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Spreading of near-inertial energy in a 1/12° model of the North Atlantic Ocean

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[1] Near-inertial energy in the ocean is thought to be redistributed by β-dispersion, whereby near-inertial waves generated at the surface by wind forcing propagate downward and equatorward. In this letter, we examine the spreading of near-inertial energy in a realistic 1/12° model of the North Atlantic driven by synoptically varying wind forcing. We find that (1) near-inertial energy is strongly influenced by the mesoscale eddy field and appears to be locally drained to the deep ocean, largely by the chimney effect associated with anticyclonic eddies, and (2) the interior of the subtropical gyre shows very low levels of near-inertial energy, contrary to expectations based on the β-dispersion effect. **Citation:** Zhai, X., R. J. Greatbatch, and C. Eden (2007), Spreading of near-inertial energy in a 1/12° model of the North Atlantic Ocean, *Geophys. Res. Lett.*, *34*, L10609, doi:10.1029/2007GL029895.

1. Introduction

[2] Near-inertial waves are believed to be an important source of energy for generating diapycnal mixing in the ocean, contributing to the maintenance of the meridional overturning circulation [*Munk and Wunsch*, 1998]. The traditional view is that near-inertial energy is redistributed in the ocean largely by the β-dispersion effect, whereby near-inertial waves are free to propagate equatorward, but are restricted in their poleward propagation by the planetary vorticity gradient [e.g., *Anderson and Gill*, 1979; *Garrett*, 2001]. Observational evidence has been found to support this idea [e.g., *Chiswell*, 2003; *Alford*, 2003a]. However, the ocean is not homogeneous, and similar to the idea of β-dispersion, the horizontal gradient of the relative vorticity can influence the propagation of near-inertial waves [*Kunze*, 1985; *Young and Ben Jelloul*, 1997; *van Meurs*, 1998; *Lee and Niiler*, 1998; *Klein and Llewellyn Smith*, 2001; *Zhai et al.*, 2005a]. It has also been pointed out [*Zhai et al.*, 2005a] that there is a remarkable coincidence between regions with strong mesoscale variability (storm tracks) in both the atmosphere and the ocean. It follows that regions where there is a strong energy input to the ocean at near-inertial frequency (the atmospheric storm tracks) and also regions of strong mesoscale variability in the ocean, making studies of the interaction between near-inertial waves and mesoscale eddies necessary. Using an idealized ocean channel model, *Zhai et al.* [2005a] showed the important role played by anticyclonic eddies for draining near-inertial energy from the surface to the deep ocean through the "inertial chimney" effect [e.g., *Kunze*, 1985; *Lee and Niiler*, 1998]. The basic mechanism at work was discussed by *Kunze* [1985; see also *Mooers*, 1975], who showed that in the presence of the relative vorticity ζ, the effective Coriolis parameter, f_{eff}, is

$$f_{eff} = f + \zeta/2 \tag{1}$$

where f is the planetary vorticity. It then follows that if the relative vorticity gradient is strong enough, near-inertial energy generated inside anticyclonic eddies can be trapped and reflected downward locally to the deep ocean.

[3] Most previous studies on the interaction between near-inertial oscillations and mesoscale eddies have been conducted in idealized model set-ups, and it is not clear how significant the chimney effect is in reality in comparison with β-dispersion. In this letter, we make a first attempt to address this issue using a realistic eddy-resolving (1/12°) model of the North Atlantic Ocean driven by synoptically varying wind forcing.

2. Description of the Model

[4] The model used in this study is based on a rewritten version of MOM2, and is identical to the one used by *Eden et al.* [2007]. The horizontal resolution is about 10 km at the equator decreasing to about 5 km in high latitudes, corresponding to roughly 1/12° in longitude. The model domain extends between open boundaries at 20°S and 70°N formulated following *Stevens* [1990], with a restoring zone in the eastern Mediterranean Sea. There are 45 vertical geopotential levels with increasing thickness with depth, ranging from 10 m at the surface to 250 m near the maximal depth of 5500 m. The model was spun-up for 10 years with monthly climatological forcing. After that, it was forced using daily wind stress taken from 24-hour forecasts of the operational weather forecast model from ECMWF started from operational analyses at 12 Universal Coordinated Time (UTC) on each day from year 2001 to 2004 [see *Eden and Jung*, 2006]. The horizontal resolution of the ECMWF model is about 40 × 40 km and here we use forcing from 2001 starting on January 1.

