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When land breezes collide: Converging diurnal winds over small bodies of water

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Over enclosed and semi-enclosed bodies of waters, the land-breeze/sea-breeze circulation is expected to be modified by the presence of opposing coastlines. These effects are studied using satellite scatterometer surface wind observations from the QuikSCAT and ADEOS-2 tandem mission from April to October 2003. Winds are studied for six bodies of water: the Red Sea, the Gulf of California, the Mediterranean, the Adriatic Sea, the Black Sea, and the Caspian Sea. These bodies of water are large enough for the geographic orientation of the diurnal winds relative to the coastline to match the expected orientation for a straight coastline. Land breezes from opposite coastlines converge in the middle of these bodies of water, and in some cases the convergence line is shifted substantially away from the mid-point between opposite coastlines. Displacements in the convergence line appear likely to be explained by differences in the strength of the diurnal winds emanating from opposite coastlines, associated with differential heating or with island/peninsula effects, and by geographic displacements associated with large-scale mean wind patterns. Copyright © 2013 Royal Meteorological Society

Key Words: Diurnal winds; scatterometer winds; enclosed and semi-enclosed seas

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1. Introduction

Daytime heating on land causes warm air to rise over the land surface, and results in onshore flows of cool air, while nighttime cooling over land reverses the process (e.g. [Simpson 1994](#); [Miller et al. 2003](#)). For centuries this wind pattern has been known as the sea breeze when it flows from the ocean to land during the day (e.g. [Dampier 1699](#)) and as the land breeze when it flows from land to sea at night. (As a shorthand, in this study, we will use the term land breeze to refer to both the landward and seaward components of the diurnal winds over water.) Satellite scatterometer winds have demonstrated themselves to be a valuable tool for assessing the ubiquitous character of diurnal winds along coastlines spanning a wide range of latitudes ([Gille et al. 2003, 2005](#); [Wood et al. 2009](#)).

The QuikSCAT scatterometer demonstrated that over the ocean land-breeze effects are detectable at all latitudes,

and at distances up to 500 km from shore, particularly in summer ([Gille et al. 2003](#)). The far reach of the land breeze implies that over bodies of water with diameters up to 1000 km, land breezes from opposite coasts might be expected to converge and therefore to interact. The objective of this study is to make use of data from the 2003 tandem QuikScat/ADEOS-2 scatterometer mission to evaluate locations where land breezes from opposite coastlines would be expected to converge.

We examine six large enclosed or semi-enclosed bodies of water, as listed in Table 1. These are selected to cover a range of Northern Hemisphere latitudes and a range of sizes, all sufficiently large to be observable from microwave scatterometry with a 12.5 km footprint. We also examined Lake Superior, but it proved to be too far north and/or too small to exhibit a consistent pattern of diurnal variability. Large enclosed or semi-enclosed bodies of water in the Southern Hemisphere are few in number and were not

Table 1. Enclosed or semi-enclosed bodies of water considered in this study, ordered by latitude. Angular deflections of the major axis are measured in degrees to the right of a line perpendicular to the coast. Average angles are computed using only points in which the direction of flow is offshore in the morning and onshore in the evening. Here, to be consistent with the figures, the angular deflection for Mediterranean represents only the Eastern Mediterranean, encompassing the region to the East of Sicily and excluding the Adriatic. The angular deflection for the full Mediterranean, excluding the Adriatic, is $41 \pm 1^\circ$.

Body of water	area (km ²)	mean latitude	major axis deflection
Black Sea	4.4×10^5	44° N	$54 \pm 2^\circ$
Adriatic Sea	1.4×10^5	43° N	$49 \pm 6^\circ$
Caspian Sea	3.7×10^5	41° N	$49 \pm 2^\circ$
Mediterranean	2.5×10^6	35° N	$37 \pm 2^\circ$
Gulf of California	1.6×10^5	28° N	$26 \pm 3^\circ$
Red Sea	4.4×10^5	22° N	$16 \pm 3^\circ$

considered, because the land breeze is predominantly a summertime phenomenon, and the QuikSCAT/ADEOS-2 tandem mission took place during Northern Hemisphere summer.

