcing (HYCOM), and atmospheric forcing (GFS). The State-Estimate is constrained by the physics of the model (rather than prescribed statistics) and minimized the residuals between the observations and the model (Figure 2).

- As state-estimation relies on the model physics, the impacts provide a means for identifying which dynamics connect the ocean. We have implemented and calculated the impact of these observations on a single metric in the region and will use other metrics to get at vorticity and super-inertial energy. Information from the observations can be connected to an ocean metric of our choosing via advection, baroclinic waves, or barotropic waves. We have quantified the impact of the observations to constrain the eastward transport of the NECC across 142E for 20 months of the reanalysis (20148/2015). The analysis alters the transport on average by 0.5 Sv (Figure 3). Examining how each individual observation changes the transport estimate, we sum by instrument platform and examine the percentage of the increment that is contributed by each platform. The Spray Gliders and TAO have significant contribution to the transport in relation to the number of observations from those platforms.

- We have developed a 4D-Var ROMS model of the FLEAT region at 1/44 that is nested within the 1/14 state estimate, including remotely generated baroclinic tides, etc. We have assimilated one year of observations and will continue once all FLEAT obs are recovered. Fine-scale model (1/44) nested within the state-estimate and forced by the reanalysis ocean and atmosphere. This model is used to examine the role of topography compared to global-scale. Output from this fine-scale is used by Merrifield (UH) and Simmons (UAF) groups and available for others.

- Analysis of the region find that values of $N/(f+|\zeta|)$ below 10 suggest that an inverse cascade of energy is possible [Marino, et al., 2015]. We find values within this range around the topography in the fine-scale solution. Calculating the energy flux as a function of wavenumber from the fine-scale model shows that wavelengths above 45km have energy input from shorter wavelengths. The spectral energy flux is calculated for a 100m layer from the surface and it reveals that energy in our model has both a forward cascade as expected by three-dimensional stratified geostrophic turbulence theory and an inverse cascade towards larger scales that is characteristic for two-dimensional geostrophic turbulence. The strength of both the inverse and forward cascades is stronger in the topography diverse western half of the domain than it is in the relatively flatter eastern half, which are partially separated by a north-south aligned ridge and the island of Palau.

- We find that energy injected is into the ocean by the steep topography via conversion from barotropic to baroclinic tides and from lateral flow into vorticity). Positive dominates negative vorticity on both sides of Palau in the large-scale model; however, in the fine-scale, negative vorticity dominates the western side. This injection into vorticity from the topography depends on the flow.

- As 2015 El Nio ended and the basin-wide pressure gradient reformed, the NECC meandered north of Palau from MayOct, 2016. The additional topography resolved by the fine-scale enhanced and broadened the NECC meander. Local impacts on Palau were significant (Terrill group). Upon the end of an El Nio event, the restoration of the Pacific pressure-gradient forces the NECC to the North, and warm waters return to the region. The shift is rather sudden at Palau, but the NECC flowed North of Palau from late-March, 2016 until Oct, 2016 as the western warm pool reformed.

Year 3 Plans

- We will work with Cornuelle to examine how the control vectors of the two state-estimates account for mismatches in resolved energy between island-scale, medium-scale regional, and large-scale global models. The state-estimate will adjust the boundaries of the models, which provides valuable information into the energy flux to/from the outer model.

- Working to characterize the role of vorticity on the large-scale. Dynamical analysis with adjoint tools (observational impacts).

- Process observations collected in the FLEAT field experiment (including HF radials, moorings, etc.)

- Produce a state-estimate of the fine-scale grid assimilating FLEAT observations from 2015–2017.

- Repeat dynamical analysis on new state-estimate

- Examine the control vector from the fine-scale reanalysis to identify spectral biases in the large-scale model: indicative of missing energy

- Provide state-estimate model output to other FLEAT PIs

From the results accomplished, we are working on a manuscript to detail the state-estimate solution. We are also working on a second manuscript investigating the meander of the NECC. Using the 1/48° model, we will compare to the 1/12° to examine increased vorticity and resulting variability in NECC meanders. In addition, using the state-vectors of the 1/48° simulation, we can understand what the coarser model is not resolving.

IMPACT/APPLICATIONS

This is an important multi-institute, multi-investigator team including MIT, NRL, SIO, UAF, and UH. In collaboration with Bruce Cornuelle, Maarten Buijsman, Hemantha Wijesekera, and others, the results from this collaborative proposal will be made available with the expectation that they will be incorporated into NRL operational systems that utilize a wide variety of oceanographic observations.

At UH, one female post-doctoral scholar is funded by this effort, and will be trained in assimilation, prediction, and ocean energy budgets.

TRANSITIONS

We will be working with Maarten Buijsman to evaluate the new HYCOM 1/25° model with tides and provide information about the small-scales that influence the NECC to help with NRL transitions and parameterizations. Using the adjoint model, we will identify the corrections that are often made to the HYCOM simulation from our work to provide information about biases, unresolved scales, etc. to the NRL group.

