Understanding Predictability of the Ocean

Brian Powell
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; and, (iii) to compare these results with full ocean-state estimates generated from the ΨEX acoustic experiment.

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). 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 understanding 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 my other funded projects.

Despite their relatively small size, the Hawaiian island chain has a significant impact upon the atmospheric and oceanic circulations of the northern, sub-tropical Pacific. High volcanic mountains block the NE trade winds, forcing them to squeeze between the islands. Further west, these winds coalesce to form a wake that extends for 3000 km behind the Islands Xie et al. (2001). These island disturbances create significant energies at scales ranging from the sub- to meso-scale along with near-coastal processes interacting with mesoscale eddies due to the steep island topography. In addition, Hawaii is subject to large barotropic tides and combined with the steep topography, is a major source of barotropic-to-baroclinic tidal energy conversion. In the region around the islands, the internal tidal energy is as much as 50% of the dominant flow. These factors combine to create a challenging region for state-estimation and prediction (Natarov et al., 2010; Natarov and Powell, 2010).

As part of the NOAA-funded Integrated Ocean Observing System (IOOS) effort, I lead the modeling effort of the Pacific IOOS (PacIOOS) region including atmosphere, ocean, and waves. 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), 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.

Because each of the grids are nested, tidal solutions must be conveyed from one grid to the next. Global NCOM is run without tides, so the 4km grid imposes the barotropic tidal harmonics on its boundaries. The traditional one-way nest would simply use the fields from the 4km to impose the boundaries on the 1km nested grid; however, in this case, the grid's size makes it prohibitively expensive to store at the frequency required to properly resolve the M_2 tide in the region. The primary issue is that the baroclinic tides are not deterministic as they interact with the mesoscale and changing stratification means internal waves surface in different time and places. These two processes act to create a random phasing of the tidal expression in the surface temperature and velocity fields.

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 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.

WORK COMPLETED

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

i) To overcome the issues outlined by the nesting of tidal solutions, we have developed an idealized experiment to examine how best to nest numerical models within strong baroclinic tide domains.

ii) We have performed a nearly 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.

iii) 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.

iv) I have developed a method to directly assimilate high-frequency (HF) radar radial values into the model without the need for orthogonal vectors from two or more radar sites.

v) Working with Bruce Cornuelle, we have been trying to understand the role that multiple outer-loops plays in the variational assimilation procedures.

vi) Continued collaboration with the ΨEX that is underway in the North Philippine Sea. I will be attending the NPAL annual meeting in Virginia in Oct., 2010, to present the results of (iii). Of interest is how these variational methods will apply to the tomographic data once they are available, and we have added the ability to directly assimilate travel times into ROMS. I have hired a new Ph.D. student, Colette Kerry, to work on these efforts.

vii) An M.S. graduate student, Rebecca Baltes, funded under this work has been developing observing system sensitivity experiments (OSSE) for the Hawaiian region and will be defending her Masters Thesis in the Spring of 2011. Her results remain preliminary and for lack of space are not discussed in detail here. Her results will be a good foundation for comparing the observational sensitivity.

viii) I hosted the 2010 International ROMS/TOMS Workshop at the Imin Center on the campus of the University of Hawaii in April, 2010. More than 50 registered participants came to present and discuss the latest developments and results from the ONR sponsored ROMS/TOMS model. A small portion of the YIP budget was used to pay for hosting the conference as a benefit to the ROMS/TOMS and ONR community.

ix) Along with Dr. Bruce Cornuelle from Scripps Institute of Oceanography and Dr. Gregg Jacobs from NRL, Stennis, I convened a new session at the AGU Ocean Sciences meeting in Portland, OR, titled "Science of Ocean Forecasting from Advanced Data Assimilation Methods." The goal of this session was to explore the science of predictability and what can be learned (as opposed to reciting metrics versus persistence). The session was very well attended with four imminent invited speakers.

x) A number of manuscripts are completed or are in preparation: Janeković and Powell (2010); Janeković et al. (2010); Matthews and Powell (2011); Natarov et al. (2010); Natarov and Powell (2010); Cornuelle and Powell (2010); Powell et al. (2011); Powell (2011)

