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Modeling thermal structure and circulation in Lake Michigan

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Abstract

A three-dimensional primitive equation numerical ocean model, the Princeton model of Blumberg and Mellor (1987), was applied to Lake Michigan for the 1982-1983 study period. The model has a terrain following (sigma) vertical coordinate and the Mellor-Yamada turbulence closure scheme. This two-year period was chosen because of an extensive set of observational data including surface temperature observations at permanent buoys and current and temperature observations from subsurface moorings. The emphasis of this paper is on the large-scale seasonal variations of thermal structure and circulation in Lake Michigan.

The hydrodynamic model of Lake Michigan has 20 vertical levels and a uniform horizontal grid size of 5 km. The model is driven with surface fluxes of heat and momentum derived from observed meteorological conditions at eight land stations and two buoys from April 1982 to November 1983. The model was able to reproduce all of the basic features of the thermal structure in Lake Michigan: spring thermal front, full stratification, deepening of the thermocline during the fall cooling, and finally an overturn in the late fall. The largest currents occur in the fall and winter when temperature gradients are lowest and winds strongest. Large-scale circulation patterns tend to be cyclonic (counterclockwise), with cyclonic circulation within each subbasin. All these facts are in agreement with observations.

Introduction

There has been significant progress in hydrodynamic modeling of short-term processes such as water level fluctuations due to seiches or storm surges in the Great Lakes (Schwab, 1992). On the other hand, long-term circulation modeling efforts have been rare. For example, since the pioneering works of Simons (1974, 1980) created the basis for numerical studies of circulation and thermal structure in the

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Great Lakes, Lake Michigan experienced only two long-term modeling exercises: Allender and Saylor (1979) simulated three-dimensional circulation and thermal structure for an 8-month period, and Schwab (1983) studied circulation with a two-dimensional barotropic model also for an 8-month period.

Currently, with increases in computer power, seasonal variations in thermal structure and circulation can be more easily studied using three-dimensional hydrodynamic models. Many oceanographers and limnologists have used the Princeton Ocean Model (POM) of Blumberg and Mellor (1987) in the ocean, coastal areas, and lakes. In particular, over the past 5 years, POM has been adapted for use in the Great Lakes and has been successfully applied to Lake Erie as part of the Great Lakes Forecasting System (Schwab and Bedford, 1994), and to Lake Michigan (Beletsky et al., 1997).

In this paper, the Princeton model was applied to Lake Michigan in support of the EPA Lake Michigan Mass Balance Project (LMMBP). Model output is being used as an input for sediment transport and water quality models to study the transport and fate of toxic chemicals in Lake Michigan for the 1982-1983 study period. This 2-year period was chosen for the model calibration because of an extensive set of observational data (Fig. 1) including surface temperature observations at two permanent buoys, and current and temperature observations during June 1982 - July 1983 at several depths from 15 subsurface moorings (Gottlieb et al., 1989). The emphasis of this paper is on the large-scale seasonal variations of thermal structure and circulation in Lake Michigan.

There is no ice modeling component in the present version of the model, which can be a problem for the annual cycle modeling in general, because ice cover can cause significant changes in winter circulation patterns in a large lake. The Great Lakes are usually at least partially ice-covered from December to April. Maximum ice extent is normally observed in late February, when ice typically covers 45% of Lake Michigan (Assel et al., 1983). The 1982-83 winter was very mild and therefore, Lake Michigan was practically ice-free during the whole period of our study.

Model description

The Princeton model (Blumberg and Mellor, 1987) is a nonlinear, fully three-dimensional, primitive equation, finite difference model that solves the equations of fluid dynamics. The model is hydrostatic and Boussinesq so that density variations are neglected except where they are multiplied by gravity in the buoyancy term. The model uses wind stress and heat flux forcing at the surface, zero heat flux at the bottom, free-slip lateral boundary conditions, and quadratic bottom friction. Horizontal diffusion is calculated with a Smagorinsky eddy parameterization (with a multiplier of 0.1) to give greater mixing coefficient near strong horizontal gradients. Horizontal momentum and thermal diffusion are assumed to be equal. The equation of state (Mellor, 1991) calculates the density as a function of temperature, salinity, and pressure. For applications to the Great Lakes, the salinity is set to a constant

