Rate of Work Done by Atmospheric Pressure on the Ocean General Circulation and Tides

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ABSTRACT

Quantitative analysis of the energetics of the ocean is crucial for understanding its circulation and mixing. The power input by fluctuations in atmospheric pressure $p_a$ resulting from the $S_1$ and $S_2$ air tides and the stochastic continuum is analyzed here, with a focus on globally integrated, time-mean values. Results are based on available $1^\circ \times 1^\circ$ near-global $p_a$ and sea level fields and are intended as mainly order-of-magnitude estimates. The rate of work done on the radiational and gravitational components of the $S_2$ ocean tide is estimated at 14 and $-60$ GW, respectively, mostly occurring at low latitudes. The net extraction of energy at a rate of $-46$ GW is about 10% of available estimates of the work rates by gravity on the $S_2$ tide. For the mainly radiational $S_1$ tide, the power input by $p_a$ is much weaker (0.25 GW). Based on daily mean quantities, the stochastic $p_a$ continuum contributes $3$ GW to the nontidal circulation, with substantial power input being associated with the $p_a$-driven dynamic response in the Southern Ocean at submonthly time scales. Missing contributions from nontidal variability at the shortest periods ($\leq 2$ days) may be substantial, but the rate of work done by $p_a$ on the general circulation is likely to remain $<1\%$ of the available wind input estimates. The importance of $p_a$ effects when considering local, time-variable energetics remains a possibility, however.

1. Introduction

Understanding what maintains the large-scale ocean circulation involves detailed knowledge of the energy sources and sinks and the pathways and mechanisms involved in the source-to-sink energy fluxes over the global ocean. Over the years, a detailed picture of the energy sources has emerged, with wind and gravitational tidal forcing supplying most of the mechanical energy to the ocean (Munk and Wunsch 1998). Quoting typical time-mean, globally integrated values, wind energy input into surface waves can be quite large at $-6 \times 10^{13}$ W, or 60 TW (Wang and Huang 2004a), and total input into the Ekman layer is $-3$ TW (Wang and Huang 2004b). Such input is, however, thought to be mostly dissipated by turbulent processes very near the surface, and thus its importance to the energetics of the large-scale circulation remains unclear (Wang and Huang 2004a). More relevant in this regard is the rate of work done by the winds on the large-scale geostrophic circulation, estimated at $-1$ TW by Wunsch (1998). The power input by the gravitational potential is $-3.5$ TW (Munk and Wunsch 1998), but only up to 1 TW is believed to be involved in large-scale mixing over the deep ocean (Egbert and Ray 2000), again with the rest being dissipated over shallow shelves.

As the dominant wind and gravity terms become better known, for a quantitative analysis of the energetics one needs to consider other contributions, such as the work done by atmospheric pressure $p_a$ on the general circulation. Our unpublished preliminary estimates of $-10$ GW, quoted in the review by Wunsch and Ferrari (2004), were based on short test runs of both barotropic and baroclinic models forced by realistic atmospheric fields including $p_a$, but excluding the effects of barometric air tides. More recently, Wang et al. (2006) used altimeter measurements from Ocean Topography Experiment (TOPEX)/Poseidon at crossover points and daily mean $p_a$ values from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis to arrive at a value of $-40$ GW, with most of the power input occurring at mid- and high latitudes.

As acknowledged by Wang et al. (2006), one difficulty in using altimeter data is the relatively sparse sampling...
in time. In addition, the work done by $p_a$ on the ocean tides, in particular the semidiurnal $S_2$ tide, which has a nonnegligible contribution forced by the corresponding barometric air tide (Cartwright and Ray 1994), has not been discussed in the literature (R. Ray 2007, personal communication). In this note, we revisit the calculation of the work rates associated with $p_a$, using the model results of Ponte and Vinogradov (2007) and the near-global ocean-state estimates produced as part of the Estimating the Circulation and Climate of the Ocean–Global Ocean Data Assimilation Experiment (ECCO–GODAE) project (Wunsch and Heimbach 2007).

