Enhanced vertical propagation of storm-induced near-inertial energy in an eddying ocean channel model

Xiaoming Zhai, Richard J. Greatbatch, and Jun Zhao
Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada

Received 26 May 2005; revised 9 August 2005; accepted 16 August 2005; published 16 September 2005.

[1] The interaction between inertial oscillations generated by a storm and a mesoscale eddy field is studied using a Southern Ocean channel model. It is shown that the leakage of near-inertial energy out of the surface layer is strongly enhanced by the presence of the eddies, with the anticyclonic eddies acting as a conduit to the deep ocean. Given the ubiquity of the atmospheric storm tracks (a source of near-inertial energy for the ocean) and regions of strong ocean mesoscale variability, we argue that this effect could be important for understanding pathways by which near-inertial energy enters the ocean and is ultimately available for mixing. **Citation:** Zhai, X., R. J. Greatbatch, and J. Zhao (2005), Enhanced vertical propagation of storm-induced near-inertial energy in an eddying ocean channel model, *Geophys. Res. Lett.*, *32*, L18602, doi:10.1029/2005GL023643.

1. Introduction

[2] There is a remarkable coincidence of regions with strong mesoscale variability (storm tracks) in both the atmosphere and the ocean. This coincidence inevitably means that regions where there is a strong energy input to the ocean at near-inertial frequencies (Figure 1a) are also regions of strong mesoscale variability in the ocean (Figure 1b). The question therefore arises as to how the presence of an eddy field in the ocean affects the vertical propagation of near-inertial energy from the surface layer to depth where, ultimately, it is available for mixing [*Munk and Wunsch*, 1998]. In the absence of eddies or a mean flow, near-inertial energy generated at the surface spreads both vertically and horizontally [*Gill*, 1984; *Zervakis and Levine*, 1995]. The near-inertial wave propagation and energy transport are largely governed by the horizontal scale of the near-inertial motions, which, on an f plane, is primarily set by the scale and propagation speed of the applied wind field [*Kundu and Thomson*, 1985]. Including the β-effect, it has been shown that near-inertial energy generated at a particular latitude is free to propagate equatorward, but is restricted in its poleward propagation by the planetary vorticity gradient [*Anderson and Gill*, 1979; *D'Asaro*, 1989; *Garrett*, 2001; *Alford*, 2003a]. Similar to the β effect, the horizontal gradient of the relative vorticity can also be important for near-inertial energy propagation and the decay of the near-inertial energy in the mixed layer [*van Meurs*, 1998]. *Kunze* [1985; see also *Mooers*, 1975] had earlier argued that near-inertial waves propagating in geostrophic shear are subject to the absolute, not the planetary vorticity gradient, and can be trapped in regions of anticyclonic relative vorticity. The ubiquity of the atmospheric and oceanic storm tracks strongly suggests that the transfer of near-inertial energy out of the surface layer into the deep ocean should not be studied without considering the inhomogeneity of the absolute vorticity field associated with mesoscale eddies. *Young and Ben Jelloul* [1997] have studied how near-inertial oscillations propagate through a three-dimensional geostrophic flow and noted that a field of eddies with horizontal scale much smaller than that of the inertial oscillations can greatly increase the vertical propagation rate of the near-inertial energy. *Klein and Llewellyn Smith* [2001] studied the horizontal dispersion of near-inertial oscillations in a mesoscale eddy field and found the prevalence of the trapping regime, inside regions of negative relative vorticity. *Lee and Niiler* [1998] have also pointed out the possibility that anticyclonic eddies can act as a chimney, draining near-inertial energy from the surface to the deep ocean.

[3] In this letter, we consider the response of an eddy-rich channel model to a moving storm, and, in particular, how the presence of the eddies affects the vertical propagation of the near-inertial energy generated by the storm.

