Analyzing the ocean with the latest ECCO Ocean State Estimate

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Interannual to decadal variations of the ocean are described using the latest estimate from the "Estimating the Circulation and Climate of the Ocean" (ECCO) project. The estimate combines a state-of-the-art ocean general circulation model (MITgcm) with nearly all extant observations of the ocean from 1992 to 2015, including sea level from satellites (e.g., Jason-2), and in situ hydrographic profiles from ships (e.g., WOCE) and floats (e.g., Argo). The model is of moderate spatial resolution (40-100km) but with a domain that is truly global including the Arctic Ocean. The estimate's enhancements from earlier analyses include its longer period (4 additional years), use of new observations (e.g., GRACE ocean bottom pressure and Aquarius sea surface salinity), model improvements (e.g., geothermal heating, sea ice model), and accounting of correlated uncertainties (e.g., forcing bias).

The new analysis has improved agreements with observations than before, allowing a more accurate accounting of processes contributing to their variation. In particular, the ECCO analysis is characterized by its physical consistency in the sense of the estimate's temporal evolution being accounted for explicitly in terms of physical processes resolved by the model. The estimation's infrastructure (e.g., model adjoint) allows analyses that cannot be easily performed from observations or models alone.

The new estimate and its infrastructure will be presented with a focus on sea level variations and associated changes in ocean heat and mass. Regional and vertical distribution of the variable heat and mass fields will be explored and the nature of their evolution will be examined in relation to the ocean circulation.

Keywords: Ocean Circulation, Sea Level, Climate Change, Data Assimilation, Ocean Modeling

On the discretization of the Onsager-Machlup functional

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When taking the model error into account, one needs to evaluate the prior distribution (the Onsager-Machlup functional), which contains the divergence term difficult to be calculated for large systems. However, the Euler method for time discretization of the functional can eliminate the need for evaluating the divergence term. This property is of use for solving nonlinear data assimilation problems with sampling methods such as the Metropolis-adjusted Langevin algorithm.

Keywords: data assimilation, Markov chain Monte Carlo

Reconditioning the observation error covariance matrix in the local ensemble transform Kalman filter: experiments with the Lorenz-96 model

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It is natural that the observation errors are correlated if measured with the same instrument, such as radiosondes, radars, and satellite sensors. Radiosonde observations would have the error correlations in the vertical. Satellite radiances would have the horizontal and inter-channel error correlations. However, in the operational data assimilation systems, the observation errors are usually assumed to be uncorrelated for simplicity and computational efficiency.
The condition number of the observation error covariance matrix affects to the convergence efficiency when minimizing the cost function when the observation error correlation is considered in the variational data assimilation methods. However, it is still unknown how the condition number affects in the local ensemble transform Kalman filter (LETKF). In this study, we explore the potential impact of the condition number of the observation error covariance matrix in the LETKF. We performed a series of observing system simulation experiments (OSSEs) to account for the observation error correlations in the LETKF with the simple toy Lorenz-96 model using different observation error covariance matrices of the low and high condition numbers. The results show that the LETKF becomes very unstable when the condition number is large. ‘Reconditioning’ is a method to reduce the condition number of a matrix by slightly modifying the original matrix. The experiments using the ‘reconditioned’ observation error covariance matrix show that the LETKF is significantly stabilized, while the impact on the analysis accuracy is minimal.

Keywords: Data assimilation, Observation error correlation, Condition number, Reconditioning

Toward real forecast of aurora electrojet index using the data assimilation

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The auroral electrojet indices (AU, AL, AE) are a proxy of substorm as well as auroral activity, so that the forecast of these indices is important for the space weather forecast. In this study, we develop a data assimilation code to estimate the AU index based on Goertz et al. [1993] model. In the data assimilation, the state space model consists of the system model and the observation model. The model of Goertz et al.[1993] is used as the system model, which calculates time variation of the AU index using the electric fields of the solar wind. The state vector includes the AU index and coupling parameters for solar-wind, magnetosphere and ionosphere. The AU index provided from World Data Center for Geomagnetism, Kyoto is used as the observation vector. The sequential data assimilation includes the following three steps; prediction, filtering, and smoothing. We use the particle filter that can apply for non-linear/non-gaussian problems. Furthermore, we use the particle smoother as the smoothing scheme. To apply the real-time forecast of the AU-index, we develop a system that includes hindcast and forecast. The hindcast investigates probable past state using the data assimilation, while the forecast investigates propable future state. Using the estimated coupling parameters at the hindcast, the AU index is predicted by the Goertz model. The test calculation shows that the forecast performance is improved by estimating the coupling parameters with the data assimilation at the hindcast. This system has been coupled with the SUSANOO-SW that simulates the solar wind and IMF at 1 AU for the next 7 days based on the MHD model, and the electric fields of the solar wind provided from the SUSANOO-SW is used as an input for both hindcast and forecast. Our developed system has been operated and provided weekly variations of the AU index.