RESULTS

i) As discussed, nested tidal solutions in the presence of strong internal waves that interact with the mesoscale are a difficult challenge, particularly in regions where assimilation is conducted. To overcome the issues of nested barotropic and baroclinic tidal signals, we developed an idealized seamount problem that models the M_2 tide, generating internal tides on the seamount, a stratified density field that changes via advected waters, and mesoscale eddies. As shown in Figure 1, specifying the outer boundary conditions to the child every 3 hours significantly reduces the amplitude of the M_2 tide. We have solved this problem by using the 3 hour solutions to generate a harmonic tidal fit of known frequencies. These harmonics are then applied to the nested child grid, and the barotropic detided parent boundary conditions are used. This improves the child's estimates of the tides significantly (improves the RMS by a factor of 14) as shown in the figure. This work (Janeković and Powell, 2010; Janeković et al., 2010) has found that this method preserves the well represented baroclinic boundaries and the improved barotropic harmonics put the energy into the correct frequencies. These solutions have made a significant improvement in our initial work on nesting in the region.

ii) we have conducted a large, incremental, strong-constraint 4D-Var assimilation experiment using the 4km model with full tides and 4-day assimilation windows that span from 1 January, 2008 through 30 April, 2010. One newer aspects of the ROMS 4D-Var framework allows for the dynamic adjustment to the atmospheric forcing. We found that without this adjustment, unrealistic perturbations were required in the model to account for differences between the model and observations. For example, to decrease the SST, the strong-constraint method had to upwell cooler water in the lee of the islands; however, employing the atmospheric adjustments, small increases to the wind stress and/or decreases in the downward heat flux are made instead. These have made significant improvements to the assimilation. A manuscript is in preparation (Matthews and Powell, 2011) for publication in early 2011.

   Another unique aspect of this work is the use of raw observational data. We are working directly with the satellite along-track height data, the SST swath data (which provides multiple swaths throughout the day), SeaGlider data, and others. Interestingly, the assimilation results (Figure 2) show that the fit to the SST is very strong (90% of all data available is from SST), with an RMS of ≈ 0.3K; however, the fit to the *in situ* data is more difficult with an RMS of ≈ 0.7K. The atmospheric adjustments are not capable of driving changes below the mixed layer on a 4-day scale.

iii) Using the results of (ii), I have been working to quantify the impact of each observation on our estimate of circulation features around Hawaii. One important metric is the transport across Kaena Ridge, which is the primary site for barotropic energy conversion. The top panel of Figure 3, shows the contribution of each observation type to the total change in the transport estimate across Kaena ridge. During cycles when the SeaGlider data were available, they dominate the transport adjustment (while only accounting for 2% of the data). Likewise, when more SSH tracks are within a cycle, it contributes significantly. The bottom panels of Figure 3 show that the relative contribution of individual glider observations (as shown by the total RMS of impact) is three orders of magnitude greater than the individual SST observations. It isn't the number of data, but what and where that is important. In fact, the most important measurements from the glider were salinity measurements below 500m. This work is currently being drafted in a manuscript (Powell, 2011).

In addition, we have been working to generate representers for each of the most significant observations identified by the impact. The representer is the covariance between the observation and the model, and it allows us to examine how much of the ocean that a single observation samples. The representers are important because they provide a means to quantify what the observation will see in the future in addition to what it has seen previously. This work is still underway, and the results (not shown) are promising for understanding the role that the most significant observations have in the predictability of the field.

iv) A comprehensive HF Radar network is being constructed to monitor the coastal US waters (out to 50-100km). Currently, most work to utilize these data in models require the use of HF radar vectors, which are combined from overlapping orthogonal radial measurements of two or more radars. Unfortunately, most measurements are not fully orthogonal, which means that there are correlated errors. In 4D-Var, we are solving an inverse problem, and the solution of the field with the radial currents is possible without any assumptions of orthogonality. In assimilation, we rely upon the $\mathbf{H}$ operator to map between observation- and model- space (e.g., the innovation vector: $\mathbf{d} = \mathbf{y} - \mathbf{H}\mathbf{x}_b$). I have added code to ROMS for handling the radials via the $\mathbf{H}$ operator. This work was presented at the 2010 ROMS International Workshop, and I showed that in a twin experiment, these radials produce a better estimate of the true field than vectors alone. It should be noted that by using radials, far more of the HF data is available because overlapping regions are not required. This work is being transitioned to the operational system to handle the newly operational HF radar sites in Hawaii. A new manuscript detailing this work is in progress (Powell et al., 2011).

