NOTES AND CORRESPONDENCE

Cold Front Acceleration over Lake Michigan

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ABSTRACT

High-resolution Eta Model simulations of a strong but relatively dry late winter surface cold front that occurred during the STORM-FEST project depicted a pronounced acceleration of the front during the afternoon hours over the southern end of Lake Michigan. In this note, the impact of the lake on the front is examined. Reduced lower atmosphere turbulence due to both thermal stabilization and diminished surface roughness acting on postfrontal northerly winds increased frontogenesis strongly over the lake. The enhanced frontal circulation increased the front speed so that a noticeable frontal bulge occurred over the southern end of Lake Michigan. Some observational evidence is available to support the simulated frontal acceleration.

1. Introduction

Large inland bodies of water, such as the Great Lakes in North America, are known to significantly impact the weather of nearby regions. When the lake water is relatively cold compared to nearby land areas (such as occurs frequently in late winter, spring, and summer), thermal stabilization of the lower atmosphere can occur over and near the water. Lakes have been shown to sometimes result in downwind clearing of cumulus clouds, as the convective boundary layer is suppressed over the lake, and dynamically induced subsidence occurs behind the lake breeze (e.g., Purdom 1990; Segal et al. 1997).

Regions of relatively cool water, or the interface between water and land, have also been shown to produce mesoscale variations in fronts. Garratt (1986) has observed the channeling of cold air along the south coast of Australia during a daytime summer cold front event, and has attributed the channeling to the modification of boundary layer air in both the offshore (prefrontal) and onshore (postfrontal) flow. The channeling resulted in a bulge in the surface cold front, with apparently faster (slower) motion over the water (land). Garratt argues that decreased thermal contrast as cool postfrontal air moves over warm land slows the portion of the front over land, as would be expected from gravity current theory (Garratt and Physick 1987).

In this note, we describe a pronounced acceleration that occurred in a high-resolution Eta Model (Mesinger et al. 1988; Janjic 1994) simulation of a cold frontal passage over Lake Michigan on 9 March 1992 during the Storm-Scale Operational Research Meteorology Fronts Experiment Systems Test (STORM-FEST). The simulation was motivated by the following: (i) operational forecasters in this region have observed changes in frontal movement apparently induced by the lake, and have indicated that fronts approaching from the northwest occasionally advance from the northeast into the Chicago metropolitan area (K. Labas 1998, personal communication); and (ii) the question whether boundary layer friction is a frontogenetic or frontolytic process would require evaluating a variety of frontal situations in order to provide a credible answer. Typically, 2D model simulations have been carried out to address this question. In the simulations, runs with and without frictional effects are compared (e.g., Garratt and Physick 1987; Becker et al. 1997). Alternatively the relative role of the friction is evaluated by analyzing its contribution in the frontal convergence equation (e.g., Garratt and Physick 1987). The passage of a front over a large lake provides an opportunity to compare simultaneously the friction enhanced frontal portion over the land and the juxtaposed offshore portion where the friction is reduced. Evaluating such situations by modeling and observational analysis would provide an additional insight...
into the role of frictional effects on real world frontal situations.

The 9 March cold front is a good case with which to investigate frictional effects because the lake surface temperatures were very cold, a large temperature contrast existed between the warm sector and the air behind the cold front, and the front moved generally from north-northwest to south-southeast, nearly following the long axis of the lake. The front crossed the southern half of Lake Michigan during the afternoon hours, reaching the southern shore in the early evening (~0000 UTC). Flow behind the front was almost directly from the north (with a small easterly component), allowing for long duration of air parcels over the water. Ahead of the front, unseasonably warm air with temperatures 15°C or so warmer than the lake temperatures advected northward on flow almost directly out of the south, again over the long axis of the lake.

Output from the Eta simulations of the event is used to show that the reduced impact of lower atmospheric turbulence over the lake during the daytime (because of thermal stabilization over the cold lake waters and reduced surface roughness over the water) allowed stronger convergence to occur along the offshore portion of the front compared with the onshore portion. This enhanced both the temperature gradient and the low-level frontogenesis, particularly along the portion of the front crossing southern Lake Michigan. As would be expected assuming that gravity current theory provides an initial approximation of the speed of this strong temperature gradient and shallow surface front, this portion of the front moved faster than the portions over nearby land areas. It is worth pointing out that Miller et al. (1996) observed density current characteristics at the leading edge of a section of the front away from Lake Michigan.