Keywords: Aurora, Data assimilation, Space Weather

Utilization of fisherman-logging data for enhancement of the coastal ocean monitoring network in Japan

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An operational ocean observing system around Japan is mainly composed of satellite observation, ARGO floats, and repeated section surveys by central and local governmental research agencies. The data from the observing system are conveyed to operational ocean forecast systems based on data-assimilative ocean general circulation models in near real-time basis. Here we examine impacts of fisherman-logging Conductivity, Temperature, Depth sensor (FCTD) data on the ocean observing system using an operational ocean forecasting system JCOPE2. Additional assimilation of the FCTD data provided from Miyazaki prefectural fisheries research institute is effective for modifying representation of oceanic conditions for a period from April to August 2016 in nearshore region southeast of the Kyushu Island. The Kuroshio front position averaged for the period moves to nearshore side as observed by the additional assimilation. In particular, the FCTD assimilation leads to finer representation of a subsurface warm water tongue varying with a few days time scale, which is never detected by the satellite remote sensing and existing in-situ monitoring data, demonstrating a potential key role of FCTD for enhancement of the coastal ocean monitoring network in Japan.

Keywords: data assimilation, ocean observing system, fisherman-CTD

4DVAR with ensemble background error covariance estimation in a coastal ocean model

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Traditionally 4DVAR implementations for ocean forecasting proceed in a series of relatively short time windows and assume that the model background error covariance is static in time. Offshore Oregon/Washington (USA west coast) this static assumption on the background error covariance is unlikely to hold as the outflow of the Columbia River creates a fresh water plume of which the location and extent vary depending on wind direction and river outflow. To better capture the natural variability in the system we have implemented E4DVAR data assimilation in Oregon State University’ s ocean forecasting system. In this system the initial conditions at the beginning of each 3-day window are corrected by combining the previous 3-day model forecast from a 2-km ROMS (Regional Ocean Modeling System) model with observations of GOES sea-surface temperatures, high-frequency radar surface current observations and Jason satellite altimetry using 4DVAR. For the tangent linear and adjoint parts of the 4DVAR algorithm the system uses the in-house developed AVRORA codes. The background error covariance is estimated by localizing, using a new Monte-Carlo localization scheme, the sample covariance of a 50-member ensemble. The members of this ensemble are generated by running the system using different wind fields and perturbed observations. Results show that the new system provides better forecasts for the subsurface temperature and salinity fields and a more accurate representation of the temperature-salinity relationship. However, the surface salinity in the new system turned out to be overly sensitive to observation errors in sea-surface temperature. Interestingly, introduction of approximate salinity conservation in the assimilation scheme has been shown to suppress unrealistically large sea-surface salinity corrections and additionally modify the shape of the river plume. This indicates that implementation of data assimilation in models with tracers is non-trivial and should be handled with care.

Keywords: data assimilation, 4DVAR, coastal ocean, localization, river plume

Estimation of a posterior error covariance using a linear quasi-Newton method and its application to an inversion of CO_2 sources and sinks

