Reply

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We welcome this opportunity to further discuss the interpretation of the results of Wunsch and Heimbach (2006, hereafter WH). Saunders et al. (2008, hereafter S2008) compare the WH results to what they label the “observed” circulation and particularly emphasize issues at high latitudes. We agree completely that our result is approximate, and we note only that no general circulation model (GCM) will ever produce perfect results. All models are numerical approximations to continuous partial differential equations that are themselves approximations, through incompletely understood parameterizations, to the underlying fluid and thermodynamic equations, driven by incomplete initial and boundary conditions. Of course, no noisy data can produce a perfect result either: the interpretation of the data S2008 refer to and prefer is totally dependent on a nonnumerical model. But the assumptions made in their model are much more rigid than in our GCM.

The Estimation of the Circulation and Climate of the Ocean (ECCO)–Global Ocean Data Assimilation Experiment (GODAE) solution described by WH was not claimed to be “correct,” only that it was generally consistent with a large dataset. It differs from other published global general circulation model results in having been determined from a least squares fit (“harmonized”) to more than 200 million distinct oceanographic data points, including almost all hydrography, altimetry, XBTs, Argo float profiles, gravity, etc., some of the same hydrography as in the Bryden et al. (2005) calculation, as well as about two billion meteorological estimates. In the configuration reported by WH, initial conditions and meteorological variables were adjusted through the least squares fit until the model, run freely forward from the adjusted conditions and forcing, was within acceptable error bars of the data. The result is best understood as an interpolation of the global datasets by a self-consistent dynamical model. Interpolation is a generally robust procedure, and contrary to the S2008 assertion, no extrapolations or “predictions” were made by WH. But as in any least squares fit, residuals always exist (they should never vanish) and, particularly in the subtropical and tropical North Atlantic, they were deemed acceptably small in the published result. The model configuration had a 1° spatial resolution, 23 layers, and a wall at 80°N. These and numerous other model approximations necessarily imply that the resulting circulation cannot be completely realistic, particularly at high northern and equatorial latitudes, but the very strong imposition of the observations renders the results distinct from ordinary forward modeling. We will therefore not here address the general shortcomings of ocean general circulation models except to note that many (not all) model errors are significantly reduced by use of the data. Note that the fits to the available data (see Wunsch and Heimbach 2007 for more detail), in the subtropical gyre of the North Atlantic, are everywhere quite good except in the western boundary currents. The S2008 comment implies a different, important question than the one they put: Does a model displaying misfits near its northern boundary—which nonetheless, almost everywhere else, fits the global WOCE hydrography, the hydrographic climatologies, Argo profiles, all of the altimetric data, both time mean and time varying, and so on—produce a less credible solution in the subtropical gyre than does a handful of temporally and spatially aliased hydrographic measurements in an analysis that ignores all of the other data?

The particular issue raised by S2008, that of failure by $z$-coordinate models to reproduce dense-water plumes in the Greenland–Iceland–Norwegian (GIN) Seas, is a well known problem for both coarse- and fine-resolution models (e.g., Campin and Goosse 1999;
Ezer and Mellor 2004). That all such models, however, have overturning circulations that are too shallow is much less clear. For example, Forget et al. (2007) demonstrate that least squares state estimation can alleviate the problem of a shallow overturning circulation through correction of the initial conditions. Because their control space was restricted to initial conditions, the influence of those corrections was limited in time by the eventual accumulation of model error (and the limited magnitude of the initial condition adjustment). Although our control space includes time-varying elements, they are all surface fields with little expected impact on the deep ocean baroclinicity over the short time period considered. Additional fully three-dimensional controls of internal model parameters are expected to have a significant impact over longer time scales, but they have not yet been included in production calculations.

Whatever the high latitude shortcomings, the focus of the WH inference was the subtropical gyre and, in particular, the variability along the line nominally at 26°N, which has been the subject of a number of overheated pronouncements. The major conclusions of WH, as it pertains to this location and issue, were 1) the month-to-month variability at 26°N is so large that deducing multidecadal trends from a handful of circulation “snapshots,” whatever their accuracy and strong assumptions about reference level velocities, is not credible because of the temporal aliasing, and 2) in using the continuous (daily) estimates available from the ECCO–GODAE fits, some minor trends in properties do inevitably appear in the interval 1992–2004. These latter are weak and their long-term significance too little understood to warrant loud publicity. Given, too, that the model does not resolve the geostrophic eddy field, the estimated variability in the WH results must be a lower bound, with the determination of true secular trends being considerably more difficult than estimated there [see Wunsch (2008), and results to be discussed elsewhere, comparisons to the recently acquired Rapid Climate Change–Meridional Overturning Circulation and Heat Flux Array (RAPID–MOCHA) data]. Despite the difficulties of modeling at high latitude, the WH variability results are consistent with those of Schott et al. (2006), who conclude from in situ current meter data that there is no evidence for any overall trends above the noise level in the subpolar regions.

S2008 refer to observed change (italics theirs) in the deep transports at 26°N. In practice, however, they do not observe the transports, rather they infer them from the thermal wind and a series of rigid assumptions about how to determine reference-level velocities; these assumptions include, among many others, constancy of the Florida Strait transports. This is not the place to review the intrinsic nonuniqueness of the conventional dynamic method, but note only that Wunsch and Grant (1982) showed two examples of radically different North Atlantic flows, equally consistent with the same thermal wind, differing only in then-plausible reference-level assumptions. Alternatively, a meridional flow of 1 mm s⁻¹ occupying 1000 m of water depth and spread over 5000 km produces a volume transport of 5 Sv. Are the reference-level velocity assumptions discussed by S2008 accurate to 1 mm s⁻¹? Ganachaud (2003) showed that his transport estimates, cited by S2008, had errors dominated by the temporal variability, consistent with our own inferences. Finally, the GCM is, almost everywhere, in a state of near geostrophic balance: the ageostrophic terms in the oceanic interior are everywhere very small. Thus the WH solution is, just as is the solution of S2008, in interior thermal wind balance—but it is one where the reference-level velocity is a far more complex function of position and time than that imposed by Bryden et al. (2005, but not discussed by them) and one that is also consistent with a much greater dataset.

The WH estimates are not the last word; indeed, with the optimization ongoing, some model features enhanced, improved data quality, and new data sources, the results have continued to improve. Searches must continue for better and more realistic models, for better continuous global coverage by observations—particularly in the abyss—and for improved understanding of the skill in such combined estimates as in our own. The degree to which model-data misfits in one region of the ocean degrade the solution everywhere else for all time must be determined. Production of accurate, but never perfect estimates of the behavior of the ocean in the past is a prerequisite to, but no guarantee at all of the eventual ability to forecast its future state.

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