2. Calculating $p_a$ work rates

Atmospheric pressure $p_a$ exerts a normal force on the ocean surface, with the power input or rate of work done per unit area $w$ being simply given by

$$ w = -p_a \dot{\zeta}, $$

where the velocity in the direction of the $p_a$ force is approximated by the time derivative of the sea surface height $\zeta$. (In our sign convention, decreases in $\zeta$ correspond to positive work done on the ocean.) All temporal variability in $\zeta$, including that forced by the gravitational potential, surface winds, and heat fluxes, as well as $p_a$, can contribute to $w$. For analysis of steady energy balances, one can average (1) in time to obtain

$$ \bar{w} = \overline{(p_a \dot{\zeta})}, $$

where the overbar denotes time-mean quantities and prime variables represent anomalies from the mean. The term $\overline{p_a \dot{\zeta}}$ tends to be small if trends in time are weak compared to the overall variability in $\zeta$. Temporal correlations between $p_a$ and $\zeta$ are important in determining the values of $\bar{w}$. In the case of periodic signals of the form $\cos(\omega t + \phi)$, such as those involved with tides, integrating (1) over a full cycle gives

$$ \bar{w} = \frac{1}{2} \omega p_a \sin(\phi_\zeta - \phi_{p_a}), $$

where $\zeta$ and $p_a$ now denote amplitudes, and $\phi_\zeta$ and $\phi_{p_a}$ are the respective phases. Maximum work rates occur for $p_a$ and $\zeta$ signals that are 90° out of phase. Given time series of $p_a$ and $\zeta$, one can use (1)–(3) to estimate the $p_a$ work rates on the ocean.

Power in $p_a$ series is characterized by red spectra with marked periodicity at 12 and 24 h, associated with the barometric expression of the $S_2$ and $S_1$ air tides (Ray and Ponte 2003; Ponte and Vinogradov 2007). The peaks at 12- and 24-h periods dominate variability at daily time scales and give rise, respectively, to the so-called radiational $S_2^r$ and $S_1^r$ tides in the ocean (Cartwright and Ray 1994; Ray and Egbert 2004). Ponte and Vinogradov (2007) have calculated the radiational tides associated with forcing by the mean climatological barometric tides $S_{1,2}$, with results very similar to other studies (Ray and Egbert 2004; Arbic 2005). The barometric tides used by Ponte and Vinogradov (2007) are the well-resolved interpolated solutions from Ray and Ponte (2003) derived from the 6-hourly operational analyses of the European Centre for Medium-Range Weather Forecasts. Their estimates of the amplitudes and phases of $p_a$, and the respective $\zeta$ solutions in Fig. 2 of Ponte and Vinogradov (2007), are used in (3) to calculate $\bar{w}$ for the periodic air tides.

Another tidal issue to consider is the presence of gravitationally forced ocean tides $S_{1,2}^g$ at the same exact periods of the radiational tides. For the case of $S_1$, the barometric tide is the primary driver, and thus the effects of gravity on $\zeta$ can be neglected (Ray and Egbert 2004). For $S_2$, however, forcing by the $S_2$ air tide is much weaker than that by gravity, and the gravitational ocean tide is not only considerably larger but also quite similar to and correlated with the radiational component (Cartwright and Ray 1994; Arbic 2005). Thus, the work done by the $S_2$ air pressure tide on $S_2^g$ is likely to be important and is also considered here. For an estimate of amplitudes and phases of $\zeta$ associated with $S_2^g$, we take the radiational tide calculated by Ponte and Vinogradov (2007), and, using the conversion factors derived by Arbic (2005), simply scale the amplitudes by 6.81 and subtract 109.4° from the phase values.

