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The Fidelity of Ocean Models With Explicit Eddies

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Abstract

Current practices within the oceanographic community have been reviewed with regard to the use of metrics to assess the realism of the upper-ocean circulation, ventilation processes diagnosed by time-evolving mixed layer depth and mode water formation, and eddy heat fluxes in large-scale fine resolution ocean model simulations. We have striven to understand the fidelity of these simulations in the context of their potential use in future fine-resolution coupled climate system studies. A variety of methodologies are used to assess the veracity of the numerical simulations. Sea surface height variability and the location of western boundary current paths from altimetry have been used routinely as basic indicators of fine-resolution model performance. Drifters and floats have also been used to provide pseudo-Eulerian measures of the mean and variability of surface and sub-surface flows, while statistical comparisons of observed and simulated means have been carried out using James tests. Probability density functions have been used to assess the Gaussian nature of the observed and simulated flows. Length and time scales have been calculated in both Eulerian and Lagrangian frameworks from altimetry and drifters, respectively. Concise measures of multiple model performance have been obtained from Taylor diagrams. The time-evolution of the mixed layer depth at monitoring stations has been compared with simulated time series. Finally, eddy heat fluxes are compared to climatological inferences.

Introduction

The assessment of the fidelity of ocean simulations has become more meaningful and rigorous as ocean models have become more realistic in their representation of ocean processes. Furthermore, data have become available which permit comparisons over a wide range of spatial and temporal scales. The use of increased horizontal and vertical resolution, improved atmospheric surface forcing and bottom bathymetry products, as well as the use of increasingly sophisticated parameterizations of physical processes on temporal and spatial scales not resolved by the model, have all contributed to the improved realism of model simulations. The advent of ocean observing satellites and the World Ocean Circulation Experiment in the 1990's have provided unprecedented numbers of observations for diagnostics. These diagnostics can be based on model/data comparisons, statistical measures, budgets and dynamical balances, as appropriate. While metrics can be used to assess the realism of a model simulation, it should be noted that an ocean model can never be verified or validated, but can only be confirmed to be consistent with the available observations (Oreskes et al., 1994).

The choice of metrics selected to evaluate the performance of an ocean simulation is based on the application and the questions that the model is being used to address. Metrics need to account for the spatial and temporal scales resolved in the simulation along with the representation of processes relevant to the problem being addressed. In coupled climate simulations, these are the processes governing air-sea exchanges and the uptake, transportation, and storage of heat, freshwater, and energy. For synoptic forecasting, high-frequency variability (up to five days) of the upper ocean thermohaline structure and flows are important.

The majority of the kinetic energy in the ocean circulation is generally accounted for by flows with spatial scales of 50 to 500 km, which is referred to as the oceanic mesoscale (Stammer, 1997). Advances in high performance computing architectures and the increased availability of such platforms for "grand challenge" calculations over the past decade have lead to ocean simulations in which much of this variability is resolved. Hurlburt and Hogan (2000) conducted basin-scale simulations at 1/8° to 1/64° with 5-6 layers. Horizontal resolution of 5-10 km and higher vertical resolution: 40-60 levels (Smith et al., 2000; Masumoto et al., 2004; Maltrud and McClean, 2005, hereafter referred to as MM05), 16 layers (Chassignet and Garraffo, 2001) and 32 hybrid layers (Chassignet et al., 2006) were used in subsequent basin and global integrations. These simulations are of sufficiently high resolution to allow for the analysis of eddy processes; however at what horizontal and vertical resolution these models can be considered truly "eddy-resolving" is still to be understood. Siegel et al. (2001) suggest that resolutions as high as 1 km are needed for numerical convergence. Smith et al. (2000) argued that since the first baroclinic Rossby radius was resolved up to about 50ºN in a 0.1º North Atlantic (NA) ocean simulation using the Parallel Ocean Program (POP) and that typical length scales for mesoscale eddies were somewhat larger than the first baroclinic Rossby radius, then eddies would be reasonably well resolved in most of the model domain.

Model	Horizontal Resolution	Vertical Resolution	References
NLOM	1/8º - 1/64º	6 layers	Hurlburt and Hogan (2000)
POP	1/10º	40 levels	Smith et al. (2000) Le Traon et al. (2001) McClean et al. (2002) Tokmakian and McClean (2003) Brachet et al. (2004) Maltrud and McClean (2005) Treguier et al. (2005) Tokmakian (2005) McClean et al. (2006) Rainville et al. (2007)
OFES	1/10º	54 levels	Masumoto et al. (2004) Du et al. (2005) Aoki et al. (2007)
MICOM	1/12º	16 layers	Paiva et al. (1999) Chassignet and Garraffo (2001) Garraffo et al. (2001) Bracco et al. (2003) Treguier et al. (2005)
HYCOM	1/12º	32 hybrid layers	Chassignet et al. (2006) Kelly et al. (2007)

Table 1: Listing of selected eddying models discussed in this review, NLOM is the Navy Layered Ocean Model, POP is the Parallel Ocean Program, OFES is the Ocean General Circulation Model based on the Modular Ocean Model 3 for the Earth Simulator, MICOM is the Miami Isopycnic Coordinate Ocean Model, and HYCOM is the Hybrid Coordinate Ocean Model.

Fine-resolution ocean grids such as those referred to above, in addition to largely resolving eddying processes, produce more realistic depictions of narrow western boundary currents whose dynamics influence the gyre-scale circulation and jets like those in the Antarctic Circumpolar Current (ACC). Their proper representation is essential to the realistic simulation of key climatic quantities such as mass, heat, and salt transports. They also allow for a more realistic representation of ocean bottom bathymetry and coastal geometry, which affects the ocean dynamics and communication between ocean basins and/or marginal seas. In coupled systems, more accurately positioned fronts are important in air-sea interaction processes since large sea surface temperature errors can result from biases in flow paths.

Centennial global coupled climate simulations are routinely conducted using ocean models whose horizontal resolution is nominally one degree for example, the Community Climate System Model3 (CCSM3; Collins et al., 2006). In these models, ocean eddies are not resolved and are represented using sub-gridscale parameterizations such as Gent and McWilliams (1990) and Ferrari et al. (2007). These coupled models have provided depictions of past and present climatic states and are the main tools for projecting future planetary changes. To realistically represent eddies in climate models it is critical to understand their contribution to the total variability, their transport properties and dynamics, and their impact on the representation of the model mixing on short spatial scales. Measurement of the eddy contribution at basin and global scales, however, is an extremely challenging observational problem. Fine-resolution ocean models, as a type of large eddy simulation (LES), that resolve most of the eddy scales can be used as “truth” to verify the accuracy of eddy parameterizations.

