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Wind work in a model of the northwest Atlantic Ocean

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[1] The work done by the wind over the northwest Atlantic Ocean is examined using a realistic high-resolution ocean model driven by synoptic wind forcing. Two model runs are conducted with the difference only in the way the wind stress is calculated. Our results show that the effect of including ocean surface currents in the wind stress formulation is to reduce the total wind work integrated over the model domain by about 17%. The reduction is caused by a sink term in the wind work calculation associated with the presence of ocean currents. In addition, the modelled eddy kinetic energy decreases by about 10%, in response to direct mechanical damping by the surface stress. A simple scaling argument shows that the latter can be expected to be more important than bottom friction in the energy budget. **Citation:** Zhai, X., and R. J. Greatbatch (2007), Wind work in a model of the northwest Atlantic Ocean, *Geophys. Res. Lett.*, *34*, L04606, doi:10.1029/2006GL028907.

1. Introduction

[2] Following *Duhaut and Straub* [2006], the formula for computing surface wind stress exerted by the atmosphere on the ocean can be expressed as:

$$\tau_1 = \rho_a c_d |\mathbf{U}_a - \mathbf{U}_o|(\mathbf{U}_a - \mathbf{U}_o) \qquad (1)$$

where τ is the wind stress, ρ_a the density of air at sea level, c_d the drag coefficient as a function of wind speed and air-sea temperature difference (in this paper, we use *Large and Pond* [1981]), $\mathbf{U}_a$ the 10-m wind speed, and $\mathbf{U}_o$ the surface ocean velocity. Equation (1) states that the wind stress depends on the relative motion between the 10-m wind and the ocean surface current. However, since over most of the ocean the speed of the ocean surface current is at least one order of magnitude smaller than that of the 10-m wind, the wind stress is often computed using the 10-m wind alone, i.e.,

$$\tau_0 = \rho_a c_d |\mathbf{U}_a|\mathbf{U}_a, \qquad (2)$$

neglecting the contribution from the surface ocean currents. The use of equation (2) rather than equation (1) has been questioned by a number of authors. For example, *Pacanowski* [1987] noted that in equatorial regions, surface currents approach 1 m s^{-1} while surface wind speeds are around 6 m s^{-1}, and including ocean surface currents in the wind stress calculation leads to a considerable improvement in simulations of the tropical Atlantic in comparison with observed data. *Luo et al.* [2005] found a similar improvement in simulating the cold tongue in the tropical Pacific in coupled models when using equation (1) rather than equation (2). Scatterometers, on the other hand, measure wind stress relative to the moving ocean surface, instead of relative to the earth, and ocean surface currents can be recovered from scatterometer measurements in energetic regions, e.g., the western boundary currents and the tropics [*Cornillon and Park*, 2001; *Kelly et al.*, 2001; *Chelton et al.*, 2004], lending credence to equation (1). For example, *Cornillon and Park* [2001] inferred the presence of a warm core ring from NSCAT data.

[3] The work done by the wind on the ocean can be computed as

$$P = \tau \cdot \mathbf{U}_o, \qquad (3)$$

and it is conventional to compute τ using equation (2) instead of equation (1). Using equation (3), one can calculate the wind energy input to the near-inertial motion [*Alford*, 2003] or the geostrophic circulation [*Wunsch*, 1998]. For example, *Wunsch* [1998] recently estimated the wind work on the oceanic general circulation to be about 1 TW (1 TW = 10^{12} Watts) using altimetry and wind stress depending on the 10-m wind alone. However, using simple scaling arguments plus a quasi-geostrophic (QG) model, *Duhaut and Straub* [2006] argued that accounting for the ocean surface current dependence in the wind stress could reduce the calculation of the mechanical energy input to the ocean by 20% – 35%. Indeed, *Dawe and Thompson* [2006] found a decrease of 27% in the wind energy input using a 1/5° horizontal resolution model of the North Pacific Ocean. Given the importance of the mechanical energy input from the wind for driving the meridional overturning circulation [*Munk and Wunsch*, 1998], it is clearly important that the effect of including the ocean surface current in the wind stress parameterisation be investigated further. In this study, we examine the work done by the wind over the northwest Atlantic Ocean using a realistic high-resolution ocean circulation model.

