On the seasonal variability of eddy kinetic energy in the Gulf Stream region

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[1] In the Gulf Stream region, eddy kinetic energy (*EKE*) peaks in summer while, as measured by the baroclinic eddy growth time scale, the ocean is most baroclinically unstable in late winter. We argue that the seasonally-varying Ekman pumping is unlikely to be responsible for the seasonal variation in growth time, and that the summer peak in EKE results from a reduction in dissipation in summer compared to winter. **Citation:** Zhai, X., R. J. Greatbatch, and J.-D. Kohlmann (2008), On the seasonal variability of eddy kinetic energy in the Gulf Stream region, *Geophys. Res. Lett.*, *35*, L24609, doi:10.1029/2008GL036412.

1. Introduction

[2] Eddies play an important role in shaping the large-scale ocean circulation and transporting physical and biogeochemical tracers, especially in the western boundary regions and the Southern Ocean [e.g., *Rintoul et al.*, 2001]. *EKE* in the ocean is also highly variable in time, although the mechanisms behind the variability are far from understood. For example, *Stammer and Wunsch* [1999] studied temporal changes in EKE and found nothing conclusive about the relationship between the variations in the eddy field and the local wind stress forcing. Variability in EKE in the western boundary current systems has also been investigated by other authors [e.g., *White and Heywood*, 1995; *Brachet et al.*, 2004; *Penduff et al.*, 2004]. However, the question of what physical processes govern the variability of *EKE* is still under debate. More than three decades ago, *Gill et al.* [1974] proposed that the available potential energy built up by wind-driven Ekman pumping of the subtropical thermocline is released by the eddies through baroclinic instability in the western boundary regions. This idea is discussed by *Wunsch* [1998] and has been recently revived by *Marshall et al.* [2002] who demonstrated that the production of available potential energy by Ekman pumping and differential heating can be balanced by the release of available potential energy by baroclinic instability. It is tempting to extend this theory to explain the observed variability of *EKE*, i.e. linking the variability to changes of Ekman pumping, either local or remote. On the other hand, as also noted by *Gill et al.* [1974], changes in the density structure in the top few hundred meters can lead to large changes in the stability properties of the ocean, suggesting that the production of baroclinic eddies could be strongly influenced by local heating/cooling. This idea is supported by *Qiu* [1999], who showed that the North Pacific Subtropical Countercurrent is subject to strong baroclinic instability in spring, but is only weakly unstable in fall, due to seasonal variation of the background stratification. The dissipation of *EKE* might also vary seasonally. *Alexander and Deser* [1995] have discussed how sea surface temperature anomalies can disappear beneath the summer thermocline only to re-emerge the following winter and we suggest that eddies can be similarly shielded from interaction with the atmosphere during summer, leading to less damping at that time of year. Likewise, direct mechanical damping of eddies [see *Duhaut and Straub*, 2006] depends on wind speed, which implies less damping in summer than in winter. In this letter, we revisit the seasonal variability of *EKE*, primarily in the Gulf Stream region, using satellite altimetry, the NCEP (National Centers for Environmental Prediction) reanalysis product and data from the World Ocean Atlas 2005 [*Locarnini et al.*, 2006].

2. Data

[3] The wind-driven Ekman pumping velocity (W_E) is computed for the period 1995 to 2006 using the 6-hourly NCEP reanalysis product. The surface *EKE* is calculated (with respect to a seven-year mean) for the period from January 1995 to December 2006 using the global sea surface height (*SSH*) anomaly dataset compiled by the CLS Space Oceanographic Division of Toulouse, France. This dataset merges the TOPEX/POSEIDON and *ERS*-1/2 along-track SSH measurements with a temporal resolution of a week and spatial resolution of $1/3° \times 1/3°$. For detailed description of the dataset, readers are referred to *Le Traon et al.* [1998]. In addition, changes in ocean stability properties are calculated using monthly temperature and salinity taken from the World Ocean Atlas. The seasonal cycle of W_E is computed by taking the mean value of W_E for each individual calendar day over the total 12 years. Since the data used to compute *EKE* have a much lower temporal resolution, the seasonal cycle of *EKE* is computed by binning into each individual calendar month and then taking the mean value over the total of all available 12 years.

