Response of Lake Superior to mesoscale wind forcing: A comparison between currents driven by QuikSCAT and buoy winds

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[1] The satellite scatterometer QuikSCAT wind field has been available every 12 hours on Lake Superior since 19 July 1999. The wind data cover most of the interior area of the lake with a spatial resolution of about 25 km. Driving the three-dimensional Lake Superior circulation model by the QuikSCAT winds, we resimulated the 1999 seasonal variability of currents in Lake Superior. A comparison was made with our previous simulation results, which relied on the wind field interpolated from moored buoys and land-based meteorological stations. The model driven by QuikSCAT winds improved the simulation of the spatial coverage area of the cold band during upwelling favorable wind events and the current jet during downwelling favorable wind events observed along the Keweenaw coast in July–October 1999. A statistical analysis shows that these improvements were mainly reflected in the low-frequency variation of the long-shore current, even though the overall deviation between computed and observed surface temperature and currents was measurably reduced. This study suggests that the wind field constructed from either moored buoys plus land-based meteorological stations or QuikSCAT is not sufficient to provide a reliable and accurate simulation of coastal currents and stratification in Lake Superior. A mesoscale meteorological model assimilated with observed winds on all the available weather measurement sites or stations or QuikSCAT is needed to provide an accurate meteorological forcing for the Lake Superior physical model. *INDEX TERMS:* 4255 Oceanography: General: Numerical modeling; 4528 Oceanography: Physical: Fronts and jets; 4546 Oceanography: Physical: Nearshore processes; 4504 Oceanography: Physical: Air/sea interactions (0312); 4512 Oceanography: Physical: Currents; *KEYWORDS:* mesoscale variation, frontal dynamics, wind-driven circulation

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1. Introduction

[2] As one modeling component of the NSF/NOAA Coastal Ocean Program funded Keweenaw Interdisciplinary Transport Experiment (KITE) Program in Lake Superior, we developed a nonorthogonal coordinate transformation circulation model and used it to simulate the formation, intensification, and breakdown of the thermal front and Keweenaw Current jet in southern Lake Superior for 1973 and 1999 [*Chen et al.*, 2000, 2002; *Zhu et al.*, 2000; C. Chen et al., Model simulation of the seasonal variability of circulation and stratification in Lake Superior, unpublished manuscript, 2002, hereinafter referred to as Chen et al., unpublished manuscript, 2002]. Driven by winds received at a land-based weather station near Eagle Harbor, *Zhu et al.* [2000] simulated the local variability of the Keweenaw Current observed in July 1973. An hourly interval synoptic wind field was generated on the basis of wind measurement data recorded at moored buoys, automated network (CMAN) stations and other land-based meteorological station for 1 April to 31 October 1999 (Figure 1). Using this wind field plus surface heat flux to drive the model, we simulated the 1999 stratification and currents in Lake Superior. The model reasonably predicted the surface water temperature, but failed to capture the spatial scale of the wind-induced upwelling and the rapid intensification of the Keweenaw Current (Chen et al., unpublished manuscript, 2002).

[3] From view of circulation dynamics, Lake Superior is a typical closed basin in which currents and stratification are controlled by the external surface wind forcing and surface heat flux. It is no doubt that the wind field used to drive the model plays an essential role for the accuracy of current simulation. In our previous modeling experiments, since there were only 4 buoys in the interior of the lake, the wind velocity at each grid point of the model was provided by the synoptic wind field interpolated from the wind data at the buoys on the lake and other land-based meteorological stations around the lake. An empirical method, which was

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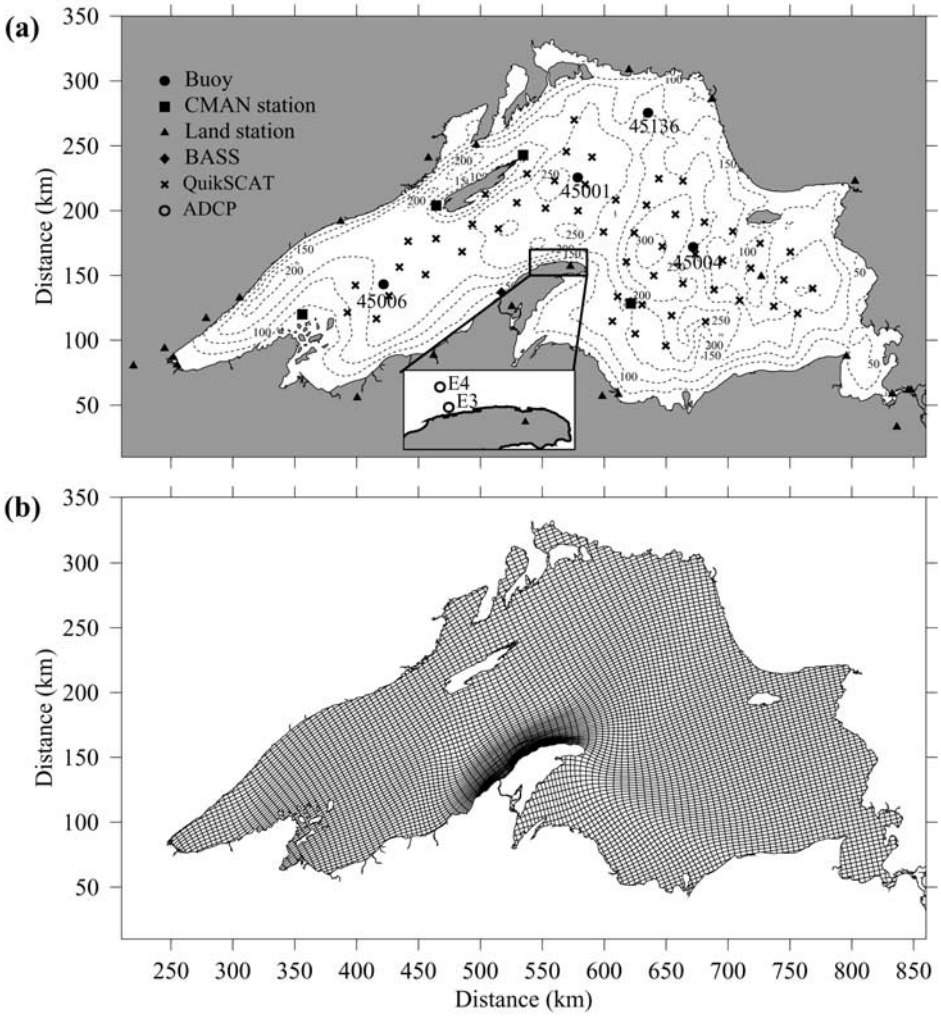

Figure 1. (a) Bathymetry (in meters) and locations of buoy, QuikSCAT, and other meteorological measurement stations and bottom-mounted tripods and ADCP sites over and around Lake Superior as well as (b) the nonorthogonal grids of the Lake Superior model. Solid and dashed lines in Figure 1a indicate the contours of the isobath in meters, and E3 and E4 shown in the box enclosed by heavy solid lines are the locations of the bottom-mounted ADCPs.

recommended for Lake Michigan and southeastern coastal ocean [*Schwab*, 1978; *Hsu*, 1986], was used to convert over-land winds to over-water winds on Lake Superior. The parameters used in the empirical formula, however, were directly adopted from previous modeling experiments in Lake Michigan with no objective validation or calibration. It is not surprising that the model driven by this synoptic wind field did not provide an accurate simulation of the Keweenaw Current, because the cross-shore scale of this current was too small (about 5 to 10 km) to be resolved accurately by a wind field interpolated from the measurement data over a horizontal resolution of about 100 km or greater and converted from over-land winds.

