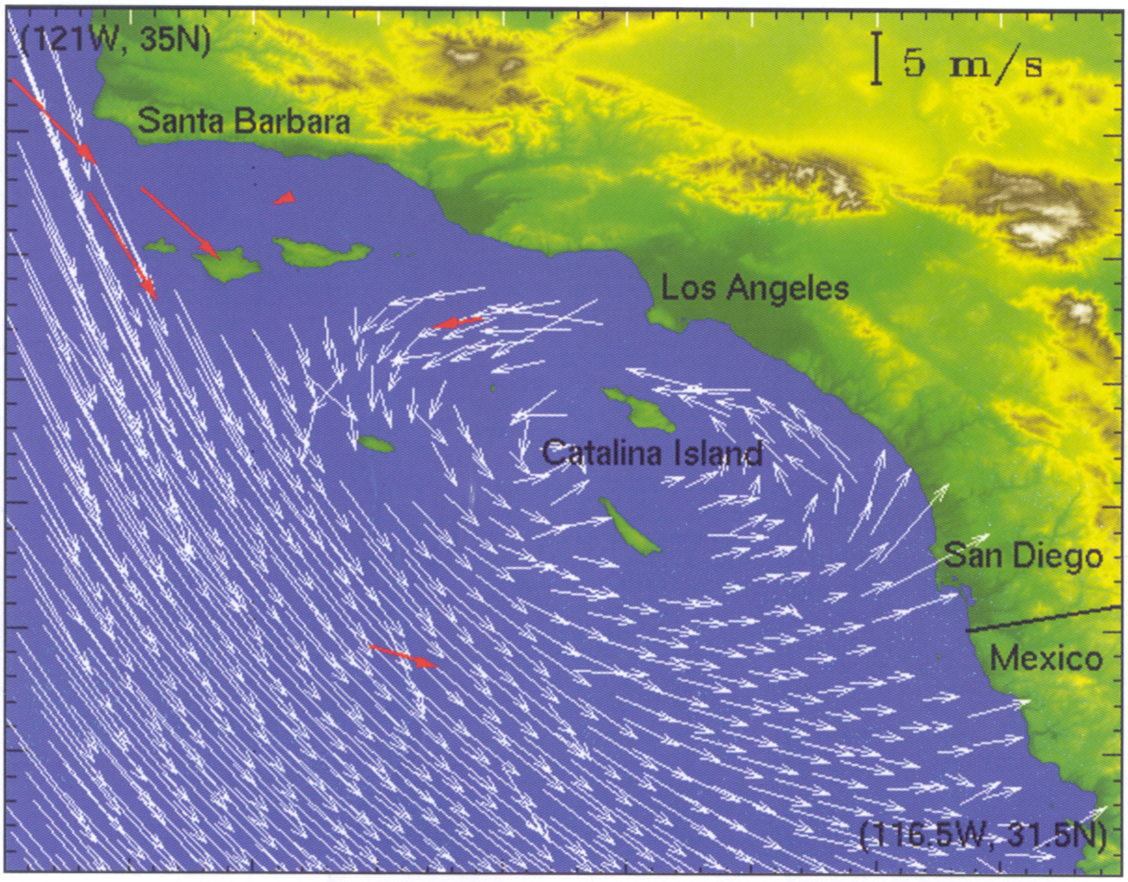
Geophysical Research Letters

1 SEPTEMBER 2002
VOLUME 29 NUMBER 17
AMERICAN GEOPHYSICAL UNION



Better weather for Southern California • Burning seasons cut solar energy • Carbon dioxide in the North Atlantic

GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 17, 1821, doi:10.1029/2001GL014203, 2002

QuikSCAT reveals the surface circulation of the Catalina Eddy

Hua Hu and W. Timothy Liu

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Received 9 October 2001; revised 30 January 2002; accepted 27 February 2002; published 4 September 2002.