3. Seasonal Cycle

[4] *EKE* in the North Atlantic averaged over the winter and summer seasons is shown on a log scale with base 10 in Figures 1a and 1b, respectively. The log scale is used in order to reveal the regions of moderate eddy activity. The spatial pattern is rather similar in both seasons. Most mesoscale variability is found along the Gulf Stream system, including the North Atlantic Current and Azores Current, with maximum values exceeding 5000 $cm^2 s^{-2}$. The subpolar gyre and eastern subtropical gyre are relatively quiet by

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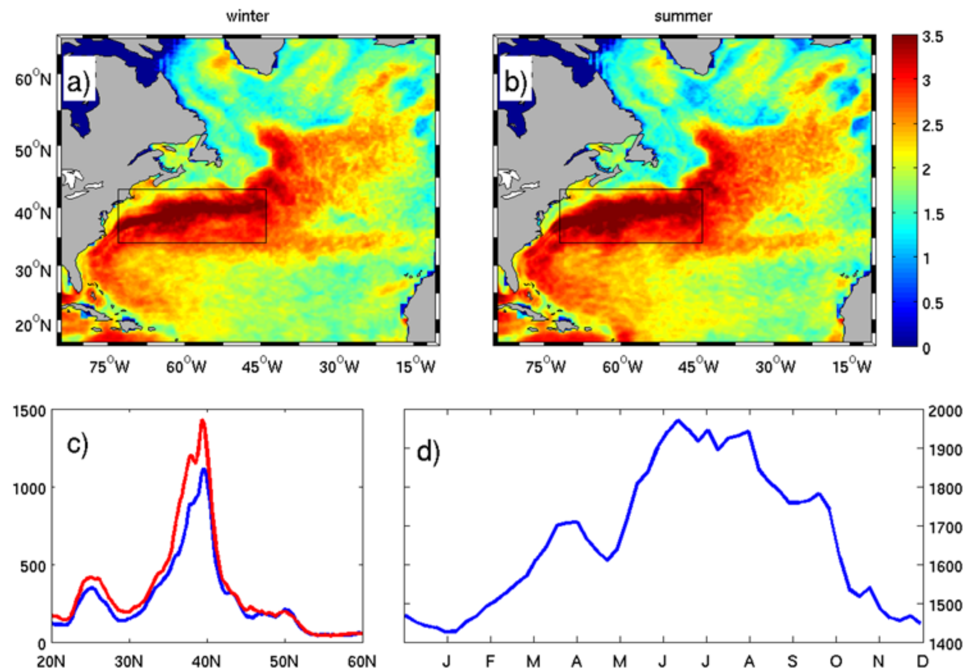

Figure 1. *EKE* averaged over (a) December, January and February and (b) June, July and August plotted on a log scale with base 10. (c) Cross-basin average of *EKE* from (Figure 1a; blue) and (Figure 1b; red) as a function of latitude and (d) seasonal cycle of *EKE* averaged in the rectangular box. Units: $cm^2\ s^{-2}$.

comparison. A higher *EKE* level is, nevertheless, found over most of the ocean basin in summer. One noticeable exception is in the Labrador Sea, where *EKE* generated through barotropic instability of the West Greenland Current reaches its maximum strength in late winter. The zonally-averaged picture (Figure 1c) confirms that *EKE* is higher in summer, especially south of 40°N. Since *EKE* and its variability in the North Atlantic is dominated by the Gulf Stream region, the seasonal evolution of *EKE* averaged over a rectangular box bounded to the south and north by 34°N and 43°N, and to the east and west by 44°W and 73°W is plotted in Figure 1d. Sensitivity studies by slightly changing the size of the box do not qualitatively change the results. *EKE* peaks in summer, exceeding that in winter by over 30%, consistent with previous studies [e.g., *Brachet et al.*, 2004]. It can be shown that the difference of *EKE* between summer and winter (and also the difference in the eddy growth rate discussed in the next section) is significantly different from zero at the 95% level. Is the Gulf Stream more prone to produce eddies in summer than in winter?