Pursuing an illustrative model simulation would be useful to provide complementary insight into the impact of Lake Michigan on cold frontal movement. Improved understanding of the impact is essential for improved forecasts in this region, since the cold lake waters will tend to intensify the large changes in weather conditions that occur with frontal passage. The ability to predict acceleration of the front along some portion of the lake would reduce timing errors for temperature and wind changes in those regions. In addition, enhanced convergence due to the lake impacts could affect the evolution of precipitation in the region. Although the small scale of the phenomena greatly limits its ability to be resolved by conventional data networks, an attempt is made to compare the model simulation with observational data.

2. Conceptual evaluation of lake impacts on frontal intensity

Two primary mechanisms exist by which a lake of sufficient size could alter the movement of a cold front. The first would be through a change in the frontal temperature gradient directly caused by changes in thermal fluxes compared with those over land (Garratt 1986). A second mechanism by which lakes could alter a front’s speed would be through changes in surface roughness and near-surface thermal stratification that alter the effect of friction. The two mechanisms are somewhat related, as relatively cool water would reduce or prevent sensible heat flux upward, which would retard the formation of a convective boundary layer over the lake, reducing the frictional effect on flow. Reduced friction over a lake could increase cold advection behind the front, increase convergence along the front, and produce a stronger temperature gradient and faster frontal movement.

As in Gallus and Segal (1999), frontogenesis functions will be used to interpret the behavior of the simulated front. The functions take the form \( F(\cdot) = (D/Dt)[Q(\cdot)/\partial x] \), where \( x \) is the cross-front direction. Following Garratt and Physick (1987)

\[
\frac{D}{Dt} \frac{\partial}{\partial x} + c \frac{\partial}{\partial x} \tag{1}
\]

where \( c \) is the frontal speed of propagation. The value of \( F(\cdot) \) is therefore evaluated at any given time at the frontal location.

The first frontogenesis function \( F_o \) is related to the cross-front potential temperature gradient. It is a classical indicator of front strength introduced by Miller (1948) and has been used in many studies. Adopting Garratt and Physick (1987), its cross-front value is given by

\[
F_o = \frac{D\theta}{Dt} = -u_x \theta_x - (V - ci) \cdot \nabla(\theta_x) - w_z \theta_z + Q_z, \tag{2}
\]

where \( V = (u, w) \), \( \nabla = \partial/\partial x + k \partial/\partial z \) with \( i \) and \( k \) unit vectors along \( x \) and \( z \) directions. The first term on the rhs is related to horizontal convergence, the second relative advection, the third a tilting of isentropes from differential vertical motion, and the fourth differential diabatic heating. The diabatic heating in the model can be due to moist processes, surface sensible heat flux, and radiation.

The second indicator, \( F_u \), is related to temporal changes in the convergence across a front. It provides a direct indication of lifting associated with the front (whereas \( F_o \) provides only an indirect indicator of lifting intensity). Following Garratt and Physick (1987), \( F_u \) is given by

\[
F_u = \frac{D(-u_x)}{Dt} = u_x u_x - (V - ci) \cdot \nabla(-u_x) + w_z u_z - fu_x + \frac{p}{\rho} F_u, \tag{3}
\]
where similar notation is used as in Eq. (2). The first
term represents convergence, the second relative
avduction, the third tilting, the fourth Coriolis effects on
the alongfront winds (\( f \) is the Coriolis parameter),
the fifth changes in pressure gradient across the front, and
the last term changes in friction across the front (change
in acceleration per unit distance). From considerations
of the potential impact of frontogenesis on precipitation,
\( F_v \) as an indicator of the time evolution of vertical mo-
tion should be seen as an improved indicator compared
with \( F_g \).

3. Model configuration and initial conditions

In the simulations of the 9 March cold front, a high-
resolution workstation version of the National Centers
for Environmental Prediction (NCEP) Eta Model was
used. This version of the model uses the same physical
and dynamic code as the operational Eta Model did in
late 1997. The Eta Model was chosen because it is cur-
rently the primary short-range forecasting model used
operationally in the United States. In addition, the land
surface physics were markedly improved in 1997 (Chen
et al. 1997) with the inclusion of a modified Oregon
State University parameterization (e.g., Pan and Mahrt
1987; Holtslag and Ek 1996), which captures the main
biophysical controls on evapotranspiration (these pro-
cesses would be mostly pertinent in the warmer section
of the simulated domain). It was felt that the land surface
parameterization of the model could reasonably simulate
the important processes for this case.