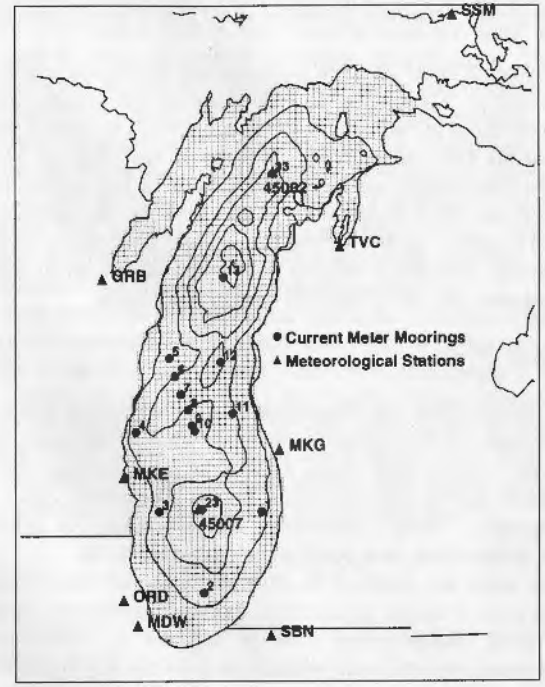

Figure 1: Observation network and computational grid. Isobaths every 50 m.

value of 0.2 ppt. The equations are written in terrain following sigma coordinates ($\sigma = z/h$, where h is depth) in the vertical, and in tensor form for generalized orthogonal curvilinear coordinates in the horizontal. 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).

A body of water such as a lake has two separate types of motions, the barotropic (density independent) mode and the baroclinic (density dependent) mode. The Princeton model uses a mode splitting technique that solves the barotropic mode for the free surface and vertically averaged horizontal currents, and the baroclinic mode for the fully three-dimensional temperature, turbulence, and current structure. This necessitates specifying separate barotropic and baroclinic mode time steps in accordance with the Courant-Friedrich-Lewy computational stability criterion.

The model includes the Mellor and Yamada (1982) level 2.5 turbulence closure parameterization. The vertical mixing coefficients for momentum and heat are calculated from the variables describing the flow regime. The turbulence field is described by prognostic equations for the turbulent kinetic energy and turbulent length scale.

The hydrodynamic model of Lake Michigan has 20 vertical levels and a uniform horizontal grid size of 5 km (Fig. 1). To initialize the model, we used surface temperature observations at two buoys (45007 and 45002) located in the southern and northern parts of the lake, respectively. The model run starts on March 31, 1982. Vertical temperature gradients are very small because of convection during that time of the year when the water temperature is less than the temperature of maximum density (4°C). Therefore, we set vertical temperature gradients to zero, but retained horizontal gradients. The initial velocity field in the lake is set to zero. The model run ends on November 20, 1983, after 600 days of integration.

Forcing functions

In order to calculate heat and momentum flux fields over the water surface for the lake circulation model, it is necessary to estimate wind, temperature, dew point, and cloud cover fields at model grid points. Meteorological data were obtained from the eight NWS weather stations and two NDBC buoys. The marine observation network is shown in Figure 1. These observations form the basis for geuerating gridded overwater wind, temperature, dew point, and cloud cover fields.

Three main steps are required to develop overwater fields from the marine observation data base: 1) height adjustments, 2) overland/overlake adjustment, and 3) interpolation. First, measurements must be adjusted to a common anemometer height. Ship observations are usually obtained at considerably higher distances above the water surface than buoy measurements. Measurements are adjusted to a common 10 m height above the water surface using profile methods developed by Schwab (1978). This formulation adjusts the wind profile for atmospheric stability and surface roughuess conditions. Liu and Schwab (1987) show that this formulation for the overwater wind profile is effective in representing typical conditions in the Great Lakes.

The second problem in dealing with the combination of overland and overwater measurements is that overlaud wind speeds generally underestimate overwater values because of the marked trausition from higher aerodynamic roughness over land to much lower aerodynamic roughness over water. This transition cau be very abrupt so that wind speeds reported at coastal stations are often not representative of conditions only a few kilometers offshore. Schwab and Morton (1984) found that wind speeds from overland stations could be adjusted by empirical methods to obtain fair agreement with overlake wind speeds measured from an array of meteorological buoys in Lake Erie. For the eight NWS weather stations in Fig. 1 we apply the empirical overland-overlake wind speed adjustment from Resio and Vincent (1977). Air temperature and dew point reports from the overland stations are adjusted with similar empirical formulas.

