

NOTES AND CORRESPONDENCE

Temporal Changes in Ocean Eddy Transports

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ABSTRACT

New estimates from 11 yr of altimetric data are made of the global time-average variability kinetic energy and its decadal-scale variability. Making the approximation that the variability reflects primarily eddy motions, a time-mean, but spatially varying, eddy mixing coefficient is then estimated along with its changes over the last decade. With a record length more than 2 times that previously available, the time-mean variability kinetic energy K_E is statistically more reliable and smoother in its spatial pattern. Minimum values of K_E are present in the subpolar North Pacific Ocean and in the eastern South Pacific (both less than $100 \text{ cm}^2 \text{ s}^{-2}$). In contrast to the North Pacific, the subpolar North Atlantic Ocean shows relatively enhanced K_E . Eddy kinetic energy and eddy mixing appear to have declined during the last decade over large parts of the western Pacific Ocean, in some regions by as much as 50% of the time-mean value. Increased eddy variability can be found in the Kuroshio and Gulf Stream regions, as well as in the Agulhas region, east of Australia, and at several locations along the Antarctic Circumpolar Current. Somewhat enhanced eddy variability and eddy mixing are also apparent in the eastern tropical Pacific. A numerical simulation of the ocean circulation at 1° spatial resolution over a 10-yr period suggests that variations in eddy mixing of this order of magnitude measurably affect the deep temperature field in the vicinity of permanent frontal structures on a time scale of less than 4 yr. The meridional overturning circulation also reacts on these time scales. If persistent over longer periods in the ocean, these effects would be important for climate simulations.

1. Introduction

In an earlier paper, Stammer and Wunsch (1999, hereinafter SW99) investigated temporal changes in the kinetic energy associated with variability over the global ocean using 4 yr of altimetric data. The authors hypothesized 1) that parts of the observed variations in the flow field are caused by changes in direct wind forcing, especially in high latitudes, and 2) that an indirect

nonlocal response of large-scale circulation in mid- and low latitudes results from shifts in mean wind stress curl and storm tracks particularly in the North Atlantic Ocean.

In the period since SW99 was published, the 4-yr altimetric record has grown to 11+ yr, and with more than a decade of altimeter data available at the time of writing, it is worthwhile revisiting the earlier results: A well-known rule of thumb in time series analysis is that records are worth reanalyzing whenever they double in duration to obtain more reliable statistical estimates. We therefore seek here, first, a statistically more stable estimate of the time-mean kinetic energy of oceanic variability. Second, temporal changes in variability over

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a decade are now accessible in the observations. To the extent that the observed variability of the flow field can be associated with pure eddy motions, one can then use the estimated changes in kinetic energy to estimate decadal-scale changes in mixing and in their potential impact on the general circulation. The extent to which observed fluctuations can influence the mean oceanic state both directly and through the changes in the hydrodynamic stability properties of a time-varying flow field (e.g., Pedlosky and Thomson 2003) has to be evaluated.

To keep this note concise, we will rely heavily in the following on the theoretical analysis and definitions provided in SW99. In contrast with that paper, we will use the terminology “variability” here more broadly to describe the general class of time-varying motions usually observed by an altimeter from the specific narrow-band “eddy variability” associated with mesoscale motion. However, we will also explore potential implications of observed changes in the ocean velocity variability, assuming that those changes result predominantly from changes in motion of eddies. Over most parts of the global ocean, this assumption is reasonable and consistent with an earlier detailed analysis of variability which showed that altimetric estimates of ocean kinetic energy and slope variability to first order presents the mesoscale eddy scale (Stammer 1997, hereinafter S97). We note that such a claim is an oversimplification but is likely to be qualitatively correct. Our inferences are generally directed at the relationship between general circulation shifts and eddy variability changes of approximately the level observed.

