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Observations over an annual cycle and simulations of wind-forced oscillations near the critical latitude for diurnal–inertial resonance

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ABSTRACT

Sea breezes are characteristic features of coastal regions that can extend large distances from the coastline. Oscillations close to the inertial period are thought to account for around half the kinetic energy in the global surface ocean and play an important role in mixing. In the vicinity of 30°N/S, through a resonance between the diurnal and inertial frequencies, diurnal winds could force enhanced anti-cyclonic rotary motions that contribute to near-inertial energy.

Observations of strong diurnal anti-cyclonic currents in water of depth 175 m off the Namibian coastline at 28.6°S are analysed over the annual cycle. Maxima in the diurnal anti-cyclonic current and wind stress amplitudes appear to be observed during the austral summer. Both the diurnal anti-cyclonic current and wind stress components have approximately constant phase throughout the year. These observations provide further evidence that these diurnal currents may be wind forced. Realistic General Ocean Turbulence Model (GOTM) 1-D simulations of diurnal wind forcing, including the first order coast-normal surface slope response to diurnal wind forcing, represent the principal features of the observed diurnal anti-cyclonic current but do not replicate the observed vertical diurnal current structure accurately. Cross-shelf 2-D slice simulations suggest that the first order surface slope response approximation applies away from the coast (> 140 km). However, nearer to the coast, additional surface slope variations associated with spatial variations in the simulated velocity field (estimated from Bernoulli theory) appear to be significant and also result in transfer of energy to higher harmonics. Evidence from 3-D simulations at similar latitude in the northern hemisphere suggests that 3-D variations, including propagating near-inertial waves, may also need to be considered.

1. Introduction

This paper re-examines diurnal currents, which are apparently forced by a resonance between the diurnal wind forcing (i.e. a sea breeze) and the local inertial period of 25.06 h, at a location off the Namibian coast at 28.6°S, 14.6°E (Simpson et al., 2002). The aims of this paper are:

(1) To extend the observations presented by Simpson et al. (2002) to cover a complete annual cycle, and to present new wind observations which, for the first time, allow direct comparison between observed and simulated surface current phases.
(2) To use novel simplified experiments with a 1-D model to gain process insight into the dynamics of rotary diurnal currents forced by diurnal wind stress and its first order surface slope response near a coast, after Craig (1989b).
(3) To make a direct comparison between realistic 1-D process simulations and the observations, particularly the rotary phases, and highlight any differences (that could be evidence of missing 3-D processes such as propagating waves).
(4) To use an idealised simulation from 2-D cross-shelf model to assess the validity of the Craig (1989b) first order approximation for the coast-normal surface slope response to diurnal wind stress.

In this section, we first introduce sea breezes and then inertial resonance to provide background to rather similar wind-forced, tidal and free inertial currents, which often occur simultaneously and need to be carefully distinguished. Next we specifically consider the dynamics of diurnal wind forcing near a coast. In Section 2, we discuss an extended set of observations over a full annual cycle from the same location on the Namibian shelf that

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was presented by Simpson et al. (2002). In Section 3, we present details of the GOTM 1-D and 2-D cross-shelf slice turbulence closure model configurations used to simulate these currents. Section 4 presents the results from the simulations. Finally, in Section 5, we discuss the results and conclude.

1.1. Sea breezes

Sea breezes are characteristic features of the coastal regions that occur along approximately two-thirds of the earth's coastlines (Simpson, 1994). This daily cycle of generally onshore and offshore breezes results from differential land–sea heating and cooling during the day and night. Sea breezes can be very energetic, for example up to 10 m s^{-1} in the case of the 'Fremantle Doctor' off Western Australia (Pattiaratchi et al., 1997). They have also been observed to extend over 100 km from the coast at several locations (Simpson, 1994; Halpern, 1977; Chen et al., 1996; Gille et al., 2003; Aparna et al., 2005). Due to the earth's rotation, at some locations sea breeze winds rotate until they are approximately coast parallel, particularly at offshore locations.

Gille et al. (2003, 2005) inferred the global variation in the diurnal wind component from the difference between morning and evening wind observed by the QuikSCAT scatterometer (QSCAT). These observations confirm that significant diurnal winds extend far from the coast in many regions offshore and tend to be strongest during summer (Fig. 1). They also suggest that weaker diurnal winds ($\sim$1 m s^{-1} amplitude) can extend thousands of km into the open ocean from the continental coasts. Diurnal changes in the marine boundary layer and the associated effective ocean surface roughness are additional mechanisms that could result in diurnal winds far from land (Barthelmie et al., 1996).

Sea breezes are strong in many regions close to 30°N/S, particularly during summer, due to intense diurnal heating-cooling and the resulting strong land–sea temperature gradients (Fig. 1). Rotunno (1983) and Walsh (1974) present discussions of the linear theory of land and sea breezes which suggests there are fundamentally different resonant responses to diurnal forcing equatorward and poleward of 30°N/S. An interesting question remains as to whether there is an atmospheric resonance between the diurnal forcing and inertial period near 30°N/S. An initial inspection of the global dual scatterometer observations between April and October 2003 (not shown) suggests that the cyclonic diurnal wind rotary components are generally stronger than the anti-cyclonic component. There also appear to several regions of high ellipticity relatively close to the diurnal resonant latitudes. Further work is required to understand this potential resonance. The Namibian and Southwest African coastal regions and seas are known to be regions where sea breezes are strong (Fig. 1) and large land–sea thermal mean temperature gradients also exist (Preston-Whyte and Tyson, 1988; Jury and Spencer-Smith, 1988).

