Lake-Effect Snowstorms

Grand Bend 2008
Mark Robinson

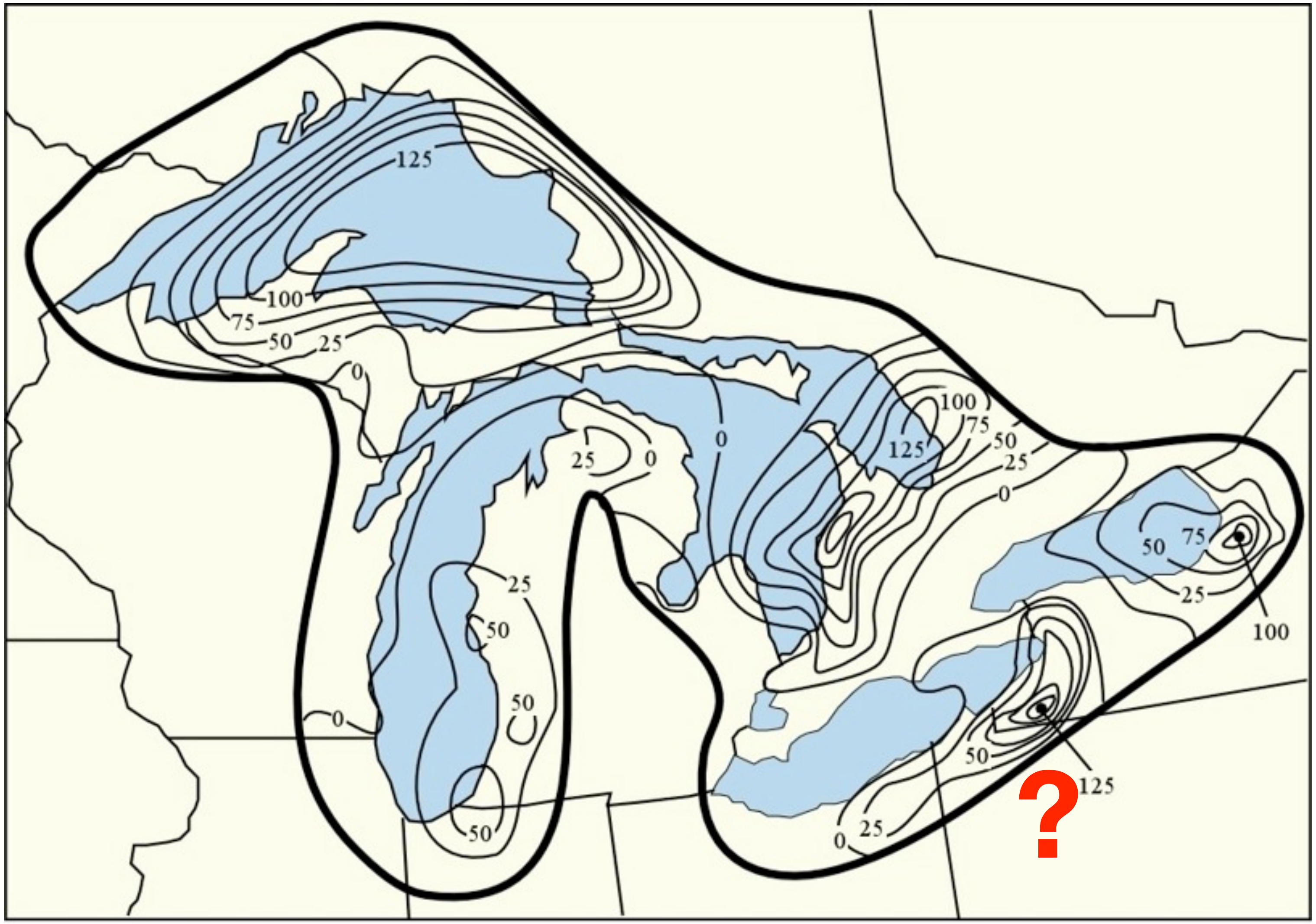
Wasaga Beach 2004
Tom Stefanac

Buffalo 2001
larc.hamgate.net

Impacts

- Hazardous air and road travel due to near-zero visibility, gusty winds, and rapidly accumulating snow
- Results in school closures and businesses, and in some cases power outages
- Can last for several days
- Positive impacts — skiing, snowmen, tobogganing, and work and school closures!

Climatology of Lake-Effect Snows



Courtesy of the Journal of Great Lakes Research

Additional wintertime precipitation expressed in mm of melted precipitation attributed to the Great Lakes. Dark line is 80 km boundary around shorelines. 125 mm X 20 = 2.5 m average snow depth!

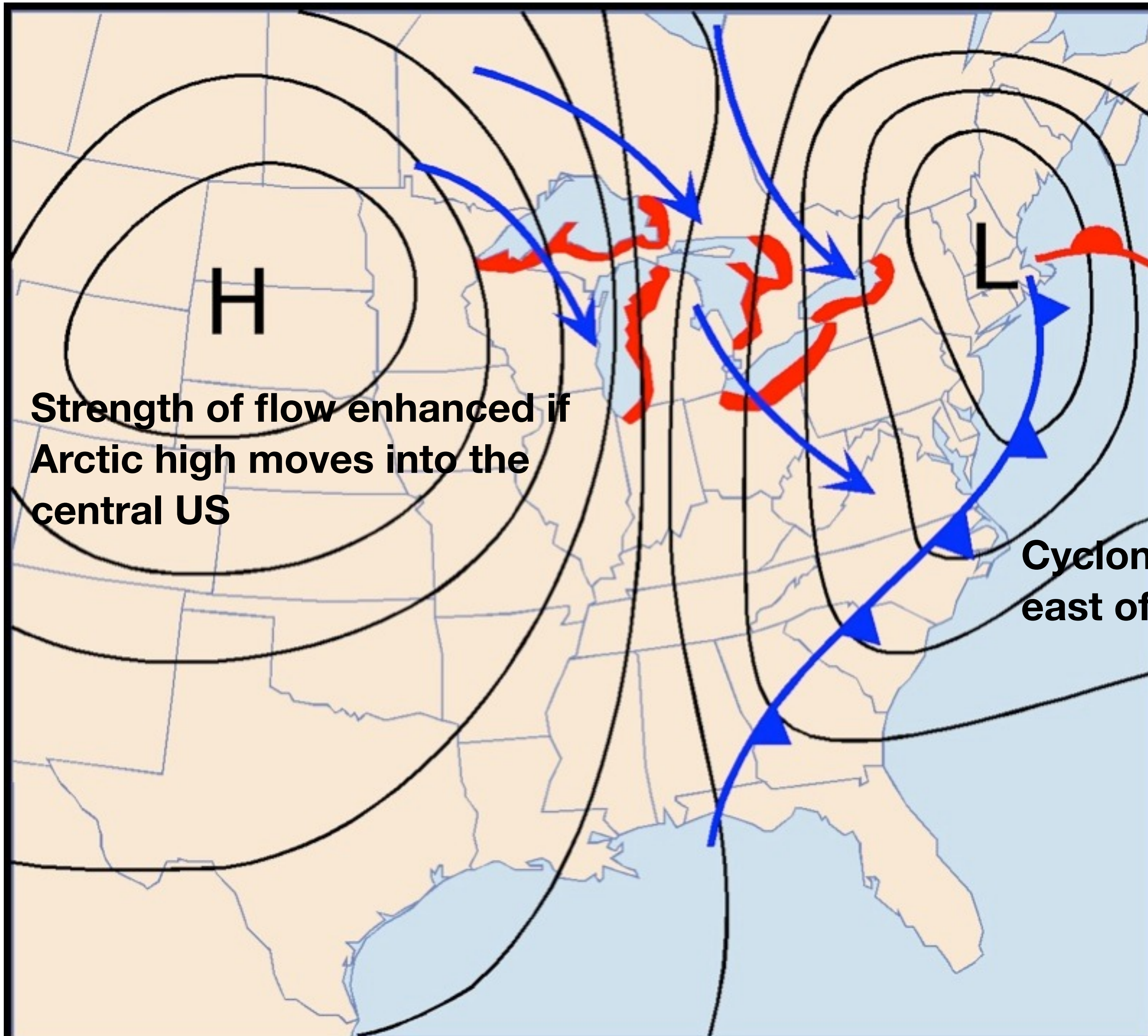
Climatology of Lake Effect Snows

- **Great Lake snow belts extend 50 to 80 km inland.**
- **80 km is the point where most of the moisture in the air has precipitated, and 80 km is well beyond the area where frictional convergence leads to lifting of air over the downwind shoreline.**

Large Scale Weather Patterns for Lake Effect Snowstorms

- **Typically, extra-tropical cyclone passes over the region and cyclone's cold front is well east of Great Lakes.**
- **Cold air behind cold front flows southeastward across Great Lakes.**
- **Strength of flow enhanced if Arctic High moves into the central US.**

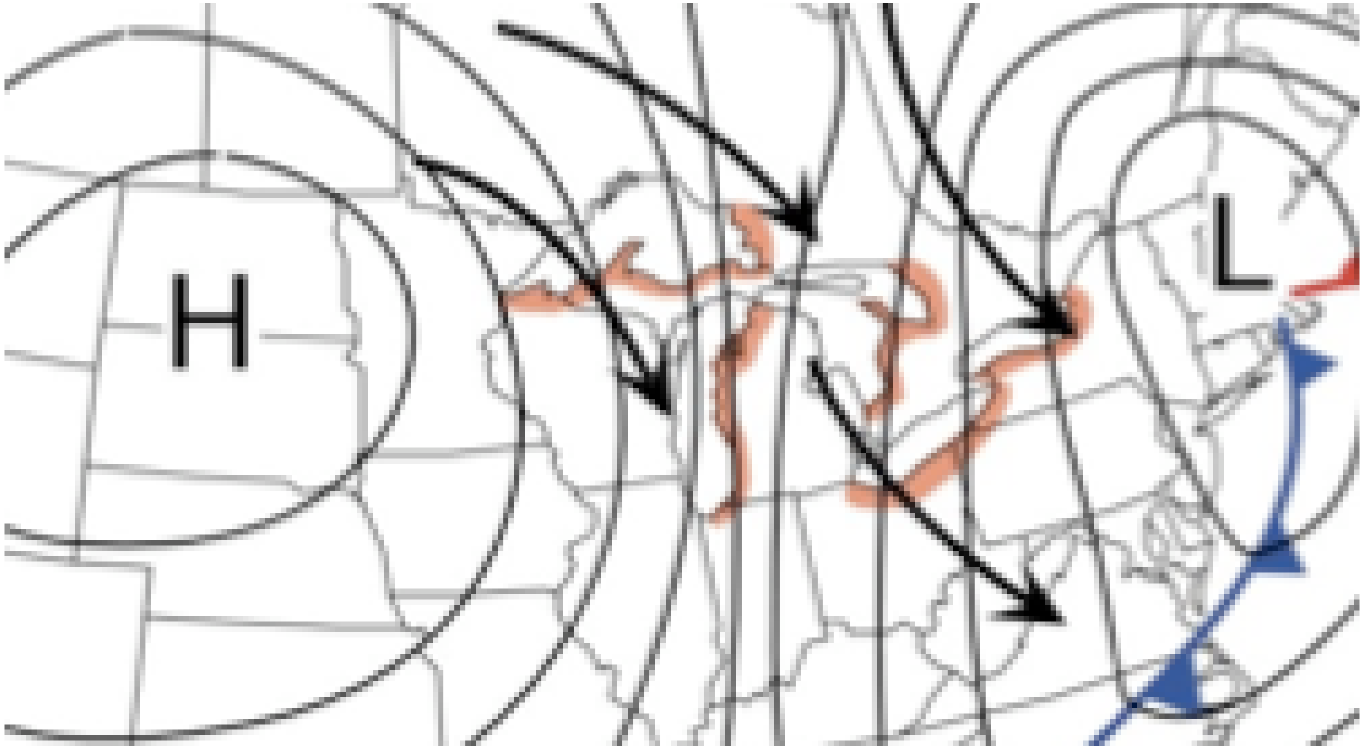
Cold air behind cold front flows southeastward across Great Lakes



Strength of flow enhanced if Arctic high moves into the central US

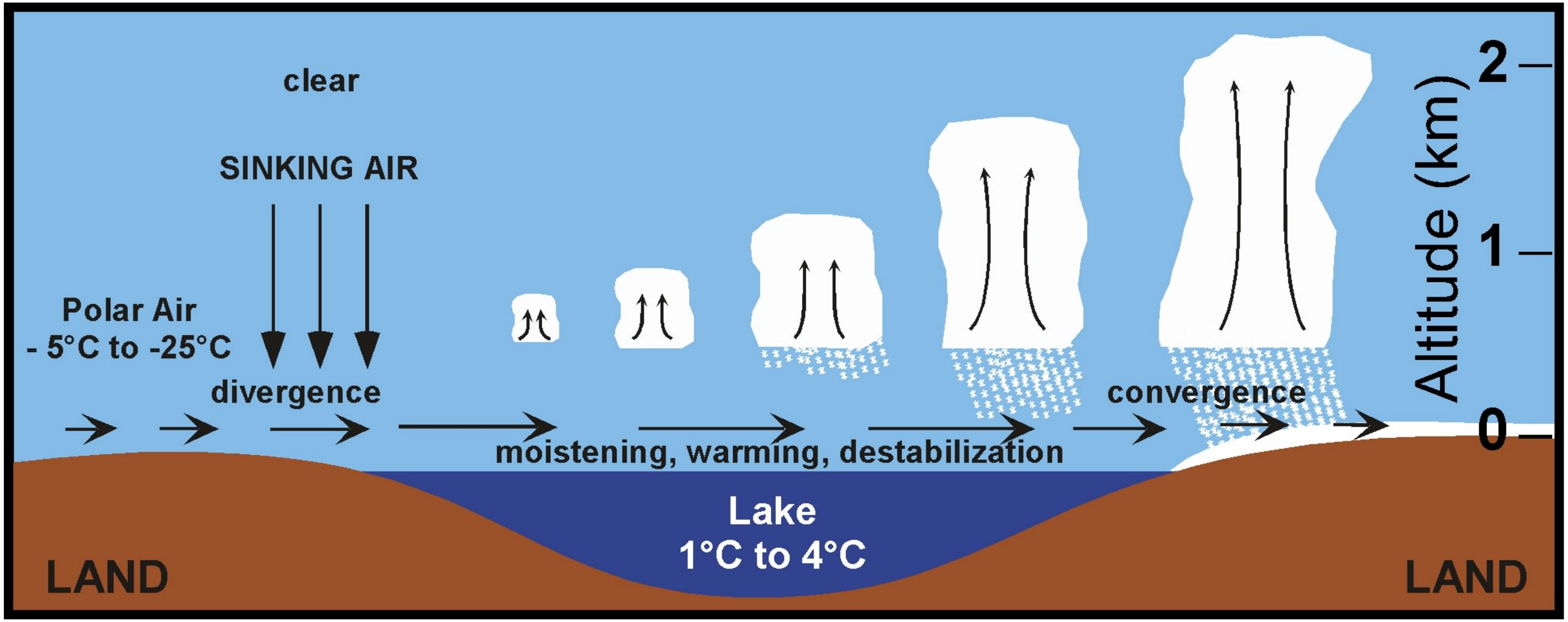
Cyclone's cold front is well east of Great Lakes

A strong pressure gradient develops across the Great Lakes that drives cold air southeastward over the Lakes.



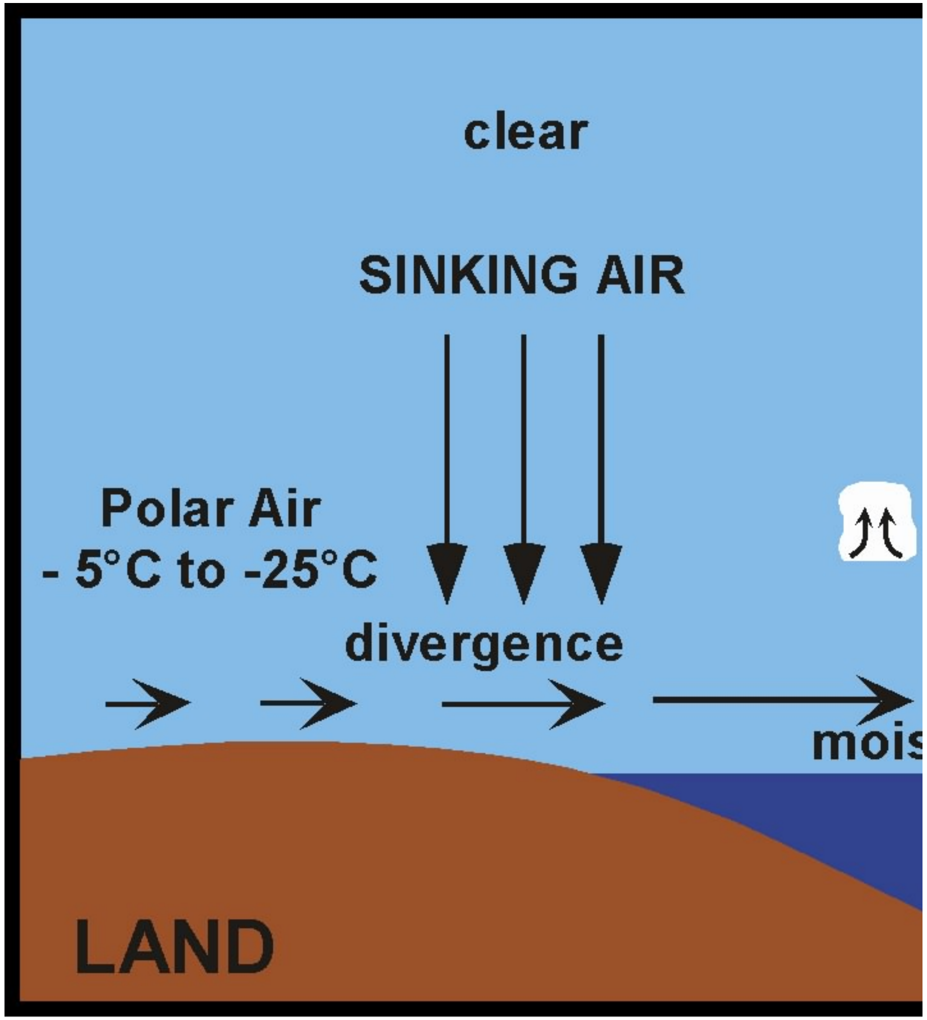
Lake effect storms occur most often in late fall and early winter when very cold air moves across the Lakes while the Lakes remain warm and ice free.

Lake-Effect Snowstorm Development

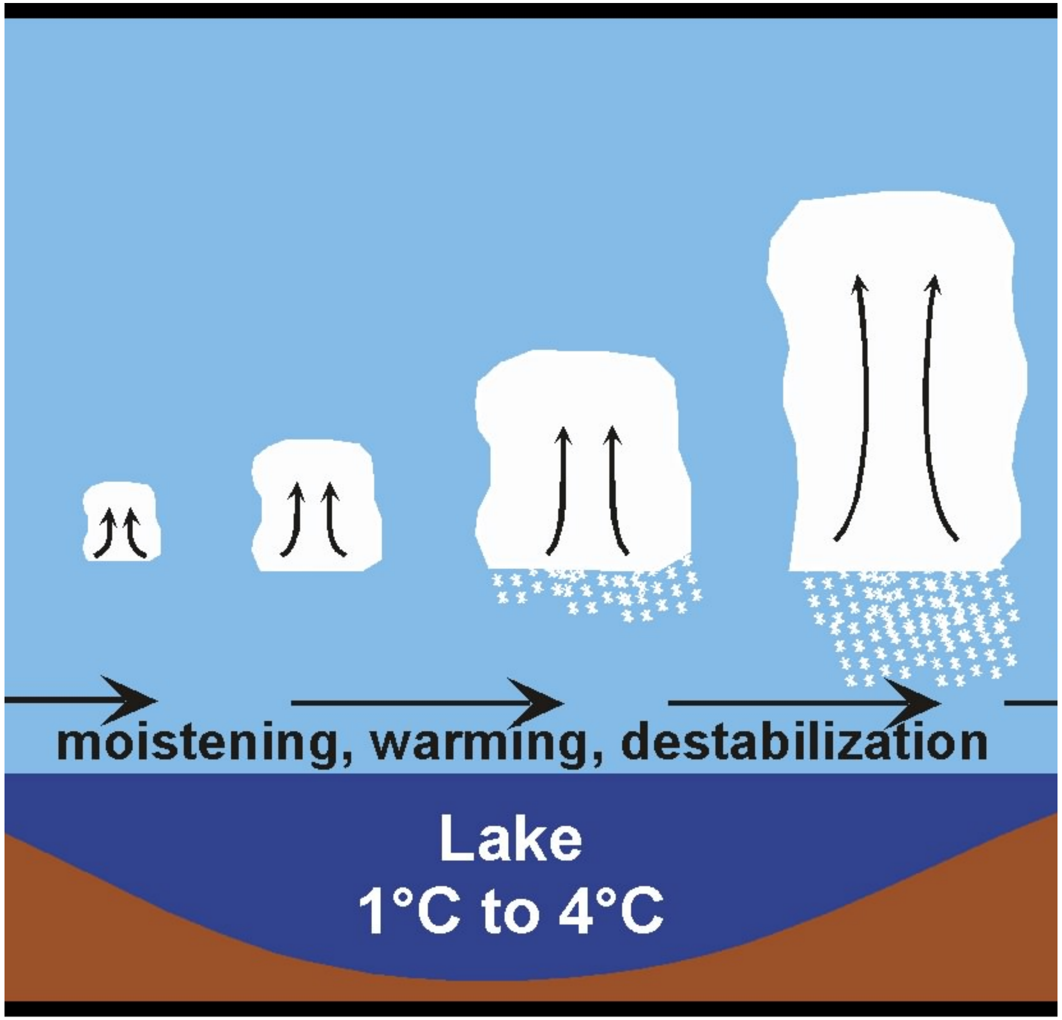


- As cold air (-5C to -25C) approaching lake moves out over smooth surface of lake, it accelerates because there are no objects (e.g., trees, building, hills) to impede air flow.