The land-breeze circulation over a semi-enclosed sea can be thought of as a simple reversal of the sea-breeze circulation over an island or peninsula. Island sea breezes have been the subject of considerable modeling and theoretical work (e.g. [Malkus and Stern 1953a,b](#); [Stern 1954](#); [Olfe and Lee 1971](#); [Neumann and Mahrer 1974](#); [Mahrer and Segal 1985](#); [Niino 1987](#); [Jiang 2012a](#); [Robinson et al. 2011](#)). On islands and peninsulas, the convergence lines where sea breezes from opposite coasts intersect are associated with vertical convection, enhanced cloud cover, high precipitation, and thunderstorm activity (e.g. [Frank et al. 1967](#); [Pielke 1974](#); [Simpson 1994](#); [Carbone et al. 2000](#); [Jury and Chiao 2013](#)). Sea-breeze ‘collisions’ are thought to contribute to high precipitation rates over some tropical islands ([Carbone et al. 2000](#)) and to trigger formation of the Morning Glory bore in north Queensland, Australia ([Clarke 1984](#)). One of the complications in studying converging sea breezes over land is that the processes are dependent on orography and land surface (e.g. [Carbone et al. 2000](#)).

Enclosed or semi-enclosed bodies of water offer a simpler framework for assessing converging diurnal wind fronts, since the water surface is relatively homogeneous. In the vicinity of the convergence line, the flow is not subject to orographic effects or land-surface variations. [Neumann and Mahrer \(1975\)](#) reviewed historic land-breeze observations associated with lakes and formulated an idealized axisymmetric theory for a small lake with no background wind field. A number of more recent investigations have brought newer modeling approaches to the question, including for example [Prtenjak et al. \(2008\)](#) in the Adriatic, [Jiang et al. \(2009\)](#) in the Red Sea, and [Efimov and Barabanov \(2011\)](#) in the Black Sea region. However, in general diurnal land breezes over semi-enclosed bodies of water have been less scrutinized than island sea breezes and to our knowledge the basic descriptive characteristics of land-breeze convergence have not previously been explored.

In this study we use scatterometer wind observations to evaluate the behavior of converging land breezes in situations where mean winds, rotation, and orography can

influence wind patterns. The Earth’s rotation deflects the land breeze so that it is not strictly orthogonal to the shoreline (e.g. [Alpert et al. 1984](#)). One might hypothesize that interactions of converging land-breeze fronts could weaken the land breeze or rotate the orientation of wind vectors away from the circulation predicted for semi-infinite coastlines. A more fundamental issue is to assess the processes that influence the position of the convergence line, to determine when the sea-breeze convergence is essentially at the center of the body of water, and when and why it can be displaced from the center.

In this paper, in section 2, we introduce the scatterometer data used for this analysis. Section 3 evaluates whether the orientation of the land breeze or other basic characteristics differ for small bodies of water compared to the full ocean. Section 4 evaluates conditions in which one coastline dominates another coastline. Finally results are summarized in section 5.

2. Data

Scatterometers are normally flown in sun-synchronous orbits, meaning that they cross the equator at the same local time everywhere (see e.g. [Gille et al. 2003, 2005](#); [Wood et al. 2009](#)). For example, the QuikSCAT scatterometer measured at about 6:00 and 18:00 on its ascending (northward) and descending (southward) satellite passes, and the SeaWinds scatterometer aboard ADEOS-II measured at 22:30 on its ascending pass and 10:30 on its descending pass. The diurnal wind ellipse (e.g. [Haurwitz 1947](#); [Schmidt 1947](#)) cannot be characterized by one satellite alone, as the sun synchronous orbit samples at the Nyquist frequency of the diurnal cycle. For six months, from April to October 2003, the QuikSCAT and SeaWinds flew as a tandem mission, and these measurements have provided a means to tease out details of the diurnal variability of the wind on a global scale (e.g. [Gille et al. 2005](#); [Wood et al. 2009](#)).

Here we use the high-resolution (12.5 km) QuikSCAT and ADEOS-2 wind products to repeat the land-breeze analysis carried out by [Gille et al. \(2005\)](#) for the six bodies of water listed in Table 1. Figure 1 shows the time-averaged winds for these six bodies of water.

Following the procedure discussed by [Gille et al. \(2005\)](#), we average swath wind vectors measured by the two scatterometers onto a 0.125° latitude by 0.125° longitude grid for four time bins corresponding to the four satellite equatorial crossing times: 6:00, 10:30, 18:00, and 22:30. Averaged measurements from these four times are used to project winds onto an ellipse and to identify the orientation of the wind ellipse, the amplitude of the diurnal variability, and the time of maximum offshore wind. Figure 2 shows the length of the semi-major axis of the diurnal wind ellipses (in colors) and sample ellipses (black ellipses).