RELATED PROJECTS

This project is collaborating with a number of ONR sponsored investigators:

- Pierre Lermusiaux, MIT
- Hemantha Wijesekera, NRL
- Bruce Cornuelle, Scripps
- Dan Rudnick, Scripps
- Harper Simmons, UAF
- Mark Merrifield, UH

In addition, work from this project is being used as data and boundary conditions for other groups within FLEAT.

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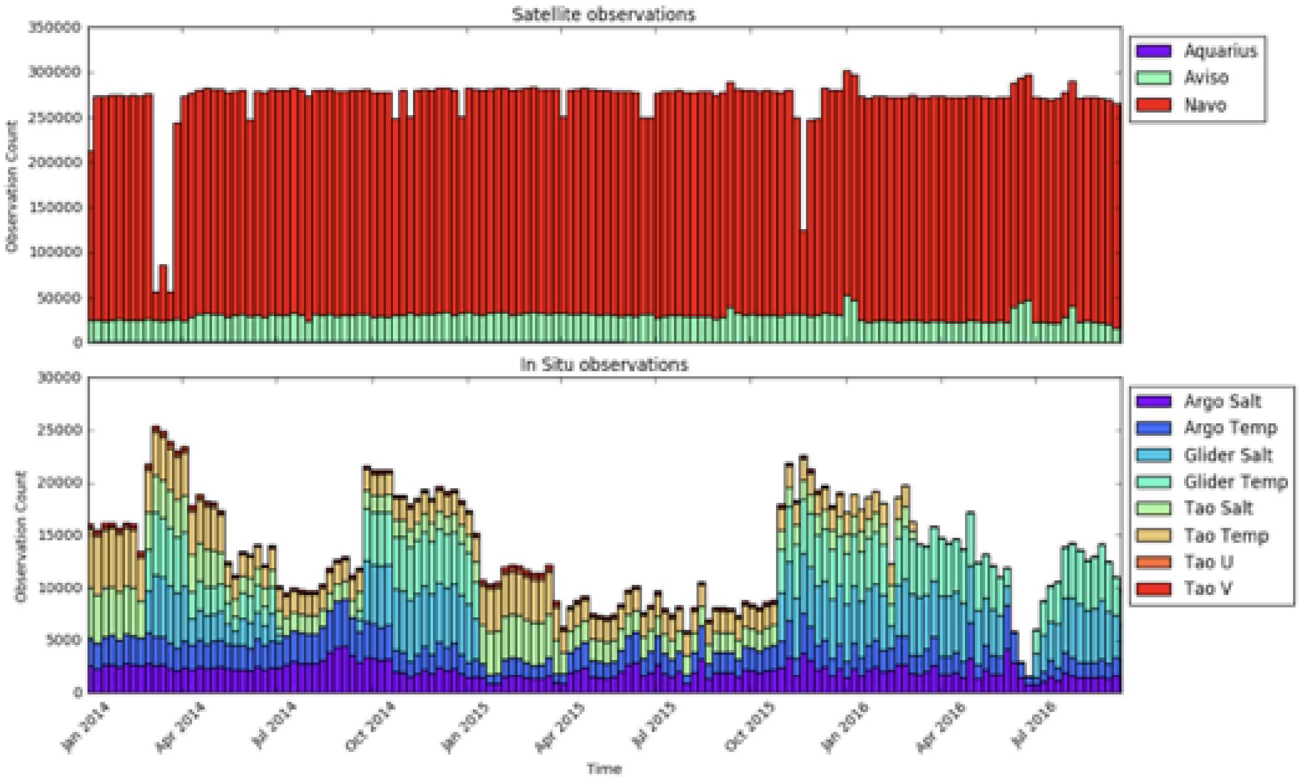

Figure 1: Number of observations used for the state estimate. Nearly 41M observations were used over 18 months.