2. The mean eddy kinetic energy and eddy transports

Our analysis is based entirely on a study of surface current (i.e., slope) variability, which is distinct from earlier studies of sea surface height (SSH) variability in that it shows primarily variability on the eddy scale. For that purpose, we use Ocean Topography Experiment (TOPEX) data from the 11-yr period January 1993–December 2003 to compute the kinetic energy of the time-varying surface geostrophic flow field, and SSH variability scales. Data were processed and corrected as described in detail by Stammer and Wunsch (1994) and S97. Poseidon data were not included because of lingering questions about the noise levels in the Poseidon measurements. Variability kinetic energy K_E is defined here as in S97:

$$K_E = \left(\frac{g}{f}\right)^2 \left\langle \left(\frac{\partial \eta'}{\partial s}\right)^2 \right\rangle, \quad (1)$$

where η' is the along-track SSH anomaly, relative to its 11-yr mean, s is the along-track distance, f is the local Coriolis parameter, and the bracket denotes expectations. The variability kinetic energy is related to a slope variability, $K_S = K_E \sin^2 \phi$, where ϕ is latitude; K_S is used for some computations to avoid the high values in K_E near the equator due to the vanishing of f . The along-track η' slope was computed here from the unfiltered values of η' by least squares fitting a straight line over several along-track data points (differing from the SW99 method that involved a fixed-length filter). The fitting distance varied linearly from 150 km near the equator to 50 km around 60°N to account for meridionally varying spatial scales and a higher noise sensitivity near the equator. These filter scales produce velocity estimates consistent with the results of Leeuwenburgh and Stammer (2002).

Here, K_E was computed according to Eq. (1) locally at each along-track position and was gridded subsequently on a 2° geographic grid for further analysis and graphical display. Figure 1a displays the estimate of K_E from the 11-yr analysis period; the spatially extremely inhomogeneous variability in the ocean is apparent once again. Owing to the geographically varying SSH filter length scale used here to compute K_S , levels in velocity variance are somewhat reduced in low latitudes as compared with S97. In contrast, values are greater in mid- to high latitudes and now reveal a complex regional K_E distribution apparently related to structures of the bottom topography (see also Heywood et al. 1994).

The spatial patterns and amplitudes of the kinetic energy are generally consistent with both earlier (Stammer and Böning 1996) and more recent (Niiler et al. 2003) estimates from surface drifters. Although those drifter estimates carry no error bars, we estimate that our own values are uncertain by about a factor of 2 (based upon calculating the number of degrees of freedom in our estimates, and the noise elements in the data).

Fields like the one shown in Fig. 1 (or equivalently those for rms SSH variability) were previously associated primarily with the spatially inhomogeneous mesoscale eddy field in the ocean [see LeTraon and Morrow (2001) for a review]. We adopt here this generally accepted notion that we are dealing with a variability that outside intense boundary currents is primarily in the form of baroclinic eddies and that one can use the associated eddy statistics to infer otherwise difficult-to-obtain insight about spatially varying eddy mixing [an idea dating back at least to Holloway (1986)]. This hypothesis was previously explored by Stammer (1998, hereinafter S98) to provide estimates of time-mean but geographically varying eddy mixing coefficient κ from

