Oceanic thermal and biological responses to Santa Ana winds

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[1] Ocean surface wind vectors with improved spatial resolutions were derived from the National Aeronautics and Space Administration's (NASA's) Quick Scatterometer (QuikSCAT) satellite. They allow us to examine the details and extent of oceanic influence of a Santa Ana event - a strong offshore and downslope wind in southern California that may spread wide fires, damage properties, and endanger aviation. The oceanic thermal and biological responses to the surface wind jets were observed with other spaceborne sensors. It is found that surface wind jets reduce sea surface temperatures and increase biological productivities. Spacebased measurements demonstrate the inadequacy of current operational numerical weather prediction (NWP) models to accurately and consistently predict the characteristics of Santa Ana winds over the coastal ocean. *INDEX TERMS:* 4247 Oceanography: General: Marine meteorology; 4504 Oceanography: Physical: Air/sea interactions (0312); 4572 Oceanography: Physical: Upper ocean processes. **Citation:** Hu, H., and W. T. Liu, Oceanic thermal and biological responses to Santa Ana winds, *Geophys. Res. Lett.*, *30*(11), 1596, doi:10.1029/2003GL017208, 2003.

1. Introduction

[2] A "Santa Ana" is a local weather condition in southern California that is characterized by strong offshore surface winds, low relative humidities, and clear skies [*Lynn and Svejkovsky*, 1984]. Forecasting Santa Anas is important because such events can threaten public safety-spreading wildfires, causing power outages, damaging property with strong winds, making aviation hazardous because of low-level wind shear, and causing injury from falling debris. Santa Ana winds occur mainly in the fall and winter, and may last one to several days. The formation of a Santa Ana is associated with an intense high-pressure system in the Great Basin (Nevada and Utah regions) and a weak low-pressure system just off the southern California coast [*Sommers*, 1978; *Small*, 1995]. The strong pressure gradients and the complex surface terrain that intervenes between the high- and low-pressure systems produce warm and dry downslope winds. When downslope winds are channeled by mountain gaps such as canyons and passes, they accelerate and form wind jets. The name of "Santa Ana" may have been given to this condition by early settlers of Santa Ana, California, downwind of the Santa Ana Canyon, through which such wind jets commonly course.

[3] Using high-resolution ocean surface wind vector measurements produced by QuikSCAT specifically for this study, we present a case study of air-sea interactions driven by a Santa Ana event in February of 2002. The intensity of Santa Ana wind jets, their extent over the ocean, and the surface dust they transported are presented in section 2. The thermal and biological responses to the wind event in the coastal ocean are discussed in section 3. The capability of high-spatial resolution operational weather forecast models for capturing the essential characteristics of Santa Ana events is analyzed in section 4.

2. Observations of Santa Ana Winds

[4] QuikSCAT measures ocean surface wind vectors, under clear and cloudy conditions, night and day, over 90% of global ocean daily [*Liu*, 2002]. The standard wind product has a spatial resolution of 25 km and is produced from non-range compressed backscatter measured by the scatterometer. In this study, higher resolution wind product at 12.5-km resolution was produced from range-compressed backscatter, using the Direction Interval Retrieval with Thresholded Nudging (DIRTH) method [*Stiles*, 1999], specially adapted for high-resolution retrieval. These high-resolution data are found to have bias and root-mean-square differences similar to those of standard data when compared with off-shore buoy measurements, but have slightly larger values when compared with measurements from coastal buoys (within 10–30 km from shore) [*Tang et al.*, 2003]. The application of QuikSCAT high-resoultion data on Catalina Eddy events in the Southern California Bight has been reported by *Hu and Liu* [2002].

