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Modeling the 1998–2003 summer circulation and thermal structure in Lake Michigan

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[1] A three-dimensional primitive equation numerical model was applied to Lake Michigan on a 2 km grid for 6 consecutive years to study interannual variability of summer circulation and thermal structure in 1998–2003. The model results were compared to long-term observations of currents and temperature at seven moorings and two NOAA buoys. The accuracy of modeled currents improved considerably relative to previous summer circulation modeling done on a 5 km grid, while the accuracy of temperature simulations remained the same. Particle trajectory model results were also compared with satellite-tracked surface drifter observations. Large-scale circulation patterns tend to be more cyclonic (counterclockwise) toward the end of summer as the thermocline deepens and density effects become more important. Circulation in southern Lake Michigan appears to be more variable than circulation in northern Lake Michigan. An important new feature not previously seen in observations was found in southern Lake Michigan: an anticyclonic gyre extending northward from the southern shore of Lake Michigan, sometimes occupying the entire southern basin.

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1. Introduction

[2] The current knowledge of circulation patterns and thermal structure in the Great Lakes is still somewhat fragmentary despite significant progress in numerical modeling of lake hydrodynamics [*Beletsky and Schwab*, 2001]. Lake circulation climatology and interannual variability are still distant goals which will require many more simulations and observations than are currently available. Growing computer power allows us to move closer to these goals and also helps to describe medium and small scale processes better due to increased model resolution. This is especially true for the horizontal resolution improvement which is crucial for accurate modeling of lake hydrodynamics in summer when the Rossby radius of deformation is on the order of 5 km. Using grid sizes less than 5 km is critical for resolving processes within the coastal boundary layer, which is 8–10 km wide [*Murthy and Dunbar*, 1981], and improving the simulation of internal Kelvin waves and coastal upwelling fronts in summer [*Beletsky et al.*, 1997]. While moving toward eddy-resolving models of the Great Lakes, it is also important to document the progress along the way.

[3] Lake Michigan has recently been the subject of three comprehensive modeling studies performed with the Princeton Ocean Model [*Blumberg and Mellor*, 1987]. First, in order to predict long-term transport of contaminants for the Lake Michigan Mass Balance Study (LMMBS), thermal structure and circulation in the lake were modeled on a 5 km grid in 1982–1983 and 1994–1995 [*Beletsky and Schwab*, 2001]. Next, the same model was applied to Lake Michigan on a 2 km grid as part of the Episodic Events – Great Lakes Experiment (EEGLE) to study cross-margin transport of biogeochemically important materials during storm events in 1998–2000 [*Beletsky et al.*, 2003]. Finally, the 2001–2003 circulation and thermal structure were modeled in the course of a larval fish transport study [*Beletsky et al.*, 2004] with a particular focus on summer months (June–August).

[4] While model results for unstratified conditions were successfully tested against field observations in 1998, results for summer circulation and thermal structure have not yet been reported. The 2 km model results showed an improvement over 5 km model results during unstratified conditions in early spring, but a question arises whether the same improvement will hold in summer when the lake is strongly stratified. Finally, the accuracy of surface currents modeling (either with Eulerian or Lagrangian methods) was rarely tested in the Great Lakes due to insufficient observations. In 2002–2003, an opportunity to fill this gap presented itself when a new experiment involving drifter observations was conducted in southern Lake Michigan.

[5] The main goals of this paper are: (1) to study the interannual variability of summer circulation and thermal structure in Lake Michigan, (2) to further test the hydrodynamic model with available temperature and current observations, (3) to test predictions of a Lagrangian model with satellite-tracked drifter observations; and finally (4) to provide the physical background information for a larval

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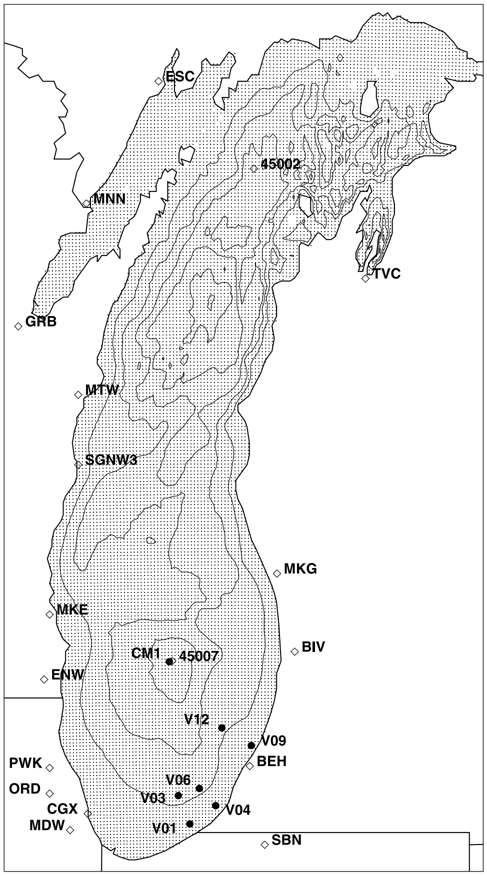

Figure 1. Numerical grid and bathymetry (isobaths every 50 m). Solid circles, current meters; diamonds, meteorological stations.

fish transport study focused on the southern Lake Michigan [*Beletsky et al.*, 2004].

[6] The paper is organized as follows. The hydrodynamic models are described in section 2. Meteorological data and Lagrangian observations are presented in sections 3 and 4 respectively. Model results are analyzed and compared with observations in sections 5 and 6. Discussion and conclusions are presented in section 7.

2. Hydrodynamic Models

2.1. Eulerian Model

[7] A three-dimensional circulation model of Lake Michigan [*Beletsky and Schwab*, 2001] is used to calculate lake circulation and thermal structure. The model is based on the Princeton Ocean Model [*Blumberg and Mellor*, 1987] and is a nonlinear, hydrostatic, fully three-dimensional, primitive equation, finite difference model. The model uses time-dependent wind stress and heat flux forcing at the surface, free-slip lateral boundary conditions, and quadratic bottom friction. The drag coefficient in the bottom friction formulation is spatially variable. It is calculated based on the assumption of a logarithmic bottom boundary layer using constant bottom roughness of 0.1 cm. Horizontal diffusion is calculated with a Smagorinsky eddy parametrization (with a multiplier of 0.1) to give a greater mixing coefficient near strong horizontal gradients. The Princeton Ocean Model employs a terrain following vertical coordinate system (sigma-coordinate). The equations are written in flux form, and the finite differencing is done on an Arakawa-C grid using a control volume formalism. The finite differencing scheme is second order and centered in space and time (leapfrog). The model includes the *Mellor and Yamada* [1982] level 2.5 turbulence closure parameterization. The hydrodynamic model of Lake Michigan has 20 vertical levels (sigma levels, which represent a proportion of a vertical column) with finer spacing near the surface and the bottom (0, −.0227, −.0454, −.0681, −.0908, −.1135, −.1362, −.1589, −.1816, −.2043, −.2270, −.2724, −.3405, −.4313, −.5448, −.6810, −.7945, −.8853, −.9534, −1) and a uniform horizontal grid size of 2 km (Figure 1).

2.2. Lagrangian Model

[8] The 2-d particle trajectory code is based on the second order accurate horizontal trajectory code described by *Bennett and Clites* [1987]. The horizontal currents are first interpolated from velocity points to grid square corners on the Arakawa-C grid. By assuming bilinear variation of the horizontal currents within a grid square, the Taylor series expansion of velocities about the particle position in the trajectory equations yields a pair of simultaneous equations for the new particle position. The time step is chosen to limit the maximum excursion of a particle to 1/8 the distance between horizontal grid points. Particles are prevented from crossing the lake horizontal boundaries. This method generally predicts more realistic trajectories than traditional first-order horizontal methods and does not allow particles to accumulate in ‘stagnation’ zones at grid square corners along the shoreline.

3. Forcing Functions

[9] We use a bulk aerodynamic formulation to calculate heat and momentum fluxes over the water surface at each grid point for the lake circulation model. Hourly meteorological data (wind speed and direction, air temperature, dew point and cloud cover) for April–October 1998–2003 were

Table 1. Monthly Mean Wind Stress Components in 1998–2003[a]

Year	Month	X-Component	Y-Component
1998	Jun	0.06	0.04
1998	Jul	0.12	−0.03
1998	Aug	−0.04	0.03
1999	Jun	0.02	0.00
1999	Jul	0.10	0.13
1999	Aug	0.04	−0.08
2000	Jun	0.08	0.12
2000	Jul	0.02	−0.03
2000	Aug	−0.03	−0.03
2001	Jun	0.03	0.05
2001	Jul	−0.01	−0.04
2001	Aug	0.06	−0.01
2002	Jun	0.03	0.04
2002	Jul	0.02	0.03
2002	Aug	0.04	0.09
2003	Jun	0.00	−0.06
2003	Jul	0.09	0.00
2003	Aug	0.00	−0.03

[a]Units are in dyn/cm^2. Positive direction is east and north.