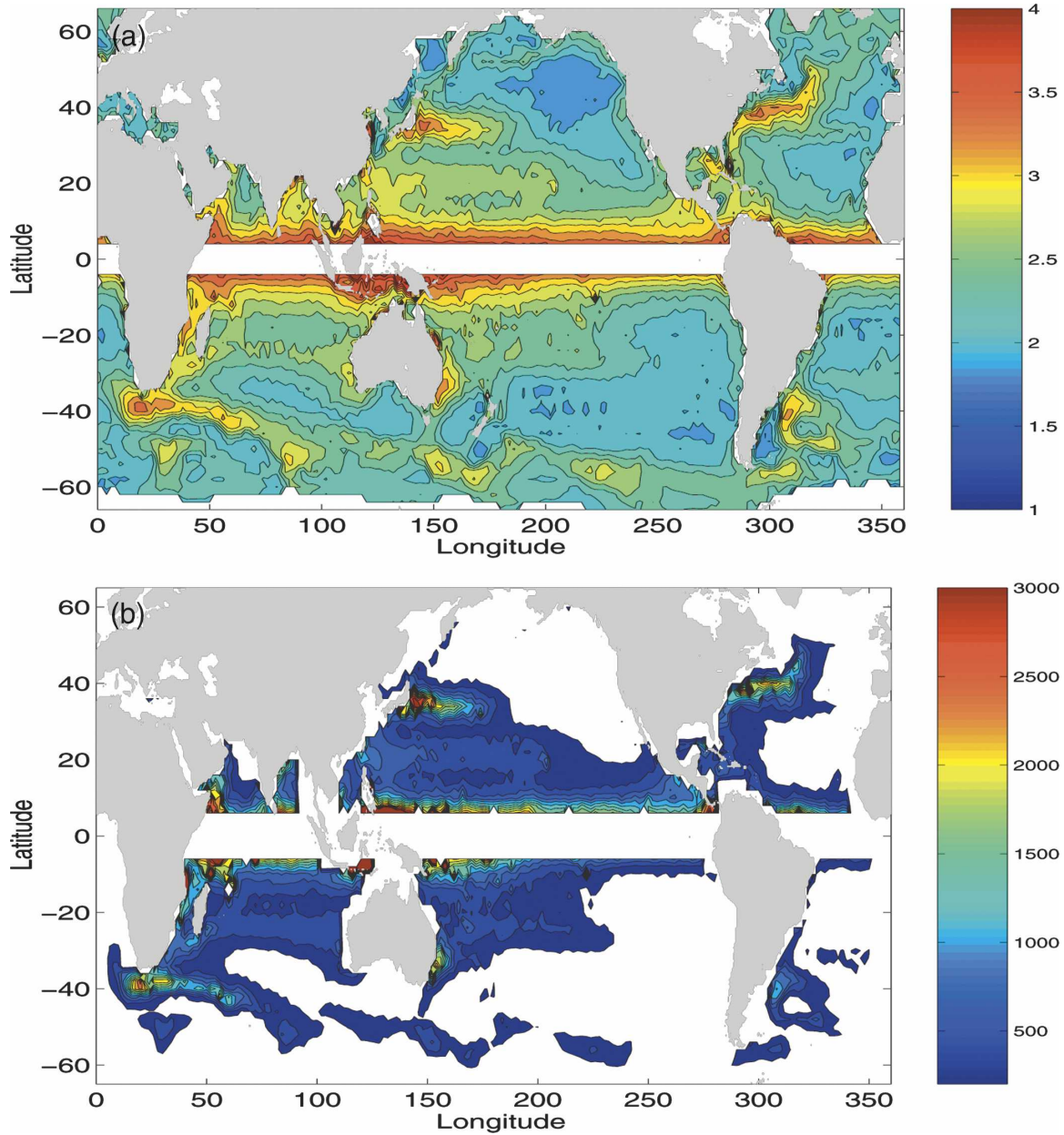


FIG. 1. (a) The \log_{10} of the kinetic energy ($\text{cm}^2 \text{s}^{-2}$) computed from along-track data from the 9-yr period 1993–2001 and gridded subsequently on a 2° spatial grid (contour interval = 0.2). See text for details. (b) Time-mean eddy mixing coefficient $\kappa(t) = 0.1K_E(t)\bar{T}_{\text{alt}}$ representing the nine-year period 1992–2001. White regions in (b) have amplitudes less than $250 \text{ m}^2 \text{ s}^{-1}$.

statistics inferred from altimetric data on a 5° geographical grid. Following S98, we calculate κ now as a function of time according to

$$\kappa(t) = 2\alpha K_E(t)\bar{T}_{\text{bc}}, \quad (2)$$

where $K_E(t)$ is the time-varying estimate of near-surface eddy kinetic energy, similar to the field shown in Fig.