[4] The satellite scatterometer QuikSCAT has been recorded wind data on the water surface of Lake Superior since 19 July 1999. The near-surface neutral winds are estimated through the microwave backscatter from the wind-disturbed water surface (M. C. Haddock and E. A. Ralph, Spatial and temporal variability of winds over the world's largest lakes, submitted to *Journal of Great Lakes Research*, 2003, hereinafter referred to as Haddock and Ralph, submitted manuscript, 2003). As the satellite moves around the earth following a polar orbit, the wind vectors are provided with a spatial resolution of about 25 km and time interval of 12 hours over the interior of Lake Superior (Figure 1). Because of spurious reflection from ices, land and rain, the reliable QuikSCAT wind data are only available in the interior region of about 35 km away from the coast in spring through fall. The RMS measurement uncertainty of the QuikSCAT winds is about 1.4 m/s in speed and 18° in direction (Haddock and Ralph, submitted manuscript, 2003). The cross-lake time taken by the satellite is only 30 seconds s for Lake Superior, so that the winds measured by the QuikSCAT every 12 hours in Lake Superior can be treated as a snapshot of the wind field.

[5] Haddock and Ralph (submitted manuscript, 2003) made a comparison between wind data recorded by QuikSCAT and surface buoys on Lake Superior from 19 July to 31 October 1999. A correlation coefficient between these

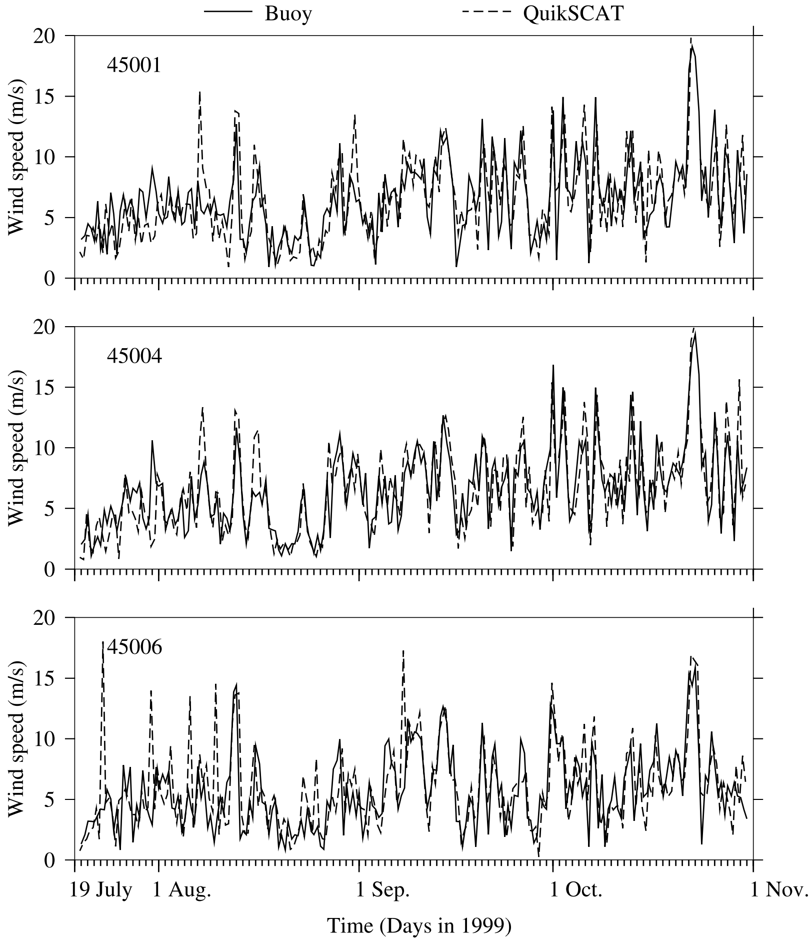

Figure 2. Comparison of the time series of the surface wind speed measured on buoys and QuikSCAT at buoys 45001, 45004, and 45006 for 19 July to 31 October 1999. The figure was replotted using the data shown by Haddock and Ralph (submitted manuscript, 2003).

kinds of winds was 0.95 for speed and 0.91 for direction. The comparison also showed that the satellite QuikSCAT captured not only the low-frequency trends of the wind field but also a mesoscale gust that occurred in early August over Lake Superior. A linear regression function was found to fit the scatterplots of QuikSCAT winds via buoy winds for both speed and direction, which was used to calibrate the QuikSCAT wind data. Time series comparisons of calibrated QuikSCAT and buoy winds indicated close agreement between the two devices (Figure 2). These calibrated QuikSCAT wind data allow us to examine the response of Lake Superior to mesoscale variability of the wind. A model experiment was conducted to resimulate the stratification and currents in Lake Superior for 19 July to 31 October 1999, and results were directly compared with those simulated using the winds interpolated from buoys and land-based meteorological stations.

2. Design of Numerical Experiments

[6] The numerical model used in this study is the 3-D, nonorthogonal coordinate transformation, primitive equations, Lake Superior circulation model developed by *Chen et al.* [2000]. This model is a modified version of the estuarine and coastal ocean model (ECOM-si) developed originally by *Blumberg* [1994]. It is a free-surface model with incorporation of *Mellor and Yamada*'s [1982] level 2.5 turbulent closure scheme for parameterization of vertical mixing and *Smagorinsky*'s [1963] closure scheme for horizontal diffusivity. A nonorthogonal coordinate transformation was used in the horizontal, which provided a fine grid resolution of 250 to 600 m in the cross-shore direction and of about 4 to 6 km in the alongshore direction on the coast of the Keweenaw Peninsula (Figure 1b). A σ coordinate transformation was used in the vertical. 41 nonuniform σ layers were specified and the thickness of each layer was determined by a quadratic equation with a high vertical resolution near the surface and bottom. The time step for numerical integration was 360 seconds s. For a detailed description of the nonorthogonal coordinate transformation Lake Superior model and mixing parameters used in the model, please refer to *Chen et al.* [2000] and *Zhu et al.* [2000].

[7] The model was driven by the 1999 observed fields of wind stress and surface heat flux. Numerical experiments were conducted for the two cases with winds measured from (1) buoys, CMANs, BASS on the lake and coastal meteorological stations on the land and (2) the satellite QuikSCAT, respectively. Wind velocities were

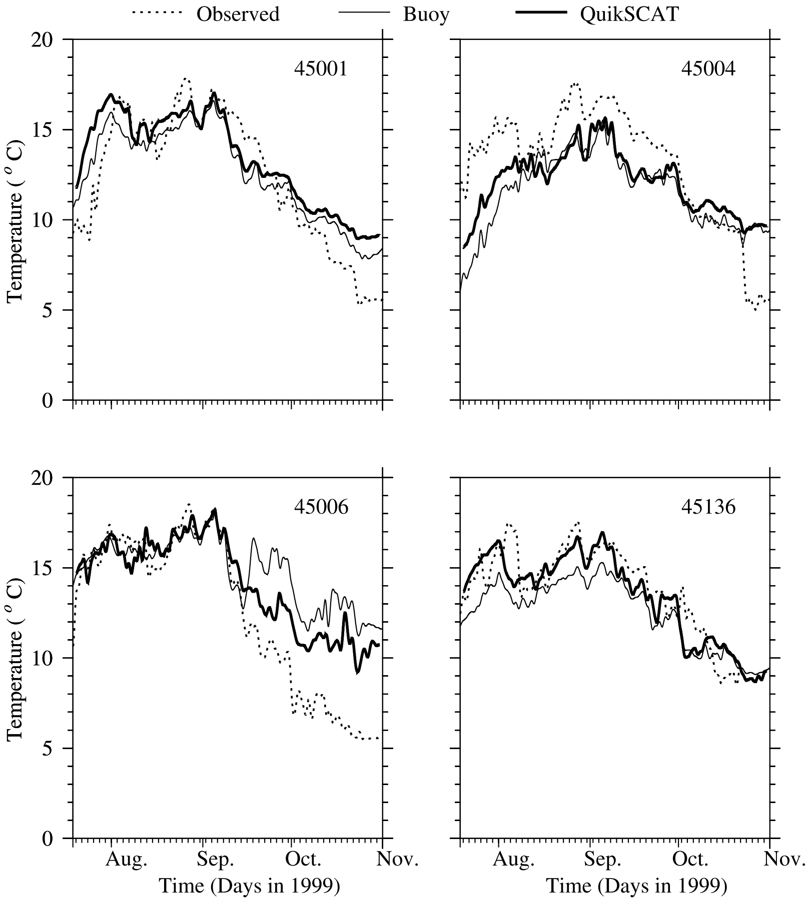

Figure 3. Comparison of the temporal variation trends of surface water temperatures observed on buoys and predicted by the model runs with the buoy and QuikSCAT winds on buoys 45001, 45004, 45006, and 45136 for 19 July to 31 October 1999.