v) Data-space variational methods provide additional tools for uncertainty as presented in Moore et al. (2010c,a,b). There are numerous difficulties and problems with data-space methods in an operational context, including the large number of inner-loops required before reaching convergence. A further complication exists in the presence of non-linearity, such as Hawaii. As formulated, there are no outer-loops in the data-space methods. Bruce Cornuelle and I have finished a manuscript addressing the issue of multiple outer-loops in data-space methods (Cornuelle and Powell, 2010). Basically, a new forcing term must be added to the data-space solution that accounts for the previous increments. The results show that the problem is now well-posed; however, it continues to suffer from the slow inner-loop convergence issue.

IMPACT/APPLICATIONS

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

The new methods for assimilating HF radar and acoustic tomography and assessing observational impacts that are developed as part of this project will be made available to the ROMS community and will hopefully be actively used and further developed by other research groups in the U.S. and elsewhere as user competence increases.

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.
- "The ROMS IAS Data Assimilation and Prediction System: Quantifying Uncertainty", PI Andrew Moore, grant number N00014-08-1-0556.

REFERENCES

B. Cornuelle and B. S. Powell. Updating the Nonlinear Background in Data-Space Variational Assimilation: A Tale of Two Cost Functions. *Mon. Weather Rev.*, in final prep, 2010.

I. Janeković and B. S. Powell. Nesting Numerical Models of Hawaii with Mesoscale and Internal Tide Interaction, Part I: Idealized and Realistic Examples. *Ocean Modelling*, in prep, 2010.

I. Janeković, B. S. Powell, and D. Matthews. Nesting Numerical Models of Hawaii with Mesoscale and Internal Tide Interaction, Part II: 4D-Var Assimilation Experiments. *Ocean Modelling*, in prep, 2010.

D. Matthews and B. S. Powell. 4D-Var Assimilation in the Hawaiian Islands, Part I: Results. *J. Phys. Oceanogr.*, in prep, 2011.

A. M. Moore, H. G. Arango, G. Broquet, C. Edwards, M. Veneziani, B. S. Powell, D. Foley, J. Doyle, D. Costa, and P. Robinson. The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilation systems. Part II: Performance and application to the California Current System. *Prog. Oceanog.*, in prep., 2010a.

A. M. Moore, H. G. Arango, G. Broquet, C. Edwards, M. Veneziani, B. S. Powell, D. Foley, J. Doyle, D. Costa, and P. Robinson. The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilation systems. Part III: Observation impact and observation sensitivity in the California Current System. *Prog. Oceanog.*, in prep., 2010b.

A. M. Moore, H. G. Arango, G. Broquet, B. S. Powell, J. Zavala-Garay, and A. T. Weaver. The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilation systems. Part I: System overview and formulation. *Prog. Oceanog.*, in prep., 2010c.

A. Natarov and B. S. Powell. A numerical study of the effects of wind and upstream conditions on the Hawaiian circulation, Part II: Adjoint Sensivities. *Dyn. Atmos. Oceans*, in final prep, 2010.

A. Natarov, B. S. Powell, and D. Matthews. A numerical study of the effects of wind and upstream conditions on the Hawaiian circulation, Part I: Observations and Models. *Dyn. Atmos. Oceans*, in final prep, 2010.

B. S. Powell. 4D-Var Assimilation in the Hawaiian Islands, Part II: Assessing the Observations. *J. Phys. Oceanogr.*, in prep, 2011.

B. S. Powell, D. Matthews, and P. Flament. Assimilating High Frequency Radar: Radials or Vectors? *J. Geophys. Res.*, in prep, 2011.

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.