1a, but estimated individually for every year of the TOPEX/Poseidon (T/P) mission; \bar{T}_{bc} was computed as the 11-yr time mean of $T_{\text{bc}}(t)$, as described in S97. The resulting baroclinic time scale, T_{bc} , (not shown) basically agrees with the corresponding figure of S97. In agreement with Visbeck et al. (1997) and S98, we use $\alpha \approx 0.05$.

The resulting 9-yr time-mean $\bar{\kappa}$ field is shown in Fig. 1b. Values are higher than in S98, because in the earlier computations, altimetric K_E estimates were weighted so as to represent an average over the top 1000 m, accounting for the overall decline in energy with depth. Here, we use the raw values. Largest amplitudes of the eddy diffusivity can be found over the Gulf Stream and the Kuroshio, as well as the Agulhas. Note also smooth, and relatively low, values over the Antarctic Circumpolar Current (ACC). Despite the rather modest value of $\bar{\kappa}$ there, the net mixing effects are nevertheless important, because of the large zonal extent of the ACC and its weak meridional flows. The values obtained are generally lower but within a factor of 2 of estimates using in situ data (e.g., Krauss and Böning 1987; Ollivraut and Colin de Verdière 2003), which would be consistent with our error estimate alone (not accounting for the generally unknown errors in the independent estimates).

3. Temporal variations in variability kinetic energy and eddy transports

Anomalies of K_E from the individual years 1993 and 1996 minus the long-term mean can be seen in SW99 (their Fig. 1). We show here instead, in Fig. 2a, the standard deviation of the amplitude of K_E fields that were computed separately for each individual year. Normalization by the 11-yr mean was applied first, and thus the figure shows the percentage of interannual changes in K_E . Results were then smoothed over 6° in longitude and 4° in latitude. Interannual variations in K_E are largest near western boundary currents where up to 30% changes can be found. In contrast, interannual changes in K_E appear negligible in high latitudes, including the entire Southern Ocean and the subpolar North Atlantic. The North and South Equatorial Currents are also relatively stable.

To determine the causes of the observed changes in variability is not straightforward, and in principle, requires studies of local and nonlocal correlations with surface forcing fields such as wind stress (see, e.g., Lipert and Müller 1995). SW98 hypothesized that changes in K_E observed in high latitudes are directly related to local wind forcing. Penduff et al. (2004) tested the local high-latitude, wind-driving hypothesis by examining, in a $1/6^\circ$ resolution numerical model of the North Atlantic, the relationship of eddy behavior to the North Atlantic Oscillation. They found that variations in model eddy kinetic energy followed wind energy input variations with a lag of about 12 months, a time interval strongly suggestive of complex nonlocal processes. The physical mechanisms underlying the observed changes

therefore have to be sought not only in direct wind-induced variability, but also in the spinup/spindown of the gyre circulation modifying its stability properties.

Assume as we did before, that not only the time mean K_E field arises from the oceanic mesoscale eddy variability, but that also temporal changes in the K_E estimates are related to temporal adjustments of the eddy variability period. We use the individual annual mean K_E fields to estimate the long-term temporal variation of K_E by least squares fitting a trend. Note that the standard deviation of estimates of T_{bc} from individual years (not displayed) shows that interannual variations in T_{bc} are small, and insignificant, outside the tropical region. With these results, we compute from Eq. (2) potential long-term changes in the eddy mixing according to

