6.5 THE SUBTROPICAL SEA BREEZE

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1. INTRODUCTION

The sea breeze is perhaps the most well-known thermally-driven circulation in the world. Everybody knows that the sea breeze begins in the late morning or early afternoon, is strongest in the late afternoon, and is replaced by a comparatively weak and shallow land breeze at night. Despite occasional reports of the sea breeze extending hundreds of kilometers inland in the Tropics, most people are familiar with a sea breeze that penetrates less than 100 km inland, and would imagine that the land breeze probably doesn't make it more than a few tens of km offshore.

How, then, does one explain a sea breeze which is strongest after midnight and stretches out to the middle of the Gulf of Mexico?

2. DATA

The Texas 2000 Air Quality Study (TexAQS-2000) was a major field program involving federal and state agencies, with the goal of understanding the formation and transport of ozone and particulate matter in eastern Texas, particularly in and around Houston. The experiment ran from August 15, 2000 to September 15, 2000, a period of time that coincides with the highest levels of ozone in Houston.

The meteorological phenomenon of greatest interest during TexAQS-2000 is the sea breeze, which governs the transport and recirculation of pollutants during days with light large-scale winds. To observe and document the sea breeze and its interaction with the urban heat island, six wind profilers and three radiosonde launch sites supplemented a permanent network of surface-based observations run by the Texas Natural Resource Conservation Commission and the National Oceanographic and Atmospheric Administration.

This paper presents some preliminary results, using data from coastal platforms and buoys. The locations of observing sites mentioned in the text are given in Fig. 1. Future analysis will incorporate profiler measurements and high-resolution numerical modeling.

3. OBSERVATIONS

The land/sea breeze dominates the wind variability along the coast in southeast Texas. Figure 2 shows the August 2000 time series of wind components from the Sabine Pass C-MAN platform (SRST2), located on the beach.

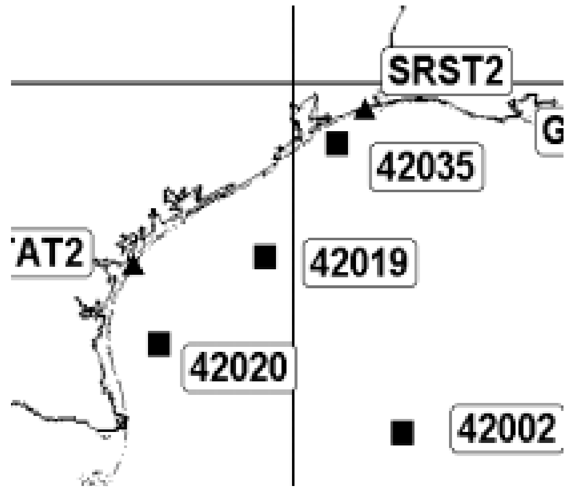

Fig. 1. Locations of C-MAN platforms (triangles) and buoys along the Texas Gulf Coast. Total domain of figure is 700 km by 700 km.

In this and subsequent figures, the onshore wind component is defined to be toward 330 degrees and the alongshore wind component is defined to be toward 60 degrees, reflecting the orientation of the coastline in southeast Texas. In order to isolate the land/sea breeze, a 24-hour running mean is computed for each wind component, and the hourly observed winds are subtracted from the running mean centered on the hourly observations. This difference is called the perturbation wind here, and it includes variations on diurnal and shorter time scales.

The strong diurnal signal is particularly apparent in the onshore wind component, shown by the thick line in Fig. 2. On all but one or two days during the month, the onshore wind reaches a maximum near 0000 UTC (1900 LST) and a minimum near 1200 UTC (0700 UTC). The diurnal oscillation, while regular, does not resemble a sinusoidal curve. Indeed, on many days, such as the days just past the midpoint of the month, the perturbation winds are weakly onshore for most of the day and strongly offshore for a few hours near dawn. The days in which a strongly offshore wind component occurs are precisely those days when the 24-hour average onshore wind component is weak. Careful comparison of the curves in Fig. 2 shows that strongly offshore perturbation wind corresponds to a total (perturbation plus 24-hour average) wind that is offshore, while with the weaker perturbation winds the total wind remains onshore all day and all night.