- Because of this, air near the surface diverges along the upwind shoreline.
- To compensate for this divergence, air above descends to the surface.
- This descending air remains clear (no clouds).

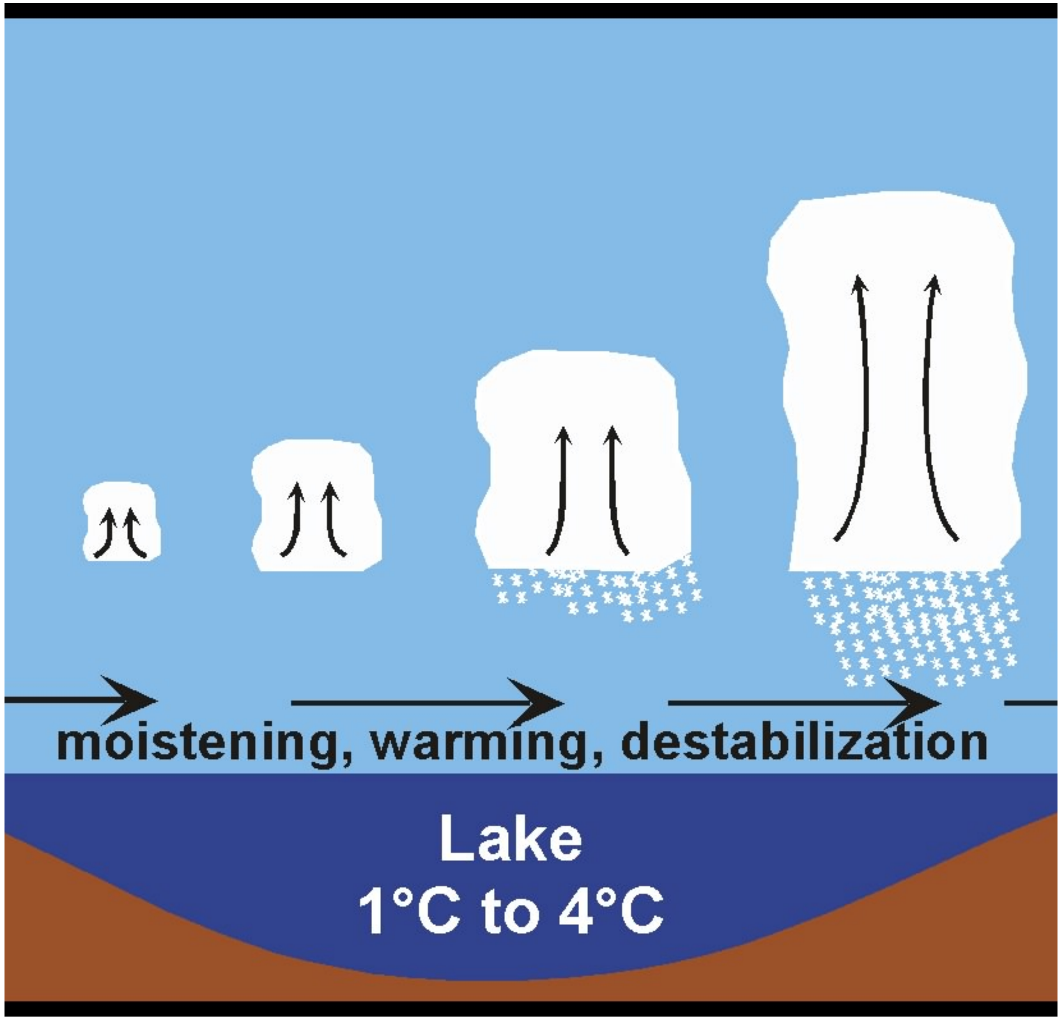


- As cold air first moves over warm lake, heat is transferred from lake surface to air just above lake surface.
- As this air's temperature increases, so does its SVP as
- Water from lake rapidly evaporates into the air blowing over lake.
- Air can warm by as much as 20C while crossing lake.



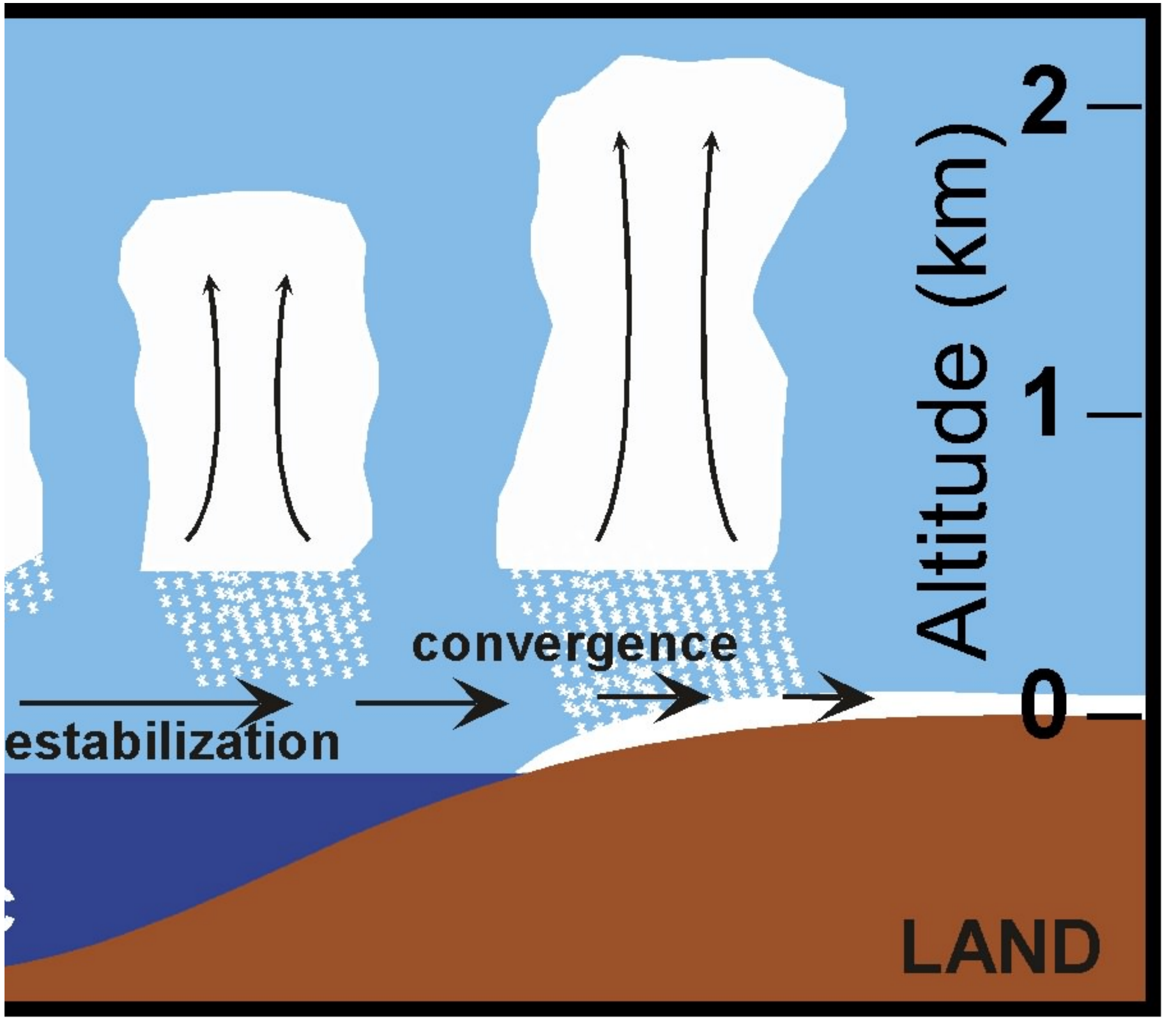
SVP=saturation vapor pressure

- Above this warm surface layer of air, the air remains cold.
- Condition leads to rapid destabilization.
- Air near lake surface becomes unstable, rises to form clouds
- Clouds grow in height and intensity as air moves closer to the downwind shoreline.



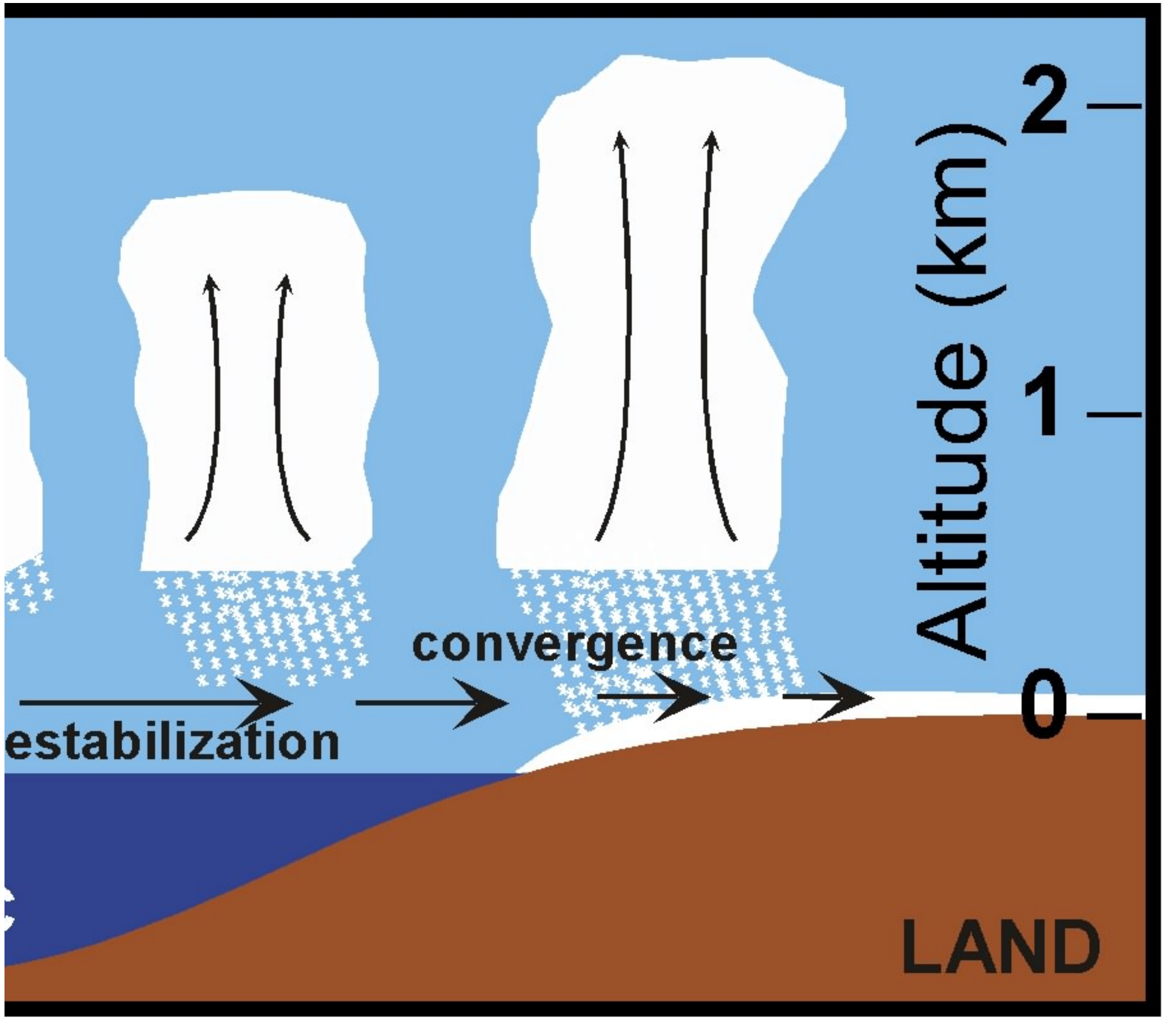
- As air crosses downwind shoreline, friction over land surface reduces wind speed.

- Air converges here, forcing air upward, strengthening upward motion in cumulus clouds, enhancing convection in unstable air.



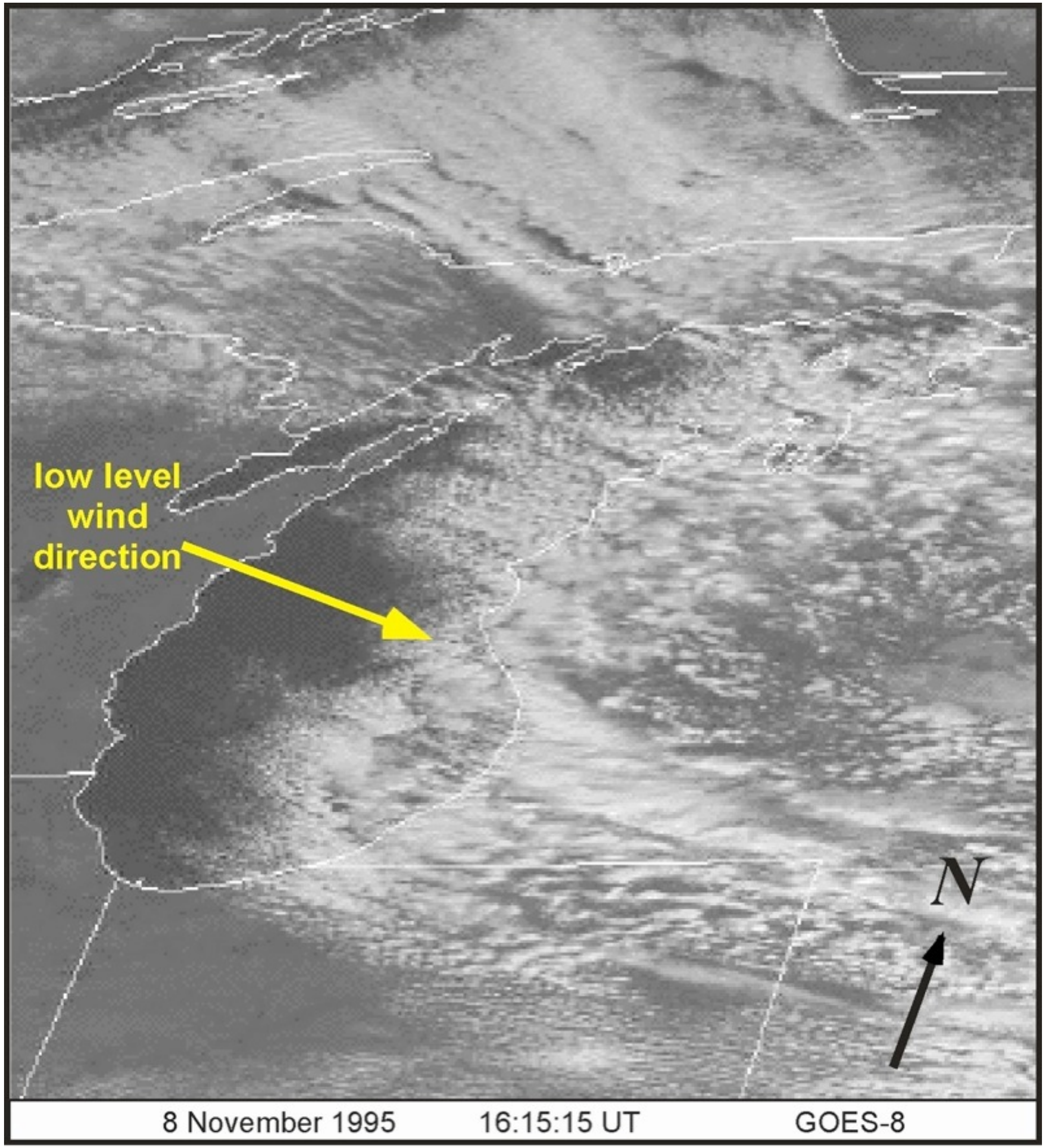
- Snowfall is heaviest within and just downwind of this frictional convergence zone.

- The greatest snowfalls occur when air resides over the warm water for a long time (high fetch), which happens when flow is more along the length of individual lakes.



Typically

- **clouds begin to form soon after air moves over lake, and snowfall normally begins well before air crosses the lake, and**
- **lake effect clouds grow to altitudes of 2 to 3 km, shallow compared to thunderstorm clouds, but deep enough to produce heavy snow squalls.**
- **A capping inversion can limit the height of lake-effect clouds.**



Courtesy of Cooperative Institute for Meteorological Studies
University of Wisconsin-Madison

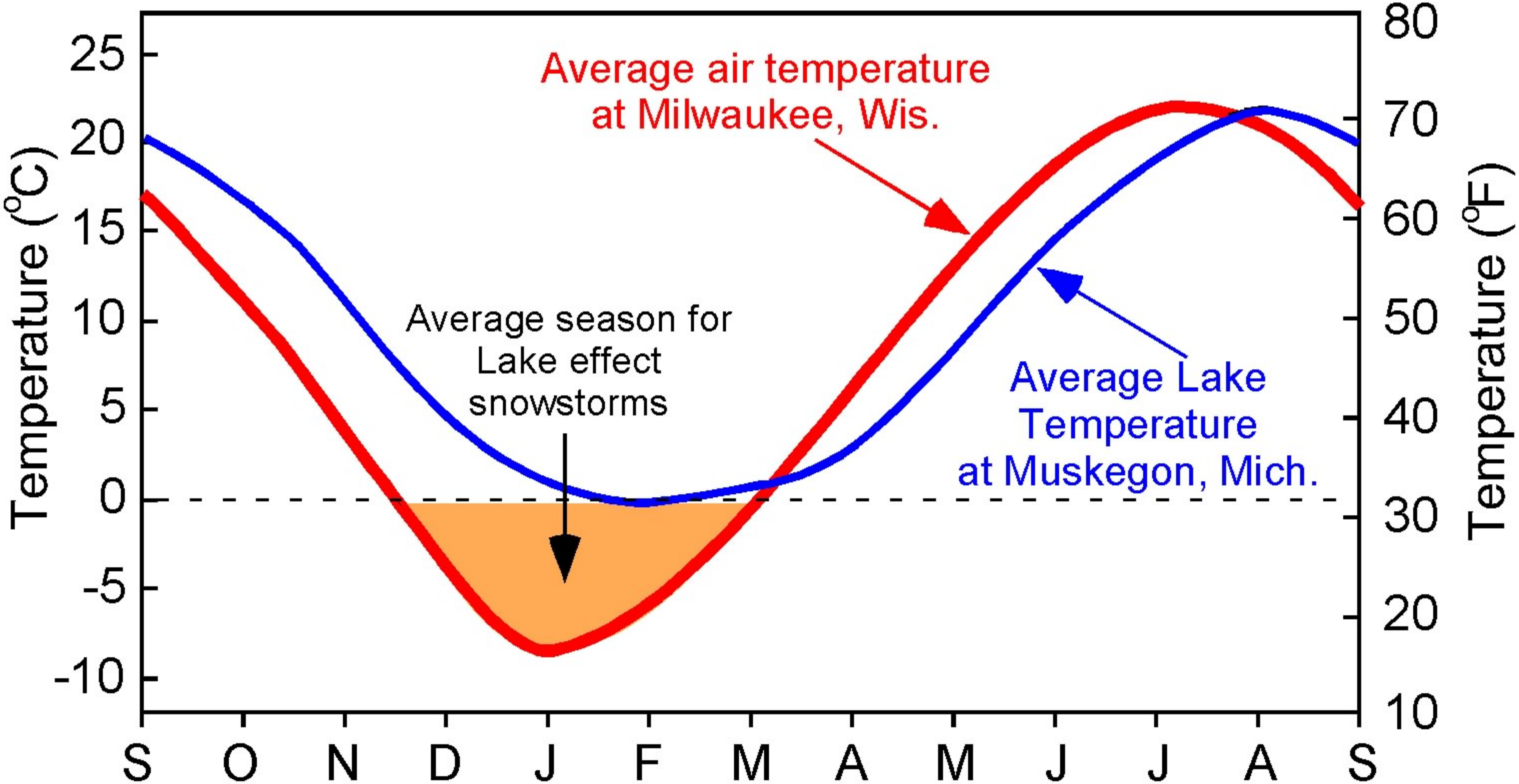
- Amount of snow that falls during lake effect storms depends on temperature of lake and temperature of air crossing lake (Fig 12.5).