$$\Delta\kappa = 2\alpha\Delta K_E \bar{T}_{bc}. \quad (3)$$

Now ΔK_E is the change in K_E between 1993 and 2002 estimated from the least squares trend and $\Delta\kappa$ is the respective change in the eddy mixing coefficient. Results, shown in the lower panel of Fig. 2b after normalization by the mean κ field, illustrate that changes in κ can reach more than 30% of the mean value over large regions and, in some cases, are as large as 50%. Most notably, for parts of the western Pacific Ocean, we infer a decrease, by up to 50%, in eddy mixing (and associated K_E amplitudes), while at the same time, over parts of the eastern Indian Ocean and parts of the ACC, the eddy activity seems to have increased by similar amounts. Note also the decrease of eddy activity in the subpolar North Atlantic that, to some extent, is counterbalanced by an increase over the Gulf Stream. Large relative changes occur near the conventionally expected areas of intense eddy activity, such as the Gulf Stream, Kuroshio, and parts of the Agulhas and the ACC. Although the assumption that K_E changes near the western boundary currents reflect primarily changes in eddy motions is obviously suspect, the largest observed changes do not coincide with the main current regions (cf. Fig. 1a) and occur in relatively eddy quiescent regions.

4. Physical significance of changes in eddy mixing

Quantitative estimates of ocean mixing rates from altimeter data have many problems and the same will be true for the inferred temporal changes. Among these problems are that Eq. (2), strictly speaking, holds only for homogeneous turbulence. More proper is that it should be defined in terms of particle velocity variance and the Lagrangian time scale. Here, estimates are based on an Eulerian eddy statistic under the assumption that those scales are not fundamentally different