[5] The model variables are saved every 0.1 day, so aliasing of the near-inertial frequency band in the model output is not a problem. We examine the model results in winter when the near-inertial energy input is at its maximum, and leave the question of seasonality to a future study. To compute near-inertial energy, the horizontal velocity is filtered (using a Butterworth filter) to retain periods of less than 1.3 days. By near-inertial energy in the model we mean

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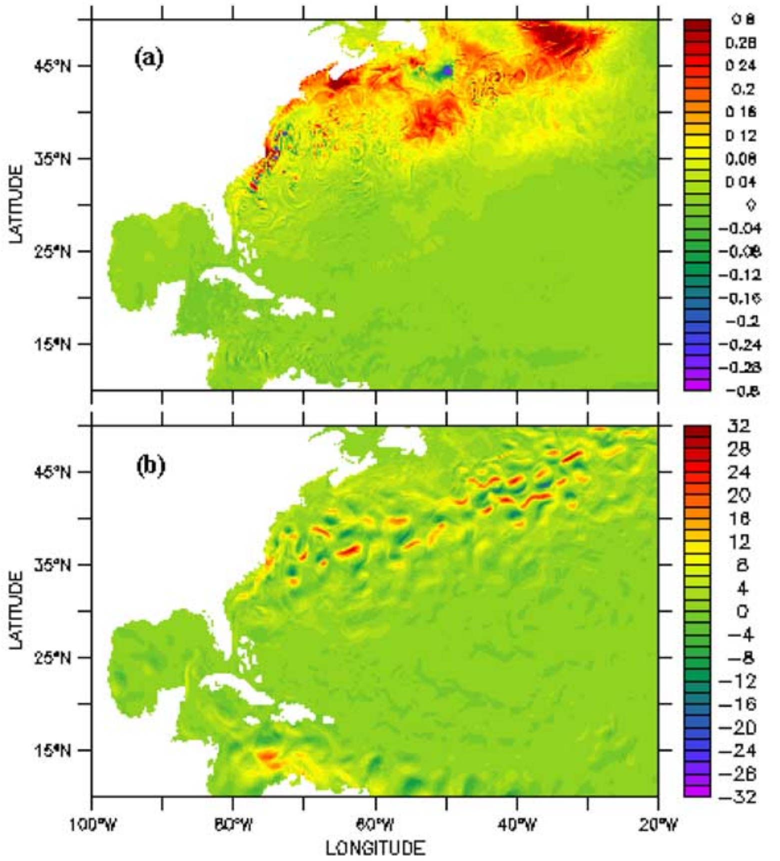

Figure 1. (a) Energy input to near-inertial motions. (b) Total wind work. Both are integrated for 10 days. Unit, ×8640 N m^{-1}.

the kinetic energy computed from the high pass filtered velocity. The cutoff period of 1.3 days is sufficient for the regions that we are interested in, and further refinement of the band-pass filter does not lead to any major changes of the near-inertial properties in the model.