[5] A strong Santa Ana event occurred in February of 2002. Figure 1 is the hourly wind speed and gust peak recorded from an automated weather station (station ID FMC) operated by California Data Exchange Center. The station is located at (117.7°W, 33.8°N) in the Santa Ana River Basin at Fremont Canyon. Santa Ana winds started from February 9, 2002 and lasted less than three days. The wind gust was as high as 35 m/s (78 m.p.h. or 69 knots), far in excess of 25 knots, the minimum required for classification as a Santa Ana wind [*Small*, 1995]. QuikSCAT passes through the Southern California Bight twice daily, but may miss the area one day every three to four days. Observations within 15 km of coastlines were not used in this study because of possible land contamination. At 13:51 UT on February 9, 2002, QuikSCAT observed that the winds off the southern California and northern Baja Mexico coasts had changed from a normal alongshore directions to an offshore direction. The strongest Santa Ana winds observed by QuikSCAT were at 13:25 UT on February 10, 2002, with speeds as great as 16 m/s, and at some locations formed distinguished jets (Figure 2). These ocean jets are the extensions of terrestrial wind jets, originating in mountain gaps and passes (see the topographic map in Figure 2). At the same time, the surface wind recorded at the FMC station

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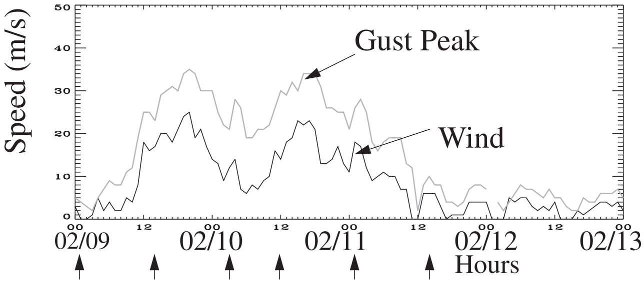

Figure 1. Hourly wind speed (black line) and gust peak (grey line) recorded from February 9 to 12, 2002 at an automated weather station (station ID FMC) operated by California Data Exchange Center. The station is located at (117.7°W, 33.8°N) in the Santa Ana River Basin at Fremont Canyon. The arrows indicate the time when QuikSCAT passed through the Southern California Bight.

had a hourly average of 24 m/s and gust peak of 30 m/s. According to QuikSCAT, wind jets with speeds above 8 m/s extended about 400 km into the coastal waters. Besides these jets, offshore winds blew far beyond coastal regions and pushed marine clouds about 1000 km out to sea, before merging with the alongshore flow. The distance over which Santa Ana winds extend their influence in the ocean was revealed for the first time by QuikSCAT. The cloud-free area observed by other spaceborne sensors also confirmed the wide boundaries of this influence (see Figure 3).

[6] The effect of Santa Ana winds on local cloud and dust distributions can be seen in optical sensors on NASA's Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite. Figure 3 is a high resolution picture transmission (HRPT) true-color image at 1-km resolution obtained at 20:15 UT on February 10, 2002 at station HUSC (34.4°N, 119.7°W) at the University of California, Santa Barbara. During a Santa Ana event, wind gusts may pick up surface dust and spread it over coastal waters. SeaWiFS image in Figure 3 shows dust plumes with a length of several hundred kilometers co-located with some of the wind jets.

3. Oceanic Thermal and Biological Responses

[7] The Southern California Bight is often covered by marine clouds, and its oceanic thermal and biological characteristics can not be revealed by spacebased infrared and optical sensors when marine clouds are present. Owing to the clearing of these clouds by Santa Ana winds, however, these sensors were able to observe the oceanic thermal and biological responses to the Santa Ana event.

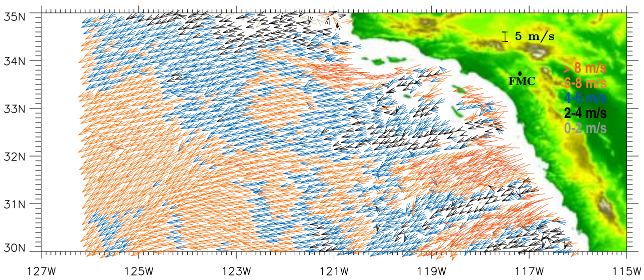

Figure 2. Ocean surface winds measured by QuikSCAT at 13:25UT, February 10, 2002. Data are at 12.5-km resolutions. Observations within 15 km of coastlines were not used in this study. The color scale indicates the magnitude of wind speed. The location of the weather station FMC is labeled on the plot.