linearly interpolated from measurement sites to model grids. In the first case, an empirical method was used to convert over-land winds to over-water winds before the interpolation was conducted. Heat fluxes used for these two cases were the same, and they were estimated by empirical methods in which sensible, latent heat fluxes were calculated by the bulk transfer equations, long-wave and short-wave radiations were computed using approximate formulas proposed by *Wyrtki* [1965], *Guttman and Matthews* [1979], *Ivanoff* [1977], and *Cotton* [1979]. The downward penetration of short-wave radiation is given as an exponential decay form used by *Zhu et al.* [2000] and *Chen et al.* [2002].

[8] Numerical experiments for the first case were conducted in our previous work described in Chen et al. (unpublished manuscript, 2002). The simulation started on 1 April 1999, the day on which buoy's wind data began available and then ran prognostically until 31 October 1999, the day on which the wind stopped recording on buoys. The initial temperature was assumed to distribute homogeneously in the lake, with a constant value of 2°C everywhere. Numerical experiments for the second case started on 19 July 1999, the day on which the QuikSCAT winds began available, and ran prognostically until 31 October 1999. The initial fields of temperature and currents were specified using model output at the end of 18 July 1999 from the first case. Comparisons of the model results between these two cases were made only on the common period from 19 July to 31 October 1999. For simplification, we refer the first case to "the buoy wind case" and the second case to "the QuikSCAT wind case" in the following sections.

3. Comparison of Model Results

3.1. Low-Frequency Trends of Surface Temperature

[9] The water temperature observed on buoys in Lake Superior showed a very similar seasonal variation trend: increasing rapidly in late-June through July, remaining the maximum in August, and then dropping quickly in September through October. Given the same surface heat flux, the simulation of the low-frequency (40-h low-passed) trend of model-computed surface water temperature was improved markedly at buoys 45004, 45006 and 45136 after wind forcing was replaced by the QuikSCAT data, but it became worse at buoy 45001 (Figure 3). On buoys 45004, 45006, and 45316, overall standard deviations (σ_T) of the difference between model-predicted and observed surface water temperatures were 2.71°, 2.73° and 1.68°C in the buoy wind case but reduced to 2.23°, 2.57°, and 1.18°C in the QuikSCAT wind case. On buoy 45001, however, σ_T was 1.58°C in the buoy wind case but increased to 1.95°C. A coherence analysis of model-predicted and observed surface water temperatures clearly

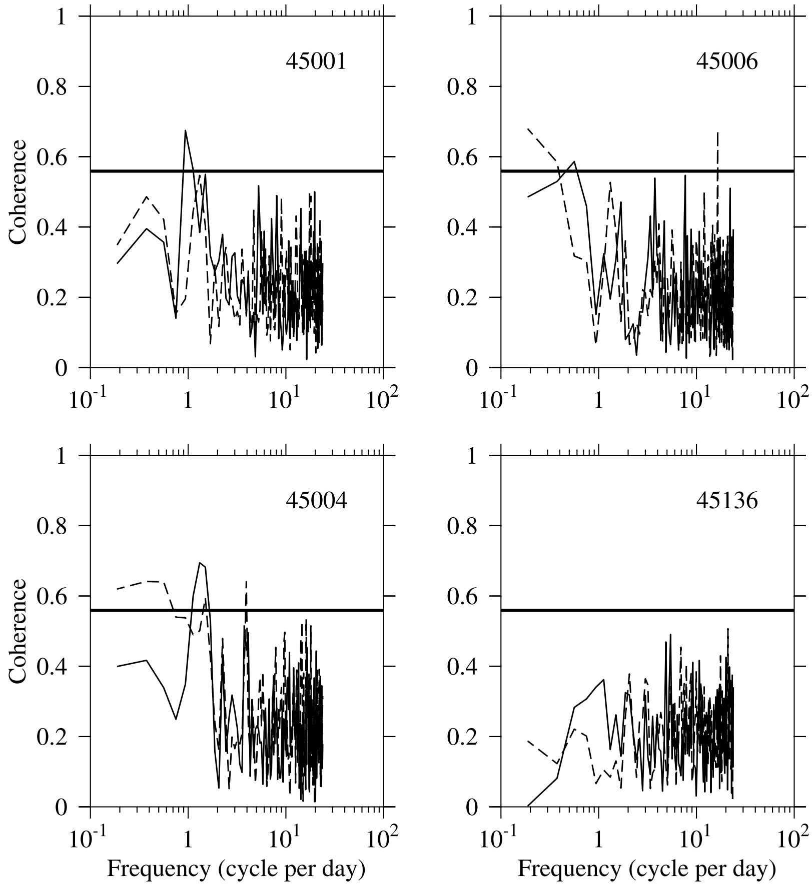

Figure 4. Coherence between model-predicted observed surface water temperatures at buoys 45001, 45004, 45006, and 45136. Solid line is the buoy wind case, dashed line is the QuikSCAT wind case, and heavy solid line is the 95% conference level. The time series shown in Figure 3 were used for coherence analysis.

showed that the QuikSCAT wind tended to improve the accuracy of the surface temperature simulation in the low-frequency band at sacrifice of losing the diurnal signal (Figure 4). This suggests that the highly spatial resolution of the QuikSCAT winds had a measurable contribution to the low-frequency variation of the water temperature, but its poor temporal resolution could cause a negative response at the diurnal variation.

[10] It should be pointed out here that model-predicted surface temperatures from buoys 45001, 45006 and 45004 were always higher than observed values in September through October 1999 no matter whether the buoy or QuikSCAT winds were used. This was not a surprising result because the MY 2.5 turbulent closure scheme used in the model did not include a convective overturning process due to surface cooling. This scheme is a typical *q-l* (*q*: turbulent kinetic energy, *l*: macro-mixing length) mixing model in which vertical mixing due to surface cooling is parameterized through diffusion mechanism without consideration of vertical convection. Since the timescale was much longer for vertical diffusion than for convective overturning, it was not doubt that the model tended to underestimate vertical mixing during cooling events. Therefore a convective adjustment must be incorporated into the existing MY 2.5 turbulent closure scheme in order to capture the right physics of surface cooling in fall and early winter in Lake Superior.

3.2. Upwelling and Downwelling Events

[11] A cold water band, an indicator of the upwelling, was clearly identified along the Keweenaw Peninsula in the satellite-derived surface temperatures received at 0454 LT on 14 August (Figure 5). Although this cold water band was resolved in both cases with buoy and QuikSCAT winds. It seemed that its spatial coverage was underestimated in the buoy wind case. The cold water band detected on the satellite image appeared in a long and narrow area from the northeastern end of the Keweenaw Peninsula to the southwestern end of the lake (Figure 5a). This spatial pattern was reproduced in the QuikSCAT wind case (Figure 5c), but it was limited only to the northeastern coastal area of the northern entrance of the waterway of the Keweenaw Peninsula in the buoy wind case (Figure 5e).