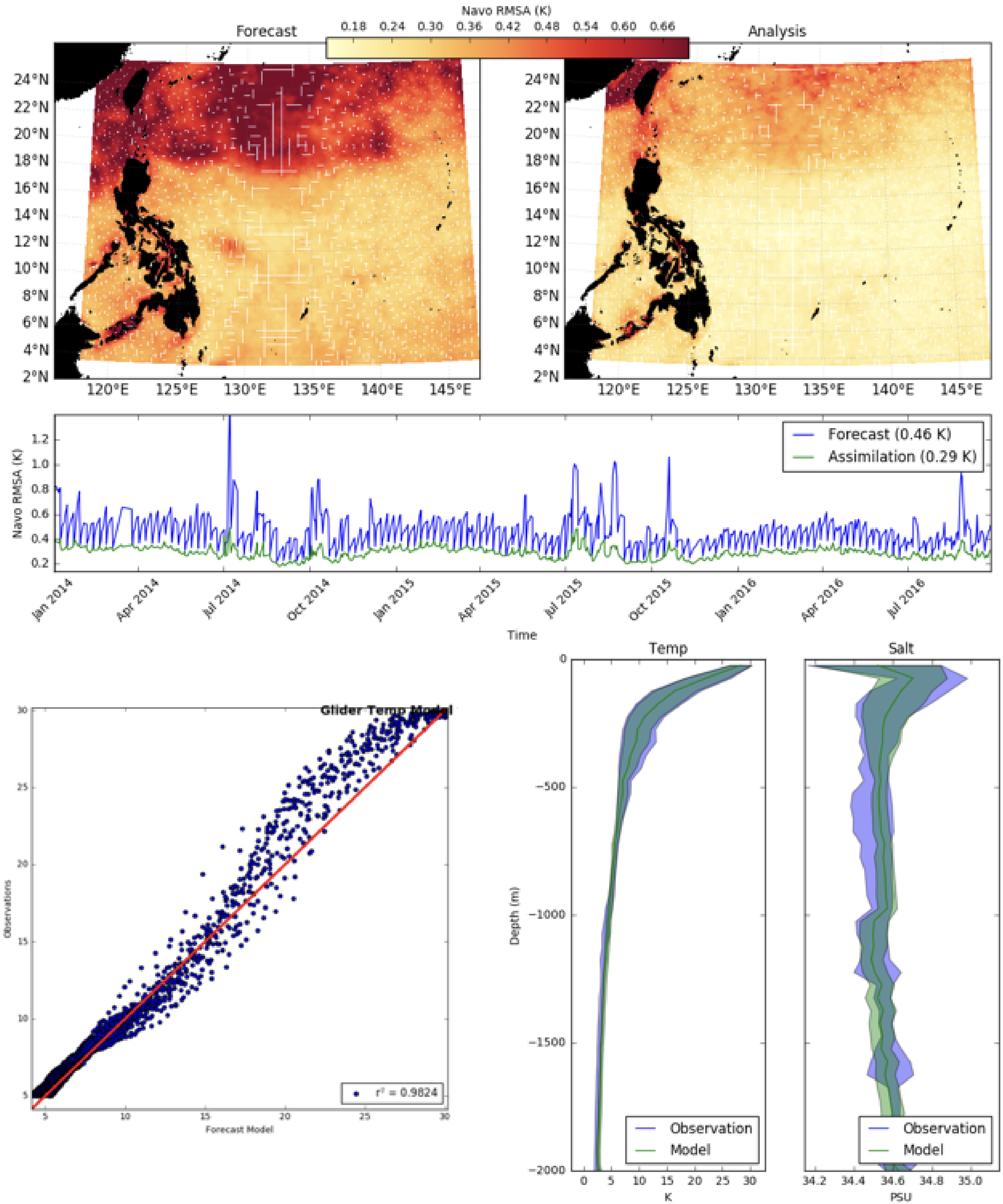

Figure 2: Comparison of the state estimate and observations. Upper panel shows the forecast and analysis maps of RMS between SST observations and model. Lower left panel compares Spray glider temperatures with model, and Lower right panel shows comparison of all *in situ* observation profiles.

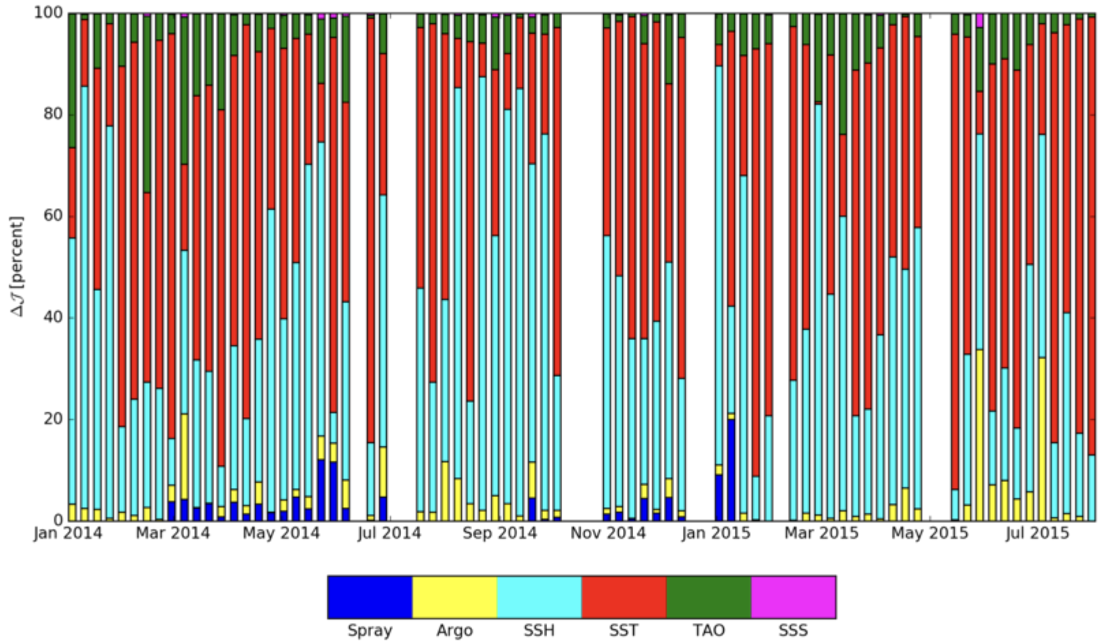

Figure 3: The relative impact of each observation type in determining the transport of the NECC. Despite the small number of Spray and TAO observations, they exhibit a strong impact upon the transport estimates.