A three-dimensional run with 22-km horizontal res-
olution (somewhat finer than the 32-km resolution used
operationally in 1998) was performed in a roughly 2000 ×
2000 km domain centered on the midwestern United
States. The lowest model level was roughly 60 m above
ground, with vertical resolution varying from around
125 m in the lowest of the 32 model layers to around
1 km at model top. Initial and boundary data for the
simulations were supplied from 40-km data taken from
a prior 48-km Eta run initialized at 0000 UTC 9 March
1992. A small southward adjustment was made in the
positioning of features in the initial data to account for
an underestimate of frontal speed (most pronounced in
the Great Lakes region) that occurred in the Gallus and
Segal (1999) simulations of the event. Seven layers of
soil were prescribed (compared with four in the oper-
atinal Eta version) in order to improve the resolution
of subsurface physical processes. An extensive descrip-
tion of the synoptic pattern over the central United States
during this event can be found in Martin et al. (1995),
Wang et al. (1995), and Miller et al. (1996). More thor-
ough discussion of model simulations over this region
can be found in Gallus and Segal (1999).

Initial soil moisture and temperature data were taken
from the National Centers for Environmental Predict-
ion–National Center for Atmospheric Research
(NCEP–NCAR) reanalysis data (Kalnay et al. 1996) for
this case, and interpolated from the original two layers
to the seven layers used in the high-resolution version
of the model. Gridded fields of eight soil types and 12
vegetation types were determined from Environmental
Protection Agency and United Nations Food and Ag-
riculture Organization datasets, respectively. Topo-
graphic data were provided from a 30-s United States
Geological Survey dataset. Vegetation fraction in the
model was prescribed based on vegetation type and lat-
titude. Lake water temperatures were initialized using
the NCEP reanalysis dataset, which uses both in situ
data (ship and buoy) and bias-corrected satellite tem-
perature data. Although the reanalysis dataset has rel-
etively coarse resolution (1° grid), the model initial lake
temperature data agree well with the National Oceanic
and Atmospheric Administration Great Lakes Environ-
mental Research Laboratory CoastWatch program da-
taset, showing nearly uniform temperatures of 0°–1°C
across Lake Michigan. A sensitivity test found almost
no change in model results for a small change (within
1°C) in the initial lake temperatures.

In the model, a land–sea mask is used to differenti-
ate between land and lake regions. Vertical turbulent ex-
change is calculated based on the Mellor–Yamada Level
2.5 Model (Mellor and Yamada 1982) with some recent
modifications (Lobocki 1993; Gerrity et al. 1994). The
turbulent kinetic energy (TKE) is a fully prognostic var-
iable in the model. The solution of the production–dis-
sipation part of the predictive equation for TKE is ob-
tained from analytic integration while considering phys-
ical realizability constraints (Gerrity et al. 1994). Changes
in TKE due to vertical diffusion and advection are found numerically. Updated values of TKE are used
to compute exchange coefficients for transfer of heat,
mobility, and momentum vertically.

The exchange between the earth’s surface and the
lowest model layer uses the Mellor–Yamada Level 2
model (Lobocki 1993), in which TKE is assumed to be
constant. The surface layer is parameterized following
similarity theory, with surface fluxes determined using
Monin–Obukov functions obtained by numerical inte-
gration. A viscous sublayer is present over water sur-
faces (Janjic 1994) in order to describe the difference
in values of temperature, moisture, and momentum at
the surface itself and what the bulk atmosphere feels.
Over open water surfaces, the values at the interface of
this viscous sublayer and the turbulent layer on top of
it are used as lower boundary conditions. The height of
the viscous sublayer is dependent upon the flow regime.
When a threshold value for friction velocity is exceeded,
the sublayer for momentum collapses. Tests for an ide-
alized case of free convection have shown that param-
ers like time-averaged buoyancy flux and turbulent
exchange coefficient for heat are in reasonable agreement
with observations and large eddy simulations (Janjic
1996).
4. Simulation of the front–lake interaction

A strong cold front, accompanied by only small amounts of precipitation along it, traveled southeastward across the central United States 8–10 March 1992. At 1200 UTC on 9 March, the front was moving slowly south-southeastward across the upper Midwest and Great Lakes, extending from northwestern Missouri across Iowa and southern Wisconsin and into the northern portion of lower Michigan (see Fig. 5 of Miller et al. 1996). By 0000 UTC 10 March, the front had generally advanced to a line from central Missouri across northern Illinois, far northwestern Indiana, and into southern Michigan.

