Understanding Predictability of the Ocean

Brian Powell, Ph.D.
University of Hawaii
1000 Pope Rd., MSB
Honolulu, HI 96822
phone: (808) 956-6724 fax: (808) 956-9225 email:powellb@hawaii.edu

Award Number: N00014-09-1-0939

LONG-TERM GOALS

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

1. To develop an understanding of how some observations affect ocean predictability.
2. To further develop the state-of-the-art ROMS 4D-Var by extending the observational types and applications.
3. To gain experience and develop ideas for the limitations to the predictability of oceanic processes.
4. To train a new generation of students in data assimilation and ROMS.
5. As a YIP award, to strengthen the early career and build the research path for myself as young faculty.

OBJECTIVES

The primary objectives of this project are: (i) explore the capabilities of a real-time ocean state-estimation and prediction system; (ii) to assess how particular observations may affect predictability; (iii) to compare these results with full ocean-state estimates generated from the ΨEX acoustic experiment; and, (iv) provide means to build a research program for early career scientist.

APPROACH

In this YIP award, my aim is to characterize the factors that control predictability in the ocean, particularly around Hawaii and the North Philippine Sea (which resides within the internal wave train from the Luzon Strait as well as interacting internal waves generated at the Mariana islands). To accomplish this goal requires a number of studies into understanding the role of internal tides interacting with mesoscale energy, quantifying the role of observations in sampling such difficult dynamical regimes, extending the capability of the assimilation procedure to utilize advanced observational datasets (high-frequency radar and acoustic tomography), develop further improvements to the state-estimation procedure, and to help quantify the role of errors in models. Furthermore, as a YIP award, the goal is to build a successful academic research program under my direction. Because of the large scope of these issues, the work carried under this YIP award both leverages and contributes to work in other funded projects.

As part of the NOAA-funded Integrated Ocean Observing System (IOOS) effort, I lead the ocean modeling effort of the Pacific IOOS (PacIOOS) region. The ocean model used in this research is the ONR-funded Regional Ocean Modeling System (ROMS): a free-surface, hydrostatic, primitive equation ocean model discretized with a terrain following vertical coordinate system (Shchepetkin and McWilliams, 2005). ROMS has been successfully used to model many regions of the world ocean (see `http://www.myroms.org/papers`) and is a widely used community resource.

The oceanic modeling component of PacIOOS currently employs four nested ROMS models: 4km island-chain, 1km Oahu, 100m Oahu South-Shore, and 80m Oahu West-Coast. Each grid is nested in the grid above it (both the South and West models are nested in the Oahu grid), and the 4km is nested in the real-time NCOM. This system is currently running operationally, and it assimilates the previous four days of real-time observations into the 4 and 1 km models using 4D-Var to produce nowcast state-estimates. From the nowcasts, a seven day prediction is made, which is used by the local community (e.g., Coast Guard search and rescue, Shipping Routes, etc.). These efforts are both leveraged and extended from the work in this YIP. The system currently does not employ tides, and this is a significant shortcoming, as described above.

In addition, we have developed a model of the Philippine Sea for conducting corollary research in a region with significant energies at all oceanic length-scales from planetary (with the formation of the Kuroshio current) down to sub-mesoscale and strong internal tides. In collaboration with ONR Acoustics, we have worked on the ΨEx program to study the Philippine Sea and develop a technique for assimilation of acoustic travel time data from the experiment. The Philippine Sea is characterized by strong tidally induced internal waves, and internal tides are known to influence acoustic propagation (Duda et al., 2004). What is not well known is the combined effect that these varying energetic dynamical scales (internal tides, sub-mesoscale and mesoscale, and low-frequency dynamics) have upon the travel-times of acoustic rays in the Philippine Sea.

To improve forecasts of the ocean circulation, we must understand how both observations and model error (such as the incorrect tidal phasing) impact the predictability. Forecasts are limited by the growth of uncertainty, and the aim is to quantify the uncertainty in forecasting regional oceans to the observations and configuration. To expand our operational capabilities, we have developed and implemented assimilation techniques for HF radar and acoustic travel-times. To understand the importance of observations, we have implemented an adjoint of the observation-space assimilation procedure for the Hawaiian regional model to quantify the sensitivity of the forecast to satellite, autonomous gliders, and long-term fixed mooring data.