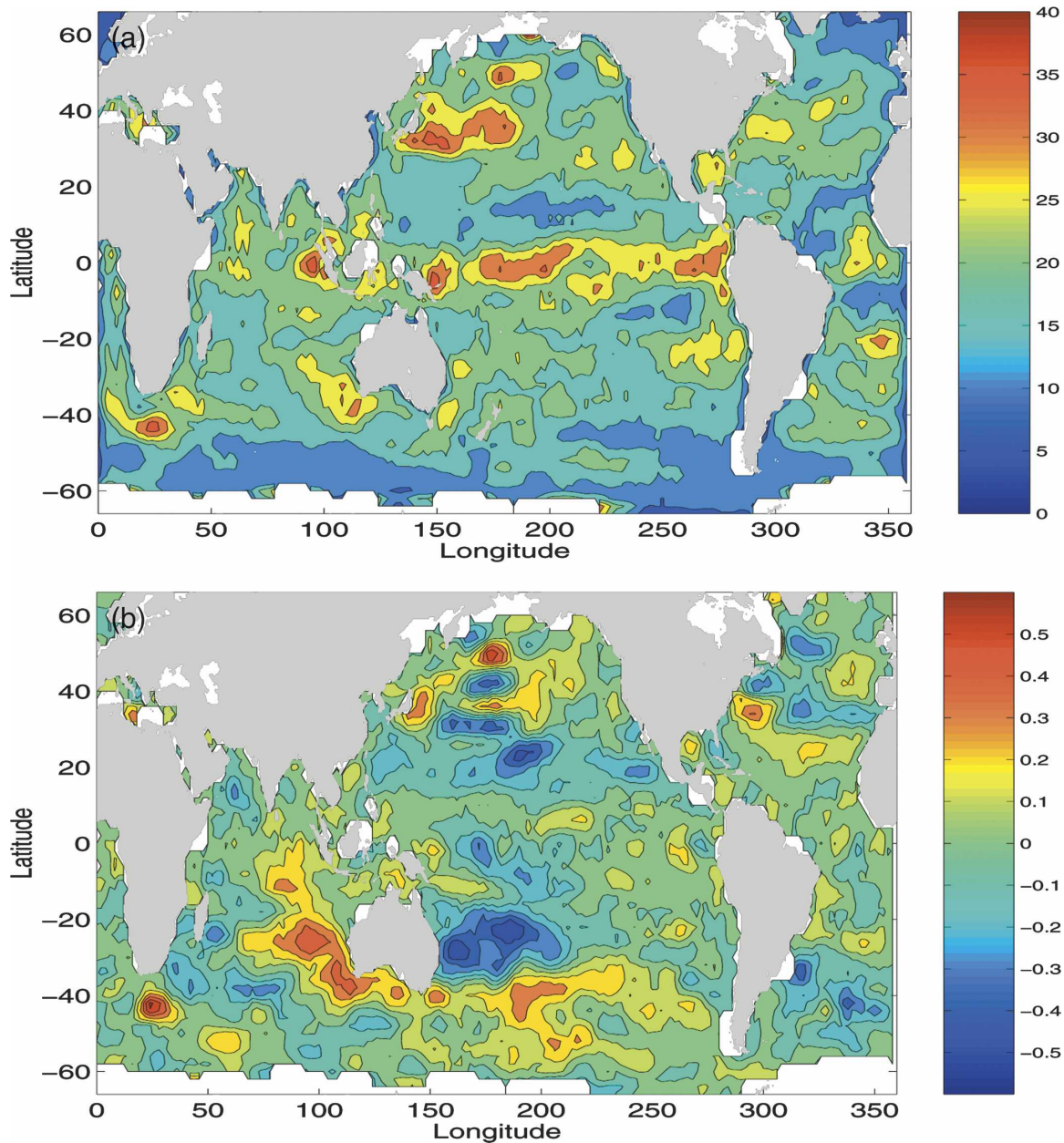


FIG. 2. (a) Variations in slope variance displayed as normalized standard deviation of the slope variance computed from nine individual years. The field was smoothed over 6° in longitude and 4° in latitude prior to plotting (contour interval = 5%). (b) Long-term (1993–2003) fractional changes in κ , estimated by fitting at each grid location a least squares line to estimates from individual years. White regions in (b) indicate amplitudes of κ smaller than $250 \text{ m}^2 \text{ s}^{-1}$.

from Lagrangian eddy scales. However, the T/P-based Eulerian integral time scale estimates are likely overestimating the Lagrangian ones probably by a factor of 2 in boundary currents but are roughly of equal size in the interior ocean (see the discussion in Lumpkin et al. 2002). The amplitude of the correlation factor α in Eq. (2) is generally uncertain as well, probably by a factor of 2 or more. Nevertheless, as discussed by S98, ampli-

tudes and the spatial variations of resulting mixing coefficients are not unlike those inferred from Lagrangian data (e.g., cf. Krauss and Böning 1987; Ollittraut and Colin deVerdière 2002), the most natural data source for computing eddy mixing coefficients, but for which global observations remain out of reach.

Assuming that the amplitudes and spatial pattern of variations in K_E and eddy mixing inferred here from

altimetry reflect changes of eddy mixing that could realistically occur, how significant would those variations be for the general circulation? We expect a 40% increase lasting for 6 months in an eddy-rich area would not generate much change in the larger scales. However, such an increase lasting for a decade or longer is of concern for climate simulations. Although the time scale over which the deep ocean reacts to mixing and to changes in mixing is generally believed to be long, details of the response processes are unknown.

In the following we will use the Massachusetts Institute of Technology Ocean General Circulation Model (MITOGCM; see Marshall et al. 1997a,b; Adcroft et al. 2002) to provide a measure of the extent to which temporal shifts in ocean mixing amplitudes or pattern of the magnitude inferred here from altimeter data can affect the general circulation of the ocean. Effects of the time-averaged spatial nonuniformity are suppressed in the following. The model setup is similar to that described by Köhl et al. (2005, manuscript submitted to *J. Phys. Oceanogr.*). The model was run over a 10-yr period using a spatially uniform horizontal [Laplacian and Gent and McWilliams (1990)] tracer diffusion coefficient. The uniform Laplacian background was then modified in a second run to be spatially nonuniform, with the magnitude of the changes proportional to those seen in Fig. 2b. The differences in the model flow, tracer, and transport properties between those two runs were analyzed subsequently, so as to infer amplitudes and time scales of changes in the general circulation owing to changes in tracer mixing. (Because of the way the mixing was implemented in our run, effects diagnosed here are probably an underestimate of the impact of mixing on the model circulation.)