The front has been the subject of several research studies (e.g., Miller et al. 1996; Blumen et al. 1996) since it occurred during the STORM-FEST project and was associated over a large region with extensive postfrontal cloud cover, but limited clouds in the warm sector. This distribution of cloud cover relative to the front resulted in a general intensification and acceleration of the cold front over land regions away from Lake Michigan during the daytime hours on 9 March 1992, noted in both observational studies (e.g., Miller et al. 1996; Blumen et al. 1996) and simulations (Gallus and Segal 1999) of the event. The intensification was shown to be due in large part to a reduction in sensible heat flux occurring behind the cold front due to the greatly reduced solar insolation reaching the surface. Ahead of the front where skies were generally clear, greater sensible heat fluxes occurred.

In the following, we focus on the portion of the front in the vicinity of Lake Michigan. Satellite imagery (from GOES-7) for 9 March indicated that prefrontal clear skies were confined to the region southwest of Lake Michigan through the entire event, although some partial clearing ahead of the front did pass across the southern tip of the lake after 2000 UTC, so that differential sensible heat flux may have had some influence on the frontal strength. The effect was limited, however, by the small area with clearing and the low sun zenith angle by that time.

By 1600 UTC, the cold front was moving south-eastward into central Lake Michigan (Fig. 1a). Because lake temperatures were around 274 K, the air ahead of the front throughout the day was much warmer than the lake water, with small air–lake temperature differences behind the front. Pronounced changes would take place in the frontal temperature gradient near the lake between 1600 (Fig. 1a) and 0000 UTC (Fig. 1d). The temperature gradient was relatively weak compared with nearby land areas at 1600 UTC but had become a local maxima there by 2200 UTC (Fig. 1c). The large changes were apparently facilitated by the larger-scale near-surface wind direction, which was directly from the south in the warm sector, and from the north in the cold sector (Fig. 2). At 1600 UTC, the cold lake waters relative to the air temperature generated downward sensible heat flux ahead of the front over southern Lake Michigan. The long over-water trajectory therefore resulted in progressively lower temperatures as air advected by the southerly flow toward the front, reducing the frontal temperature gradient. Only the far southern portion of the lake was as warm as nearby land areas.

As the front moved southward during the next several hours (into the afternoon), winds both ahead and behind it over the water were significantly stronger than winds over nearby land areas due both to changes in thermal stability over the lake waters (less thermal instability north of the front and increased thermal stability south of it), and a reduction in the roughness length $z_0$ over water. At 1800 UTC (Fig. 2), lowest model layer ($\sim 60$ m) wind speeds reached $20$ m s$^{-1}$ both from the north in the cold air and the south in the warm air over the lake. These speeds were generally several meters per second higher than those found over land. Comparing the cross-front wind component, the increased northerly winds intensified convergence over Lake Michigan at this time (Fig. 3a), and both measures of frontogenesis discussed earlier ($\Delta\theta/\Delta t$ and $\Delta u/\Delta t$) were maximized over the lake. Through 1800 UTC, a region of simulated prefrontal clear skies remained to the southwest of the lake, so that the differential radiative heating mechanisms found to be important in this event (Miller et al. 1996; Blumen et al. 1996; Gallus and Segal 1999) were not occurring here.