The main objective of this paper is to review fidelity studies of fine-resolution basin and global eddying ocean general circulation models over the past decade. We will concentrate on ocean models whose horizontal resolutions are $1/10^{th}$ degree and higher. We review a broad base of ocean metric studies however the experience of these authors is with POP. Other papers in this monograph review layered models and some further relevant material may be found within these chapters. The focus here will be on the representation of ocean processes important to climate change and variability, as well as the space-time scales resolved by the models in the upper ocean. The duration of the latter, limited to several decades by the capability of present generation computational platforms, is sufficient to allow the flow to mostly adjust dynamically to its initial state (“spin-up” the circulation) but not to bring the model into thermodynamic equilibrium. Below the thermocline in regions away from strong currents or deepwater formation sites water mass properties do not evolve far from this initial state. Nevertheless, such models can be used for the study of the wind- and buoyancy-driven circulation on time scales up to a decade (Böning and Semtner, 2001). As well, the data upon which to base metrics were primarily sampled in the upper ocean.

We will reflect on the differences between the representation of parameterized eddy heat fluxes in the ocean component of the current generation coupled climate models and the resolved fluxes in the fine resolution models. It is not possible to do side-by-side comparisons for several reasons. The fine-resolution stand-alone ocean models are typically forced with reanalysis atmospheric surface fluxes from prediction systems. The coupled system is subject to present day green house gas forcing and does not represent a hindcast. It is therefore only possible to discuss statistical representations of the fluxes in such models.

Finally, we will discuss the need to advance the state of metrics to quantitatively assess the fidelity of the relevant ocean processes at both eddy resolving and non-eddy resolving scales.

Ocean Data

The assessment of the fidelity of ocean models has become more quantitative over the past several decades. This, in part, is due to the increasing availability of *in-situ* and satellite data on unprecedented scales that can be used for consistent statistical comparisons with ocean model output. The World Ocean Circulation Experiment (WOCE) provided a collaborative framework for countries all over the world to participate in ocean sampling. Measurement programs already underway were incorporated into WOCE, new measurement techniques were developed, and complementary satellite missions were launched. Both remotely sensed and *in-situ* measurements have increased since that period using improved technologies. The data sources discussed here are by no means exhaustive; rather they represent the means by which model performance has been judged to date.

Three data sets in particular, have spatial coverage on a near-global basis with high temporal resolution: sea surface height anomalies (SSHA) from altimetry (Wunsch and Stammer, 1995), blended sea surface temperature (SST) from satellites and *in-situ* sources, and velocities from surface drifting buoys at 15 m (Pazan and Niiler, 2001). The TOPEX/POSEIDON/JASON-1/Ocean Surface Topography Mission is a 15-year time series of SSHA whose spatial coverage is global equatorward of 66°N and 66°S. Along-track samples are spaced approximately 1 s and 6 km apart; the spacing between tracks is about 315 km at the equator, and the global sampling pattern is repeated every 9.92 days. Lagrangian data from the surface drifting buoys are interpolated to create uniform 6-h time series of positions and velocities. The data spans the period 1979-2007; its spatial coverage has progressively approached global extent (apart from the polar oceans) over this period. For more information about these data see http://www.aoml.noaa.gov/phod/dac/dacdata.html. Very recently, two new high resolution SST analysis products were developed using optimal interpolation that have a spatial grid resolution of 0.25° and a temporal resolution of one day. One product uses Advanced Very High Resolution Radiometer (AVHRR) infrared satellite SST data. The other uses AVHRR and Advanced Microwave Scanning Radiometer (AMSR) on the NASA Earth Observing System satellite SST data. Both products also use *in situ* data from ships and buoys and include a large-scale adjustment of satellite biases with respect to the in situ data (Reynolds et al., 2007). Other global data sets include the unprecedented numbers of profiles of temperature and salinity over the top 2000 m of the ocean being collected as part of the Argo program (Gould et al., 2004) and the GRACE satellite mission which is supplying the Earth's time-varying gravity field on a monthly basis from which ocean bottom pressure at a spatial resolution of approximately 500 km can be obtained (Wahr et al., 1998; 2002).

Other data sets are spatially limited but have provided regional or point-wise time series over long periods. These include the monthly repeat IX1-expendable-bathythermograph (XBT) transect line between Java and Australia (Meyers, 1996), which has provided long-term (1987 to the present) monitoring of the Indonesian Throughflow. Profile spacing is about 100 km and their depth extent is 750 m. Also 30 repeat high-resolution (1/2° in the basin interior) XBT transects were collected during 1991-1999 in the North

Pacific at about 22°N (Roemmich and Gilson, 2001). Tide gauge data collected at coastal and island stations across the globe (see http://uhslc.soest.hawaii.edu/) have provided measures of sea level rise and variability over a range of temporal scales. Time series of vertical profiles of upper-ocean temperature data collected at particular geographical locations, the so-called "Ocean Time Series" are available on a long-term regular basis. The Hawaii Ocean Time-series (HOT) and the Bermuda Ocean Time-series Study (BATS), nominally located at 22°N, 158°W and 32°N, 64°W, respectively, have been collected since 1988 to the present on a roughly monthly basis.

Data from several sources have been combined to produce mean volume transports through key inter-basin passages and straits. Using a combination of data from current meters, pressure gauges, and hydrography, Whitworth and Peterson (1985) obtained an annual net flow through the Drake Passage of 134±11.2 Sv. Larsen (1992) using cable data from 1969 to 1990 obtained a value of 32±3.2 Sv at 27°N for the Florida Current volume transport. From current meter data collected in the southern Indonesian passages, Gordon (2005) reports a value of about 10 Sv entering the southern Indian Ocean from current meter data; a better estimate of this value is the object of the International Nusantara Stratification and Transport (INSTANT) program (Sprintall et al., 2004). Meridional sections of upper ocean zonal currents, potential temperature, and salinity are estimated at ten longitudes from 143°E to 95°W using Conductivity–Temperature–Depth (CTD) and Acoustic Doppler Current Profiler (ADCP) data from 172 synoptic sections taken in the tropical Pacific between 138°E and 86°W, mostly in the 1990s (Johnson et al. 2002).

Ocean Metrics

Here we review metrics that have typically been used by the oceanographic community to assess the fidelity of basin and global scale eddying ocean models, defined here as having horizontal resolutions of nominally 1/10° and higher. These metrics provide assessments of simulated upper ocean sea surface height and velocity fields where satellite and surface drifter observations are plentiful. Typically the paths of simulated western boundary currents and sea surface height (SSH) variability from altimetry have provided zero-order indications of model bias. Turbulent statistics of the upper ocean circulation in these fine-resolution ocean models has been compared with that depicted by near global scale observations with temporal resolution of days. Both Eulerian (repeated sampling in time at a particular location such as along a satellite track or by a moored instrument) and Lagrangian (measurements collected in time while following a water particle) statistics have been used as a means of model verification. Lagrangian statistics have long been recognized as a most sensitive statistical means of testing the validity of eddy resolving models (Krauss and Böning, 1987). We also examine the time varying vertical structure of mixed layer depth at monitoring stations and surface ventilation processes where temperature and salinity data from hydrography and profiling floats furnish information on water masses. Finally, eddy heat fluxes are compared to climatological inferences.