2. Ocean Model

2.1. Model Description

[4] The model is the same as the northwest Atlantic Ocean model described by *Greatbatch and Zhai* [2006]. The model domain spans the area between 30°W and 76°W and 35°N and 66°N with a horizontal resolution at each latitude of 1/5° in longitude. There are 31 unevenly spaced z levels. The model is initialized with January mean temperature and salinity fields and forced by monthly mean surface heat flux from *da Silva et al.* [1994] and 12-hourly NCEP 10-m wind starting at the beginning of January 1990 (see below). The sea surface salinity in the model is restored to

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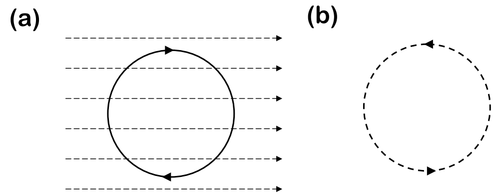

Figure 1. (a and b) Schematic illustrating the damping effect on a warm core ring. The dashed lines in Figure 1a represent the surface wind and the solid circle the surface current (northern hemisphere) associated with the eddy. Since the wind stress depends on the relative motion between the atmosphere and ocean, the stress exerted by the wind is smaller on the northern side of the warm eddy, where the current flows in the same direction as the wind, and larger on the southern side where it against the wind. This arises partly from the stress that is exerted on the overlying atmosphere by the ocean surface currents (the first term on the right hand side of equation (6) and illustrated schematically in Figure 1b for the case $\mathbf{U_a}$ = 0) and partly because the magnitude of the relative motion between the atmosphere and the ocean is larger on the southern side of the eddy than on the northern side (the second term on the right hand side of equation (6)). In Figure 1b, the dashed circle represents the drag exerted on the ocean when the atmosphere is at rest.

the monthly mean climatology on a time scale of 15 days. Along the model's open boundaries, temperature and salinity are restored to climatology and the transport is specified as described by *Sheng et al.* [2001].

2.2. Semi-Diagnostic Method (SDM)

[5] The model runs in this study use the SDM introduced by *Zhai et al.* [2004]. The SDM is a special case of the semi-prognostic method [*Greatbatch et al.*, 2004]. In the version used here, the density variable in the model's hydrostatic equation is computed on large spatial scales from the climatological data of *Geshelin et al.* [1999], whereas on the mesoscale, the corresponding density variable is the model density. In this way, the large scale flow in the model is strongly constrained, while the mesoscale is completely free, ensuring a rich eddy field. Readers are referred to *Zhai et al.* [2004] for details. Use of the SDM eliminates the common problems of Gulf Stream overshooting and the disappearance of the northwest corner in models [*Willebrand et al.*, 2001].

2.3. Experiment Design

[6] Two model runs are conducted with the difference only in the way of computing the surface wind stress. The control run (CONTROL) is forced by the wind stress calculated from NCEP 10-m wind using equation (2), as is the common practice in ocean circulation models. Correspondingly, the wind work in CONTROL is

$$P_0 = \tau_0 \cdot \mathbf{U}_o = \rho_a c_d |\mathbf{U}_a| \mathbf{U}_a \cdot \mathbf{U}_o. \tag{4}$$

An additional model run (DS) is conducted for comparison, where the wind stress is calculated from NCEP 10-m wind using equation (1). In DS, the wind stress depends on the relative motion between the atmosphere and the ocean. The wind work is then computed using

$$\begin{aligned} P_1 &= \tau_1 \cdot \mathbf{U}_o \\ &= \rho_a c_d |\mathbf{U}_a - \mathbf{U}_o| (\mathbf{U}_a - \mathbf{U}_o) \cdot \mathbf{U}_o \\ &= \rho_a c_d |\mathbf{U}_a - \mathbf{U}_o| \mathbf{U}_a \cdot \mathbf{U}_o - \rho_a c_d |\mathbf{U}_a - \mathbf{U}_o| \mathbf{U}_o \cdot \mathbf{U}_o. \end{aligned} \tag{5}$$