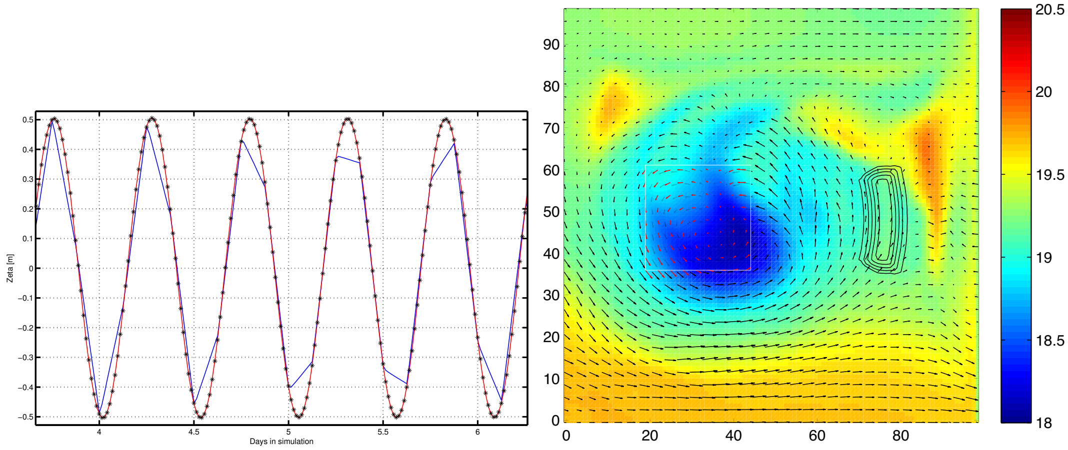

Figure 1: (left) Barotropic tide solution using harmonics (blue cross) versus boundary nesting (blue line) and truth (black). (right) Temperature solution (shown in °C) of internal tide in both the parent and child nests of the model. A large, mesoscale eddy is shown interacting with the internal tides.