The power input by the $p_a$ variability continuum is calculated using $p_a$ fields from the NCEP–NCAR reanalysis and $\zeta$ fields from the optimized ECCO–GODAE solutions. The latter are produced in an iterative optimization procedure, described in Heimbach et al. (2006) and Wunsch and Heimbach (2007), that fits, in a least squares sense, a general circulation model to most available datasets, including all altimetric and hydrographic observations, within expected model and data uncertainties. The basic solution used here is from version 2, iteration 216 (v2.216), analyzed in detail by Wunsch et al. (2007) in the context of decadal sea level trends. The model configuration (grids, topography, and frictional parameters) is the same as in the air tide experiments of Ponte and Vinogradov (2007). To the nominal forcing by surface fluxes of momentum, heat, and freshwater, we have added $p_a$ for comparison with results that do not include $p_a$ driving. The solution with $p_a$ forcing will be denoted as v2.216+$p_a$. The analysis is focused on the 12-yr period from 1993 to 2004. In addition, because the 6-hourly NCEP–NCAR $p_a$ fields give only a crude representation of the air tides and other near-daily variability (e.g., Ray and Ponte 2003),

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the $p_a$ continuum analysis is based for the most part on daily mean $p_a$ and $\zeta$ fields. Effects from variability at periods $\leq 2$ days are thus not included in the main results, but are briefly discussed in the final section of the paper.

Full $\zeta$ variability includes a large inverted barometer component, but it is easily shown that this term yields $w \sim -(2gp)^{-1}(p_a^2)_{\zeta}$, which can be neglected in a time-mean sense. For our calculations, the relevant parameter is dynamic $\zeta$ (i.e., full $\zeta$ minus the inverted barometer signal). The standard deviation of the daily averaged dynamic $\zeta$ values (Fig. 1) ranges from a few centimeters over most of the deep ocean to more than 10 cm in some western boundary regions and more than 20 cm in shallow coastal areas. Note that our $\zeta$ estimates attempt to represent only the large-scale variability. Contributions by the eddy field to $\zeta$, which can be quite large near strong currents (western boundaries and the Southern Ocean), are not considered, but given the mismatch in oceanic eddy scales compared to those of synoptic atmospheric weather systems, their effects on $w$ are expected to be small.

An estimate of the effects of $p_a$ driving on dynamic $\zeta$, evaluated by differencing solutions with and without pressure forcing, also shown in Fig. 1, reveals patterns and amplitudes very similar to earlier calculations by Ponte (1993) and Ponte and Vinogradov (2007). Standard deviations range from $< 1$ cm over most of the ocean, 1–3 cm in several Southern Ocean regions, and considerably larger values in shallow or semienclosed areas. Most of this variability is at submonthly periods (e.g., Ponte and Vinogradov 2007). Although weak compared to the full $\zeta$ variability, the $p_a$-driven signals are expected to be well correlated with $p_a$ and thus important in the energetics.

3. Results

a. Work by mean air tides

Values of $\mathbf{w}$ corresponding to the rate of work done by the climatological air tides $S_1$ and $S_2$ on the respective radiational ocean tides are displayed in Fig. 2. Largest values of $\sim \pm 0.5$ mW tend to occur at low latitudes, where the air tides have their strongest signatures (Ray and Ponte 2003). The spatial patterns of $\mathbf{w}$ reproduce mostly those of the largest amplitudes of the radiational tides, with a string of maxima along equatorial latitudes for $S_2$ (Arbic 2005; Ponte and Vinogradov 2007) and maxima in the western Indian Ocean, the Indonesian seas, and the Gulf of Mexico for $S_1$ (Ray and Egbert 2004; Ponte and Vinogradov 2007). These patterns are themselves related to the particular resonances associated with the oceanic response to the air tides. Compared to $S_1$, $S_2$ is far more resonant and also more strongly forced, as the air tide amplitudes estimated by Ray and Ponte (2003) suggest. Thus, $\mathbf{w}$ values for $S_2$ are larger than those for $S_1$.