3.1. Eddy Growth Rate

[5] Eddies in the western boundary regions are believed to be generated mostly through baroclinic instability processes. The intensity of baroclinic instability can be measured by the eddy growth time scale T_{bc} [see, e.g., *Stammer*, 1998], which is set by stratification and local shear derived from thermal wind,

$$T_{bc} = \sqrt{Ri}/f, \tag{1}$$

where Ri is the Richardson number and f the Coriolis parameter. Monthly Ri is estimated using monthly temperature and salinity taken from the World Ocean Atlas, and then averaged over the top 500 m. Our annual mean Ri (not shown) is broadly consistent with that given by *Stammer* [1998], i.e., small values in the western boundary currents and along the path of the Antarctic Circumpolar Current. The eddy growth time scale, T_{bc}, averaged over each of late winter and late summer is shown in Figures 2a and 2b. The shortest timescale is found in the Gulf Stream region and also at high latitudes on the order of a few days, while it takes the eddies tens of days to grow in the interior subtropical gyre. The difference between Figure 2a and 2b shows that most of the North Atlantic is more baroclinically unstable, as measured by T_{bc}, in the late winter than in late summer (Figure 2d). Focussing on the Gulf Stream region (Figure 2e) we see that eddy growth times are indeed shortest in late winter and early spring (less than 10 days) but somewhat longer (approaching 14 days) in summer and autumn.

3.2. Ekman Pumping

[6] We next test whether seasonal variations in Ekman pumping can explain the seasonal variation in the eddy growth rate. On the seasonal time scale, ocean basin adjustment in mid-latitudes to the large-scale wind forcing is thought to be a barotropic process, with little influence on the thermocline structure which is largely governed by local processes [*Gill and Niiler*, 1973]. To estimate the seasonal displacement of the thermocline, h_{EK}, due to Ekman pumping, we therefore time-integrate the local seasonally varying Ekman pumping anomaly. We note that for available potential energy it is the anomalous differential h_{EK} in space that measures the anomalous vertical tilting of the thermocline relative to its mean state. The anomalous thermocline displacement measured by h_{EK} is presented in Figures 3a–3d for different months. The computed displacements are of