Diurnal winds are influenced by the surrounding land surface. Topography (e.g. [Jury and Spencer-Smith 1988](#); [Dai and Deser 1999](#)) and vegetation (e.g. [Anthes 1984](#)) have both been identified as potential controls on the land/sea-breeze circulation. To consider the potential role of vegetation (i.e. land usage), in Figure 1 we indicate land surface types from the Biosphere-Atmosphere Transfer Scheme (BATS) ([Dickinson et al. 1986](#)). BATS data are released at nominally 1-km horizontal resolution. In Figure 2 and in subsequent figures, we show land surface elevation derived from the U.S.

For each gridcell over water, the distance from the coastline is computed through a simple search algorithm that identifies the point on the coast closest to the patch of water. The angular orientation of the coastline is computed from the geographic spacing between adjacent points along the coastline: $\tan \alpha = dy/dx$, where dy is the meridional distance (in km), dx is the zonal distance, and both dx and dy can be positive or negative depending on the relative positions of adjacent points. Here the angle α is defined to be perpendicular to the coastline and projecting into the water.

3. Orientation of the land breeze relative to the coast

Because of the Earth's rotation, the land breeze turns through the course of the day, tracing out a clockwise ellipse in the Northern Hemisphere and reversing the pattern in the Southern Hemisphere (Alpert *et al.* 1984). Most analytical studies of the sea and land breeze have concentrated on the diurnal response of a two-dimensional linear coast separating land and sea (Haurwitz 1947; Schmidt 1947; Walsh 1974; Ueda 1983; Niino 1987; Dalu and Pielke 1989; Young and Ming 1999; Crosman and Horel 2010). The deflection angle varies with latitude, and for the open ocean the QuikSCAT/ADEOS-2 data suggest that it is roughly equivalent to the latitude (Gille *et al.* 2005). In linearized theory using the Boussinesq approximation, diurnal winds over a sea are analogous to diurnal winds over an island, as modeled by e.g. Niino (1987). It is possible to rewrite the island model used by Niino (1987) so as to represent a circular lake or sea. This provides a formalism for evaluating the deflection angle of the diurnal wind ellipses, but the bodies of water listed in Table 1 in fact all have aspect ratios that are 4 or greater and hence hardly circular. Given the decay rate of the land breeze in the model, it is more appropriate to model all these seas as infinite strips of water.

Figure 2 shows wind ellipses for the six bodies of water considered in this study. At first glance, wind ellipses for the Black Sea (northwest quarter of Figure 2d) might appear to suggest azimuthal flow, rotating around the sea instead of oscillating onshore and offshore. However, in reality as summarized in the fourth column of Table 1, the dominant orientation of the land breeze in all six bodies of water is approximately the same as the latitude and thus closely aligns with the orientation expected for the global ocean in general (Gille *et al.* 2005), consistent with the predictions of Alpert *et al.* (1984). (Here, as noted in the table caption, average angles are computed using only data points for which the land breeze follows a conventional pattern with offshore flow in the morning and onshore flow in the evening.) Within the uncertainties of the analysis, there is no indication that the proximity of two coastlines or the curvature of the coastlines alters the orientation of the mean nearshore diurnal winds for these six bodies of water. This is consistent with the earlier discussion about the aspect ratio of the bodies of water. The Rossby radius of deformation, $L_R = u/f^{-1}$, is typically of the same order as the horizontal length scale of Niino (1987) (which is diffusive). This confirms the fact that the effect of rotation is relevant to the theoretical modelling of the sea breeze for such situations.

One might hypothesize that smaller seas and seas closer to the Equator would be more likely to have diameters of the order of L_R and hence would be sensitive to the shape of the sea. However, the results tabulated in Table 1 do not show evidence for the diurnal wind ellipse orientation deviating from the semi-infinite coastline prediction. For grid points for which the land breeze is offshore in the morning, the average land-breeze orientations vary roughly linearly with latitude. These are depicted graphically for the Mediterranean (partially shown in Figure 2d), the Red Sea (Figure 2a), the Gulf of California (Figure 2b), and the Caspian Sea (Figure 2c).

