Decadal variability of wind energy input to the world ocean

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Deep Sea Research II, in press

Aug. 17, 2005

Abstract

Wind stress energy input to the oceans is the most important source of mechanical energy in maintaining the oceanic general circulation. Previous studies indicate that wind energy input to the Ekman layer and surface waves varied greatly over the past 50 years. In this study wind energy input to surface current and surface geostrophic current was calculated as the scalar product of wind stress and surface current and surface geostrophic current. The surface geostrophic current was calculated in two ways: the surface geostrophic velocity diagnosed from the TOPEX/POSEIDON altimeter data over period (1993 to 2003) or calculated from the sea surface height of the numerical model. The surface velocity was obtained from a numerical model. Estimate of wind energy input based on altimetric data averaged over the period from 1993 to 2003 is 0.84TW (1TW= 10^{12} W), excluding the equatorial band (within $\pm 3°$ of the equator). Estimate of the wind energy input to the surface geostrophic current based on the numerical model is 0.87TW averaged from 1993 to 2003, and wind energy input to the surface current for the same period is 1.16TW. This input is primarily concentrated over the Southern Ocean and the equatorial region ($20°S$ - $20°N$). This energy varied greatly on interannual and decadal time scales, and it increased 12% over the past 25 years and the interannual variability mainly occurs in the latitude band of $40°S$ - $60°S$ and the equatorial region.

1. Introduction

A new paradigm of the oceanic general circulation is emerging. Although the ocean receives a huge amount of thermal energy, it cannot convert such thermal energy into mechanical energy very efficiently because the ocean is heated and cooled from the same geopotential level, the upper surface. The inability of thermal forcing in driving the oceanic circulation can be traced back to the classical theorem postulated by Sandström (1908, 1916), and it has been discussed in many recent studies, e.g., Huang (1999), Paparella and Young (2002). Recently, Wang and Huang (2005) have demonstrated the basic idea through laboratory experiments.

Therefore, the oceanic circulation requires external sources of mechanical energy to balance the loss of mechanical energy due to friction and dissipation. As a result, for a quasi-steady circulation the distribution of mechanical energy sources and sinks dedicates the strength of circulation and its variability.

Historically, the old wisdom was that thermohaline circulation is driven by surface thermohaline forces. For a long time, nobody paid much attention at the connection between tidal dissipation and thermohaline circulation. It is only during the past ten years the oceanic community has waken up and realized the important role of tidal dissipation in driving diapycnal mixing in the deep ocean. The recent estimate of tidal dissipation in the open ocean is 0.7-0.9TW (Munk and Wunsch 1998). Due to the inspiration by Munk and his colleagues, tidal dissipation has become one of the hottest research frontiers in recent years, with large-scale field observation program being carried out and many excellent papers reporting observational, theoretical and numerical results published. However, tidal dissipation may not be the most important problem for oceanic general circulation and climate due to the following reasons:

First, wind stress energy input into the open ocean is at least 50 times larger than that due to tidal dissipation (Huang, 2004). Wind stress energy input to the surface geostrophic current is estimated as 0.88TW (Wunsch, 1998). Wind stress energy input to the surface waves is estimated as 60TW (Wang and Huang, 2004a); wind stress energy input to the Ekman layer is estimated as 0.5-0.7 TW over the near-inertial frequency (Alford, 2003; Watanaba and Hibiya, 2002), and the energy input over the sub-inertial range is about 2.4TW (Wang and Huang, 2004b). A major part of wind energy input to surface waves and Ekman layer may be lost in the upper ocean; however, even if a small portion of this energy is transported into the subsurface ocean, it will play a major role in regulating the oceanic general circulation.

Second, in the open ocean tidal driven mixing is mostly bottom trapped. On the other hand, wind stress energy input plays a dominating role in setting up the density structure and circulation in the upper 500-1000 m in the open ocean. Thus, wind stress energy plays a much more important role than tidal mixing for many applications that are intimately related to the circulation in the top 1000 m, including climate variability, ecology, fishery, and environments.

