Variations of the Large-Scale Ocean Circulation Estimated by Combining Data with a Numerical Model

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Summary:

Rigorous global ocean state estimation methods are required to produce dynamically consistent time-varying model/data syntheses that can serve as the basis for quantitative climate studies.

The consortium for "Estimation of the Circulation and Climate of the Ocean" (ECCO) is a NOPP-funded collaborative data assimilation effort at MIT, JPL and SIO. Its goal is to obtain a dynamically consistent description of the time-varying circulation through the combination of ocean data with global general circulation models (GCMs) by applying rigorous estimation techniques. We summarize the current status of one of ECCO's ocean state estimation efforts and describe first applications. Both Climate Variability and Predictability (CLIVAR) and Global Ocean Data Assimilation Experiment (GODAE) programs built to a great extent around routine and dynamically consistent state estimates.

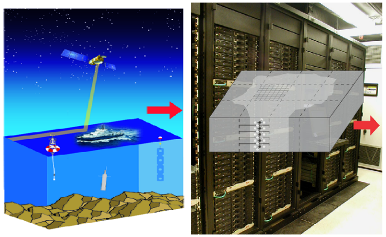


Figure 1 shows a schematic of an ocean observing and assimilation system. The observing system on the left is providing near-realtime global ocean observations. Combined with the dynamics embedded in state-of-the-art circulation models that are run on super-computers (right panel) ocean syntheses are obtained that form the basis for studies of the ocean circulation and its climate relevance.

We show here results from a first global WOCE synthesis on a 2° global grid (± 80°) and over the 9-year period 1992-2000. Those results, obtained with only a limited set of model physics and ocean data, must still be considered preliminary. But we find improved skill of the estimates in simulating independent ocean observations that suggest that results can be used for first analyses of the ocean circulation.

Methodology:

An ocean synthesis is obtained by forcing the model to consistency, within a complex, specified error margin, with those fields by using the model adjoint (Marotzke et al., 1999) to modify the initial temperature and salinity conditions over the full water column and to adjust the time-varying meteorological forcing fields over the full estimation period. The adjoint component is obtained from the forward code in a semi-automatic way by using the Tangent Linear and Adjoint Model Compiler (TAMC) [*Giering and Kaminski*, 1998].

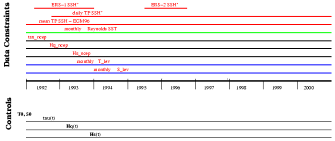


Figure 2 shows the schematic of the optimization. The top part of the figures shows the data constraints and their distribution in time. The lower part shows the "control" parameters, which are the initial T and S fields, and the time-varying surface forcing (wind stress, heat and fresh water fluxes), which are adjusted over the full 9 year period 1992 through 2000 to bring the model into consistency with the data. With these parameters, the control vector contains 8 million elements.

Results:

Within ECCO, a particular science focus is on the determination of transports and the budgets of mass, heat, freshwater, and energy in various regions of the global domain. The state estimates are also being examined to assess the accuracies of various estimates of air-sea fluxes of momentum, heat, and freshwater; to quantify the relative impact of different observing systems; to study ocean dynamics; and to improve forecasting skills.

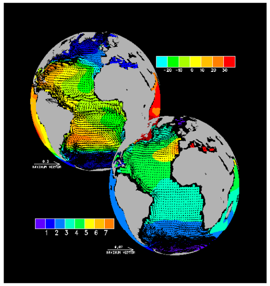


Figure 3 shows the mean flow field at 27m and 1975 m depth from the 2° WOCE synthesis calculation, together with the mean sea surface height and the temperature field at 1975 m. All major circulation structures are simulated, but are overly smooth due to the present low model resolution.

Testing the Skill:

The skill of the constrained model is demonstrated in the next two figures by comparing it against independent data that were withheld from the optimization.

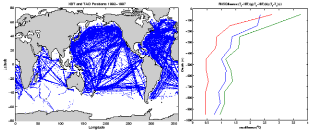


Figure 4: (left) Available XBT data sampled over the world ocean during 1992-1997; also included are the data from the TOGA-TAO buoy network. (right) Global and time averaged RMS difference as a function of depth of the XBT data minus the estimate (blue line) and minus the control run (green line). The red curve shows the RMS differences between the first guess and the estimate.