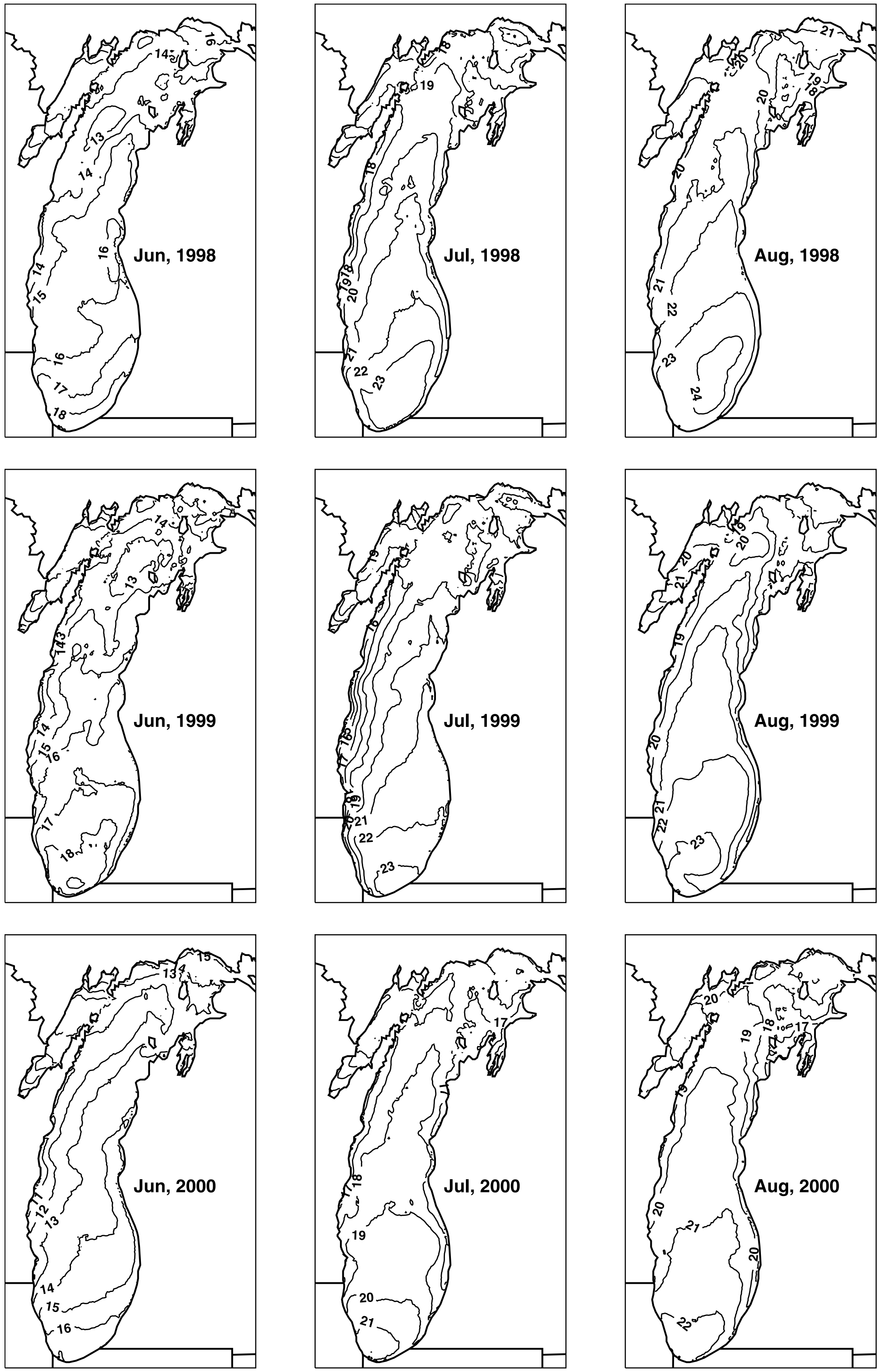

Figure 2a. Monthly averaged lake surface temperature, 1998–2000.

obtained from 18 National Weather Service stations around Lake Michigan and NOAA buoys 45002 and 45007 (Figure 1). These observations form the basis for generating gridded meteorological fields. Details of heat and momentum flux calculations are presented in *Beletsky and Schwab* [2001], and details of a new spatial interpolation technique ("natural neighbor") for meteorological data used in 1998–2003 simulations are presented in *Beletsky et al.* [2003]. Because overland wind speeds generally underestimate overwater values, we apply the empirical overland-overlake wind speed adjustment from *Resio and Vincent* [1977] to data from the 18 land stations.

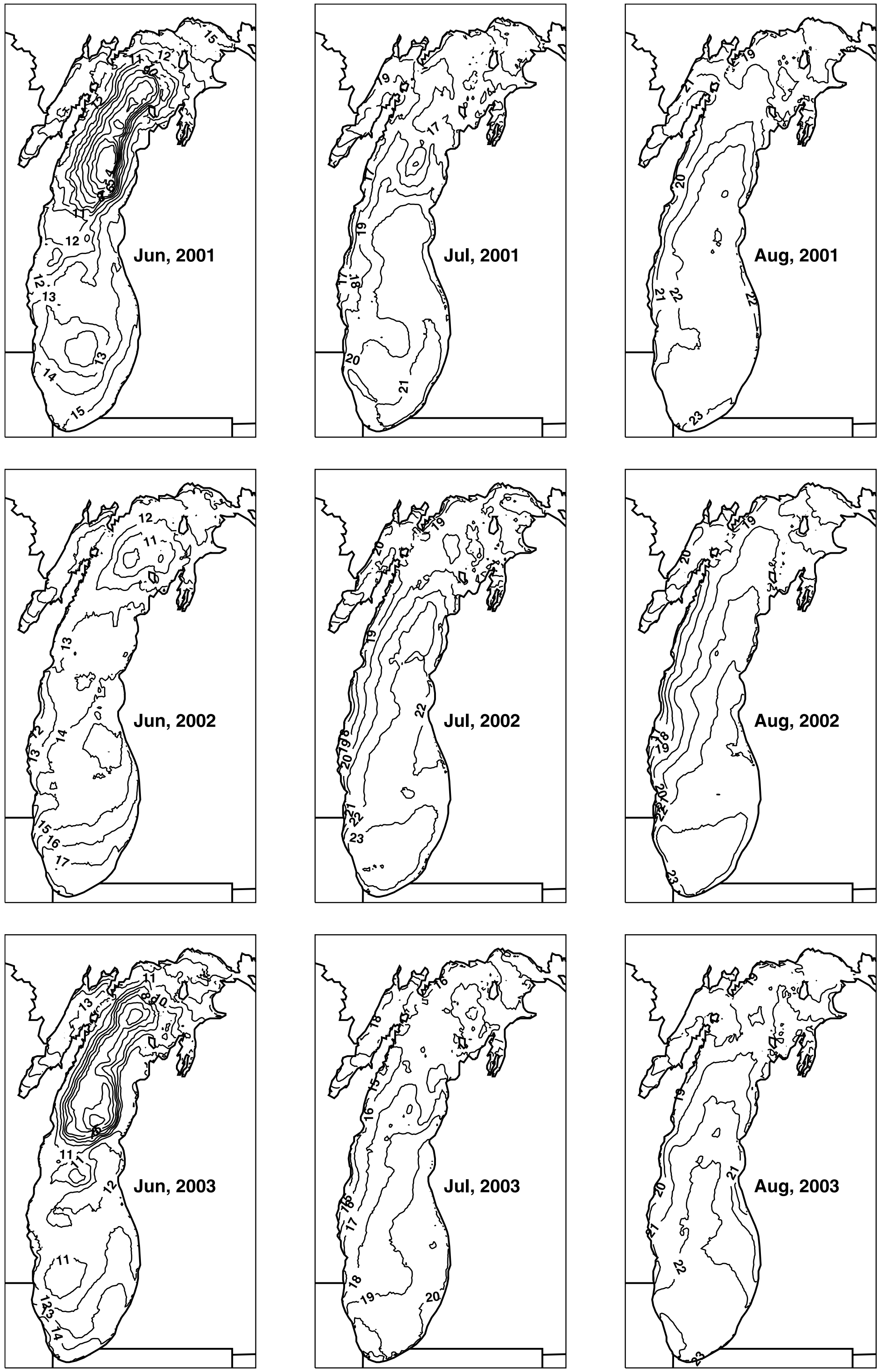

Figure 2b. Monthly averaged lake surface temperature, 2001–2003.

[10] Table 1 shows monthly mean wind stress in 1998–2003, which reflects prevailing southerly and south-westerly winds over Lake Michigan in summer. In addition, an anticyclonic vorticity was evident in the wind stress field in June (not shown) in all years except 2003 when northerly winds dominated. Winds in July and August showed more divergence and more cyclonic vorticity. As was previously shown, wind stress vorticity is an important factor in determining lake circulation patterns [*Schwab and Beletsky*, 2003] and implications of this fact will be related to the circulation patterns discussed later in the paper.

4. Lagrangian Observations

[11] Drifter buoys were deployed in southern Lake Michigan in 2002 and 2003 to measure the near-surface

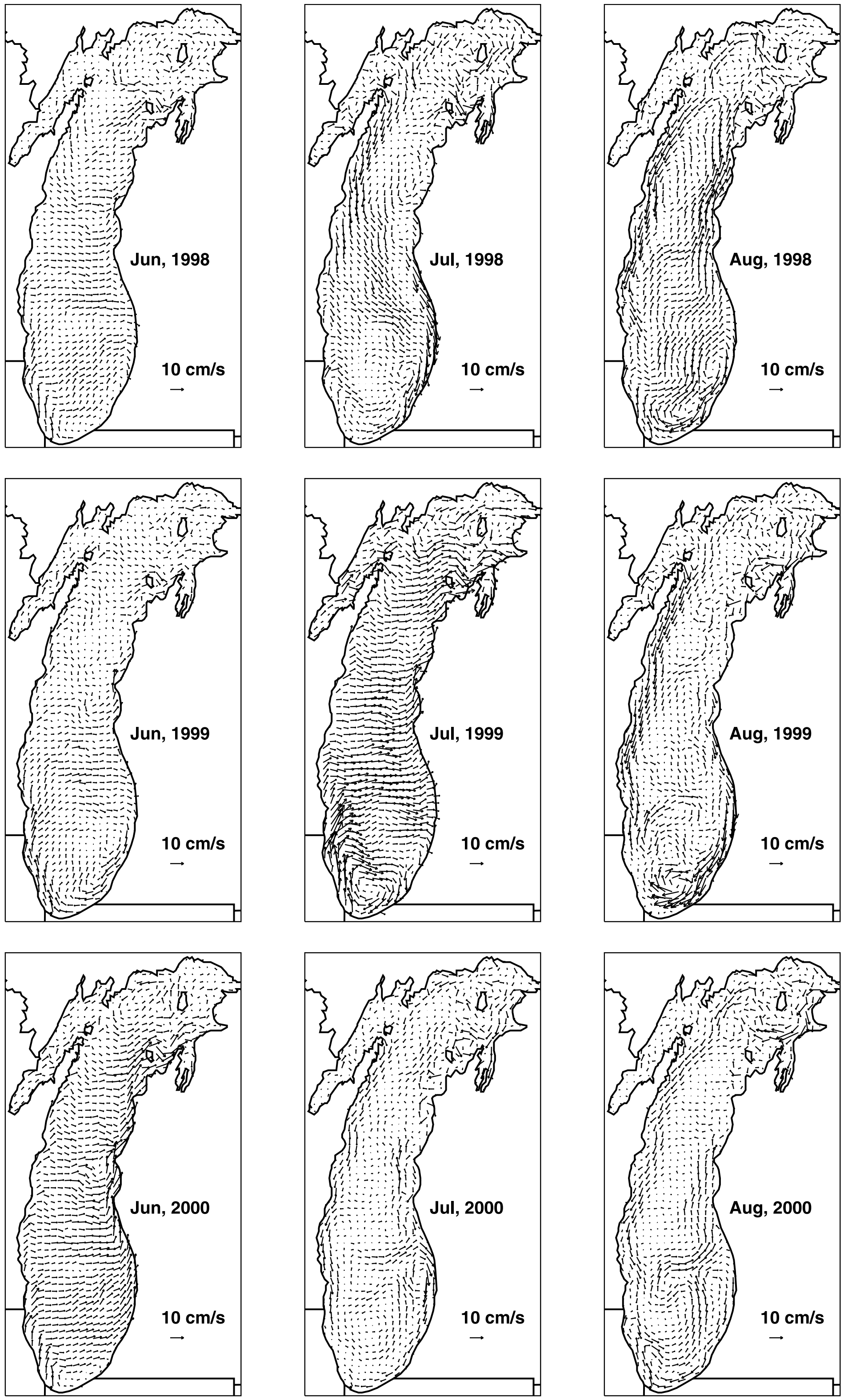

Figure 3a. Monthly averaged surface currents, 1998–2000.