2. The Model

[4] The model is a 5000 m deep reentrant channel of length 50° longitude. The numerical code is the same as used by *Eden et al.* [2004] and is a revised version of the MOM2 code. The northern and southern boundaries of the channel are at 30°S and 38°S, respectively. The horizontal resolution is 1/3° in both latitude and longitude and there are 45 unevenly spaced z levels in the vertical. The initial conditions are a state of rest and a horizontally homogeneous but vertically stratified ocean. A cosine-shape eastward wind stress is applied at the surface to generate baroclinic instability. A quadratic drag law is used for bottom friction with a coefficient of 1.5×10^{-2}. Lateral biharmonic viscosity of 2×10^{11} m^4/s and explicit vertical viscosity of 2×10^{-4} m^2/s are also employed. The QUICKER advection scheme is used for the only tracer (potential temperature) with no explicit diffusion.

[5] A year-long spin-up forced by the cosine-shape zonal wind was used to allow the turbulence to fully develop and reach a quasi-equilibrium state before the storm forcing is introduced. The wind stress for the storm is specified following *Chang and Anthes* [1978] as

$$\tau = \tau_{\max} \times \begin{cases} r/r_{\min} & 0 \le r \le r_{\min} \\ (r_{\max} - r)/(r_{\max} - r_{\min}) & r_{\min} \le r \le r_{\max} \\ 0 & r \ge r_{\max} \end{cases} \quad (1)$$

0094-8276/05/2005GL023643$05.00

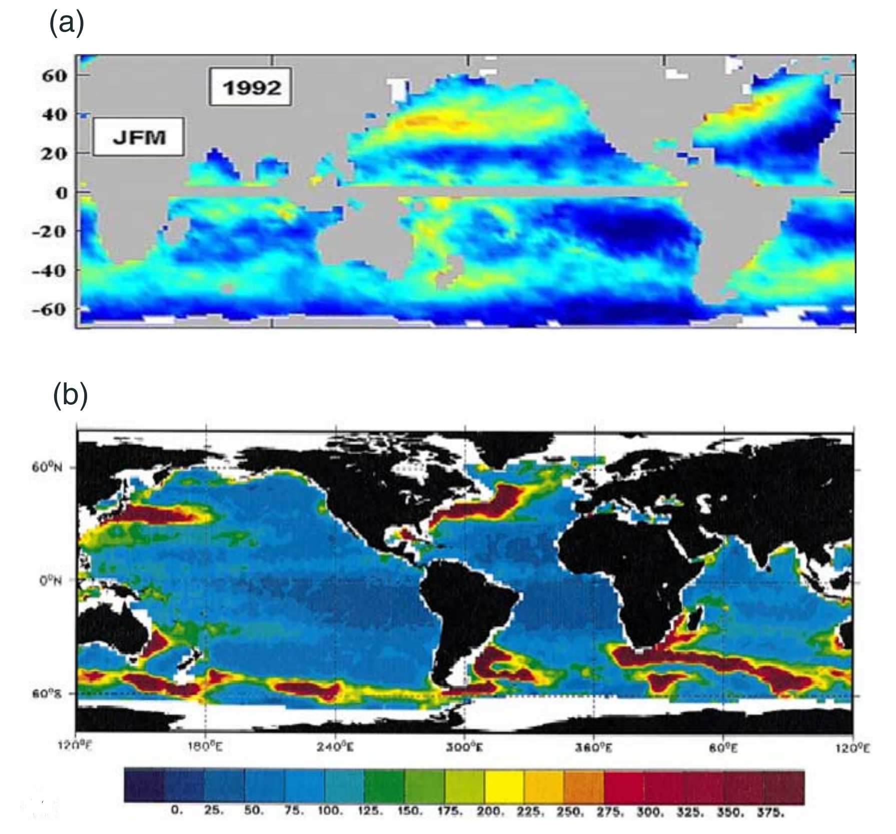

Figure 1. (a) Near-inertial energy input at the surface of the world ocean in the winter season [from *Alford*, 2003b, Figure 4]; (b) Eddy kinetic energy at the surface of the world ocean [from *Stammer and Wunsch*, 1999, Figure 1]. Note the use of different reference longitudes in the two figures.

where τ is the amplitude of the tangential wind stress with respect to the storm center, and r is the radial distance from the center (the radial wind stress is put to zero). Here, we put $r_{\min}$ = 30 km, $r_{\max}$ = 300 km, and $\tau_{\max}$ = 3 Nm^{-2}. The storm centre moves along 34°S from the west to the east at 10 m s^{-1} and decays so as not to reenter the channel at its western end. The storm forcing was added to the zonal wind stress at the end of the spin-up. A model run using the storm forcing applied to a resting ocean was also carried out and used to determine the difference between the response of an eddying and a resting ocean to the storm.