3. Model Results

[6] Figure 1a shows the input of near-inertial energy at the sea surface calculated using $\tau \cdot \mathbf{u_I}$, where τ is the wind stress vector and $\mathbf{u_I}$ the high pass filtered surface velocity, and integrated for 10 days starting on March 8. For simplicity, we focus on the subtropical gyre and its neighbourhood. The overall pattern and magnitude is broadly consistent with the estimate given by *Alford* [2003b] who used a slab model and did not account for mesoscale eddies. In particular, south of the atmospheric storm track, over the subtropical gyre, much lower levels of energy input are found than beneath the atmospheric storm track itself. Clearly, however, integrations using wind forcing with higher temporal resolution and averaged over many years will be required to provide a reliable comparison with *Alford* [2003b]. Our purpose here is simply to show that the energy input to the inertial frequency band in the model is at a reasonable level. For comparison, Figure 1b shows the total wind work ($\tau \cdot \mathbf{u}$, where $\mathbf{u}$ is the total surface velocity) over the same region, integrated over the same 10 days. Here, the mesoscale eddy field clearly dominates; in particular, the wind transfers energy into (and out of) the ocean mostly through the mesoscale eddy field [*Zhai and Greatbatch*, 2007], and the peak value is more than one order of magnitude larger than that of the near-inertial energy input.

[7] The distribution of the near-inertial energy itself is illustrated in Figure 2. At the surface (Figure 2a), the near-inertial energy shows a smooth maximum over the Grand Banks of Newfoundland, where the relative vorticity is small compared with the Coriolis frequency. By contrast, much smaller spatial scales, reflecting the mesoscale eddy field, are found in other parts of Figure 2a, in contrast to expectations based on traditional theory in which the spatial scale is set by the scale of the applied wind field [e.g., *Greatbatch*, 1984; *Kundu and Thomson*, 1985]. The same effect can be seen in the idealised study of *Zhai et al.* [2005a] (compare their Figures 2a and 2c), and has been noted in observed data by *Kunze and Sanford* [1984] for a frontal situation, demonstrating the influence of the mesoscale in regulating the near-inertial energy field. Deeper down at 516 m depth (Figure 2b), large near-inertial energy levels are also confined in the western boundary current region and again exhibit small spatial scales associated with the eddy field. Vertical transects (Figures 2c and 2d) reveal a similar picture, with relatively high levels of near-inertial energy in "chimneys" confined to the neighbourhood of the Gulf Stream. The association between high levels of near-inertial energy and negative relative vorticity is shown in Figure 3. The Gulf of Mexico (Figures 3a and 3c) offers a very clear example of the "chimney effect" with nearly all