Identification of Primary Ocean Model Biases

Sea surface height (SSH) variability from altimetry has routinely been used as a basic indicator of fine-resolution model performance on both global and basin scales (Paiva et al., 1999; Hurlburt and Hogan 2000; Smith et al. 2000; Masumoto et al., 2004; MM05; McClean et al., 2006; Chassignet et al., 2006). At these horizontal resolutions, the magnitude of the SSHA variability agrees more closely with that from altimetry than in lower resolution cases (for example, see, MM05; Figure 12), however significant biases are also seen. In the fully-global 0.1°, 40-level POP (MM05; Figure 12a), the 1/12° Hybrid Coordinate Ocean Model (HYCOM) (Chassignet et al., 2006; Figure 3), and near-global 1/10°, 54-level OFES (Ocean General Circulation Model based on the Modular Ocean Model3 for the Earth Simulator) (Masumoto et al., 2004; Figure 3b) the North Atlantic Current is too zonal and it fails to turn to the northwest to form the Northwest Corner off the Grand Banks. On the other hand, these models can be used to understand observational biases such as aliasing arising from data sampling strategies. Le Traon et al. (2001) used the 1/10° North Atlantic (NA) POP to quantify the high frequency, short-wave number SSH variability not resolved in the altimeter-derived variability, highlighting the issue of observational sampling biases in model/data comparisons.

Paiva et al. (1999), Hurlburt and Hogan (2000), and Smith et al. (2000) examined the separation location and accuracy of the path of the Gulf Stream (GS) between Cape Hatteras and the Grand Banks, in emerging fine resolution ocean models of the NA. The GS separated at Cape Hatteras in the 1/12°, 16-layer Miami Isopycnic Coordinate Ocean Model (MICOM) and followed an offshore path that lay within the observed northern and southern limits of the GS path as depicted by infra-red satellite-derived sea surface temperature (SST) (Paiva et al., 1999; Figure 1). The 0.1°, 40-level NA POP also showed a realistic separation, however the GS offshore pathway was displaced to the south by 1 to 1.5 degrees compared with results from moored observations during the Gulf Stream Dynamics and Synoptic Ocean prediction (SYNOP) Experiments (Smith et al., 2000; Figure 6). Hurlburt and Hogan (2000) used the mean GS path from satellite-derived SST and sea surface height (SSH) altimetry to assess the improvement in the realism of their 1/8°-1/64°, 5-6 layer Navy Layered Ocean Model (NLOM) simulations with increasing horizontal resolution; they found the best depicted mean GS path in their 1/32° simulation (see their Figure 7). Tokmakian (2005) also used observed SST to assess the change in the GS path when forcing the NA 0.1°, 40-level POP with daily fine-resolution (0.25°) scatterometer winds rather than coarser daily 1.25° European Center for Medium Range Forecasts (ECMWF) winds. All these findings were significant in that the simulated GS path in these fine-resolution simulations was much more realistic than in their lower resolution counterparts where the pathway was typically too northward and/or displayed an anticyclonic circulation on separating from the coast. Kelly et al. (2007) advanced beyond path evaluations by developing a hierarchy of metrics to evaluate the Kuroshio Extension (KE) region in a 1/12° Pacific basin HYCOM simulation over a variety of time scales. They compared the simulated KE path and strength and the upper ocean heat budget with those obtained from altimetric SSHA and observed sea surface temperature. They found that away from the separation region mean quantities and variations were realistic however upstream of 150°E the KE jet was overly energetic.

Observed values of volume transports through key straits and basins provide another straightforward diagnostic of model performance. MM05 compared observed mean volume transports with those from the 1/10° global POP through key Caribbean and Arctic passages, the Mozambique Channel, the Indonesian Throughflow, the Drake Passage, and from the Agulhas Current. Good agreement with transport estimates of the major current systems was obtained in general, such as 140 and 12 Sv through the Drake Passage and Indonesian Throughflow, respectively. Masumoto et al. (2004) reported values of 153 Sv for the Drake Passage and 9 Sv the Indonesian Throughflow from the 1/10° OFES model. MM05 compared volume transports in surface and intermediate (0-1250 m), deep (1250-3500 m), and bottom waters (below 3500 m) across latitudinal sections such as 24°N with observational estimates obtained by Schmitz (1995) and by Ganachaud and Wunsch (2000) from an inverse model. Du et al. (2005) compared the annual mean Indonesian Throughflow transport from the monthly repeat IX1-XBT transect line with equivalent 1/10° OFES fields. Readers are referred to these papers for further details of these comparisons.

Du et al. (2005) also validated the simulated mean vertical temperature structure along the IX1 transect and found that the model thermocline was quite a bit tighter than observed in the northern part of the IX1 line, suggesting that the model is underestimating the effects of vertical mixing. MM05 compared the mean zonal POP velocities at 140°W with the observational results from Johnson et al. (2002; Fig. 2), they found the model currents to be very close to their correct location with appropriate strengths. They also noted that the strength of the model Equatorial Undercurrent weakened considerably during the height of El Niño events in agreement with observations.

Space-Time Depiction of the Upper-Ocean Circulation

A comparative wavelet analysis of sea surface height variability from NA 0.1° POP, tide gauges, and altimetry was used by Tokmakian and McClean (2003) to assess the realism of the model's variability at periods of less than a year. Along the coast, they found the simulated SSH fields to be realistic since the correlations with tide gauges were on the order of 0.8. Eulerian length scales, representative of the simulated eddy fields, from NA 1/12° MICOM (Paiva et al., 1999) and 1/10° POP (Smith et al., 2000) agreed well with those calculated from altimetry. Paiva et al. (1999) used autocorrelation function zero-crossings to define length scales, while Smith et al. (2000) used the Tennekes and Lumley (1972) microscale length. The microscale length is defined as the square root of the ratio of SSHA to SSHA slope variances:

$$L^2 = \frac{<\hat{h}\hat{h}>}{<\hat{h}'\hat{h}'>}$$

where $\hat{h}$ denotes the SSH residuals and $\hat{h}'$ represents their slopes in a particular direction. A comparison of these methodologies can be found in McClean et al. (1997). Brachet et al. (2004) focused on the representation of the mesoscale in 0.1° NA POP. They calculated Eulerian sea level height space and time scales and propagation velocities. They found a high level of agreement between the model and the altimeter values for the spatial scales and propagation velocities, however the POP timescales were significantly longer than those from altimetry in the subtropical regions. They also found good agreement of the high-frequency eddy kinetic energy (EKE) seasonal variations in the Caribbean Sea and at high latitudes, despite a phase advance.