3. Model Results

[6] At the end of the spin-up, the model domain is characterized by strong warm-core anticyclonic eddies aligned close to the north wall of the channel (see Figure 3b below) and weaker cold-core cyclonic eddies further south. The maximum velocity reaches 2 m s^{-1} at the surface. In order to isolate the near-inertial response of the model, a 5th order Butterworth bandpass filter centred at the local (32°S) inertial frequency was applied to the model-computed velocities. Figure 2 shows the kinetic energy calculated from the band-pass filtered velocity fields and integrated over a 15 day period following the passage of the storm. When the ocean ahead of the storm is at rest (Figure 2c), the near-inertial energy at the surface is found along and to the left (north) of the storm track, and integrates over the area of the channel to a value of 3.6×10^{17} m^4 s^{-1}. The leftward bias results from the surface current being turned by the Coriolis force in the same direction as the wind stress to the left of the track, but in the opposite direction to the right of the track [*Chang and Anthes*, 1978]. When there are eddies, a much more complicated

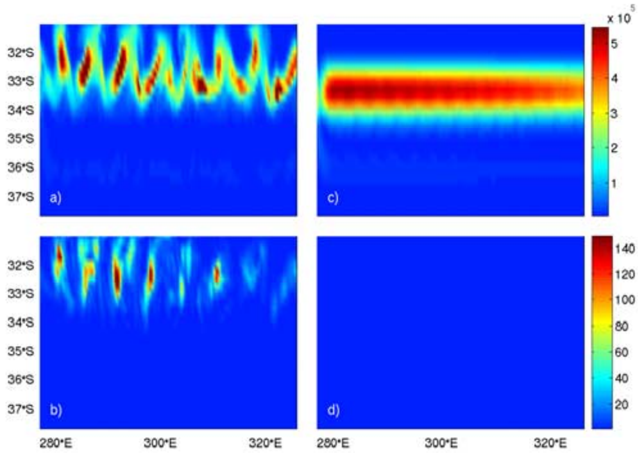

Figure 2. Near-inertial energy associated with the storm at 5 m depth [(a) and (c)] and 1641 m depth [(b) and (d)] and integrated over a 15 day period following the storm. (a) and (b) are for the case with eddies, (c) and (d) for the case without eddies. The units are m^2 s^{-1}. Note that the scale used at 5 m depth [(a)and (c)] is different from that used at 1641 m depth [(b) and (d)].

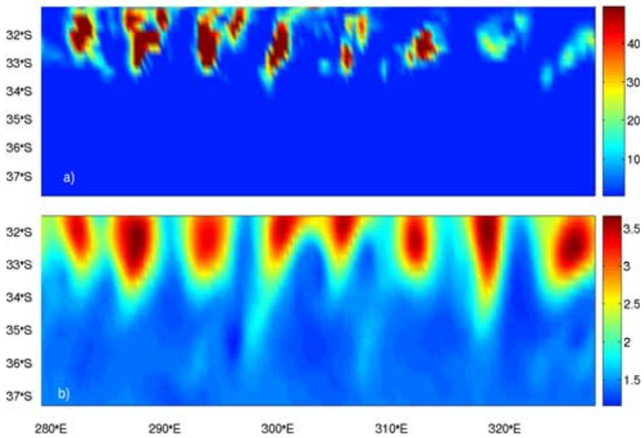

Figure 3. (a) The difference between Figures 2b and 2d in $m^2\ s^{-1}$ and (b) a snapshot of the temperature (°C) field at 1641 m depth.