Some enhancement of low-level convergence can be seen at 1800 UTC in western Illinois. Several weak disturbances appeared to propagate northeast along the cold front throughout the day. The low-level convergence maximum in western Illinois at 1800 UTC first developed at 1600 UTC farther to the southwest. Over the next few hours, the convergence center moved toward the lake and may have helped to enhance the convergence occurring over the lake later in the afternoon (Fig. 3b). A separate convergence maximum was no longer identifiable after 2000 UTC, and the main convergence center remained near the south end of the lake through 0000 UTC. All of the higher values of convergence that occurred between 1600 and 0000 UTC (Fig. 3b) were found over or along the southwestern shore of Lake Michigan; peak values at other times occurred away from the lake. Thus it appears that the lake itself and its impact on winds played the primary role in increasing the convergence along the front. In addition, acceleration of the front southeastward occurred both prior to and after the passage of the mesoscale disturbance, again suggesting the impact on frontal evolution of any mesoscale disturbances was of secondary importance.

By 2000 UTC (Fig. 1b), the front had moved far enough south that warm air from land areas could advect over the lake toward the front over relatively short distances, and thus was being only mildly cooled by the water through sensible heat flux exchange. Consequently, the frontal temperature gradient had become larger.
over the lake than over the land. In addition, by this time partial clearing of the skies had expanded north-eastward into the far southwestern tip of the lake south of the cold front, so that differential diabatic heating contributed to an increased temperature gradient. A pronounced acceleration of the front occurred by 2200 UTC (Fig. 1c) producing a bulge in the isotherms, with a small region near the southwest shore of Lake Michigan having a temperature gradient 20%–40% larger than that of regions about 100 km away. Relatively clear skies were present at this time across most of the southern tip of the lake ahead of the front, but the low sun angle at this time reduced the impact of prefront surface sensible heat flux on frontogenesis.

The accelerating influence of Lake Michigan was most pronounced at 0000 UTC (Fig. 1d) when signifi-
significant cooling had spread up to 50 km southeast of the lakeshore in northwestern Indiana. Although the frontal bulge was most apparent in the near-surface temperature field, a small influence from the lake did extend upward through about the lowest 800 m of the troposphere. This influence can be seen in vertical cross sections of potential temperature taken through the lake-induced bulge (Fig. 4a) and to its west (Fig. 4b) at 0000 UTC (see locations of cross sections in Fig. 1d). The cross sections are taken perpendicular to the general southwest–northeast axis of the front and show a maximum forward displacement (from this “smoothed” SW–NE line) over the lake of around 40 km near the surface, with little difference between the two cross sections above 1.0 km above mean sea level. The largest differences were confined to the lowest 200 m or so, where frictional differences were largest. Horizontal plots of temperature at 25-mb intervals in the lowest 1.5 km of the atmosphere (not shown) indicated a tendency for the lake-induced frontal bulge to deepen slightly with time, reaching its maximum depth at 0000 UTC.

The significant increase in temperature gradient over the lake during the afternoon hours resulted in an emphasized resemblance to a density current and consequently an increase in frontal speed. The maximum in frontal temperature gradient in this region should also increase the intensity of the frontal circulation (e.g., Sawyer 1956; Eliassen 1962), resulting in a stronger cross-front ageostrophic component and an additional increase in speed. The estimated frontal speed over the lake around 1600 UTC was generally 6 m s⁻¹. This speed increased rapidly during the day, with peak speeds reaching 10–12 m s⁻¹ between 2200 and 0000 UTC as the front approached the shoreline. The acceleration was most pronounced in the southwest portion of the lake, with less impact toward the southeastern shore. This variation may have been related to the small easterly component of the winds in the cold air, which would cause the greatest impact from the lake to be felt at its southwest end, where the winds were more perpendicular to the shoreline. The frontal speed inland to the south of the lake decreased after 0000 UTC and was generally around 6 m s⁻¹ by 0400 UTC.

The frontal speed also increased over land areas away from the lake in regions where an increased temperature gradient developed due to differential radiative heating caused by postfrontal cloud cover (such as Illinois), but
not to the extent that occurred over the cold water. The general peak speeds to the west of the lake, around 8–9 m s\(^{-1}\), were reached slightly earlier in the afternoon, between 2000 and 2200 UTC. East of the lake, where cloud cover remained on both sides of the front throughout the day, the speeds remained slower. The frontal bulge gradually became less pronounced during the evening hours (see Fig. 1e).

An analysis of frontogenetic forcing (\(F_u\)) averaged over a roughly 100-km wide band along the axis of highest values within the frontal zone also shows that the time tendency of the temperature gradient became much larger over the lake than over land areas (Table 1), especially close to the surface during the afternoon hours. At 1400 UTC, \(F_u\) was generally smaller over the lake than over the land. By 1600 UTC, near-surface values had become substantially larger than those over land, and remained larger through 2200 UTC. The larger values also extended through a deeper layer, especially at 1800 UTC. Of the terms contributing to \(F_u\), by far the largest was the convergence term.