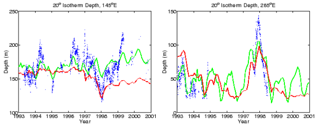
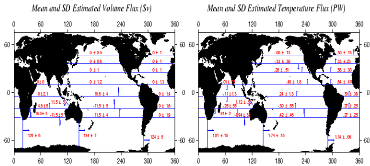
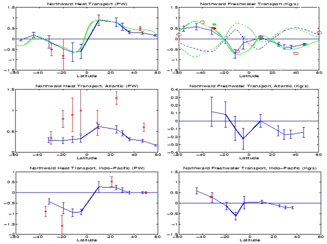


Figure 5 shows the monthly mean estimated depth of the 20°C isotherm together with observations from TOGA-TAO (Tropical Ocean Global Atmosphere-Tropical-Atmosphere-Ocean) buoys on the equator between 140°-150°E and at 265°E; these data were not used as constraints. In contrast to the discontinuous TAO measurements, the constrained model simulates the isotherm depth continuously over the full estimation period. It tracks the data where they exist and allows one to infer changes and their dynamics even when data are absent.

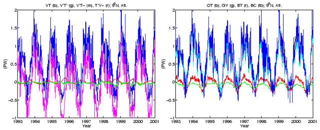
Estimated Transports:



Map of mean and standard deviation of volume and temperature flux. Note the circulation around Australia of about 11 Sv. Results converged with previous findings, e.g., from Ganachaud and Wunsch (2000). Major difference exists in the North Atlantic where our solution provides too small a poleward heat transport.

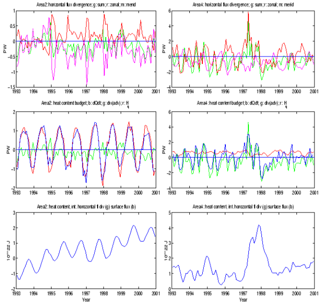


Top panel: Integrated time-mean meridional heat (left) and freshwater (right) transports for the global ocean estimated for various zonal sections in the model (blue curve). The blue bars are the standard deviation of individual annual mean estimates. The green curve represents the ocean heat transport inferred from estimated surface heat fluxes. Middle and bottom panels: Estimated meridional heat and freshwater transports across zonal sections in the model, evaluated separately for the Atlantic, Pacific-Indian Oceans. All red symbols on the left side represent estimates from *Ganachaud and Wunsch* [2000] and their formal uncertainties. Green dotted line on the right side an estimate of atmospheric moisture flux obtained as the negative of the green line. The dash-dotted line is an estimate inferred by *Peixoto and Oort* [1983] . The red open circles represent estimates from *Wijffels et al* [1992] . Solid red and green dots are results from *Wijffels et al.* [2001] and *Macdonald and Wunsch* [1996] , respectively.



(left) Timeseries $H_Q(t) = \int\int v\theta dzdx$ (blue curves) across 9° N in the Atlantic Ocean. Also shown are $\int\int v'\theta' dzdx$, $\int\int \overline{\theta} v' dzdx$ and $\int\int \overline{v}\theta' dzdx$ as green, magenta and red lines, respectively. (right) Temperature transport time series evaluated as contributions from the overturning (OT; blue), the gyre (GY; green), the vertical average (BT, red) and baroclinic circulation (BC, light blue), respectively.

Regional Heat Budgets:



(top) Horizontal temperature flux convergence in two regions, one centered at 30° N and covers the Pacific east of 180° E. The second region represents ± 10° latitude, 230° to 280° E. Plotted separately in the top panel plotted are contributions for the zonal (red), the meridional horizontal (magenta) transport divergences and the net convergence (green). (middle) Horizontal temperature flux convergence (green), net surface heat flux (red) and time-rate of change of heat content in the region (blue). (bottom) Timeseries of heat content (blue).

Ongoing ECCO Activities

All results shown above are quantities that can not directly be observed: ocean state estimation is important for obtaining estimates of all climate relevant observable and unobservable time-dependent fields. Those include the flow field, transports, mixed layer depths, overturning, and especially the surface heat, freshwater and momentum fluxes that are consistent with ocean observations.

Currently we are working towards a global ocean state estimation with 1° spatial resolution that includes all WOCE data over the 10 year period 19929 through 2001. The overall ECCO goal is to provide near-operational, continuing oceanic state estimates, to be made publicly available. A major scientific goal is to describe and contribute to the understanding of the global general circulation of the oceans by using the results. An ultimate technical goal is a complete ocean estimate over the period 1985 - present and with 1/4° resolution with error estimate. For climate applications, we will also need a longer run with reduced resolution (e.g., 50yrs with 1° resolution).

All ECCO state estimate products (e.g., three dimensional velocities, temperature, salinity, etc.) are available through the web page http://www.ecco.ucsd.edu.

References

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