4. Identifying the dominant coastline

The second goal of this study is to determine the dominant coastline that controls the land breeze. Figure 3 shows the time at which the sea breeze is aligned along the major axis of the wind ellipse, computed following the procedure used by Gille *et al.* (2005) to identify the dominant axis. Winds are aligned with the major axis twice per day, and are usually oriented so that winds flow offshore in the morning and onshore in the evening, since the offshore flow typically begins around 6 or 7 am. Thus colors in Figure 3 are typically red or purple near the coast, and they change with distance from the coast, corresponding to the offshore propagation of the land breeze (e.g. Gille *et al.* 2005).

The maximum wind speeds shown in Figure 2 are typically $O(1\text{--}2 \text{ ms}^{-1})$, while the phase of the land breeze (Figure 3) propagates offshore at $O(10 \text{ m s}^{-1})$ (e.g. Gille *et al.* 2005). The observed maximum wind speeds are consistent with predictions from linear theory (e.g. Alpert *et al.* 1984; Niino 1987), while the faster phase propagation speeds are more consistent with gravity current speeds, defined by $U = \sqrt{g'h}$, where h is the height of the current, and $g' = g\Delta\rho/\rho$ is reduced gravity, g is gravity, ρ is density, and $\Delta\rho$ is the density difference between the ambient air and air in the sea-breeze front (e.g. Reible *et al.* 1993). In this example, we assume h to be roughly equivalent to the height of the planetary boundary layer (which typically averages between 250 and 500 m in summertime over the bodies of water considered in this study, as determined from the database compiled by von Engeln and Teixeira (2013)), and we estimate $\Delta\rho/\rho$ as $\Delta\theta/\theta$, using reanalysis estimates of potential temperature, with $\Delta\theta$ representing the difference between potential temperature in the boundary layer and above the boundary layer. This predicts U to be between 5 ± 1 and $7\pm 1.5 \text{ m s}^{-1}$, roughly consistent with the phase propagation in Figure 3. Over land, in some locations the sea-breeze front is reported to resemble a fast-moving gravity current that rapidly transports pollutants or salt spray inland (e.g. Simpson 1987). Observations over water are less extensive, but do not show evidence for the frontogenesis commonly needed to develop a strong gravity current over water. This suggests that the land-breeze convergence that occurs over water typically does not represent a convergence of strong gravity currents transporting air of different properties, but instead is a convergence of local diurnal winds, with comparatively small density contrast between oppositely moving diurnal winds. Thus the phasing corresponding to the times of maximum wind speed in Figure 3 is best thought of as gravity-wave phase propagation, which also would be expected to move like $\sqrt{g'h}$.

If land breezes from opposite coastlines were equally strong, as in an idealized axisymmetric framework (e.g. Neumann and Mahrer 1975), then land breezes originating at opposite coasts would converge precisely in the middle of the sea. However, we observe that for some points, the diurnal winds imply onshore flow in the morning, implying a reversal of the conventional sea breeze/land breeze circulation. For these points, the orientation of the land breeze differs from what would be predicted for a semi-infinite coastline.

To determine the orientation of the diurnal winds relative to α (the angular orientation of a line perpendicular to the coastline and oriented towards the water, defined in section 2), we defined β to be the angular orientation of the wind ellipse, defined to represent the direction of wind in the morning. Then the orientation of the wind relative to the coast $\beta - \alpha$ is predicted to be roughly equivalent to the latitude ϕ (Alpert *et al.* 1984; Gille *et al.* 2005).

If the observed orientation of the morning diurnal wind (β) differs by less than $\pm 90^\circ$ from the predicted orientation ($\alpha - \phi$), then the diurnal winds are consistent with a land breeze initiated at the nearest shore. If the angular difference ($\beta - (\alpha - \phi)$) exceeds $\pm 90^\circ$, then the land breeze is more consistent with a wind initiated from the opposite shore. This is represented in Figure 4. Blue pixels indicate locations where winds follow a conventional land-breeze pattern relative to the nearest coastline, with offshore flow in the morning. Red pixels indicate places where flow is counter to the standard land-breeze pattern. Black contours show isolines of constant distance from the coast. If all pixels were blue, this would indicate that at the sea surface, land breezes converge at the mid-point between opposite coastlines. Red pixels indicate places where, as detected from surface-level scatterometry, the land-breeze convergence is displaced relative to the geographic center of the body of water, so that the land breeze appears to be controlled by a more distant coastline. (Since scatterometers detect only winds at the sea surface and since the temporal sampling of the tandem scatterometer mission was limited to four observations per day, the available information is insufficient to detect the vertical structure of the diurnal convergence or temporal shifts in the position of the convergence line.) In most locations, the diurnal land/sea-breeze circulation is controlled by the closest coastline, as indicated by the preponderance of blue pixels. For example, in the Caspian (Figure 4c), most pixels are blue, and land breezes from opposite shores appear to meet roughly along a line that is equidistant from the two coastlines. At the convergence line, the diurnal wind strength can be statistically insignificant (white pixels), or the phasing may suggest that within a couple of 12.5 km by 12.5 km pixels, the land breeze is controlled by the more distant coastline (red pixels).