Convergence tendencies can be examined in more detail by comparing values of \(F_u\) averaged along the axis of highest values within the frontal zone over the lake and land (Table 2). This measure of frontogenetic forcing already showed at 1400 UTC increased values over the lake at the lowest levels compared to land. The magnitude of differences at the surface peaked slightly earlier (1600 UTC) than that in the \(F_u\) field (1800 UTC). A deepening of the layer in which \(F_u\) was greater over the lake than over the land also occurred through 2000 UTC.

These fields imply that lake-induced reduction of turbulence and the resulting increased wind speeds and convergence over the lake acted to increase the temperature gradient. The effect was first evident in \(F_u\), followed after a small time lag by \(F_u\). An examination of individual terms in the computation of \(F_u\) (not shown) indicated that the largest positive contributors were from the convergence term and the pressure gradient term. Both of these terms were larger over the lake than over the land. In addition, the friction term, which contributes negatively to \(F_u\), was reduced over the lake beginning at the lowest levels at 1600 UTC and deepening to roughly the lowest 1-km layer at 1800 and 2000 UTC. This term was reduced by roughly 50% or more in the 900–950 mb layer at these two times.

Table 1. Average \(F_u\) [in K (100 km)\(^{-1}\) h\(^{-1}\)] for roughly 100-km wide portion of front over Lake Michigan (lake) and over land areas to its west (land) at the surface and at the indicated pressure levels (mb). Values are given for selected hours on 9 Mar 1992. Regions have been chosen to coincide with zone of most significant \(F_u\) generally located toward the rear of significant temperature gradients shown in Fig. 1.

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Fig. 4. Vertical cross sections of potential temperature (K) taken at 0000 UTC (a) through the region of frontal bulge and (b) west of Lake Michigan (locations of both cross sections are indicated by dark lines in Fig. 1d). A horizontal distance scale relative to the mean frontal axis is indicated below both cross sections.
5. Observations

Although operational forecasters near southern Lake Michigan have noted frontal bulging in the past (K. Labas 1998, personal communication), it has been difficult to document because of a paucity of standard meteorological surface observations in the region of interest. Fairly high resolution surface reports are available from the Chicago area on the southwestern shore of the lake, but few if any reports are available from the northwestern part of Indiana west of South Bend. Although generally clear skies in the prefrontal region were the rule for the 9 March case farther west, extensive cloud cover near Lake Michigan prevented the use of satellite data to infer frontal location for this event.

To supplement standard meteorological data, some wind and temperature data were obtained from utility company power plants throughout northwestern Indiana at Hammond (HMD), Dune Acres (DUN), Michigan City (MIH), and Coolspring (COP) in Fig. 5a. In addition, data from a power plant at Bridgman, Michigan (COO), were also obtained. Wind information at 10-m elevation was used for these sites. Hourly surface analyses using all data from 2100 UTC 9 March (Fig. 5a) through 0100 UTC 10 March (Fig. 5e) do provide some evidence of Lake Michigan–induced frontal acceleration, especially while the front was passing through the relatively data-abundant Chicago region. Estimated frontal positions in Fig. 5 have been drawn to maintain temporal continuity (i.e., frontal speed should not vary randomly between each hour), and make use of data from outside the domain region over a longer time period than the 2100–0100 UTC times shown. The acceleration was most noticeable on the southwest shore of the lake. At 2100 UTC (Fig. 5a), the front had a generally WSW to ENE orientation, although this orientation was disturbed near the southwest shore of the lake. Station NBU in the northern part of the Chicago area had experienced frontal passage while other Chicago region sites had not.

One hour later (Fig. 5b), the most clear evidence exists for frontal acceleration. A noticeable southward bulge can be seen along the Lake Michigan shore in the Chicago area. Although the front has not yet passed DuPage (DPA), about 50 km west of the lake, where the temperature is 61°F, frontal passage has clearly occurred at Meigs Field (CGX) on the lakeshore at a slight-ly farther south latitude, where the temperature has fallen from 60°F to 42°F in the last hour. At this same time, Midway Airport (MDW), only 15 km to the southwest of CGX was still 62°F as the front had not yet passed. The model simulation valid at this time (Fig. 1c) also suggested a slightly faster frontal passage at the immediate lakeshore in this region.