[12] The underestimation of the August upwelling event in the buoy wind case was due to mesoscale variation in the wind field that was unresolved by sparsely located buoy winds. Wind records on buoys and QuikSCAT showed a significant upwelling favorable wind around 14 August (Figure 6). Although both buoys and QuikSCAT winds were very similar in direction and magnitude during this

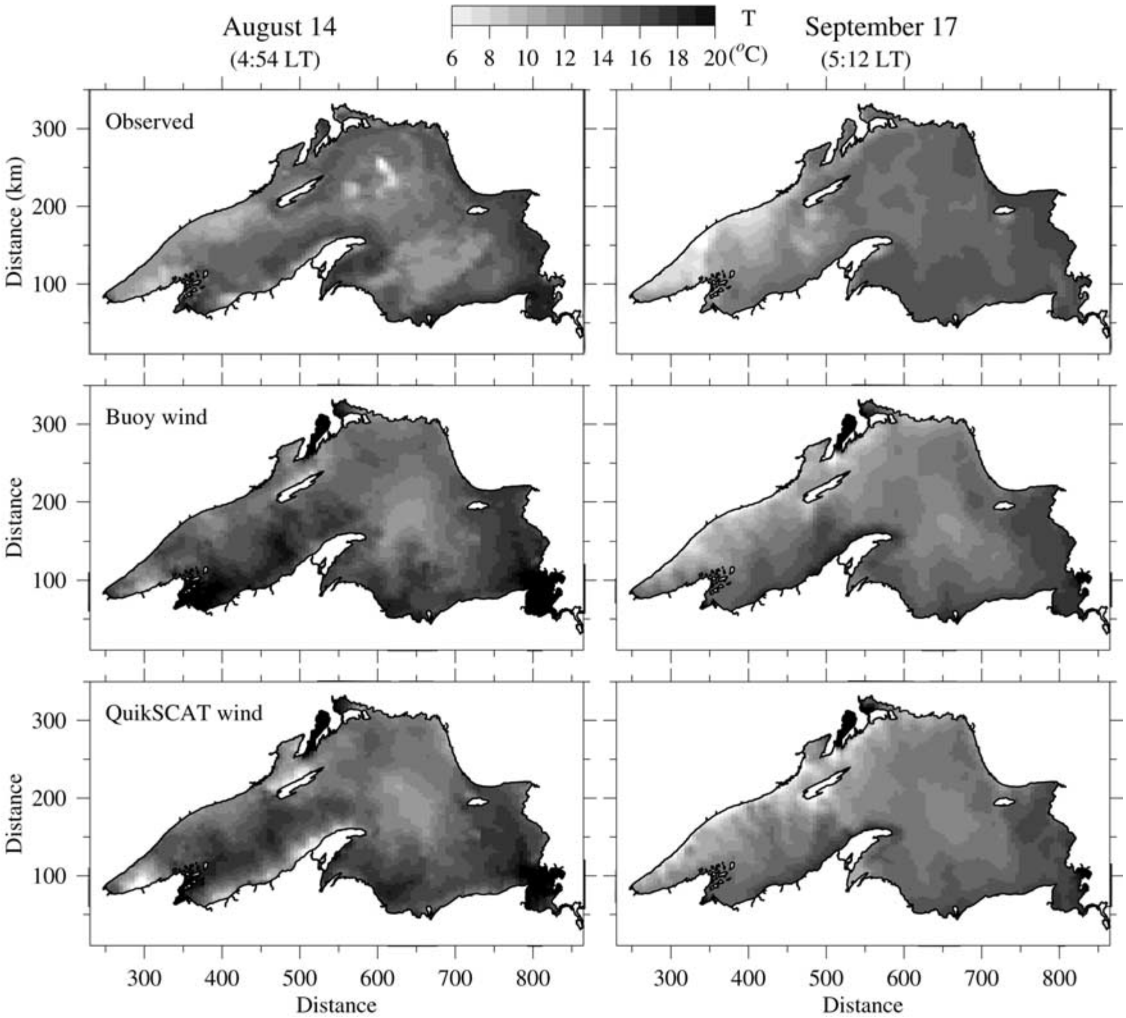

Figure 5. Comparison of surface water temperatures (a) and (b) derived from the satellite and predicted by (c) and (d) the model runs with the QuikSCAT winds and (e) and (f) the buoy winds at 0454 LT on 14 August and 0512 LT on 17 September 1999, respectively.

event, the QuikSCAT captured several upwelling favorable wind gusts in the southwestern region of the lake before 14 August (Figure 6b). These gusts, however, were either underestimated or unresolved by the wind measurement on buoy 45006 (Figure 6a). Since the distance between the closest QuikSCAT recording points and buoy 45006 was less than 20 km, it suggests that the gust occurred either on a mesoscale of a few kilometers in the coastal region south of buoy 45006.

[13] The difference in the winds measured on buoys and QuikSCAT directly affected the spatial distribution of the surface current. The southwestward flow along the southwestern coast was markedly stronger in the QuikSCAT wind case than in the buoy wind case, implying that the QuikSCAT wind drove a stronger upwelling (Figure 7). This was the reason why the model run with the buoy winds failed to predict the significant upwelling event along the coast south of buoy 45006 around 14 August.

[14] Wind records on buoys and QuikSCAT also showed a significant downwelling event around 17 September along the Keweenaw Peninsula. However, the timing and duration of downwelling favorable wind observed on the buoys and QuikSCAT significantly differed. On 12 August, for example, a northeastward wind was recorded at a location of buoy 45006 by QuikSCAT. This wind had an orientation angle of less than 45° with respect to east and was dominant in the measured area until 19 August. The northeastward wind was also measured on buoy 45006 around mid-August, but it started on 13 August, one day later than the measurement by QuikSCAT and also blew dominantly northeastward with an orientation angle of about 45° or greater with respect to east. Since the QuikSCAT wind was more parallel to the coast than the buoy wind, it appeared to cause a larger onshore transport in the upper Ekman layer.

[15] The difference in the orientation angles recorded by the buoy and QuikSCAT winds directly affected the simulation results of currents and surface water temperature. The QuikSCAT wind predicted a relatively stronger alongshore current along the Keweenaw coast, with a cross-shore scale of about 10–20 km at 0512 LT on 17 September, the day that the satellite image was available (Figure 8a). An anticyclonic eddy circulation was also found 40 km away from the coast near the north entrance of the Keweenaw waterway. This eddy caused slightly wider cross-shore scale of the northeastward alongshore current along the northeastern coast of the Keweenaw. A similar current pattern

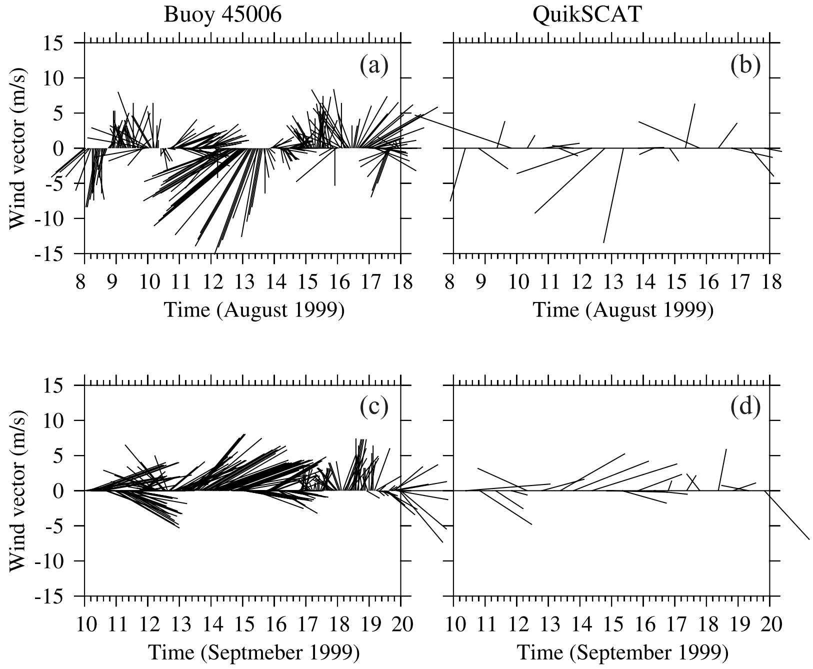

Figure 6. Time series of the surface wind vectors (a) and (b) observed on buoy 45006 and (c) and (d) interpolated by surrounding QuikSCAT winds during 1–20 August and 10–20 September 1999, respectively.

was also predicted by the buoy wind. However, the buoy wind-induced current was relatively weaker and also had a narrower cross-shore scale (Figure 8b).