Finally, in order to interpolate meteorological data observed at irregular points in time and space to a regular grid so that it can be used for input into a circulation model, some type of objective analysis technique must be used. The complexity of the analysis technique should be compatible with the complexity of the observed data, i.e., if observations from only a few stations are available, a best-fit linear variation of wind components in space might be an appropriate method. If more observations can be incorporated into the analysis, spatial weighting techniques can be used. For LMMBP we used the nearest-neighbor technique, with the addition of a spatial smoothing step (with a specified smoothing radius). We found that the nearest-neighbor technique provided results comparable to results from the inverse power law or negative exponential interpolation functions.

After we have produced hourly gridded overwater fields for wind, dew point, air temperature, and cloud cover, the momentum flux and heat flux can be calculated at each grid square in the three-dimensional lake circulation model at each model time step. To calculate momentum flux, the profile theory described above for anemometer height adjustment is used at each grid square at each time step to estimate surface stress, using the surface water temperature from the circulation model. This procedure provides estimates of bulk aerodynamic transfer coefficients for momentum aud heat. Surface heat flux, H, is calculated as

$$H = H_{sr} + H_s + H_l + H_{lr}$$

where H_{sr} is short-wave radiation from the sun, H_s is sensible heat transfer, H_l is latent heat transfer, and H_{lr} is long wave radiation. The heat flux procedure follows the methods described by McCormick and Meadows (1988) for mixed-layer modeling in the Great Lakes. H_{sr} is calculated based on latitude and longitude of the grid square, time of day, day of year, and cloud cover. H_s and H_l are calculated using the bulk aerodynamic transfer coefficients described above. H_{lr} is calculated as a function of T_a, T_w, and cloud cover according to Wyrtki (1965). McCormick and Meadows (1988) showed that this procedure works quite well for modeling mixed-layer depth in the Great Lakes. The gross thermal structure generated in the three dimensional model using these heat flux fields is similar to the profile that would be obtained from a one dimensional model. However, there is considerable horizontal variability in the three dimensional temperature field due mainly to wind forcing.

Model results and comparison with observations

Temperature

The most distinctive feature of the physical limnology of the Great Lakes is a pronounced annual thermal cycle (Boyce et al., 1989). By the end of fall, the lakes usually become vertically well-mixed from top to bottom at temperatures near or below the temperature of maximum density for freshwater, about 4°C. Further cooling during winter can lead to inverse stratification and ice cover. Springtime warming tends to heat and stratify shallower areas first, leaving a pool of cold water (less than 4°C and vertically well-mixed because of convection) in the deeper parts of the lake. In spring, stratified and homogeneous areas of the lake are separated by a sharp thermal front, commonly known as the thermal bar. Depending on meteorological conditions and depth of the lake, the thermal bar may last for a period of from 1 to 3 months. Stratification eventually covers the entire lake, and a well-developed thermocline generally persists throughout the summer. In the fall, decreased heating and stronger vertical mixing tend to deepen the thermocline until the water column is again mixed from top to bottom. When the nearshore surface temperature falls below the temperature of maximum density, the fall thermal bar starts its propagation from the shoreline toward the deeper parts of the lake. Thermal gradients are much smaller during this period than during the springtime thermal bar.

The model was able to reproduce all of the basic features of thermal structure of Lake Michigan during the 600 day period of study: spring thermal bar, full stratification, deepening of the thermocline during the fall cooling, and finally an overturn in the late fall (Fig. 2). Observed temperatures from surface buoys and subsurface moorings were compared to model output (Fig. 3). The comparison is quite good for the horizontal distribution and time evolution of the surface and bottom temperature, but it is worse in the thermocline area. In addition, the model predicted internal waves are much less pronounced than in observations. We think that because the model tends to generate excessive vertical diffusion, the modeled thermocline is too diffuse and hence temperature fluctuations are decreased. On the other hand, the simulation of the surface temperature is much more accurate, which shows correct calculation of heat fluxes near the surface. We should also note that the model performs better in the second year (at least near the surface - we do not have subsurface observations for the second year summer) which we attribute to the gradual adjustment of the temperature field to the boundary conditions as the model solution drifts away from the rather crude initial conditions.

