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14. ABSTRACT
The long-term scientific goals of this research project were:
i. Examine how energy is transferred across scales in the Western Tropical Pacific
ii. Examine how topography influences the NECC and its influence on the energy transfer
iii. Using advanced state-estimation techniques identify the energy inputs and how they propagate out to large-scale models

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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 were:

1. Examine how energy is transferred across scales in the Western Tropical Pacific
2. Examine how topography influences the NECC and its influence on the energy transfer
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 were to: (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 utilized 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

This project was a collaboration with a number of other PIs in the Flow Encountering Abrupt Topography project. As such, the accomplishments highlight activities around this collaboration.

- Published a paper showing the impact that the abrupt topography has on the energy cascade of the western Pacific as part of the FLEAT special issue [Zedler et al., 2019]. Of particular interest for predictability is the result that the islands change the length-scales of energies by weakening the peak by broadening the energy across scales, as shown in Figure 1 attached. Most importantly for numerical prediction, is that to resolve this process, we must move to much higher resolution than is typically used in global ocean prediction.

- Collaborated on a published paper examining the predictability of scales around Palau and how numerical downscaling improves the estimate of the small scales that shed from the island [Simmons et al., 2019]. This is a complement to the above paper that shows these small scales impact the larger-scale predictability. The attached Figure 2 shows that as finer scales are resolved, there is a further broadening of the energy across scales, with a particular shift towards cyclonic flows.

- Collaborated on a published paper examining the breakdown of the NEC at the end of El Niño phase [Qiu et al., 2019]. These changes lead to abrupt and significant changes in the upper water column temperatures that impact corals (particularly deep corals) around Palau.

- Processed, quality controlled, and validated observations from satellites (SSH, SST, SSS), Argo, TAO, FLEAT (gliders, CTDs, acrobat, and moorings)

- Generated methods to analyze the location and variations of the NECC intrusion latitude to examine the role of upstream variability in vorticity, drag, and other fields in the variability of the HLCC

- Provided data and atmospheric forcing fields to Harper Simmons's group at UAF for their high-resolution simulations.

- We have developed a 4D-Var ROMS model of the Western Pacific at 1/14° and performed a 4D-Var state estimate from 2014—Oct., 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 142°E for 20 months of the reanalysis (2014—8/2015). 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 Niño ended and the basin-wide pressure gradient reformed, the NECC meandered north of Palau from May–Oct, 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 Niño 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.

- Using the above model, we have collaborated with other FLEAT investigators to obtain the data collected as part of the FLEAT program including: Spray Gliders, HF radar, Pressure instruments, mooring data from multiple groups, SeaSoar, and ship-based CTD. In addition, satellite data (temperature and height anomalies) along with Argo, TAO, and other observations of opportunity were gathered. This resulted in a total of over 7.6 million observations that were processed to be assimilated into the 1/44° model. This effort was significant to process more than a dozen different file formats, analyzing errors of each instrument type, etc.

- As per the hypothesis laid out in the original proposal, there is a significant difference in the energy regime and transfer between the 1/44° and 1/14° models. As shown in Figure 1, the energy input is at the same scales between the coarse and fine models at the Rossby radius scale; however, there is virtually no inverse cascade in the larger-scale 1/14° model; whereas, the finer scale has a strong inverse cascade that begins around the 300km wavelength.

- The energy cascade, however, is highly variable in time. During the FLEAT project, we experienced the large 2015 El Niño event with the 2016 restoration to normal conditions. Examining the annual mean energy cascade for the FLEAT period in Figure 2, we see the variability present. In 2016, there was no inverse cascade, while 2015 and 2014 were very similar. The reasong for this was the arrival of multiple planetary Rossby waves signalling the end of the El Niño phase and restoring the thermocline depth. As these waves arrived, they had a significant impact upon the region by deflecting the NECC to the north and breaking down the mean flow. This chnaged the way that energy was transferred by destroying the NECC jet into multiple gyres and a forward cascade toward dissipation.

IMPACT/APPLICATIONS

This is an important multi-institute, multi-investigator team including MIT, NRL, SIO, UAF, and UH. In collaboration with Bruce Cornuelle, Hemantha Wijesekera, and others, the results from this collaborative proposal will be made available to the FLEAT group, NRL, and other interested parties.

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

TRANSITIONS

The results of the energy cascade help to provide an estimate of the importance of parameterizing Palau in large-scale models.