[1] The Catalina Eddy, a small, recurring cyclonic vortex in the ocean off Los Angeles, is of keen interest to local weather forecasters because of the moderating oceanic effect it brings to the city. Its small size and shallow vertical extent have made it difficult to monitor and predict using conventional data. The microwave scatterometer on the QuikSCAT spacecraft has generated high-resolution surface wind vectors that provide the first visualization of the complete cyclonic flow of the eddy. Moreover, the superior performance of the QuikSCAT scatterometer demonstrates the relative inaccuracy and inconsistency of predictions of the eddy based upon numerical weather prediction models. *INDEX TERMS:* 4572 Oceanography: Physical: Upper ocean processes; 4504 Oceanography: Physical: Air/sea interactions (0312); 4247 Oceanography: General: Marine meteorology. **Citation:** Hua, H., and W. T. Liu, QuickSCAT reveals the surface circulation of the Catalina Eddy, *Geophys. Res. Lett.*, *29*(17), 1821, doi:10.1029/2001GL014203, 2002.

1. Introduction

[2] In the southern California bight, an area off the coast between the Point Conception and the Mexican border, the surface wind blows predominantly from the northwest. Occasionally, this typical pattern is interrupted when upper-level large-scale flow off the Point Conception interacts with the complex topography of the southern California coast to form a low-level cyclonic wind circulation called the Catalina Eddy, with its center near Catalina Island. During a Catalina Eddy event, the northwesterly flow within 100 km of the southern California coast becomes southerly; marine layers deepen and spread into the Los Angeles basin; and low-level cloudiness increases, resulting in cooler temperatures and better air quality inland [*Mass and Albright*, 1989]. Catalina Eddy events last from a few hours to several days and are most common from late spring through early fall, with a maximum frequency in May and June. During fall, winter and early spring, cold fronts passing through tend to be deleterious to eddy formation or maintenance.

[3] Several mechanisms have been proposed regarding the evolution and dynamics of the Catalina Eddy: a wake low produced by the topography east of the Point Conception [e.g., *Rosenthal*, 1972; *Wakimoto*, 1987], topographically trapped Kelvin waves [e.g., *Dorman*, 1985; *Clark*, 1994], leeside topographic troughing [e.g., *Bosart*, 1983; *Mass and Albright*, 1989], and others. Numerical simulations of the eddy have been attempted [e.g., *Ueyoshi and Roads*, 1993; *Ulrickson et al.*, 1995; *Thompson et al.*, 1997; *Davis et al.*, 2000]. But forecasting Catalina Eddy events has often been an uncertain exercise, partly due to the lack of a coherent physical model of its origin and structure. And conversely, given the small size of the eddy and the sparsity of coastal observations, comparisons between numerical simulations and observations are few and inconclusive. The effect of this eddy on the ocean is little known. Any change in local ocean upwelling caused by such a transient vortex is often obscured by cloud cover and cannot be detected by space-based visible and infrared sensors. Furthermore, there has not been any wind field with sufficient spatial resolutions to force general ocean circulation model in the simulation of oceanic responses to the Eddy.

[4] This paper demonstrates the capabilities of the high-resolution surface wind vectors produced by the scatterometer on QuikSCAT for measuring the complete surface circulation of the eddy. Such capabilities will be compared with those from conventional data and numerical weather predictions (NWPs).

2. Conventional Data

[5] In the bight of southern California, there are several moored buoy stations operated by the National Data Buoy Center (NDBC). Station identifiers are shown in Figure 1. We used 10-minute average values of continuous wind speed and direction, air temperature, sea surface temperature, and dewpoint temperature. For comparison with QuikSCAT winds at 10-m height, NDBC buoy winds at different heights were converted to equivalent neutral winds at 10-m height, using a method developed by *Liu and Tang* [1996].

[6] Upper air sounding observations from balloons that record temperature, humidity, and winds were used in this study. There are two available sites (shown in Figure 1): Vandenberg Air Force Base (VBG) near the Point Conception at (34.65°N, 120.57°W) and Miramar Nas (NKX) near San Diego at (32.85°N, 117.12°W). Observations from theses sites were obtained from the Radiosonde Data Archive at Forecast Systems Laboratory.

