Improving Air-Sea Flux Estimates Through Global Ocean Data Assimilation

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Summary:

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.

Oceanic state estimation is a powerful tool to improve estimates of surface momentum, heat and freshwater fluxes, available from reanalysis projects, in a way that they are consistent with ocean observations. Here we use the ECCO data assimilation results from nine years during the World Ocean Circulation Experiment to assess the quality of surface flux adjustments made to NCEP products through the data assimilation procedure. Independent estimates of the adjustments from bulk formula and regional field observations are also employed to evaluate the results. Adjustments are all within the crude prior error bars on these fields, and on the large scale are consistent with known deficiencies in the NCEP products. Wind stress adjustments are also everywhere within the prior error bars, but exhibit regional features that reflect ocean model failures to resolve intense boundary currents. On the largest scales, the inferred adjustments to NCEP winds are consistent with inferences made from satellite wind measurements. Further improvements in the surface flux estimates obtained using data assimilation are anticipated as the estimation procedure becomes more complete and the ocean model more accurate.

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].

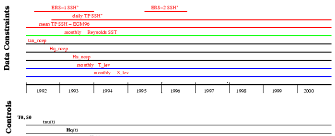


Figure 1 shows the schematic of the ongoing optimization. The top part of the figures shows the data constraints and their distribution in time. The lower part shows the "control" parameters, which are the initial T and S fields, and the time-varying surface forcing (wind stress, heat and fresh water fluxes), which are adjusted over the full 9 year period 1992 through 2000 to bring the model into consistency with the data. With these parameters, the control vector contains 8 million elements. and the cost-function has the form:

$$
\begin{aligned}
J \;=\; & \frac{1}{2}[(\overline{\zeta}-\overline{\zeta}_{obs})^T\mathbf{W}_{EGM96}(\overline{\zeta}-\overline{\zeta}_{obs}) + (\zeta'-\zeta'_{TP})^T W_{TP}(\zeta'-\zeta'_{TP}) \qquad (1)\\
& +(\zeta'-\zeta'_{ERS})^T W_{ERS}(\zeta'-\zeta'_{ERS}) + \sum_{k=1}^{72}(\overline{\mathbf{T}}_{\mathbf{s_i}}-\overline{\mathbf{SST}}_{\mathbf{i}})^T W_{SST}(\overline{\mathbf{T}}_{\mathbf{s_i}}-\overline{\mathbf{SST}}_{\mathbf{i}})\\
& +(\tau_{\mathbf{u}}-\tau_{\mathbf{u}NCEP})^T W_{NSCAT_x}(\tau_{\mathbf{u}}-\tau_{\mathbf{u}NCEP}) + (\tau_{\mathbf{v}}-\tau_{\mathbf{v}NCEP})^T W_{NSCAT_y}(\tau_{\mathbf{v}}-\tau_{\mathbf{v}NCEP})\\
& +(\mathbf{H_Q}-\mathbf{H_Q}_{NCEP})^T W_{H_Q}(\mathbf{H_Q}-\mathbf{H_Q}_{NCEP}) + (\mathbf{H_F}-\mathbf{H_F}_{NCEP})^T W_{H_F}(\mathbf{H_F}-\mathbf{H_F}_{NCEP})\\
& +\sum_{k=1}^{6}\sum_{i=1}^{12}(\overline{\mathbf{T}}_{\mathbf{i,k}}-\overline{\mathbf{T}}_{\mathbf{i}Lev})^T W_T(\overline{\mathbf{T}}_{\mathbf{i,k}}-\overline{\mathbf{T}}_{\mathbf{i}Lev}) + \sum_{k=1}^{6}\sum_{i=1}^{12}(\overline{\mathbf{S}}_{\mathbf{i,k}}-\overline{\mathbf{S}}_{\mathbf{i}Lev})^T W_S(\overline{\mathbf{S}}_{\mathbf{i,k}}-\overline{\mathbf{S}}_{\mathbf{i}Lev}).
\end{aligned}
$$

Present choices for the weight matrices are:

$$
\begin{aligned}
\mathbf{W}^{-1}_{EGM96} &= inverseerrorcovariance(EGM96) - - fullmatrix \qquad (2)\\
diag(\mathbf{W}^{-1}_{TP}) &= (rms(\zeta)/2)^2 \qquad (3)\\
diag(\mathbf{W}^{-1}_{ERS}) &= diag(\mathbf{W}^{-1}_{TP}) + (5cm)^2 \qquad (4)\\
diags(\mathbf{W}^{-1}_{NSCAT_x,NSCAT_y}) &= (rms(NSCAT - ECMWF))^2 \qquad (5)\\
diag(\mathbf{W}^{-1}_{Q}) &= (rms(H_Q)/3)^2 \qquad (6)\\
diag(\mathbf{W}^{-1}_{F}) &= (rms(H_F))^2 \qquad (7)
\end{aligned}
$$

Results:

The emphasis of this present paper is establishing the quality of the adjusted ECCO air-sea fluxes of momentum, heat and freshwater by comparing them with independent estimates available from Large and Nurser (2001; hereafter LN01), although uncertainties abound in all available flux data sets.

Changes in surface heat and freshwater fluxes are consistent on the large scale with estimates from LN01.