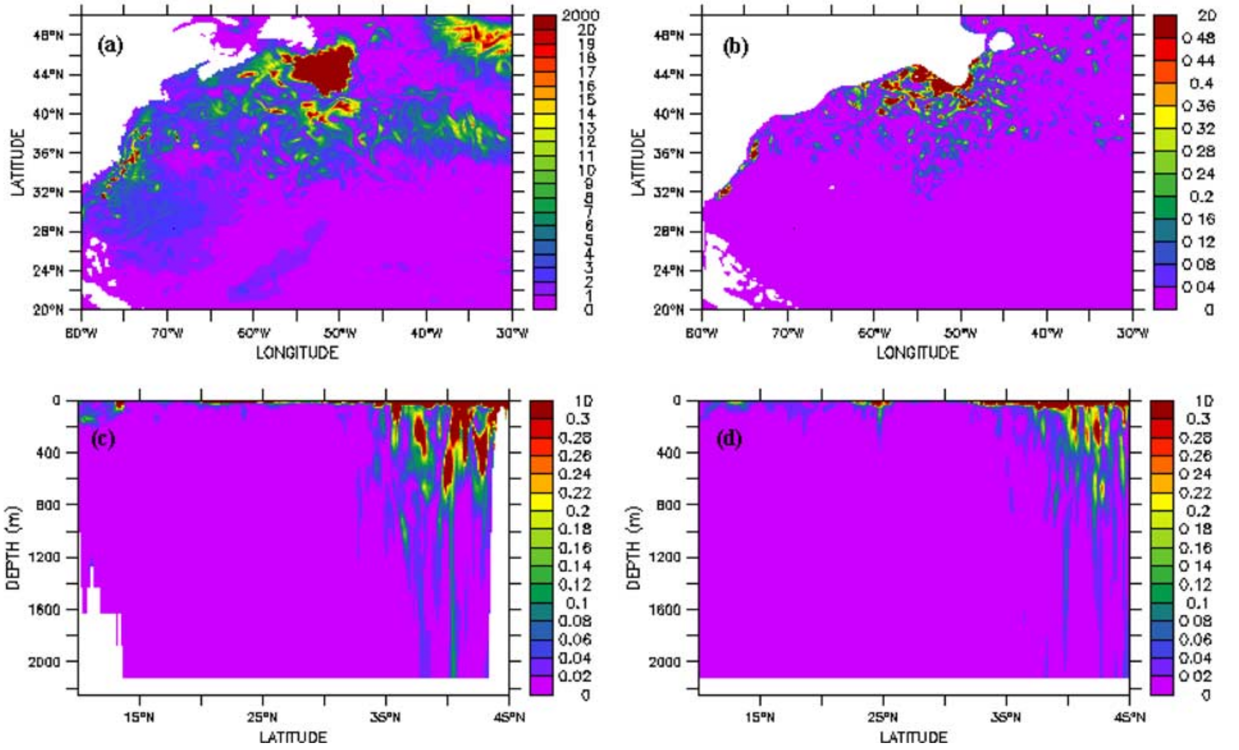

Figure 2. Near-inertial energy at (a) 5 m depth, (b) 516 m depth, (c) 59°W, and (d) 45°W. Figures 2a, 2b, and 2c are on March 8th, and Figure 2d is on March 13th. All are averaged over a day. Unit, 10^{-3} m^2 s^{-2}.