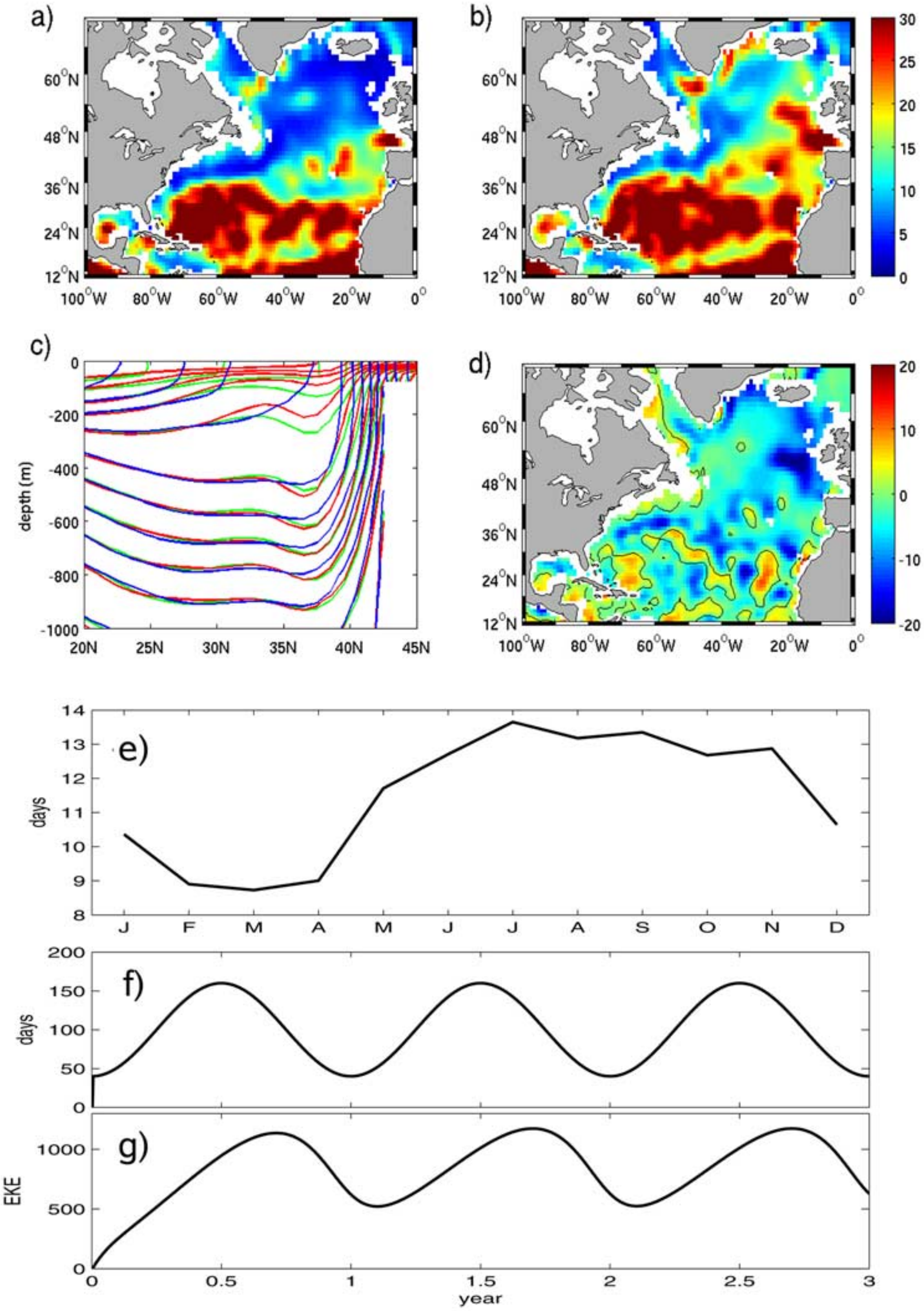

Figure 2. The baroclinic timescale T_{bc} averaged over the top 500 m and over (a) February, March and April and (b) August, September and October. (d) Figure 2a minus Figure 2b. The zero contour is shown in black. Units: days. (c) Vertical thermocline structure (potential temperature) along 60°W in March (blue), August (red) and November (green) and (e) the seasonal cycle of T_{bc} averaged in the box shown in Figure 1. (f) Dissipation time scale γ and (g) the resulting *EKE* variability from the model with seasonally varying dissipation. Note the different scales for the time axis in Figures 2f and 2g compared to Figure 2e.

the order of 5 m or so. The implied velocity anomalies can be estimated using the thermal wind balance and are much less than 1 cm s^{-1}, and are therefore tiny compared to the mean flow. It follows that seasonally-varying Ekman pumping is unlikely to be responsible for the seasonal changes of the eddy growth rate and therefore the seasonal changes in the eddy field in the Gulf Stream region.

3.3. Seasonal Evolution of the Thermocline

[7] It is instructive to examine the seasonal changes in the structure of the thermocline. Figure 2c shows vertical sections across the Gulf Stream along 60°W in March, August and November. Most of the seasonal changes take place in the top 200 m or so. In August, the surface ocean is strongly stratified due to surface heating and weak wind-