circulation. The drifter data also helps to evaluate the level of confidence and identify potential areas of high uncertainty in the hydrodynamic model simulations. The CODE-type drifters manufactured by Clearwater Instrumentation Inc. are designed to accurately follow the currents in the presence of winds and surface waves. The drifting buoys have dual positioning capability and an onboard microprocessor to store water temperature data and up to 17 previous positions. At hourly time intervals, the drifter attempts to fix its GPS position and then store it internally. An

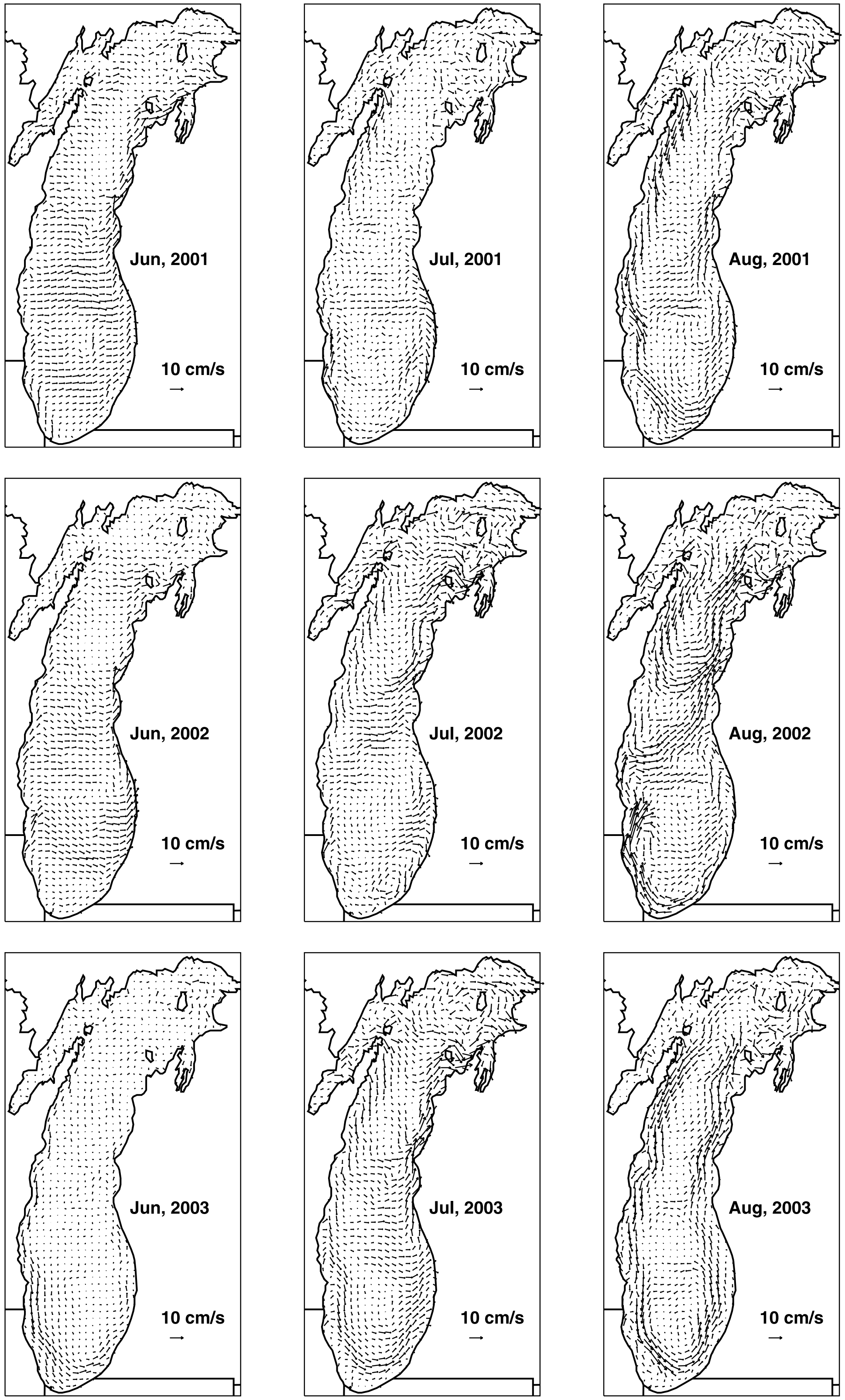

Figure 3b. Monthly averaged surface currents, 2001–2003.

ARGOS transmitter broadcasts these data approximately every 90 s, and when a satellite is in position to receive it, the entire data stream is uploaded to the satellite and returned to the user on a near real-time basis through Service ARGOS. Service ARGOS also has the capability of determining the drifter's position independent of GPS, although not nearly as accurately. In June 2002, we conducted a pilot experiment with new drifters. Five drifters

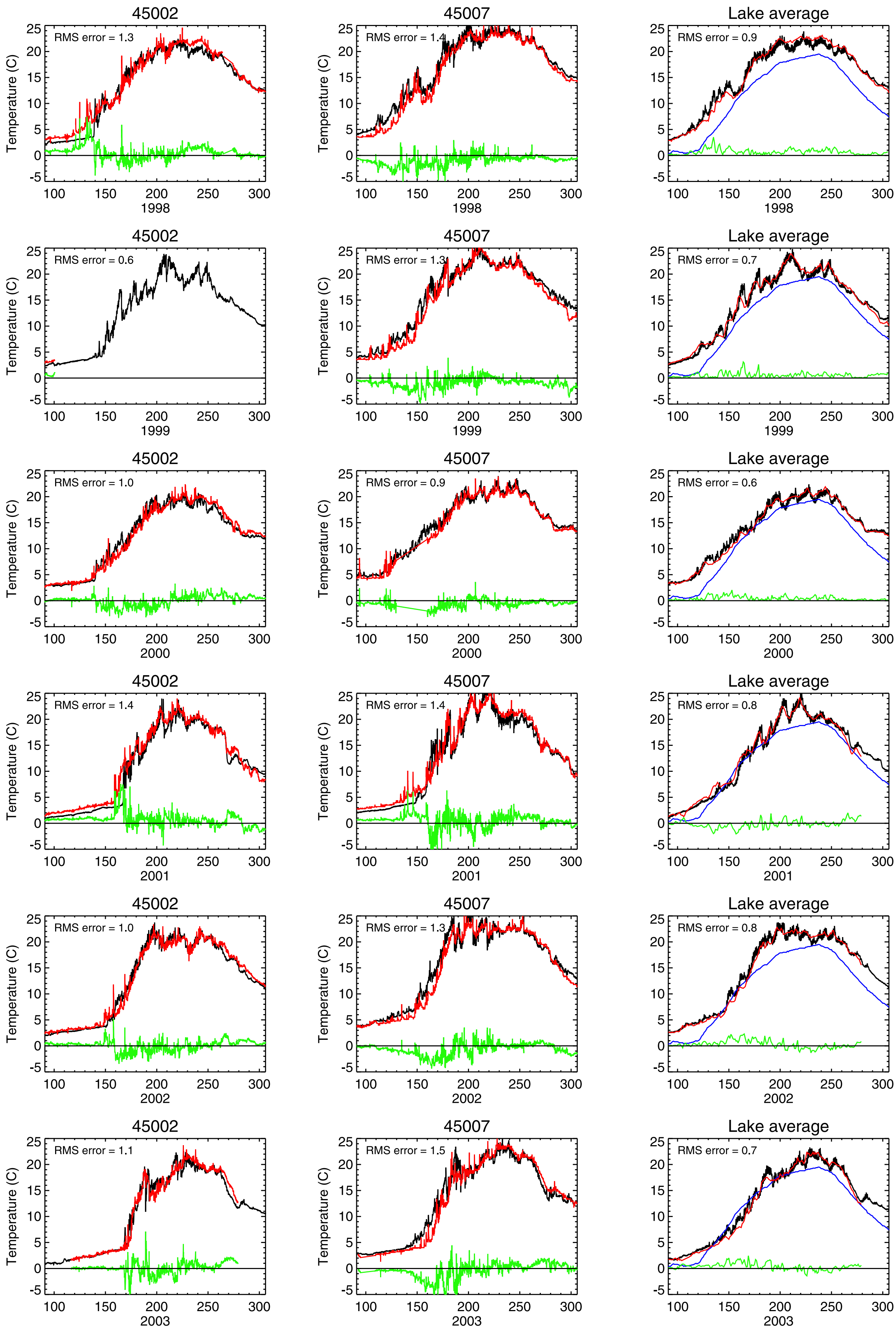
45002
45007
Lake average
RMS error = 1.3
RMS error = 1.4
RMS error = 0.9
RMS error = 0.6
RMS error = 1.3
RMS error = 0.7
RMS error = 1.0
RMS error = 0.9
RMS error = 0.6
RMS error = 1.4
RMS error = 1.4
RMS error = 0.8
RMS error = 1.0
RMS error = 1.3
RMS error = 0.8
RMS error = 1.1
RMS error = 1.5
RMS error = 0.7
Temperature (C)
1998
1999
2000
2001
2002
2003

Figure 4

were released along the eastern shoreline of southern Lake Michigan along the 25 m depth contour. Most drifters moved alongshore northward in a cyclonic fashion, which was consistent with circulation model predictions for June 2002. The 2002 experiment results gave us necessary experience for a longer observation campaign in 2003, for which results are discussed in section 6 along with the particle trajectory model results.