Third, wind stress energy input varies greatly over broad time scales, from interannual, decadal, centennial to millennial. On the other hand, tidal dissipation does not vary much for time scales shorter than centennial. Noticeable changes in tidal dissipation take place over long geological time scales. For example, during the

Last Glacial Maximum, tidal dissipation rate was substantially higher than the present-day rate (Egbert et al., 2004). As Wang and Huang (2004 a, b) showed, wind stress energy input to surface waves and Ekman layer increased nearly 25% over the past 50 years. Thus, it is postulated that mixing in the upper ocean should also vary accordingly. As a result, the oceanic general circulation should vary in response.

Since wind stress energy input to surface waves and Ekman layer varied so much over the past 50 years, similar changes in wind energy input to the surface geostrophic current are expected. The variability of the latter turns out to be more important for the study of climate variability. Although deep mixing driven by tidal dissipation in the open ocean is a vital component in maintaining the meridional overturning circulation in the ocean, wind stress energy input into the surface geostrophic currents in the Southern Ocean is another very important contributor. Toggweiler and Samuels (1995, 1998) have demonstrated that wind stress plays a dominating role in setting up the meridional overturning circulation observed in the world oceans. Even if the vertical mixing coefficient was set to zero, there was still a meridional overturning circulation rather similar to the observed circulation in the world oceans. (Note that due to the artificial diapycnal mixing in a z-coordinates model, their numerical experiment should be interpreted with caution; nevertheless, their results indicate an important factor that wind stress is the dominating controller in setting up the meridional overturning circulation under the modern climate.)

Thus, the main goal of this study is to estimate the interannual variability of wind energy input to surface geostrophic current over the world oceans. Early attempt to estimate wind energy input based on ship drift data was made by Oort et al. (1994). However, their estimate turns out to be inaccurate due to the limitation of ship drift data. More accurate estimate of surface geostrophic current can be obtained from satellite data. Paralleling the study by Wunsch (1998), wind energy input to the surface geostrophic current is calculated as the scalar product of wind stress and surface velocity.

$$w = \left\langle \vec{\tau} \cdot \vec{u}_g \right\rangle, \tag{1}$$

where $\vec{\tau}$ is wind stress, $\vec{u}_g = \left(u_g, v_g\right)$ is the surface geostrophic velocity and the bracket denotes a time average. The wind generates a multiple of small-scale oceanic motions: ripples, gravity waves, Longmuir cells, turbulent mixing motions, Ekman-like flow, etc. (Lueck and Reid 1984). Use of Eq (1) assumes that all such small-scale motions are dissipated within the surface mixed layer and do not directly produce any motions included in the general circulation (Wunsch, 1998).

Wind stress energy input to surface geostrophic current is closely related to gravitational potential energy in the ocean, and this energy supports the Ekman upwelling of cold and dense water in the subpolar oceans and strong upwelling in the Antarctic Circumpolar Current (ACC) and coastal upwelling zones (Gill et al., 1974; Wang and Huang, 2004b).

Two kinds of wind stress data sets were used in this study. The wind stress dataset of the daily-mean NCEP-NCAR Reanalysis was taken from the website (http://iridl.ldeo.columbia.edu/SOURCES). This dataset covers the period from 1948 to 2003 and has a zonally uniform spacing of $1.875°$ and a meridionally nonuniform spacing that varies from $1.89°$ at the poles to $2.1°$ near the equator. The daily-mean ECMWF ERA-40 Reanalysis dataset was taken form the website (http://data.ecmwf.int/data/d/era40_daily). This dataset covers the period form 1958 to 2001 and has a spatial resolution of $2.5°$ both in zonal and meridional directions.