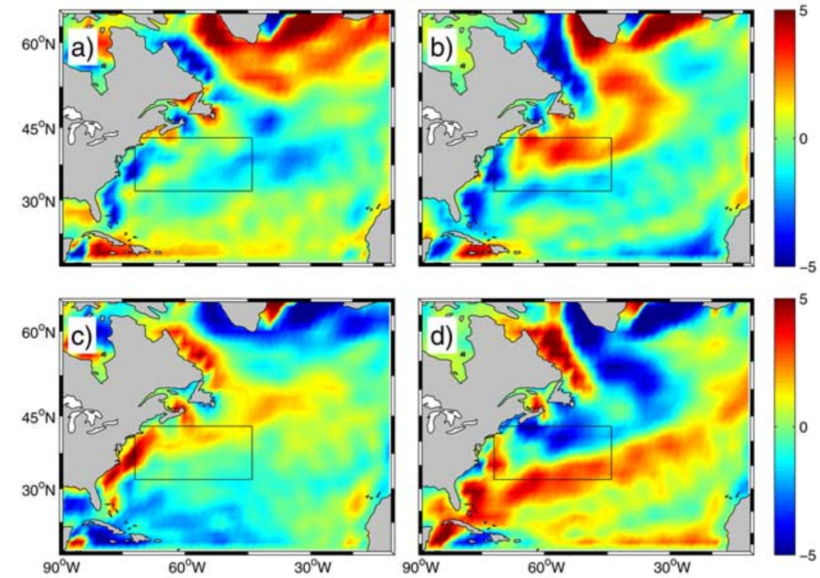

Figure 3. The time-integral of the seasonally varying Ekman pumping anomaly (time mean set to zero) in (a) February, (b) May, (c) August and (d) November. Units: m.

induced vertical mixing whereas in March, the thermocline becomes well-mixed in the top few 100 m due to cooling-induced convection and strong wind-induced vertical mixing. It is possible that the seasonal changes in the upper few 100m effect the eddy growth rate, as noted by *Gill et al.* [1974] (although the seasonal cycle of T_{bc} shown in Figure 2e is not dominated by the upper few 100 m). It is also possible that the seasonal capping of the thermocline significantly decreases the dissipation for *EKE* during summer compared to winter, by shielding eddies from direct thermal interaction with the atmosphere [e.g., *Zhai and Greatbatch*, 2006a, 2006b]. We now explore these ideas further using a simple model.

4. A Simple Model

[8] The equation for the variation of *EKE* can be taken from equation (6) of *Eden and Greatbatch* [2008]. For simplicity, we drop the nonlocal terms and assume that the baroclinic conversion term $\overline{\rho' w'}$ dominates so that

$$\frac{\partial(EKE)}{\partial t} = f(Ri) - \frac{EKE}{\gamma} \quad (2)$$

where $f(Ri)$ is the eddy production term and we assume that it is an inverse function of Ri. γ is the eddy dissipation time scale. If we assume $EKE = Ee^{i\omega t}$ and $f(Ri) = Ae^{i\omega t}$, where ω is the frequency of *EKE* and $f(Ri)$ variation, then for constant γ, equation (2) implies that

$$E = \frac{\gamma A}{1 + i\omega\gamma} \quad (3)$$

[9] There are two natural limits associated with equation (3): i) $\omega\gamma \gg 1$ (short time scales/slow decay), $E = -iA/\omega$, $f(Ri)$ leads *EKE* by 90° and $EKE \sim \int_t f(Ri)\, dt$; ii) $\omega\gamma \ll 1$ (long time scales/fast decay), $E = \gamma A$, then *EKE* and the eddy production term are in phase. We note that the maximum lag between *EKE* and the eddy production term allowed by equation (3) is 90°, that is 3 months for the annual cycle, corresponding to the short time scale/slow decay limit, whereas a comparison between Figures 1d and 2e show that in the Gulf Stream region the seasonal variation of *EKE* and the production term, measured by T_{bc}, are actually about 180° out of phase. It follows that we cannot explain the seasonal cycle of *EKE* in the Gulf Stream region using the baroclinic production term computed from the World Ocean Atlas. It is possible, of course, that the World Ocean Atlas data is too smooth to capture the true seasonal cycle of T_{bc} or that the seasonal cycle of *EKE* is controlled by seasonal variations in the barotropic instability of the Gulf Stream (unfortunately the latter is hard to assess). Another possibility, which we argue here, is that rather than seasonal variations in production being important, it is seasonal variations in the dissipation time scale that matter.

[10] To illustrate the effect of seasonally varying dissipation, we now integrate equation (2) with a constant eddy production term but use $\gamma = \gamma_0 + \gamma_1 \sin(\omega t)$, where $\gamma_0 =$ 100 days and $\gamma_1 = 60$ days. (The choice of 100 days is based on *Wunsch* [1998] who noted that eddies can sometimes survive for several years. The choice of 60 days is more arbitrary and could, of course, be adjusted to fit the observed *EKE* seasonal cycle). The result, shown in Figure 2g, shows a seasonal cycle in *EKE* that is now not unlike the observed seasonal cycle (Figure 1d), with maximum *EKE* in late summer.