Currents

Wind-driven transport is a dominant feature of circulation in the lakes. As shown by Bennett (1974), Csanady (1982), and others, the response of an enclosed basin with a sloping bottom to a uniform wind stress consists of longshore, downwind currents in shallow water, and a net upwind return flow in deeper water. The streamlines of the flow field form two counter-rotating closed gyres, a cyclonic gyre to the right of the wind and an anticyclonic gyre to the left (in the northern hemisphere). As the wind relaxes, the two-cell streamline pattern rotates cyclonically within the basin, with a characteristic period corresponding to the lowest mode topographic wave of the basin (Saylor et al., 1980). Numerical models approximating actual lake geometry have proven to be effective in explaining observed short-term circulation patterns in lakes

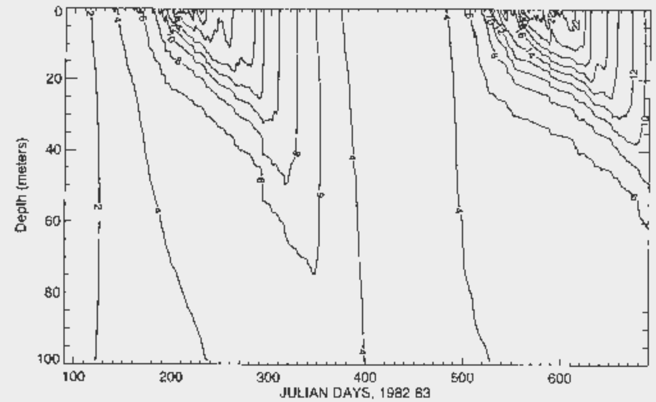

Figure 2: Simulated mean temperature profile, March 31, 1982- November 20, 1983 (600 days).

(Simons, 1980; Schwab, 1992). The results of these modeling exercises show that the actual bathymetry of each of the Great Lakes tends to act as a combination of bowl-shaped sub-basins, each of which tends to support its own two-gyre circulation pattern.

Besides bathymetry and geometry, two other important factors tend to modify the simple two-gyre lake circulation model described above, namely non-uniform wind forcing and stratification. Thus, during the stratified period, longshore currents frequently form a single cyclonic gyre circulation pattern driven by onshore-offshore density gradients. The effect of horizontal variability in the wind field enters through the curl of the wind stress field (Rao and Murty, 1970). Any vorticity in the forcing field is manifest as a tendency of the resulting circulation pattern toward a single gyre streamline pattern, with the sense of rotation corresponding to the sense of rotation of the wind stress curl. Because of the size of the lakes, and their considerable heat capacity, it is not uncommon to see lake-induced mesoscale circulation systems superimposed on the regional meteorological flow, a meso-high in the summer (Lyons, 1971) and a meso-low in the winter (Petterssen and Calabrese, 1959). There are also indications that nonlinear interactions of topographic waves can contribute to the mean single gyre cyclonic circulation (Simons, 1985).

Recent long-term current observations in Lake Michigan suggested a cyclonic large-scale circulation pattern, with cyclonic circulation within each subbasin, and anticyclonic circulations in ridge areas (Gottlieb et al., 1989). Our model results coincide with their conclusions (Fig. 4). To study seasonal changes in circulation patterns, we averaged model results over two 6-month periods: from May to October (summer period), and from November to April (winter period), approximately