Figure 3. A true-color image obtained from SeaWiFS at 20:15 UT on February 10, 2002. The 1-km HRPT data were received at the station HUSC (34.4°N, 119.7°W). The size of the area is the same as in the Figure 2. There were dust plumes in the coastal waters. Marine clouds were located about 1000 km from coastlines.

[8] The ocean's thermal response to the Santa Ana can be seen in Figure 4, which shows the sea surface temperature (SST) at 20:38 UT on February 10, 2002, as observed by the Advanced Very High Resolution Radiometer (AVHRR) on the National Oceanic and Atmospheric Administration's (NOAA's) polar-orbiting weather satellite, NOAA-16, at 1.1-km resolution. The figure is a composite image of two regions, Southern California and Northern Baja Mexico, obtained from the NOAA CoastWatch Program. Black areas over the ocean represent data that are lacking-whether because an area was obscured by clouds, or because the data were not available for these CoastWatch regions. Figure 4 shows plumes of cold water in the same locations as the Santa Ana wind jets shown in Figure 2. The cold-water plumes have SSTs as much as 4°C lower than those of ambient waters. Along the jets, strong winds apparently cause intense vertical mixing, bring cold water and nutrients

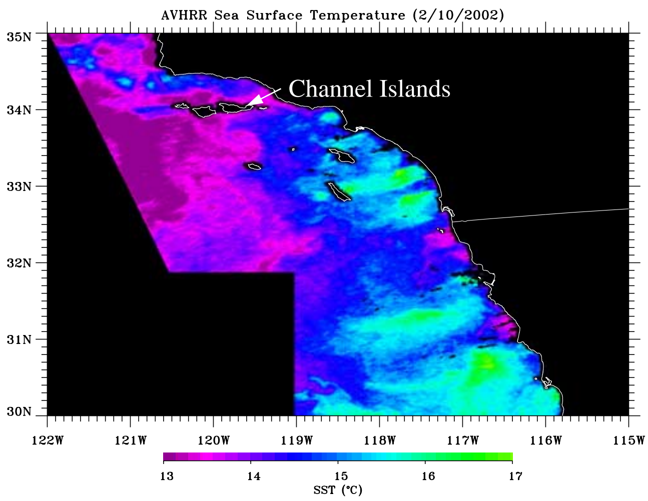

Figure 4. Sea surface temperatures measured at 20:38 UT on February 10, 2002 from AVHRR at 1.1-km resolutions. Black areas over the ocean represent missing data due to clouds or data not available from NOAA CoastWatch regions.

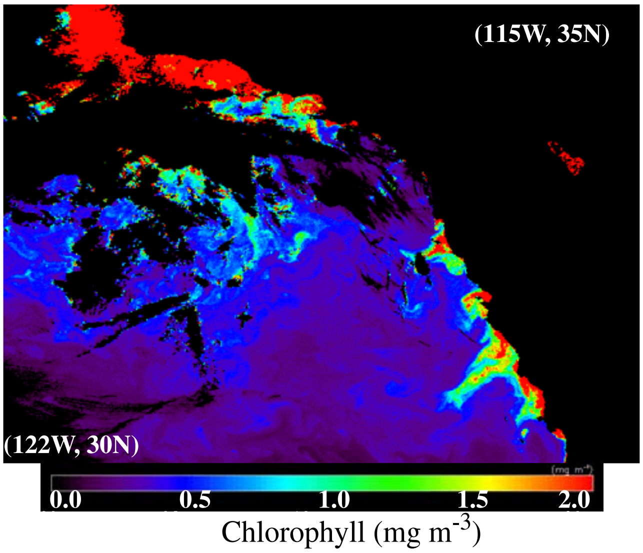

Figure 5. Ocean color chlorophyll data at 1-km resolutions from SeaWiFS HRPT HUSC station. The data were obtained at 20:00UT on February 12, 2002, a dust-free and normal wind condition. Black areas over the ocean indicate missing data due to clouds. The size of the plotted region is the same as in Figure 4.