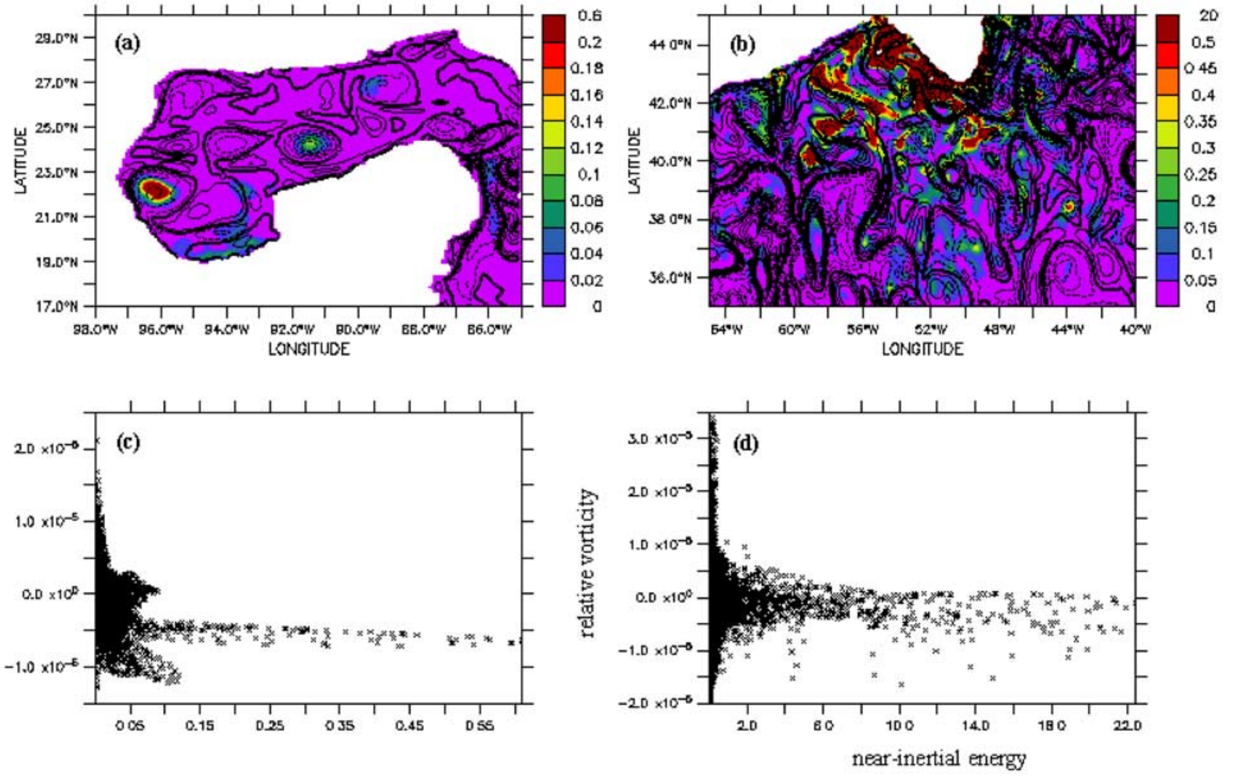

Figure 3. The relative vorticity (contours) and near-inertial energy (colour shading) (a) in the Gulf of Mexico and (b) in the western boundary current region. (c, d) Corresponding scatter plots. Unit for the near-inertial energy, 10^{-3} m^2 s^{-2}; unit for the relative vorticity, s^{-1}.

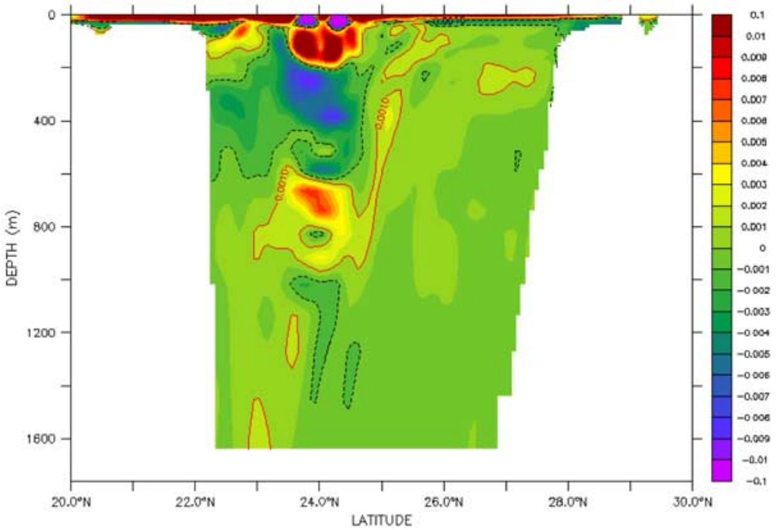

Figure 4. Instantaneous eastward velocity component of the near-inertial filtered velocity along 92°W in the Gulf of Mexico on March 16th. Unit, m s^{-1}. The trapping of near-inertial energy inside a warm core ring is evident.

the significant inertial energy confined within two warm core rings (see also Figure 4). The situation is more complicated in the neighbourhood of the Gulf Stream, where advection [*Zhai et al.*, 2004] and doppler shift effects [e.g., *Zhai et al.*, 2005b] are likely to be important, but there is still a clear association between high levels of near-inertial energy and regions of negative relative vorticity.

[8] Finally, we see no evidence in the model of the equatorward spreading of near-inertial energy from its generation over the Gulf Stream region, in association with the passage of atmospheric storms, to the interior of the subtropical gyre further south. Both the horizontal plan views and the vertical transects (Figure 2) indicate very low levels of near-inertial energy south of 35°N and below the surface layer of 100m depth, much lower, for example, than found by *Nagasawa et al.* [2000] in their study without eddies using a 1/6° model of the North Pacific. Rather the picture that emerges is of near-inertial energy input at the surface in the western boundary current region that propagates locally down to the deep ocean, with no significant leaking equatorward through β-dispersion. Therefore, the majority of the subtropical gyre, apart from the top 100 m, can be described as a "desert" for the near-inertial energy. It should be noted that the model run starts from January 1 with synoptic wind forcing, so near-inertial waves should have adequate time to ventilate the subtropical gyre by the time in March of our plots if β-dispersion is at work [*Anderson and Gill*, 1979; *Nagasawa et al.*, 2000].

