3.3 THE ROLES OF WIND STRESS AND WIND STRESS CURL IN FORCING THE OCEAN DYNAMICS IN A COASTAL BAY

Darko Koracin* and Adam Kochanski
Desert Research Institute, Reno, Nevada

Clive Dorman[12]
[1]Scripps Institution of Oceanography, San Diego, California
[2]San Diego State University, San Diego, California

James Pringle
University of New Hampshire, Durham, New Hapshire

1. INTRODUCTION

One of the outstanding problems to be resolved is the roles of along-shore wind stress and the wind stress curl in generating coastal upwelling. Moreover, temporal and spatial scales relevant to the air-sea interaction are not understood well. A Wind Events and Shelf Transport (WEST) study, sponsored by the U.S. National Science Foundation (NSF), was conducted during 2001 and 2002 over the northern California coastal waters (Largier et al. 2006). This comprehensive field program including meteorological, oceanic, and marine biology measurements was carried out over the Bodega Bay area and its vicinity. The main objective of the project was to investigate the effects of wind forcing on ocean dynamics and marine biology. A special set of five buoys, arranged in a diamond formation, and three coastal stations provided detailed wind measurements in the bay (Fig. 1). This setup allowed us to directly compute wind stress curl using wind stress spatial variation computed from the buoy winds (Dorman et al. 2005; Kochanski et al. 2006). For the wind stress curl calculations, a triangular set of buoys (D090, E090 and National Data Buoy Center (NDBC) buoy 46013) was used. Buoy measurements included wind speed components, air and sea surface temperatures, radiation fluxes, and humidity. Three-month long, 1 km horizontal resolution simulations with Mesoscale Model 5 (MM5) and data from a field program conducted over the California and Oregon coastal waters were used to investigate the effects of the along-shore wind stress and wind stress curl on the ocean dynamics in the Bodega Bay region, California. The data from five buoys arranged in a diamond shape with sides of about 30 km revealed the complex structure of the wind stress and the wind stress curl relevant to the ocean dynamics and marine biological cycle in Bodega Bay. One of the reasons for this temporally variable inhomogeneous flow field, which induces significant wind stress curl, is that Bodega Bay lies at the downwind edge of the temporally and spatially variable expansion fan caused by the Point Arena topography. To complement scarce measurements over the ocean, atmospheric modeling provides estimates of the winds, wind stress, and wind stress curl over the ocean as well as an insight into the physical processes that are relevant to air-sea interaction (Dorman et al. 2000; Koracin and Dorman 2001; Samelson et al. 2002; Koracin et al. 2004).

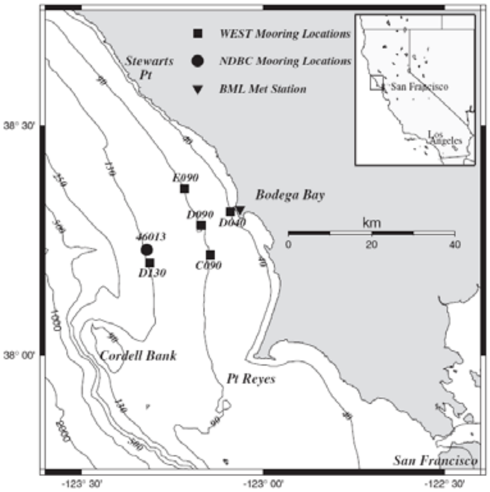

Fig. 1. Locations of the wind and oceanographic data used in this study. Oceanographic moorings are indicated by black squares. National Data Buoy Center (NDBC) 46013 is indicated by the circle, and the Bodega Marine Laboratory (BML) coastal meteorological station is indicated by the inverted triangle.

*Corresponding author address: Darko Koracin, 2215 Raggio Pkwy, Desert Research Institute, Reno, NV 89512; e-mail: darko@dri.edu

In this study, month-long Mesoscale Model 5 (MM5) simulations have been used to investigate the spatial and temporal structure of the marine-layer winds, wind stress, and wind stress curl during upwelling-favorable winds along the California and Baja California coasts. Previous work by Koracin et al. (2004) has shown that the most intense wind stress and wind stress curl are expected in the lees of coastal capes. To resolve the atmospheric dynamics in this highly complex coastal zone, we have used model grids with high horizontal resolutions of 9, 3, and 1 km.