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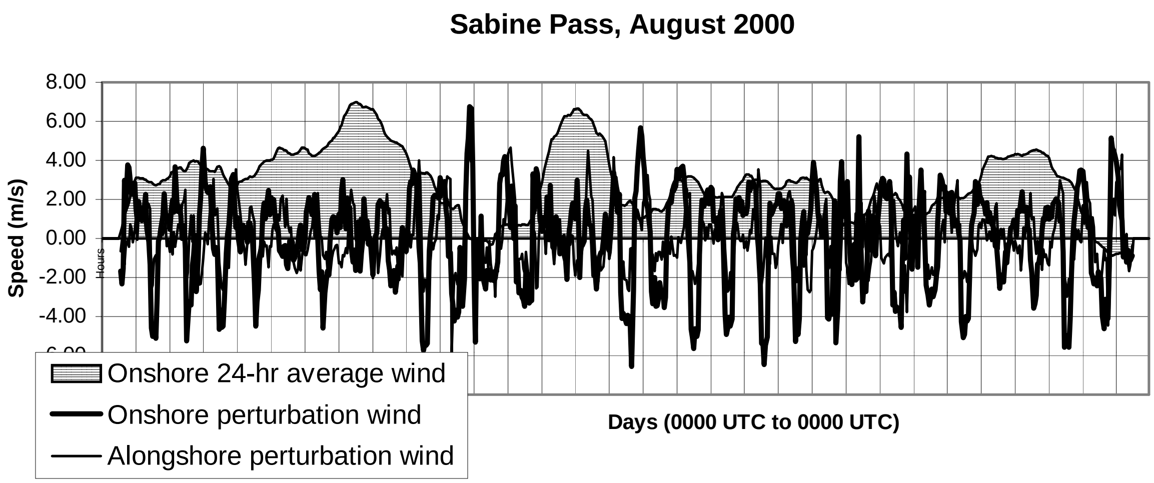

Fig. 2. August 2000 winds from Sabine Pass C-MAN station (SRST2). Each vertical grid line corresponds to 0000 UTC (1900 LST). Onshore and alongshore perturbation winds are indicated by thick and thin solid lines, respectively, while the 24-hour mean onshore wind is indicated by the hatching.

The alongshore component of the wind undergoes a weaker diurnal cycle. The alongshore component peaks during the evening, between 1900 LST and 0100 LST, a few hours after the onshore wind reaches its maximum. This clockwise turning of the wind with time is consistent with the well-known effect of the Coriolis force on the sea breeze. The occurrence of the minimum alongshore perturbation wind is less regular, sometimes occurring in the late morning, sometimes around dawn.

The enhancement of the land breeze on days with a weak onshore 24-hour average wind is presumably a nonlinear effect associated with near-surface air stagnating and developing a strong temperature gradient immediately adjacent to the coastline.

Fig. 3 shows the departure from 24-hour mean winds at buoy 42002, far into the Gulf of Mexico. Despite being hundreds of km from the nearest land, a clear diurnal signal is still present in the winds. The amplitude of the diurnal cycle is more than 50% of the diurnal amplitude at the immediate coastline, with typical peak-to-trough amplitudes of 4 to 5 m/s. The alonshore wind oscillation has similar amplitude and lags the onshore wind by about six hours

