

Current Research My current area of research is in the predictability and dynamics of geophysical systems, specifically the ocean. My thesis work involves developing and implementing data assimilation methods to investigate ocean and ecosystem dynamics and improve nowcasting, forecasting, and hindcasting capabilities.

Simulating a dynamical system requires both a predictive model and an estimate of the initial state of the system. Physical ocean models are generally derived from the Navier-Stokes equations for fluid dynamics in a rotating frame of reference. To facilitate computation many assumptions and approximations are typically used and sub grid-scale phenomena are parameterized. These models are deterministic, so given an initial condition they produce the same single output each time they are run. In some applications, a direct, accurate measurement of the system state is possible. However, for a large scale system, such as the ocean, direct measurement of the initial state is impossible; so the initial state must be estimated from available observational data.

While the observational data is neither perfect nor complete, it can be combined with previous estimates to yield a more accurate set of initial conditions. Data assimilation cycles—which consist of forecasting using a predictive model, performing this statistical combination of the forecast and observational data, and then using the result to initialize the model for the next forecast—are used at operational weather forecasting centers to facilitate better predictions. In data assimilation schemes, the combination of previous estimates with current observations is done through a statistical procedure such as a Bayesian Maximum Likelihood estimate. Data assimilation also enables the creation of a more complete and accurate historical record by combining past observational data with model output. There are a number of different data assimilation schemes which are derived from different mathematical fields such as estimation theory, optimization theory, and control theory. At the heart of most methods is the minimization of some error norm, usually a least-squares norm in practical applications.

Data assimilation hinges on having not only an estimate of both the observations and the forecast, but an estimate of their respective error statistics. Ideally, the error probability distribution functions would be evolved along with the state estimate, but it is impractical for the ocean because of the size of the model (normally 10^6 - 10^8 grid points). Instead, distributions are usually approximated as Gaussian and the mean and covariances are tracked. For a large system, maintaining and updating covariance information is difficult and expensive, so many conventional methods for oceanic data assimilation use a fixed approximation for the forecast error covariance derived from climatological data. In Ensemble Kalman Filter (EnKF) methods, by contrast, a Monte Carlo type approach is used where the covariance is parameterized using an ensemble of forecast states which come from the full dynamical model. Consequently, the error covariance used for EnKF varies based on the system dynamics at the assimilation time and therefore provides a more accurate estimate of the current uncertainties.

In my research I have interfaced this Ensemble Kalman Filter with a model of the Chesapeake Bay as part of a Chesapeake Bay ecosystem modeling initiative funded through the NASA/NOAA GOES-R project. Using observations of temperature, salinity, and currents for assimilation, the EnKF-Chesapeake system produces more accurate forecasts and nowcasts in simulated cases. Because of the flexibility of the EnKF framework, this system will eventually be able to assimilate and predict biological and other ecosystem variables. The biological modeling and assimilation problem is still a very open field and one that I am interested in exploring. In addition to providing more accurate initial conditions, the EnKF can pinpoint areas where observations would be most beneficial. This information can then be used to advise future observing missions. A paper on the first phase of this research is in preparation now and I am presenting it at the American Geophysical Union Fall Meetings in December.

I have also studied instabilities in the global ocean through the use of the breeding method. The breeding method begins with an arbitrary small perturbation of the initial state of an unstable system,

such as the atmosphere represented by a numerical model. This model is integrated forward for a time interval, Δt , beginning from both the perturbed and unperturbed (or control) initial state. The vector difference in state variables (u , v , w , T , S) between the two resulting nonlinear forecasts is called the bred vector (BV). At Δt this bred vector is rescaled to the size of the initial perturbation and then is added to the control simulation to form the perturbed initial state for a new simulation. Twin simulations beginning with the control and newly perturbed control initial state at Δt are then integrated forward from Δt to $2\Delta t$ to create a new simulation pair. The bred vector at time $2\Delta t$ is then computed, rescaled, and the process is repeated. When carried out over many cycles, the resulting time series of bred vectors has been shown by Toth and Kalnay to isolate and identify the components of the system that grow most rapidly on a time-scale of Δt , and to separate them from other rapidly growing components that saturate in times shorter than Δt . I extended this framework to a global ocean model and was able to demonstrate the utility of breeding in this context. To help diagnose the dynamic causes of the instabilities, I developed a set of energy equations (bred vector energy equations), which are analogous to the more traditional eddy energy equations but are obtained without approximations due to the fact that both the unperturbed and the perturbed runs satisfy the model dynamical equations. This approach was applied to diagnose the instabilities of the South Atlantic and tropical Pacific and the results have been presented at the American Geophysical Union Fall conference, the International Union of Geophysics and Geodesy conference, and have been submitted for publication in the Geophysical Research Letters.

I have also been involved with a couple of other applications of the ensemble Kalman filter. I was invited to Brazil as a Visiting Specialist of the Brazilian Science and Technology Ministry to work along with Brazil's National Center for Weather Forecasts and Climate Studies (CPTEC) in interfacing the LETKF with a global ocean implementation of the MOM4 model. After completing the interfacing, perfect model experiments were run which determined that, using simulated observations, the LETKF-MOM4 system was quickly able to reduce both analysis and forecast errors and keep them below the simulated observational error. In addition to reducing global errors, the LETKF was able to accurately represent the spatial patterns in the extremely unstable Brazil-Malvinas confluence. Results from this work were presented at the Brazilian Meteorological Congress (CBMet) conference in Brazil and I was first author on a short paper published in the conference proceedings.

The other project I have been working on is applying the LETKF framework to a predictive model of the Martian atmosphere. This work is part of a NASA funded project to provide forecasts of the Martian atmosphere for future observing missions as well as to further study the Martian climate.

Future Work

I intend to continue my current line of research in developing data assimilation systems for oceanographic applications, as well as expanding to coupled, nested, and ecosystem models. However, I am also open to and interested in other related areas and other mathematical modeling problems. In addition to delving more into the mathematics of data assimilation, I would also like to pursue the model physics problem. I have an interest in some of the unresolved, interesting mathematical issues in modeling, such as ocean turbulence. While turbulence has been widely studied, the fact that the ocean is so stratified makes modeling ocean turbulence particularly challenging. Although my knowledge of the subject is cursory at the moment, it is something I wish to learn more about and have the chance to investigate.

There are also many problems still unresolved in my current research. For example, regional ocean systems are extremely dependent on the forcing of surface winds. Typically, these winds come directly from an atmospheric model; however, surface winds usually have a lot of uncertainties associated with them. Although not directly observed, the EnKF has the ability to correct these winds using information from other observations. Corrections to the sea surface wind field could then be applied to the atmospheric model as well to improve the forecast.

Having worked on data assimilation in both global and regional ocean models, I am interested in working on a nested system. In this type of system, large scale models are assimilated and used to

initialize more detailed models. Advanced data assimilation can be performed on every scale and the end result is can be scaled down to solve local problems, while at the same time being able to capture global and regional information.

One of the longer term goals of the Chesapeake Bay project I am working on is to assimilate biological observables. The whole subject of biological predictive models is very open and there exist only a handful of sophisticated assimilation efforts to date. Variables such as ocean color, which is a measure of the level of biological activity at the sea surface, particularly from phytoplankton, are observed from NASA satellites and are thus promising ways to inject for information into ocean models. However, interpreting and extracting that information and assimilating it is a challenging and poorly understood problem. I would like to investigate this problem further as well.

In addition, the basic tools used for oceanic data assimilation are readily applicable to a wide range of fields ranging from biology to robotics. I look forward to exploring some of these other areas over the course of my career.