Estimating Climate Changes of the Deep Ocean

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Summary:

We use results from the ECCO 2° global state estimation as described by Stammer et al., 2002a,b,c) to analyze changes in the deep ocean occurring during 1993 - 2000. The model drift in sea surface height over the estimation period is consistent with observations from TOPEX/POSEIDON in their spatial pattern, but smaller in their amplitudes by about a factor of 2. Associated abyssal temperature and salinity changes are complex in their geographical pattern and point toward air-sea interaction over water mass formation regions as the primary cause of changes in the model's deep density fields. Changes in the model's heat content are twice as large as those reported by Levitus. However, the deep model temperature change could be showing patterns similar to that of the real ocean.

Methodology:

An ECCO ocean synthesis is obtained by forcing the MIT 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].

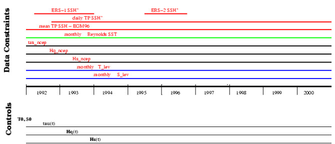

Figure 1 shows the schematic of the ongoing optimization. The top part of the figures shows the data constraints and their distribution in time. The lower part shows the "control" parameters, which are the initial T and S fields, and the time-varying surface forcing (wind stress, heat and fresh water fluxes), which are adjusted over the full 9 year period 1992 through 2000 to bring the model into consistency with the data.

During the estimation procedure, changes in the temperature and salinity initial conditions and surface fluxes are estimated so that the model-data misfit is reduced. Also important for this study is that the model drift in temperature and salinity was minimized over the entire period. Constraining this drift speeded up the surface flux adjustments during the optimization.

Although small, regional drifts of the model sea surface height, temperature and salinity fields are not eliminated altogether by this procedure and we here analyze the remaining drift with the view that it probably represents real oceanic change.

Sea Surface Height Changes:

The model adjustment in sea surface height was estimated by least-squares fitting a straight line to sea surface height fields over the period 1993 - 2000.

The largest changes are of the order of ±15 cm and can be found in the sub-polar regions of both hemispheres. Smaller changes are visible in the tropical and subtropical oceans. All these changes show intriguing gyre or circulation structures. Sea surface height changes along two positive ridges across the Pacific in both hemispheres. A somewhat similar structure seems to be present also in the North Atlantic.
The model's SSH drift has to be compared with with T/P observations. In many locations, the altimeter-alone changes are similar to those estimated by the data/model combination, but they do show substantially larger amplitudes, suggesting that the drift of the physical ocean state may have been too firmly suppressed in the model. Most changes in the model can be explained by steric (density) shifts, but some fraction cannot be explained completely that way, but is due to mass redistribution.

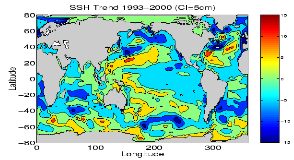

Figure 2 sohes estimated mean sea surface height changes over the 8 year period 1993 through 2000 estimated from a least-squares fit procedure. Contour interval is 5 cm.

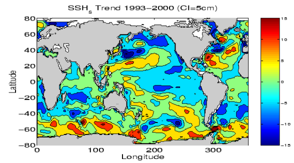

Figure 3: Estimated steric sea level change over the 8 year period 1993 through 2000 estimated from the model potential density field. Contour interval is 5 cm.

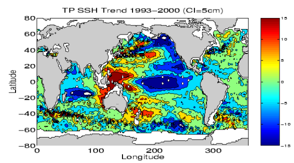

Figure 4: Least-squares fitted changes in sea level as observed by TOPEX/POSEIDON over the same period, 1993 through 2000.

Temperature and Salinity Changes:

Temperature and salinity changes associated with trends in the model's SSH occur at all depth levels. Shown here are the changes from 600m and 2500m depth respectively.

At 600m depth, changes in both fields are largest over the ACC, the Kuroshio extension and over the North Atlantic. However, they are not identical in pattern and are not compensated in density. As an example, salinity changes are large over the Kuroshio, while temperature seems to change more pronouncedly further east over the central Pacific as one would expect from a Pacific Decadal Oscillation (PDO).