[7] Clouds are identified from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) true-color images provided by the Distributed Active Archive Center (DAAC) at the National Aeronautics and Space Administration's (NASA's) Goddard Space Flight Center. The SeaWiFS sensor is carried by the SeaStar spacecraft, launched in August 1997, its primary objective is to provide quantitative data on global ocean bio-optical properties. For this paper, we used

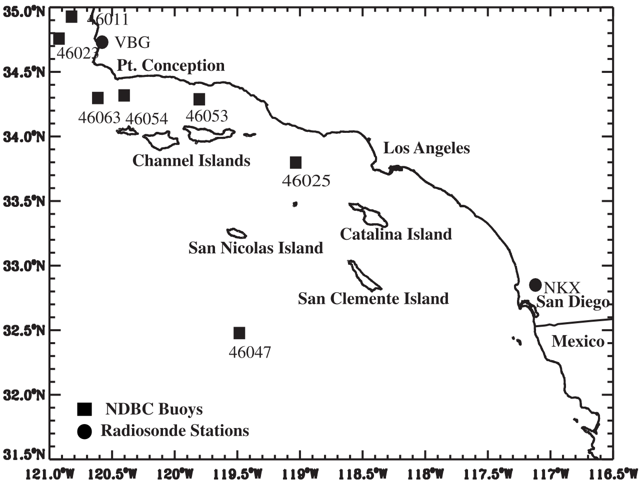


Figure 1. A map which shows the bight of southern California, seven locations of NDBC buoys, and two Radiosonde stations.

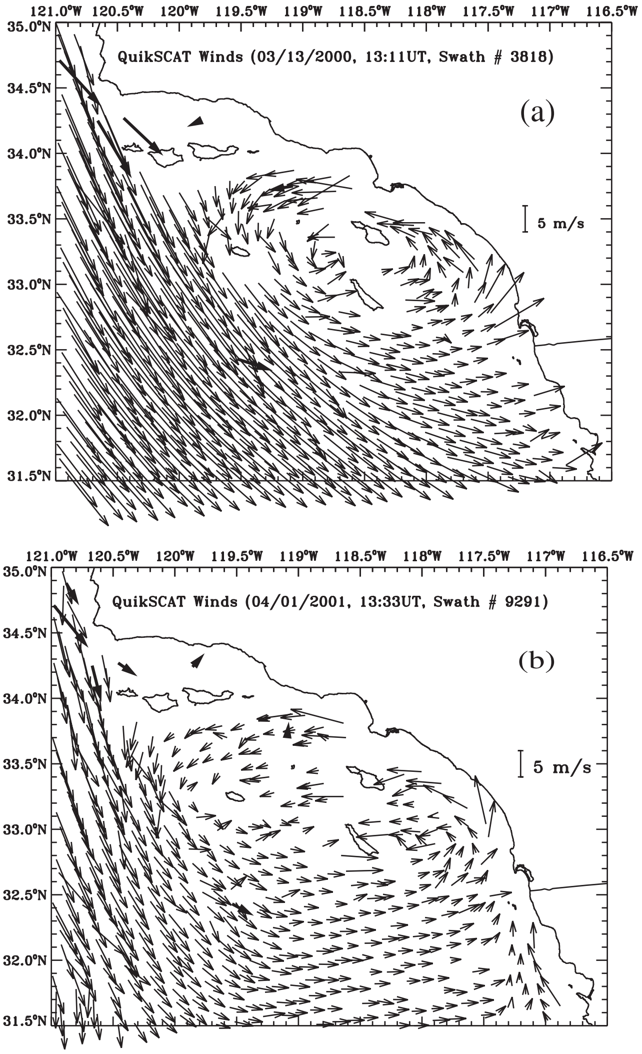


Figure 2. A complete Catalina Eddy circulation captured by QuikSCAT surface wind observations, (a) on 13 March 2000, and (b) on 1 April 2001. Thick arrows are equivalent neutral winds at 10-m height derived from NDBC buoys.

the SeaWiFS High-Resolution Picture Transmission (HRPT) data at 1-km resolution, obtained at HUSC station (34.4°N, 119.7°W) at the University of California, Santa Barbara.

3. QuikSCAT

[8] QuikSCAT was launched by the NASA in June 1999. The microwave scatterometer on the spacecraft measures oceanic surface wind speeds and directions, under clear and cloudy conditions, night and day, covering 93% of the global ocean in a single day. The principle of scatterometry has been summarized, the accuracy of data has been described, and historical scientific applications have been reviewed, by *Liu* [2002]. The latest validation study using collocated QuikSCAT and buoy measurements [e.g., *Wentz et al.*, 2001] showed that there is almost no mean difference (bias) in wind speed and only 6 degree in wind direction. The root-mean-square differences are 0.7 m/s and 13 degree. In the southern California bight where the Catalina Eddy occurs, the QuikSCAT passes through twice daily, but may miss the area one day every three to four days.