4. Discussion and Summary

[9] Near-inertial energy is traditionally thought to be redistributed in the ocean largely by β-dispersion, whereby the near-inertial energy propagates both equatorward and downward [e.g., *Garrett*, 2001]. If this is the case, then near-inertial energy generated in the western boundary current region could fuel the deep subtropical ocean, where there is only a limited energy source at the surface. However, the ocean is turbulent and inhomogeneous in its nature, and the propagation of near-inertial waves can be strongly influenced by the mesoscale flow field. For example, enhanced near-inertial energy levels have been observed on the negative vorticity sides of fronts [e.g., *Kunze and Sanford*, 1984; *Mied et al.*, 1986] and in warm eddies [e.g., *Kunze and Sanford*, 1986]. Given the remarkable coincidence of the atmospheric storm tracks (the source regions for near-inertial energy in the ocean) and the oceanic storm track, mesoscale eddies need to be taken into account when studying the distribution of near-inertial energy in the ocean. Using an idealized model, *Zhai et al.* [2005a] showed the important role played by anticyclonic eddies for draining near-inertial energy from the surface to the deep ocean through the "inertial chimney" effect [e.g., *Kunze*, 1985; *Lee and Niiler*, 1998]. However, there have been no previous studies with high-resolution realistic simulations. In this letter, we examine the spreading of near-inertial energy in an eddy-resolving (1/12°) model of the North Atlantic Ocean driven by synoptic wind forcing. The picture that emerges from this study is as follows:

[10] (1) The horizontal scale of variations in near-inertial energy in the model, both at the surface and subsurface, is strongly influenced by the mesoscale eddy field and, as a result, is much smaller than that of the applied wind forcing.

[11] (2) Most of the near-inertial energy input at the surface is drained locally to the deep ocean by the mesoscale eddy field, and in particular, by the chimney effect associated with anticyclonic eddies.

[12] (3) The interior of the subtropical gyre is a "desert" for near-inertial energy, contrary to expectations from β-dispersion theory [*Garrett*, 2001; *Nagasawa et al.*, 2000].

[13] Enhanced near-inertial energy in warm eddies has been observed to generate turbulence and mixing through shear instability at the critical depth where the vertical group velocity goes to zero [e.g., *Lueck and Osborn*, 1986; *Kunze et al.*, 1995]. Therefore, strong diapycnal mixing associated with near-inertial wave breaking is expected to occur in the Gulf Stream system and other regions of the world ocean with high levels of eddy kinetic energy (e.g. the Southern Ocean). Furthermore, since a given energy level at higher latitude causes much more mixing than at lower latitudes

[*Gregg et al.*, 2003; *Garrett*, 2003], mesoscale eddies could be efficient in generating mixing at depth, since they can drain the near-inertial energy to depth locally, rather than transferring it to lower latitudes as in β-dispersion.

[14] More detailed calculations are necessary to provide accurate estimates of the near-inertial energy input to the ocean in the presence of a mesoscale eddy field, updating *Alford* [2003b], and also to study the fate of near-inertial energy within eddies and the associated mixing, building on the observation work of *Lueck and Osborn* [1986] and *Kunze et al.* [1995]. Longer integrations, including the seasonal cycle, and using wind stress forcing with higher temporal and spatial resolution are clearly required, as well as further relatively short model integrations using even higher model resolution than we have used here. Nevertheless, our results clearly suggest that energy input from the wind to the near-inertial frequency band may well be dissipated, and lead to mixing, locally within mesoscale eddies in the ocean rather than being spread equatorward by β-dispersion. If this result holds up to closer scrutiny, then the diapycnal diffusivity that is specified in the ocean component of climate models will need to be adjusted accordingly, with relatively large values in regions of relatively large eddy kinetic energy in the ocean, complementing recent work by *Hibiya et al.* [2006] on the spatial distribution of the diapycnal diffusivity resulting from tidal forcing.

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