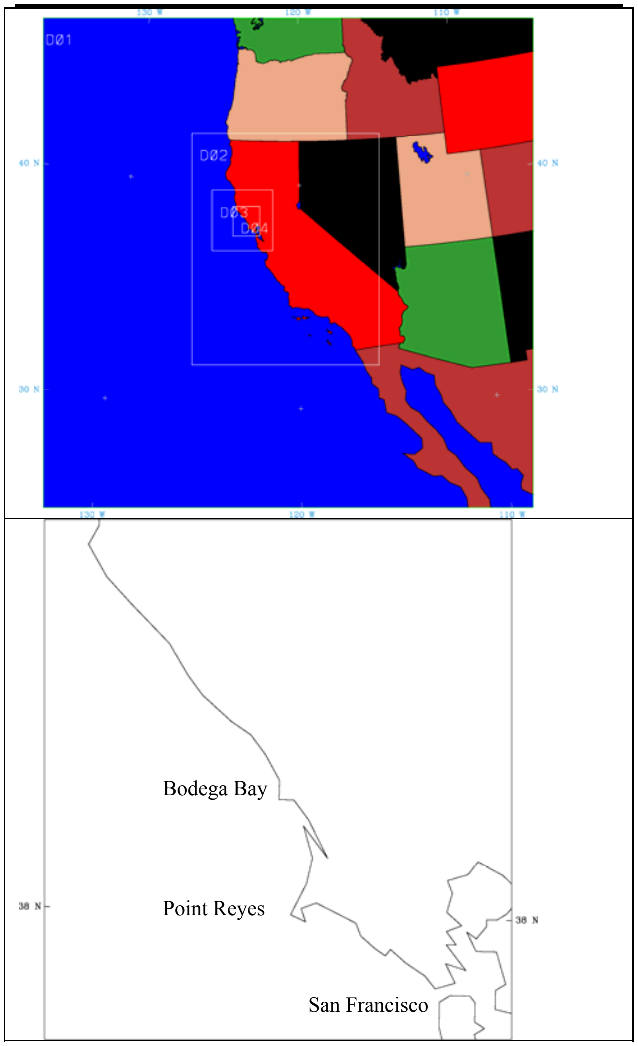

Fig. 2. MM5 setup of the four modeling domains (upper panel) and the fourth domain with 1 km resolution (lower panel).

2. MM5 EVALUATION

Figure 3 shows a time series of measured and simulated wind speed and direction for all of July 2001. The model was able to reproduce well the magnitude and multiday oscillations as measured by the buoy. Notice that there are three major areas of elevated wind and two relaxation areas. The high winds were associated with persistent wind direction, while during the relaxation periods the wind direction was more variable.

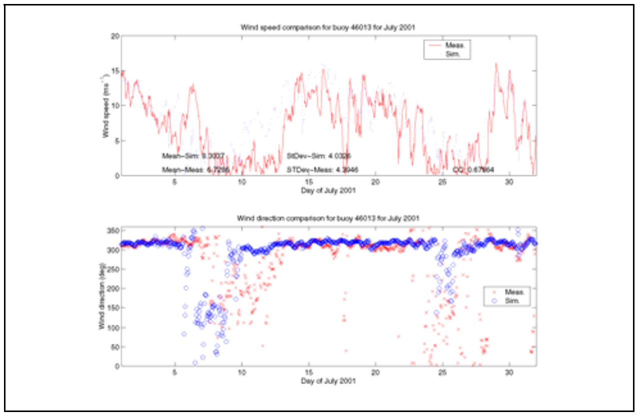

Fig. 3. Time series of the surface wind speed and direction as measured at the Bodega Bay Buoy (46013) ad predicted by MM5 for all of July 2001.