The surface geostrophic velocity can be calculated in two ways. First, it can be diagnosed from sea surface height obtained from satellite data, assuming geostrophy. Second, it can be obtained from the sea surface height of an oceanic general circulation model. This study is organized as follows. We begin with surface geostrophic velocity diagnosis based on satellite data in Section 2. This approach is limited due to the following reasons. First, inferring geostrophic velocity does not work for the equatorial regime. Second, satellite data covers the past ten years only and thus cannot be used to study the long-term variability of wind energy input. To overcome these problems, in Section 3 we will use a numerical model to simulate surface geostrophic velocity field and the surface velocity field for the past 50 years. This approach can provide wind energy input over the world oceans for the past 50 years. Finally, we conclude in Section 4.

2. Estimation of energy input based on altimetric data

In this study we use the TOPEX/POSEIDON altimeter data at the crossover point of the orbits provided by AVISO. It has an 11-year long time series with a basic sampling rate of 10 days. This dataset is from Jan 1, 1993 to Dec 10, 2003 (cycle 11-414), which covers $66°S-66°N$ with a sample matrix of 127×116. The zonal resolution is $2.8°$ and the meridional resolution is $0.02°$ at the northern and southern boundary, and it is $3°$ near the equator. In this study the altimetric data was used in forms of 10-day average field, *H*, and the geoid undulation at each crossover point, $\eta(x,y)$, was computed from EGM96 solution (Lemoine et al., 1997). The dynamic topography field, $\phi = H - \eta$, was interpolated onto a regular grid with a uniform horizontal resolution of $1° \times 1°$. Therefore, the 10-day mean geostrophic velocity, $\vec{u}_g$, can be estimated using the geostrophic relation

$$\vec{u}_g = \frac{\vec{g}}{f} \times \nabla\phi, \qquad (2)$$

where $\vec{g}$ is the gravitational acceleration and f is the Coriolis parameter.

The annual mean energy input rate can thus be calculated by

$$\bar{W} = \frac{1}{n}\sum_{i}^{n}\iint \vec{\tau}(x,y)\cdot\vec{u}_g(x,y)dxdy$$

where *n* is the number of cycles of the specific year. For the purpose of estimating the total work done by wind stress on geostrophic current, we did not separate the wind stress and the geostrophic current into mean and anomaly. Since surface height signals obtained from satellite altimetry are in forms of average over 10-day period, the wind stress data, $\vec{\tau}$, were also averaged over the same 10-day period and were interpolated onto the regular grid of $1° \times 1°$.

Using wind stress from the NCEP-NCAR Reanalysis dataset, the global-mean rate of mechanical energy input is $2.7 mW/m^2$, with the global sum of 0.84TW, averaged over the period of 1993-2003. Note that the trajectories of the satellite altimeter do not cover latitudes higher than $66°$. Furthermore, energy input for the equatorial band (within $\pm 3^{\circ}$ of the equator) is also omitted because geostrophic approximation is invalid near the equator. Thus, this value of 0.84 TW is an underestimate the total energy flux. The mean energy input averaged from 1993 to 1996 is 0.81TW, which is slightly smaller than the previous estimate value of 0.88TW averaged over the same period by Wunsch (1998).

The variability of the work done by wind on the geostrophic current is shown in Figure 1 and the mean distribution is shown in Figure 2. The mechanical energy input through geostrophic current varies greatly with time and the amplitude is about 20% of the mean value over the past decade.

As discussed by Scott (1998, 1999) that the uncertainty in the sea surface height arises from several sources, but the dominant uncertainty in the ocean dynamic topographic is mainly associated with the geoid height field, which can cause large errors in the Northern Hemisphere. However, for the world ocean the error in estimating $\bar{W}$ is greatly reduced to 6.4% (Table 4.2, Scott, 1998). The relatively sparse crossover points of altimetric data at low latitude is unable to distinguish the various narrow and counter flow and the inability to estimate the geostrophic current at the equatorial band will also cause errors in the estimation of the $\bar{W}$. In studying the decadal variability of the wind work input to geostrophic current, 11-year long dataset is obviously insufficient. To overcome these difficulties, we can use velocity field obtained from a numerical model.