Length scales, calculated using the microscale length, are seen in **Plate 1c** from global 0.1° POP in the Southern Ocean for 1993-1994 at the full horizontal model resolution. The model was forced with synoptic National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) atmospheric surface fluxes of momentum, heat, and freshwater for the period 1979-2003 (MM05). These length scales can be compared with those from TOPEX/POSEIDON (T/P) for the same period by binning both fields onto 2°x2° grids (**Plates 1a and b**). The magnitude and spatial distribution of the simulated length scales are generally in good agreement with the altimetric length scales however the short scales seen south of 50°S in the model fields are absent in the T/P scales. This is due to T/P not sampling sufficiently often at these high latitudes and thus producing overestimated length scales. Histograms of the distributions of these scales in the region 10°- 60° S are shown in **Figure 1**; the T/P scales occur predominantly in the 100-160 km range while those from the model largely lie between 60 and 160 km.

Garraffo et al. (2001) and McClean et al. (2002) compared pseudo-Eulerian and Lagrangian statistics from surface drifting buoys and fine-resolution MICOM and POP basin simulations of the NA, respectively. Garraffo et al. (2001) compared NA surface drifter Eulerian statistics and Lagrangian time scales from 1989-1998 with those from 1/12º MICOM simulation forced with monthly Comprehensive Ocean-Atmosphere Data (COADS) climatology. They found that the model underestimated the eddy kinetic energy (EKE) in the Gulf Stream extension and in the ocean interior. A James test (Seber, 1984), which can be used to statistically compare two vector fields with different variances, was used to determine if the differences between the drifter and model mean velocity fields were significant over the domain (see their Figure 4b). Their *in-situ* and modeled Lagrangian time scales were longest in the eastern Atlantic; however in the interior the model scales were roughly a factor of two larger than the observed scales. They attributed these results to the lack of a high frequency wind component in the model forcing.

McClean et al. (2002), using a NA 0.1°, 40-level POP simulation with a mixed layer and forced with daily Navy Operational Global Atmospheric Prediction System (NOGAPS) wind stresses from 1993-2000 and climatological heat fluxes, focused on single-particle dispersion of the surface flow. Diffusivities, length and time scales were calculated from the *in-situ* and simulated velocities. Histograms of drifter and simulated time scales cover a range of 1 to 7 days and 1 to 9 days, respectively, however most of the scales in both cases are in the 1-4 day range. Bracco et al. (2003) computed probability density functions of average velocity from numerically simulated surface drifters and 1500-m floats in the NA configuration of MICOM. The distributions and their kurtoses (fourth-order moments) at both depths were non-Gaussian in agreement with analyses of ocean float trajectories (Bracco et al., 2000).

Treguier et al. (2005) report generally good agreement in the Irminger and Labrador Seas between mean velocities from surface drifters and those from three fine-resolution NA simulations (1/10° POP, 1/12° MICOM, and 1/12° Family of Linked Atlantic Ocean Model Experiments–FLAME) using multi-year averages when the NAO index was positive. They also compared simulated mean velocities at 700 m with those from floats. Near the East Reykjanes Ridge the model velocities were seen to more closely follow contours of potential vorticity (*f/h)* than those from the floats, indicating limitations in the model's dynamics.

Model Inter-Comparison Metric

It is sometimes necessary to represent concisely how a model field compares with a given observational data set, especially if several different models or model variables are being inter-compared with the data. The suite of coupled climate simulations conducted for the 4th Intergovernmental Panel on Climate Change is such a case. Single numbers such as the correlation coefficient and the root mean square (RMS) difference provide an overall measure of how well two fields agree, with the former giving information about the structure (or phase) of the two fields, and the latter about relative amplitude. In fact, these two measures are related to each other through the following relation:

$$E^2 = 1 + \sigma^2 - 2\,\sigma R$$

where σ is the ratio of the standard deviation of the model field to the standard deviation of the data, E is the RMS difference between the model and data (normalized by the data standard deviation), and R is the correlation coefficient. By noting that this relationship is simply the triangle law of cosines (with one side of length unity and $cos(angle) = R$), Taylor (2001) introduced a concise way of representing these quantities as a single point on a two-dimensional diagram.

McClean et al. (2006) used a Taylor diagram to consider how well the SSHA variability of the 0.1º global POP simulation compared with AVISO altimetry data, and how it related to another global POP simulation that differed only in the horizontal resolution (0.4º) and the magnitude of horizontal friction coefficients (**Plate 2**). The red/blue circles denote the agreement of the 0.4º/0.1º simulation with the data over the entire globe (from 70°S to 70°N) and three specific oceanic regions representing differing levels of eddy activity: high eddy intensity (Southern Ocean), relatively low intensity (open Pacific Ocean) and mixed (North Atlantic Ocean). In this diagram, the distance from the origin to a given point is equal to σ, the angle between the point and the x-axis is related to R, and the distance of the point from unity on the x-axis is equal to E. The black semicircle represents the location of perfect agreement (based on these measures) between the simulated field and the data, since such a comparison would yield $\sigma = 1$ (both have the same standard deviation), $R = 1$ (perfect correlation), and $E = 0$ (no RMS difference).

In all four geographical regions a marked improvement in terms of the agreement with data is seen in the higher resolution simulation. In particular, the standard deviation ratio (σ) for the global domain increases from 0.7 to just over 1, but that is only part of the story, as the correlation has also improved from $R = 0.5$ to $R = 0.65$. Only in the North Atlantic is an improvement in σ not necessarily seen since the 0.1° run overshoots unity by about the same amount as the 0.4° undershoots. All regions show an increase in correlation (R) and reduction in normalized RMS difference (E). It also appears that much of the apparent improvement in σ for the global domain is likely due to an overestimate of variability in eddy-active regions, while the more quiescent regions still have too low variability. This diagnostic tool can be used in the future for model inter-comparison studies.

Ventilation Processes

Up to this point, we have discussed the representation of the horizontal circulation of the ocean, but it is also important to investigate the fidelity of the time varying vertical structure of these fine resolution simulations. Hydrographic, moored observations, and data from profiling (e.g. PALACE and Argo) floats and ADCPs all can be used for this purpose. As mentioned in the data description section, the Ocean Time Series are monitored long term on a monthly basis, providing a more complete analysis of trends and variability on interannual scales at a single point. Since the ocean communicates with the atmosphere only at its surface, the fidelity of the model's mixed layer is very important for correctly simulating ventilation processes. Oschlies (2002) compared mixed layer depths (MLDs) from three such locations in the subtropical and subpolar NA with spatially co-located time series from two configurations of a NA primitive equation model: one eddy-permitting (1/3°) and eddy-resolving (1/9°) with both models using identical topographies, monthly climatological forcing fields at the surface, and restoring at the lateral boundaries. He found that the simulated winter MLDs in mid and high latitudes were systematically shallower by some 50 to 500 m in the higher resolution run, and agreed better with observations than those from the lower resolution model. He attributed this improvement to enhanced levels of baroclinic instability leading to a decrease in potential energy and an associated increase in stratification.