[9] The standard QuikSCAT wind product has 25-km spatial resolution. The 12.5-km resolution data used in this study were specifically produced to demonstrate the capability of QuikSCAT. The scientific significance of the high spatial resolutions has been demonstrated by *Liu et al.* [2000, 2001]. The 12.5-km resolution QuikSCAT wind data set was derived using the Direction Interval Retrieval with Thresholded Nudging (DIRTH) method, which improves the quality of the less accurate portions of the swath, in particular near the far swath and nadir [*Stiles*, 1999]. To avoid land contaminations, observations within 15 km of coastlines were not used in this study.

4. Observation of the Catalina Eddy

[10] Figures 2a and 2b are two examples of Catalina Eddy events observed by QuikSCAT. Figure 2a shows observations at 1311 UT on 13 March 2000, and Figure 2b at 1333 UT on 1 April 2001. The heavy arrows are equivalent neutral winds at 10-m calculated from continuous 10-minute averages of wind speed and direction at each NDBC station. It is evident that QuikSCAT provides a complete coverage of the cyclonic circulation not achievable by sparsely distributed buoy stations. QuikSCAT has obtained the first complete visualization of the eddy using observed surface wind vectors.

[11] Although the buoy winds were within 10 minutes of the QuikSCAT overpassing time, some discrepancies between buoy and QuikSCAT observations are expected. This is because each QuikSCAT observation represents a spatial average of 12.5 km in an instant while each buoy measurement is a 10-min average at a single point, and the local winds are highly variable. As measured by QuikSCAT, the average speed of southly winds of the Catalina Eddy was about 3–5 m/s, a finding consistent with that of a comprehensive study by *Mass and Albright* [1989] using NDBC buoys.

[12] One of the important features of the Catalina Eddy is that it deepens the marine boundary layer and cools the temperature in the southern California. The marine boundary layer is characterized by cooling temperatures and topped by persistent stratus [*Rosenthal*, 1972]. Figure 3 shows the upper air sounding of relative humidity (in black) and air temperature (in grey) from Miramar Nas (NKX) near San Diego on a non-eddy day at 1200 UT 31 March 2001 (dashed lines) and during an eddy event at 1200 UT on 1 April 2001 (solid lines). The marine boundary layer showed a depth of 800 meters during the eddy event on April 1, deepening to over 1000 meters on April 2 (not shown). The air temperatures also dropped 2–4°C while the eddy was present. Sometimes, a Catalina Eddy event can cause air temperature to drop over 20°C.

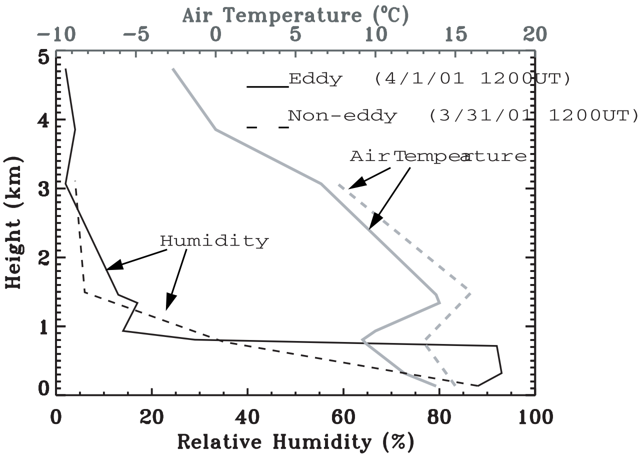


Figure 3. Radiosonde measurements from NKX station near San Diego. The gray lines are air temperatures, and black lines are relative humidity. The solid lines are for a eddy event at 1200 UT on 1 April 2001, and the dashed lines represent a non-eddy day on 1200 UT on 31 March 2001.