pattern results (Figure 2a). Several "hot spots" are formed, reflecting the pattern of the eddy field. Nevertheless, integrating over the area of the channel, the total near-inertial energy at the surface is now only $2.4 \times 10^{17}\ m^4\ s^{-1}$, about 70% of that when there are no eddies. A different picture emerges at 1641 m depth (Figures 2b and 2d). In the absence of eddies, the energy level is so low that no contours appear on the plot (Figure 2d), whereas in the presence of eddies (Figure 2b), there are localized regions where the integrated, near-inertial energy is at least one order of magnitude larger. Integrated over the area of the channel, the total near-inertial energy in Figure 2c is more than $2.4 \times 10^{13}\ m^4\ s^{-1}$ compared to only $1.1 \times 10^{13}\ m^4\ s^{-1}$ in Figure 2d. These results indicate a much more efficient transfer of near-inertial energy to depth when there are eddies compared to when there are not.

[7] Figure 3 compares the difference in integrated, near-inertial energy between Figures 2b and 2d (Figure 3a) with the temperature field at the same depth (Figure 3b). It should be noted that Figure 3b is a snapshot, whereas Figure 3a shows the difference between quantities integrated over a 15 day period. Nevertheless, the two figures roughly correspond to the same time period, and clearly show that each hot-spot for near-inertial energy at 1641 m depth (Figure 3a) corresponds to an individual anticyclonic (warm) eddy (Figure 3b). The correspondence is not exact because the anticyclonic eddies are not steady, but rather move around, and the near-inertial energy trapped in these anticyclones is carried by them and redistributed. Nevertheless, our results support the contention of *Lee and Niiler* [1998] that anticyclonic eddies can act as a conduit, draining near-inertial energy to depth (what they call the "chimney effect"). Figure 4 shows vertical transects of the near-inertial energy along 32°S for the two cases, with and without eddies. The chimney effect can be clearly seen in Figure 4a. Each high-energy conduit corresponds to an anticyclonic eddy (Figure 3b) and carries the near-inertial energy to more than 1500 m depth in the case with eddies (Figure 4a), compared to the much weaker and more diffuse downward spreading of near-inertial energy in the case without eddies (Figure 4b). *Young and Ben Jelloul* [1997] describe an example in which the horizontal scale of the near-inertial oscillations is much larger than that of the eddy field and also find enhanced propagation of the near-inertial energy to depth in association with the eddies. By contrast, our model results show a strong correspondence between the horizontal scale of the storm-generated near-inertial oscillations, and that of the eddy field, and highlight the importance of the chimney effect.

[8] The basic mechanism at work was introduced by *Kunze* [1985; see also *Mooers*, 1975]. He argued that in the presence of the relative vorticity ζ, the effective Coriolis parameter, f_{eff}, is replaced by

$$f_{eff} = f + \zeta/2 \qquad (2)$$

where f is the planetary vorticity. To examine this effect, we have looked at time series of the bandpass filtered velocities within the hot spots at depth 1641 m. These reach up to 4 cm/s, somewhat greater than the 1 cm/s maximum found in the case with no eddies. A spectral analysis shows that the dominant frequency is shifted from about 19 hours (the local inertial period) when there are no eddies to close to 23 hours when there are eddies. For a typical anticyclonic eddy in the channel, the relative vorticity ζ is roughly $2 \times 10^{-5}\ s^{-1}$. Based on equation (2), the effective inertial period in such an eddy is approximately 23 hours, consistent with the model results. The same frequency shift can also be seen in the surface level of the model where it is also consistent with equation (2). This result differs from *D'Asaro* [1995], who found a much smaller frequency shift associated with near-inertial oscillations generated in the Northeast Pacific by a strong storm. The reason for this difference is not clear.

4. Discussion and Summary

[9] The thermohaline circulation of the ocean results primarily from deep water formation at sites in the Nordic and Labrador Seas, and around Antarctica, and upwelling throughout the rest of the global ocean. Mechanical energy input from the wind and tides is thought to be necessary to generate the diapycnal mixing required to support the