3. HYDRAULIC EFFECTS

As shown by previous studies, high winds are persistent in the lees of major capes (Koracin and Dorman 2001). Bodega Bay buoy is in the area downwind of the Point Arena with high winds. Although the buoys 46013 and 46014 are separated by 120 km, they exhibit the same regime (Fig. 4). The Bodega Bay buoy is at the developed end of the expansion fan and shows even higher winds compared to the Point Arena buoy. Notice that Koracin and Dorman (2001) found same characteristics for June 1999. A recent study by Pringle et al. (2006) shows that the atmospheric forcing of upwelling at a certain location should not be generally considered as a local effect. The structure and evolution of wind fields over a certain region can influence ocean dynamics in far distant places due to complexity of ocean circulations and air-sea interaction.

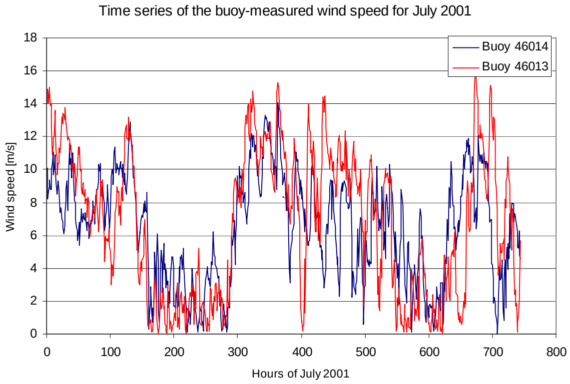

Fig. 4. Hourly wind speed for buoys 46013 and 46014 for all of July 2001.

Figure 5 shows monthly average of the wind speed and the standard deviation of the wind speed for July 2001.

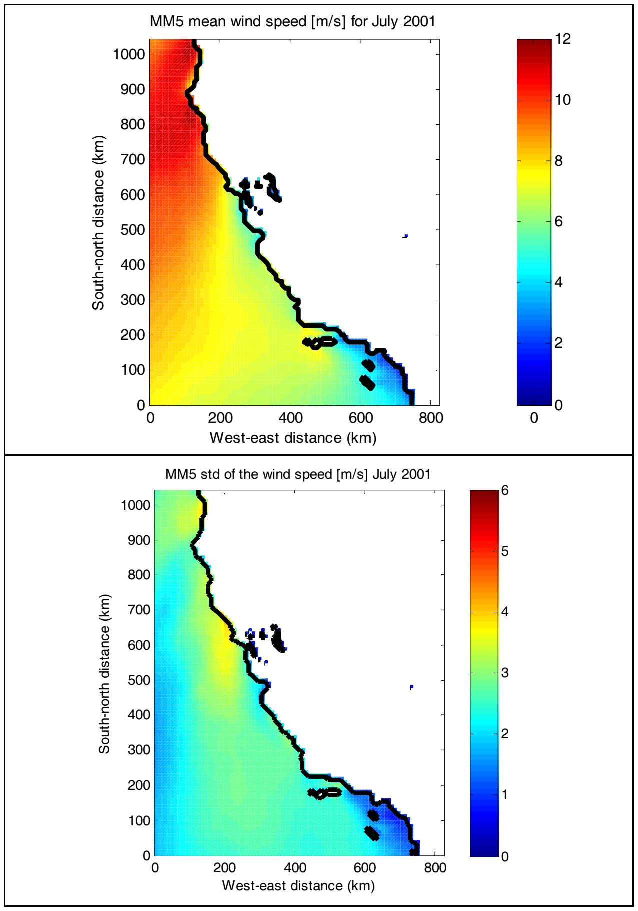

Fig. 5. Monthly average wind speed (m/s) (upper panel) and the standard deviation of the wind speed (m/s) (lower panel) computed from the MM5 results for July 2001.

The Bodega Bay area is in the pronounced expansion fan in the lee of Point Arena and according to the standard deviation computation, this is an area of significant variations in the wind speed.