5. Model Results

5.1. Temperature

[12] Hydrodynamic model runs begin on April 1 and end on October 30 of each year in 1998–2003. This way, we avoid dealing with significant ice cover in winters 2000–2001 and 2002–2003. Long-term temperature observations near the buoy 45007 show that in the beginning of the model run in early April, the lake is nearly homogeneous in the vertical. Therefore, the model was initialized with spatially variable surface temperature data derived from Great Lakes CoastWatch analysis but assumed to be vertically homogeneous. The mean temperature in the lake varied during that time from 1.4°C in 2001 to 3.4°C in 2000. Initial currents are set to zero.

[13] Monthly surface temperature patterns for June–August 1998–2003 are shown in Figures 2a and 2b. Heat retention in winter is important for the spring-early summer thermal structure development and is responsible for strong interannual variability of temperature field. When lake's heat content is low by the end of winter (i.e. lake temperature is less than 4°C), a thermal front develops in spring dividing the stratified areas of the lake from the homogeneous ones. There is a general north-south temperature gradient seen in all months in all years, which is somewhat more pronounced in 1998–2003 than in 1982–1983 and 1994–1995 simulations [*Beletsky and Schwab*, 2001]. In both 2001 and 2003, strong cross-isobath gradients are seen in northern Lake Michigan due to the presence of a thermal bar front, which indicates that water temperature decreased below 4°C during these two cold winters. Another prominent feature of lake-wide temperature patterns is a wind-driven upwelling at the west coast. It is seen in most summer months, which is typical of summer conditions in Lake Michigan [*Beletsky and Schwab*, 2001].

5.2. Currents

[14] In general, the surface circulation pattern looks simplest in June (Figures 3a and 3b) when it is mostly wind-driven (density-driven currents are weak because the thermocline is still shallow in early summer) and becomes more complex and cyclonic in July and especially in August when density effects become more important. Analysis of model results shows that in June, surface currents resemble depth-averaged currents primarily in shallow areas. This situation changes gradually as the thermocline deepens during the summer, and by August, surface currents do match depth-averaged currents in most areas. The speed of mean surface currents varied from 10 to 20 cm/s. Circulation in southern Lake Michigan appears to be more variable than circulation in northern Lake Michigan.

[15] In June, mostly southerly winds drive strong northward coastal currents along both the west and east shores of the lake, whereas classic Ekman drift dominates the middle of the lake. June 2000 is a good example of this situation when strong northerly currents originating near the eastern shore in southern Lake Michigan penetrate into the northern Lake Michigan. In some years, strong wind stress vorticity makes circulation more complex with resulting anticylonic (in 1999) or cyclonic (in 2003) circulation gyres in southern Lake Michigan (Figures 3a and 3b, respectively).

[16] In July, circulation becomes more complex as a lake-wide density-driven cyclonic circulation continues to develop. At the same time, an anticyclonic gyre in southern Lake Michigan appears in all years. Its size, shape, and location vary greatly between years, though. In some years, as in 2003 for example, it has all but disappeared except for a narrow area north of Chicago.

[17] In August, cyclonic circulation is strongest as the thermocline deepens further and baroclinic pressure gradients grow. Again, an anticyclonic gyre is present in southern Lake Michigan most of the time, sometimes wrapping around a cyclonic gyre which typically occupies the deep area of that basin.

6. Comparison With Observations

[18] To test the hydrodynamic model's ability to predict temperature and currents, observations obtained in the course of the EEGLE experiment were used along with some of the more recent data. The EEGLE data relevant for this study include 1998 observations of currents and temperature at 12 m and 1 m above the bottom at seven moorings shown in Figure 1. At mooring CM1 located in the middle of southern Lake Michigan, near buoy 45007, there were additional measurements at 22 and 117 m. Here, we mostly focus on a north-south transect formed by the nearshore mooring V01 (20 m deep), offshore mooring V03 (60 m deep), and midlake mooring CM1 (155 m deep), which are representative of different flow regimes in the lake. The Lagrangian model is tested with observations of four drifting buoys.

6.1. Temperature

[19] Time series of modeled versus observed surface temperature at buoys 45002 and 45007 during April–October 1998–2003 are presented in the left and middle columns of Figure 4. The model accurately depicts both the seasonal thermal cycle and interannual variability, with 1998 being an exceptionally warm year and 2001 and 2003 being closer to the climatological mean derived by *Schneider et al.* [1993] for a period of 1966–1993 (right panel of Figure 4), although all six years are warmer than the climatology. There appears to be a small bias (decreasing in time) in the southern basin with modeled temperature

Figure 4. Time series of simulated (black line) surface water temperature versus observed (red line) at 45002, 45007, and lake-averaged in 1998–2003. Green line represents the difference between modeled and observed temperature. Blue line is a 1966–1993 climatology by *Schneider et al.* [1993].

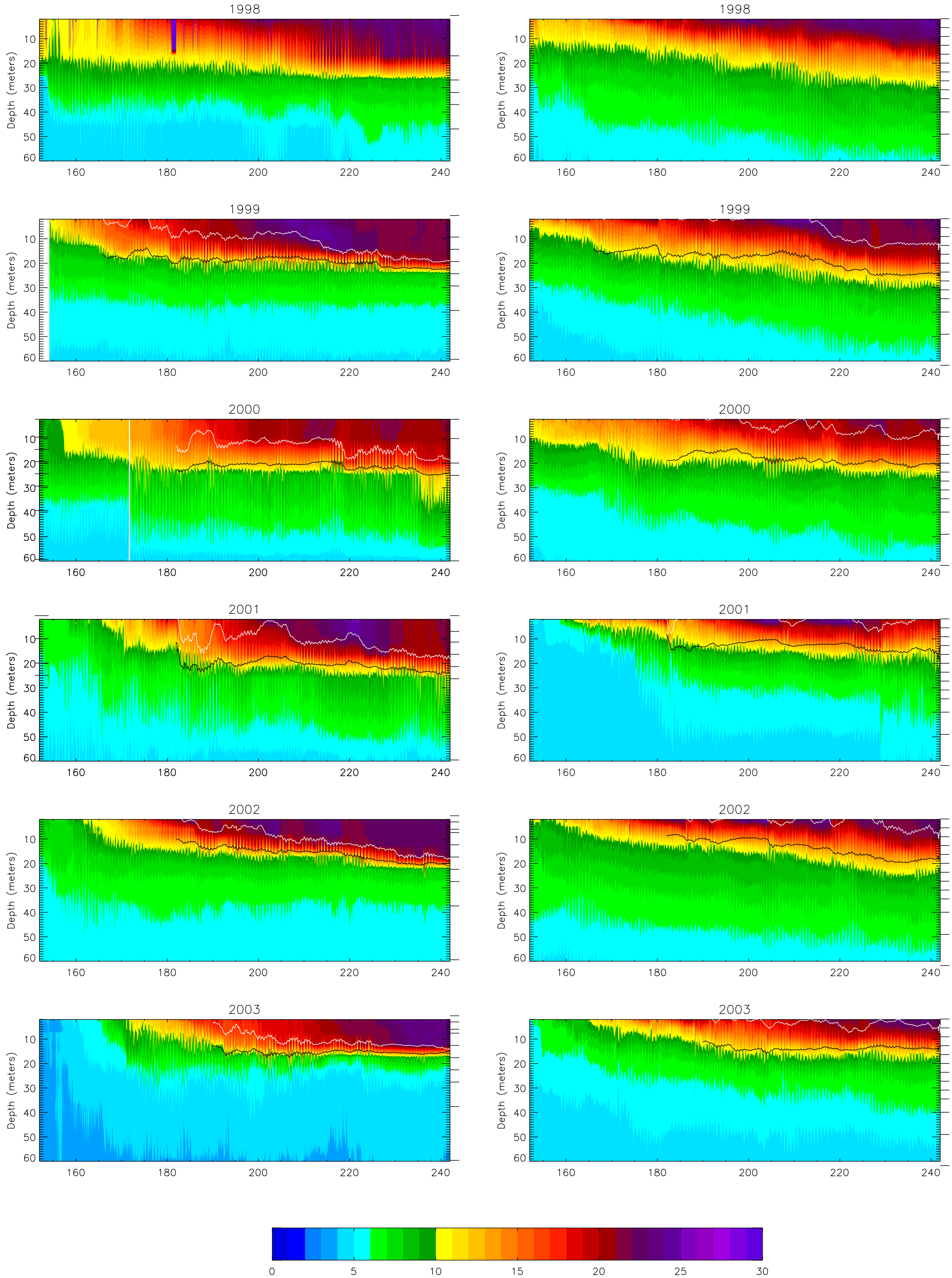
1998
1998
1999
1999
2000
2000
2001
2001
2002
2002
2003
2003
Depth (meters)
10
20
30
40
50
60
160
180
200
220
240
0
5
10
15
20
25
30