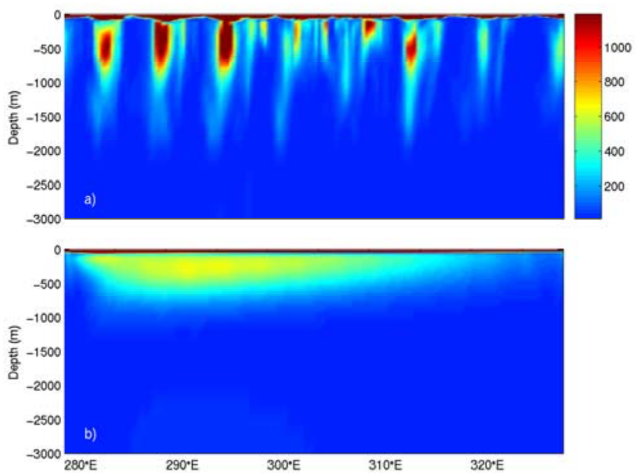

Figure 4. Vertical transect of the near-inertial energy in $m^2\ s^{-1}$ along 32°S in the experiment (a) with eddies; (b) without eddies.

upwelling branch of the thermohaline circulation [*Munk and Wunsch*, 1998; *Wunsch*, 2002]. Global maps of the wind-induced energy flux to inertial motions at the surface have been drawn by *Watanabe and Hibiya* [2002] and *Alford* [2003b], but there is a question as to how the near-inertial energy generated at the surface is transferred to the deep ocean where it is available to participate in deep ocean mixing.

[10] Wind-induced near-inertial energy is thought to be redistributed by the propagation of inertial-gravity waves to lower latitudes, for example by the beta-dispersion effect [see *Alford*, 2003a; *Chiswell*, 2003], and by advective processes [e.g., *Zhai et al.*, 2004, 2005]. However, there is a strong similarity between the distribution of the input of near-inertial energy at the surface [*Alford*, 2003b] and the distribution of eddy kinetic energy in the world ocean [*Stammer and Wunsch*, 1999] (see Figure 1), making it necessary to examine the effect of a mesoscale eddy field on the vertical propagation of the near-inertial energy.

[11] Our model results suggest that the vertical propagation of near-inertial energy is somewhat enhanced by the presence of eddies. *Young and Ben Jelloul* [1997] had earlier arrived at a similar conclusion. However, in contrast to *Young and Ben Jelloul* [1997], our model results emphasize the important role played by anticyclonic eddies, which in our model, drain near-inertial energy quickly to the deep ocean through the "inertial chimney" effect of *Lee and Niiler* [1998]. Since a given energy level at higher latitudes causes much more mixing than at lower latitudes [*Gregg et al.*, 2003; *Garrett*, 2003], the "inertial chimneys" could be an efficient way to generate mixing at depth, since they can drain wind-generated near-inertial energy to depth more locally, at middle to high latitudes, rather than transferring it first to lower latitudes as in the β-dispersion effect [*Garrett*, 2001]. We argue that the "inertial chimney" effect could be particularly important in the Southern Ocean, where there is both an abundance of eddies, and strong near-inertial energy input at the surface due to passing storms. Such an effect could be important for understanding diapycnal mixing levels in the Southern Ocean, and ultimately, the pathways of the meridional overturning circulation.

[12] **Acknowledgments.** This project has been supported by grants from NSERC and CFCAS through the Canadian CLIVAR Research Network. We are grateful to Carsten Eden for providing us with the basic numerical code used here. We also wish to thank reviewers for critical comments that led to a significantly improved manuscript.

References

Alford, M. H. (2003a), Redistribution of energy available for ocean mixing by long-range propagation of internal waves, *Nature*, *423*, 159–162.

Alford, M. H. (2003b), Improved global maps and 54-years history of wind-work on ocean inertial motions, *Geophys. Res. Lett.*, *30*(8), 1424, doi:10.1029/2002GL016614.

Anderson, D. L. T., and A. E. Gill (1979), Beta dispersion of inertial waves, *J. Geophys. Res.*, *84*, 1836–1842.

Chang, S. W., and R. A. Anthes (1978), Numerical simulations of the ocean's nonlinear baroclinic response to translating hurricanes, *J. Phys. Oceanogr.*, *8*, 468–480.

Chiswell, S. M. (2003), Deep equatorward propagation of inertial oscillations, *Geophys. Res. Lett.*, *30*(10), 1533, doi:10.1029/2003GL017057.