from deep waters to the surface layer. It is worth mentioning that aerosols may cause errors on SST retrievals, however, the observed cold water plumes under the Santa Ana dust might be still realistic. There are no dust clouds over the cold-water plumes along the wind jet near the Channel Islands; the ocean cooling registered there should not be attributed to an error in SST retrieval caused by aerosols. Similar SST measurements observed on this date by Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's earth-observing system (EOS)-Terra satellite (not shown) confirm this oceanic response to the Santa Ana event. Moreover, similar cold-water plumes generated by mountain jets have been observed by NASA scatterometer (NSCAT) in coastal waters of the Japan Sea [*Kawamuram and Wu*, 1998] and off the Pacific coast of Central America [*Chelton et al.*, 2000].

[9] The ocean's biological response to the Santa Ana event can be seen in Figure 5, which shows ocean color, representing chlorophyll concentration, measured by SeaWiFS. The measurements were taken at 20:00UT on February 12, 2002, a dust-free condition identified by SeaWiFS true-color image and a normal wind condition indicated by the weather station FMC (QuikSCAT did not have coverage on this date). Elevated chlorophyll concentrations were observed along the Santa Ana wind jets. The black areas in the ocean indicate lack of chlorophyll measurements due to cloud cover. *Mouliin et al.* [2001] showed that Saharan dust has strong absorption to the blue, and hence hinders ocean color chlorophyll retrievals. Although dust concentration in Santa Ana event is much lower than that in a Sahara dust event, we avoided any risk of distortion by using chlorophyll data from after the Santa Ana dust event. During normal conditions, coastal biological activity in the Southern California Bight is enriched by a strong upwelling caused by alongshore northerly surface winds (an effect called Ekman transport). During a Santa Ana event, the surface winds change to offshore directions, thus upwelling due to Ekman transport was suppressed. However, entrainment of deep water into the surface layer due to vertical mixing of the ocean was increased. The interplay of these two determines the net impact of a Santa Ana event on the ocean's physical and biological processes.

[10] By comparing SST and chlorophyll data collected during the Santa Ana event on February 10, 2002 and during a clear-sky normal wind condition on February 5, 2002, it is found that over the strong Santa Ana wind jet areas, the vertical mixing process dominates, thus the SST decreases and chlorophyll increases; elsewhere in coastal waters affected by Santa Ana winds, the downwelling process dominates so SST increases, and chlorophyll shows little changes from normal.

4. Model Forecasts

[11] Accurate forecast of Santa Ana events is highly desirable because with adequate preparation, people can reduce the risks associated with Santa Ana winds. QuikSCAT measurements for the Santa Ana event discussed above were compared with forecast products from a hydrostatic mesoscale numerical weather prediction (NWP) model, the Eta model, developed at the National Centers of Environment Prediction (NCEP). The model is so named for its vertical coordinate, known as the "eta" or "step-mountain" coordinate. For this study, we used the operational Eta-12 model with a 12-km horizontal e-grid and 60 step-mountain eta levels [*Rogers et al.*, 2003].

[12] The 12-h forecast of sea-level pressure, valid at 12:00 UT on 10 February 2002, is obtained from the NCEP Eta-12 operational model. A strong surface high (over 1045 mb) is found in the Great Basin area, and a weak low (below 1030 mb) in the Southern California Bight. The model successfully predicted a Santa Ana scenario on the basis of these large-scale dynamics. Figure 6 is a 12-h forecast of 10-m winds obtained from the same model. The model did predict strong off-shore Santa Ana