Figure 5

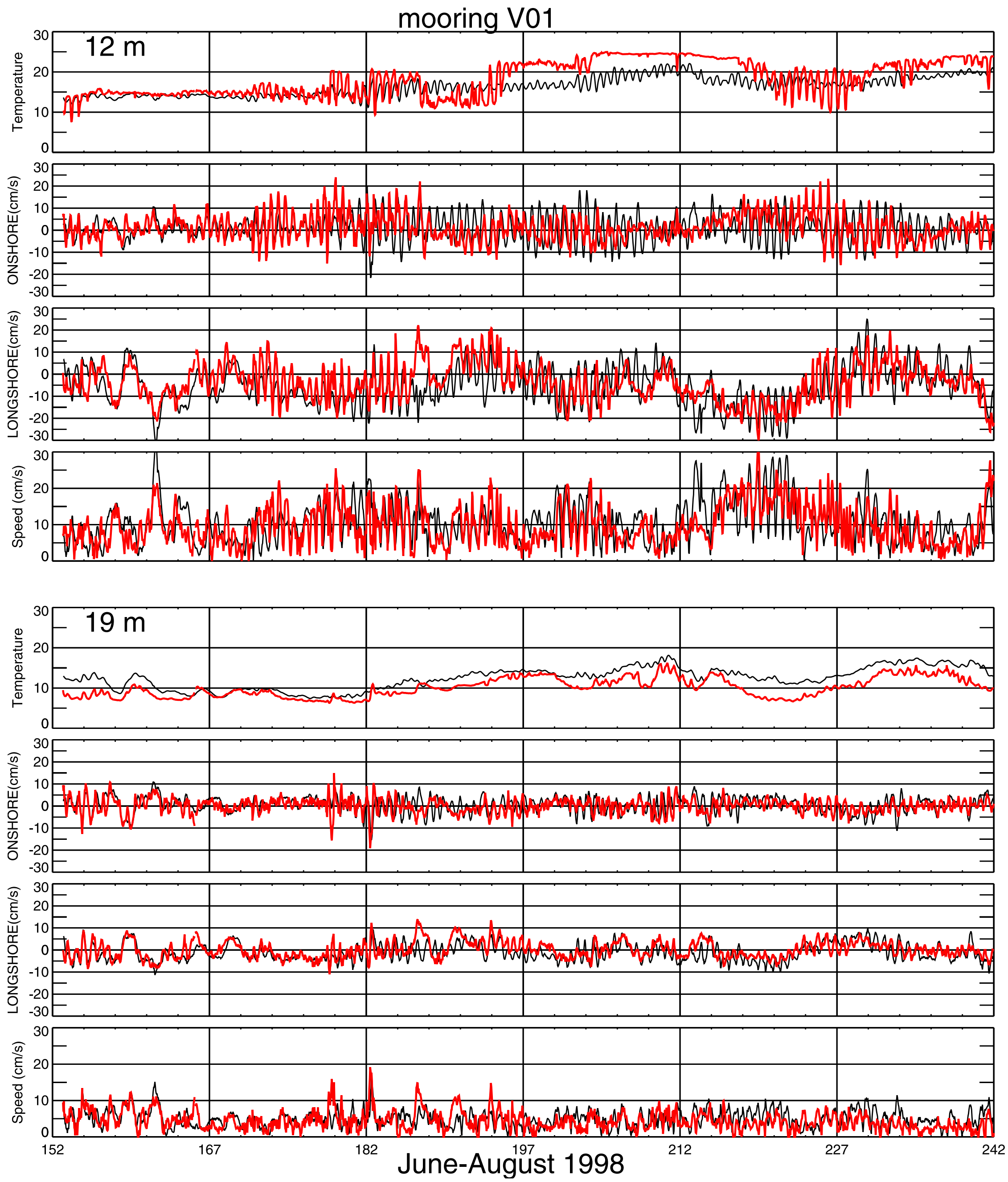

Figure 6a. Time series of observed (red line) and modeled (black line) lake temperature, longshore and onshore current component, and current speed in June–August 1998 at mooring V01.

being warmer than observed which is most likely because of inadequate prescription of initial conditions. Overall, the RMS error is between 0.9 and 1.5°C. The fact that errors tend to decrease as the season progresses indicates that most errors come from inaccuracies in model initialization. Lake-wide averaged modeled temperatures look even more accurate than modeled temperatures at individual locations (the RMS error is between 0.6 and 0.9°C).

[20] Modeled and observed temperature profiles near buoy 45007 in July–August 1998–2003 are presented in Figure 5. To identify mixed layer and thermocline depth more objectively, each vertical temperature profile (both

Figure 5. Observed (left) and simulated (right) water temperature profile (2–60 m) at buoy 45007 in 1998–2003. White line shows mixed layer depth, black line shows midthermocline depth (both are 24-hour smoothed) in all years except 1998 (because of data gaps in the top 17 m layer). Observation levels are shown on the right. Observation levels shown on the left in 2000 and 2001 are from before instrument replacement on JD = 172 and JD = 182, respectively.

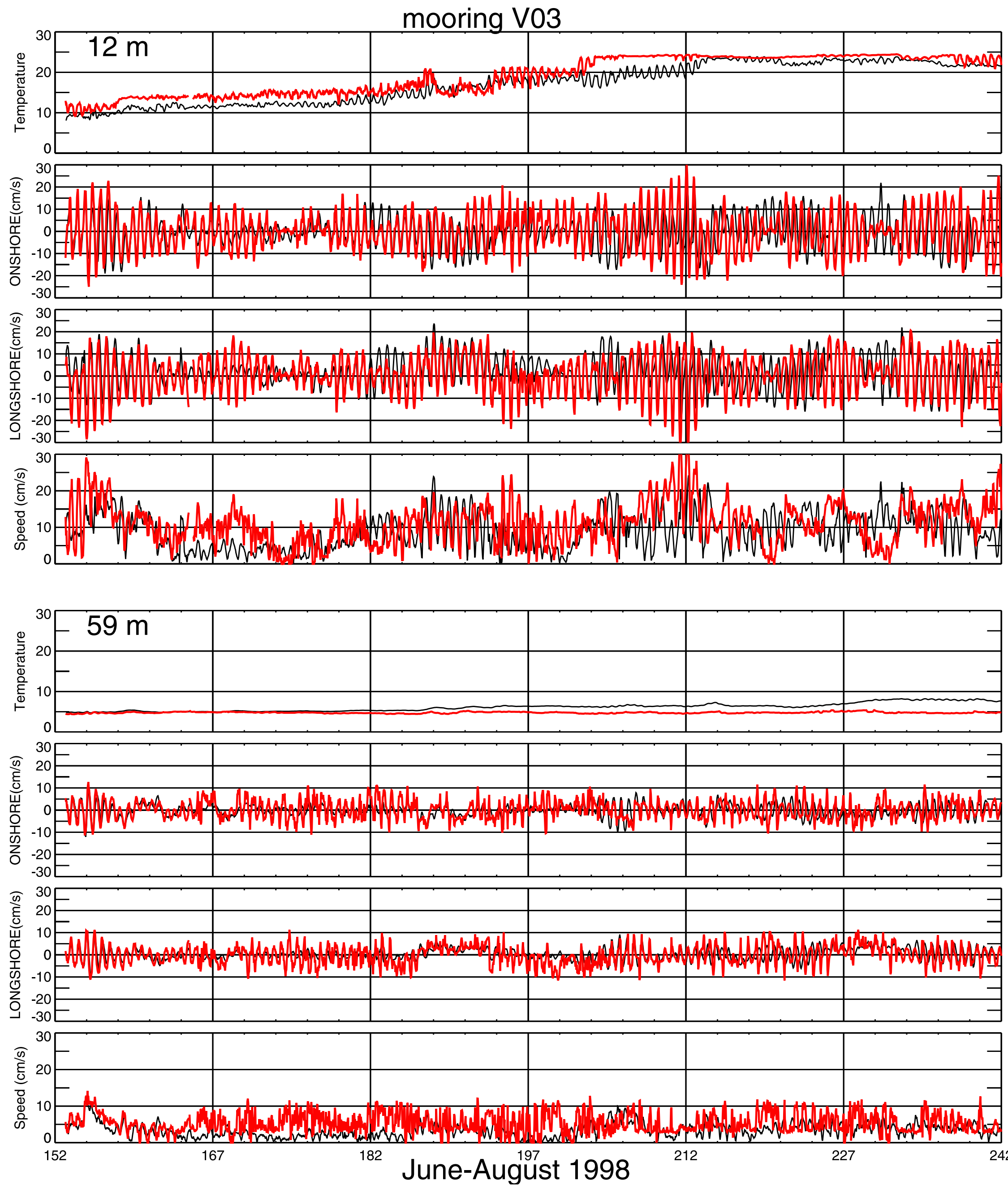

Figure 6b. Time series of observed (red line) and modeled (black line) lake temperature, longshore and onshore current component, and current speed in June–August 1998 at mooring V03.

modeled and observed) was approximated (in a least squares sense) with a 3-layer structure with uniform temperature in the top and bottom layers, and a linear temperature decrease between the top and bottom layers. The mixed layer depth is then taken as the depth of the uniform temperature top layer and the thermocline depth is the middepth of the middle layer. Observations showed slow deepening of the thermocline and faster deepening of a mixed layer in summer, so that by the end of August the 3-layer structure was getting close to the 2-layer structure with a thin and very sharp thermocline, i.e., in 2002 and 2003. The model successfully simulated generation and gradual deepening of the thermocline in the course of summer, but the modeled thermocline was too diffuse and the mixed layer was too shallow in all six years.

[21] This rather significant problem was demonstrated previously in a 5 km grid multiseason modeling study [*Beletsky and Schwab*, 2001]. Apparently, an increased horizontal resolution did not solve the problem (there was an argument that finer horizontal resolution could diminish the artificial temperature diffusion across the sloping bottom along the sigma levels). Experiments with doubled vertical resolution (39 sigma-levels) or different prescriptions of short-wave radiation penetration in the model did not

