Atmospheric forcing of the oceanic semidiurnal tide

Brian K. Arbic
Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, New Jersey, USA

Received 4 October 2004; revised 28 November 2004; accepted 27 December 2004; published 29 January 2005.

[1] The principal solar semidiurnal tide (S2) in the ocean is forced by the pressure loading of the atmospheric thermal tide as well as by the gravitational tidal potential. This paper examines the effects of adding the atmospheric S2 forcing to a forward tide model. When the model is forced only by the gravitational potential, the S2 relative elevation error with respect to pelagic tide gauges is anomalously large. After atmospheric S2 forcing is added, the relative error reduces to levels seen in other tidal constituents. In the global average, Fukumori general not periodic, hydrodynamical models [Munk and Cartwright, 1966] and by atmospheric pressure loading and winds [Ponte, 1994]. Global observations of sea level are provided by satellite altimeters such as TOPEX/POSEIDON and JASON-1. The 10-day orbit times of these satellites lead to aliasing of high-frequency oceanic motions [Stammer et al., 2000; Tierney et al., 2000]. Because tides and the altimeter orbits are both periodic, tides remain periodic in the aliased altimeter record [Parke et al., 1987]. Advantage is taken of this to extract tides from altimetric data. The high accuracy of open-ocean surface elevations in tide models derived from or constrained by altimetric data has been verified [Shum et al., 1997] by comparison to a set of 102 pelagic tide gauges. The elevation accuracy of forward tide models, that is, hydrodynamical tide models that run unconstrained by data, is not as high as that in altimeter-constrained models. However, recently forward models have been improved with the inclusion of parameterizations of internal wave drag of topographic origin [Jayne and St. Laurent, 2001; Carrère and Lyard, 2003; Egbert et al., 2004; Arbic et al., 2004 (hereinafter referred to as AGHS)]. The drag schemes are motivated by inferences from both altimetric [Egbert and Ray, 2003] and in-situ [Polzin et al., 1997] data of enhanced dissipation in regions where the seafloor is rough.

[5] Since high-frequency atmospheric fluctuations are in general not periodic, hydrodynamical models [Fukumori et al., 1998; Stammer et al., 2000; Tierney et al., 2000; Hirose et al., 2001; Carrère and Lyard, 2003; Stepanov and Hughes, 2004] must be used to remove atmospherically driven sea-level variability from altimeter data. High quality models are needed to remove both tides and atmospherically driven sea-level variability from GRACE, which measures bottom pressures from an orbit that is not periodic. The GRACE satellite mission thus provides motivation for models [Carrère and Lyard, 2003; Stepanov and Hughes, 2004] that are simultaneously forced by the atmosphere and by the gravitational tidal potential. In such models, one might also consider adding topographic drag, which Hirose et al. [2001] and Carrère and Lyard [2003] demonstrate improves the accuracy of simulated atmospherically driven sea-level variability.

[4] In the forward tide model of AGHS, driven only by the gravitational potential, the S2 relative elevation error with respect to the pelagic tide gauges is anomalously large compared to those of other constituents. The suggestion is that physics specific to the S2 frequency is missing from the model. The thermally forced atmospheric tides [Lindzen, 1990], also called “air tides”, provide regular forcing of the ocean at periods of half a solar day (S2) and of a solar day (S1), on top of the S2 and S1 forcings present in the gravitational potential. The pressure loading of the atmospheric S1 tide is the primary forcing of the small oceanic S1 tide, which was mapped on a global scale for the first time in Ray and Egbert [2004]. In contrast, the oceanic S2 tide is forced mainly by the gravitational potential and secondarily by the atmosphere. As the second largest tide in the ocean, S2 has been mapped on a global scale in numerous altimeter-constrained models. Here we examine the effects of adding the atmospheric S2 forcing to the AGHS tide model. We test whether such an addition improves the accuracy of the forward modeled S2 ocean tide. We also separate the atmospherically and gravitationally forced components of S2, and relate differences in their amplitudes and phases to differences in the respective forcings. The S2 air tide is aliased in the atmospheric pressure products put out by analysis centers, unless special processing is introduced [Ray and Ponte, 2003, and references therein]. Thus, to the best of our knowledge, previous models of atmospherically driven sea-level variability do not well represent the atmospherically forced S2 ocean tide. This tide is well represented here because we use the Ray and Ponte [2003] S2 air tide map. Since the oceanic S2 tide is periodic and well known, it presents a uniquely simple test of the ability of dynamical models to reproduce the sea level response to atmospheric pressure loading, and to simultaneously capture gravitationally and atmospherically driven sea-level variability.