- Higher lake T's, more heat and moisture transferred to air, and the

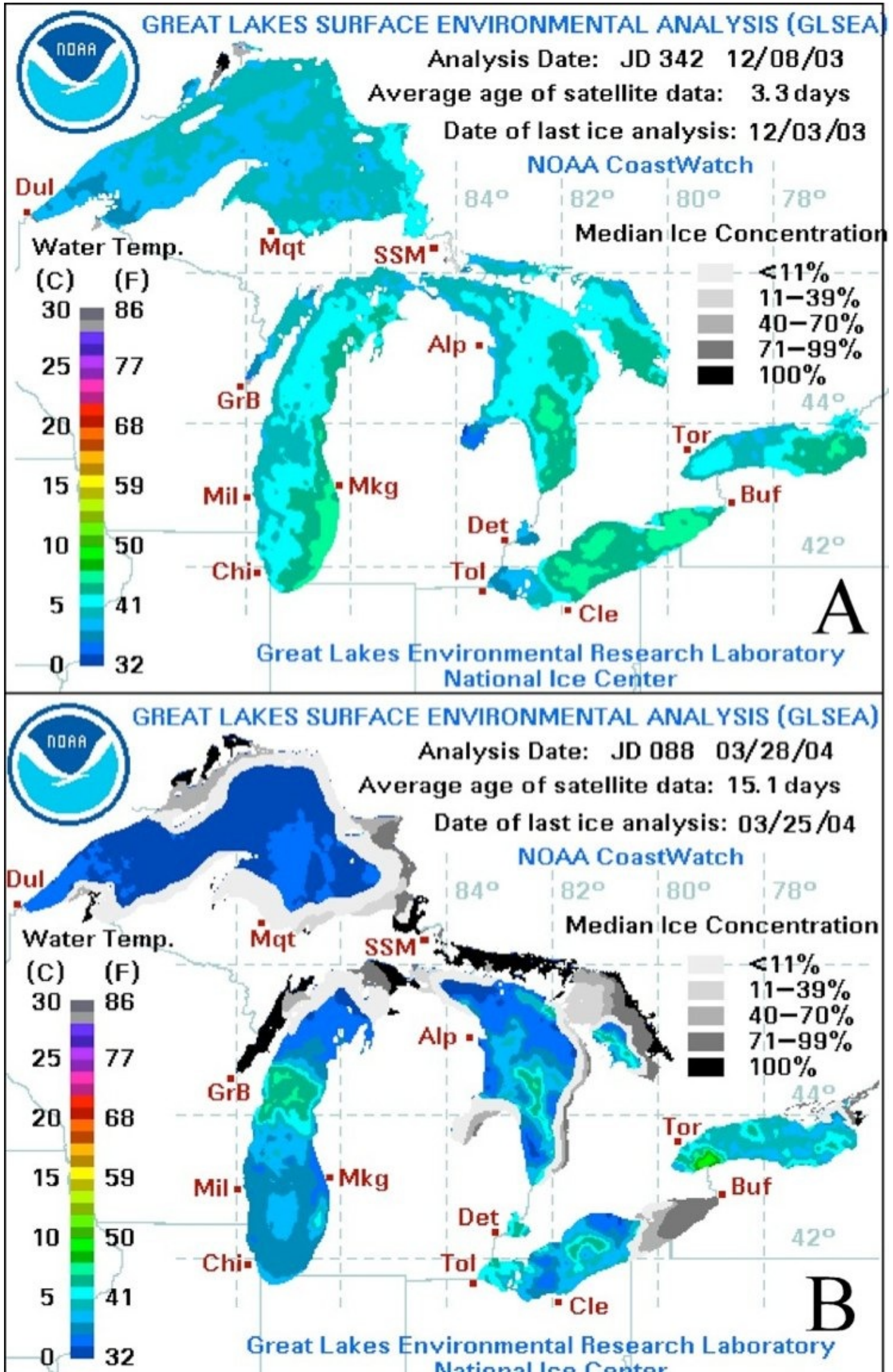
- colder the air just above lake surface air, the more quickly air will destabilize as heat is added from lake.

- Minimum temperature difference between water surface and 850 mb altitude needs to be at least 13C.

Climatology of Lake Effect Snows



Courtesy of David Kristovich



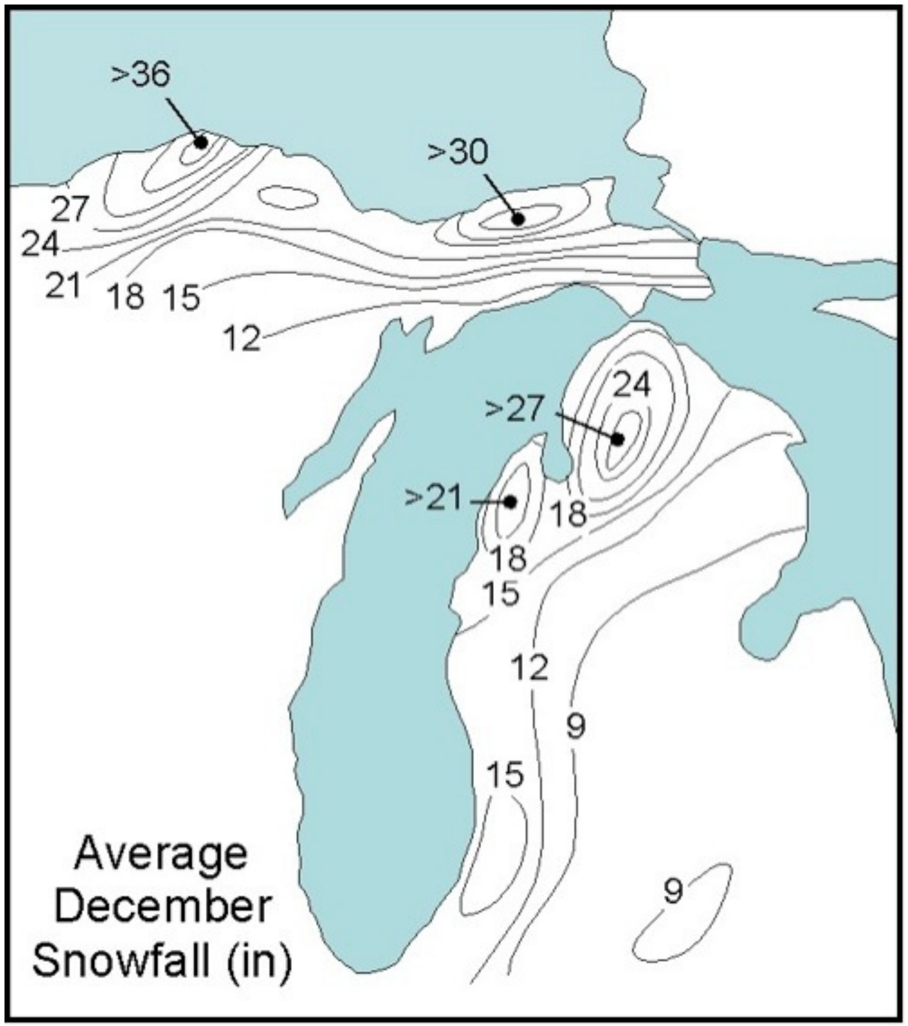
Lake temperatures and ice concentrations of the Great Lakes (A) Dec and (B) March.

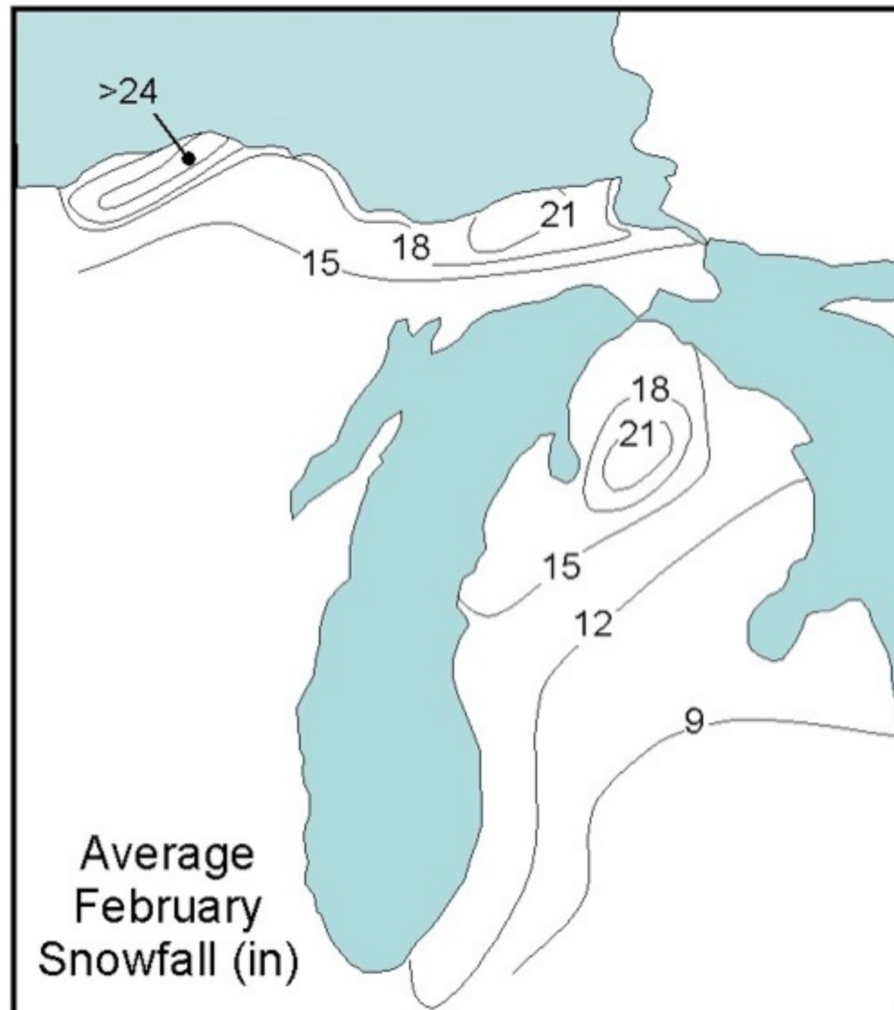
Note that cooling occurs over Dec to March, particularly over (shallow) Lake Erie.

In general, lakes are coldest in February.

Average Michigan snowfall around Great Lakes in December and February.

Note the differences in snowfall. In February Lake temperatures are low, and part or all of the Lakes are ice covered.





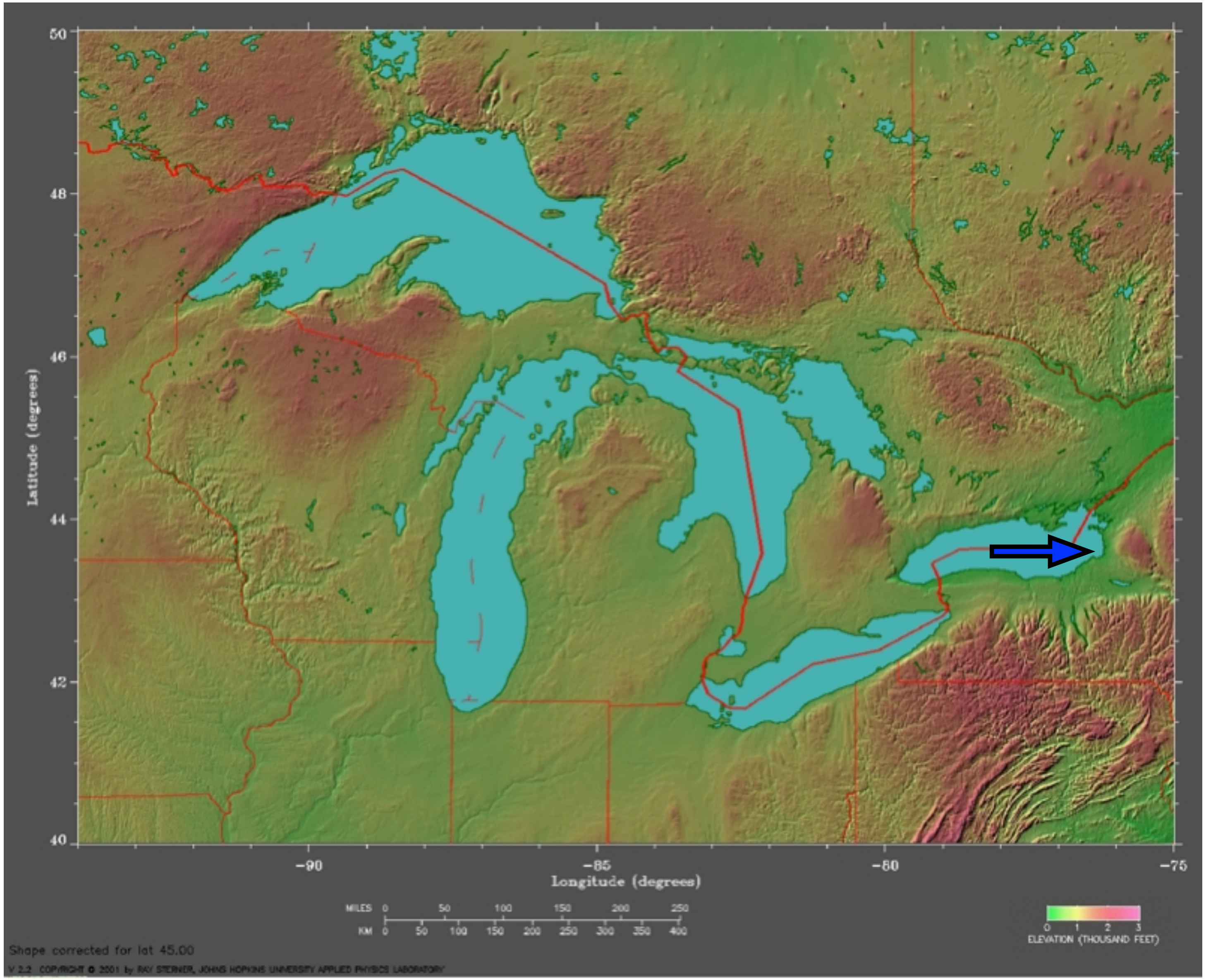
Courtesy of University of Notre Dame Press

- Amount of snowfall also depends on wind direction, wind speed, amount of ice cover on the lake, and topography downwind of lake.

- Topography enhances surface friction, contributing to increased convergence and lifting on downwind side of lake; hills also a physical barrier to flow, forcing it to rise. Both effects contribute to upward air motion necessary to produce clouds and snow.

- Hills also a physical barrier to flow, forcing it to rise.

    - Both effects contribute to upward motion necessary to produce clouds and snow.



Courtesy of Ray Sterner, Johns Hopkins University

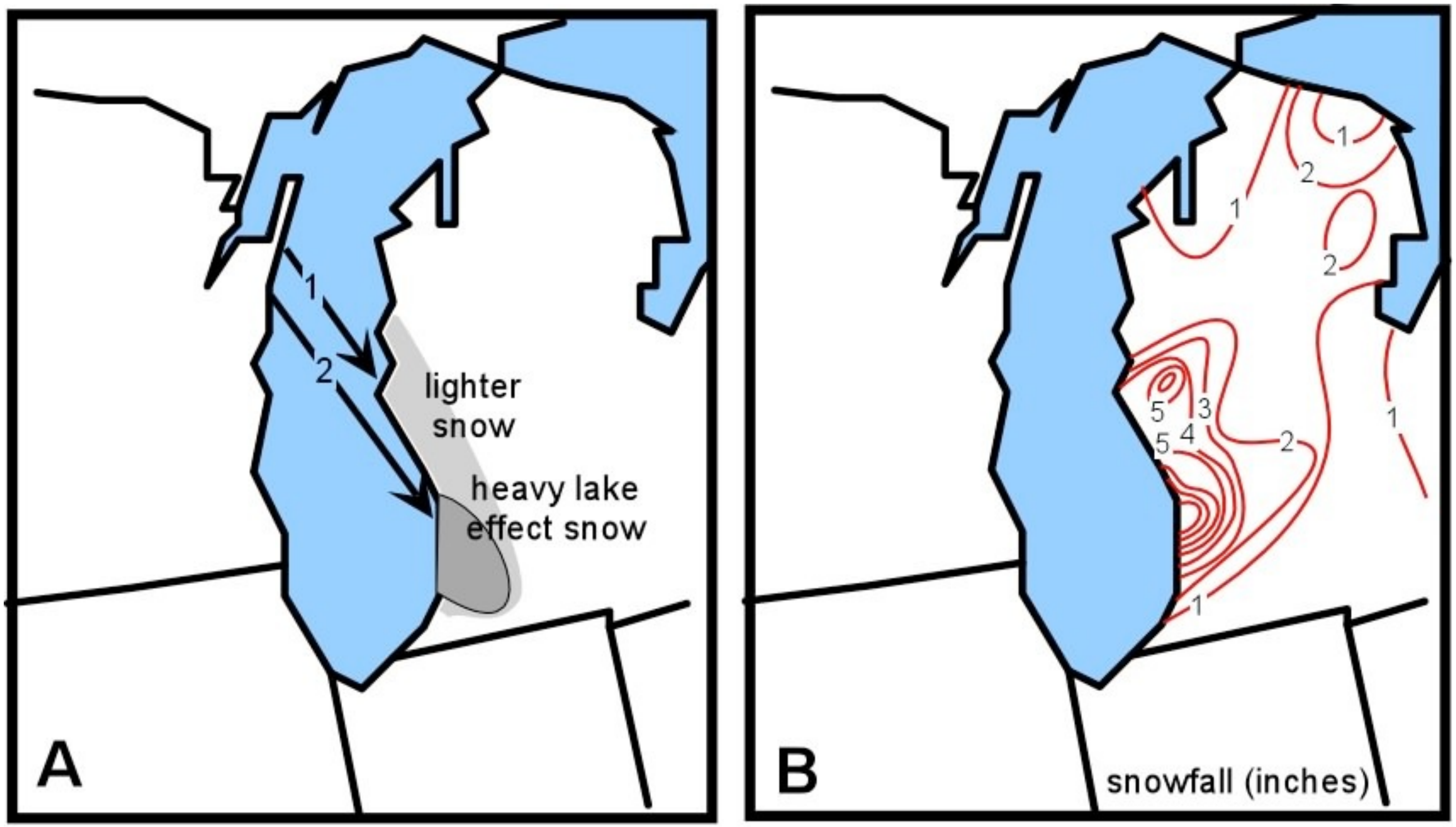
- **Higher elevations in red-brown**
- **Enhanced lifting and snowfall in these regions**

- **Air residence time over lake affects evaporation and heat transfer rates.**

- **Both wind speed and direction determine residence time of air over lake.**

- **Longer paths to the downwind shore increase residence time, and therefore amount of snowfall downwind.**

- **Fetch usually must be at least 75 km, preventing small lakes for generating lake-effect snow.**



Courtesy of University of Notre Dame Press

Residence time of air over Lake Michigan is much longer along path 2 compared to path 1 in A. Snowfall heavy in this area as shown in B.

Effect of wind speed more complicated.

- Slower winds allow air longer residence time, increasing heat flux from lake to air.
- Faster winds create waves and enhance evaporation of moisture.
- Wind speed and direction influence how clouds organize over the lake.
- Less directional shear results in a more intense snow squall.

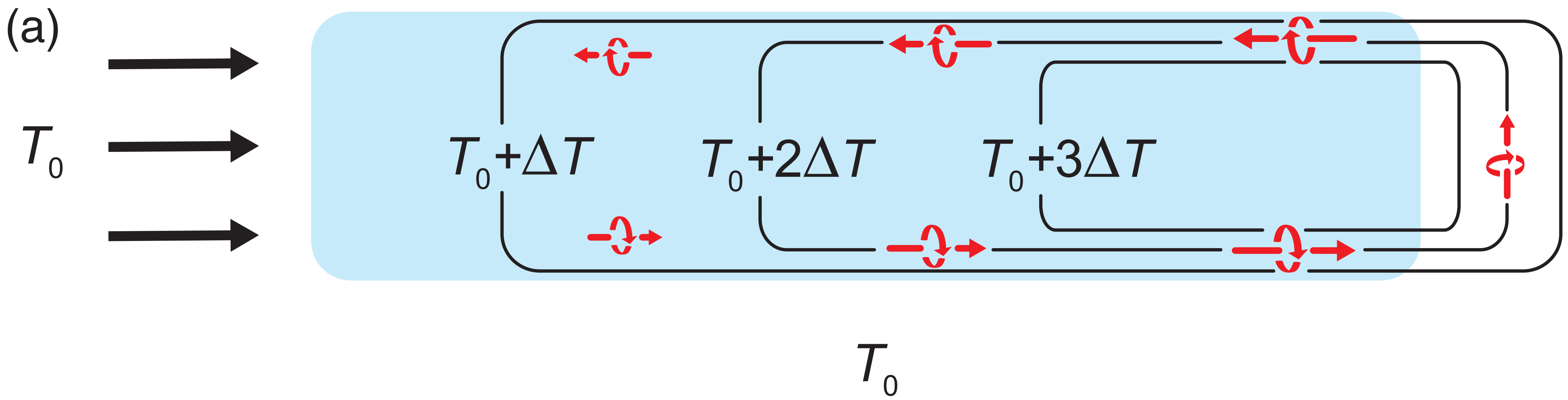
Organization of Lake Effect Snowfall

Lake effect clouds organize in 3 ways:

- **wind parallel rolls,**
- **shore-parallel bands, and**
- **vortices.**

Each depends on speed and orientation of wind relative to lake.