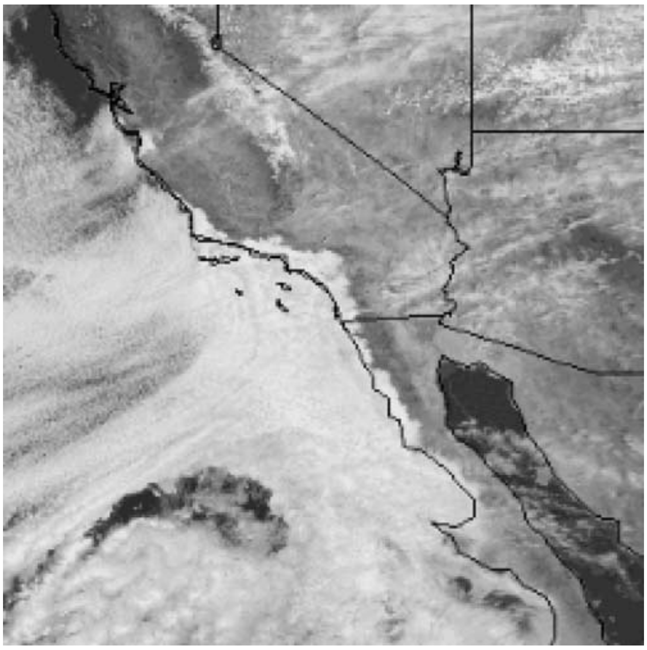


Figure 4. A SeaWiFS cloud image illustrates low-level stratus spreading into Las Angeles basin during a Catalina Eddy event on 1 April 2001.

[13] As strong onshore winds develop, fog and low stratus move inland [*Thompson et al.*, 1997]. The radiosonde profiles in Figure 3 indicated a cloud layer between 300–750 meters where relative humidity was above 90% and the lapse rate was significantly reduced from the dry adiabatic. This feature is also confirmed in a cloud image at 2022 UT 1 April 2001 (Figure 4) from the SeaWiFS satellite which shows low clouds spreading inland from the coastal ocean, another result of the Catalina eddy circulation that spells cool and overcast weather over southern California.

5. Model Forecast

[14] The 12-hr forecasts are products of National Centers of Environment Prediction's (NCEP's) mesoscale numerical weather prediction (NWP) model, known as the NCEP Eta Model. The name "Eta" derives from the model's vertical coordinate, known as the "eta" or "step-mountain" coordinate [*Rogers et al.*, 1996]. The Eta model used in this analysis is called Eta-32, with a 32-km horizontal resolution and 45 vertical layers, and output horizontal grids on 40 km. It covers most of North America and the nearby oceans. The data set is archived at the National Center for Atmospheric Research (NCAR).

[15] Figure 5a is the 12-hour forecast of Eta-32 winds at 10-m height valid at 1200 UT 13 March 2000, about 71 minutes earlier than the QuikSCAT overpass shown on Figure 2a. The cyclonic flow pattern of the Catalina Eddy can be discerned. However, the eddy's wind speeds are lower compared to the QuikSCAT measurements. For example, the southly wind speeds are about 1 m/s, much lower than those of the QuikSCAT, which are about 3–5 m/s. Figure 5b show a similar forecast at 1200 UT on 1 April 2001, about 93 minutes earlier than the QuikSCAT overpass shown on Figure 2b. For this event, however, the model forecast failed to predict the cyclonic vortex of the eddy.

[16] Previous studies [e.g., *Mass and Albright*, 1989] have pointed out that forecasting the Catalina Eddy is a very challenging task, and one of the causes is that the operational forecast models do not have enough horizontal resolutions to simulate eddy circulations accurately. To address this issue, we have investigated some Catalina Eddy events using data from Eta models with higher spatial resolutions, models only recently made available. One is the operational Eta-22 model with 22-km resolutions (outputs at grids on 20 km) and another one is an experimental Eta-10 model with 10-km resolutions for the western United States. Figure 6 shows the 12-hour forecast of Eta-22 winds valid at 1200 UT 1 April 2001. Even at higher spatial resolution, the model is still unable to forecast realistic eddy circulation. We also examined an Eta-10 model forecast for this event, and found no eddy circulation. (Eta-10 and Eta-22 results are not available for March 2000.)

[17] A recent investigation of the Eta-10 model has uncovered some problems, especially in boundary layer processes; and many of these problems are likely present in the coarser resolutions of the other Eta models [*Staudenmaier and Mittelstadt*, 1997]. Although current operational Eta models often provide valuable information on the larger-scale flow responsible for eddy formation [*Hu et al.*, 2002], they cannot forecast the Catalina Eddy accurately and consistently. Space-based scatterometers, on the other hand, provide an unprecedented opportunity to initiate and validate numerical simulations of Catalina Eddy events.