3. Estimation of energy input based on a numerical model

Wind stress applied to the sea surface drives both surface currents and waves. Ignoring the high-frequency component associated with wave motion, the surface velocity can be separated into two components:

$$\vec{u}_o = \vec{u}_{o,G} + \vec{u}_{o,AG} \tag{3}$$

i.e., the geostrophic current and the ageostrophic current (the surface Ekman transport). The velocity field in the upper ocean obtained from a numerical model is a combination of these two components and there is no easy way to separate them. According to the classical theory of Ekman layer, the vertically integrated volume flux associated with the ageostrophic flow is perpendicular to the surface wind stress. As a result, if the surface layer is thick enough, errors in wind energy contribution due to the ageostrophic current will be maximally reduced. The spatial averaged thickness of the first layer in our numerical model was about 30m, it varied with the buoyancy forcing from place to place. As a result, the contribution of the wind energy input to the ageostrophic current is not negligible. Another way of calculating the geostrophic current is to infer it from sea surface height obtained from the numerical model. However, geostrophy does not apply to the equatorial band, so this approach does not apply to this area.

The NCEP-NCAR (or ECMWF ERA-40) daily wind stress dataset interpolated onto regular grid of $1°\times1°$ was used as surface stress forcing in the numerical model. The surface velocity field and the surface height field were obtained, using the Hallberg Isopycnal Model (HIM; Hallberg, 1997). In the model, the temporal resolution is 20 minute, the horizontal resolution is $1^\circ \times 1^\circ$. The model has 19 layers in the vertical direction, including a Kraus-Turner (1967) bulk mixed layer and a layer underneath that plays the role as a buffer layer between the mixed layer and the layers below. The model domain covers the global ocean from $72^\circ S$ to $72^\circ N$. The Levitus annual mean temperature and salinity fields were interpolated onto the model grid as initializing fields and the restoring fields in the uppermost level.

The model was firstly run with NCEP-NCAR monthly-mean wind stress of 1948 for 100 years to reach a quasi equilibrium. Afterward, the model was restarted from this quasi equilibrium state and run with the NCEP-NCAR daily-mean wind stress of 1948 for 50 years to achieve at a second quasi-steady state. Finally, the model was restarted from this second quasi-equilibrium and run under the NCEP-NCAR daily-mean wind stress from 1948 to 2003. Daily-mean surface velocity from this final run was used to calculated wind energy input. For the numerical experiment with ECMWF ERA-40 wind stress followed the same procedure, except a slightly different starting (ending) time at 1958 (2001). Unless specified, all results in the following studies are attributing to the case with NCEP-NCAR wind stress.

The annual wind energy input to the oceanic general circulation is defined as the average of the energy input based on the daily-mean value, i.e.,

$$W = \frac{1}{N}\sum_{i}^{N} W_i \tag{4}$$

where N is the number of days of a specific year and W_i is the wind energy input for the i th day in this year.

The horizontal distribution of wind energy input to the surface current, $\vec{u}_0$, averaged over the past 56 years is shown in Figure 3. Note that the wind energy input is primarily due to work by the zonal wind in the Southern Ocean, the equatorial region (from $20°S$ to $20°N$) and the Kuroshio and Gulf Stream regions. From the meridional distribution of the zonal integrated results (left panel, Figure 3) it is readily seen that most of the energy input is accumulated in the ACC region and the equatorial region. The contribution due to the meridional wind stress component is much smaller than the zonal one, with exceptions along the western/eastern boundaries of the basins where wind energy input is strong due to comparatively strong along-shore wind. Note that, although the latitudinal band used in our numerical model is larger than that used in the calculation based on altimeter data, it does not cover the global and leaves out a small part of the Southern Ocean and the Arctic. Thus, the value calculated from our model may also slightly underestimate the total wind energy input.