By 2300 UTC, temperature data from a power plant in Hammond, Indiana, continue to support the faster southward movement of the front in this region, with temperatures having fallen from 62°F to 43°F between 2200 and 2300 UTC. Frontal passage has not yet occurred at Marseilles (MMO), roughly 100 km west-southwest of Hammond. Additionally, a northeast wind at MDW at 2300 UTC (Fig. 5c) suggests a continued lake influence on the immediate postfrontal environment. Temperatures at CGX near the lake are still 4°F cooler than those just inland at MDW. Power plant data from DUN just east of Hammond suggest the front was just passing through the site at 2300 UTC. Thus, the observed frontal bulge was concentrated on the southwest shore of the lake with a more NE–SW orientation of the front near the southeastern shore of the lake.

This change in the orientation of the front was even more apparent at 0000 UTC (Fig. 5d). At this time, all of the power plant data in Indiana suggest frontal passage, but the data from COO in far southwestern Michigan do not. The more rapid southward progression of the front observed on the west side of the lake with relatively less acceleration on the southeast side supports the model results at 2200 and 0000 UTC (Figs. 1c,d). The easterly component of the winds behind the front likely cause the greatest impact of the lake to be felt on its southwest shore. The postfrontal winds would be more shore-parallel on the southeast side of the lake. By 0100 UTC, the front had just passed through South Bend (SBN) and Grand Rapids (GRR). A lack of data inland from the lake in northwestern Indiana prevents analysis of small-scale variations in the front. The general larger-scale orientation of the front at this time is similar to that simulated by 0400 UTC (Fig. 1e), with a gradual cyclonic curvature through northwestern Indiana.

6. Conclusions

Eta simulations of a shallow cold front with strong temperature gradient that occurred on 9 March 1992
during the STORM-FEST experiment depict a pronounced acceleration and frontal bulge over southern Lake Michigan. South winds ahead of the cold front and north winds behind it were roughly parallel to the orientation of Lake Michigan. During the morning of 9 March, while the front was sufficiently far north of the southern shore, the cold lake waters reduced the frontal temperature gradient as air advected by the south winds had to cross an expansive section of the lake. However, as the front moved closer to the shore, warm advection from the land offset the cooling impact of the lake. Meanwhile, north winds behind the front, enhanced by
reduced friction, increased cold advection as well as convergence and frontogenesis over the lake. The relatively shallow depth of the front and its sharp temperature gradient suggest some resemblance to a density current. In addition, the increased frontal speed associated with the enhanced temperature gradient would be expected from density current theory.

Observational evidence is somewhat limited for this case by a lack of standard meteorological observations southeast of Chicago. However, some additional insight was gained by including data from several power plants in this region. Stations in the Chicago area did depict a noticeable bulge in the front during the late afternoon hours of 9 March, particularly on the southwest shore of the lake. Similar frontal bulges have been noted occasionally by forecasters in that area.

The reduction in friction over the lake is primarily caused by the greatly reduced daytime buoyancy-generated turbulence within the boundary layer due to cold lake waters relative to the air. This effect would be most pronounced for cold fronts occurring from late winter to early summer. In addition, for a relatively narrow lake like Lake Michigan, the effect should require a strong northerly component to the flow in the cold sector. Strong winds in the warm sector should also aid in the acceleration process by advecting warm air toward the portion of the front over the lake, increasing the temperature gradient.

Although the studied frontal case was relatively inactive in terms of significant precipitation, the enhanced convergence occurring near the southern end of the lake in the region of frontal acceleration could be a favored area for convective initiation, or enhancement of precipitation. With the horizontal resolution of the operational Eta Model currently approaching that used in this study, it is likely that model guidance will depict lake-induced modifications such as frontal acceleration increasingly often. Operational forecasters may also be able to use radial velocity data from nearby Weather Surveillance Radar-1988 Doppler (WSR-88D) sites to detect these small-scale frontal accelerations, although the shallow nature of the features would limit the use to within a few tens of kilometers. Future work should address the impact of frontal strength, near-front wind speeds and wind directions on the frontal acceleration.

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