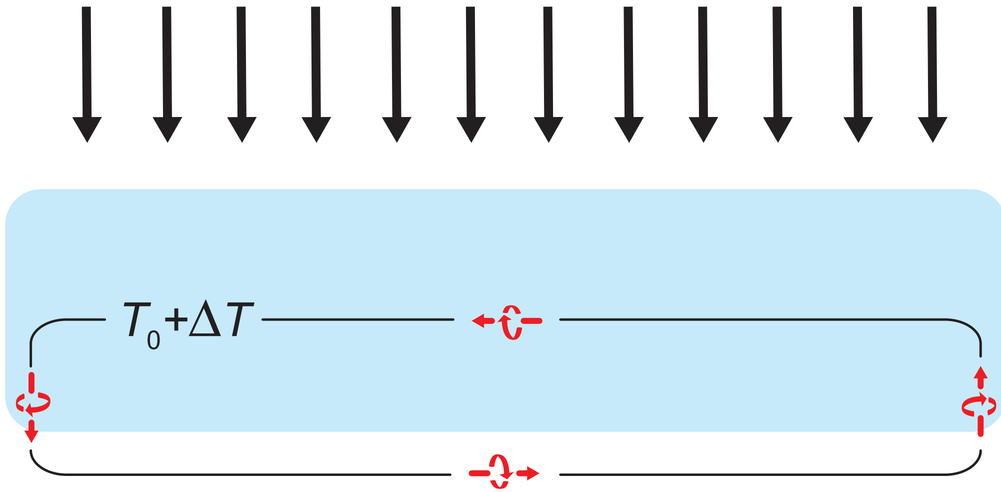
Elongated Lake: Flow along long axis



The horizontal temperature gradient that arises from the modification of the boundary layer over the relatively warm lake generates thermally direct solenoids, with intensity increasing in the downwind direction (the degree of air mass modification increases downwind). (a) In the case of an elongated lake (blue) with the wind blowing parallel to the major axis of the lake, the solenoids give rise to mesoscale convergence and updraft along the major axis that can promote the formation of an intense, single convective band. The fetch is also maximized, thus the strength of the solenoids is maximized (the horizontal vorticity vectors associated with the solenoids are indicated with red arrows, as is the sense of rotation; the magnitude of the horizontal vorticity is proportional to the size of the vectors).

Elongated Lake: Flow along short axis

(b)



(b) In the case of winds blowing across the same lake parallel to the minor axis, the fetch is minimized. Boundary layer modification is therefore minimized as well, resulting in weaker solenoids. Moreover, the lake geometry relative to the wind direction further reduces the contribution of the solenoids to upward motion over the lake (even if the air mass were somehow equally modified despite the shorter fetch, the horizontal temperature gradient between the shore and lake center would be less than in the case of winds blowing down the major axis of the lake). Mesoscale convergence and updraft are weaker than in (a) and largely confined to the downwind shoreline. In the case of relatively weak mean winds, shore-parallel convective bands can form or, in the case of faster mean winds, HCRs may be observed (by 'shore-parallel' bands, we are referring to bands that are parallel to the downstream shoreline, and thus approximately perpendicular to the mean wind, in contrast to HCRs, which tend to be parallel to the mean wind).

Convergence due to Differential Surface Drag

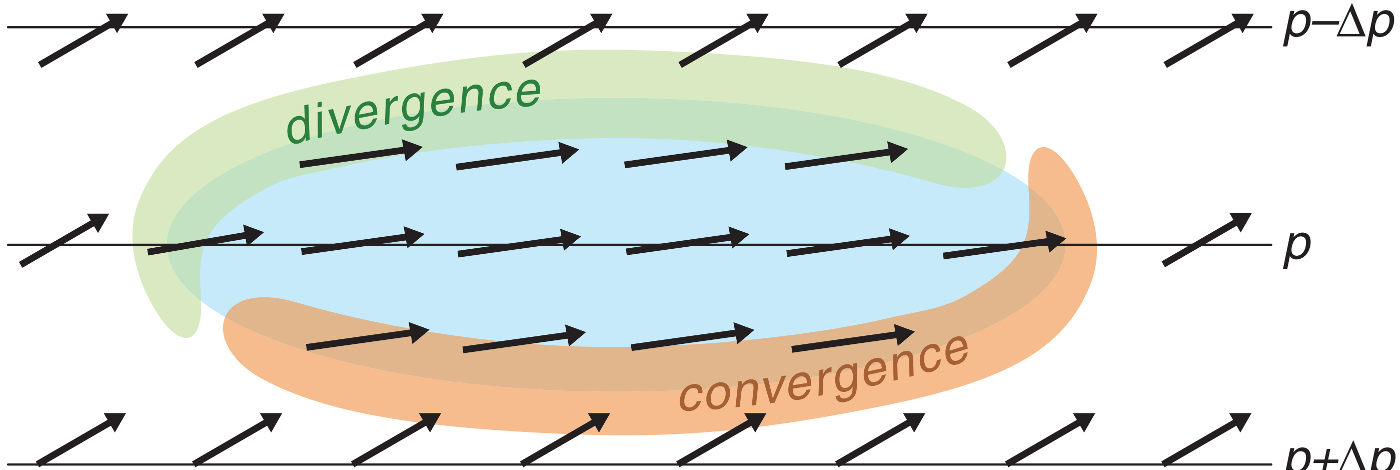


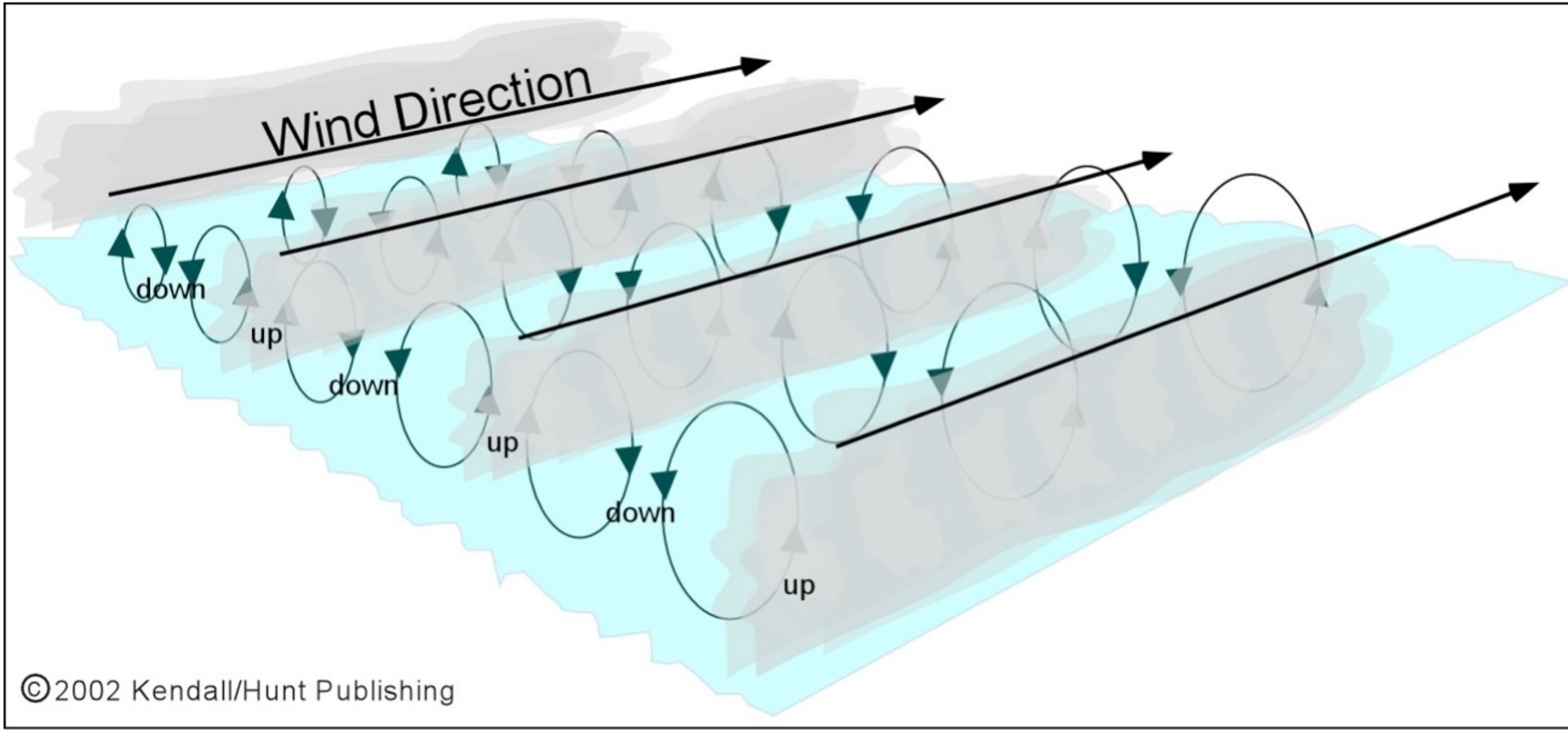
Figure 4.24 Differential surface drag promotes mesoscale convergence (divergence) along the shorelines downwind (upwind) and to the right (left) of the mean wind. The wind–pressure relationship shown above is valid in the northern hemisphere. In the southern hemisphere, the pressure gradient would point toward the north and convergence (divergence) would be found along the shorelines downwind (upwind) and to the left (right) of the mean wind.

Wind Parallel Rolls

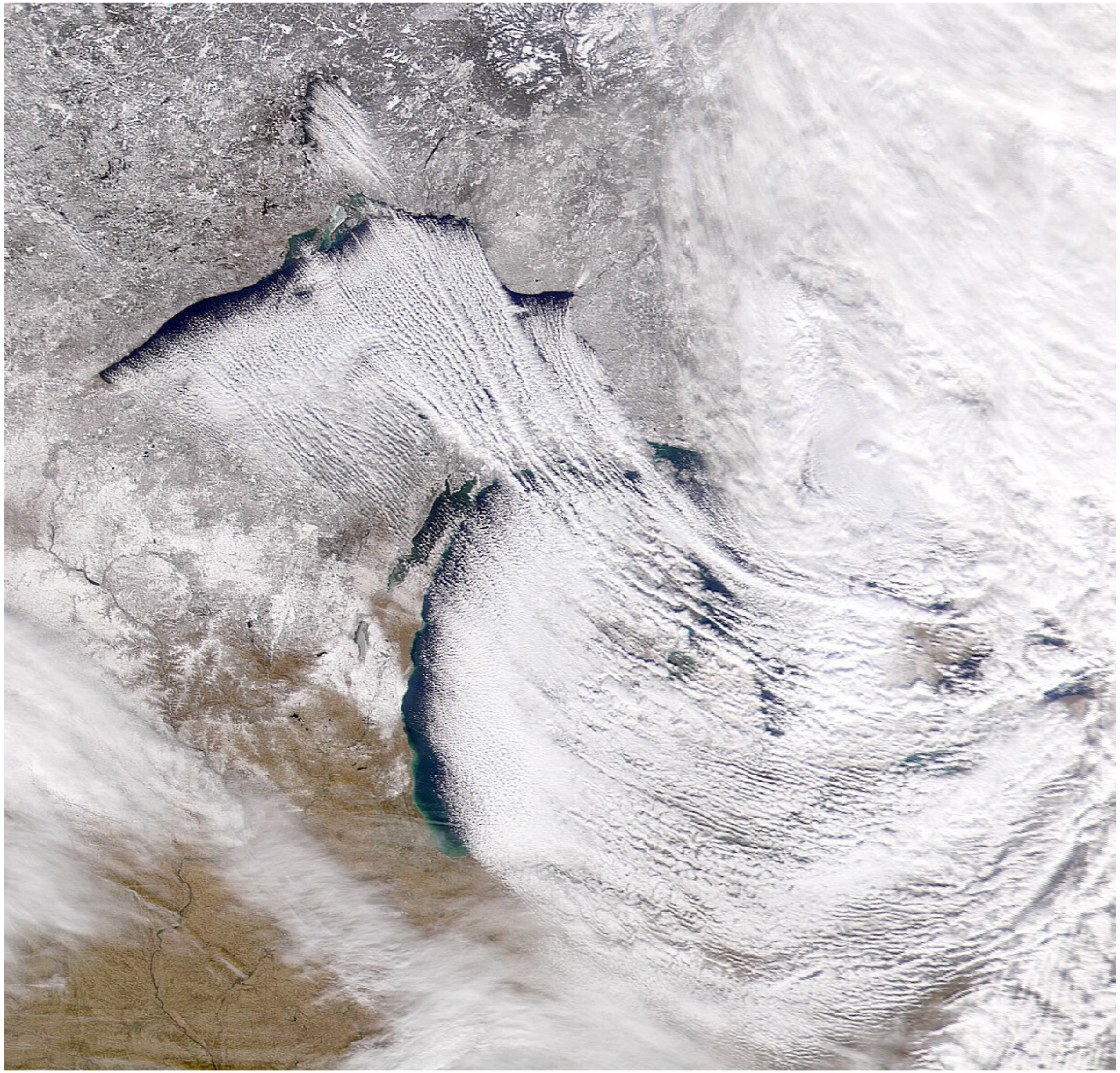
When strong winds blow across the lake, they transfer heat between lake and air, causing air to warm and rise.

Cooler air aloft sinks to replace warm rising air.

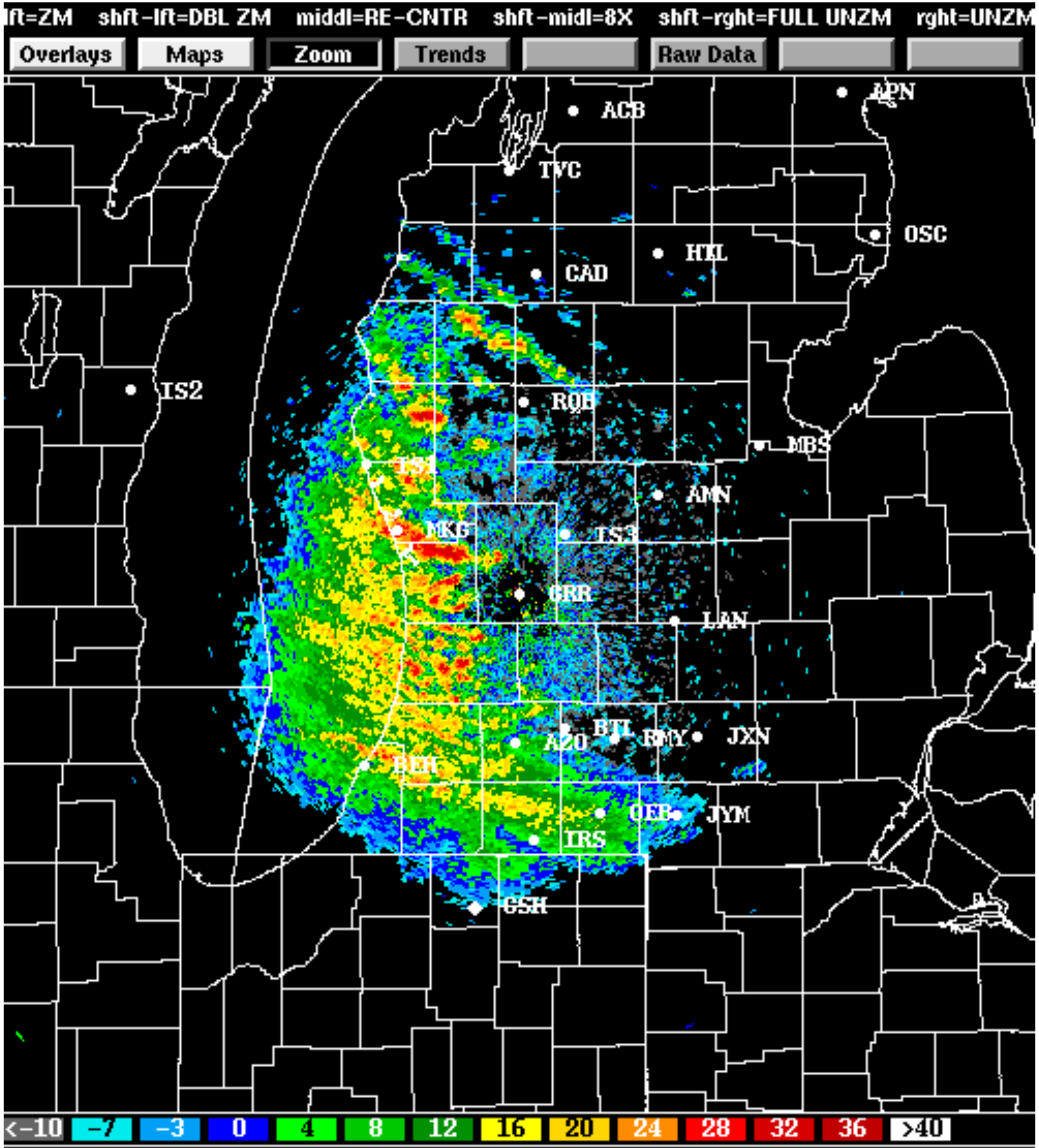
These rising and sinking motions form rolls aligning parallel to the wind.



Circulations and cloud associated with wind-parallel rolls. Note that clouds form in rising branches of rolls and dissipate in sinking branches. Cloud bands develop parallel to wind.


Courtesy of NASA

Wind-parallel rolls over Lakes Superior, Michigan, Huron and Erie.



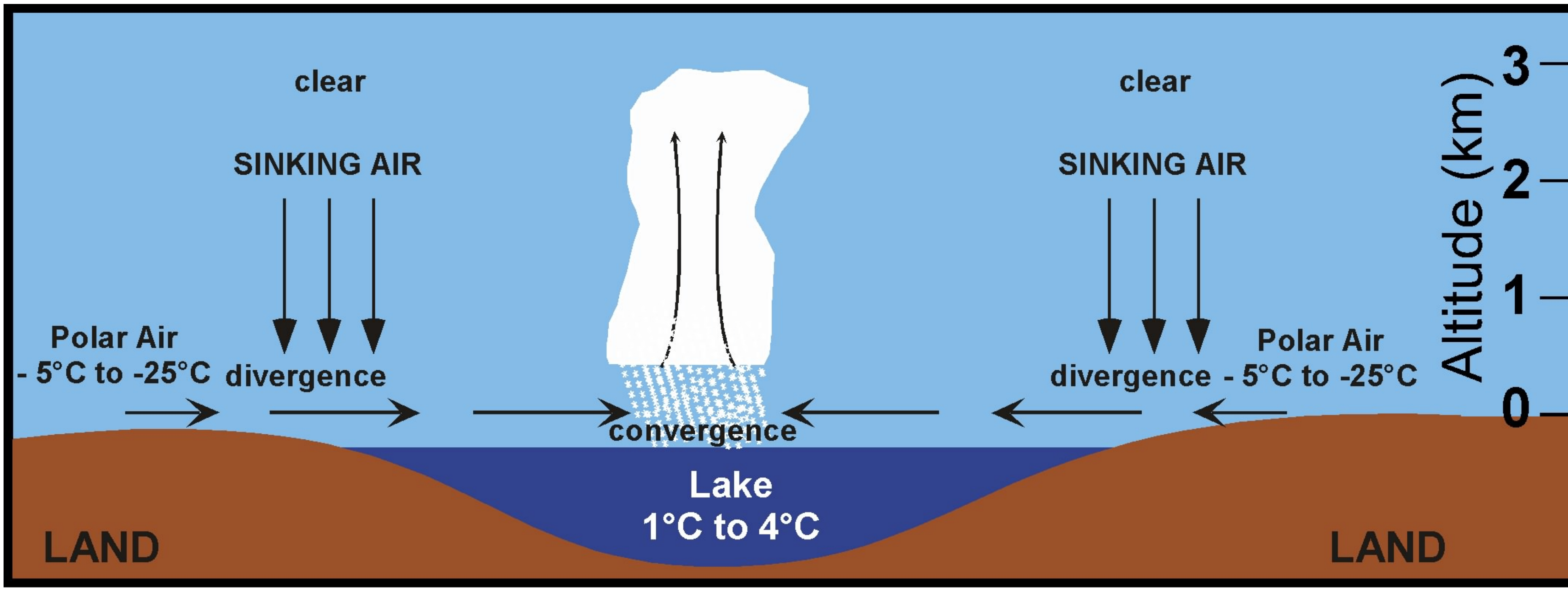
- Radar image of precipitation associated with wind-parallel rolls over eastern side of Lake Michigan

- Precipitation forms linear bands, separated by relative precipitation free areas