The annual mean rate of wind energy input to the surface current, $\vec{u}_0$, varied greatly over the past 56 years, and the results that correspond to the wind stress dataset of ECMWF ERA-40 for time period of 1958 to 2001 showed a very similar pattern (Figure 4). For better comparison, the data shown in Figure 4 were normalized by their individual mean. The mean energy input rate due to wind stress of NECP-NCAR is 1.10TW and 1.14TW averaged over the period of 1958 to 2001 and 1993 to 1996 respectively. The mean energy input due to wind stress of ECMWF ERA-40 is 1.20TW and 1.21TW averaged over the same period mentioned above. For time period of 1993 to 1996, these two results were comparable with the estimated value of 1.0TW by Wunsch (1998). It is clearly seen that the results from NCEP/NCAR wind stress and ECMWF ERA-40 wind stress are quite close to each other, with less than 10% in the mean value and almost the same time-evolution profile over the past 40 years.

Figure 5 shows the comparison of the numerical model results and that diagnosed from satellite data. Also shown in Figure 5 is the comparison of wind energy input to the surface current, $\vec{u}_0$ and wind energy input to the surface geostrophic current, $\vec{u}_{0,G}$. For time period of 1993 to 2003 when altimetric data are available, mean wind energy input rate diagnosed from the altimetric data is 0.84TW for the area between $66°S$ to $66°N$ and excluding the equatorial band. Mean wind energy input rate diagnosed from sea surface height of the numerical model for the same area and time period is 0.83TW, which is identical to the result of that diagnosed from the altimetric data. Furthermore, interannual variability diagnosed from these two approaches is quite similar. For the area between $72°S$ to $72°N$ and excluding the equator band, wind energy input rate diagnosed from sea surface height of the numerical model averaged over the same time period is 0.87TW, increased about 5% due to the contribution of the additional $12°$ area at high latitudes, where there is no ice coverage in the numerical model, in contrast to the altimeter data. The mean wind energy input to the surface current, $\vec{u}_0$, in the area between $72°S$ to $72°N$ for the same time period is 1.16TW, which implies that the contribution of ageostrophic current, $\vec{u}_{0,AG}$, of the numerical model to the wind energy input is about 0.3TW.

For time period of 1948 to 2003, the interannual variability of the wind energy input to the surface current and to the geostrophic current is also quite consistent with each other (Figure 5). Therefore, the discussions below will be focused on the wind energy input to surface current.

It was suggested by Kistler et al. (2001) that the climatology based on the years 1979-present is most reliable due to the introduction of satellite data in 1979. Also shown in Figure 4 is that the interannual variability of the wind energy input to surface current before 1979 changes greatly and does not show an obvious trend. However, the amplitude of the interannual variability after 1979 is largely reduced and shows an obvious trend as illustrated by the black straight line in Figure 4, which has a slope of about 5×10^{-3} that corresponds to a 12% increase of wind energy input to surface current over the past 25 years. The horizontal distribution of the variability can be clearly seen from the standard deviation of the wind energy input for time period from 1979 to 2003 (Figure 6). The variability is mainly distributed in the Southern Ocean and in the equatorial region. Although both the equatorial region and the Southern Ocean are regions of strong wind energy input and strong interannual variability of wind energy input, the trend of energy input for these two regions are quite different (Figure 7). In fact, most of the large interannual variability in the total amount of energy input shown in Figure 4 during time period from 1948 to 1978 can be attributed to the variations in the equatorial region. In contrast, the wind energy input to the equatorial region only slightly increased from 1979 to 2003 with a slope of about 1/3 of that in the ACC region for the same period and the amplitude of the interannual variability greatly reduced. The different slopes of the energy input to the

ACC region and to the equatorial region for time period from 1979 to 2003 result in a continuous change in the partition of wind energy input to the world oceans. Thus, at present time the ACC region becomes a more and more dominant site for wind energy input to the surface current in the world oceans although the annual mean zonal velocity of the ACC remains nearly constant, with a variability of less than 3% (Figure 8). Since wind energy input may directly related to the baroclinic instability activity in the ocean, the global distribution of baroclinic eddy activity must vary greatly over the past 25 years.