Assuming for now that the ocean surface velocity, $\mathbf{U}_o$, is same in both simulations, the difference $(P_0 - P_1)$ between the wind work in the two models can be expressed as

$$\begin{aligned} P_0 - P_1 = &\rho_a c_d |\mathbf{U}_a - \mathbf{U}_o| \mathbf{U}_o \cdot \mathbf{U}_o \\ &- \rho_a c_d (|\mathbf{U}_a - \mathbf{U}_o| - |\mathbf{U}_a|) \mathbf{U}_a \cdot \mathbf{U}_o. \end{aligned} \tag{6}$$

The first term on the right hand side of equation (6) is sign definite and is a sink term associated with the presence of surface ocean currents in P_1 and is believed to dominate the wind work difference. It should be noted that the sink term exists even when the wind velocity is zero and is associated with the stress that the ocean surface currents exert on the overlying atmosphere. The second term, on the other hand, operates only when the wind velocity is non-zero and arises from the dependence of the wind stress on the magnitude of the relative velocity, $\mathbf{U}_a - \mathbf{U}_o$. Both these effects are illustrated in Figure 1 for the case of a uniform wind blowing over a warm ocean eddy. The second term is also sign definite and is a sink term. This is because $|\mathbf{U}_a| < |\mathbf{U}_o - \mathbf{U}_a|$ for $\mathbf{U}_a \cdot \mathbf{U}_o < 0$, and vice versa. However, the instantaneous $\mathbf{U}_o$ in the two model runs turns out (not surprisingly) to be different and the wind work difference between CONTROL and DS associated with the second term on the right hand side of equation (6) has locally both positive and negative values (shown later) when computed using the ocean surface velocity, $\mathbf{U}_o$, taken from DS.

3. Results

[7] Figure 2a shows the work done by the wind in the second year of CONTROL. The wind acts primarily as a mechanical source in the model domain, especially along the Gulf Stream and near the northwest corner. The most noticeable regions where the wind blows, on average, against the ocean surface currents are the slope region to the south of the Canadian shelf, where the shelf break current flows southwestward, and to the south of Greenland, where the West Greenland Current moves northwestward along the shelf. The magnitude and pattern of the wind work in CONTROL compares reasonably well with the estimate for the same region made by *Wunsch* [1998, Figure 2a], except that we resolve more detailed structure (e.g. the shelf break current) because of the higher horizontal resolution used here, and our estimate also includes a contribution from the near-inertial frequency band [*Alford*, 2003]. Integrating over the whole model domain, the total wind power input in CONTROL is slightly more than 2×10^{10} W. We note that there is no accounting for the ocean surface current dependence of the wind stress in the estimates of *Wunsch* [1998] and *Alford* [2003].

[8] Figure 2b shows the work done by the wind in DS, and takes account of the ocean surface velocity dependence

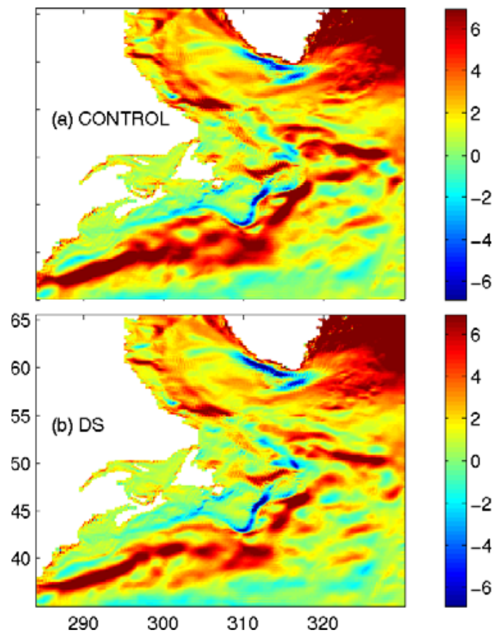

Figure 2. The work done by the wind in the second year in (a) CONTROL and (b) DS. Unit, 10^{-3} W m^{-2}.