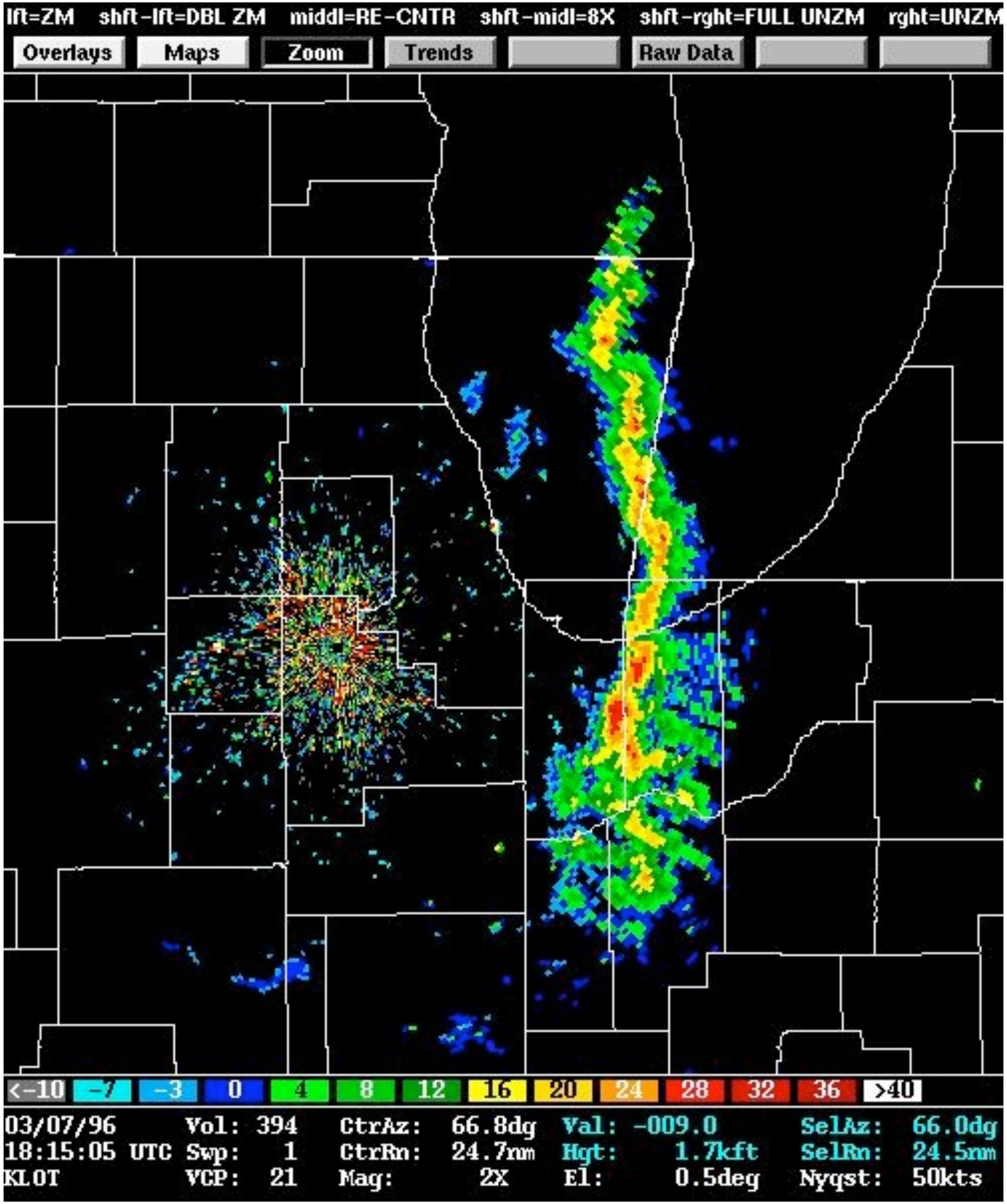
- Precipitation develops over lake and increases in intensity along shoreline and inland

Shore-Parallel Bands

Heat of lake forces air over lake to rise, drawing in air from both shores towards the centre of the lake – land breezes!

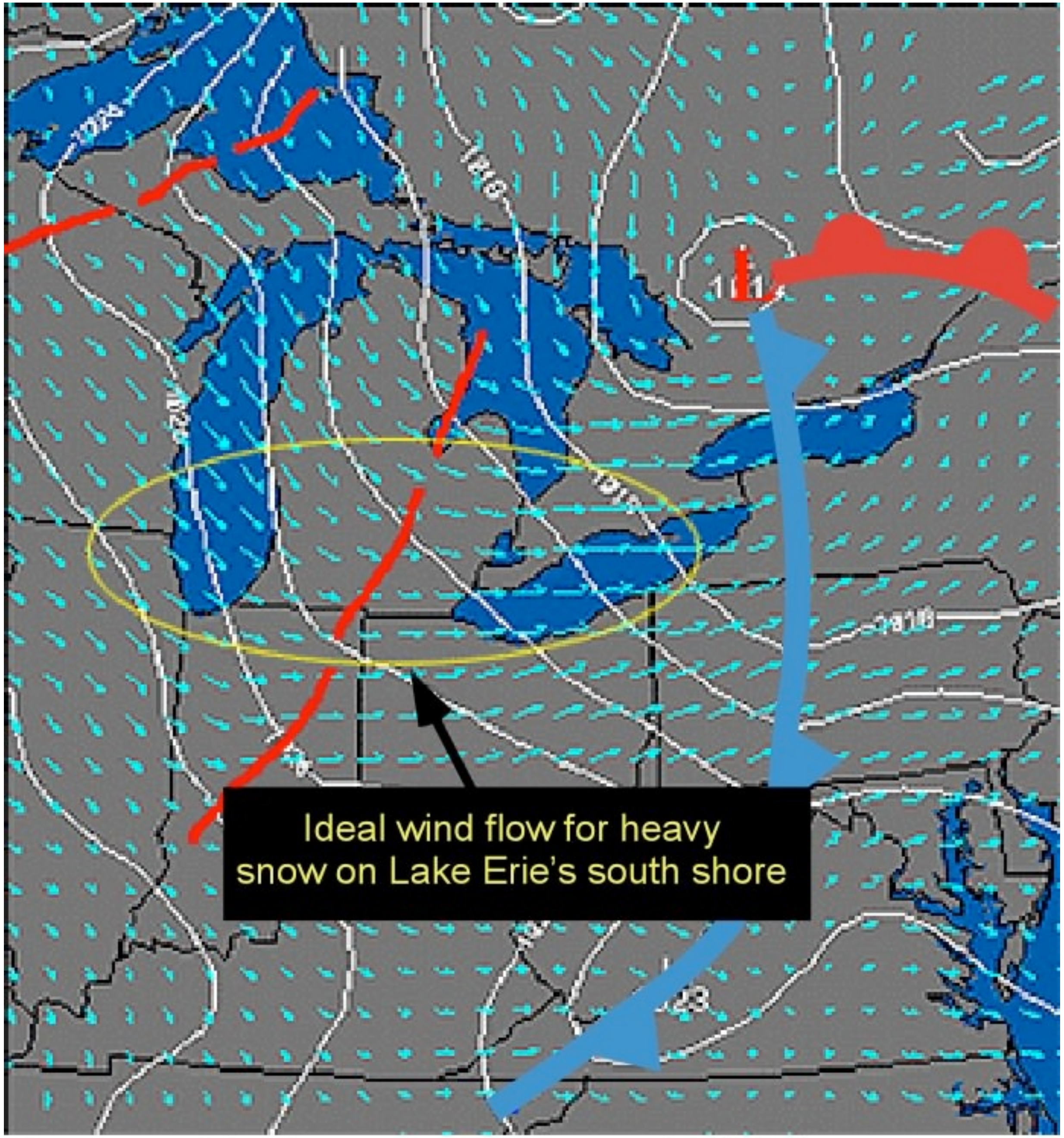


Circulation associated with shore-parallel bands (note deeper cloud)



Radar image of precipitation associated with shore-parallel band over Lake Michigan

Note: band is still effectively 'parallel' to the wind — problem with terminology



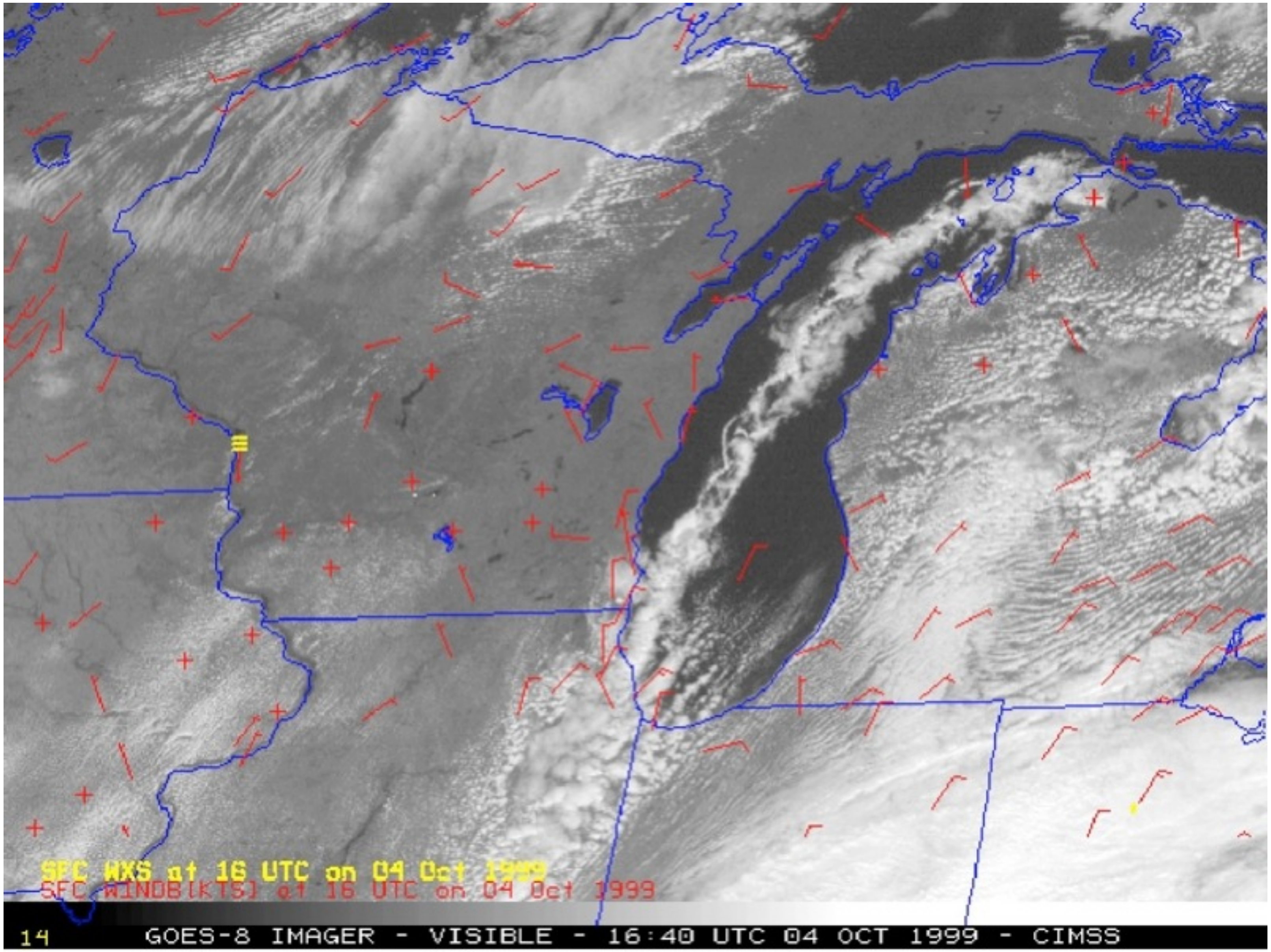
Courtesy of the Department of Atmospheric Sciences
University of Illinois at Urbana-Champaign

This formation also occurs when winds are strong and parallel to the long axis of the lake. Common over Lakes Erie and Ontario.

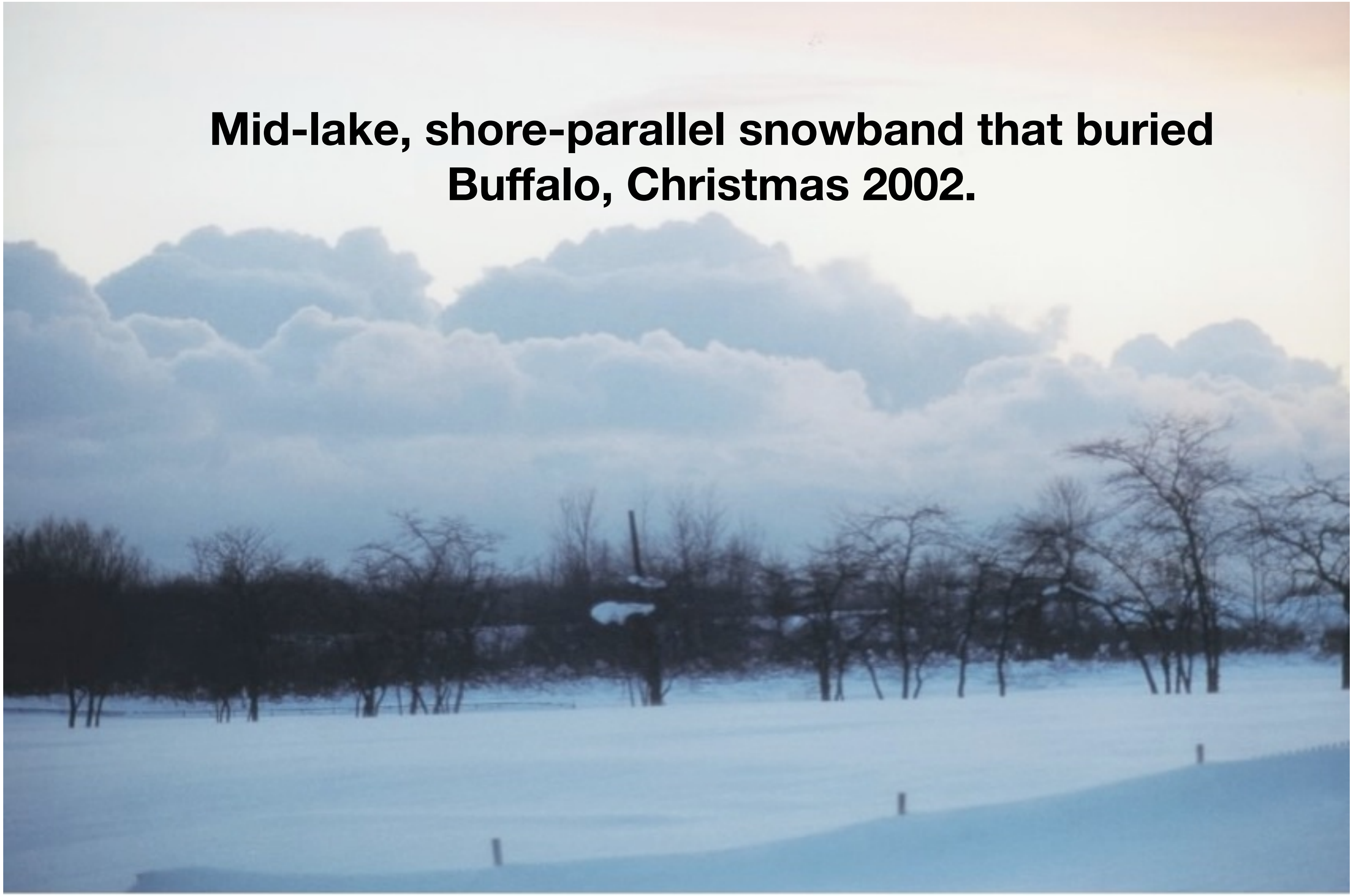
Shore parallel bands difficult to forecast

- **only few kms wide,**
- **may last a long time or dissipate rapidly;**
- **sometimes they migrate during day, sometimes they remain stationary.**
- **Positioning of bands can mean heavy snow/ precipitation in a single locality, yet sunny skies not far away.**

Visible satellite image with surface wind bars showing a shore-parallel band over Lake Michigan; shore-parallel band extends along length of lake



Courtesy of the Cooperative Institute for Meteorological Satellite Studies
University of Wisconsin-Madison