McClean et al. (2006) compared simulated co-located time series of MLD from the 0.1° global POP with those from BATS and HOT. The comparison at BATS was extremely good except for winter; during this season the model was only able to reproduce the maximum depth of the mixed layer. The main reason for the wintertime discrepancy is that the model forcing and output are averaged over a day, while the data are essentially instantaneous samples taken over a day or two for each cluster of observations. This allows measurement of the rapidly evolving mixed layer in different stages of formation, while the model has averaged out such high frequency motions. At HOT, the density of the model water column was too stably stratified to allow realistically deep penetration of the mixed layer, which was thought to be due to deficiencies in the surface forcing, possibly the use of monthly solar radiation and precipitation climatologies which are part of the NCEP/NCAR reanalysis fluxes used to force this model.

Rainville et al. (2007) analyzed the global 0.1º POP simulation to investigate the formation and destruction of subtropical mode water (STWM) in the Kuroshio Extension region of the North Pacific. The regional mean state as depicted by merged altimetric SSHA measurements and Rio05 absolute dynamical topography (Rio and Hernandez, 2004) displayed a smoother jet and a weaker southern recirculation than those simulated by the model, in part a result of the large spatial scale (about 200 km at these latitudes) of the altimetry objective mapping. The observed altimetric variance in the region was in general agreement with that from the model as were the properties of the Kuroshio Current compared to a hydrographic survey of the region. The STMW distribution was found to be highly variable in both space and time, a characteristic often unexplored because of sparse observations or the use of coarse resolution simulations. Furthermore, its distribution was highly dependent on eddies, as was where it was renewed during the previous winter. Overall they concluded that eddies were essential to the dynamics of the STWM. Aoki et al. (2007) examined the properties of the deep winter mixer layer in the Southern Ocean where Subantarctic Mode Water (SAMW) forms using 1/10° OFES output and Argo float data. General deepening of MLD occurred eastward from 50°-180°E and from 180°-80°E, with distinct maxima near bathymetric features. The overall trend and significant peaks of MLD derived from the Argo data were very similar to those from OFES. However the peaks south of New Zealand, at 130°W-120°W, and at 100°W-80°W were underestimated. This was attributed to sampling irregularity and interannual variability that was not captured in the model due to the use of climatological forcing.

Eddy Heat Fluxes

It is critical to realistically resolve or parameterize eddies in climate models since they interact with the mean flow and transport heat, fresh water and momentum. The measurement of the eddy heat contribution at basin and global scales is an extremely challenging observational problem. Stammer (1997) used T/P altimeter data and Levitus et al. (1994) climatology together with a mixing length hypothesis to obtain the zonally-integrated global eddy heat flux over the top 1000 m of the water column; these fluxes accounted for up to 20% of the mean meridional fluxes as calculated by MacDonald and Wunsch (1996). **Figure 2a** shows the same quantity from the 0.1° global POP for the same period (1993-1995). Peak values are found just to the north and south of the equator (-1.1 and 0.5 PW, respectively) and in the ACC (-0.5 PW). The locations of peak values are generally co-located with those of Stammer (1998, Fig. 8a) however the model significantly over-estimates the values derived from altimetry and Levitus et al. (1994) climatology, which are between ±0.3 PW. Stammer's use of climatology is one likely cause for these different results. Stammer (1998) himself commented that he expected his results to represent the lower bound of instantaneous heat flux estimates due to his use of climatology.

Figure 2b shows the total, Eulerian-mean, and eddy heat components from CCSM3. CCSM3 uses Gent and McWilliams (1990) to parameterize the eddy heat transport of eddies. It is clear that, apart from in the Southern Ocean and north of 45°N, CCSM3 underestimates the eddy heat flux component found in the 0.1° POP (**Figure 2c**). Close to the equator the lack of strong signal seen in both the observations and the fine-resolution model is due to the fact that tropical instability waves (TIWs) are not simulated in this nominally one-degree class model. TIWs make a significant contribution to the equatorial mixed layer budget and hence to the El Niño Southern Oscillation (ENSO). Weisberg and Weingartner (1988) reported that the equatorward heat flux of the TIWs in the upper 50m of the ocean was comparable to the atmospheric heat flux in the tropics. A dynamical model analysis by Jochum et al. (2004) found that their contribution to the mixed layer heat budget appeared to be smaller than expected, however it was not unimportant. TIWs also have a dynamical impact on the equatorial circulation as well by removing kinetic energy from the equatorial undercurrent and dissipating it in the equatorial thermocline. Further, TIWs could have an important influence on the phase of the seasonal cycle and the position of the equatorial cold tongue and the intertropical convergence zone (Jochum et al. 2004).

Discussion and Conclusions

Current practices within the oceanographic community have been reviewed with respect to the use of metrics to assess the realism of the upper-ocean circulation, ventilation processes diagnosed by time-evolving MLD and mode water formation, and eddy heat fluxes in large-scale eddying ocean general circulation model simulations. We have striven to understand the fidelity of these simulations in the context of their potential use in future fine-resolution coupled climate system studies. The availability of data on a near-global basis of sufficiently long duration for statistical analyses posed another constraint leading to the use of both Eulerian and Lagrangian methods for the comparisons of consistent analyses of model output and observations. Overall, these quantitative and semi-quantitative metrics provided a gauge of the veracity of the simulated upper ocean general circulation, indicating that in this regard these fine resolution models will be useful in future climate simulations.

SSH variability and the location of western boundary current paths from altimetry have been used routinely as zero-order indicators of fine-resolution model performance. Kelly et al. (2007) have advanced these metrics by considering the path strength and the upper ocean heat budget in the KE. Drifters and floats have also been used to provide pseudo-Eulerian measures of the mean and variability of surface and sub-surface flows, while statistical comparisons of observed and simulated means have been carried out using James tests. Probability density functions have been used to assess the Gaussian nature of the observed and simulated flows. Length and time scales have been calculated in both Eulerian and Lagrangian frameworks from altimetry and drifters, respectively. Concise measures of multiple model performance have been obtained from Taylor diagrams. The time-evolution of the MLD at monitoring stations has been compared with simulated time series.