[16] The difference in the current distributions predicted by buoy and QuikSCAT winds directly affected the distribution of surface water temperatures. At 0512 LT on 17 September, the satellite image showed a narrow warm water band along the Keweenaw coast and a relatively cold water area in the interior as a result of combined wind-induced onshore transport and mixing. These structures were captured in reasonable agreement on the field of the surface water temperature predicted by the QuikSCAT wind but not by the buoy wind. Although the buoy wind predicted a warm water band along the Keweenaw coast, its temperature was much higher and also its coverage was much bigger.

3.3. Temporal Variation of the Keweenaw Current

[17] Two bottom-mounted Acoustic Doppler Current Profilers (ADCPs) were deployed at sites E3 and E4 in mid-July 1999 by Ralph's research group at the University of Minnesota-Duluth. The current vectors were recorded continuously with a vertical bin average of 4 m and a time interval of 1 hour during a period of 28 May 1999 through 26 May 2000. The time series of the velocity at each measurement level was filtered using a 40-h low-passed WH64 filter (provided by Beardsley at Woods Hole Oceanographic Institution). The filtered data for a period of 19 July to 31 October were compared directly with the low-passed water velocity predicted by the buoy and QuikSCAT winds.

[18] No matter what kinds of the wind fields were used, the model underestimated the magnitude of the Keweenaw Current during the comparison period, though it did captured all the wind-induced variation trends of the current (Figure 9). No significant difference was found in the overall accuracy of the current simulation between the buoy and QuikSCAT wind cases. At site E3, the standard deviation of the difference between model-predicted and observed currents over a period from 19 July to 31 October was 1.8 cm/s in u and 6.2 cm/s in v in the buoy wind case, while it was 1.5 cm/s in u and 5.6 cm/s in v in the QuikSCAT wind case. Similarly, at site E4, the standard deviation was 9.2 cm/s in u and 5.8 cm/s in v in the buoy wind case, while it was 7.6 cm/s in u and 5.5 cm/s in v in the QuikSCAT wind case. The improvement accounted by the QuikSCAT wind was about 0.3–1.6 cm/s in u and 0.3–0.6 cm/s in v. A comparison between the monthly averaged distribution of the east-west and south-north components of the surface wind velocity estimated by buoys plus available land-based meteorological stations and by QuikSCAT were presented in Figure 10. The results show that the difference between these two kinds of winds was generally smaller than 1 m/s, except in regions close to the eastern coast and islands. This means that QuikSCAT winds have an insignificant correction to the long-term averaged field.

[19] In spite of this, the coherence analysis did show that the QuikSCAT wind provided a better simulation in the low-frequency band of the long-shore current (Figure 11). For example, at site E4, the coherence coefficient between model-predicted and observed alongshore currents in a low-frequency band of less than 0.5 (a period longer than 2 days) was about 0.42 in the buoy wind case, while it jump up to 0.6–0.8 in the QuikSCAT wind case. According to a 95% conference level of 0.56, the QuikSCAT wind measurably increased the statistical significance in improving the accuracy of the current simulation at site E4. Similar results were also found at the nearshore site E3. Although the distributions of the coherence coefficient in the low-frequency band remained the same for both the buoy and

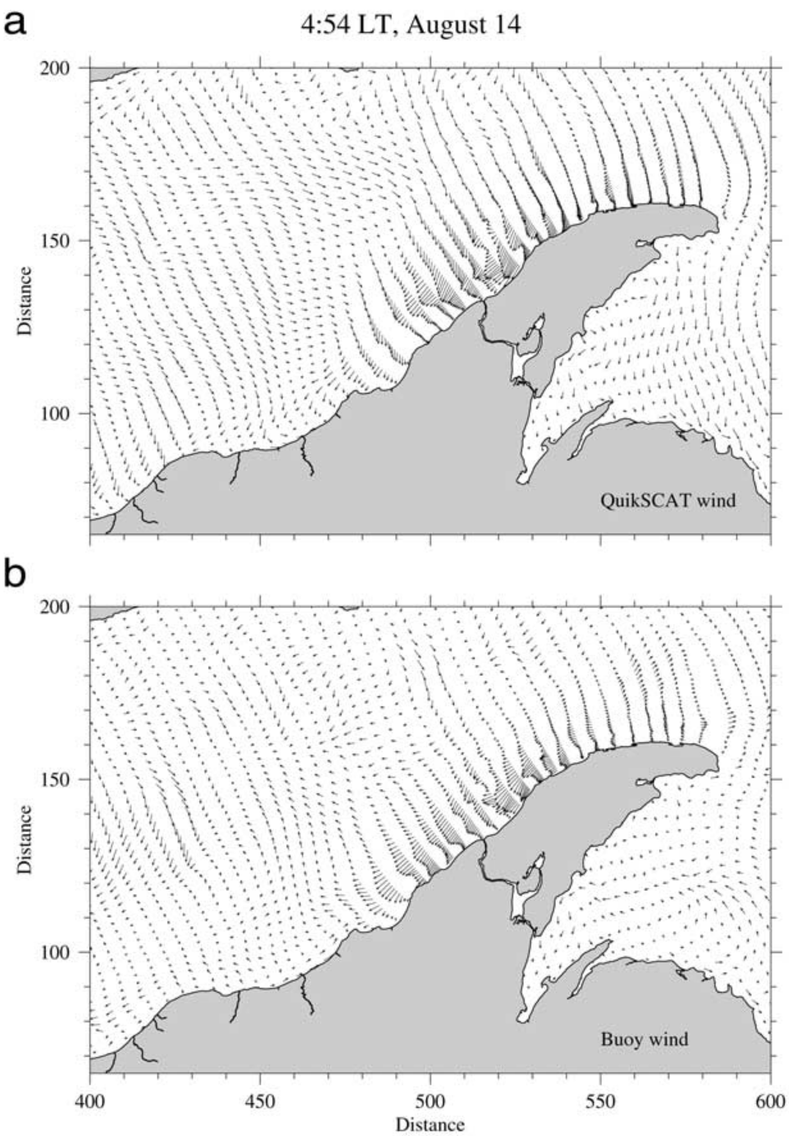

Figure 7. Distribution of surface water current vectors predicted at 0454 LT on 14 August by the model runs with (a) QuikSCAT and (b) buoy winds, respectively.

QuikSCAT wind cases, the absolute value of the coefficient was higher in the QuikSCAT wind case than in the buoy wind case.

[20] The improvement in the simulation of the low-frequency alongshore current by the QuikSCAT wind was clearly evident during the downwelling favorable wind events in mid-September. The ADCP data showed two strong alongshore currents at site 3 during 9–11 September and 13–15 September, respectively. The currents weakened with depth, having a vertical scale of about 60 and a speed of 60 cm/s at a depth of 17 m (Figure 12). These alongshore currents were captured up to 50∼67% by the QuikSCAT wind, while only to 40%∼50% by the buoy wind (Figures 9a and 9b). The currents predicted by the QuikSCAT wind were clearly evident in the upper 60 m: the same vertical scale as the observed currents (Figure 12c). The current predicted by the buoy wind, however, was only limited in the upper 40–50 m (Figure 12e). Similar results were found at site E4, where temporal and vertical distributions of the velocities observed by ADCP and predicted by the QuikSCAT winds were in reasonable agreement, but were underestimated significantly by the buoy winds (Figure 13 (left)). Even in the cross-shore direction, the velocities predicted by the QuikSCAT wind provided a better agreement with observed velocities than that predicted by the buoy wind (Figures 12 and 13 (right)). Again, this implies that the mesoscale wind fluctuation recorded by the QuikSCAT had a considerable contribution to the temporal variation of the low-frequency water current along the Keweenaw coast in Lake Superior.