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Data assimilation and inversion methods are widely used in earth science problems to estimate optimal initial/boundary conditions or parameters of a numerical model from given limited observations. A four-dimensional variational method (4D-Var), one of prominent data assimilation/inversion methods, is attractive in that it estimates optimal model variables in a high-resolution without explicitly dealing with a model operator matrix whose size is too large to store in a memory or storage. However, a conventional 4D-Var does not estimate a posterior error covariance owing to its deterministic nature based on the maximum likelihood estimation. A posterior error covariance could provide valuable information not only of uncertainties of estimated variables but also of observation impacts, which is beneficial, for instance, for designing observation networks. In this study, we have developed a new method to estimate a posterior error covariance in a 4D-Var framework. The descent scheme of the 4D-Var method is based on Preconditioned Optimizing Utility for Large-dimensional analyses (POpULar: Fujii, 2005), which employs a quasi-Newton method with Broyden–Fletcher–Goldfarb–Shanno (BFGS) algorithm. One prominent feature of POpULar is that it does not require difficult decomposition of a prior error covariance matrix. In iterative calculations of the BFGS formula, an inverse Hessian is approximated and then used to determine a next search direction. If accurately approximated, this inverse Hessian can be considered as the posterior error covariance. Although the developed method assumes the model linearity and the perfect forward-adjoint relationship, it successfully calculates an accurate inverse Hessian. Furthermore, the convergence speed of the estimation of the inverse Hessian can be efficiently accelerated by ensemble calculations. Applying this method to a linear problem of CO_2 sources/sinks inversion with a system named NICAM-TM 4D-Var (Niwa et al., 2016a,b), we demonstrate its validity and practical utility.

Keywords: inversion, posterior error, quasi-Newton method

The development of data assimilation in the ionospheric space weather

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An ionospheric data assimilation forecast model has been developed by ensemble Kalman filter (EnKF) to adjust ionospheric observations into a thermosphere-ionosphere-electrodynamics general circulation model (TIEGCM). Using this assimilation model, the performances of ionospheric forecast during the geomagnetic storm conditions are further evaluated in this study. Results suggest a rapid assimilation-forecast cycling (10-min in this study) can greatly improve the quality of the model forecast. Furthermore, updating the thermospheric state variables in the coupled thermosphere-ionosphere forecast model in the assimilation step is an important factor in improving the trajectory of model forecasting. Different high-latitude ionospheric convection models, Heelis and Weimer, are further evaluated in different latitude regions. Results show the better forecast in the electron density at the low-latitude region during the storm main phase and the recovery phase. The well reproduced eastward electric field at the low-latitude region by the assimilation model reveals that the electric fields may be an important factor to have the contributions on the accuracy of ionospheric forecast.

Keywords: data assimilation, ionospheric forecast model, geomagnetic storm

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Data assimilation for real-time prediction of earthquake ground shaking: “Numerical shake prediction” for Earthquake Early Warning

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Real-time prediction of earthquake ground shaking is a strong tool for prevention/mitigation of earthquake disaster, and it has been applied for earthquake early warning (EEW). EEW has been operated for general public in Japan since 2007 and in Mexico since early 1990s, and possible use of such systems has been investigated in the United States, Taiwan, EU, Turkey, and other countries. Many of the present EEW systems first quickly determine the earthquake hypocenter and magnitude, and then they predict the strengths of ground shaking at various locations using the hypocenter distance and magnitude. The 2011 Tohoku earthquake (M_w 9.0), however, revealed some technical issues with such methods: under-prediction at large distances due to the large extent of the fault rupture, and over-prediction because the system was confused by multiple aftershocks that occurred simultaneously. To address these issues, we propose a new concept for EEW, in which the distribution of the present wavefield is estimated precisely in real time (real-time shake mapping) by applying a data assimilation technique, and then the future wavefield is predicted time-evolutionally by simulation of seismic wave propagation. We call this method, in which physical processes are simulated from the precisely estimated present condition, “numerical shake prediction” by analogy to “numerical weather prediction” in meteorology. By applying the proposed method to the 2011 Tohoku Earthquake and the 2016 Kumamoto Earthquake (M_w 7.0), we show that numerical shake prediction can precisely and rapidly predict ground shaking in real time manner.
Real-time prediction of earthquake ground shaking is a strong tool for prevention/mitigation of earthquake disaster, and it has been applied for earthquake early warning (EEW). EEW has been operated for general public in Japan since 2007 and in Mexico since early 1990s, and possible use of such systems has been investigated in the United States, Taiwan, EU, Turkey, and other countries. Many of the present EEW systems first quickly determine the earthquake hypocenter and magnitude, and then they predict the strengths of ground shaking at various locations using the hypocenter distance and magnitude. The 2011 Tohoku earthquake (M_w 9.0), however, revealed some technical issues with such methods: under-prediction at large distances due to the large extent of the fault rupture, and over-prediction because the system was confused by multiple aftershocks that occurred simultaneously. To address these issues, we propose a new concept for EEW, in which the distribution of the present wavefield is estimated precisely in real time (real-time shake mapping) by applying a data assimilation technique, and then the future wavefield is predicted time-evolutionally by simulation of seismic wave propagation. We call this method, in which physical processes are simulated from the precisely estimated present condition, “numerical shake prediction” by analogy to “numerical weather prediction” in meteorology. By applying the proposed method to the 2011 Tohoku Earthquake and the 2016 Kumamoto Earthquake (M_w 7.0), we show that numerical shake prediction can precisely and rapidly predict ground shaking in real time manner.

