Decadal ocean (and ice) state estimation for climate research: What are the needs?

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The advent of the World Ocean Circulation Experiment (WOCE) and satellite altimetry in the early 1990s called for a method for synthesizing the new, globally distributed yet sparse observations of very diverse types into a coherent dynamical framework, one that would enable the calculation of accurate budgets of heat, freshwater, momentum, vorticity, their exchange with the atmosphere, and their evolution through time. A major goal was understanding the mechanistic processes underlying large-scale (multi-)decadal climate variability and change. [1]

In contrast to the practice of data assimilation (DA) in numerical weather prediction (NWP) where the problem is one of optimal forecasting or filtering (extrapolation), we are faced in ocean climate research with a smoothing or state and parameter estimation problem (interpolation). A serious consequence is that techniques used in NWP cannot be readily adopted. However, most so-called ocean "reanalysis" projects are relying on just such filtering methods. The states they produce face the same problems as the atmospheric reanalyses where assimilation increments incur unphysical sources or sinks in the conservation equations. Such artificial sources or sinks of heat or mass at the analysis time severely limit their utility for climate research. Although attention has been called to this issue repeatedly, it is being ignored by a large part of the ocean/atmosphere/climate research and DA community. Examples are atmosphere-to-ocean global net freshwater flux imbalances of the order of 5 to 10 cm per year, in stark conflict with satellite altimetric observations which place an upper bound on such global mean fluxes of roughly 3 mm per year (the satellite-altimetric estimate of global mean sea level rise since 1992). Similar conflicts exist between net surface heat flux imbalances in atmospheric reanalysis products of the order of 10 W/m^2 compared to roughly 1 (± 1) W/m^2 inferred from independent radiation balance estimates. Such violation of global and local conservation of properties are of little concern to weather prediction, but they are central to the global climate problem [14].

Over the last decade a consortium called "Estimating the Circulation and Climate of the Ocean" (ECCO) has developed a smoother approach for synthesizing much of the available oceanographic (and more recently sea ice) observations into a dynamical framework represented by the Massachusetts Institute of Technology general circulation model (MITgcm) [1]. Estimates have been produced both for the global problem [12, 17] as well as for regional domains, such as an Arctic subdomain coupled ocean-sea ice state [3] and the Southern Ocean [11]. The GCM is fit in a least-squares sense to the observations by means of the Lagrange multiplier or adjoint method [18]. A major algorithmic breakthrough that has made this approach computationally tractable is the rigorous use of automatic differentiation

[1] Oberwolfach Reports, 2012, in press, doi:10.4171/OWR

(AD) to generate and exact, efficient, scalable, and up-to-date adjoint model of the nonlinear forward model [7].

The adjoint computes the gradient of the least-squares model-data misfit cost function with respect to a very high-dimensional (10^7 to 10^9) space of independent, uncertain, adjustable control variables, consisting of three-dimensional ocean (and sea ice) initial conditions and two-dimensional time-varying corrections to the atmospheric boundary conditions, which are known to contain significant errors that are spatially and temporally inhomogeneous. Including three-dimensional (time-mean) model parameters to the control space as well, such as vertical diffusivity and eddy-induced mixing parameters, provides a significant step forward toward dealing with internal model (or parameterization) errors in a way that does not introduce artificial source or sink terms [4, 13]. The state estimates produced by ECCO, covering the satellite altimetric record (1992-present) have enabled accurate budget calculations for various applications, such as understanding the causes of the strong regional variations in sea level trends over the last two decades [19], or the spatio-temporal structure of the Global and Atlantic Meridional Overturning Circulation (MOC) [16, 15].

As a by-product of the estimation project, the availability of the adjoint or dual state (i.e., elements of the model's co-tangent space) has enabled detailed sensitivity studies of climate-relevant indices to the time-evolving state and boundary values (examples include Atlantic poleward volume and heat transport [10, 8, 5], sensitivity of Drake Passage volume transport to changes in bottom topography [9], Arctic sea ice export sensitivities to changes in atmospheric state [6], and ocean biological productivity sensitivity to nutrient supply [2]).

Challenges facing the community today are (1) improving the accuracy of these smoother-based state estimates for use in climate research, (2) the provision of formal error estimates (posterior uncertainties) on these state estimates and derived quantities in the presence of a high-dimensional uncertainty space, (3) the need to improve physical consistency through a coupled atmosphere/ocean/ice estimation system which involves highly disparate time scales, (4) the move towards improved horizontal resolution with its own issues (observed versus represented scales, nonlinear regime of the flow field, poor sampling). At least for the climate estimation problem (i.e. for the purpose of understanding the evolution of the climate state over the past few decades), filtering approaches borrowed from DA as practiced in NWP will likely be of limited use for the forseeable future.

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