The rate of work done by the $S_2$ air tide on the much more vigorous gravitational ocean tide $S_2^g$ is also shown in Fig. 2. Results are not a simple linear scaling of $\mathbf{w}$ values for the radiational tide, because there is a phase shift ($\sim 110^\circ$) between $p_a$ and $\zeta$. This phase shift causes a dominance of negative values of $\mathbf{w}$ at low latitudes, in contrast with $S_2^g$ results. The much larger amplitudes

![Fig. 1. Standard deviation of dynamic sea level (i.e., deviations from an inverted barometer; cm) for the case of (left) full forcing and (right) $p_a$ forcing, calculated as described in the text. Note the different color bar range in the two panels.](image-url)
Globally integrated values of \( W \), hereafter denoted \( \bar{W} \), are given in Table 1. As inferred from the \( w \) values in Fig. 2, the rate of work done on the \( S_1 \) tide is negligible (\( \approx 0.25 \) GW) compared to that done on \( S_2 \) (14 GW). The largest values of \( \bar{W} \) are found for the case of \( S_2 \) at about \( 2.9 \times 10^2 \) GW. The combined power input for the \( S_2 \) ocean tide is \( 2.2 \times 10^4 \) GW, or about 10% of the estimated rate of work done by the gravitational potential (Cartwright and Ray 1991). The negative values are consistent with an \( S_2 \) air tide that acts to reduce the energy in the ocean tide, given its phase relation with the gravitational forcing.

Superposed on the climatological air tides, there is stochastic variability at both diurnal and semidiurnal periods, but the associated variance is about an order of magnitude smaller than that of the mean air tides (Ponte and Vinogradov 2007, cf. their Fig. 5). Thus, assuming an approximately linear oceanic response, such stochastic variability is expected to introduce small perturbations on the estimates of \( w \) and \( \bar{W} \) discussed here.

### b. Work by \( p_a \) continuum

As explained in section 2, here we use daily mean \( p_a \) and \( \zeta \) fields, excluding poorly resolved near-daily variability.

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>( \bar{W} )</th>
<th>( \bar{W}_{200} )</th>
<th>( \bar{W}_{SO} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_2 )</td>
<td>14</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>( S_2^f )</td>
<td>-60</td>
<td>-1</td>
<td>3</td>
</tr>
<tr>
<td>( S_1^f )</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( v_{2.216} + p_a )</td>
<td>2.8</td>
<td>1.1</td>
<td>0.4</td>
</tr>
<tr>
<td>( v_{2.216} )</td>
<td>-2.9</td>
<td>0.6</td>
<td>-3.0</td>
</tr>
<tr>
<td>( v_{2.0} )</td>
<td>-4.9</td>
<td>0.2</td>
<td>-4.8</td>
</tr>
</tbody>
</table>

FIG. 2. Rate of work done by mean \( S_2 \) air tide on the equivalent (top left) radiational tide and (top right) gravitational tide. (bottom) Rate of work done by mean \( S_1 \) air tide on the equivalent radiational tide. All values are given in \( 10^{-4} \) W. Note the different color bar ranges. The land mask in the model solutions used here is shown in white.
from the analysis. Values of \( \overline{w} \) were calculated from (1), where \( \zeta \) is approximated as a centered difference.\(^1\) Figure 3 shows values of \( \overline{w} \) based on the \( v_2.216 + p_a \) estimates of \( \zeta \), representing large-scale variability associated with full atmospheric forcing including \( p_a \). Regions of the largest (> 0) values tend to occur in shallow areas (e.g., Patagonian shelf, South Australian Bight, and Hudson Bay) where strongest \( \zeta \) variability is seen in Fig. 1. Over the deep ocean, the strongest positive work rates are found in a number of Southern Ocean regions, where the dynamic response to \( p_a \) is relatively enhanced (Fig. 1; Ponte and Vinogradov 2007). The importance of \( p_a \)-driven dynamic effects to the energetics can be seen by comparing these results to those obtained without including \( p_a \) in the forcing fields, also shown in Fig. 3. Although patterns are fairly similar in both cases, when \( p_a \) forcing is excluded there is a general decrease in positive values of \( \overline{w} \) clearly seen at mid- and high latitudes, particularly in the Southern Ocean.