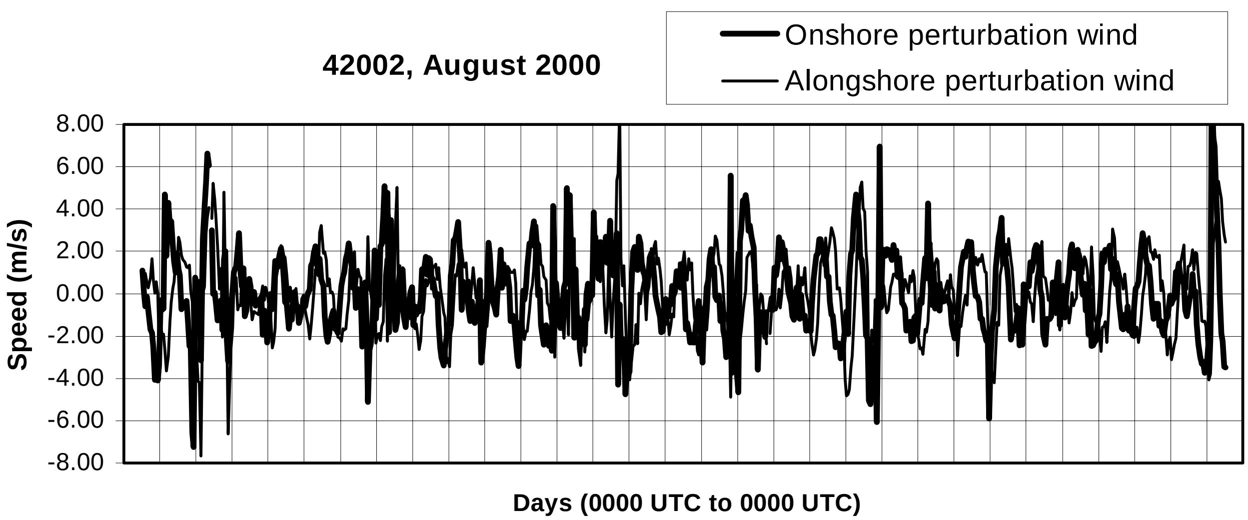

Fig. 3. August 2000 perturbation (departure from 24-hour average) winds from buoy 42002 (25.9N, 93.6W), approximately 400 km from the Texas Gulf Coast.

Intermediate buoys, such as 42035 and 42019 (see Fig. 1 for locations) exhibit similar behavior, indicating that Figs. 2 and 3 are observations of a single, large-scale diurnal wind oscillation. The time of the maximum onshore wind component occurred around 0000 UTC at the coast (Fig. 2), 0430 UTC at buoy 42035 (35 km offshore), 0700 UTC at buoy 42019 (110 km offshore), and 0800 UTC at buoy 42002 (Fig. 3).

The inertial character of the oscillation can be seen in a time hodograph of the winds from 42019. The time hodograph was constructed by averaging together the perturbation onshore and alongshore wind components hour by hour from Aug. 16, 2000 to Aug. 31, 2000.

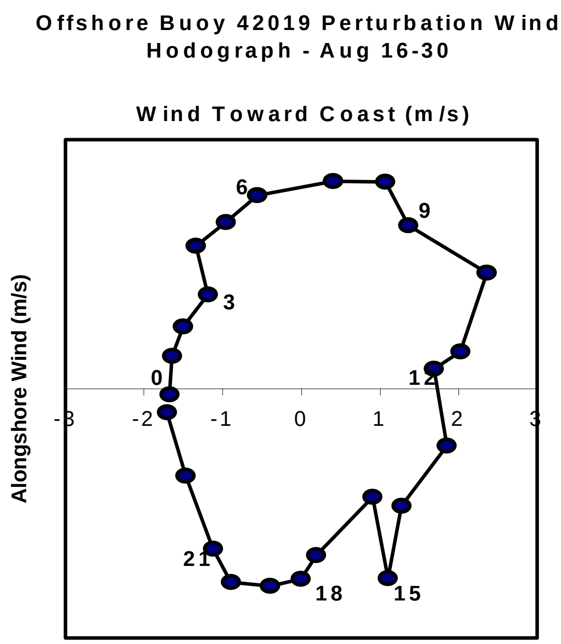

Fig. 4. Mean departure from 24-hour average wind, August 16-31, 2000. Onshore winds are indicated by points in top half of figure; offshore winds by points in bottom half. Times are labeled in hours UTC; subtract 5 to obtain LST.

The time hodograph winds are almost circular, implying a complete inertial oscillation. At 0000 UTC (1900 LST), the perturbation wind is oriented parallel to the coast, with the coastline to the right of the wind vector. Soon after 0600 UTC the strongest onshore wind is observed. By 1200 UTC, the wind is again parallel to the coast, but with the land to the left of the wind vector. By 1800 UTC, a strong offshore wind has developed which persists through most of the afternoon. Similar hodographs, with slightly different timing, are found in data from the other buoy locations.

4. THEORY

The land/sea breeze observed off the coast of Texas is inconsistent with common conceptualizations of the sea breeze. For example, the timing of the sea breeze is generally related to the arrival of the sea breeze front. Sea breeze fronts typically form in environments with weak offshore winds; by analogy, one would expect land breeze fronts to form in environments with weak onshore winds, and the onset of the land breeze offshore ought to coincide with the arrival of the land breeze front. However, such a front would have to travel 25-30 m/s in order to reach buoy 42002 on time. In any event, the perturbation winds at 42002 do not show any regular discontinuities that might be associated with the daily passage of a front.

By itself, this is not a problem. The sea breeze front is a nonlinear phenomenon, and linear theory has been used for decades to adequately describe land/sea breeze structure and behavior. Perhaps of more concern is the timing of the sea breeze: the buoy 35 km offshore (42035) normally experiences a sea breeze during the night and a land breeze during the day. Finally, the very large horizontal scale of the land/sea breeze circulation is counter to land-based experience: the distance from the Gulf Coast to buoy 42002 is comparable to the distance from Pittsburgh to the center of Chesapeake Bay.