6. Conclusion

[18] The high resolution (12.5 km) QuikSCAT observations are needed for measuring the complete wind circulation of Catalina Eddies. Buoy winds, radiosonde soundings, and cloud images have confirmed the presence of the eddies, but these conventional

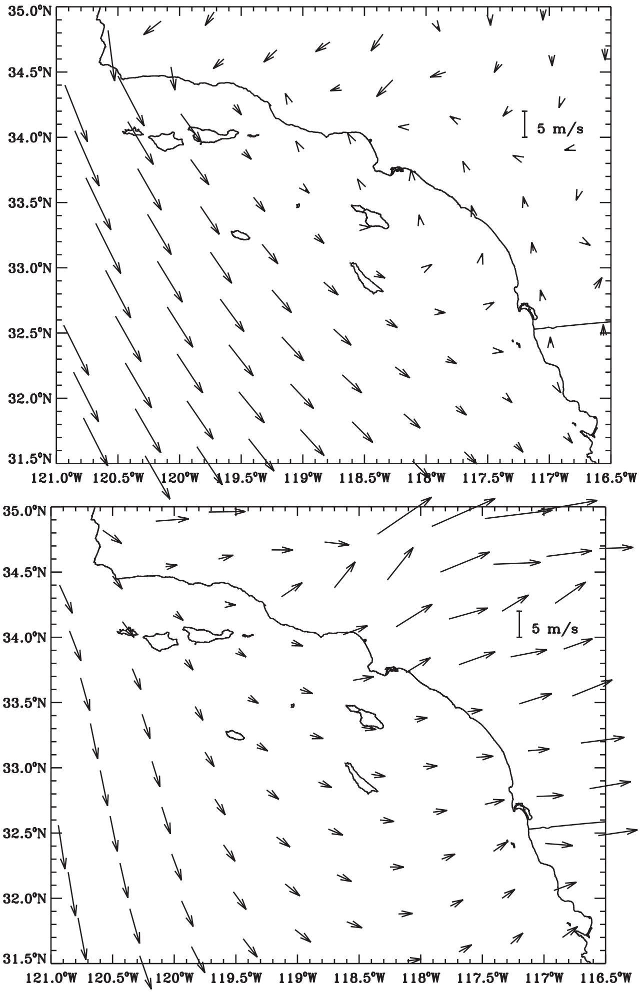


Figure 5. The 12-h forecast 10-m winds from NCEP Eta-32 model, (a) valid at 1200 UT 13 March 2000, and (b) valid at 1200 UT 1 April 2001.

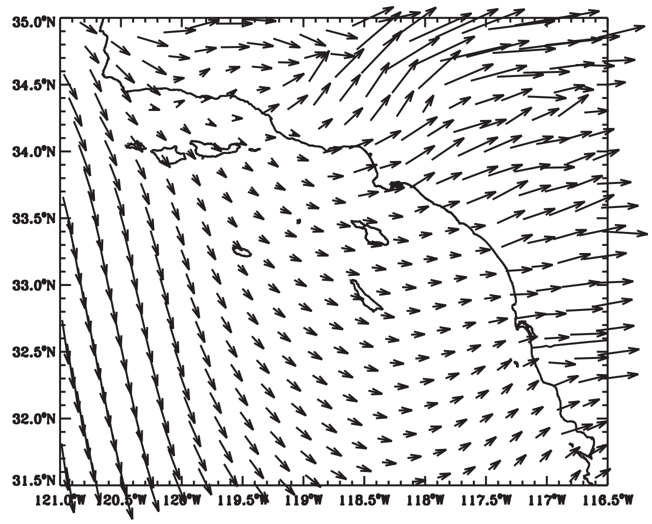


Figure 6. The 12-h forecast 10-m winds valid at 1200 UT 1 April 2001 from NCEP Eta-22 model. Wind vector scale is the same as Figure 5.

observations are not sufficient to provide a full description of the vortices. NWP products, including those new products with higher spatial resolutions, do not accurately and consistently simulate or predict the Eddies. Research and operational product of winds with higher spatial resolutions are being planned. Space-based scatterometers data will prove valuable in the monitoring and prediction of Catalina Eddies and in providing atmospheric forcing of ocean models.