RELATED PROJECTS

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

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

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

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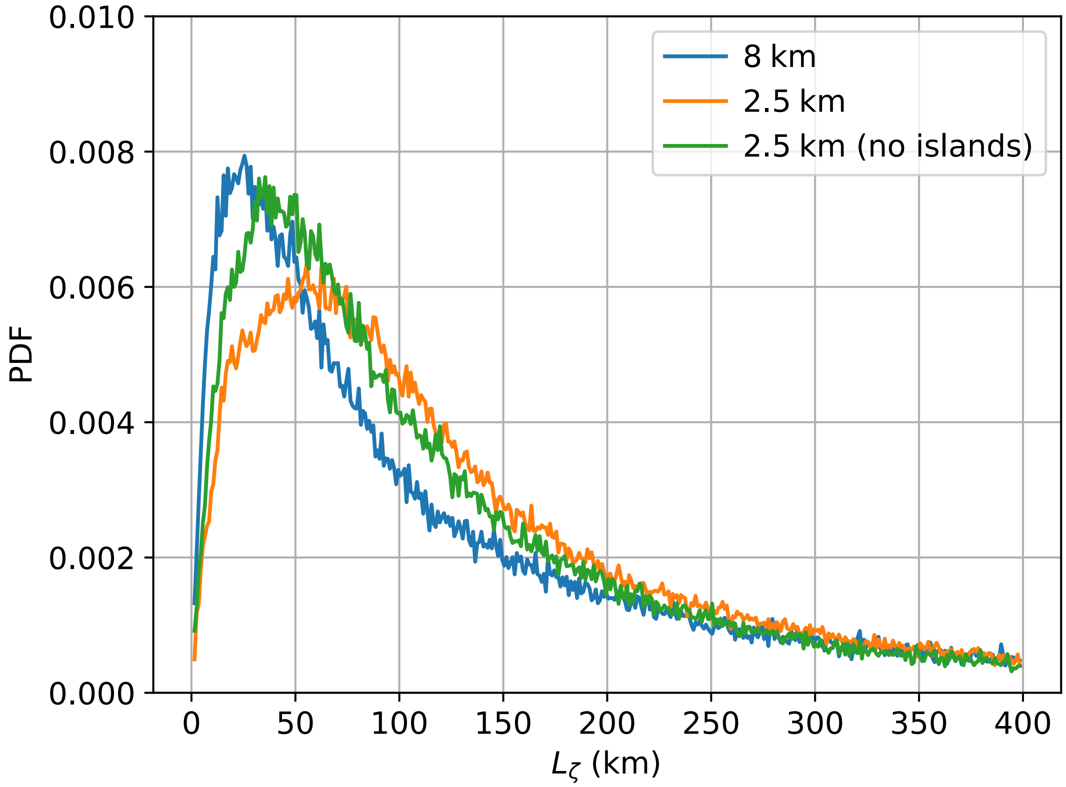

FIGURE 6. Snapshot of probability distribution of length scales in kilometers on January 16, 2015, in 8 km and 2.5 km models for Region D of Figure 1.

Figure 1: Figure 6 from Zedler et al. [2019].

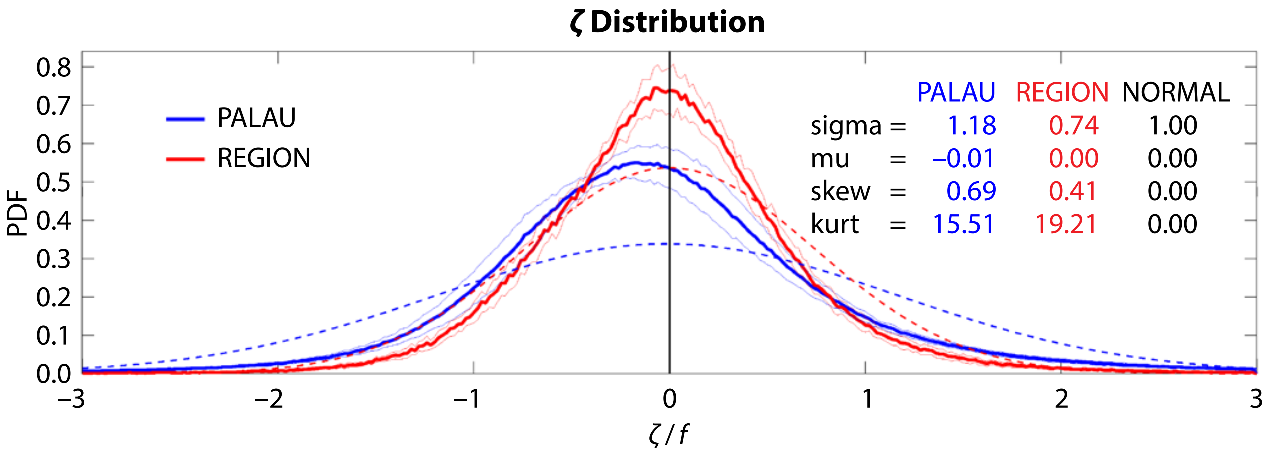

FIGURE 6. Histogram of surface relative vorticity in the PALAU and REGION models during August 2016. Bold lines are the mean histogram, and light lines indicate one standard deviation over the month. Dashed lines indicated a reference normal distribution with mean of zero and standard deviation of one.

Figure 2: Figure 6 from Simmons et al. [2019].