1. Introduction

[2] High-frequency sea level variability is forced primarily by the gravitational tidal potential [Munk and Cartwright, 1966] and by atmospheric pressure loading and winds [Ponte, 1994]. Global observations of sea level are provided by satellite altimeters such as TOPEX/POSEIDON and JASON-1. The 10-day orbit times of these satellites lead to aliasing of high-frequency oceanic motions [Stammer et al., 2000; Tierney et al., 2000]. Because tides and the altimeter orbits are both periodic, tides remain periodic in the aliased altimeter record [Parke et al., 1987]. Advantage is taken of this to extract tides from altimetric data. The high accuracy of open-ocean surface elevations in tide models derived from or constrained by altimetric data has been verified [Shum et al., 1997] by comparison to a set of 102 pelagic tide gauges. The elevation accuracy of forward tide models, that is, hydrodynamical tide models that run unconstrained by data, is not as high as that in altimeter-constrained models. However, recently forward models have been improved with the inclusion of parameterizations of internal wave drag of topographic origin [Jayne and St. Laurent, 2001; Carrère and Lyard, 2003; Egbert et al., 2004; Arbic et al., 2004 (hereinafter referred to as AGHS)]. The drag schemes are motivated by inferences from both altimetric [Egbert and Ray, 2003] and in-situ [Polzin et al., 1997] data of enhanced dissipation in regions where the seafloor is rough.

2. Model, Forcings, and Diagnostics

[5] We use the one- and two-layer shallow-water models of AGHS, forced by the four largest semidiurnal (M2, S2,
N₂, and K₂) and four largest diurnal (K₁, O₁, P₁, and Q₁) constituents, and run on a 1/2° latitude-longitude grid from 86°S to 82°N. A topographic drag scheme (Garner [2005] and appendix of AGHS) was tuned to minimize the misfit between modeled and altimetric surface elevations of M₂, the largest tidal constituent. Such a tuning will be optimal or nearly so for other semidiurnal tides, since the frequency dependence in the drag scheme is weak. In the current study, the forcing term in the governing momentum equation is $-g \nabla (\eta - \eta_{EQ} - \eta_{ATM} - \eta_{SAL})$, where $g$ is gravitational acceleration, $\eta$ is the model perturbation surface elevation, $\eta_{EQ}$ is the gravitational tidal forcing modified to account for solid earth body tides, and $\eta_{SAL}$ is the self-attraction and loading term. The new term $\eta_{ATM} = -P_{\rho \omega} [Gill, 1982]$, where $\rho$ is mean seawater density and $P$ is the annual mean atmospheric S₂ pressure map [Ray and Ponte, 2003], based on 13 years of operational analysis fields. Ray and Ponte [2003] compute an RMS discrepancy, between their map and a set of ground truth stations, of 112 microbars, much less than the 574 microbar globally averaged signal. The globally averaged signal of Ray and Ponte [2003] S₂ map differs from that of the S₂ map derived from station data by Dai and Wang [1999] by only five percent. The argument of Ray and Egbert [2004], that the wind stress forcing by the S₁ atmospheric tide is negligible compared to its pressure loading, applies to S₂ as well.