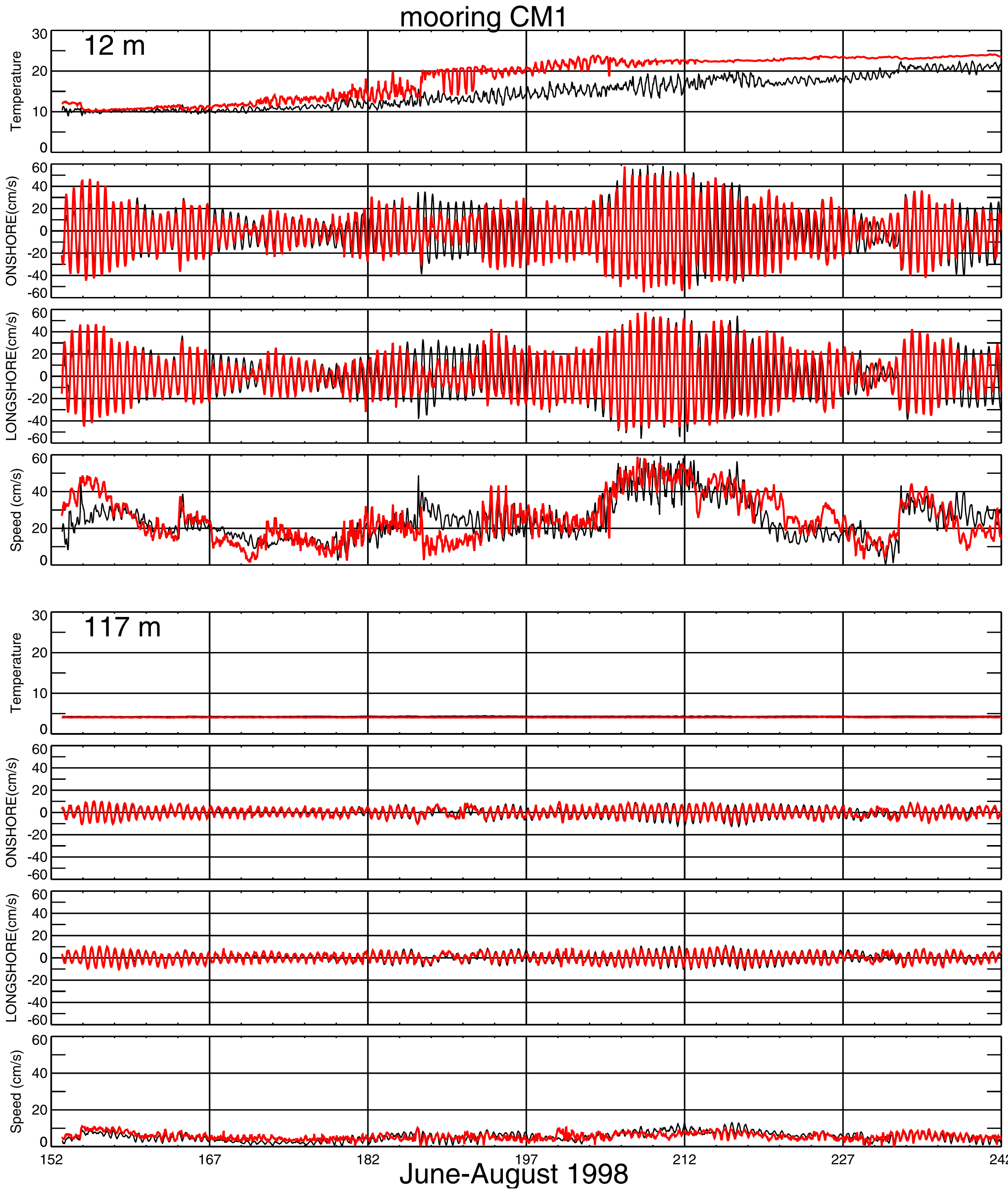

Figure 6c. Time series of observed (red line) and modeled (black line) lake temperature, longshore and onshore current component, and current speed in June–August 1998 at mooring CM1.

improve the thermocline sharpness thus confirming previous findings of *Beletsky and Schwab* [2001]. It is possible though that steepening of internal waves in the model may be artificially diffusing the thermocline. The shallowness of the mixed layer is probably due to insufficient mixing under weak and moderate winds in summer. The vertical turbulence model is currently lacking one potentially important mixing mechanism due to the Langmuir circulation [*Kantha and Clayson*, 2004].

[22] The model qualitatively reproduced the seasonal evolution of temperature at all EEGLE moorings although because of the diffusiveness of the thermocline, the upwelling-downwelling cycle in July–August 1998 is less pronounced at 12 m at nearshore mooring V01, and the model is too warm near the bottom (Figure 6a). At offshore mooring V03 (Figure 6b), the model exhibits a warming trend near the bottom as well with temperatures steadily rising all summer and reaching 7°C by the end of August, whereas observations show a constant 5°C. This is again an indication of excessive vertical mixing in the model. At midlake mooring CM1 (Figure 6c), the model predicted bottom temperature perfectly at 4°C while epilimnion temperatures are several degrees C colder than observations because of a too shallow model thermocline. The ensemble-averaged RMS error for

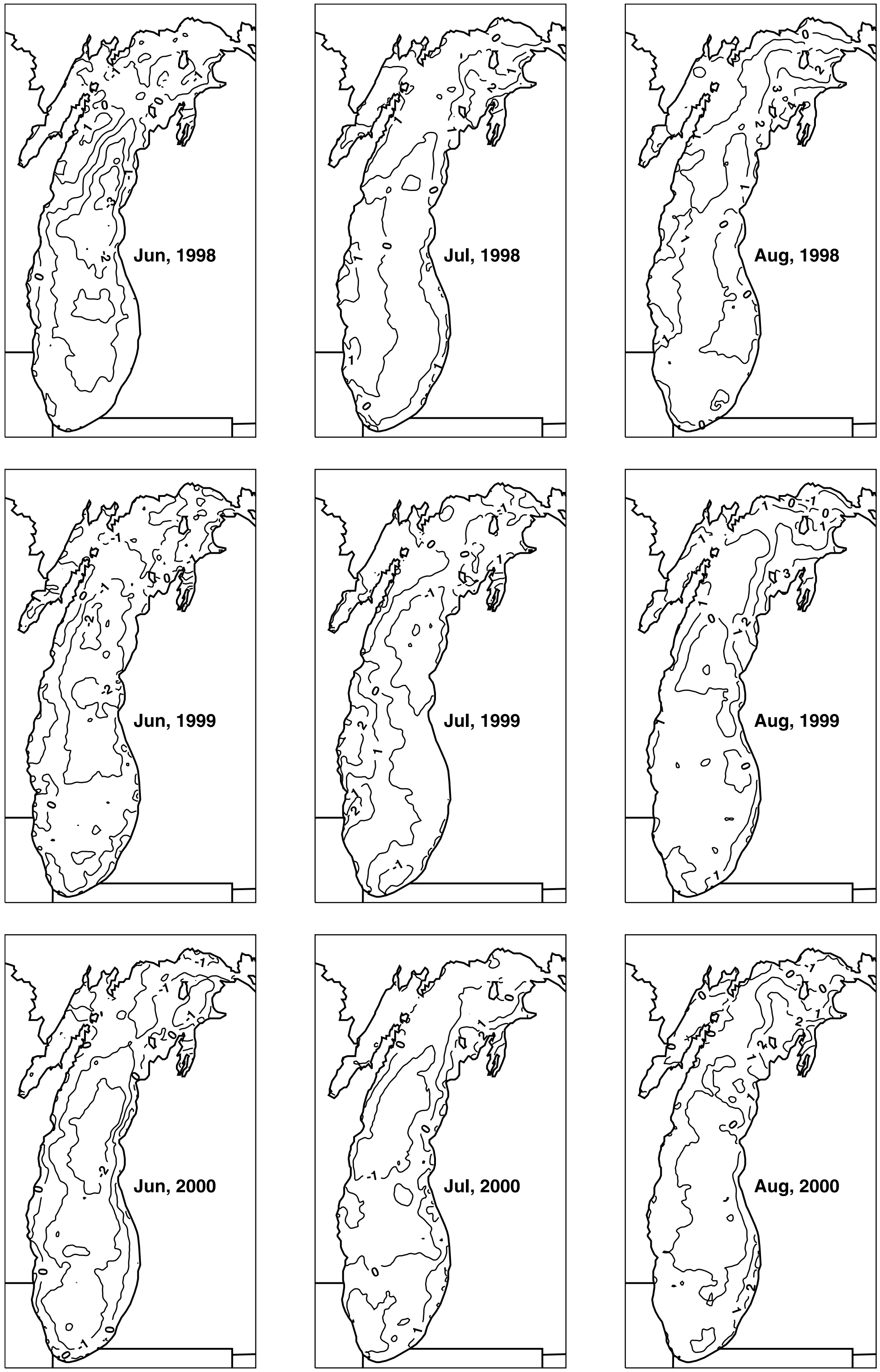

Figure 7a. Monthly averaged difference between modeled and observed lake surface temperature, 1998–2000.

temperature in the upper 20 m is 2.9°C. It decreases to 1.6°C for near-bottom temperatures at 59 m and to 0.3°C for temperatures below 100 m.

[23] Monthly averaged differences between observed and modeled lake surface temperature provide the evidence that point-to-point comparison often does not tell the whole story. The largest errors seem to occur in June (Figures 7a and 7b), and most likely are a result of inaccuracies in model initialization in early spring. During that time, strong horizontal gradients exist at the thermal bar front propagating from shallow to deep areas of the lake. Model errors were most significant in 2001–2003. The model is too warm offshore in early summer, up to 4°C in June 2002. On the other hand, in June 2001, the model is 4°C colder. The errors tend to decrease as summer progresses, and the

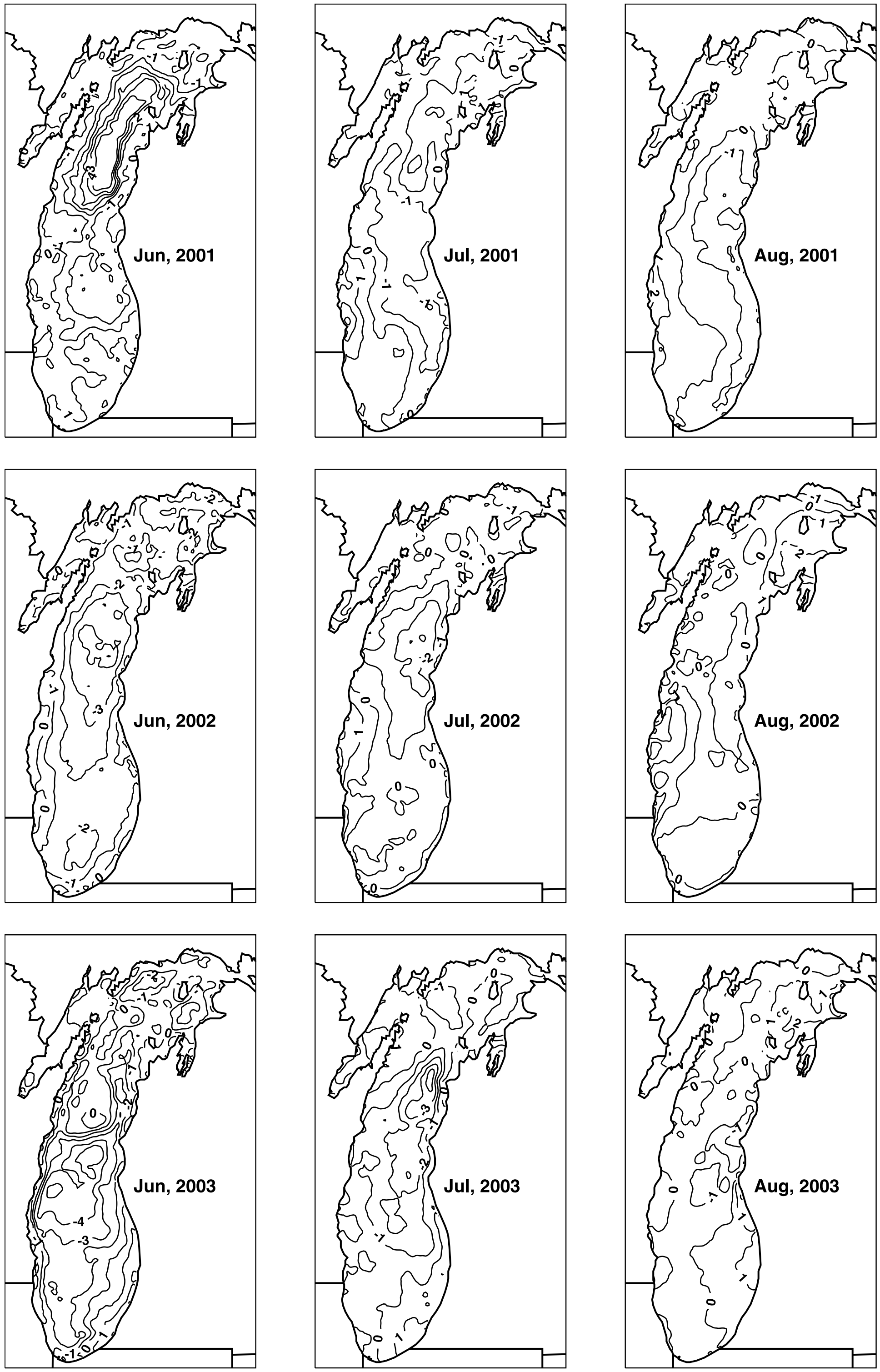

Figure 7b. Monthly averaged difference between modeled and observed lake surface temperature, 2001–2003.

temperature in the model adjusts to the surface boundary conditions.