Integrating \( \overline{w} \) in Fig. 3 over the global ocean yields \( \overline{W} \sim 2.8 \) and \( -2.9 \) GW for the cases with and without \( p_a \) forcing, respectively (Table 1). The impact of the dynamic response to \( p_a \), which is confined mostly to the shortest time scales (e.g., Ponte 1993; Ponte and Vinogradov 2007), is thus quite important and amounts to a difference of 5.7 GW. From the values in Table 1, about 60% of this difference comes from the Southern Ocean (latitudes poleward of 40°S), where the large-scale dynamic response to \( p_a \) is strongest (Fig. 1); contributions from tropical latitudes (±20°) are the same (∼0.6 GW) with or without full forcing, as expected from the weak \( p_a \) effects at low latitudes (Fig. 1). In addition, of the estimated total power input, contributions from shallow regions (depth < 200 m) are very substantial, amounting to ∼1.1 and 0.6 GW for the cases with and without \( p_a \) forcing, respectively. Combined with the results in Table 1, one infers that the dynamic response to \( p_a \) over the deep ocean contributes more than 5 GW to \( \overline{W} \), and that correlations of that response with wind and other forcing effects reduces total contributions to \( \overline{W} \) over the deep ocean to ∼1.8 GW.

Spatially integrated values of \( w \) yield the time series shown in Fig. 4. The detailed behavior of this time series is likely sensitive to many uncertain factors, like the land–ocean mask used in our calculations. Thus, these estimates are only shown to give an idea of the range of temporal variability in \( W \). Daily variability (∼40 GW) is quite large compared to the \( \overline{W} \) values in Table 1. Averaged monthly variability ranges over a few gigawatts about the mean. Means for each year are, however, fairly stable.

The impact of the ECCO–GODAE data fitting and optimization procedures in determining our nontidal

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\(^1\) We use

\[
p_a(t) \frac{\zeta(t + \delta t) - \zeta(t - \delta t)}{2\delta t},
\]

with \( \delta t = 1 \) day, but other formulations with potentially better resolution of the time derivative \( \zeta \), such as

\[
p_a(t) + p_a(t - \delta t) \zeta(t) - \zeta(t - \delta t) \frac{\delta t}{2},
\]

yielded essentially the same results.
estimates of $\overline{W}$ can be assessed by calculating $\overline{W}$ based on the first-guess, nonoptimized ECCO–GODAE solution, which is not constrained by observations (values under version 2, iteration 0 listed in Table 1). The difference of $\sim$2 GW between v2.216 and v2.0 results is considerable and comes mostly from changes in the variability of the Southern Ocean. These differences mainly reflect corrections in the wind stress fields and the consequent changes in the barotropic response of the Southern Ocean, which are effected by the optimization. In the absence of formal errors, the difference between v2.216 and v2.0 values can be taken also as a crude measure of uncertainty in $\overline{W}$ values provided here.

4. Summary and discussion

Local and global estimates of the rate of work done by $p_a$ on the ocean tides and general circulation have been derived from the radiational tides of Ponte and Vinogradov (2007) and the ECCO–GODAE state estimates (Wunsch and Heimbach 2007). From the globally integrated, time-mean results summarized in Table 1, the largest values of $\overline{W}$ are related to the $S_2$ tide, with work being done at a rate of $\sim$46 GW on the combined radiational + gravitational ocean tide, and primarily in the tropics. Power input associated with the mainly radiational $S_1$ tide is much weaker. Values of $\overline{W}$ for nontidal variability are only a few gigawatts, with a substantial contribution from shallow regions. The nontidal $p_a$-driven dynamic response is found to be very important, particularly in the Southern Ocean. From the known characteristics of such response (Ponte 1993; Ponte and Vinogradov 2007), one can conclude that most of the power input by $p_a$ is associated with submonthly variability at scales longer than a few hundred kilometers and with typical velocities $< 1$ cm s$^{-1}$.

When globally averaged, the mean power input by $p_a$ is $\sim$10% of the gravitational effects on the $S_2$ tide (Cartwright and Ray 1991) and less than 1% of the wind effects on the general circulation (Wunsch 1998). Because the work done by winds is dominated by contributions from the time-mean circulation in the Southern Ocean, $p_a$ effects can be relatively larger for local nontidal energetics away from the latitudes of the Antarctic Circumpolar Current (cf. Fig. 3 and Fig. 2 in Wunsch 1998). In addition, day-to-day fluctuations in Fig. 4 can be an order of magnitude larger than the value of $\overline{W}$. Thus, contributions from $p_a$ may be important when considering time variable nontidal energetics.