In other places, such as the Black Sea (northeast corner of Figure 4d) or the eastern Mediterranean (southern part of Figure 4d), the convergence line can appear to be shifted off center relative to the mid-point of the sea, so that a cluster of red pixels appears along one side of the middle of the basin. And in other basins, such as the Red Sea (Figure 4a), the Gulf of California (Figure 4b), or the Adriatic (northwest part of Figure 4d), large parts of a semi-enclosed sea may appear to have diurnal winds that originate from the more distant coastline (red pixels). One challenge for this study

is to determine what mechanisms can displace the land-breeze convergence away from the mid-point between two coastlines.

In long, narrow seas, such as the Red Sea (Figure 4a), the Gulf of California (Figure 4b), and the Adriatic (northwest corner of Figure 4d), nearly half of the pixels are red, indicating that a single coastline tends to control the land breeze. The dominance of a single coastline might seem more likely for the Red Sea and the Gulf of California than for the Adriatic, because they are south of 30° N, in a latitude range where the diurnal cycle is expected to propagate far offshore (e.g. Niino 1987; Gille *et al.* 2005). However, the effect is also pronounced in the Adriatic, implying that latitude may not strongly determine land-breeze convergence.

Over the open ocean, diurnal winds are also strongly influenced by the presence of mountains (e.g. Gille *et al.* 2003; Garreaud and Muñoz 2004; Wood *et al.* 2009). Thus it might appear surprising that the low topography north coasts appear to dominate mountainous south coasts in the Caspian (see red pixels near 52° , 37° S in Figure 4c) and the Black Sea (see red pixels near $34\text{--}38^\circ$ E, $42\text{--}43^\circ$ N in Figure 4d). A similar effect occurs in the Mediterranean ($19\text{--}22^\circ$ E, south of 35° N in Figure 4d). Land surface type, shown in Figure 1 is linked to topography, so it is difficult to distinguish effects of land surface type (e.g. Anthes 1984; Carbone *et al.* 2000) from effects of topography, but in general there is no obvious correlation between land surface type and the position of the convergence line.

Since the position of the land-breeze convergence line does not appear to be strongly governed by topography, land surface type, or latitude, we explore two mechanisms that do appear to matter: (a) differing land-breeze strengths on opposite coasts, driven by differential heating or by island/peninsula effects, and (b) mean wind flow.

Differential heating can occur if one coastline has larger land-sea density contrasts than the other, perhaps due to local meteorological effects, and therefore larger values of g' . Since velocities are set by g' , the convergence line will tend to be displaced away from the coastline with larger density contrasts. Differences in propagation speeds can also occur if one coastline has a stronger boundary layer inversion than the other, since strong inversions partially trap diurnal wave modes and result in more rapid propagation speeds (Jiang 2012b). Such differences in the inversion strength could arise from terrain differences, for example.

Island/peninsula effects can also result in differing land-breeze strengths if one coastline borders a large land mass while the opposite coastline is on an island or narrow peninsula that is subject to maritime climate conditions. For regions of water adjacent to islands or small strips of land, such as the strip of Mediterranean north of Cyprus (around 34° E, 36° N), the southern Sea of Azov (on the north side of the Black Sea, near 38° E, 46° N), and the western Aegean (near 25° E, 39° N), and to a lesser extent north of Crete (near 24° E, 36° N), the land breeze tends to be controlled from the “mainland” side of the channel. Thus, for example, the land-surface processes over Turkey dominate control of diurnal winds in the strip of Mediterranean between Turkey and Cyprus. This is consistent with modeling results of Xian and Pielke (1991), who found that a sea breeze resulted in weak convection over land if the strip of land was less than 100 km

wide. The same phenomenon applies for the southern part of the Gulf of California (south of about 28.5° S) and in the Adriatic, although in these seas, the presence of mountains to the northeast and ocean to the southwest, separated by a comparatively narrow strip of land, implies orographic effects that are also consistent with the land-breeze circulation being dominated by the northeast coasts. The regional Adriatic model of [Prtenjak et al. \(2008\)](#) also suggests that topography along the northeast coast plays a significant role in controlling diurnal winds.