6.2. Currents

[24] In general, agreement between model and observations looks reasonable at most moorings, including the current speed and even the magnitude of near-inertial oscillations with a period about 18 h and longer-term oscillations at mooring V01 (Figure 6a). The model overestimated the speed of near-bottom currents at mooring V03, though (Figure 6b). At mooring CM1, which is not under the direct influence of coastal currents, the near-inertial oscillations are remarkably persistent at 117 m, and the model was able to capture that rather accurately (Figure 6c).

[25] A statistical comparison of modeled and observed currents is presented in the form of the Fourier norms (RMS

Table 2. Fourier Norms for June–August 1998 Calculated for Observations/Model Results at 12 m and 1 m Above the Bottom[a]

	V01 20 m	V03 60 m	V04 20 m	V06 60 m	V09 20 m	V12 60 m	CM1 155 m
12 m	0.96	0.88	1.09	0.98	No data	0.82	0.55
1 m ab	0.99	0.92	1.10	0.95	1.0	1.59	0.96

[a]Total lake depth is shown below the mooring's name. Additional observations at 22 m and 117 m at mooring CM1 yielded Fn = 0.98 and 0.57, respectively.

of vector difference) [*Schwab*, 1983]. The Fourier norm of time series of observed current vectors v_o and computed v_c is defined as

$$\| v_0, v_c \| = \left(\frac{1}{M} \sum_{t=\Delta}^{M\Delta t} |v_0 - v_c|^2 \right)^{1/2}$$

We use a normalized Fourier norm: Fn = $\|v_o,v_c\|/\|v_o,0\|$. The Fn can also be thought of as the relative percentage of variance in the observed currents that is unexplained by the calculated currents. In the case of perfect prediction Fn = 0. In the case 0 < Fn < 1, model predictions are better than no prediction at all (zero currents). Using Fn allows us to compare our model results more objectively with previous model results.

[26] In June–August, the model tends to predict upper layer (12 m) currents least accurately nearshore and most accurately offshore. In particular, Fn decreases from 1.03 at 20 m moorings to 0.89 at 60 m moorings to 0.55 at 155 m mooring (Table 2). This is most likely due to the fact that offshore upper layer dynamics in summer are dominated by the near-inertial oscillations, while nearshore dynamics are more complex due to the presence of coastally trapped waves and upwelling-downwelling cycles [*Beletsky et al.*, 1997]. In general, near-bottom currents were predicted less accurately than the upper layer currents (Fn = 0.92–1.59).

[27] Observations at midlake mooring CM1 provide evidence of the vertical distribution of model error in summer. Model predictions are more accurate above and below the thermocline, Fn = 0.55 and 0.57 at 22 m and 117 m respectively for June–August. The model is much less accurate in the thermocline (which is hardly surprising because its depth and thickness were not accurately predicted) and near the bottom, Fn = 0.98 and 0.96, respectively.

[28] The fact that current errors were larger at nearshore moorings (V01, V04, V09) located 5–10 km from the shore indicates that even higher horizontal resolution is required to resolve the dynamics of the coastal boundary layer. Vertical resolution was also insufficient for the accurate modeling of bottom boundary layer.

[29] To examine model-data differences with respect to both magnitude and direction, progressive vector diagrams of low-pass-filtered observed and modeled currents are presented in Figure 8. Proximity to the shore makes currents at mooring V01 nearly bi-directional while offshore and midlake currents at moorings V03 and CM1 are omnidirectional. In the upper layer, model results are more accurate at nearshore mooring V01 and midlake mooring CM1. At near bottom depths, the model significantly overestimates current speed at V01 and the direction of the very low-frequency component of the motion is not reproduced by the model at CM1. Topographic waves with a characteristic period of about 4 days [*Saylor et al.*, 1980] are also evident in near bottom observations exhibiting typical counterclockwise rotation at the midlake mooring CM1 and clockwise rotation at the offshore mooring V03.

[30] Monthly averages of observed and predicted currents at 12 m are presented in Figure 9. In the observations, an anticyclonic circulation pattern is seen in all summer months. The model exhibits an anticyclonic circulation pattern in all months as well (Figure 3a), but because the shape and location of the anticyclonic gyre does not always coincide with the shape and location of the observed gyre, modeled currents differ from observed ones at several locations. Perhaps even finer horizontal resolution is needed for accurate simulation of lake hydrodynamics in summer when the baroclinic Rossby radius in the Great Lakes is only 4–5 km. On the other hand, the speed of monthly currents matches observations rather well.

6.3. Drifters

[31] Three drifting buoys were released along the 10 m depth contour north of Chicago, Illinois and one north of Benton Harbor, Michigan in June 2003. All drifters were successfully recovered by late summer. The data analysis shows that drifters 4791 and 4746 traveled along the southern shore of Lake Michigan in a counterclockwise fashion (Figure 10).

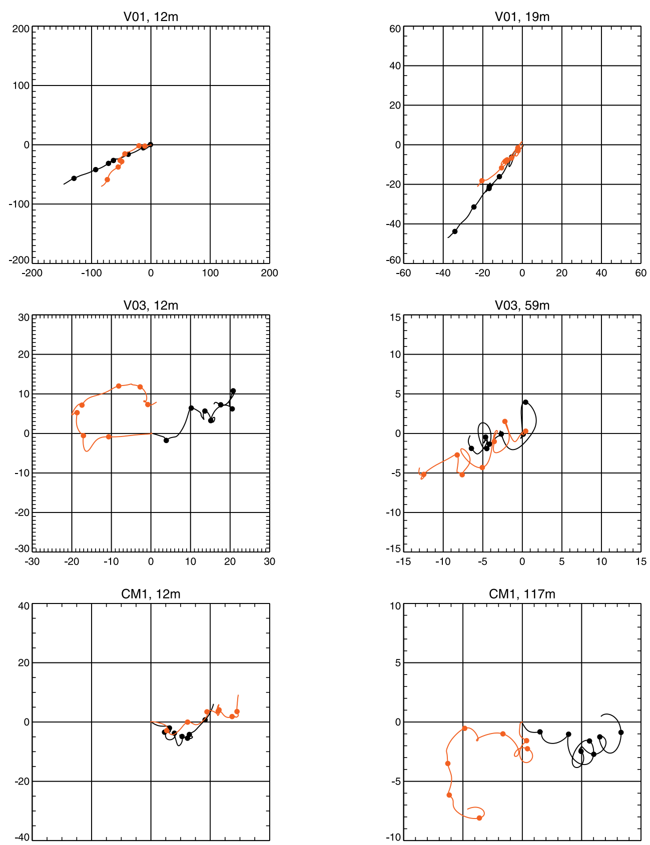

Figure 8. Progressive vector diagram of low-pass-filtered (frequencies greater than 0.5 cpd were removed) observed (red), and modeled (black) currents in June 1998 at moorings V01, V03, and CM1. Solid circles mark every 4 days from June 1. Units are km.

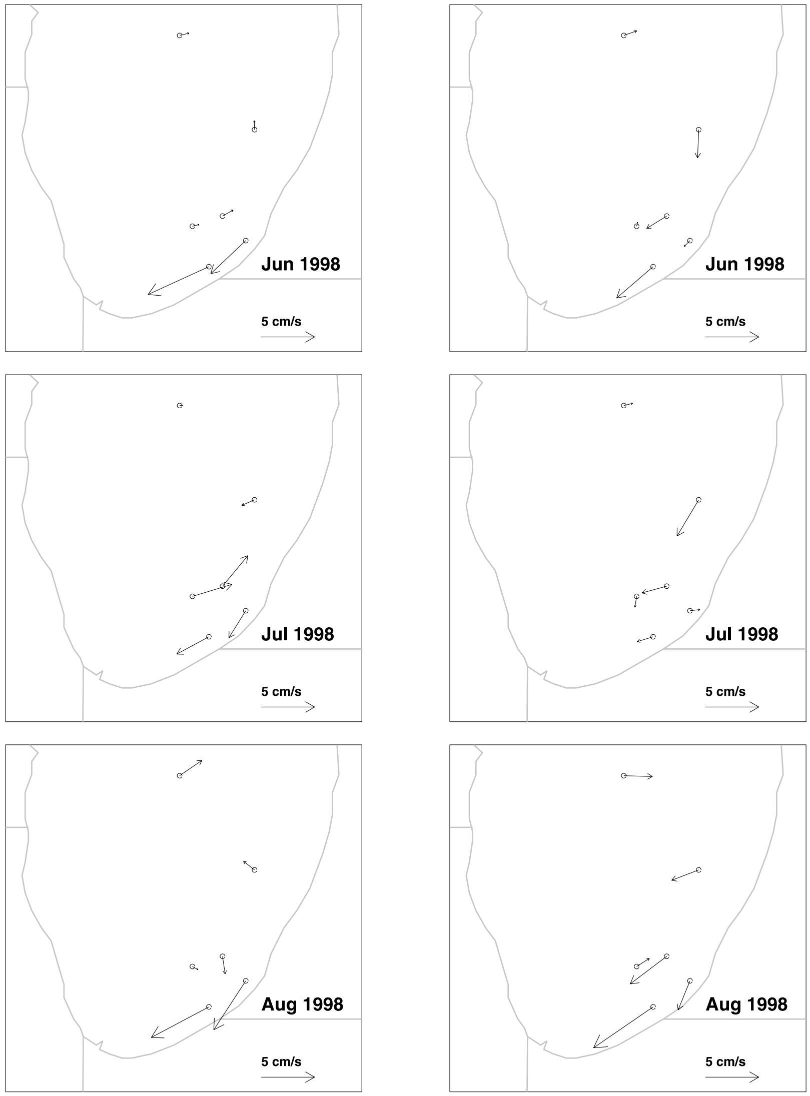

Figure 9. Monthly averaged modeled (left) versus observed (right) currents at 12 m in June–August 1998.