Our $\overline{W}$ estimates for nontidal $\zeta$ variability are approximately an order of magnitude lower than those by Wang et al. (2006), who estimated $\overline{W}\sim$40 GW from analyses of altimeter crossover data. The reasons for such discrepancy remain unclear. Comparing Fig. 3 to Wang et al.’s Fig. 1 reveals considerably different spatial patterns. In particular, $\overline{w}$ values in Wang et al. are always $> 0$ and seem to follow the patterns of variability in $p_a$ closely. We note that, in our calculations, if we use full $\zeta$ as in Wang et al., instead of dynamic $\zeta$, the results are very sensitive to the method of defining $\zeta$, because one can introduce small phase shifts between $p_a$ and $\zeta$. Thus, it is possible that in the presence of the large inverted barometer variability at rapid time scales, the results of Wang et al. may have been affected by any small time shifts between $p_a$ and $\zeta$ series. There is less sensitivity to the formulation of time derivatives, or any other issues affecting the phasing of $p_a$ and $\zeta$ series, if dynamic $\zeta$ is used. Given that, as discussed in section 2, the inverted barometer signals should not be important in determining $\overline{W}$, working in terms of dynamic $\zeta$ is preferable.

Although based on our current best estimates of $\zeta$ and $p_a$, the results in Table 1 should be taken as tentative. Estimates are not truly global, because much of the Arctic region is missing, and the resolution of coastal shallow areas is very coarse. Apart from these domain issues, if one is interested in the energetics of the deep ocean and the topic of oceanic mixing, one nontidal missing contribution to $\overline{W}$ is probably more relevant. Given the importance of $p_a$-driven dynamic signals, and their primary high-frequency nature (Ponte and Vinogradov 2007), the effects of motion at periods of 2 days and shorter are likely to be sizable. Although the shortest periods are poorly determined, tentative estimates based on 6-hourly $p_a$ and $\zeta$ fields for the

\footnote{In fact, using a backward (instead of centered) differencing scheme, which introduces a small half-day lag, leads to spatial patterns and values of $\overline{W}$ much closer to those in Wang et al. (2006).}
period of 2002–03 yielded values of $\mathbf{W}$ a factor of 2 higher than using daily fields. Thus, nontidal contributions to $\mathbf{W}$ from periods $\leq 2$ days are potentially of the same order as those from periods $> 2$ days.

In addition, we have not considered the work done by $p_a$ on the full ocean tides at diurnal and semidiurnal periods here. In addition to the largest $M_2$ tide, there are several other ocean tides at these periods with energy comparable to $S^g_2$, but the power in $p_a$ fields across these other tidal lines is much weaker than at 12- and 24-h periods. Poor spatial and temporal coherence between $p_a$ variability and ocean tides other than for $S^g_{1,2}$ is also expected, which should lead to comparatively weak contributions to $\mathbf{W}$. A thorough examination of this issue would require global $p_a$ fields of at least hourly resolution, as well as a global model of tidal heights, and should be tried in the future.

As a final point, we recall that changes in global-mean $\zeta$ are not explicitly treated in the current ECCO–GODAE solutions (Wunsch et al. 2007). Thus, those effects have not been included in our calculations. Although locally a 1 mm yr$^{-1}$ of sea level rise yields $\mathbf{W} \sim -3 \times 10^{-6}$ W, which is weak compared to values in Fig. 3, it amounts to more than 1 GW when integrated over the global oceans. Similarly, peak-to-peak annual changes of $\sim 1$ cm in the global-mean $\zeta$ associated with seasonal warming and cooling imply an annual cycle in $p_a$ work rates on the order of 10 GW. The $p_a$ power input associated with these global-mean $\zeta$ patterns does not involve, however, any ocean dynamics and is thus irrelevant as a source of mechanical energy for mixing.

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