As part of the Young Investigator Program, development of a dynamic research group is one of the primary objectives. In the reporting year, in my group there were: three post-doctoral researchers, and two graduate students (1 M.S. level and 1 Ph.D.). One M.S. student graduated in the spring, and two post-docs have received permanent positions elsewhere.

WORK COMPLETED

As discussed last year, the focus of the work for this reporting period is on the Philippine Sea, a region of strong ocean variability and of significant national interest to the Navy.

During the current reporting period, we have completed the following tasks:

i) I have published a manuscript (Powell et al., 2012b) that quantifies the sensitivity of localized barotropic to baroclinic tidal conversion in Hawaii to the effects of remotely generated internal waves.

ii) We have published a paper (Kerry et al., 2012) that shows the important effects of remotely-generated internal tides on estimates of local tidal conversion in the Philippine Sea. In many regions of the world's oceans, remote internal tides (predominately Mode-1) propagate into the region and can significantly impact local tidal conversion. For regional modeling of regions with strong tides, this has significant effect on how the regional model is configured. She is now working to understand the interaction between the internal tides and the mesoscale on our ability to predict the mesoscale and represent observations that include all scales.

iii) I have implemented a scheme for both observational and data-space assimilation techniques to assimilate acoustic travel-time data. We are now working with the ΨEx group in ONR Acoustics to use their acoustic data from the Philippine Sea in our model.

iv) I have a manuscript (Powell et al., 2012a) that has been revised and is in further review using the adjoint to examine how the Philippine Sea affects the time variability of the acoustic travel-time. This work is important to the prior point because if the sensitivity to the ocean is significant (more than 200 msecs) and varying, it requires that our ocean estimate be consistent before we can attempt to assimilate the data.

v) We have published a manuscript (Matthews et al., 2012) for a three-year 4D-Var assimilation experiment with the 4km Hawaiian domain using all available data, including: satellite sea surface height (alongtrack), satellite sea surface temperature (raw swath data), *in situ* ADCP, autonomous SeaGliders, Argo, *in situ* CTD measurements, drifters, and moorings.

vi) We have had a manuscript accepted with minor revisions that coupled waves, wind, and ocean to examine the coastal processes that control an effluent outflow plume along the south shore of the island of O'ahu (Johnson et al., 2012). The results show that the effluence is mostly controlled by wind and wave mixing with tidal forcing acting to spread the flow alongshore. We developed a coupled biological model that helped show that the mixing effects helped to sequester the bacteria away from the UV light that killed it and enhanced retention.

vii) Using the assimilation results, I have computed the contribution (or impact) of every single observation to various measures of importance in the circulation of the Hawaiian domain. These results help us to quantify which observations are crucial to the improving the predictability of the region.

viii) I have a book chapter that has been accepted (Powell, 2012) examining how to avoid overfitting of observations using additional outer-loops in data-space 4D-Var methods. The paper examines the proper constraint and how ignoring the constraint improves the fit to the observations, but reduces the predictive skill of the model.

ix) Most significantly, the lessons of these assimilation experiments and observational impacts **are now in operational use** with the PacIOOS ocean estimation and prediction system. Results can be found at `http://pacioos.org/roms`

x) A total of 9 manuscripts have been published in top peer-reviewed journals in oceanography that have been fully or partially supported by this award.

xi) Mentored two post-doctoral researchers, three graduate students, and one technician.

RESULTS

A brief summary of some of the most interesting points from the work completed is described below.