4. Discussion

[21] The comparisons between observed and model-predicted temperatures and currents have clearly demonstrated that the QuikSCAT wind field provided a better simulation of the low-frequency variation of water temperature and currents in Lake Superior. This suggests that

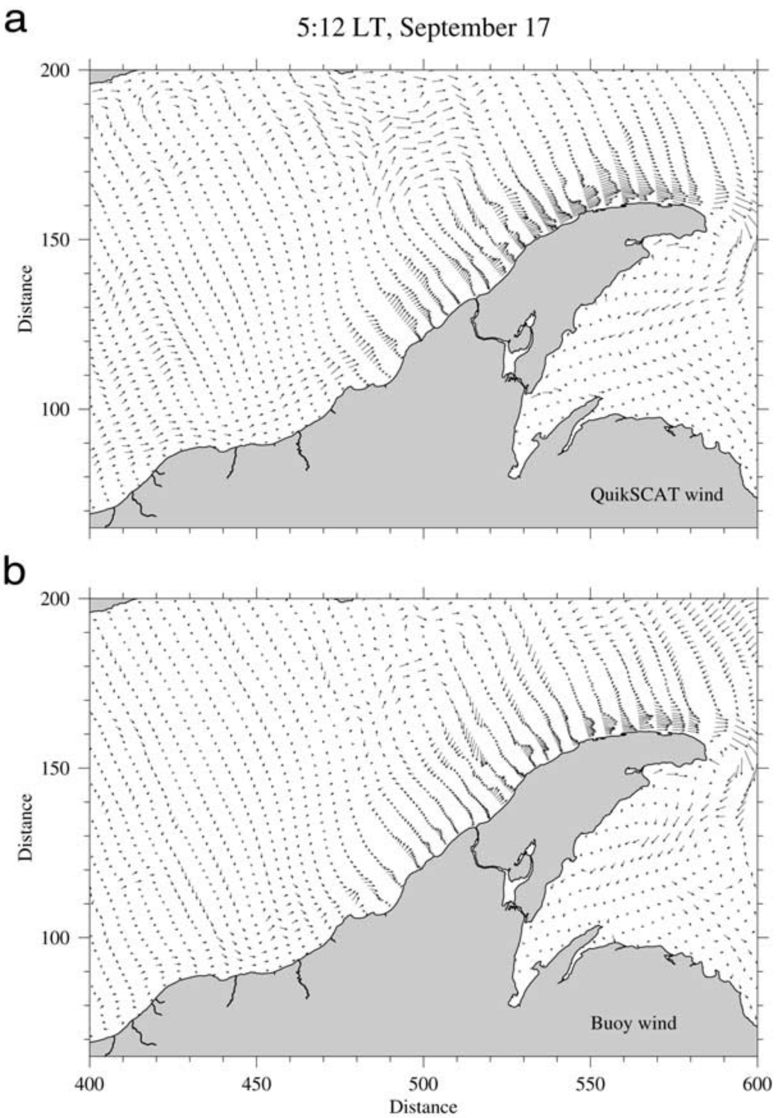

Figure 8. Distribution of surface water current vectors predicted at 0512 LT on 17 September by the model runs with (a) QuikSCAT and (b) buoy winds, respectively.

the spatial resolution of the wind measurement is one of the key issues regarding the accuracy of the model-based prediction of currents in Lake Superior. The fact that the QuikSCAT wind field did not significantly improve an overall accuracy of the simulation in the water current implies that availability of the satellite-based QuikSCAT wind field is not sufficient to meet the requirement for Lake Superior modeling experiments. It is believed that the nearshore mesoscale wind fluctuations may play an essential role in the temporal variability of the Keweenaw Current, which, however, can not be resolved by either the satellite scatterometer QuikSCAT or limited buoy wind measurements. Our studies also raise a fundamental issue in the spatial coverage of wind measurement over Lake Superior. To provide an accurate simulation and forecast of the Keweenaw Current along the southern coast of Lake Superior, the model requires the improvement of the coastal wind field. This could be achieved by coastal radar measurement systems or a mesoscale meteorological model (such as MM5) assimilated with the wind filed recorded on QuikSCAT, buoys, and other land-based meteorological stations.

[22] On the basis of our previous and current modeling experiments, we found that the model results were much more sensitive to the wind coming from the land. The reason why the buoy wind always significantly underestimated the magnitude of the eastward velocity of the Keweenaw Current was probably due to the underestimation of the land-based wind field during the downwelling favorable wind period. This suggests that the empirical method used to convert over-land wind to over-water wind in our 1999 simulation tended to underestimate the wind field during downwelling-favorable wind events. Although the empirical formula has taken the “daily varied lake breeze” into account, we have no ideas if it still works for low-frequency wind events from the land. Our modeling experiments leave an unanswered question that needs to be addressed in future modeling experiments in Lake Superior

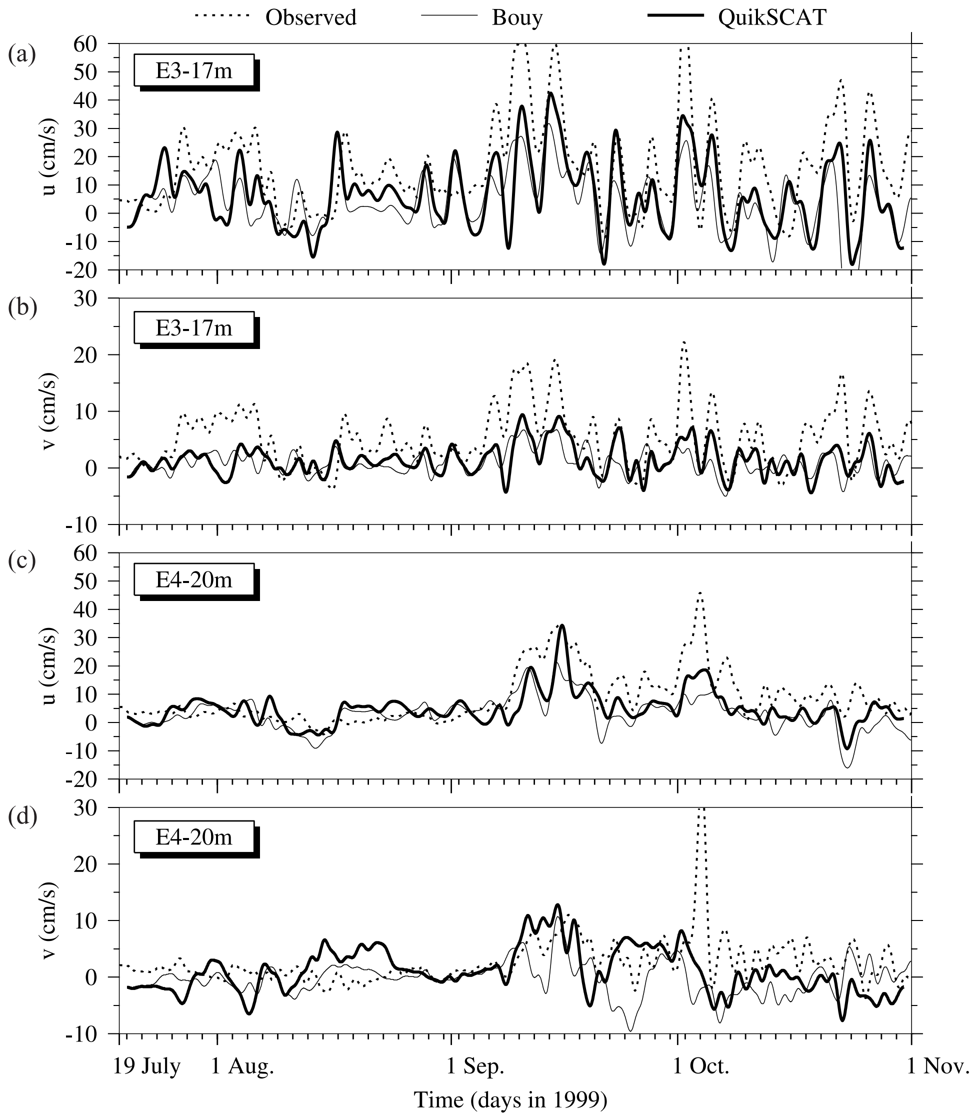

Figure 9. Comparison of observed and model-predicted water currents at depths of 17 and 20 m at site E3 and E4 for 19 July to 31 October 1999.