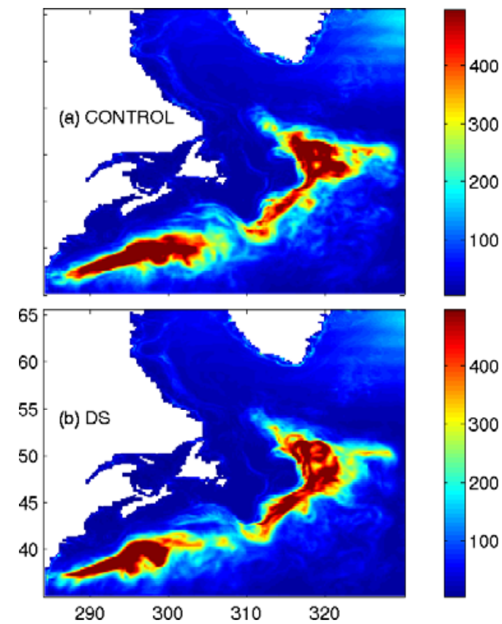

Figure 4. The eddy kinetic energy at the surface in the second year in (a) CONTROL and (b) DS. Unit, cm^2 s^{-2}.

in the wind stress. Comparison with Figure 2a (see Figure 3a) shows that the wind work is reduced in most parts of the model domain, especially over the Gulf Stream system. The total wind power input integrates over the whole model domain to 1.7×10^{10} W, a reduction of about 17% compared to CONTROL, with locally a reduction of more than 20% over the Gulf Stream system. The reduction in the total wind power input is broadly consistent with the estimate of *Duhaut and Straub* [2006], but rather less than that of *Dawe and Thompson* [2006], perhaps because their calculation extends to lower latitudes. The first term on the right hand side of equation (6) is diagnosed using the ocean surface velocity from DS and is shown in Figure 3b. It is positive everywhere in the model domain, as we expect, with large values in the energetic regions (e.g., the Gulf Stream, the North Atlantic Current, the West Greenland Current and the Labrador Sea Current). The reduction of the wind power input associated with this term integrates to 4.4×10^9 W, about 22% of the total wind power in CONTROL. This is a larger reduction than the total wind power difference between DS and CONTROL of 3.4×10^9 W, indicating that the second term in equation (6) makes a negative contribution to the wind power difference between the two model runs when computed using the ocean surface velocity from DS. This is because the ocean surface velocity $\mathbf{U}_o$ is different in the two model runs.

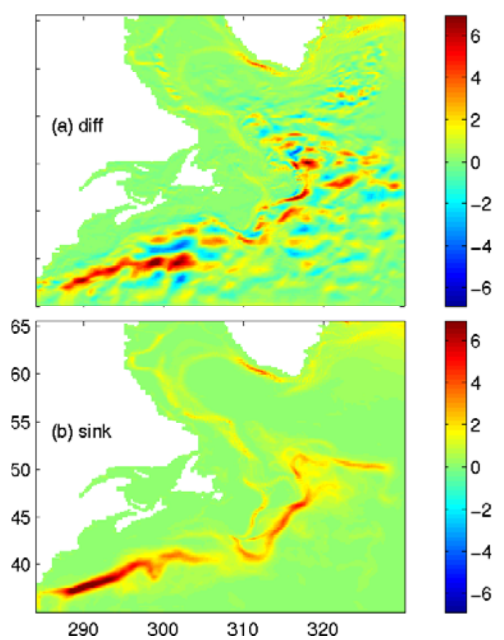

Figure 3. (a) The wind work difference, CONTROL minus DS. (b) The wind work associated with the sink term. Unit, 10^{-3} W m^{-2}.