Remote internal tides are found to affect barotropic to baroclinic conversion by altering the amplitude and phase of the bottom pressure perturbations in a complex, spatially varying pattern. In the Philippine Sea, the total conversion increases when excluding the influence of remotely generated tides from the opposite generation site. This influence depends on the amount of energy that reaches the site and the phase of the remote waves upon arrival. The flux from the Mariana Arc that reaches the Luzon Strait is weak compared to the locally generated flux; however, conversion at the Luzon Strait is increased by 11% when excluding internal tides generated at the Mariana Arc (a 1.83 GW difference) with a climatological stratification. The strong flux from the Luzon Strait most dramatically affects the energetics at the Mariana generation site. Conversion at the Mariana Arc for the simulation without the Luzon Strait generation site increases 65% without the Luzon Strait influence. The horizontal propagation patterns of the depth-integrated baroclinic energy fluxes from each site are also altered by the remotely generated fluxes.

Figure 1 illustrates how conversion at the Luzon strait is significantly impacted by the relatively weak arriving baroclinic flux from the Mariana Island Arc. When the Mode-1 energy from the Mariana arrive, conversion decreases, which in turn, will change the Marianas due to a change in the baroclinic flux from the Luzon. When Mode-2 from the Mariana arrives, it nearly coincides with the time required for the modified Mode-1 signal to arrive, and as time progresses, we see this cascade of Modal arrival and modification until reaching a steady state after nearly 60 days.

Low-mode internal tides may travel long distances across the ocean, and in this study the first three modes impact conversion at the opposing generation sites in the Philippine Sea, separated by 2600 km. There are few regions in the ocean that do not contain fluxes of internal tide energy. This work has implications for studies elsewhere, as global influence on regional conversion may be significant.

These internal tides have a significant influence on acoustic travel-times because of the isopycnal displacement that occurs along the ray path. Depending upon the phase of the internal tide when the acoustic signal propagates, there may be a change in the hundreds of msecs in the total travel-time. Examining the effects of internal tides and mesoscale using an adjoint model, we found that advection plays a significant role in distributing the sensitivity as shown in the longitude versus time of Figure 2. The panels reveal temporally varying advection, convergence, and divergence of sensitivity along the ray paths. Advection also spreads the sensitivities over 220 km over five-day periods, revealing that advective speeds of 50 cm s^{-1} are present near the turning depths. The advected sensitivities reflect the eddy field, which advects the information from the ray paths. The unfortunate implication of this is that it requires a consistent state estimate of the ocean for the period that the travel-time was observed. This will require that detailed consideration is given to the background ocean state estimate in order to attempt the tomography inverse problem in the Philippine Sea.

Mentoring of young scientists and students: Rebecca Baltes graduated with an M.S. in oceanography and is now working at the IOOS office of NOAA in Silver Springs, MD. Her degree was funded under this YIP, and her thesis was to examine the sensitivity of the forecasts around Oahu to observations performing OSSEs (Baltes, 2011).

Abby Johnson was partially supported under this award and graduated with an M.S. in oceanography in May, 2011. Her thesis (Johnson, 2012) was turned into a publication (Johnson et al., 2012) under support of this award.

Colette Kerry, a Ph.D. student in my lab, has been working to characterize the predictability of the Philippine Sea in the presence of internal tides interacting with the mesoscale. She has one paper published (Kerry et al., 2012) and one other draft near completion. Our goal is for her to defend her Ph.D. in 18 months.

IMPACT/APPLICATIONS

With our work on the interaction of internal tides with the mesoscale and the impact upon predictability, we are at the forefront of numerical modeling and oceanic mixing processes and combining these representations with observations with modified assimilation procedures. The role that the mesoscale plays in conversion will be very significant as our work has shown that the phasing of the remote internal tides is dramatically altered by the changing stratification due to mesoscale activity. This alters the flux beams and propagation speeds and greatly diminishes our predictive skill.

We are operating one of very few operational oceanic 4D-Var estimation and ensemble prediction systems. We are also the only one that generates daily observational impact analyses that we use to monitor the observations and understand how best to improve our estimate and forecasts.

As numerical models are becoming more widely accepted in oceanographic applications, a quantified estimate of the uncertainties must accompany any forecast to aid in the understanding of the generated fields. This project will contribute to the ROMS community by deploying methods to quantify how observations contribute to prediction. The foundation for this work is present only in ROMS as it is the only model that possesses such a wide range of 4D-Var algorithms. This project will contribute to further enhancement and development of these tools and algorithms.