We will decompose periodic fields into amplitudes $A$ and phases $\Phi$. The S₂ component of the gravitational forcing is $\eta_{EQ-S₂} = A_{grav} (\lambda, \theta) \cos [\omega t - \Phi_{grav} (\lambda, \theta)]$, where $\omega$ is the S₂ frequency, $t$ is time (referenced, as is the phase, to Greenwich), and $\lambda, \theta$ are longitude/latitude. Amplitudes $A_{grav}$ are maximum at, and symmetric around, the equator. This is approximately true of $\eta_{ATM}$ as well, with the largest values occurring in the eastern equatorial Pacific [Ray and Ponte, 2003, Figure 5]. Over the global ocean, the ratio of the globally averaged gravitational to atmospheric S₂ forings is 7.09. Along lines of constant longitude, $\Phi_{grav}$ is constant. Outside of high latitudes, this is also nearly true of the atmospheric forcing [Ray and Ponte, 2003, Figure 5]. To estimate the difference between the phases of the two forcing fields, we computed $\int \sin^2 [\Phi_{EQ} (\lambda, \theta) - \Phi_{grav} (\lambda, \theta) - \Phi_0] dA$ over the global ocean, where $dA$ is an element of area and $\Phi_{EQ} (\lambda, \theta)$ is the phase of $\eta_{EQ}$ for many different values of the constant $\Phi_0$. The integral is minimized when $\Phi_0$ is either 110.5° or 290.5°, and we eliminate 290.5° as a possibility after inspecting scatter plots of $\Phi_{EQ}$ versus $\Phi_{grav}$.

We define the model elevation discrepancy versus the pelagic tide gauges as

$$D = \sqrt{\frac{1}{N} \sum_{N} (\eta - \eta_{TG})^2},$$

where $\eta_{TG}$ is the tide gauge elevation, $N$ is the number of tide gauge records, and brackets denote time averaging. The tide gauge signal is

$$S_{\text{gauge}} = \sqrt{\frac{1}{N} \sum_{N} \eta_{TG}^2}.$$
Forcing) With Respect to the Gauges

Substitute for actually including atmospheric $S^2$ forcing. In values across stations covers the globally averaged values which were coastal), what it would be if forced only by the tidal gravitational values of the oceanic $S_1$ tide is markedly different from other oceanic normal modes $\text{[Platzman et al., 1981]}$ in almost the same way. In contrast, $\text{Ray and Egbert [2004]}$ show that the oceanic $S_1$ tide is markedly different from other oceanic diurnal tides (compare their Figures 4 and 6) because the very different spatial patterns of atmospheric $S_1$ forcing and diurnal gravitational forcing excite different normal modes.

\[ \text{Since } \cos(\omega t) + \left(\frac{1}{6.81}\right)\cos(\omega t - 109.4^\circ) = 0.96\cos(\omega t - 8.3^\circ), \text{ the total } S_2 \text{ tide is reduced in amplitude by a factor } R = 0.96 \text{ and shifted in phase by } r = 8.3^\circ \text{ from what it would be if forced only by the tidal gravitational potential. From an analysis of 80 tide gauges (many of which were coastal), $\text{Cartwright and Ray [1994]}$ found values of } R = 0.97 \text{ and } r = 5.9^\circ, \text{ but the considerable spread in values across stations covers the globally averaged values found here. The forward model also contains a wide scatter of } R \text{ and } r \text{ values, indicating that no simple prescription can substitute for actually including atmospheric } S_2 \text{ forcing. Differences in the amplitude maps of the gravitationally and (scaled) atmospherically forced components shown in Figure 1 are visible in, for instance, the Gulf of Alaska, New Zealand, and the Weddell Sea. The nonlocality of the oceanic response (both } S_2 \text{ components, for instance, are large in high latitudes, where forcings are small) makes it difficult to trace local differences in Figures 1a and 1b (or 1c and 1d) to local differences in forcing. However, rough connections can be made on basin scales. Ratios of the amplitudes of the atmospherically to gravitationally forced } S_2 \text{ tide (Figure 2) are generally larger in the Pacific, where the } S_2 \text{ air-tide forcing is maximum.}