Figure 3 shows the resulting differences in potential temperature at 435-m depth after two years of integration; changes after four years at about 2000-m depth are also shown. We note that the largest temperature response is not generally found where the changes in the mixing coefficients are largest, but rather and not unexpectedly near most permanent time-mean frontal structures, where temperature anomalies reach amplitudes of $\pm 0.2^\circ\text{C}$ at 435 m after two years and $\pm 0.05^\circ\text{C}$ around 2000-m depth after four years. Although anomaly amplitudes are larger toward the surface, their pattern is similar to that at 2000-m depth and both increase with increasing integration time. From our simulation, we infer that it takes no more than one year (the first cooling season) to obtain noticeable responses in the flow and tracer field to time-varying mixing, and not more than two years to reach amplitudes that appear measurable. At 400 m, the largest effects on the temperature field can be found over the Gulf Stream and

Kuroshio regions, as well as around Australia, the Agulhas, and north of the Falkland–Malvinas confluence, all of which are regions with strong permanent frontal structures. Although there is little effect visible across the near-surface ACC, at 2000-m depth, a measurable response is seen. The visible global response of the temperature field at 2000 m is essentially limited to the ACC region, except for a similar amplitude change in the subpolar North Atlantic. We note that the observed pattern and amplitudes of the temperature response is not unlike those that were observed in the ocean (e.g., Levitus et al. 2000; Gille 2002) and in principle could easily be confused with the ocean response to global warming.

To demonstrate the impact of changes in the temperature and salinity fields on the circulation and its transport properties, we computed the strength of the meridional overturning circulation in the North Atlantic. Overall, the overturning is enhanced by about 0.5 Sv ($1 \text{ Sv} \equiv 10^6 \text{ m}^3 \text{ s}^{-1}$), that is, around 2%–3% of the mean value, first locally (order 2–4-yr time scale), and subsequently reaching across hemispheres (on a 10-yr time scale). With increasing time, one expects that changes in the overturning will be associated with changes in the meridional heat transport, but that study must await longer model runs.

5. Concluding remarks

Long altimetric records now available permit us to examine decadal-time-scale changes in the oceans. The data used here display significant decadal-scale fluctuations in variability kinetic energy over the oceans. Wind-field changes are strongly implicated, but only some of the intensity fluctuations would be functions of the local wind strength and wind structure. An exhaustive analysis of a general cause and effect relationship between observed ocean variability and changes in the wind field is beyond the scope of this note and has to await a global eddy-resolving experiment that has not been carried out.

Because of the relatively short response time scale of the circulation to changes in the mixing coefficients computed from changes of T/P SSH slope variations under the assumption that they reflect mesoscale eddy motions, it is likely that eddy mixing rates in the future will have to be parameterized directly both in terms of shifting stability properties of the general circulation (now commonly done) and in terms of changes in the wind field. A major problem is the remaining ignorance of the ways and regions in which the very large eddy kinetic energy is dissipated (Wunsch and Ferrari 2003), and the uncertainties of the relationships of the corresponding local mixing to purely local wind and baro-