5. Global Picture

[11] We now describe the seasonal cycle of *EKE* in the global ocean. To reduce the noise level, *EKE* is binned into boxes of 4° × 4°. We then estimated the amplitude and phase of the seasonal cycle by fitting the data to an annual harmonic for every 4° box. The annual harmonic fitting performs well in the lower and middle latitudes, especially in the Pacific, but is less satisfactory in the Southern Ocean (not shown).

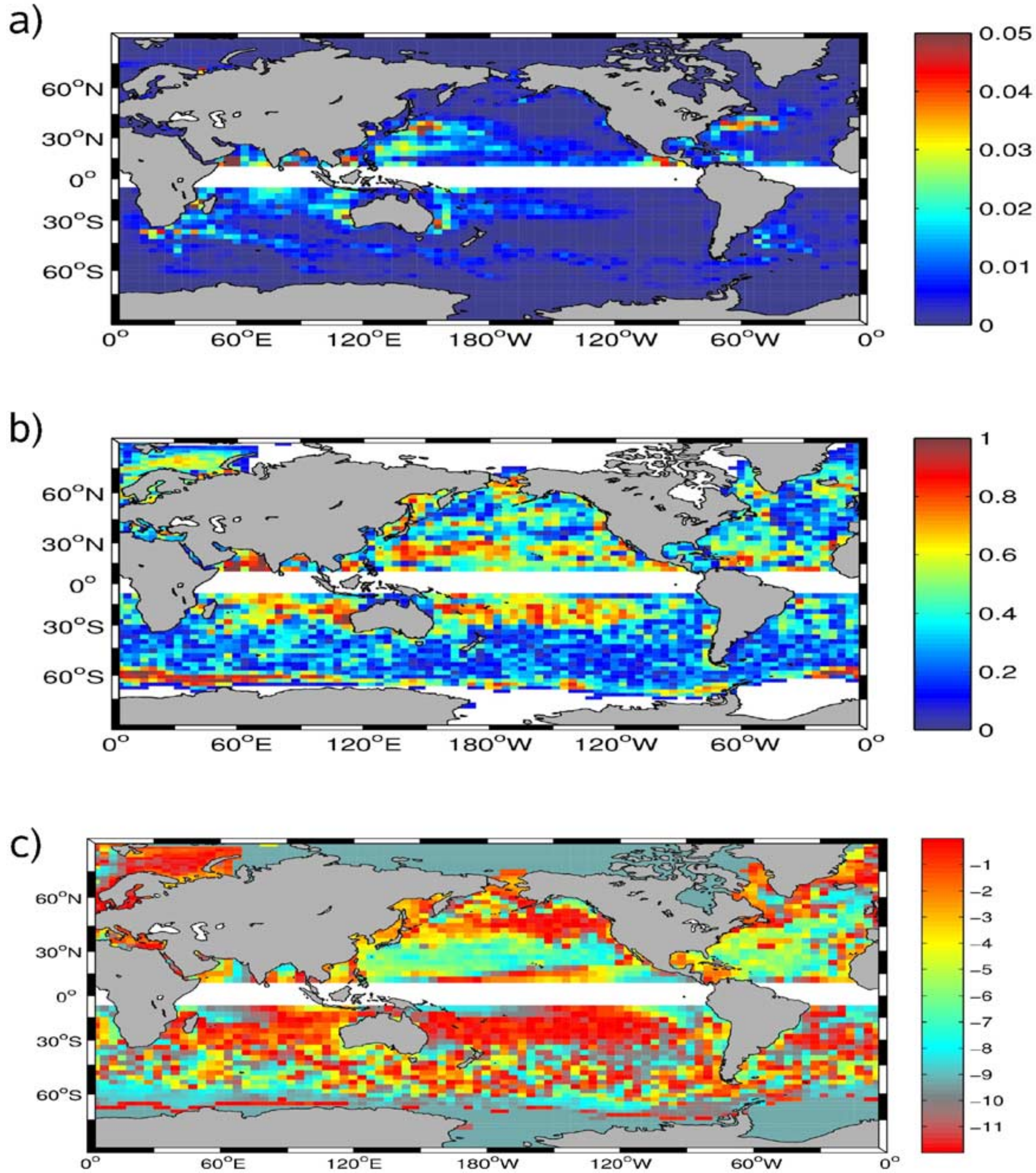

Figure 4. (a) Amplitude of the seasonal cycle of *EKE* in m^2 s^{-2}; (b) amplitude of the seasonal cycle normalized by the total variance; (c) phase of the seasonal cycle relative to January (e.g., −8 means the maximum is in August).

Energetic regions (e.g., Gulf Stream, Kuroishio) appear as regions of high amplitude in the seasonal cycle (Figure 4a), consistent with *Stammer and Wunsch* [1999], but regions where the amplitude of the seasonal cycle is a large percentage of the total variability are the interior subtropical gyres and some high latitude regions (Figure 4b). Compared to *Stammer and Wunsch* [1999], the most different and remarkable feature is the phase of the seasonal cycle. As for the Gulf Stream, *EKE* in all the subtropical gyres of the world's oceans peaks in the respective hemispheric summers (Figure 4c). (Note that we have 12 years of data available to us compared to only a four-year TOPEX-POSEIDON record available to *Stammer and Wunsch* [1999]). On the other hand, the seasonal cycle of *EKE* has the opposite phase in the subpolar North Pacific and part of the subpolar North Atlantic. The reason for the difference between the subtropical and subpolar gyres is not clear at this time. We have already noted the importance of barotropic, as distinct from baroclinic instability, in the Labrador Sea region. It is possible that seasonal variations in the barotropic production term and/or differences in the eddy dissipation time scale (or direct wind forcing [*Stammer and Wunsch*, 1999]) have a role to play. The subpolar gyre regions remain a topic for future research.

6. Summary and Discussion

[12] The eddy variability in the oceans is not always straightforward to interpret. For example, no simple conclusions were drawn in the investigation by *Stammer and Wunsch* [1999] about the relationship between temporal