4. PARAMETERIZATION OF THE WAVE-INDUCED STRESS

One of the important effects on the wind, wind stress and wind stress curl that is frequently omitted in atmospheric and oceanic studies is due to surface ocean gravity waves. Due to high winds and strong wind gradients in a coastal zone, it is important to assess what impact the waves have on atmospheric and back on oceanic circulations including upwelling. We have developed a parameterization of wave-induced stress following Janssen (1989). The wave-induced stress is computed as follows:

$$\frac{\tau_{wx}}{\tau} = \alpha_p \frac{\mu}{\pi}(28)^2\{f(X_p) + X_p g(X_p) - (X_p)^2 h(X_p)\},$$

where $X_p = c_p/28u_*$ (here c_p/u_* is the wave age)

$c_p = \omega_p/k_p$ is the phase speed

$$\alpha_p = 0.57(c_p/u_*)^{-3/2}$$

f(Xp), g(Xp), and h(Xp) are polynomial expressions (see Janssen 1989).

Phase speed is calculated as follows:

$$C_P = \sqrt{(g/k)\cdot \tanh(k\cdot h)}$$

where

k – wave number

T - peak period

λ - wave length

h – water depth

$k=2\pi/\lambda$,

$\lambda \approx gT^2/2\,\pi$

$k=4\pi^2 gT^2$

$$C_P = \frac{gT}{2\pi}\sqrt{\tanh(h\cdot\frac{4\pi^2}{T^2 g})}$$

5. WAVE-INDUCED STRESS

Figure 6 shows the estimates of the ratio between the initial atmospheric stress (without wave effects) and wave-induced stress for all of

July 2001. Since the wave phase speed does not change significantly within the buoy location, the main changes are related to wind and friction velocity variation. For many cases of low winds the asymptotic method by Janssen (1989) and also other authors approaches 0.26, which might be related to swell effects. During high winds the ratio becomes significant and approaches 0.5

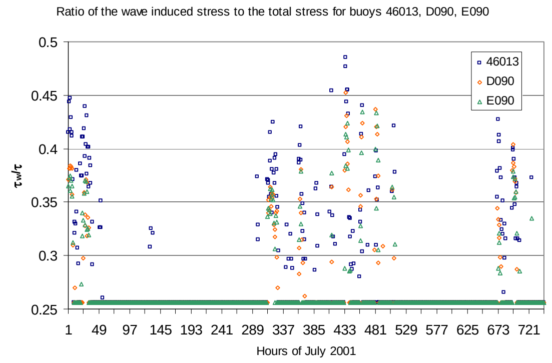

Fig. 6. Estimates of the ratio between the initial atmospheric stress (without wave effects) and wave-induced stress for all of July 2001.

6. WIND STRESS CURL MODIFIED BY THE WAVE EFFECTS

The changes on the wind stress curl by wave activity are shown in Fig. 7.

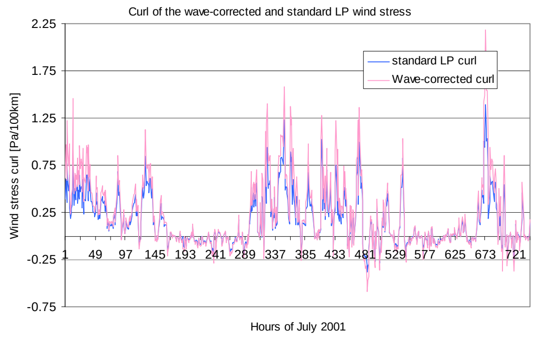

Fig. 7. Hourly wind stress curl (Pa (100 km)$^{-1}$) for July 2001 as estimated with and without wave effects.

The figure shows that the wave effects significantly increased the curl. The curl is dominantly positive and consequently curl-generating upwelling was quite frequent during this month. However, since the wave direction measurements were not available during this period, we assumed the same wave direction as the wind direction. Note that the differences between the wave direction and wind direction can lead to an increase or decrease in the final stress.

7. CONCLUDING REMARKS

The results indicate that the wave-induced stress has a significant impact on the wind stress and wind stress curl. The ratio between the initial atmospheric stress (without wave effects) and wave-induced stress appears to be limited in occurrence, but high during the moderate and large winds. Future eddy correlation wind measurements collocated with the detailed wave measurements are needed to provide the basis for a parameterization of the wave-induced stress.

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