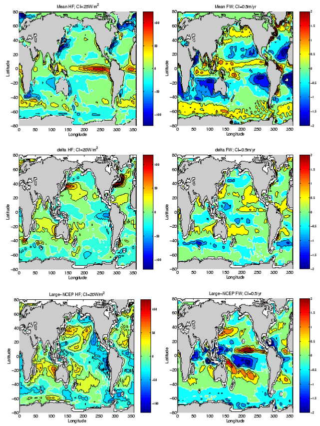
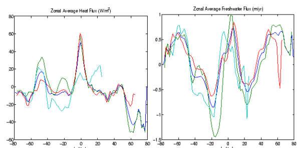
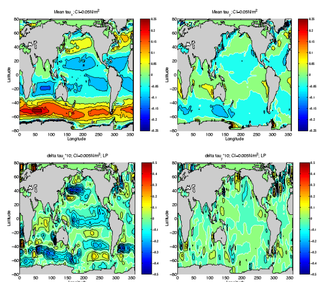


Figure 3 Top row: The mean net surface heat (left) and freshwater flux fields to/from the atmosphere (right) as they result from the optimization over the period 1992 through 2000. Middle row: Mean changes in net surface heat exchange relative to the prior NCEP fields estimated over the one-year period 1993 (in W/m^2; left panel), and for the net freshwater exchange (in W/m^2; right panel). Bottom row: Mean difference LN01 - NCEP net surface heat flux from 1993 (left panel) and for fresh water flux (right panel).



Zonally integrated heat (left) and and surface fresh water fluxes (right), evaluated globally (blue curves) and over the Atlantic, Pacific and Indian Ocean sectors (green, red and magenta), respectively.

Wind stress fields also adjust in a way consistent with differences between NCEP and ERS 1/2 scatterometer winds.



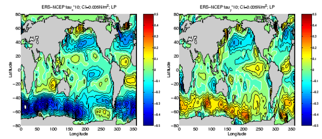


Figure 4: (left) Top row: The mean surface zonal wind stress (left) and meridional wind stress fields (right) as they result from the optimization over the period 1992 through 2000 (in N/m^2). Middle row: Mean changes in meridional wind stress relative to the prior NCEP fields estimated over the six-year period 1992-1997 (in N/m^2;left), and for the meridional component (in N/m^2, right). Bottom row: The left panel shows mean difference in ERS zonal wind stress from 1992 through 1997 minus net NCEP zonal wind stress from the same period. Right panel is the same, but for the meridional stress. All difference fields have been spatially low-pass filtered to show only structures larger than about 5000km. For the comparison, we used the ERS-1/2 gridded monthly wind stress fields on a global 1° by 1° grid (*Bentamy et al*, 1998; IFREMER, 2000).

Over most of the ocean, the dynamically relevant forcing is the wind stress curl.

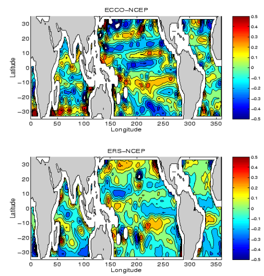


Figure 5 shows the differences in wind stress curl estimated from mean ECCO wind fields minus those from NCEP (top) and the differences with the ERS 1/2 wind stress fields for the period 1992 through 1997. Units are 10^{-7} N/m^3. The comparison is limited to the large-scales over the lower latitudes where we have seen some skill in the ECCO estimates in improving NCEP stress estimates. As is to be expected, differences in the curl adjustments can be found in the vicinity of strong boundary currents, e.g., the Kuroshio. Note also the reversal of the dipole structure around Hawaii between the two fields. Nevertheless, agreements in the curl adjustment are obvious, and include bands of positive and negative curl adjustments that extend zonally across the Pacific. Even some regional changes are similar such as the positive anomaly in the eastern South Pacific that is disconnected from the coast by a negative band.

The state estimation procedure adjusts the surface forcing on a daily basis and ultimately, as model physics and observations improve, time-varying weather events may also become correctable. A clear improvement in the ECCO estimates relative to the NCEP first guess is obvious, indicating that the estimation at this location actually brings all variation on time scales longer than about one month into better agreement with the TAO measurements.

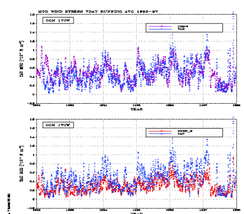
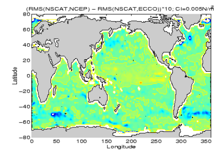


Figure 6 shows a comparison of ECCO and NCEP wind stress fields with TOGA TAO measurements at 170° W on the equator. The top panel shows a time series of zonal TAO wind stress components (blue) and ECCO results (purple). The bottom panel shows a similar plot, but with NCEP fields in red.



RMS reduction in the difference between ECCO and NSCAT wind stress time series as compared to the original NCEP-NSCAT differences. Positive values indicate a misfit reduction (in N/m^2). Improvements are limited to about ± 20° latitude, and are most obvious for the Pacific Ocean. At most other latitudes, changes in the misfits are unstructured (values fluctuate around zero). But as was discussed before, all boundary current regions clearly appear as regions with large negative amplitudes, i.e., the estimation procedure degrades not only the mean wind stress, but also the weather events there, in order to correct the flow field. Improved ocean model physics are required, particularly through higher spatial resolution, to lead to improved surface flux fields over those regions as well.

Discussion

Oceanic state estimation has advanced sufficiently that it is now possible to make estimates of the atmospheric forcing fields required to reproduce global ocean observations. Because our ocean estimates are preliminary, the fluxes presented here are preliminary as well. They will improve as more data are included and as the model physics becomes more complete. Nevertheless the comparison presented with independent information about NCEP flux products is encouraging and shows the potential at hand.

All changes in surface flux fields are inferred here entirely through ocean observations and an ocean synthesis, illustrating the large reservoir of information about the atmosphere and the climate system residing in the ocean. The long-term goal is to eventually use this information to improve predictability both for climate and medium-range weather forecast time scales.

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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