TRANSITIONS

In addition to the published papers, the cutting edge work of the observational impact was presented at invited lectures in the past year. Dr. Powell presented an invited talk at AGU Ocean Sciences on operational use of satellite data, a talk on the importance of autonomous buoyancy-driven gliders to the NOAA National Glider Plan workshop, and the observational impact algorithm to the international adjoint workshop in Italy. In addition, Ms. Kerry was able to present her Philippine Sea results at the adjoint workshop.

We are also working with projects that collaborate with NRL-Stennis to facilitate open communication.

RELATED PROJECTS

This project is collaborating with the following ONR supported projects:

- "A community Terrain-Following Ocean Model (ROMS)", PI Hernan Arango, grant number N00014-08-1-0542.
- "North Pacific Acoustic Laboratory: Deep Water Acoustic Propagation in the Philippine Sea," PI Peter Worcester, ONR Grant N00014-08-1-0840.

In addition, with CEROS funding collaborating with Kevin Heaney and Patrick Cross at Oasis, Inc. and Bruce Howe at UH, I developed an assimilation scheme that when combined with a glider dynamical model is capable of geolocating autonomous gliders while underwater.

REFERENCES

B. Baltes. Observing System Simulation Experiments on the O'Ahu Regional Ocean Model. M.S. Thesis, University of Hawaii, 2011.

Timothy F. Duda, James F. Lynch, James D. Irish, Robert C. Beardsley, Steven R. Ramp, Ching-Sang Chiu, Tswen Yung Tang, and Ying-Jang Yang. Internal Tide and Nonlinear Internal Wave Behaviour at the Continental Slope in the Northern South China Sea. *J. Ocean. Eng.*, 29(4): 1105–1130, October 2004.

I. Janeković and B. S. Powell. Analysis of Imposing Tidal Dynamics to Nested Numerical Models. *Cont. Shelf. Res.*, accepted, 2011.

A. Johnson. Characterizing the Effluence Near Waikiki, Hawai'i With a Coupled Biophysical Model. Master's thesis, University of Hawaii, 2012.

A. Johnson, B. S. Powell, and G. Steward. Characterizing the effluence near Waikiki, Hawaii with a coupled biophysical model. *Cont. Shelf. Res.*, revision in review, 2012.

C. G. Kerry, B. S. Powell, and G. S. Carter. Effects of remote generation sites on model estimates of M_2 internal tides in the Philippine Sea. *J. Phys. Oceanogr.*, in press, 2012.

D. Matthews, B. S. Powell, and I. Janeković. Analysis of Four-dimensional Variational State Estimation of the Hawaiian Waters. *J. Geophys. Res.*, 117(C03013), 2012. doi: 10.1029/2011JC007575.

D. Matthews, B. S. Powell, and R. F. Milliff. Dominant Spatial Variability Scales from Observations around the Hawaiian Islands. *Deep-Sea Res., Part I*, 58:979–987, 2011.

A. Natarov and B. S. Powell. Sensitivity of the Hawaiian Lee Countercurrent to winds and upstream conditions. *Dyn. Atmos. Oceans*, in revision, 2011.

B. S. Powell. Treating nonlinearities in data-space variational assimilation. In S. Park and L. Xu, editors, *Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications*, volume 2. Springer-Verlag, 2012.

B. S. Powell, B. D. Cornuelle, and C. Kerry. Using a numerical model to understand the connection between the ocean and acoustic travel-time measurements. *J. Acoust. Soc. Am.*, revision in review, 2012a.

B. S. Powell, I. Janeković, G. S. Carter, and M. A. Merrifield. Sensitivity of Internal Tide Generation in Hawaii. *Geophys. Res. Let.*, 39(L10606):1–6, 2012b. doi: 10.1029/2012GL051724.

A. F. Shchepetkin and J. C. McWilliams. The Regional Oceanic Modeling System: A split-explicit, free-surface, topography-following-coordinate ocean model. *Ocean Modelling*, 9:347–404, 2005.

S-P Xie, W. Liu, Q. Liu, and M. Nonaka. Far-Reaching Effects of the Hawaiian Islands on the Pacific Ocean-Atmosphere System. *Science*, 292(5524):2057–2060, 2001.