Using the linear model of [Niino \(1987\)](#), we tested the hypothesis that the convergence line can be affected by differing land-breeze strengths on opposite coasts, caused either by differential heating or island/peninsula effects. Although the angular orientation of the land breeze is sensitive to the Coriolis parameter, we found that the sensitivity of the convergence line location is not. This can be understood by the fact that strength of the offshore wind depends weakly on the Coriolis parameter, especially at low levels, and the relative magnitudes of the offshore flow from both coasts control the location of the convergence line, which is displaced away from the coastline with greater heating. The exact position of the convergence line depends on the width of the sea, which we define in nondimensionalized units following [Niino \(1987\)](#). The appropriate lengthscale $L = (N/\omega)(\kappa/\omega)^{1/2}$ depends on the buoyancy frequency, N ; diffusivity of heat in the atmosphere, κ ; and the diurnal frequency $\omega = 2\pi [24 \text{ hrs}]^{-1}$. We estimated $N^2 = (g/\theta)(\partial\theta/\partial z)$ at the base of the atmosphere, using potential temperature θ from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis ([Kalnay et al. 1996](#)). For the bodies of water considered here, average summer $N = (1.2 \pm 0.2) \times 10^{-2} \text{ s}^{-1}$. The relatively small standard deviation of N is consistent with relatively uniform stratification. On the other hand, the diffusivity κ is not well known. [Niino \(1987\)](#) chose $\kappa = 10 \text{ m}^2 \text{ s}^{-1}$, which would imply an L of about 60 km.

Using the wind at 10 m, results from this model indicate that if the ratio of heating on one coast relative to the other is greater than two, then the convergence line shifts to a point less than a third of the width of the sea, provided the sea is narrower than about $2L$ or 120 km. For wider bodies of water, greater differential heating would be needed to produce a convergence line displacement. Differential heating ratios seem unlikely to be much greater than two. Yet the scatterometer results show that convergence line shifts are detectable in seas that are substantially wider than 120 km. However, differential heating is unlikely to be the only factor contributing to convergence line displacements.

For bodies of water bordered on one side by islands or peninsulas of finite width, the theory suggests that the convergence line should be shifted away from the mainland coastline. On the basis of the [Niino \(1987\)](#) scalings, frontal displacements would again be expected to be detectable for seas narrower than about $2L$ or 120 km, and for islands/peninsulas narrower than about L or 60 km.

The narrowest seas in this study (the Adriatic and the Gulf of California) are around 120–130 km wide and are consistent with differential heating or island/peninsula effects, but other bodies of water considered in this paper are too wide for explanations that are expected to act only across distances of $2L \approx 120$ km. However, eddy diffusivity

in the boundary layer has been reported to range from 0.1 to $2000 \text{ m}^2 \text{ s}^{-1}$ (e.g. [Stull 1988](#)); in this case, if the effective κ were increased to $10^2 \text{ m}^2 \text{ s}^{-1}$, L would be $O(200 \text{ km})$, which is sufficiently large to explain the convergence line shifts observed in all of these examples. Thus the simple theoretical model of [Niino \(1987\)](#) appears consistent with the physical effects hypothesized to explain the shift in convergence line, but the results are sensitive to L .

Mean winds also appear to play a role. In the Caspian, Black Sea, and Mediterranean, the mean winds are northerly and in the Adriatic mean winds are north-easterly (see [Figure 1](#)), and this likely explains the southward shift of the convergence line relative to the geographic midpoint of the seas. Similarly, mean winds from the southwest also help to explain the fact that north of about 29° N, the southwest coast controls the land breeze in the Gulf of California. (However, mean winds do not explain the patterns seen further south in the Gulf of California.) This is supported by observations on land: for example, [Frank et al. \(1967\)](#) observed that the sea-breeze convergence line over South Florida occurs on the leeward side of the Florida peninsula, and modeling results by [Xian and Pielke \(1991\)](#) and by [Jiang \(2012a\)](#) showed weaker sea-breeze convection on the upwind side of an island. This is also consistent with global analysis by [Jiang \(2012b\)](#), who found that steady offshore winds result in diurnal perturbations that can be detected further offshore.