[9] If the surface stress systematically damps the mesoscale eddies as illustrated in Figure 1, we should observe a noticeable decrease of eddy kinetic energy (EKE) in DS compared to CONTROL due to mechanical damping by the wind stress. Figure 4 shows the surface EKE distribution in the two model runs. (Note that the magnitude of the EKE in the model is comparable to that computed from altimeter data by *Stammer and Wunsch* [1999]). The spatial patterns are similar, but the EKE level in DS is now lower than that in CONTROL. The EKE integrated over the domain is about 8.0×10^{10} m^4 s^{-2} in DS, in comparison with about 9.0×10^{10} m^4 s^{-2} in CONTROL, a decrease of over 10%. In particular, the EKE along the Gulf Stream and in the northwest corner (high EKE regions) has been most noticeably reduced.

4. Summary and Discussion

[10] The overturning circulation is thought to be driven by mechanical energy input from the wind and tides [see

Munk and Wunsch, 1998; *Wunsch*, 2002]. *Munk and Wunsch* [1998] estimated that about 2 terawatts (TW) of energy input is required, with half being of tidal origin and half due to the wind. (Note that this number can be reduced if the direct role of the Southern Ocean wind forcing is considered; see *Toggweiler and Samuels* [1998] and *Webb and Suginohara* [2001]). Recently, *Wunsch* [1998] estimated the wind work on the ocean general circulation to be about 1 TW. However, the estimate made by *Wunsch* [1998] does not consider the effect of including ocean surface currents in the wind stress. Here, we have described two model runs, in one of which we include ocean surface velocity dependence in the wind stress calculation, and in the other we do not. Our results show that accounting for the surface ocean velocity dependence has a noticeable impact. In particular, using a model of the northwest Atlantic Ocean, we find that the total wind work is reduced by about 17% when the ocean surface currents are accounted for in the wind stress, supporting the claim by *Duhaut and Straub* [2006]. The reduction of the wind work comes mostly from a sink term associated with the surface ocean velocity dependence of the wind stress. The sink term has large values in the energetic regions, where the damping of eddies by the surface stress is important. We also found a decrease of the EKE level by over 10% when integrated over the model domain, due to the damping mechanism illustrated in Figure 1. While our results are broadly consistent with previous studies [e.g., *Duhaut and Straub*, 2006; *Dawe and Thompson*, 2006], it should be noted that our model has only been run for 2 years, the second year being used for the analysis, and that model is not fully eddy-resolving. Clearly future work should involve using models of much higher resolution, longer multi-year simulations, and wind forcing with higher time and spatial resolution.

[11] It is of interest to compare the magnitude of the first term on the right hand side of equation (6), given by $\rho_a c_d |\mathbf{U}_a - \mathbf{U}_o| \mathbf{U}_o \cdot \mathbf{U}_o$ (the sink term), with the energy extracted by the bottom stress given by $\rho_o c_d |\mathbf{U}_b|\ |\mathbf{U}_b \cdot \mathbf{U}_b$, where ρ_o is a characteristic density for sea water and $\mathbf{U}_b$ is the bottom velocity. Taking $|\mathbf{U}_a - \mathbf{U}_o|$ to be 10 m s^{-1}, $\mathbf{U}_o$ to be 0.1 m s^{-1} and $\mathbf{U}_b$ to be 0.02 m s^{-1}, then the sink term is found to be one order of magnitude larger than the energy dissipation associated with bottom friction. This result stresses the importance of taking account of the ocean velocity dependence in the specification of surface stress if the energetics of the ocean circulation are to be properly represented in models.

[12] The Southern Ocean is one place that is expected to be important for the wind energy input [see *Wunsch*, 1998], since the Antarctic Circumpolar Current (ACC) moves in the same direction as the circumpolar wind. However, the Southern Ocean is also rich in eddies and, hence, we should expect to see a noticeable reduction in estimates of the wind power input over the Southern Ocean when the ocean surface velocity dependence of the wind stress is taken into account, a topic for future research.

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