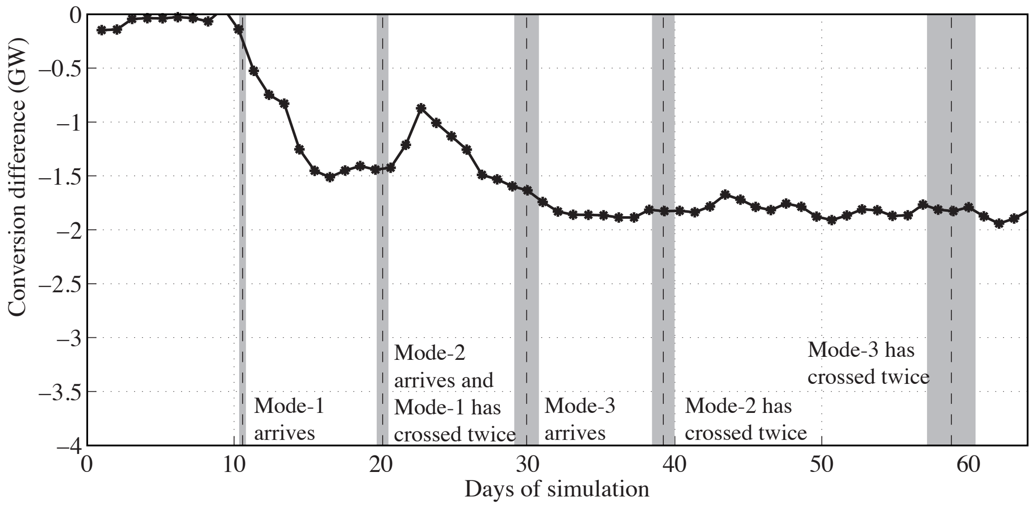

Figure 1: Anomalies of barotropic to baroclinic conversion at the Luzon Strait versus time showing how the arrival of internal tides from the Mariana island arc affect local conversion.

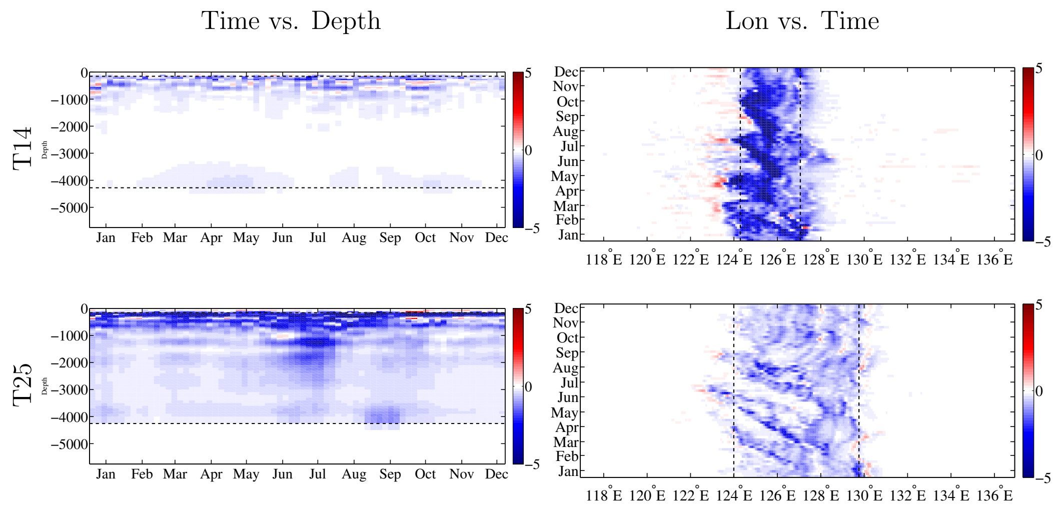

Figure 2: Hovmüller plots showing the temporal-spatial evolution of the day five sensitivity of travel time along two ray paths to temperature (msec) in depth and zonally. These figures illustrate the change in travel-time due to a single standard deviation change at the given location five days prior to the travel-time observation.