\text{[10] Table 1 shows the } S_2 \text{ and RSS values of pelagic tide gauge signals } S_{\text{gauge}} \text{ alongside the RMS discrepancies } D \text{ of our one- and two-layer forward model (forced only by gravitational potentials) with respect to the gauges. While the } S_2 \text{ variance is captured at the } 87.9/88.9 \text{ percent level by our one/two-layer models, the variance captured of other semi-diurnal constituents ranges from } 91.4/92.2 \text{ to } 92.1/ \text{93.1 percent. The } S \text{ and } D \text{ values in Table 1 differ by } 0.04 \text{ cm from those in AGHS because here the pressure of the } S_2 \text{ air tide has been removed from the bottom pressure recorder data included in the pelagic tide gauges. Table 2 shows the } S_2 \text{ and RSS elevation errors in the forward models that include } S_2 \text{ air-tide forcing. The } S_2 \text{ percent variance captured has risen to levels seen in other semi-diurnal constituents, and the improvement in } S_2 \text{ with the inclusion of air-tide forcing is much greater than the range in variance captured among the various semi-diurnal constituents. This suggests that air-tide forcing is more important than frequency sensitivities to dissipation or baroclinicity. As in the gravity-only simulations, the two layer model performs slightly better than the one-layer model when all other conditions are equal (see AGHS for more discussion.)}

\text{[11] Inclusion of the } S_2 \text{ thermal tide forcing also increases the percent of the } S_2 \text{ variance in the GOT99 altimetry-constrained model } \text{[Ray, 1999]} \text{ explained by our one/two layer model, from } 83.8/84.8 \text{ to } 88.5/89.3 \text{ (in waters deeper than } 1000 \text{ m and equatorward of } 66^\circ). \text{ The percent of } S_2 \text{ variance captured with respect to GOT00, a model that estimates } S_2 \text{ more reliably (R. Ray, personal communication, 2004), is slightly higher. Addition of } S_2 \text{ air-tide forcing does not affect the percent of the GOT99 } K_2 \text{ (mixed lunar-semidiurnal) variance captured in our one/two layer model (86.8/87.6). The other six constituents are captured at 91.6/92.6 percent or better. We do not understand why, even after } S_2 \text{ air tide forcing is utilized, our forward modeled } S_2 \text{ and } K_2 \text{ remain anomalously poor with respect to GOT99. $\text{Cartwright and Ray [1994]}$ and $\text{Egbert and Ray [2003]}$ point out that } S_2 \text{ is problematic in altimeter-constrained models, and the former points out that problems with } S_2 \text{ leak into the nearby frequency } K_2. \text{ The work here suggests that including the air tide forcing might improve satellite-constrained hydrodynamical tide models. However, the latter have already been validated to high accuracy against the pelagic tide gauges. We conclude by noting that } K_2 \text{ also experiences an air tide forcing $\text{[Cartwright and Tayler, 1971]}$. However, to our knowledge, maps of the } K_2 \text{ air tide are not readily available. We estimate that } K_2 \text{ air tide forcing would change the oceanic } K_2 \text{ tide by about } 4.7 \text{ percent, a substantially smaller correction than for } S_2.\]
Larry Horowitz, Steve Garner, Baylor Fox-Kemper, Anand Gnanadesikan, Pablo Zurita, Olivier Pauluis, Bob Hallberg, Andrew Wittenberg, and Aiguo Dai are also thanked for helpful discussions. Support from National Science Foundation Grant OCE-0327189 is gratefully acknowledged. Computations were done on the supercomputer at the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric Administration (NOAA).

References


B. K. Arbic, Program in Atmospheric and Oceanic Sciences, Princeton University, P.O. Box CN710, Sayre Hall, Princeton, NJ 08544-0710, USA. (arbic@splash.princeton.edu)