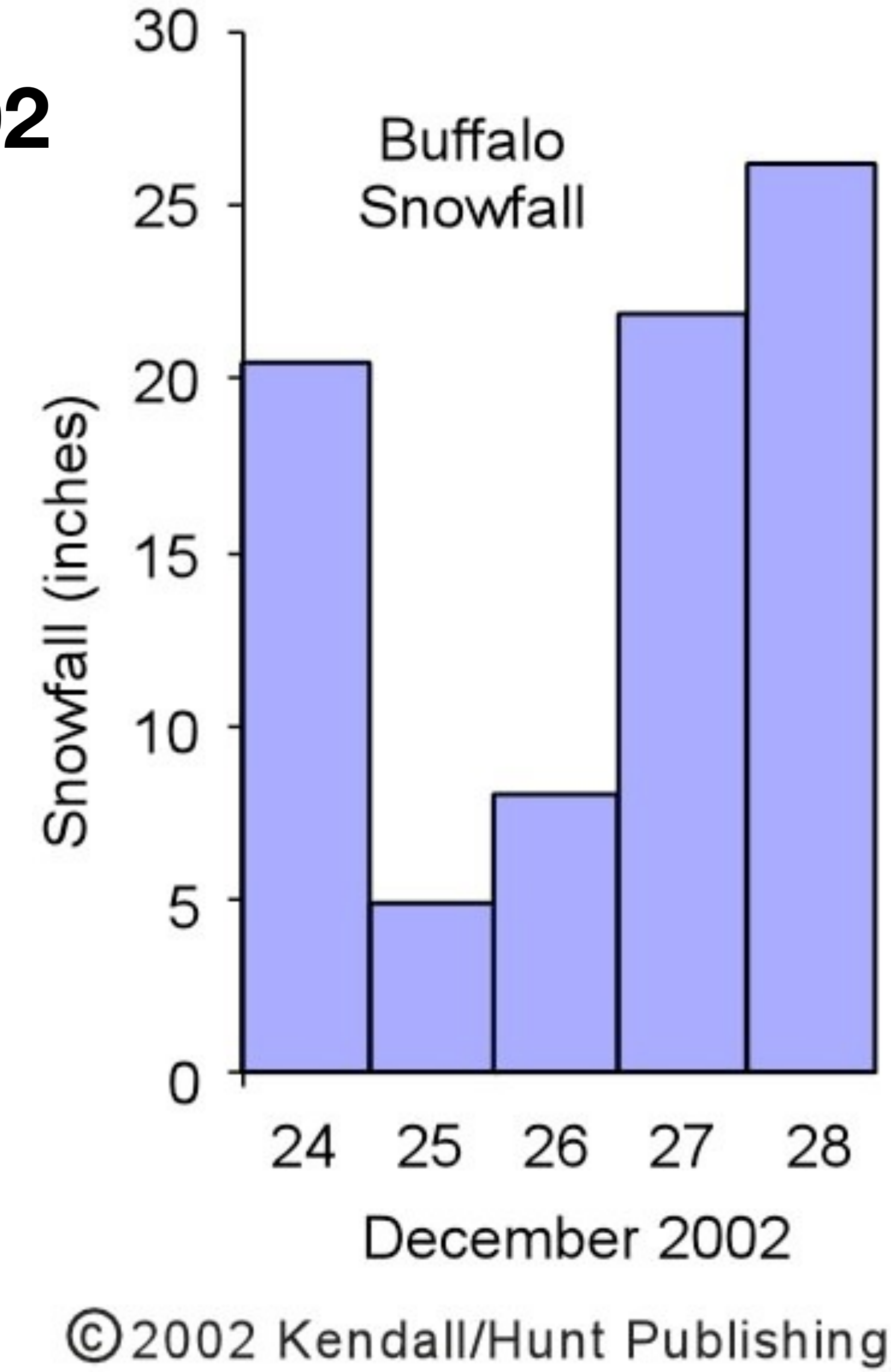


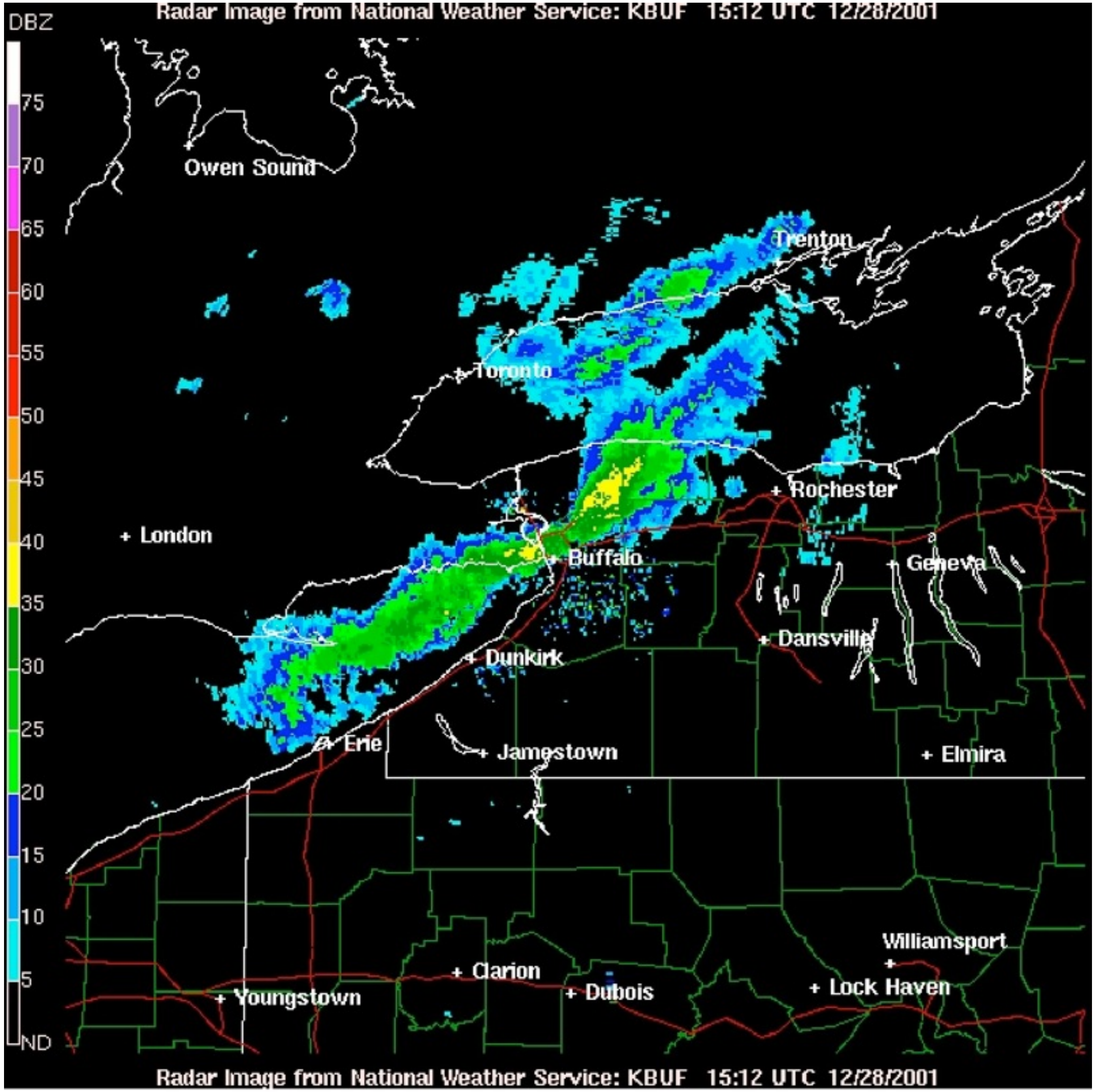
Courtesy of Tom Niziol

Christmas snowstorm 2002

Daily snow totals

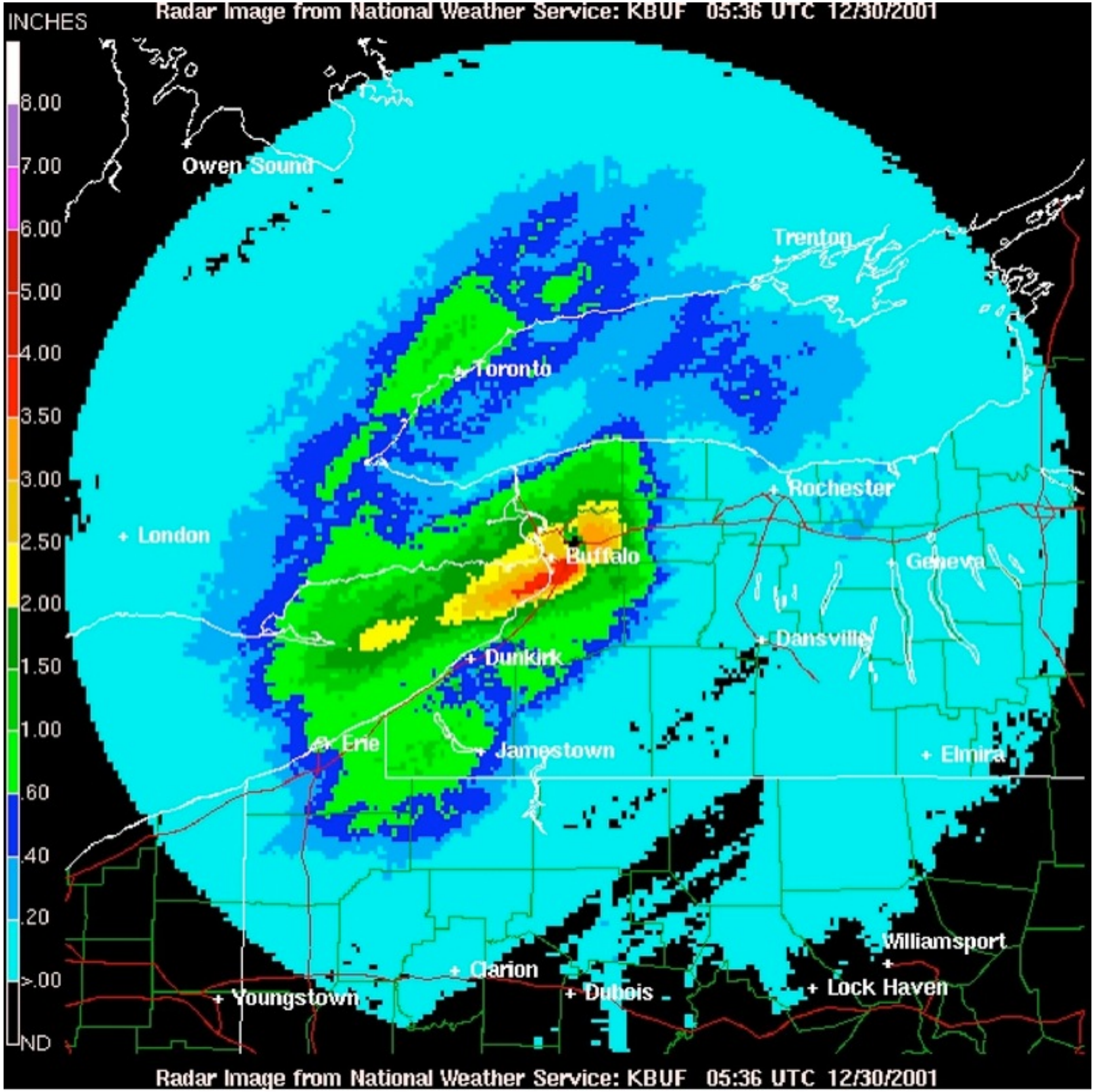
Record Amounts





Radar Reflectivity

Total precipitation lines up in a band with maximum located over Buffalo.



Shows mid-lake shore parallel band during the storm

Total storm precipitation (snow liquid equivalent)

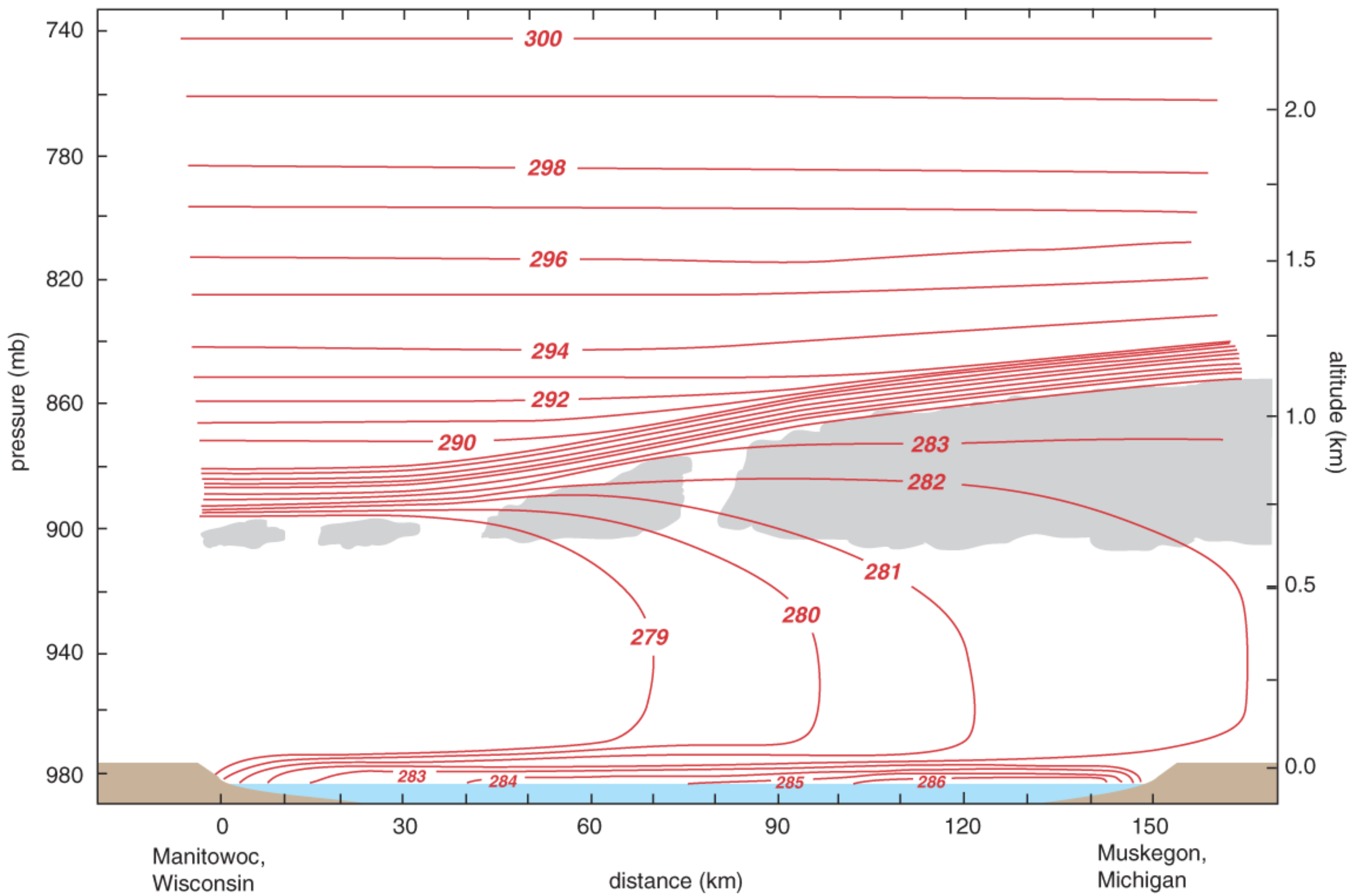
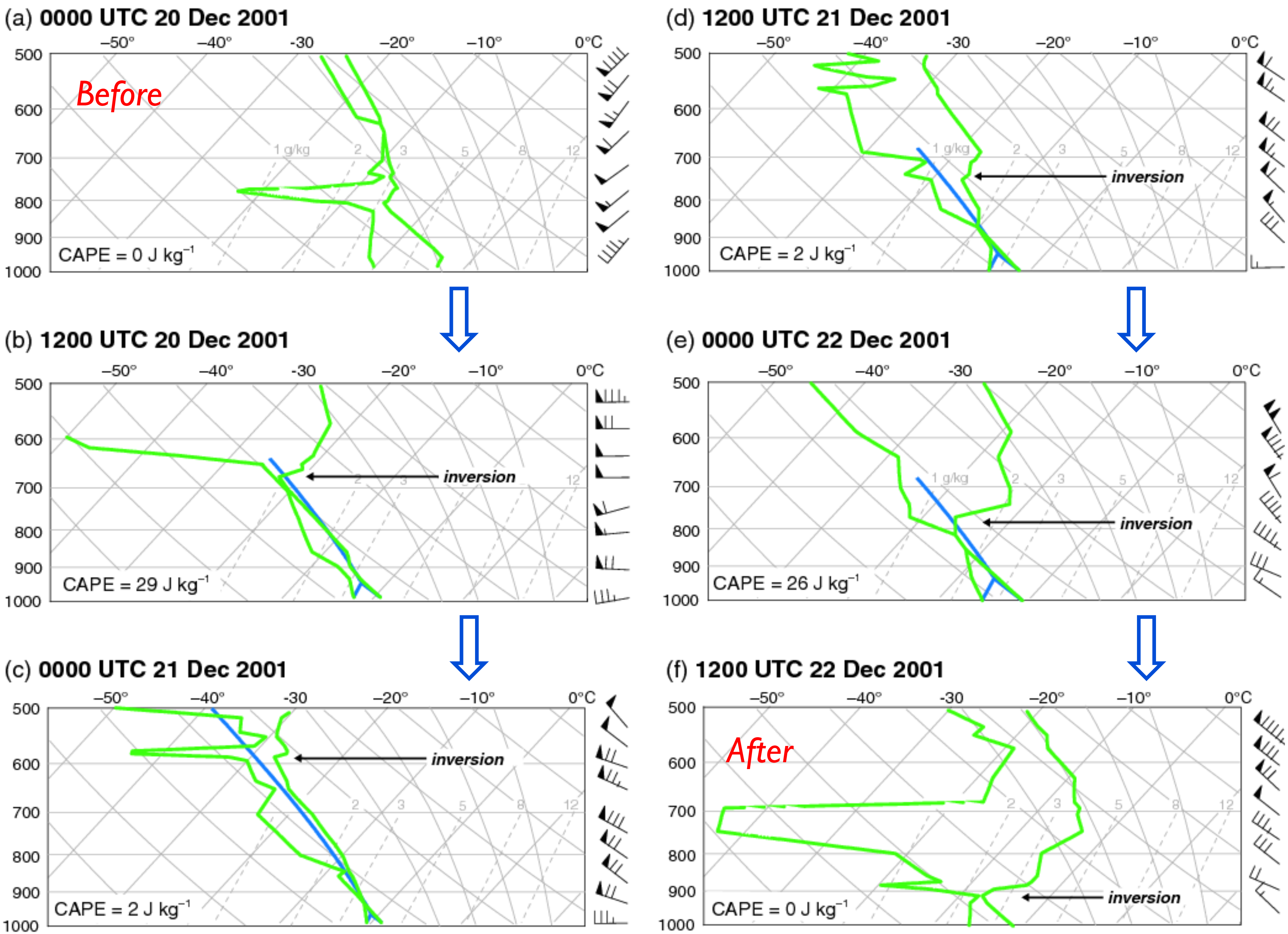


Figure 4.21

Vertical cross-section of potential temperature over Lake Michigan on 5 November 1970 obtained from aircraft transects. The mean wind is from left to right (northwest to southeast). The clouds shown are based on visual observations from the aircraft. (Adapted from Lenschow [1973].)

Buffalo NY Lake-Effect Snow Event - Soundings



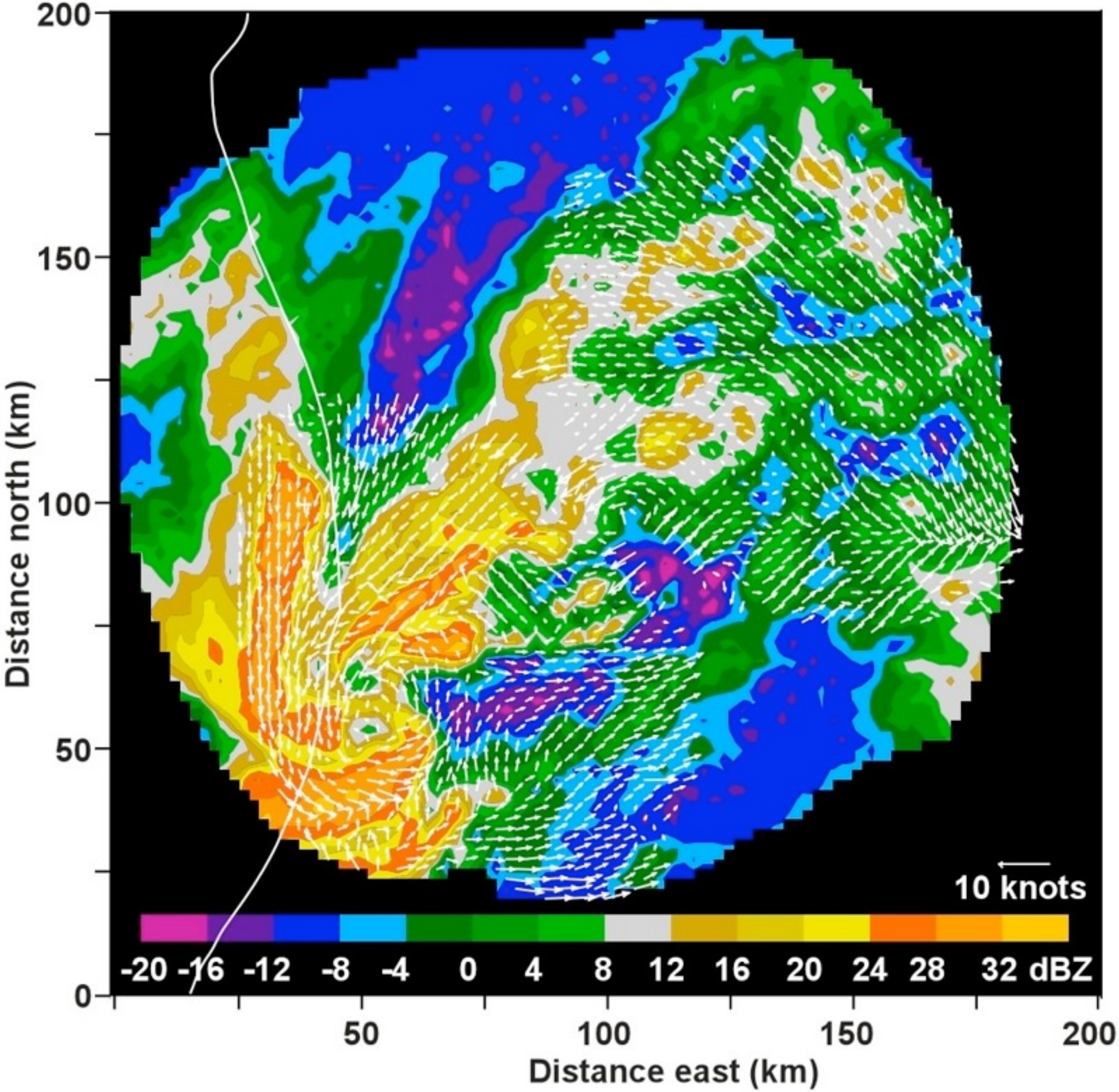
Vortices

Related to many variables such as

- **horizontal wind shear (variation of wind speed with distance),**
- **strength of wind,**
- **variations in shoreline topography,**
- **atmospheric stability, and**
- **lake-air temperature differences.**

Vortices

- normally develop over lake
- sometimes near one shoreline
- can maintain closed circulations for several hours
- typically drift slowly with background flow
- usually break up once they move inland

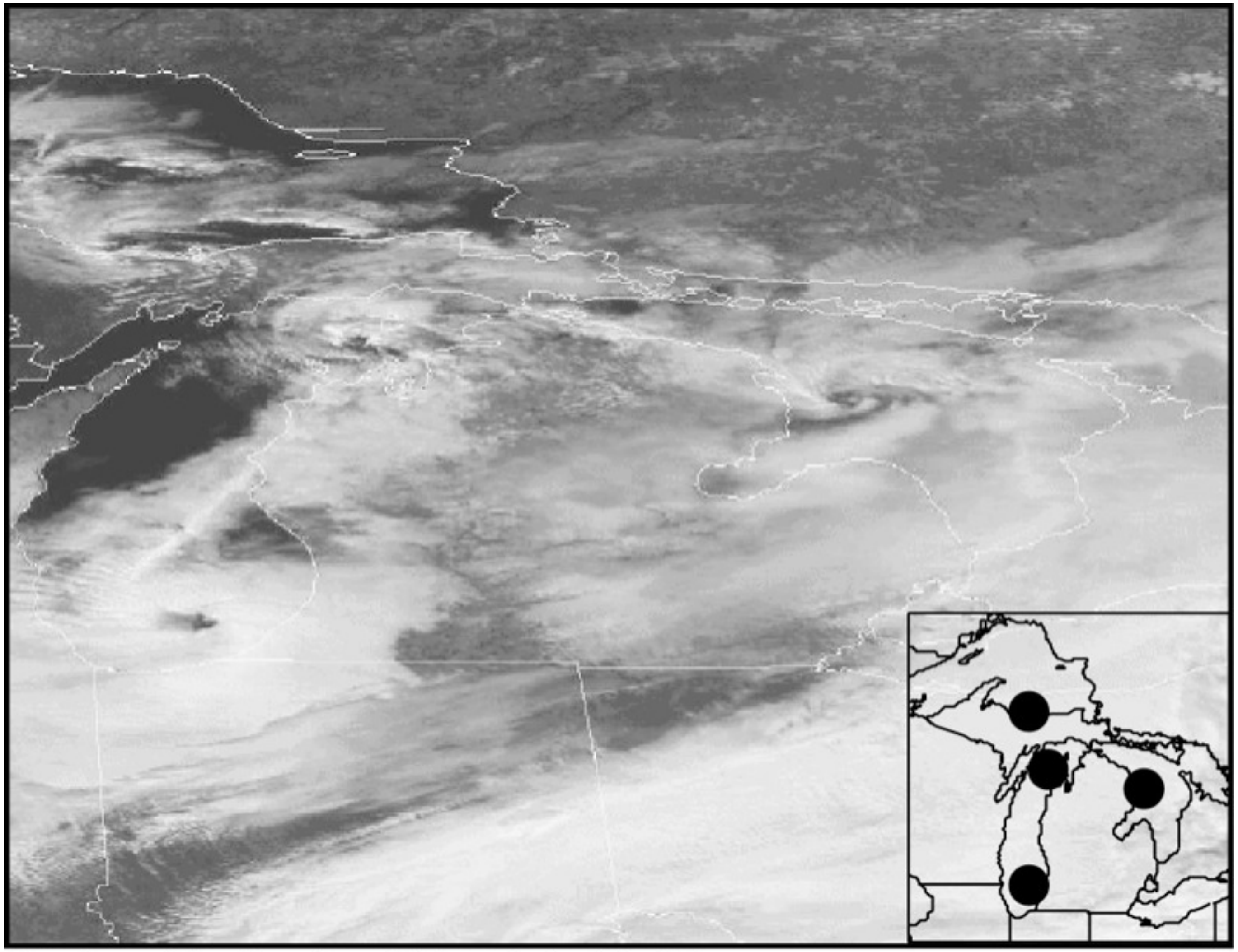


Courtesy of Neil Laird

Precipitation free "eye"

Ring of precipitation around eye similar to hurricane eyewall

Note sharp convergence zones along the snowbands that spiral outward from centre.