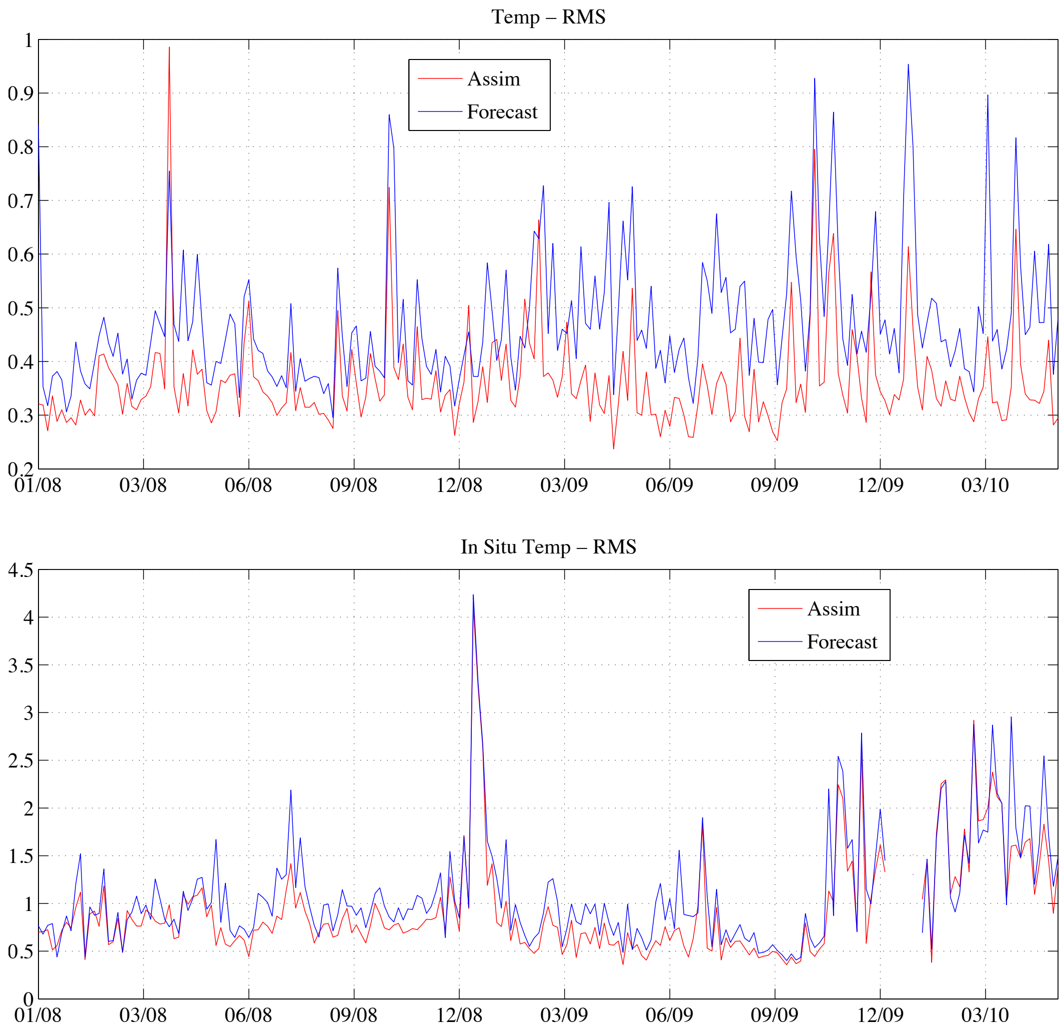

Figure 2: (top) Time-Series of RMS between model and SST observations for the prediction and assimilation cycles. (bottom) Time-Series of RMS between model and *in situ* observations for the prediction and assimilation cycles.

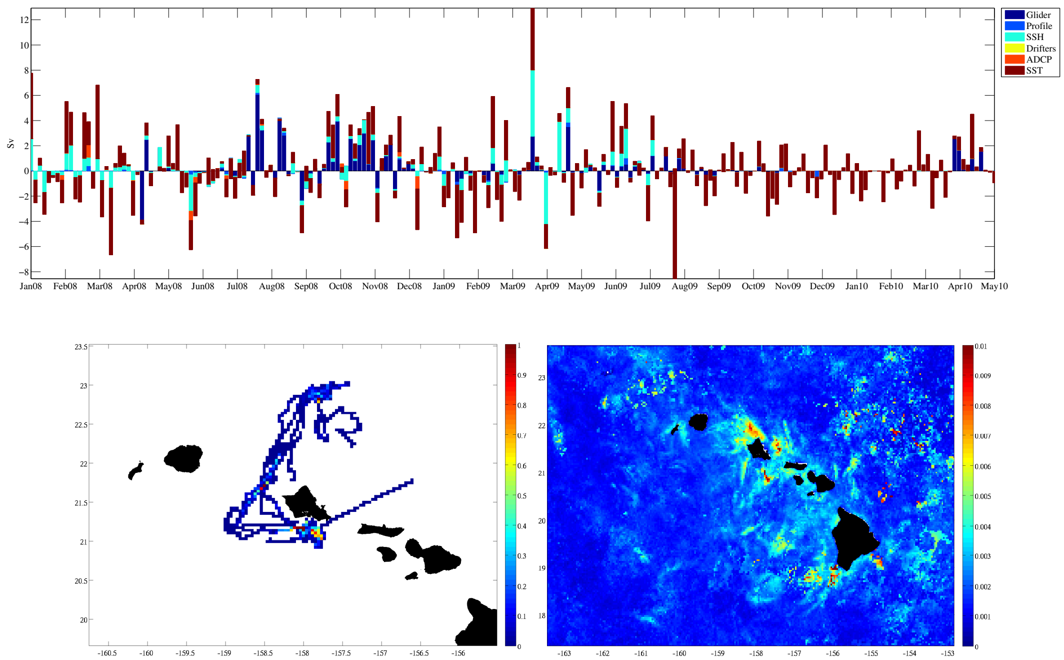

Figure 3: (top) Time-series showing the total contribution of each observation type to the transport increment made in the assimilation (e.g., a bar of 2Sv, shows that during the 4-day window, the transport was changed by 2 Sv, and the breakdown of colors illustrate the contribution of each type). (bottom, left) The RMS of the contributions from the SeaGlider over all assimilation windows as compared with (bottom,right) the contribution from the SST. The SeaGlider contributes (on average) over 3 magnitude more information on transport than the SST even though the total number of SeaGlider observations are dwarfed by the SST.