Impacting these results are the issues of the quality and frequency of the atmospheric surface fluxes used to force ocean models. Daily winds were needed to realistically simulate surface time scales in the North Atlantic. Deficits in the representation of MLDs were attributed to both the frequency and quality of the forcing. Studies reviewed here have shown that simulations with horizontal resolutions of 0.1° and higher more realistically reproduce the mean and variability of the upper ocean circulation along with the evolution of the MLD. McClean et al. (2002) demonstrated that these resolutions more accurately depict Lagrangian intrinsic scales. A comparison of Eulerian length scales from the near-global 0.28° POP simulation (McClean et al., 1997; Plate 6) for the same time period as those in Figure 1 clearly show that the higher resolution model has reproduced these scales more accurately.

The measurement of the contribution of eddies to global and basin scale meridional heat transport is an extremely challenging observational problem. Peak values of the zonally integrated global eddy heat flux from global 0.1° POP were generally co-located but significantly higher than those derived from observations (Stammer, 1998). The discrepancy may be due to the use of climatology in Stammer's calculation or to model biases. Regardless these fine-resolution eddying ocean models can be used as "truth" when assessing the fidelity of low-resolution ocean components of climate models. CCSM3 underestimates the eddy heat flux component found in the 0.1° global POP except in the Southern Ocean and north of 45°N, particularly it lacks the strong signal associated with TIWs close to the equator which are considered important to the equatorial mixed layer heat budget.

The explicit resolution of eddies in ocean models may very well be necessary to improve our projections of climate change. Very recently Hallberg and Gnanadesikan (2006) examined the role played by Southern Ocean winds and eddies in determining the density structure of the global ocean and the magnitude of the Southern Ocean overturning circulation using a suite of Southern hemispheric ocean simulations with realistic geometry at horizontal resolutions ranging from coarse (2°) to eddy-permitting (1/6°). They question the ability of coarse-resolution ocean models to reproduce changes due to eddy activity even though it maybe possible to tune models to make certain aspects of the ocean circulation realistic. They find that the low-resolution models under-represent the eddy response to changes in wind forcing and they do not think that it is clear that these eddy effects can be effectively parameterized. They recommend that accurate high-resolution ocean models be used to examine the response of the climate system to ensure the validity of climate projections.

We do see the need to advance the state of metrics to quantitatively assess the fidelity of the relevant ocean processes at both eddy resolving and non-eddy resolving scales Limited data is always a constraining factor, however we need to move beyond zero-order comparisons and find novel ways to combine data sets to carry out budget and dynamical balance calculations. The Kuroshio Extension System Study (KESS) and the CLIvar MOde Water Dynamic Experiment (CLIMODE) are providing mesoscale measurements in the KE and GS regions, respectively, that can be used as a test bed for the development of more sophisticated metrics.

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List of Figures

Plate 1: Length scales (km) from (a) TOPEX/POSEIDON, (b) 0.1° POP (2°x 2° bins) and (c) full resolution 0.1° POP for 1993-1994 in the region 10°- 60°S.

Plate 2: Taylor diagram showing the level of statistical agreement between the 1994-2001 average sea surface height anomaly from the 0.4° (red circles) and 0.1° (blue circles) global POP simulations and AVISO (TOPEX/POSEIDON and ERS 1 and 2) altimetry. The arrows connect the results of both simulations evaluated over the following regions: Global (70°S-70°N), North Atlantic Ocean (20°N-55°N, 100°W-20°W), open Pacific Ocean (30°S-30°N, 150°E-110°W), and Southern Ocean (65°S-40°S). Lines of constant correlation coefficient (R) are solid; the long dashed curves denote lines of constant standard deviation ratio (σ); the short dashed curves denote lines of constant RMS difference varying from 0.6 (small radius) to 0.9 by 0.1. The black semi-circle represents the location of perfect agreement between the simulation and the comparison data set (after McClean et al., 2006, Figure 5).

Figure 1: Histograms of length scales (km) from (a) TOPEX/POSEIDON and (b) global 0.1° POP for 1993-1994 in the region 10°- 60°S.

Figure 2: (a) Zonally-integrated global eddy heat transport (PW) over the top 1000 m of 0.1° POP for 1993-1995. May be compared with Stammer (1998, Figure 8a) (b) Zonally-integrated global eddy heat transport (PW) from CCSM3 (total depth). The red line is the parameterized eddy heat flux. (c) Zonally-averaged global 0.1° POP eddy heat flux and the parameterized eddy heat flux from CCSM3.

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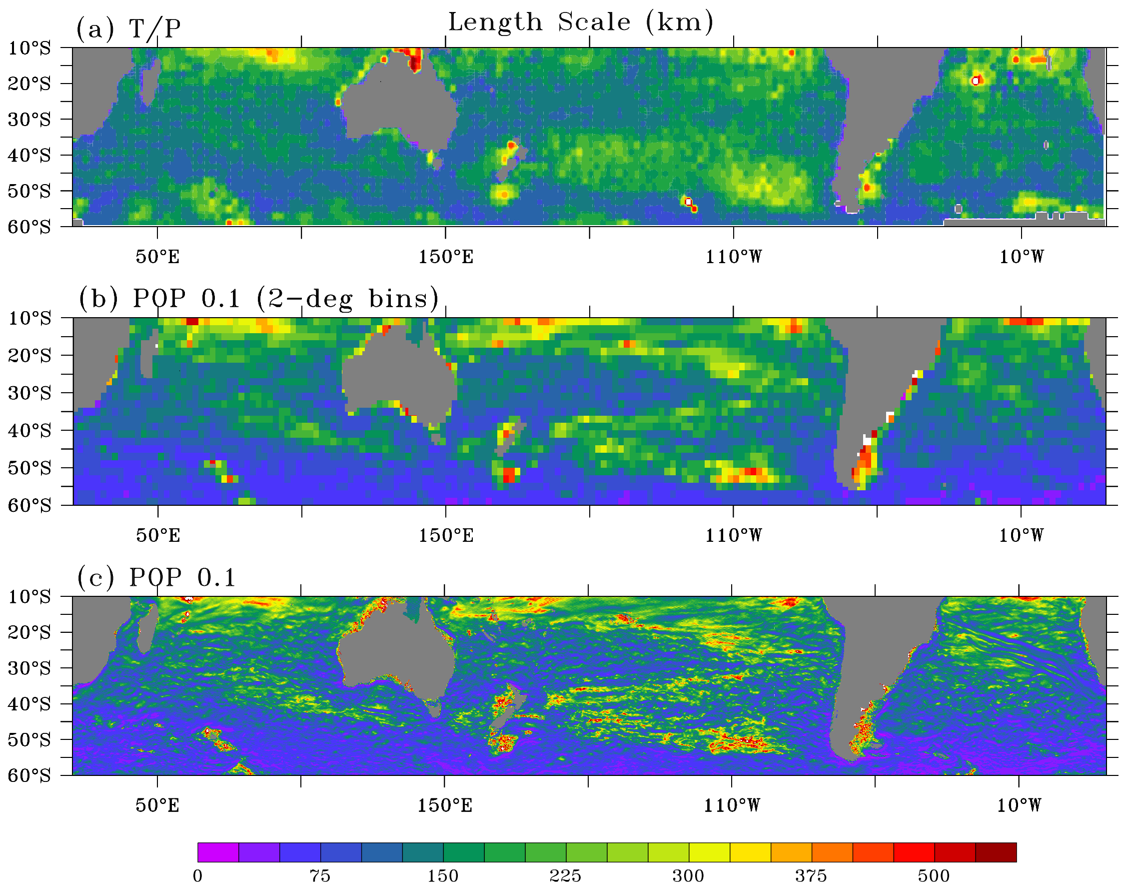
(a) T/P
Length Scale (km)
10°S
20°S
30°S
40°S
50°S
60°S
50°E
150°E
110°W
10°W
(b) POP 0.1 (2-deg bins)
(c) POP 0.1
0
75
150
225
300
375
500