1.2. Inertial resonance

Simpson et al. (2002) and Hyder et al. (2002) present theory of elliptical motion of a surface layer subject to linear friction resulting from diurnal wind forcing for rotary and Cartesian components, respectively. The solutions for clockwise and anti-clockwise forcing at the diurnal frequency were shown to be resonant for the clockwise case at 30°N where $f=\omega$ and for the anti-clockwise case at 30°S ($f=-\omega$). Close to the resonant latitudes the response was shown to tend to the purely anti-cyclonic solution. At these latitudes, a sharp change in the phase of the current response with latitude is also predicted. At latitudes further from 30° the resultant motions become elliptical and both rotary components need to be considered.

The poleward limit of known observations of wind forced rotary diurnal surface currents through diurnal–inertial resonance is in the Aegean at 40°N (Hyder et al., 2002), where $\omega/f\sim 0.77$ (inertial period 18.7 h). Hence, from theory, an expected equatorward limit might be 23°S where $f/\omega\sim 0.77$ (inertial period $\sim$30.9 h). The resulting regions of expected diurnal–inertial resonance are presented in Fig. 2. Tidal forcing would be expected to result in a similar resonant process (Maas and Van Haren, 1987; Furevik and Foldvik, 1996), although surface slope forcing acts equally through the water column. Assuming the same, ω/f limits, for diurnal tidal periods the resonant regions would be expected to be broadly similar to those for diurnal wind forcing. By contrast, semi-diurnal–inertial tidal resonance might be expected to occur for M2 (period 12.42 h) between 48 and 90°N/S with resonance at $\sim$75°N/S and for S2 (period 12 h) 50–90°N/S with resonance at the pole. However, it should be noted that, since tidal forcing acts through the water column, frictional damping and bottom boundary layer effects would be expected to be more pronounced which could considerably reduce the extent of the tidal resonant regions.

Many documented observations of surface rotary diurnal currents exist in the world's coastal seas (Fig. 2). Several of these observations have been attributed to diurnal wind forcing. Examples of diurnal currents which appear likely to be wind forced are indicated in Fig. 2 with $*$'s: (1) Simpson et al. (2002); (2) Hyder et al. (2002); (3) Chen et al. (1996); DiMarco et al. (2000); Zhang et al. (2010, 2009); Jarosz et al. (2007); (4) Rosenfeld (1988); (5) Hunter et al. (2007); and (6) Lerczak et al. (2001). Candidate observations of diurnal current, temperature or salinity variations that could be wind forced or re-analysed to establish whether they are wind forced are indicated with circles: (7) Simionato et al. (2005); (8) Poulain (1990); (9) Pidgeon and Winant (2005); (10) Kaplan et al. (2005); (11) Rippeth et al. (2002); (12) Pattiaratchi et al. (1997); (13) Halpern (1977); (14) Reynolds-Fleming and Luettich (2004); (15) Pinones et al. (2005); Sobarzo et al. (2010); (16) Kaplan et al. (2003); (17) Kaplan et al. (2003); (18); Schahinger (1988); (19) De Mesquita and Harari (2003); and (20) Zavialov et al. (2002). It should be noted that this database is not comprehensive. It is also possible that some incidences of wind forced diurnal motions are masked by, or have even been attributed to, tidal forcing.

Wind forced anti-cyclonic circular motions have long been known to occur in the surface layers of the ocean (Helland-Hansen and Ekman, 1931). They have been observed and reported in many locations and are particularly pronounced in the absence of friction resulting from strong tidal motion. Recent observations confirm earlier suggestions (Pollard and Millard, 1970; Pollard, 1980, 1970) that near-inertial oscillations comprise around half the kinetic energy in the world's oceans with an energy flux of around 0.5–0.7 TW—a value comparable with that from the internal tide of $\sim$0.9 TW (Park et al., 2005; Watanabe and Hibiya, 2002; Alford 2003a, 2003b; Munk and Wunsch, 1998). Until recently, climate models have tended to use daily coupling between the atmosphere and ocean (Bernie et al., 2007; Danabasoglu et al., 2006) so wind-forced near-inertial energy and associated mixing have not been well represented.

There are two categories of near-inertial motions, with similar dynamics, whereby Coriolis forces drive the radial accelerations. Those with a random phase (in this paper termed 'free' inertial currents) at or close to the inertial frequency are the free motions of water particles in response to impulsive injections of momentum. Those at a specific forced frequency, termed 'periodic', close to the inertial frequency with approximately constant phase are the response to more regular periodic forcing. At many locations both processes can occur. Both mechanisms efficiently transfer energy from the wind to the ocean because of the similar rotary phases of the wind and surface currents since power is given by vector product of wind stress and surface velocity. Near-inertial