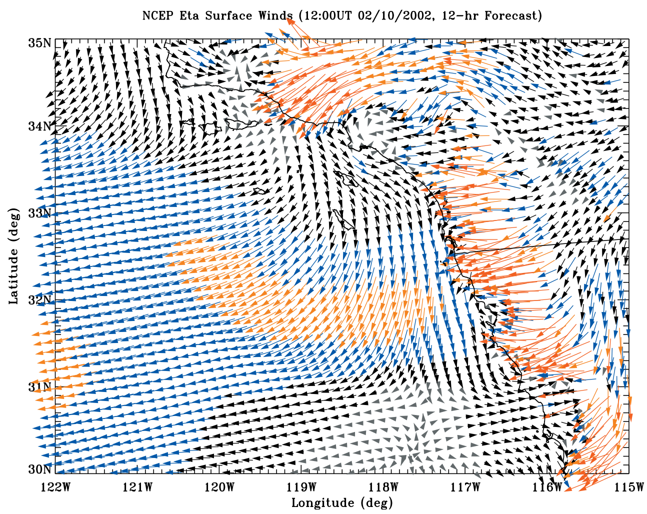

Figure 6. 12-h forecast of 10-m winds, valid at 12:00UT on February 10, 2002, from the NCEP Eta-12km model. Color scales for wind speeds are the same as those in Figure 2.

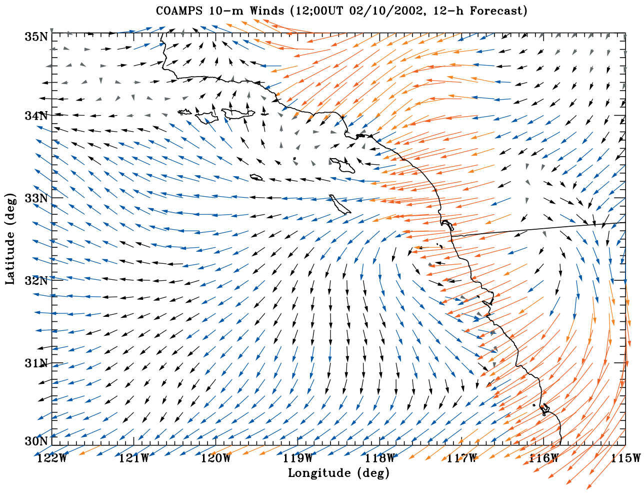

Figure 7. 12-h forecast of 10-m winds, valid at 12:00UT on February 10, 2002, from the COAMPS-27km nest model. Color scales for wind speeds are the same as those in Figure 2.

winds over coastal lands, however, over the ocean there was considerable discrepancy between the forecast wind and the QuikSCAT wind. The Eta model failed to reveal terrestrial wind jets continuing over the coastal waters. As seen in Figure 6, winds over coastal waters were mostly alongshore, with speeds much less than the QuikSCAT observations. The problem of flow separation in downslope winds has been discussed by *Gallus and Klemp* [2000]. Based on their numerical simulations, they found that downslope flow could not be properly simulated using the step-terrain coordinate (as used in NCEP Eta models) because instead of descending, the flow separates downstream of the mountain and produces a zone of artificially weak flow.

[13] We also examined forecast winds from another operational NWP model, the Coupled Ocean Atmosphere Prediction System (COAMPS) developed by Naval Research Laboratory. Figure 7 is the 12-h forecast of 10-m winds, valid at 12:00 UT on 10 February 2002, from the COAMPS Eastern Pacific 27-km nest model (horizontal outputs at 20-km resolutions). Winds over the ocean were dominated by offshore flows originating from Los Angeles and San Diego Basins, however, the model failed to produce Santa Ana wind jets near Channel Islands, and in coastal waters off northern Baja Mexico. The COAMPS model uses sigma z vertical coordinates and includes non-hydrostatic effects.

5. Conclusion

[14] High-resolution satellite observations were used to study air-sea interactions during strong Santa Ana winds. NASA QuikSCAT satellite observed the effects of a Santa Ana wind as far as 1000 km off shore, with strong wind jets transporting dust and driving oceanic response up to 400 km into the coastal ocean. Along the wind jets, cold-water plumes with high chlorophyll concentrations were created by intense vertical mixing of the surface water. This study demonstrates the capabilities of spacebased scatterometry for monitoring coastal winds, and the potential of multi-sensor applications for studying coastal air-sea interaction. Operational NWP models do not predict coastal winds with the degree of accuracy as winds over land.

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