The Red Sea is comparatively far from bodies of water, and the prevailing wind is along the axis of the Red Sea (see [Figure 1a](#) or e.g. [Jiang et al. 2009](#)), so neither mean wind nor nearby water can influence the Red Sea in the same way that they influence the Adriatic or the Gulf of California. Mountain passes on both coasts channel wind jets across the Red Sea. Using a Weather Research and Forecasting (WRF) model, [Jiang et al. \(2009\)](#) showed that the Tokar Gap, at about 17° N on the west coast of the Red Sea, is responsible for a strong summertime land breeze that dominates the diurnal circulation south of about 20° N. This summer circulation is closely tied to the monsoon circulation in the northwestern Indian Ocean. In contrast, their results showed that in winter, a series of gaps on the eastern side of the Red Sea, between about 22° N and 28° N, channel strong diurnal winds. Since only summertime data are available in the QuikSCAT/ADEOS-2 scatterometer tandem mission, in [Figure 4a](#), we see only the impact of the summer diurnal circulation, dominated by gaps on the western side of the Red Sea almost everywhere in the Red Sea, consistent with the WRF results of [Jiang et al. \(2009\)](#). At about 22° N, where mountain passes exist on the eastern coast and where [Farrar et al. \(2009\)](#) placed a mooring, the diurnal circulation is controlled by the east coast.

5. Discussion and Conclusions

This study has used scatterometer winds from the QuikSCAT/ADEOS-2 tandem mission to investigate the convergence of summer land breezes over six bodies of water. Results show that in most respects converging land breezes behave like land breezes on semi-infinite linear coastlines. In particular the angular orientation of winds relative to the coastline of a (semi-)enclosed sea is consistent with angular orientations observed for more or less semi-infinite coastlines throughout the global ocean.

Diurnal winds typically appear to propagate away from the nearest coastline, and breezes emanating from opposite

coastlines meet over the water. Often the convergence line is displaced from the mid-point. The displacement is not trivially explained as an orographic effect, a land-use effect, or a result of land-sea breezes being stronger at low latitudes. However, we identify two factors that may influence the land-breeze convergence. First, land breezes from opposite coasts can differ in strength, either due to differential heating or to maritime effects associated with islands and peninsulas. This can make the land breeze faster on one coast, which will displace the convergence line toward the more slower moving coast. Thus in seas located between the mainland and an island or peninsula, the land breeze typically appears to emanate from the mainland. Second, mean winds, typically from the north in these examples, can displace the convergence line. More detailed assessment of these phenomenon will likely require more comprehensive numerical modeling efforts.

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Figure 1. Time-mean wind speed and direction from the QuikSCAT/ADEOS-II tandem mission 12.5 km resolution data, for (a) the Red Sea (b) the Gulf of California, (c) the Caspian Sea, and (d) the Mediterranean basin (here shown as the eastern Mediterranean and Adriatic Sea) and the Black Sea. Land regions are color coded to indicate land use categories from the Biosphere Atmosphere Transfer Scheme (Dickinson *et al.* 1986).

Figure 2. Diurnal wind ellipses from the QuikSCAT/ADEOS-II tandem mission 12.5 km resolution data, for (a) the Red Sea (b) the Gulf of California, (c) the Caspian Sea, and (d) the Mediterranean basin (here shown as the eastern Mediterranean and Adriatic Sea) and the Black Sea. Reference ellipses adjacent to panel letters have semi-major axes of 1 m s⁻¹ and semi-minor axes of 0.5 m s⁻¹. Over water, colors indicate the semi-major axis length. Land regions are color coded to indicate elevation above sea level in meters.

Figure 3. Time of day when wind aligned with major axis of wind ellipse for (a) the Red Sea (b) the Gulf of California, (c) the Caspian Sea, and (d) the Mediterranean basin (here shown as the eastern Mediterranean and Adriatic Sea) and the Black Sea. Land regions indicate elevation in meters.

Figure 4. Dominant coast of sea breeze (see text for details) for (a) the Red Sea (b) the Gulf of California, (c) the Caspian Sea, and (d) the Mediterranean basin (here shown as the eastern Mediterranean and Adriatic Sea) and the Black Sea. Blue pixels indicate that on the basis of phase considerations, the morning land breeze appears to emanate from the nearest coastline; red pixels indicate that the morning land breeze appears to propagate toward the nearest coastline. The black isolines are 30 km apart. Land regions indicate elevation in meters.