Plate 1

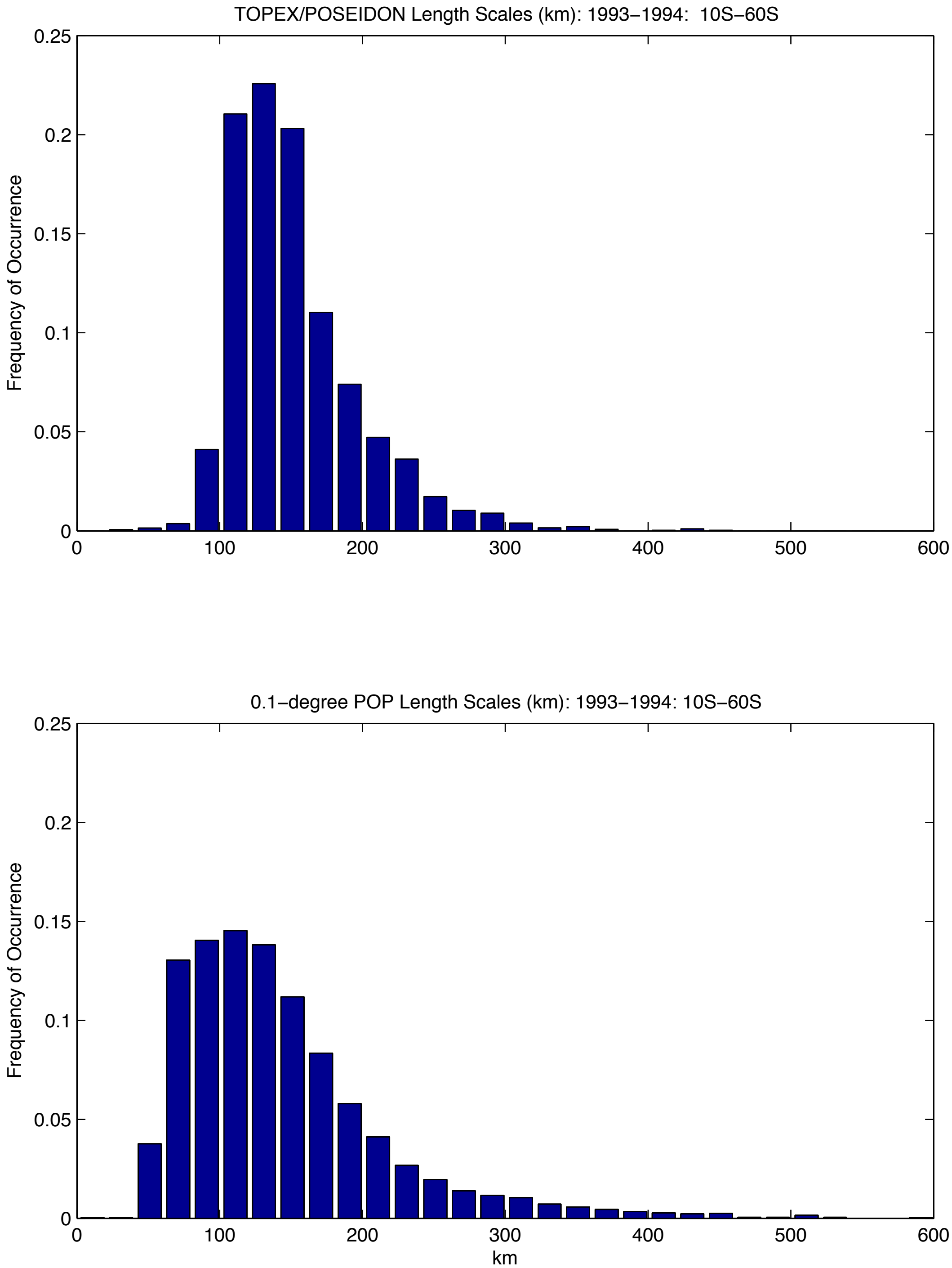
TOPEX/POSEIDON Length Scales (km): 1993−1994: 10S−60S
Frequency of Occurrence
0.25
0.2
0.15
0.1
0.05
0
0
100
200
300
400
500
600
0.1−degree POP Length Scales (km): 1993−1994: 10S−60S
Frequency of Occurrence
km