On the other hand, drifters 4795_2 and 4790 exhibit significant nearshore-offshore transport and, while drifter 4790 came back to nearshore waters rather quickly, drifter 4795_2 stayed in the middle of the lake for more than two months. The path of drifter 4795_2 is particularly interesting. First, it moved north and north-eastward within a small anticyclonic gyre seen in Figure 3b (June panel) but later began moving in a cyclonic fashion consistent with the cyclonic circulation seen in July and August panels of Figure 3b. The difference in drifter paths released at the same location with an interval of just one day can be quite dramatic. In particular, drifter 4791 was released on June 4 and traveled as far north as Muskegon, Michigan, twice the distance of drifter 4746 released on June 5.

[32] Tracks of modeled drifter paths are shown in Figure 10 as well. Because satellite-tracked drifters can only move in the surface layer, the 2D Lagrangian model is driven with surface currents provided by the circulation model (saved 3-hourly). The model satisfactorily predicts the movements of drifter 4746 and 4790 and movements of drifter 4791 and 4795_2 for about a half of their drift but eventually diverges from the observed drifter paths, which can be either a sign of inaccuracies in model calculations or sensitivity to initial conditions, or both.

7. Discussion and Conclusions

[33] A three-dimensional primitive equation numerical model was applied to Lake Michigan to study interannual variability of summer circulation and thermal structure in 1998–2003. Model results showed that large-scale circulation tends to be more cyclonic toward the end of summer as the thermocline deepens and density effects become more important. In general, summer circulation in southern Lake Michigan appears to be more variable than circulation in northern Lake Michigan. This is most likely because the southern basin is significantly shallower than the northern basin and thus is more prone to changes in wind-induced circulation from year to year.

[34] The previous summer modeling of Lake Michigan was done on a 5 km grid, therefore it is instructive to make a comparison with this work [*Beletsky and Schwab*, 2001]. In

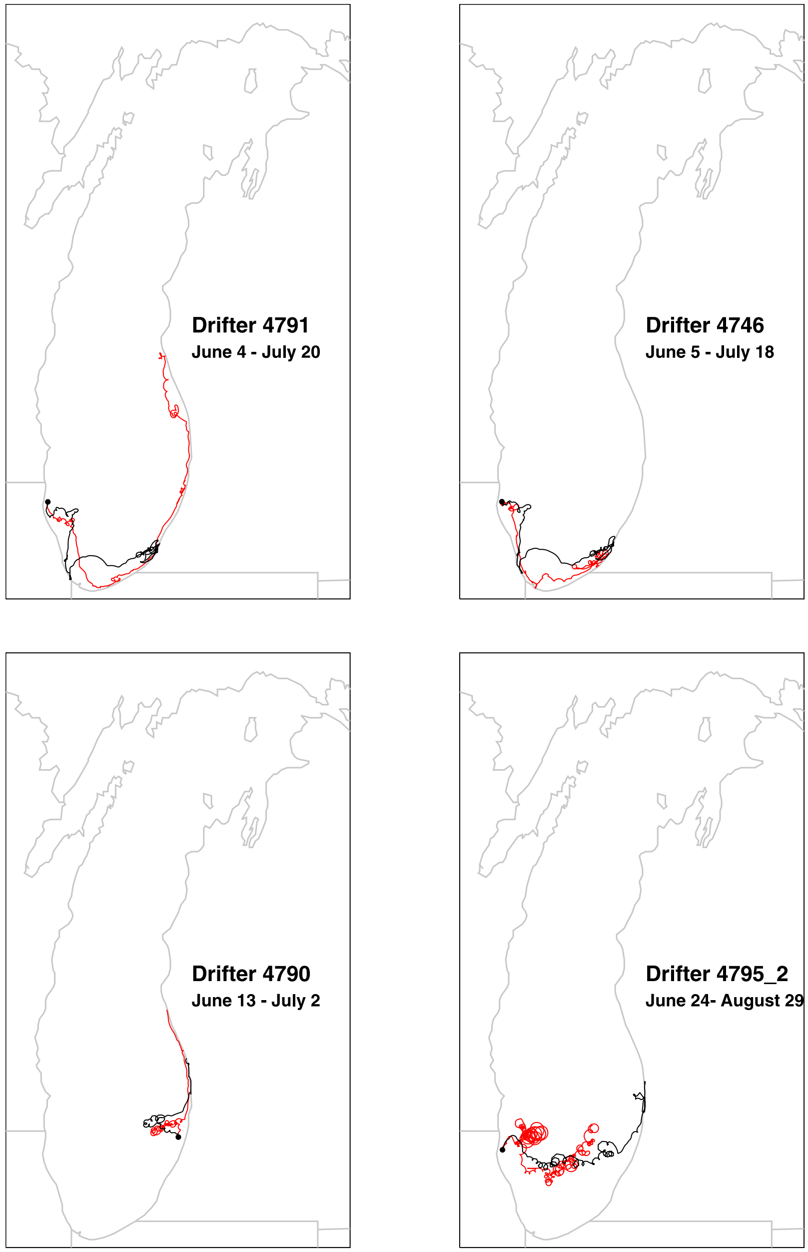

Figure 10. Observed (red line) versus modeled (black line) drifter tracks in 2003. The black circle is a site of drifter release.

general, we did not find an improvement in surface temperature predictions (RMS error about 1–1.5°C). Besides, the spatial patterns of surface temperature are normally well resolved even by a 5 km grid (with exception of a thermal bar front and a wind-driven upwelling on the west coast). A portion of total error in surface temperature predictions is due to inaccuracies of initialization. In addition, this study did not find an improvement in the two problems that were identified earlier, i.e., that the modeled thermocline was too diffuse and that the mixed layer was too shallow [*Beletsky and Schwab*, 2001]. Numerical diffusion continues to be an unresolved issue when dealing with seasonal thermocline simulations in the Great Lakes. Observations showed that thermocline frequently becomes very sharp, especially by the end of summer and this can be a difficult problem for any 3D numerical model to handle. Perhaps the issue of artificial vertical temperature diffusion in lakes can be remediated to some extent by switching from a sigma-level to a z-level model. The ensemble-averaged RMS error for subsurface temperatures modeled on the 2 km grid (0.3–2.9°C) was comparable with RMS errors for 5 km grid model (0.7–2.5°C).

[35] Statistical analysis shows that summer currents were predicted considerably more accurately on the 2 km grid relative to the 5 km grid calculations for 1982–1983 [*Beletsky and Schwab*, 2001]. In 1982–1983, there were four coastal moorings (mooring 1, 2, 3, and 4) deployed in southern Lake Michigan at 75 m depth similar to 60 meter-deep moorings V03, V06, and V12 in the 1998 experiment. The mean Fn for the 12 m observations at 1998 moorings

(in July–August subset of results presented in Table 2) dropped to 0.93 from 1.20 in July–August for 15 m observations at the 1982–1983 moorings. It is difficult to make a comparison for near-bottom currents with the 1982–1983 results since observations were made at 50 m depth, well above the bottom boundary layer, while in 1998 observations were made 1 meter above the bottom. For mooring CM1 located in the middle of the southern basin, Fn = 0.55 at 12 m in June–August 1998 which is a significant improvement over the 1982–1983 simulations when Fn = 0.83 at 15 m in July–August at a matching mooring 23.

[36] An important feature that was found in our simulations (and was barely seen in the previous 5 km simulations) is an anticyclonic gyre in the southern basin of Lake Michigan. The gyre is seen in both surface and depth-averaged currents and the match is better by the end of summer when density-driven currents become more important which indicates that the gyre is a product of a complex interplay between the wind stress vorticity and density field, two major factors affecting lake circulation patterns [*Schwab and Beletsky*, 2003]. The anticyclonic gyre is often located just south of a cyclonic gyre typically occupying the deepest part of the southern basin. The anticyclonic gyre varies greatly in size, shape, and strength, but it was seen in all six years of simulations with its minimum development in 2003 when it was confined to a narrow zone off Chicago. This gyre was not seen in the results of the 1982–1983 observational campaign that were used to produce a mean summer circulation map by *Beletsky et al.* [1999]. Obviously, the spatial coverage in 1982–1983 would be too coarse to identify the gyre in years when its presence was minimal. Thus, according to the model results, the anticyclonic gyre was practically absent in 1982 [see *Beletsky and Schwab*, 2001, Figure 5] and was confined to the northwest corner of southern Lake Michigan in 1983. The anticyclonic gyre was more pronounced in July–August 1995.

[37] Interestingly enough, the above mentioned anticyclonic gyre is also entirely missing in the historical map of *Harrington* [1894], which depicts cyclonic circulation in southern Lake Michigan. Although more than 100 years old now, Harrington's study is probably the most massive drifter experiment ever conducted (and still widely used) on the Great Lakes (in summers of 1892 and 1893). Our study provides an important update and indicates that surface circulation in Lake Michigan does change significantly from year to year and from month to month as well. This finding is potentially important for understanding the particle transport in Lake Michigan and larval transport in particular (a detailed analysis of which will be given in a companion paper, D. Beletsky et al., manuscript submitted to *Journal of Great Lakes Research*, 2006). For example, during months with the cyclonic gyre dominating circulation in the southern basin, surface particles originating on the west side of the basin will move south along the south coast of Lake Michigan (as both observations and model show), whereas during anticyclonic gyre months, particles will move offshore and either stay offshore or move farther across the lake to the east coast of Lake Michigan. This may also explain why sometimes mature fish larvae that are normally expected to be found in nearshore waters have been found in the middle of Lake Michigan.

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