It is quite interesting to compare the trend of wind energy input to surface currents with wind energy input to surface waves (Wang and Huang, 2004a) and to Ekman layer (Wang and Huang, 2004b). Since the mean values of these energy inputs differ greatly, these three datasets were normalized by the individual mean over the period from 1948 to 2003 (Figure 8). It is readily seen that the trends of all three wind energy inputs are rather similar, especially for time period from 1979 to 2003, i.e., there is a similar trend of an increasing energy input from wind stress over the past 25 years, which is closely related to the general trend of wind stress changes over the the same period. A typical scenario of global warming is a reduced equator-to-pole temperature gradient. As a result, wind stress might be reduced. However, wind stress dataset from NCEP-NCAR indicates that over the past 50 years changes in wind stress is characterized by a noticeable intensification of the southern westerly over the ACC region and a weakening of the easterly over the equatorial region (Figure 9). Wind stress variability in the Southern Ocean may be closely related to the Antarctic

Oscillation and the global environmental change, especially the intensification of the ozone hole in the South Pole. Ozone depletion can induce cooling in the lower stratosphere, making the Antarctic vortex tighter and more intense (Mahlman et al., 1994). The detailed mechanism of the wind stress change over the global oceans remains to be explored. For oceanic circulation study, however, the most challenge is what is the dynamical impact of such remarkable changes in the amplitude and distribution of wind stress energy input to the world oceans.

4. Conclusions

Wind energy input to surface geostrophic current in the world oceans was calculated through two approaches. The first approach was based on the TOPEX/ POSEIDON altimeter data on crossover points of the orbits and 10-day mean wind stress from the NCEP-NCAR reanalysis dataset; for the past 11 years (1993-2003) the rate of work input through geostrophic flow was estimated as 0.84TW. The second approach was based on the surface geostrophic current calculated form the sea surface height and surface velocity field obtained from a numerical model (HIM) and daily-mean wind stress from NCEP-NCAR; the rate of wind energy input to surface geostrophic current was estimated as 0.87TW, and wind energy input to the surface currents was estimated as 1.16TW, averaged over the period from 1993 to 2003.

Mechanical energy input from wind stress to surface geostrophic flow is one of the important sources for the maintenance of a quasi-steady circulation in the world ocean. Although this contribution is much smaller than that through surface waves and Ekman layer, it is directly converted into the kinetic energy and gravitational potential energy of the mean state (Fofonoff, 1981; Wang and Huang, 2004b).

Although diapycnal mixing in the deep ocean plays a vital role in setting up the stratification in the world ocean, wind stress energy input to the ACC is a more important controller of the meridional overturning circulation in the world oceans under current climate condition. Therefore, great changes in this energy source, including its magnitude and spatial distribution, should affect the global circulation in many ways. For an example, energy input to the ACC increases 15% over the past 25 years, such a great enhancement of energy source should induce remarkable changes, including the intensification of barotropic and baroclinic eddy activity, a stronger northward Ekman mass transport that may further enhance the meridional overturning circulation in the world ocean, in particular that in the Atlantic sector. In summary, changes in wind energy input may induce great changes in the wind-driven and thermohaline circulation in the world oceans, which should be carefully examined in further study.

Acknowledgment: CLS AVISO Operations Center generously supplied us with the TOPEX/POSEIDON altimeter data. RXH was supported by the National Oceanic and Atmospheric Administration through CICOR Cooperative Agreement NA17RJ1223 and the National Aero-Space Administration through Contract No. 1229833 (NRA-00-OES-05). WW and LLL were supported by the National Nature Science Foundation of China through grant 40476010 and Research Fund for the Doctoral Program of Higher Education through grant 20030423011. Reviwers’ comments helped to clean up the presentation.

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