Figure 1

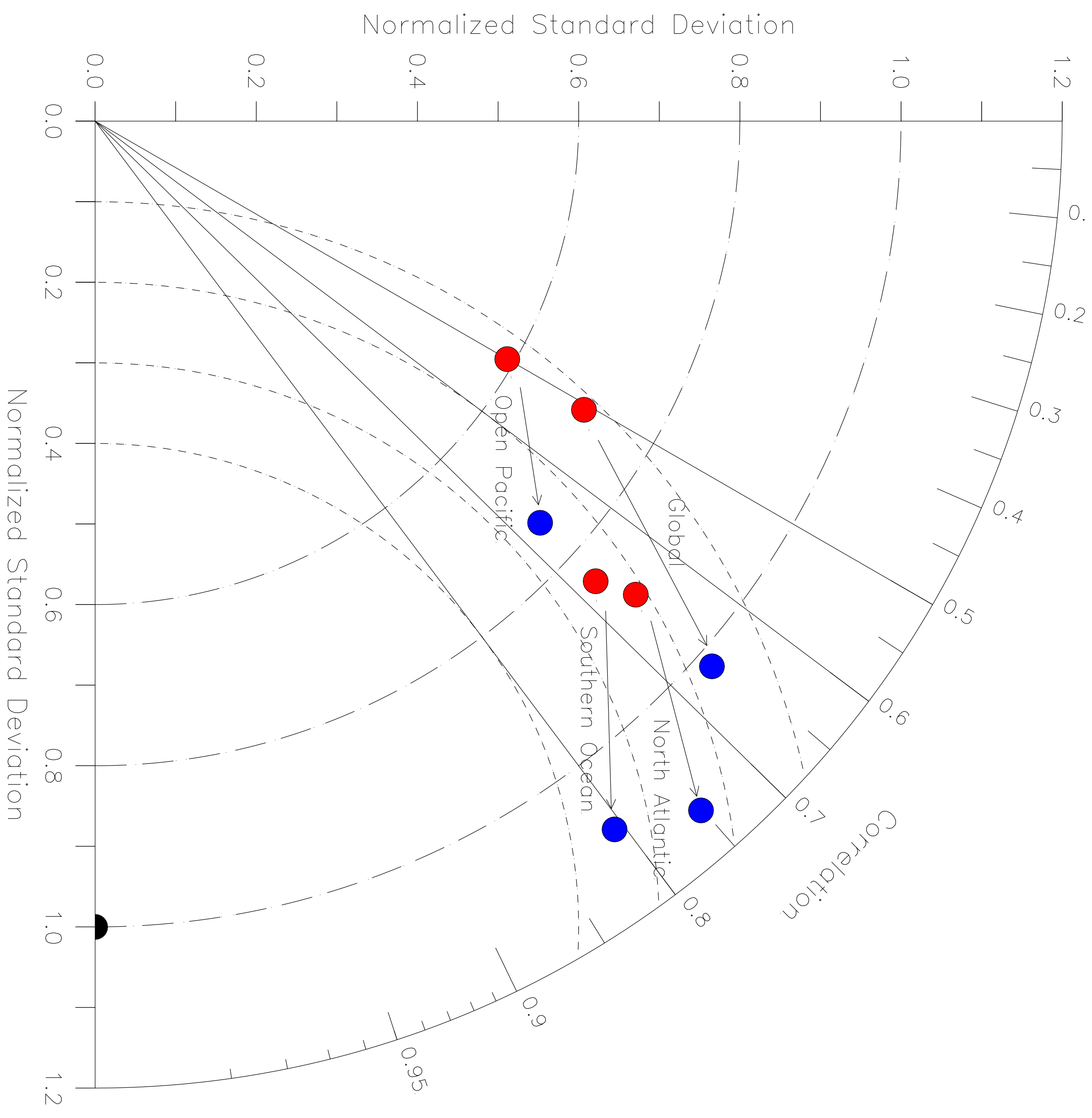
Normalized Standard Deviation
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Normalized Standard Deviation
Correlation
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.95
Open Pacific
Global
Southern Ocean
North Atlantic

Plate 2

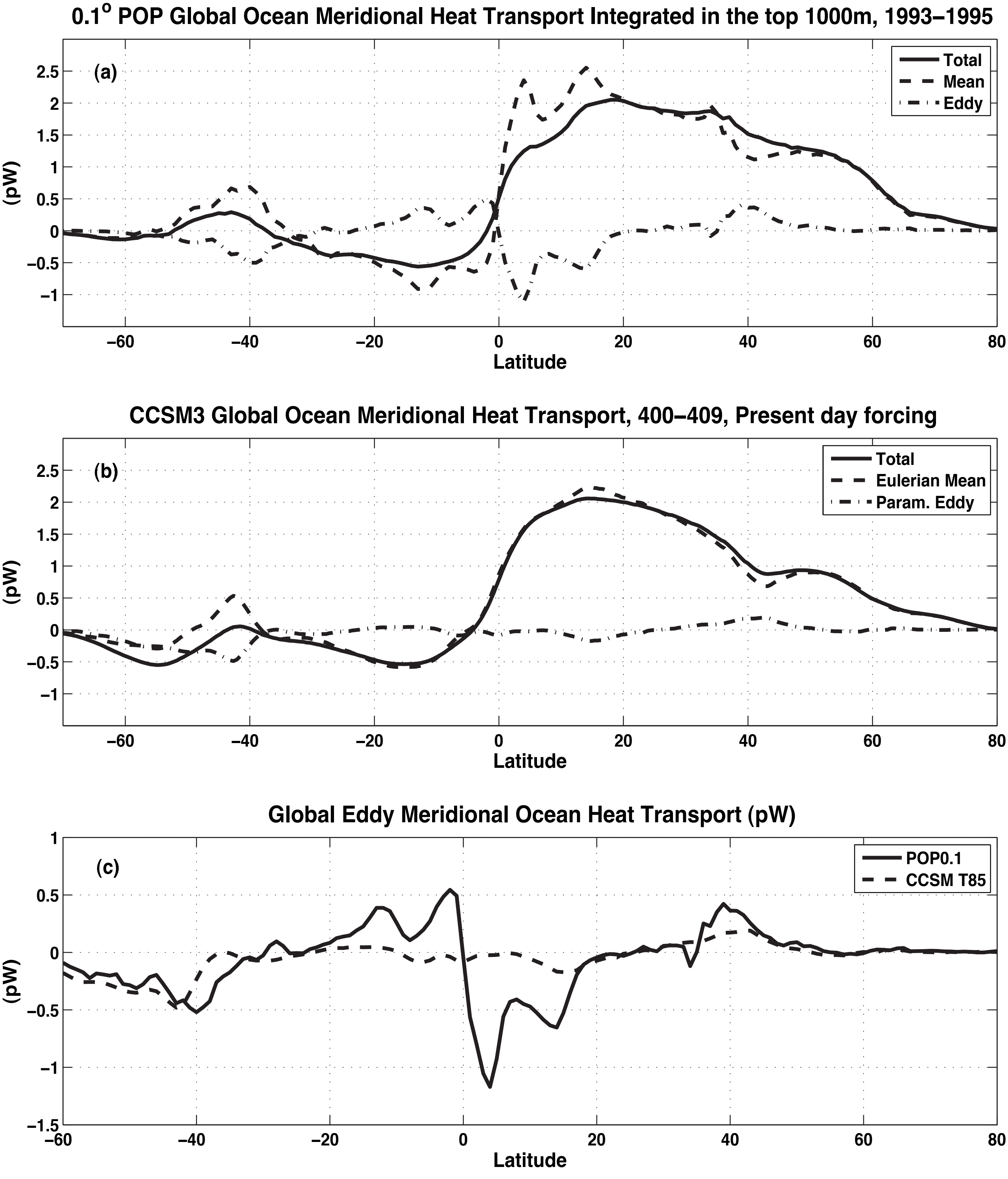
0.1° POP Global Ocean Meridional Heat Transport Integrated in the top 1000m, 1993–1995
(a)
Total
Mean
Eddy
(pW)
Latitude
CCSM3 Global Ocean Meridional Heat Transport, 400–409, Present day forcing
(b)
Total
Eulerian Mean
Param. Eddy
(pW)
Latitude
Global Eddy Meridional Ocean Heat Transport (pW)
(c)
POP0.1
CCSM T85
(pW)
Latitude

Figure 2