[19] **Acknowledgments.** This study was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. It was supported by the QuikSCAT Project and Physical Oceanography Programs of NASA. We would like to thank Bryan Stiles and Wu-Yang Tsai at the Jet Propulsion Laboratory for kindly providing the high-resolution QuikSCAT data. We also thank Eric Rogers at the National Centers for Environment Prediction for providing us the high-resolution Eta model outputs. Objectively interpolated and uniformly gridded scatterometer winds can be found at http://airsea-www.jpl.nasa.gov/data.

References

Bosart, L. F., Analysis of a California Catalina Eddy event, *Mon. Wea. Rev.*, *111*, 1619–1633, 1983.

Clark, J. H. E., The role of Kelvin waves in evolution of the Catalina eddy, *Mon. Wea. Rev.*, *122*, 838–850, 1994.

Davis, C., S. Low-Nam, and C. Mass, Dynamics of a Catalina Eddy revealed by numerical simulation, *Mon. Wea. Rev.*, *128*, 2885–2904, 2000.

Dorman, C. E., Evidence of Kelvin waves in Catalina's marine layer and related eddy generation, *Mon. Wea. Rev.*, *113*, 827–839, 1985.

Hu, H., W. T. Liu, and B. W. Stiles, Catalina Eddy captured by NASA Quik SCAT satellite, in *Proc. of Sixth Symposium on Integrated Observing Systems*, American Meteorological Society, Boston, 120–123, 2002.

Liu, W. T., Progress in scatterometer application, *J. Oceanogr.*, *58*, 121–136, 2002.

Liu, W. T., and W. Tang, Equivalent neutral wind, *JPL Publication 96–17*, Jet propulsion Laboratory, Pasadena, 16 pp., 1996.

Liu, W. T., H. Hu, and S. Yueh, Interplay between wind and rain observed in hurricane Floyd, *Eos. Trans. of AGU*, *81*, 253–257, 2000.

Liu, W. T., H. Hu, Y. T. Song, and W. Tang, Improvement of scatterometer wind vectors-impact on hurricane and coastal studies, in *Proc. of WCRP/SCOR Workshop on Intercomparison and Validation of Ocean-Atmosphere flux Fields*, World Climate Research Programme, Geneva, 197–200, 2001.

Mass, C. F., and M. D. Albright, Origin of the Catalina Eddy, *Mon. Wea. Rev.*, *117*, 2336–2406, 1989.

Rogers, E., T. L. Black, D. G. Deaven, G. J. DiMego, Q. Zhao, M. Baldwin, N. W. Junker, and Y. Lin, Changes to the operational "Early" Eta analysis/forecast system at the National Center for Environmental Prediction, *Wea. Forecasting*, *11*, 391–413, 1996.

Rosenthal, J., *Point Mugu forecasters handbook*, Pacific Missile Range Point Mugu, 1972.

Staudenmaier, M., and J. Mittelstadt, Results of the western region evaluation of the Eta-10 model, *WR-Technical Attachment 97-18*, National Centers for Environment Prediction, 1997.

Stiles, B. W., Special Wind Vector Data Product: Direction Interval Retrieval with Thresholded Nudging, SeaWinds on QuikSCAT Level 2B Documentation, Physical Oceanography Distributed Active Archive Center, Jet Propulsion Laboratory, 1999.

Thompson, W. T., S. D. Burk, and J. Rosenthal, An investigation of the Catalina Eddy, *Mon. Wea. Rev.*, *125*, 1135–1146, 1997.

Ueyoshi, K., and J. O. Roads, Simulation and prediction of the Catalina eddy, *Mon. Wea. Rev.*, *121*, 2975–3000, 1993.

Ulrickson, B. L., J. S. Hoffmaster, J. Robinson, and D. Vifmont, A numerical modeling study of the Catalina eddy, *Mon Wea. Rev.*, *123*, 1364–1373, 1995.

Wakimoto, R. M., The Catalina Eddy and its effect on pollution over southern California, *Mon. Wea. Rev.*, *115*, 837–855, 1987.

Wentz, F., D. Smith, and C. Mears, Advanced algorithm for QuikSCAT and SeaWinds/AMSR, *Proc. of IGARSS 2001*, IEEE, in press, 2001.

H. Hu and W. Timothy Liu, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, MS 300-323, Pasadena, CA 91109, USA. (hua.hu@jpl.nasa.gov)