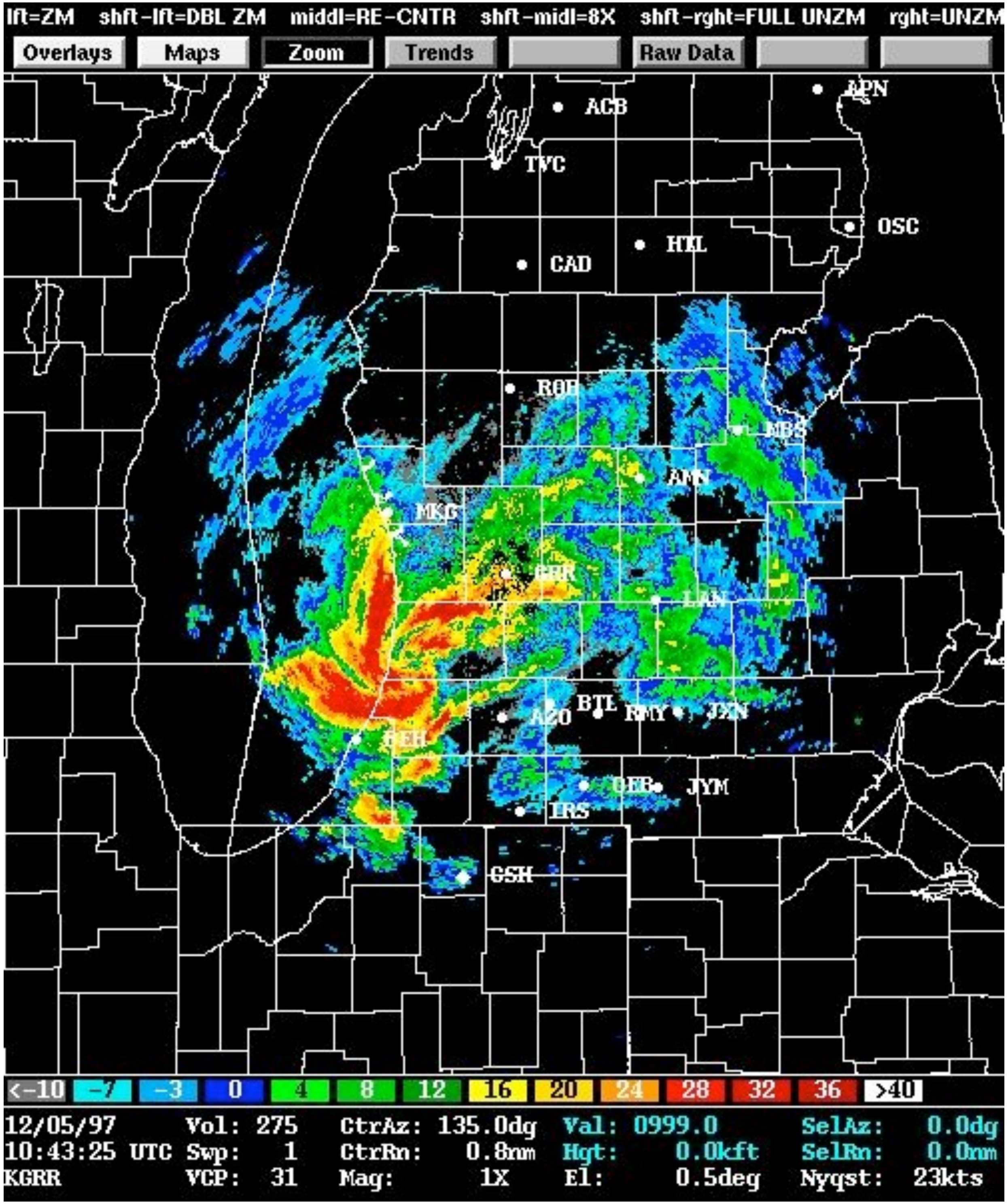


Courtesy of the American Meteorological Society

Satellite image of upper Great Lakes showing 4 separate vortices over Lakes Michigan, Huron, and Superior (see insert, black dots).

All these vortices have "eyes."

When vortices stall such that centre of vortex is located over shore, band can often promptly deliver 25 cm of snow.



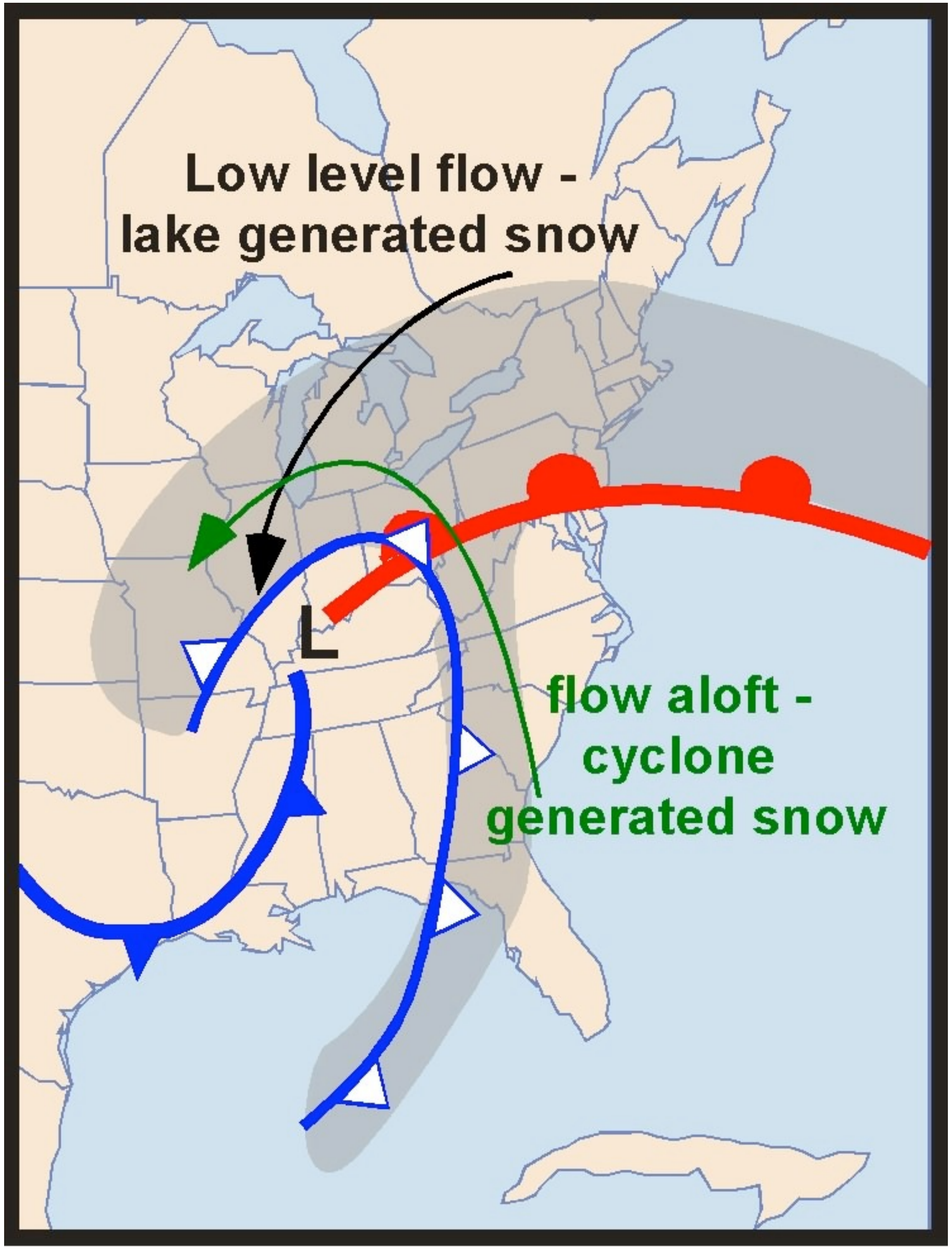
Vortex on SE side of Lake Michigan

Note distinct spiral bands, and an eye as it moved onshore.

Bands that appear to be weakening are not -- radar beam unable capture them entirely

Lake-Enhanced Snowfall

- The lake-effect storms described in the previous slides are occur in otherwise clear cold air that typically follows the passage of a larger scale cyclone.
- Under the right temperature conditions, the Great Lakes also contribute to snowfall during a cyclone passage.
  - Lake-generated snow combines with snow from the larger cyclone.
    - This can result in some of the WORST snowfall in areas like Chicago.



Cyclone circulation draws air from eastern Canada across lake Michigan.

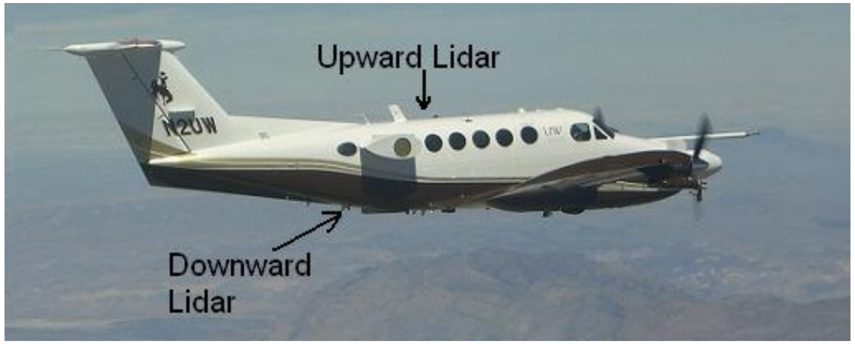
If this low-level air is sufficiently cold, evaporation of moisture and heat transfer from lake lake to formation of lake-effect clouds below the cloud generated by the cyclone's trough axis.

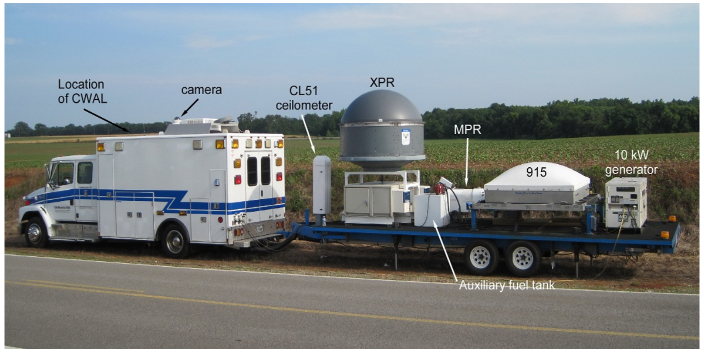
Where else might this occur?

Research – OWLES 2013-14

Ontario Winter (OW) Lake-effect Systems (LeS)

http://www.owles.org/





- US-led project focusing on lake-effect snowstorms originating over Lake Ontario
- Funded by the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration (NOAA)
- Some assistance from Environment Canada

Great Salt Lake Effect

- **Lake-effect snow around the Great Salt Lake is generated in a similar fashion to elsewhere in the world.**
- **However, the Great Salt Lake primarily provides a lifting mechanism and acts as an atmospheric destabilizer, which encourages convection.**
- **This is in contrast to the Great Lakes, where the lakes contribute significant amounts of moisture and latent heat.**
- **Great Salt Lake enhanced precipitation occurs when a strong, cold, northwesterly wind blows across a relatively warm lake.**
- **This is common after a cold front passage, where the winds are predominantly northwesterly and the air is much colder than the lake.**
- **When the land-lake breeze blows towards the lake, there is a convergence zone that acts to channel the cold air over the center of the lake and further enhance precipitation.**
- **Water vapor and latent heat added to the air moving over the lake is not a signficant element of GSL Effect.**
- **The salinity of the Great Salt Lake prevents freezing but reduces the saturation vapor pressure over the lake.**

Great Salt Lake Effect: Forecasting lake-effect snow

- **A strong northwesterly flow maximizes precipitation for the Salt Lake Valley.**
- **A minimal temperature difference of 29 °F (16 °C) between the surface and the 700 mbar (70 kPa) height is necessary, but not sufficient in itself to cause lake-effect snow.**
- **An inversion or stable layer below 700 mbar (70 kPa) has never yielded lake-effect snow.**
- **Lake-effect snow can occur in concert with synoptic scale storm systems.**
- **A large lake-land temperature difference favors over-lake convergence**

Great Salt Lake Effect: Forecasting lake-effect snow

- **Lake-effect is typically initiated during the night when land-breeze convergence is favored and convection occurs predominantly over the lake.**
- **During the daytime, lake-effect precipitation tends to dissipate as solar heating creates scattered widespread convection over the land.**
- **The 700 mbar winds typically determine the geographic position of the precipitation.**
- **Limited amounts of directional and vertical wind shear tend to produce heavier precipitation events.**
- **The Great Salt Lake contributes minimal amounts of moisture so that upstream moisture is a crucial variable.**

Great Salt Lake Effect: References

- Alcott, T.I., W.J. Steenburgh, and N.F. Laird, 2012: Great Salt Lake–Effect Precipitation: Observed Frequency, Characteristics, and Associated Environmental Factors. *Wea. Forecasting*, **27**, 954–971, https://doi.org/10.1175/WAF-D-12-00016.1

- Carpenter, D. M., 1993: The lake-effect of the Great Salt Lake: Overview and forecast problems. *Weather Forecast.*, **8,** 181-193.

- Steenburgh, W. J., S. F. Halvorson, and D. J. Onton, 2000: Climatology of lake-effect snowstorms of the Great Salt Lake. *Mon. Wea. Rev.*, **128**, 709-727

Great Salt Lake Effect

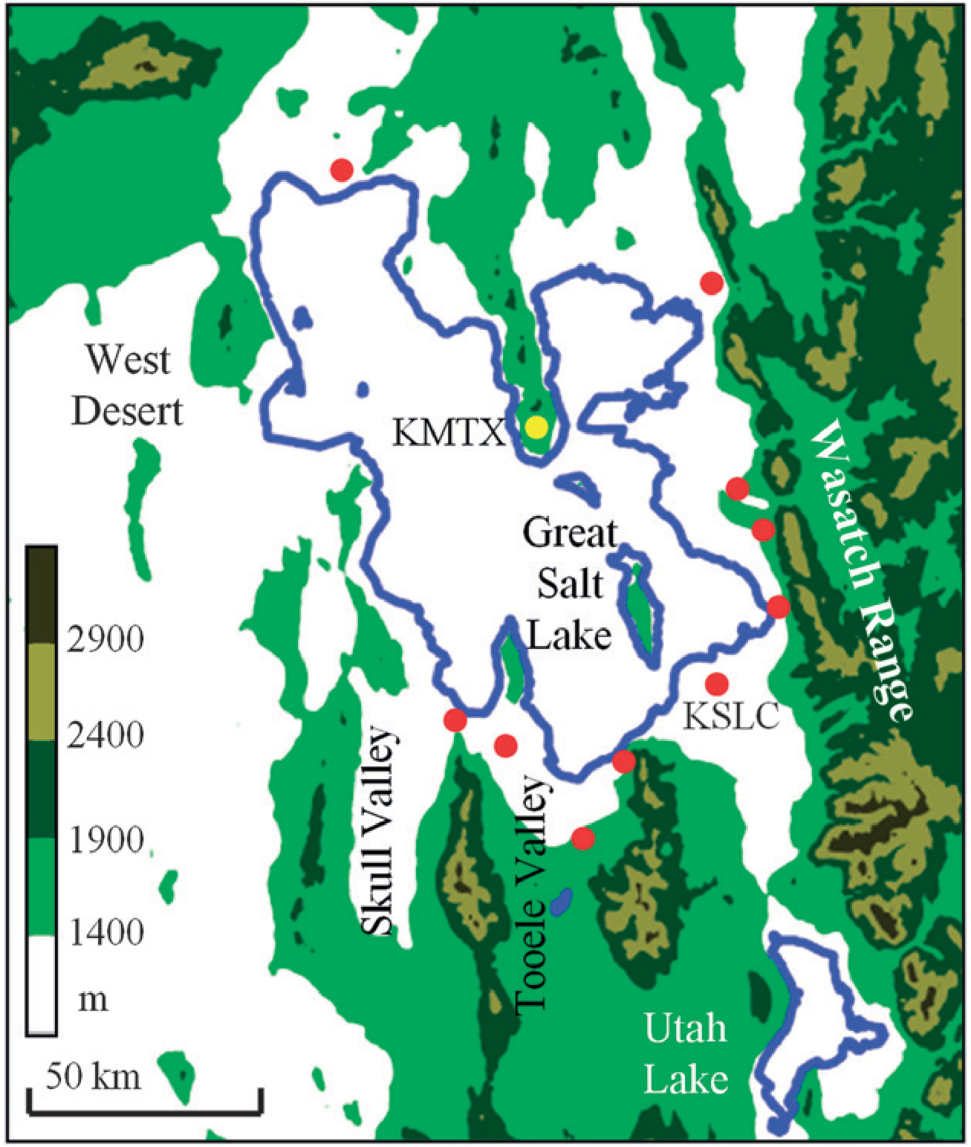


FIG. 1. Topography and landmarks of the study region; red dots mark the locations of mesonet stations used in the calculation of $\Delta T_{\text{LAKE–LAND}}$.

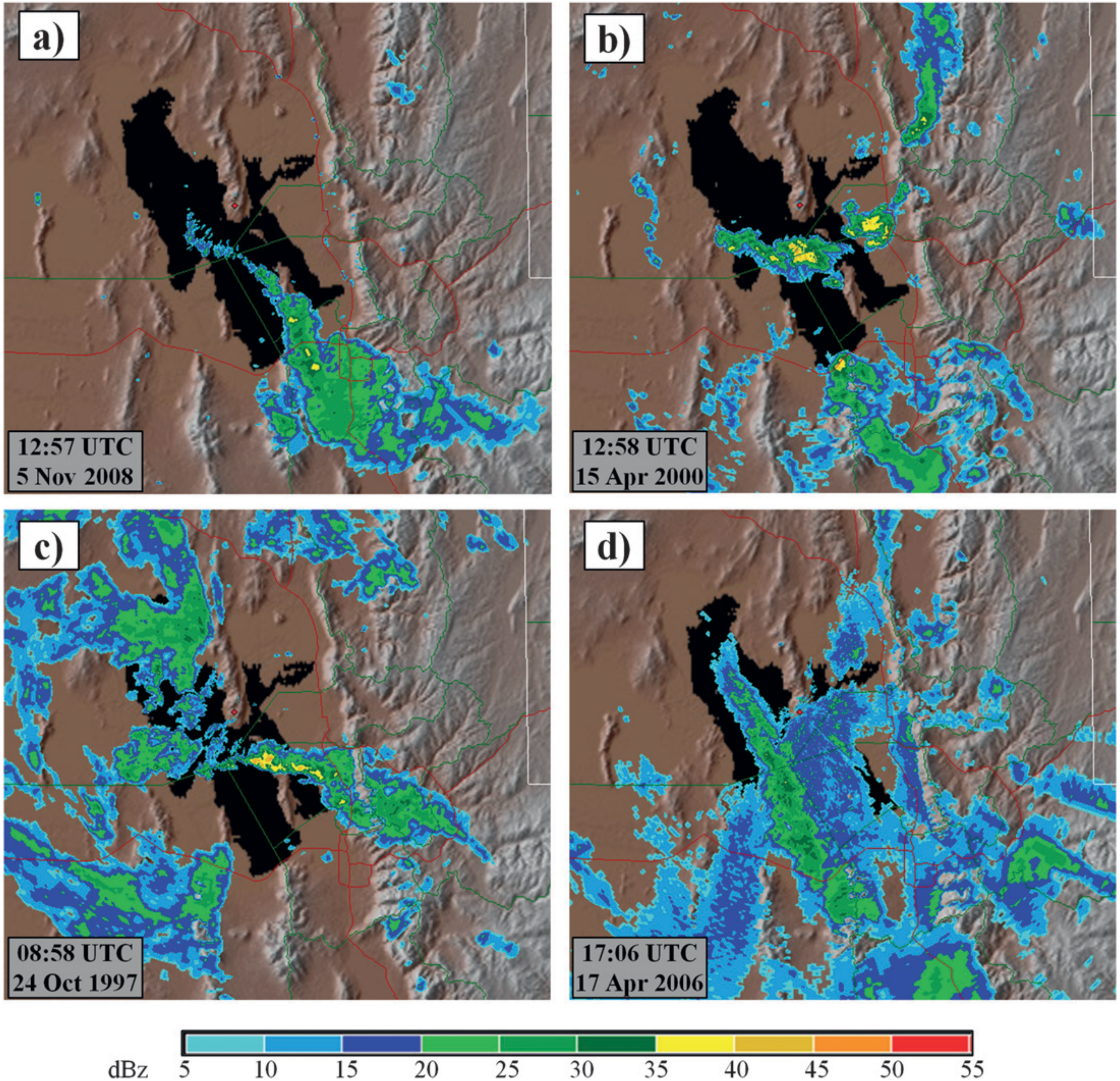


FIG. 2. Examples of GSLE precipitation context: (a) isolated areas of lake-effect precipitation, with no other precipitation falling in the surrounding valleys; (b) lake-effect precipitation concurrent with other primarily convective precipitation features; (c) lake-effect precipitation concurrent but not collocated with synoptic/transient stratiform precipitation; and (d) localized lake enhancement of transient precipitation.