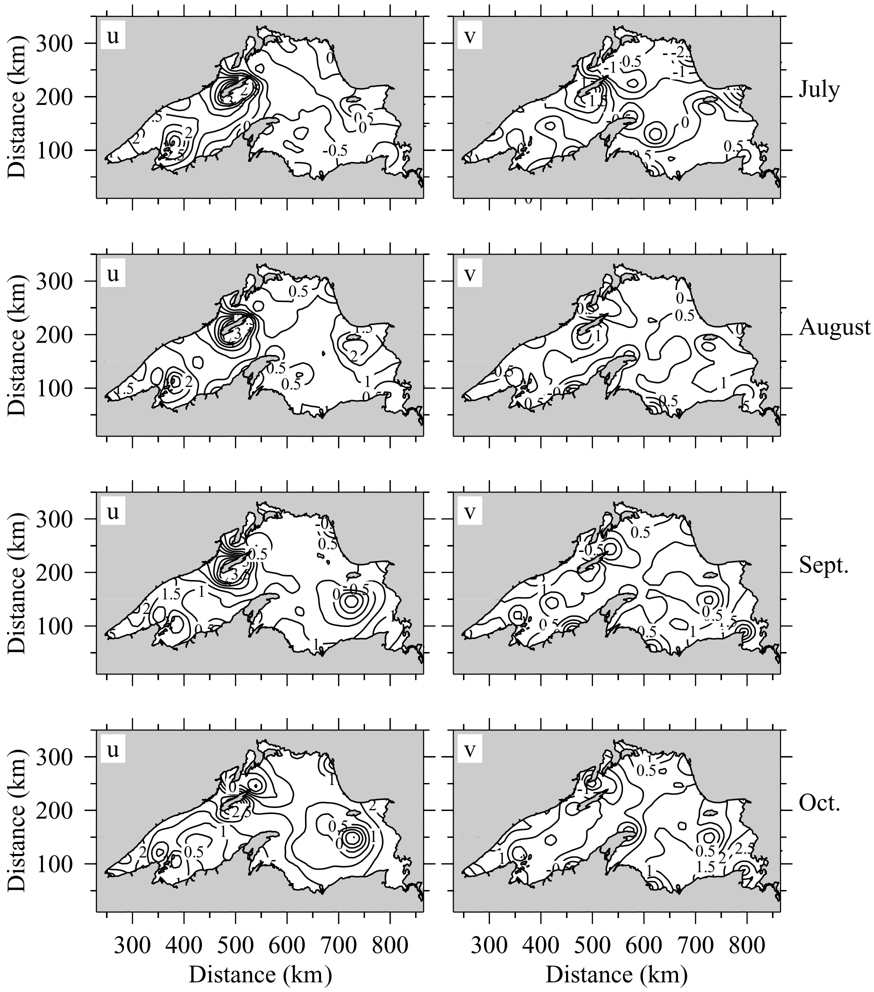

Figure 10. Difference between monthly averaged east-west and south-north components of the wind velocity measured by the QuikSCAT and on buoys plus other available meteorological stations.

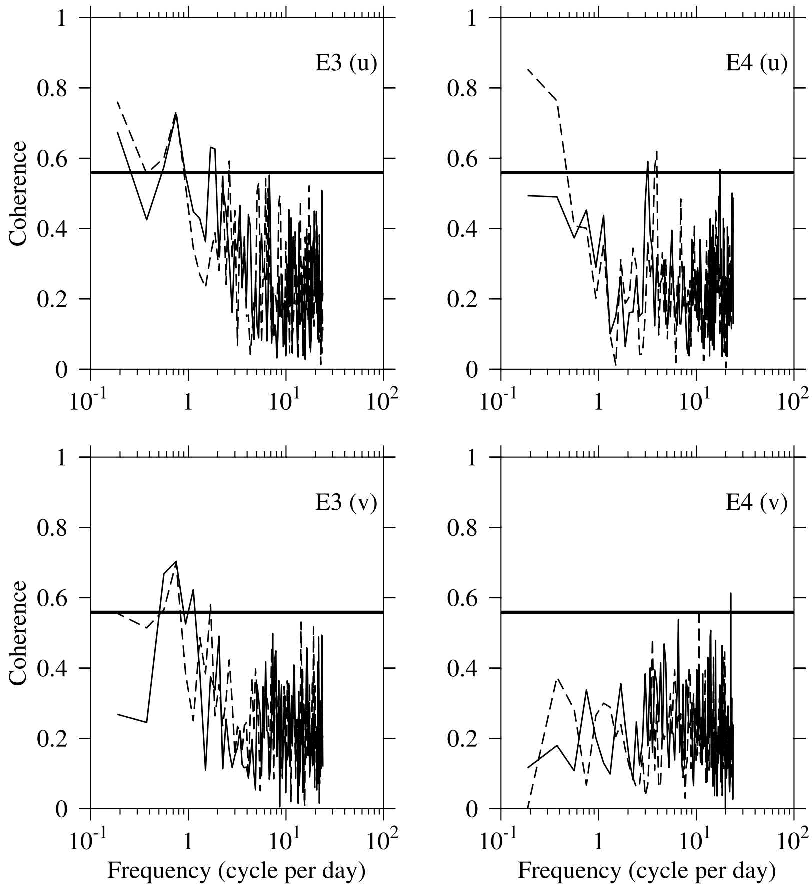

Figure 11. Coherence between observed and model-predicted surface water currents at a depth of 17 m on mooring E3 and a depth of 20 m on mooring E4, where *u* is the alongshore component, *v* is the cross-shore component, the solid line is the buoy wind case, the dashed line is the QuikSCAT wind case, and the heavy solid line is the 95% coherence level. The time series shown in Figure 9 were used for the coherence analysis.