Deeper down in the water column, temperature and salinity drifts are almost negligible in some regions, such as the tropical Pacific, indicating that vertical numerical diffusion does not play a key role in the erosion of T/S structures. But temperature and salt changes are large near source regions of deep water masses. In the southern oceans those are the Ross and Weddell Seas. In the North Atlantic a clear path of anomalously warm water along the deep western boundary current is obvious, originating from the Labrador Sea and Irminger Sea and reaching down to the latitude of Florida.

A comparison of the changes in SSH with those in temperature and salinity reveals that over the Southern Ocean, the salt effects seems to be as important as temperature, and in some places dominates SSH changes. The same conclusion applies to the Kuroshio. In contrast e.g., in the central subtropical North Pacific, shallow temperature changes seem to dominate the SSH changes, while the Southern Ocean shows a clear relationship between deep temperature changes and SSH trends.

Patterns of temperature changes similar to those shown above could underlie the global changes in temperature and hear content reported recently by *Levitus et al.* [2001; see also *Barnett et al.*, 2001]. Our results indicate that warming in the deep ocean is far from uniform, geographically and could have relatively short advective time scales in regions connected to water-mass source regions.

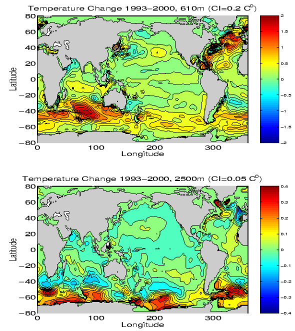

Figure 5: Estimated changes in potential temperature at (top) 610 m and (bottom) 2500m depth during the period 1993 through 2000 estimated from a least-squares fit procedure. Contour intervals in the top and bottom panels are 0.2° C and 0.05° C, respectively.

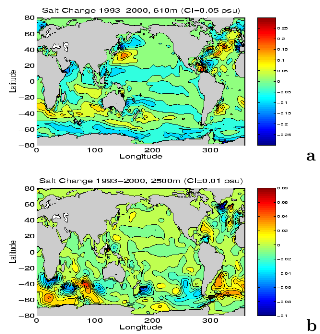

Figure 6: Estimated changes in salinity at (top) 610 m and (bottom) 2500m depth during the period 1993 through 2000 estimated from a least-squares fit procedure. Contour intervals in the top and bottom panels are 0.05 and 0.01, respectively.

Heat Content:

For a comparison with the *Levitus et al.* [2001] results, we show a time series of the global heat content of our solution together with those computed separately over the top 510m, from 510 to 2200m, and from 2200m to the bottom.

The global increase in heat content is about $2x10^{22}$ J over the 8 year period 1993 through 2000, a number that is about twice the estimate provided by *Levitus et al.* [2001]. The possibility of increased heat uptake during our estimation period, potential under sampling in the *Levitus et al.* [2001] estimate or unrealistic vertical diffusion in our result, as a causes for the discrepancy remain to be investigated. The two top layers contribute about equally, while the deep part of the water column seems less important for this computation. Interestingly, the increase in our intermediate layer almost matches the *Levitus et al.* [2001] result, but the significance of this agreement is unclear. Note also that the increase comes to a halt in the top layer during the last ENSO event.

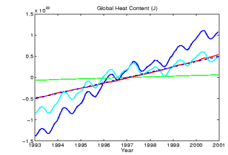

Figure 8: Global heat content (blue) and values evaluated separately over the top 510 meters, from 510 to 2200 meter and below (cyane, red and green curves, respectively). Also shown is in an estimate of global heat content increase obtained from *Levitus et al.* [2000]. A temporal mean was removed from all curves.

Discussion:

Separating real physical shifts from regional numerical drift will be a challenge for long-term climate-oriented state estimates. Several improvements will be required in future estimates. Those include an extension of the estimation period to 50 years paralleling the NCEPs re-analysis. During that period all available data will be assimilated as they have been measured thus allowing the model to drift consistent with observed changes of the deep ocean.

A climate-oriented ocean state estimation system should also provide estimates of quantities such as global sea level changes. For that purpose two important extensions will be required:
(1) The model needs to be truly global and then needs to include an ice model.
(2) The Boussinesq approximation renders the numerical model currently used as volume rather than mass conserving. This approximation needs to be removed.
This latter step is also important for studies of the Earth's changing mass field and the role the ocean plays in the overall mass balance.

References

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