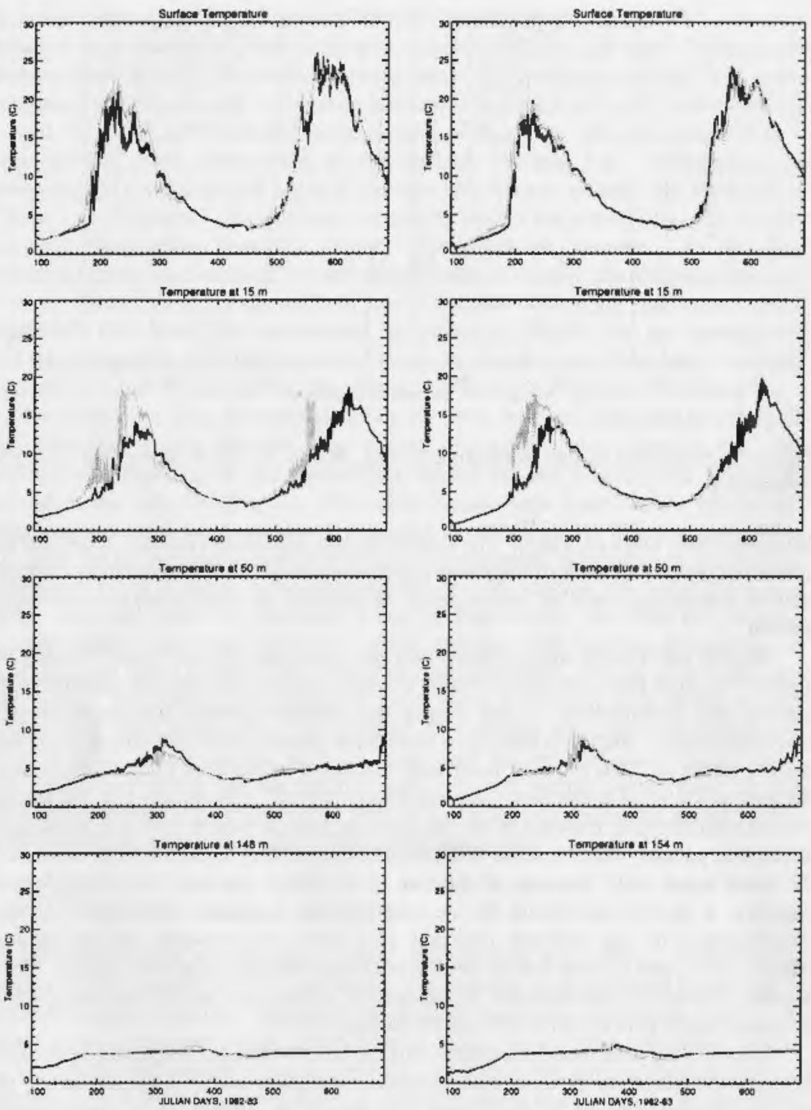

Figure 3: Time series of measured (light line) and simulated (dark line) temperature. Left: buoy 45007 and mooring 23. Right: buoy 45002 and mooring 33.

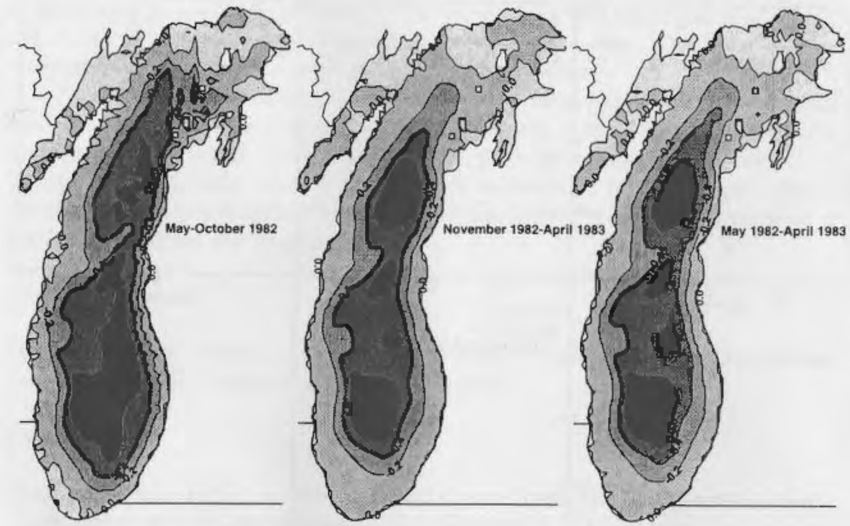

Figure 4: Normalized streamfunctions for summer, winter, and annual circulation. Negative values (dark color) indicate cyclonic vorticity, positive values (light color) anticyclonic.

reflecting stratified and non-stratified periods. Circulation is more organized and more cyclonic in winter than in summer, which is in agreement with Gottlieb et al. (1989) and earlier findings of Saylor et al. (1980). Because winter circulation is stronger than summer circulation, annual circulation looks very similar to the winter circulation (Fig. 4).