D'Asaro, E. (1989), The decay of wind-forced mixed layer inertial oscillations due to the β effect, *J. Geophys. Res.*, *94*, 2045–2056.

D'Asaro, E. A. (1995), Upper-ocean inertial currents forced by a strong storm. part III: Interaction of inertial currents and mesoscale eddies, *J. Phys. Oceanogr.*, *25*, 2953–2958.

Eden, C., R. J. Greatbatch, and C. W. Böning (2004), Adiabatically correcting an eddy-permitting model using large-scale hydrographic data: Application to the Gulf Stream and the North Atlantic Current, *J. Phys. Oceanogr.*, *34*, 701–719.

Garrett, C. (2001), What is the "Near-Inertial" band and why is it different from the rest of the internal wave spectrum, *J. Phys. Oceanogr.*, *31*, 962–971.

Garrett, C. (2003), Mixing with latitude, *Nature*, *422*, 477–478.

Gill, A. E. (1984), On the behavior of internal waves in the wake of storms, *J. Phys. Oceanogr.*, *14*, 1129–1151.

Gregg, M. C., T. B. Sanford, and D. P. Winkel (2003), Reduced mixing from the breaking of internal waves in equatorial waters, *Nature*, *422*, 513–515.

Klein, P., and S. G. Llewellyn Smith (2001), Horizontal dispersion of near-inertial oscillations in a turbulent mesoscale eddy field, *J. Mar. Res.*, *59*, 697–723.

Kundu, P. K., and R. E. Thomson (1985), Inertial oscillations due to a moving front, *J. Phys. Oceanogr.*, *15*, 1076–1084.

Kunze, E. (1985), Near-inertial propagation in geostrophic shear, *J. Phys. Oceanogr.*, *15*, 544–565.

Lee, D. K., and P. P. Niiler (1998), The inertial chimney: The near-inertial energy drainage from the ocean surface to the deep layer, *J. Geophys. Res.*, *103*, 7579–7591.

Mooers, C. N. K. (1975), Several effects of a bariclinic current on the cross-stream propagation of inertial-internal waves, *Geophys. Fluid Dyn.*, *6*, 245–275.

Munk, W., and C. Wunsch (1998), Abyssal recipes II, Energetics of tidal and wind mixing, *Deep Sea Res., Part I*, *45*, 1977–2010.

Stammer, D., and C. Wunsch (1999), Temporal changes in eddy energy of the oceans, *Deep Sea Res., Part II*, *46*, 77–108.

van Meurs, P. (1998), Interactions between near-inertial mixed layer currents and the mesoscale: The importance of spatial variabilities in the vorticity field, *J. Phys. Oceanogr.*, *28*, 1363–1388.

Watanabe, M., and T. Hibiya (2002), Global estimates of the wind-induced energy flux to inertial motions in the surface mixed layer, *Geophys. Res. Lett.*, *29*(8), 1239, doi:10.1029/2001GL014422.

Wunsch, C. (2002), What is the thermohaline circulation?, *Science*, *298*, 1179–1181.

Young, W. R., and M. Ben Jelloul (1997), Propagation of near-inertial oscillations through a geostrophic flow, *J. Mar. Res.*, *55*, 735–766.

Zervakis, V., and M. D. Levine (1995), Near-inertial energy propagation from the mixed layer: Theoretical consideration, *J. Phys. Oceanogr.*, *25*, 2872–2889.

Zhai, X., R. J. Greatbatch, and J. Sheng (2004), Advective spreading of storm-induced inertial oscillations in a model of the northwest Atlantic Ocean, *Geophys. Res. Lett.*, *31*, L14315, doi:10.1029/2004GL020084.

Zhai, X., R. J. Greatbatch, and J. Sheng (2005), Doppler-shifted inertial oscillations on a β plane, *J. Phys. Oceanogr.*, *35*, 1480–1488.

R. J. Greatbatch, X. Zhai, and J. Zhao, Department of Oceanography, Dalhousie University, Halifax, NS, Canada, B3H 4J1. (xiaoming.zhai@phys.ocean.dal.ca)