Rotunno (1983) was the first to use linear theory to systematically investigate the dependence of the horizontal scale of the land/sea breeze on latitude. Assuming inviscid flow, heating of the form $Q(x,z)e^{i\omega t}$ (where ω is the diurnal frequency), and a streamfunction response of the form $\psi(x,z)e^{i\omega t}$, Rotunno obtained a single second-order equation for ψ:

$$N^2 \frac{\partial^2 \psi}{\partial x^2} + (f^2 - \omega^2)\frac{\partial^2 \psi}{\partial z^2} = -\frac{\partial Q}{\partial x} \qquad (1)$$

The nature of solutions to (1) depends on the sign of (f^2 - ω^2): if positive, (1) is elliptic and the response decays away from the coastline; if negative, (1) is hyperbolic, supporting wavelike solutions taking the form of internal inertia-gravity waves. The transition takes place at latitudes of +/- 30 degrees, where the diurnal frequency equals the Coriolis frequency. Poleward of 30^o, the solution is evanescent; equatorward of 30^o, the solution is propagating.

Equation (1) can be used to estimate the length scale of the sea breeze. If the vertical scale *h* is imposed by the depth of the boundary layer, the horizontal scale *l* is

$$l = \frac{Nh}{\left| f^2 - \omega^2 \right|^{1/2}}.$$

At most latitudes, the horizontal scale is on the order of 100 km, but near 30^o the horizontal scale becomes considerably larger. Rotunno speculated that frictional effects would be fundamentally important near that latitude.

A final curiosity of the inviscid solutions: poleward of 30^o the sea breeze coincides with the time of maximum heating, while equatorward of 30^o the sea breeze coincides with the time of maximum cooling. This apparently counterintuitive result is easily explained: the heating affects the rate of change of the horizontal pressure gradient, so the maximum pressure gradient ought to occur at the end of the heating, near sundown. The pressure gradient affects the rate of change of the horizontal wind, so the maximum horizontal wind ought to occur six hours after the time of maximum pressure gradient, or near midnight. With sufficient friction added, Rotunno showed that the sea breeze would peak in late afternoon at all latitudes.

Niino (1987) argued that Rotunno's (1983) theory was fundamentally flawed because it assumed that the vertical scale of the heating was independent of viscosity. Instead, viscosity is physically required for vertically redistributing the surface heating contrast, so Niino developed a linear theory which included turbulent diffusion of both heat and momentum. The governing equation is eighth order and will not be reproduced here, but it reduces to Rotunno in the inviscid, hydrostatic case.

With friction included, the singularity at 30^o vanishes. Furthermore, the maximum length scale is found at the equator. No longer is there anything special near the latitude of Houston.

5. DISCUSSION

We have the annoying situation that the simpler, less complete theory better fits the observations than the more complex, more complete theory. The very large seaward extent of the land/sea breeze in the buoy observations is consistent with Rotunno's (1983) theory, but not with Niino (1987). The offshore timing of the sea breeze also agrees with Rotunno's inviscid theory.

Perhaps the key to the puzzle lies in the diurnal nature of turbulent diffusion. Diffusion strong enough to produce a deep zone of thermal forcing should only be present during daytime hours over land, as the boundary layer becomes neutrally or unstably stratified. Elsewhere, in particular offshore, friction should be considerably weaker. Perhaps the Rotunno theory, with a wavelike response, is appropriate for the offshore branch of the land/sea breeze, while the Niino theory is applicable over land, particularly during daytime.

Future work will address this issue, by utilizing a realistic, time-dependent turbulent diffusion to properly mimic the actual lower atmospheric forcing, both in idealized linear models and in fully nonlinear two-dimensional mesoscale models. In the meantime, some interesting issues are raised regarding the strength of air-sea exchange over the Gulf of Mexico and the transport of pollutants over the Gulf.

Recently, we have looked preliminarily at profiler data from TexAQS-2000. Composite profiler data shows diurnal wind cycles whose maximum onshore component occurs later and later with increasing height. The pattern is reminiscent of a propagating inertia-gravity wave, except that the phase propagation is upward, implying a downward group velocity. This paradox may perhaps be reconciled through consideration of the vertical delay in the diurnal heating: strongest heating at the surface is at midmorning, while the boundary layer does not deepen sufficiently to cause heating at 1.5 km until midafternoon.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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