changes of the eddy field and local wind stress forcing. Eddies are thought to be mostly generated through baroclinic instability, thereby releasing available potential energy built up by wind-driven Ekman pumping [e.g., *Gill et al.*, 1974], or by barotropic instability. However, the mechanisms by which the eddy field is modulated seasonally are far from clear. Here, we have examined the seasonal variability of the eddy field in the Gulf Stream region using data from satellite altimetry, the NCEP reanalysis and the World Ocean Atlas. We find that *EKE* has a maximum in summer and a minimum in winter, while the ocean is most baroclinically unstable (as measured by an estimate of the growth rate time scale using World Ocean Atlas data) in late winter. We have shown that seasonal variations in Ekman pumping cannot account for the seasonal changes in the eddy growth rate, implying that *Gill et al.* [1974] is not applicable for explaining the seasonal cycle of EKE. Rather, results from a simple model strongly suggest that it is the seasonal modulation of the dissipation time scale for *EKE* that explains the seasonal cycle, with higher *EKE* in summer when the dissipation time scale is longer. We have suggested that the longer dissipation time scale in summer arises from the thermal capping of the thermocline in summer, whereas during winter eddies are more strongly influenced by thermal interaction with the atmosphere [*Zhai and Greatbatch*, 2006a, 2006b]. We also note that the ocean surface velocity dependence of the wind stress leads to a direct mechanical damping of eddies [e.g., *Duhaut and Straub*, 2006; *Zhai and Greatbatch*, 2007]. The damping depends on wind speed and implies stronger damping in winter than in summer. Clearly further research will be required to clarify these issues using eddy-permitting models. It also remains an open question as to what governs the variability of *EKE* in the oceans on interannual to interdecadal time scales. If variations in production dominate, then for sufficiently long time scales, the long time scale/strong dissipation limit noted when discussing equation (3) should apply, suggesting that *EKE* varies in phase with the production term. However, our work also points to the possible importance of low frequency changes in the dissipation time scale, e.g. due to changes in the stratification of the upper ocean or changes in wind speed.

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