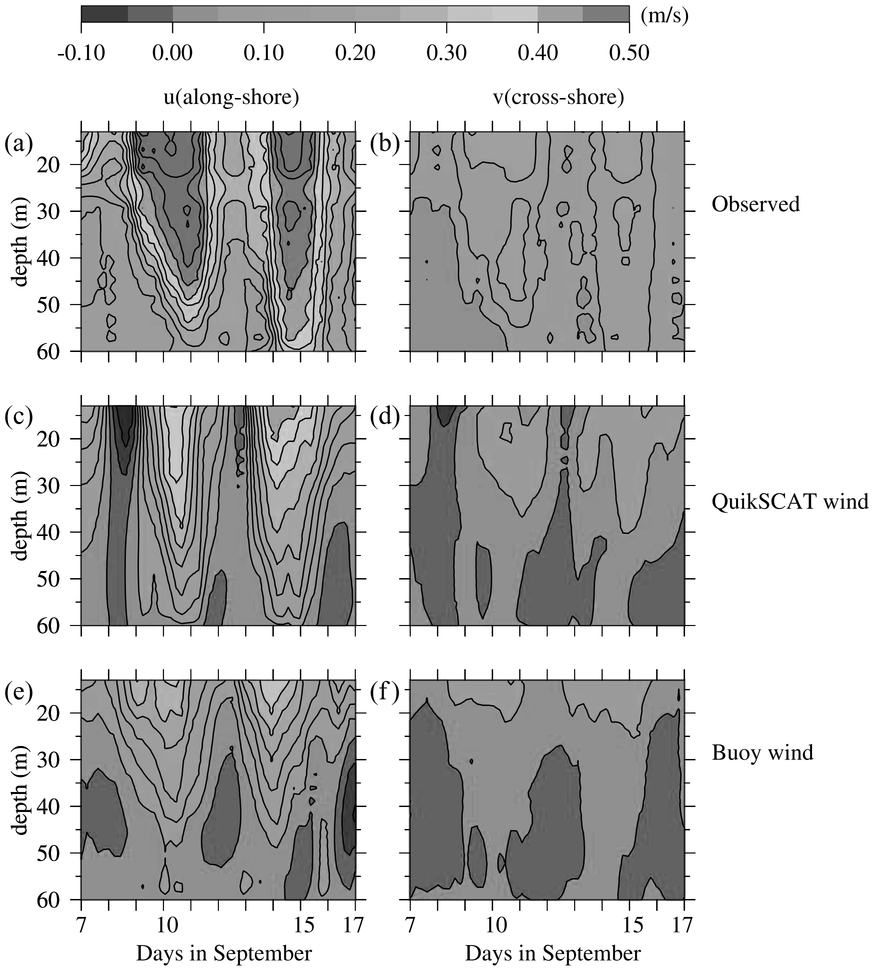

Figure 12. Comparison of the vertical structures of observed and model-computed alongshore and cross-shore velocities at E3 during 7–17 September 1999.

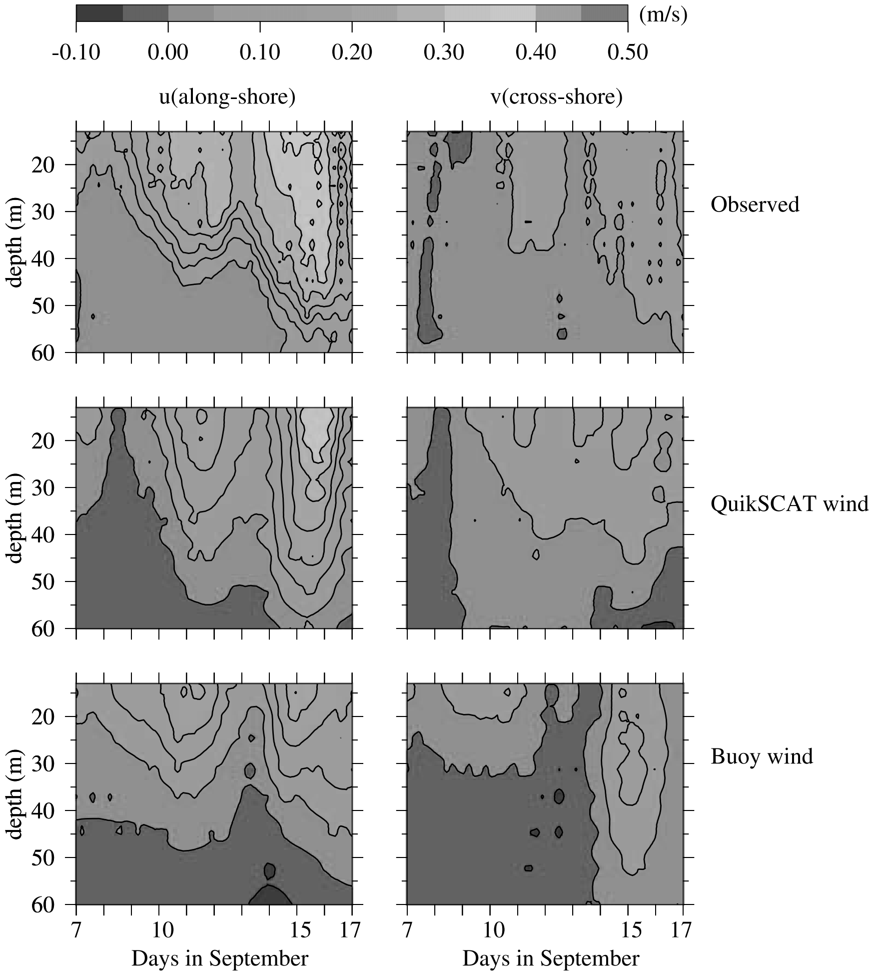

Figure 13. Comparison of the vertical structures of observed and model-computed alongshore and cross-shore velocities at E4 during 7–17 September 1999.

in order to improve the accuracy of the model simulation for the Keweenaw Current and thermal front.

5. Conclusion

[23] A direct comparison was made between water temperatures and currents predicted by the buoy and QuikSCAT winds under the same initial and boundary conditions plus the same surface heat flux forcing. The results show that the model run with the satellite-based QuikSCAT winds improved the simulation accuracy of the low-frequency temporal variability of the water currents during upwelling and downwelling events. These improvements suggest that the mesoscale variability of the wind field plays an essential role in the temporal variability and spatial distribution of coastal currents in Lake Superior.

[24] Because of failure to solve mesoscale wind processes occurring near the coast, the model runs with QuikSCAT and buoy winds tend to underestimate the magnitude of the eastward velocity of the Keweenaw Current, especially during the downwelling events. The coastal wind measurement system must be developed to provide a better coverage of the mesoscale wind field near the coast in order to improve the accuracy of the model simulation for the Keweenaw Current and thermal front.

[25] **Acknowledgments.** This research was supported by the NSF/NOAA EGGLE Program under the NSF grant number OCE-9712869 and OCE0196543 for Changsheng Chen, OCE-9712870 for Elise Ralph, and OCE-9712872 for Judy W. Budd. Quichun Xu is supported by Chen's NSF grant.

References

Blumberg, A. F. (1994), A primer for ECOM-si, technical report, 66 pp., HydroQual, Inc., Mahwah, N. J.

Chen, C., J. Zhu, E. Ralph, S. A. Green, and J. Budd (2000), Prognostic modeling studies of the Keweenaw Current in Lake Superior. part I: Formation and evolution, *J. Phys. Oceanogr.*, *31*, 379–395.

Chen, C., J. Zhu, K. Kang, H. Liu, E. Ralph, S. A. Green, and J. W. Budd (2002), Cross-frontal transport along the Keweenaw coast in Lake Superior: A Lagrangian model study, *Dyn. Atmos. Oceans*, *36*, 83–102.

Cotton, G. F. (1979), ARL models of global solar radiation, in *Final Report: Hourly Solar Radiation–Surface Meteorological Observations*, *TD-9724*, vol. 2, SOLMET, Natl. Clim. Data Cent., Asheville, N. C.

Guttman, N. B., and J. D. Matthews (1979), Computation of extraterrestrial solar radiation, solar elevation angle, and true solar time of sunrise and sunset, in *Final Report: Hourly Solar Radiation-Surface Meteorological Observations*, *TD-9724*, vol. 2, SOLMET, Natl. Clim. Data Cent., Asheville, N. C.

Hsu, S. A. (1986), Correction of land-based wind data for offshore application: A further evaluation, *J. Phys. Oceanogr.*, *16*, 390–394.

Ivanoff, A. (1977), Oceanic absorption of solar energy, in *Modelling and Prediction of the Upper Layers of the Ocean*, edited by E. B. Kraus, pp. 47–72, Pergamon, New York.

Mellor, G. L., and T. Yamada (1982), Development of a turbulence closure model for geophysical fluid problem, *Rev. Geophys.*, *20*, 851–875.

Schwab, D. J. (1978), Simulation and forecasting of Lake Erie storm surge, *Mon. Weather Rev.*, *106*, 1476–1487.

Smagorinsky, J. (1963), General circulation experiments with the primitive equations. I. The basic experiments, *Mon. Weather Rev.*, *91*, 99–164.

Wyrtki, K. (1965), The average annual heat balance of the North Pacific Ocean and its relation to ocean circulation, *J. Geophys. Res.*, *70*, 4547–4559.

Zhu, J., C. Chen, E. Ralph, and S. A. Green (2000), Prognostic modeling studies of the Keweenaw Current in Lake Superior. part II. Simulation, *J. Phys. Oceanogr.*, *31*, 396–410.

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