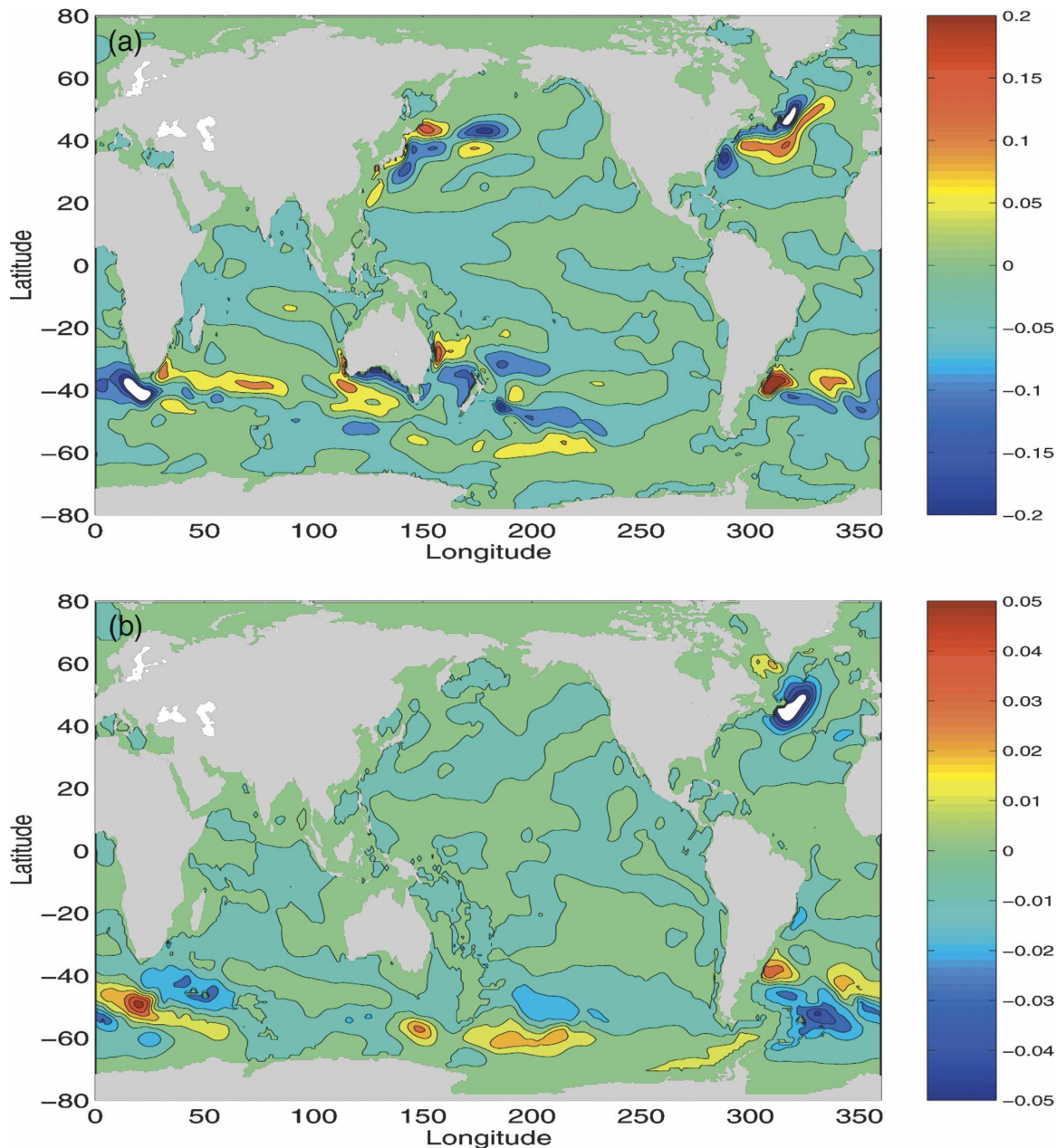


FIG. 3. Temperature anomalies ($^{\circ}\text{C}$) as they result from a numerical model, in which the isopycnal mixing tracer coefficient was altered by the field shown in Fig. 2b. The temperature anomaly is the difference between this run and a control run with spatially uniform, unperturbed mixing. (a) Results at 435-m depth after two years of integration. (b) A similar difference field, but from 1975-m depth and after four years of integration.

clinic structure. It is hoped that, in the near future, ocean state estimation will provide additional insight into the structure of spatial and temporal changes in ocean mixing in a way that is complementary to observational and theoretical studies (e.g., Stammer 2005).

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