We also compared progressive vector diagrams of simulated and observed currents (Fig. 5). The largest currents occur in the fall and winter, when temperature gradients are lowest, but winds are strongest. Nearshore currents appear to be much stronger than offshore currents, in agreement with existing conceptual models and observations (Csanady, 1982). Yet, the mean current is relatively weak. For example, according to Fig. 5 data, it will take a passive particle about a year to complete a round trip of Lake Michigan, which would be about 1000 km. The point to point comparison of currents was successful mostly in the southern basin, which is characterized by a relatively smooth bathymetry. It was more successful in fall-winter months than in summer, most probably because the horizontal resolution of the model is not adequate for proper simulation of baroclinic processes with horizontal length scales comparable to the Rossby deformation radius (which is around 5 km for summer months). In addition, model resolution was too coarse to describe precisely

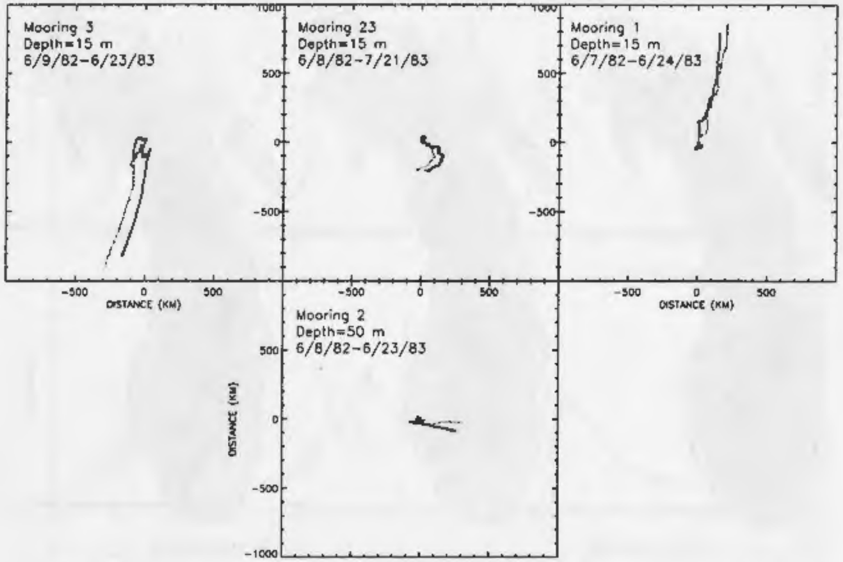

Figure 5: Progressive vector diagrams of measured (dark line) and simulated (light line) currents in 1982-1983.

the dynamics in the areas of strong depth gradients, even in the fall and winter when lake dynamics are essentially barotropic.

Discussion and conclusions

Our general conclusion is that the model realistically simulated the large scale thermal structure and circulation on the 5 km grid. We want to mention some problems, though. First, the model did not predict temperature as well in the thermocline area as it predicted near the surface. To study the effect of vertical resolution on the vertical temperature gradients, we carried out a model run with 39 sigma levels, e.g. double the vertical resolution. In this run we noticed only moderate improvement in the thermocline area. We also ran the model with a zero horizontal diffusion to test for artificial diffusion along sigma surfaces. Again, we did not notice a significant improvement in model results. Therefore, we think that in order to determine whether the problem lies in the calculation of vertical mixing or elsewhere, the next logical step will be a conduction of numerical experiments with a one-dimensional lake model.

Second, the horizontal resolution of the model was only sufficient for description of the large-scale circulation patterns. Point to point comparison of observed and simulated currents was successful only in fall-winter months in the southern basin

characterized by a smooth bathymetry. Obviously, 5 km horizontal grid resolution is too coarse to adequately resolve baroclinic motions in summer. The point to point comparison was worst in the areas of strong depth gradients.

The circulation was stronger in winter than in summer, and also more organized and cyclonic, which is in agreement with observations. Since the lake is essentially homogeneous in winter, there are two most probable explanations: existence of stronger cyclonic wind vorticity in winter, or existence of residual mean cyclonic circulation driven by nonlinear interactions of topographic waves. More research is needed to clarify the role of each factor.

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