Keywords: data assimilation, earthquake early warning, real-time prediction of ground shaking

Potential of assimilating river discharge observations into the atmosphere by strongly coupled data assimilation: Hydrometeorology as an inversion problem

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We examine the potential of assimilating river discharge observations into the atmosphere by strongly coupled data assimilation. The Japan Meteorological Agency Non-Hydrostatic atmospheric Model (JMA-NHM) is first coupled with the simple rainfall-runoff model. Next, the Local Ensemble Transform Kalman Filter (LETKF) is used for this coupled model to assimilate the observations of the rainfall-runoff model variables into the JMA-NHM model variables. This system enables to do hydrometeorology backward, i.e., to inversely estimate atmospheric conditions from the information of a flood on land surfaces. We will present our recent progress of an Observing System Simulation Experiment (OSSE) to evaluate how the assimilation of river discharge observations improves the skill of forecasting severe rainfalls and floods.

Keywords: Coupled Data Assimilation, Floods

Applycation of data assimilation to paleoclimate

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Knowledge of past climate conditions is crucial to understand the climate system and to predict the future. Historically, two approaches have been used to reconstruct paleoclimate: one based on the empirical evidence contained in proxy data, and the other based on simulation with physically-based climate models. Here, proxies are not the direct record of climate variables such as temperature, winds and pressure, but natural records representing climate such as tree-ring width and isotopic composition in ice sheets. Recently, an approach combining proxy data and climate simulations through data assimilation (DA) has emerged. DA has long been used for forecasting weather and is a well-established method. However, the DA algorithms used for weather forecasts cannot be directly applied to paleoclimate due to the different temporal resolution, spatial extent, and type of information contained within the observation data. The temporal resolution and spatial distribution of proxy data are significantly lower (seasonal at best) and sparser than the present-day observations used for weather forecasts. Therefore, DA applied to paleoclimate is only loosely linked to the methods used in the more mature field of weather forecasting. Several DA methods have been proposed for paleoclimate reconstruction, and paleoclimate studies using DA have successfully determined the mechanisms behind the past climate changes. In the previous studies, the variables used for DA have been data reconstructed from proxies (e.g., surface air temperature) because physical models for proxies have not been readily available. Recently, proxy modelers have developed and evaluated several forward models for stable water isotopic proxies. In this study, we attempted to assimilate proxy data directly for the first time, and demonstrated that the new method can reconstruct paleoclimate more skillfully.

Keywords: data assimilation, paleoclimate, stable water isotope

Data assimilation for massive autonomous systems based on a second-order adjoint method

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We propose an adjoint-based data assimilation method for massive autonomous models that produces optimum estimates and their uncertainties within reasonable computation time and resource constraints. The uncertainties are given as several diagonal elements of an inverse Hessian matrix, which is the covariance matrix of a normal distribution that approximates the target posterior probability density function in the neighborhood of the optimum. Conventional algorithms for deriving the inverse Hessian matrix require $O(CN^2+N^3)$ computations and $O(N^2)$ memory, where N is the number of degrees of freedom of a given autonomous system and C is the number of computations needed to simulate time series of suitable length. The proposed method using a second-order adjoint method allows us to directly evaluate the diagonal elements of the inverse Hessian matrix without computing all of its elements. This drastically reduces the number of computations to $O(C)$ and the amount of memory to $O(N)$ for each diagonal element. The proposed method is validated through numerical tests using a massive two-dimensional Kobayashi phase-field model. We confirm that the proposed method correctly reproduces the parameter and initial state assumed in advance, and successfully evaluates the uncertainty of the parameter.

Keywords: data assmilation, adjoint method, phase-field model, uncertainty quantification, Bayesian statistics