Great Salt Lake Effect

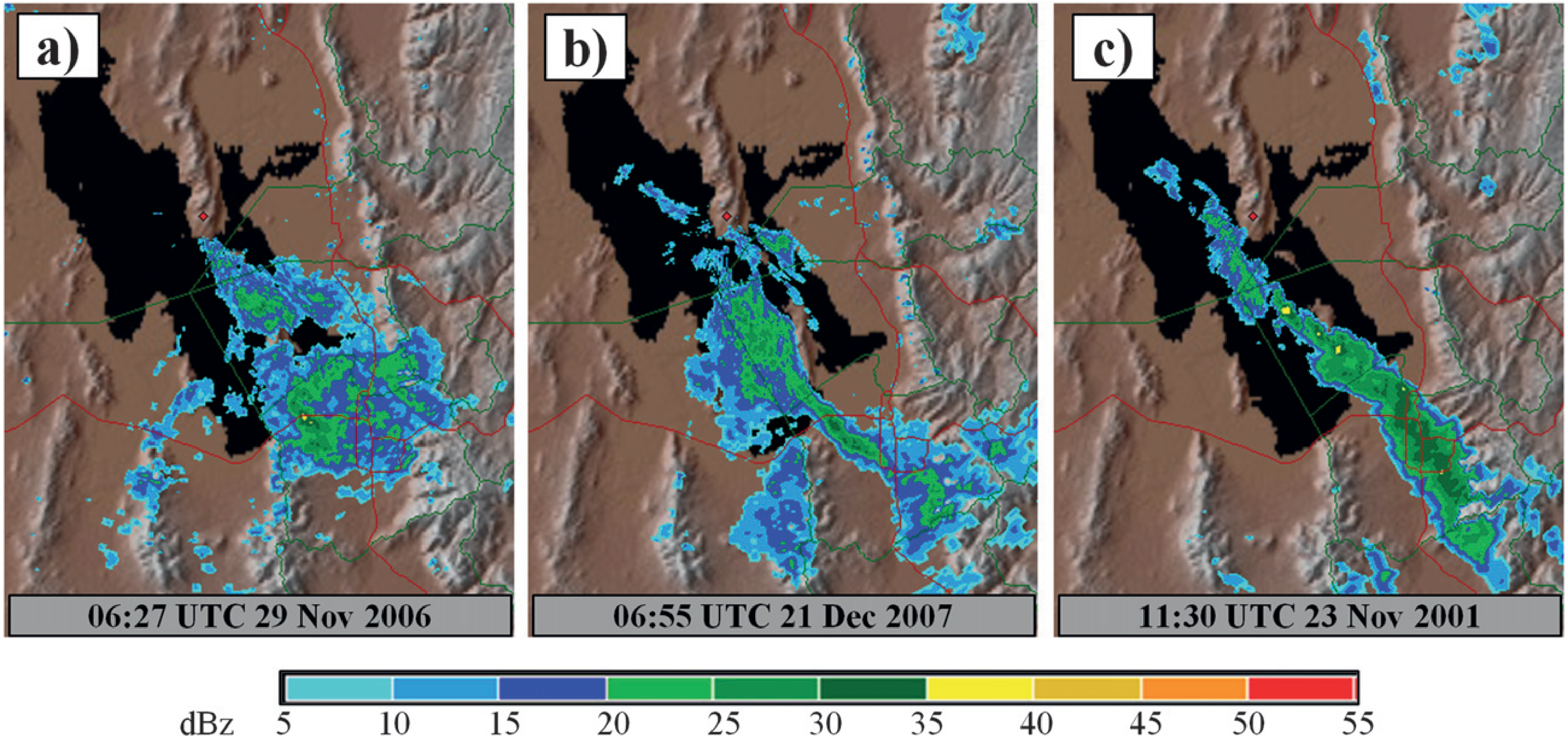


FIG. 3. Examples of GSLE morphology categories: (a) nonbanded, (b) mixed mode, and (c) banded.

Great Salt Lake Effect

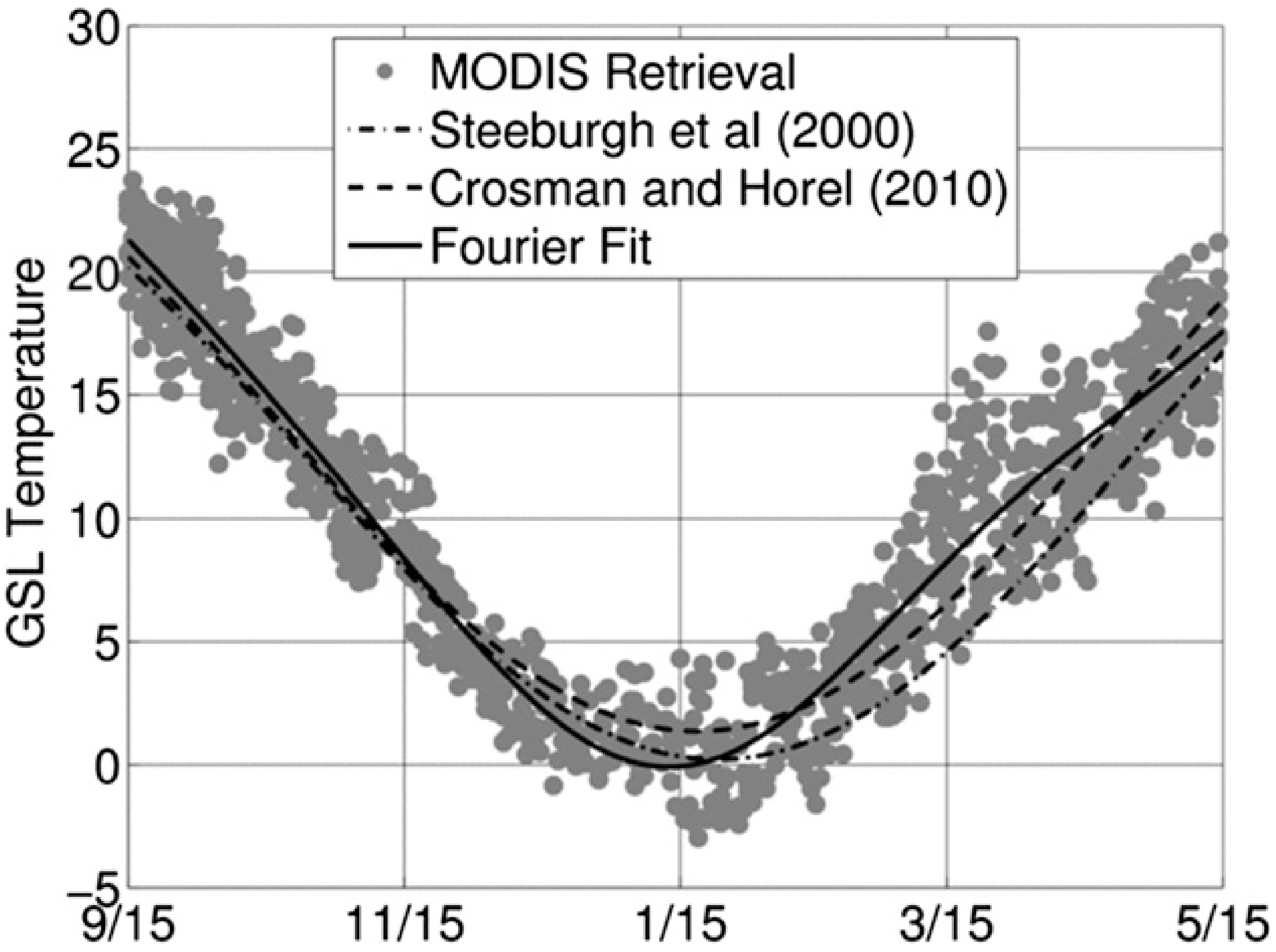
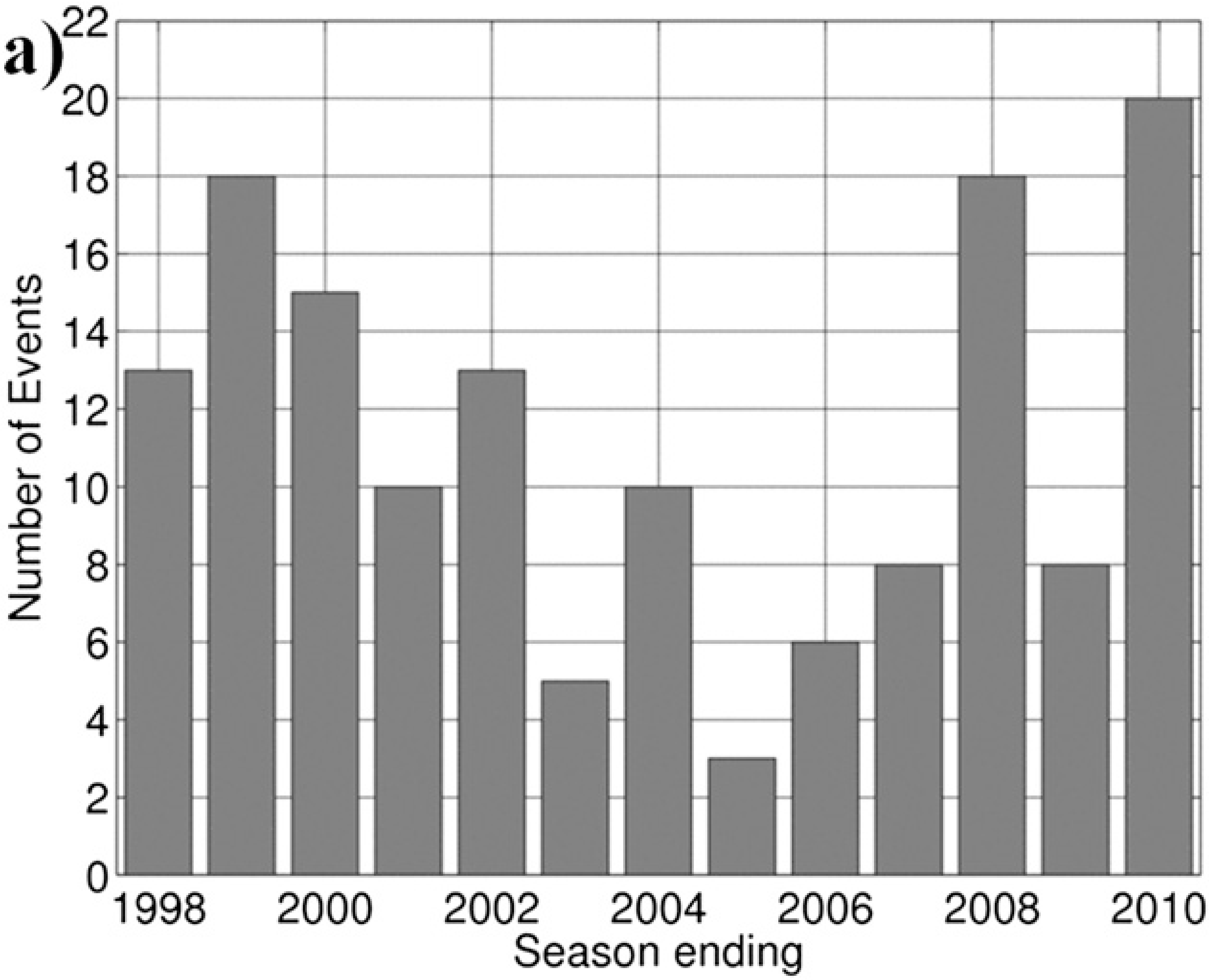


FIG. 4. MODIS GSL temperature vs three climatological curve fits.

Great Salt Lake Effect



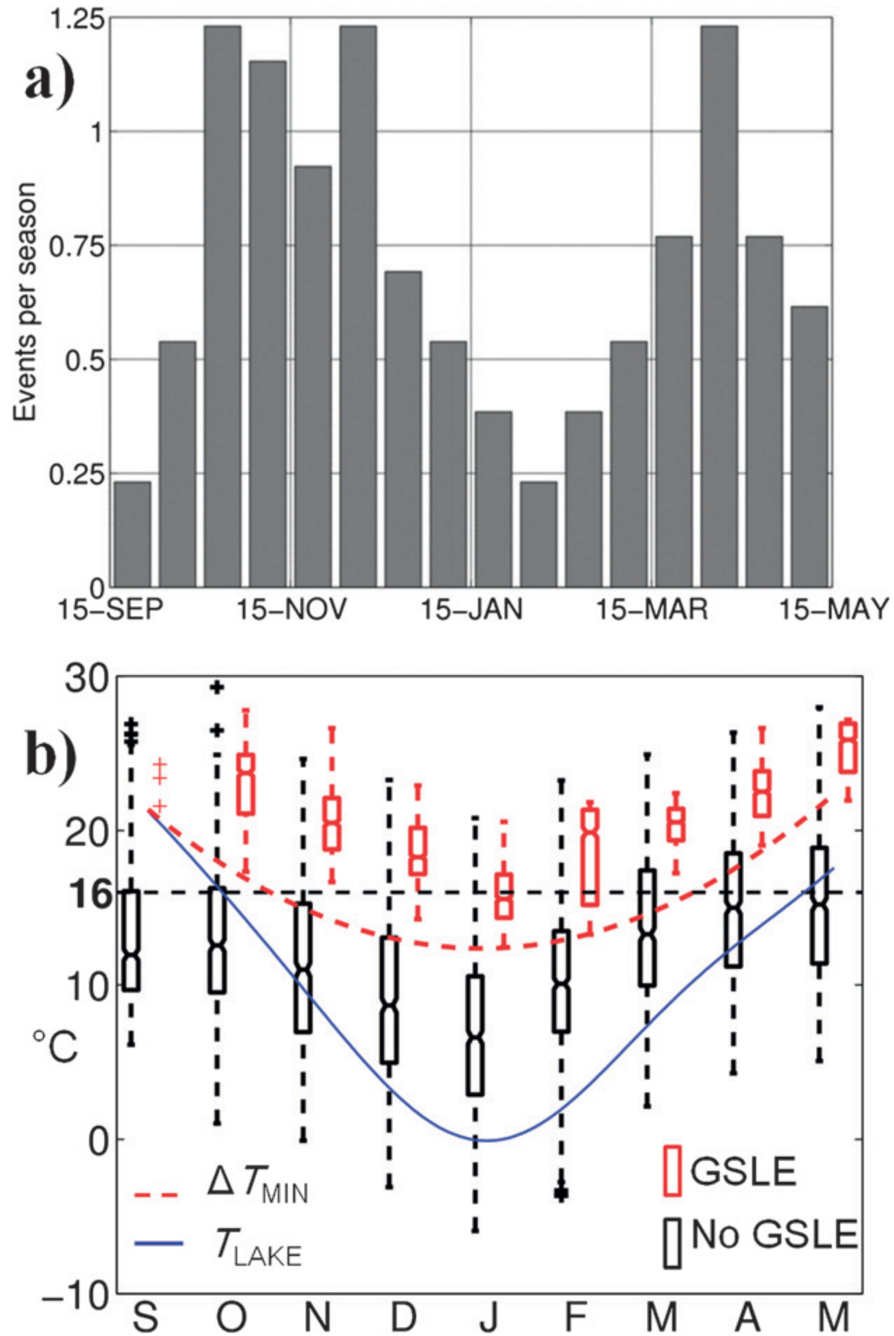


FIG. 6. (a) Number of events by half-month. (b) Standard box-and-whiskers plot of lake–700-hPa temperature difference (ΔT) by month, for non-GSLE (black) and GSLE soundings (red). Black dashed line indicates the 16°C operational forecast threshold, and red dashed line the quadratic curve fit for a seasonally varying threshold ($\Delta T_{\min}$). Blue line denotes climatological lake temperature.

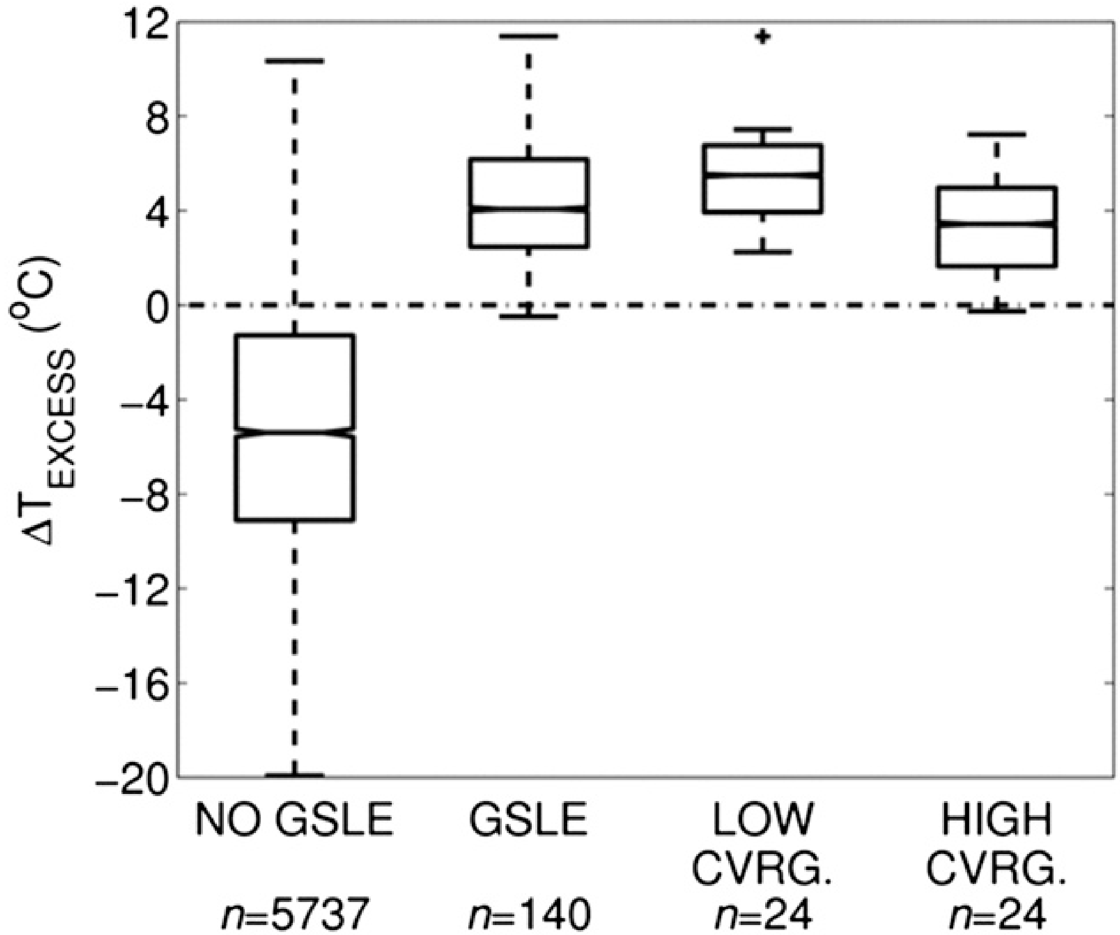


FIG. 9. Comparison of ΔT_{excess} for four categories of soundings: soundings with GSLE, without GSLE, with a pure lake effect and low coverage (<80 km^2 of 10-dBZ radar echoes, the lowest tertile), and with a pure lake effect and high coverage (>640 km^2 of 10-dBZ radar echoes, the highest tertile). Box top and bottom are the 25th and 75th percentiles, the median is denoted by a horizontal line in the box (medians of two distributions differ at the 90% level when the notches around their respective median lines do not overlap), whiskers extend to 1.5 times the interquartile range, and outliers beyond 1.5 times the interquartile range are denoted by plus signs (+).

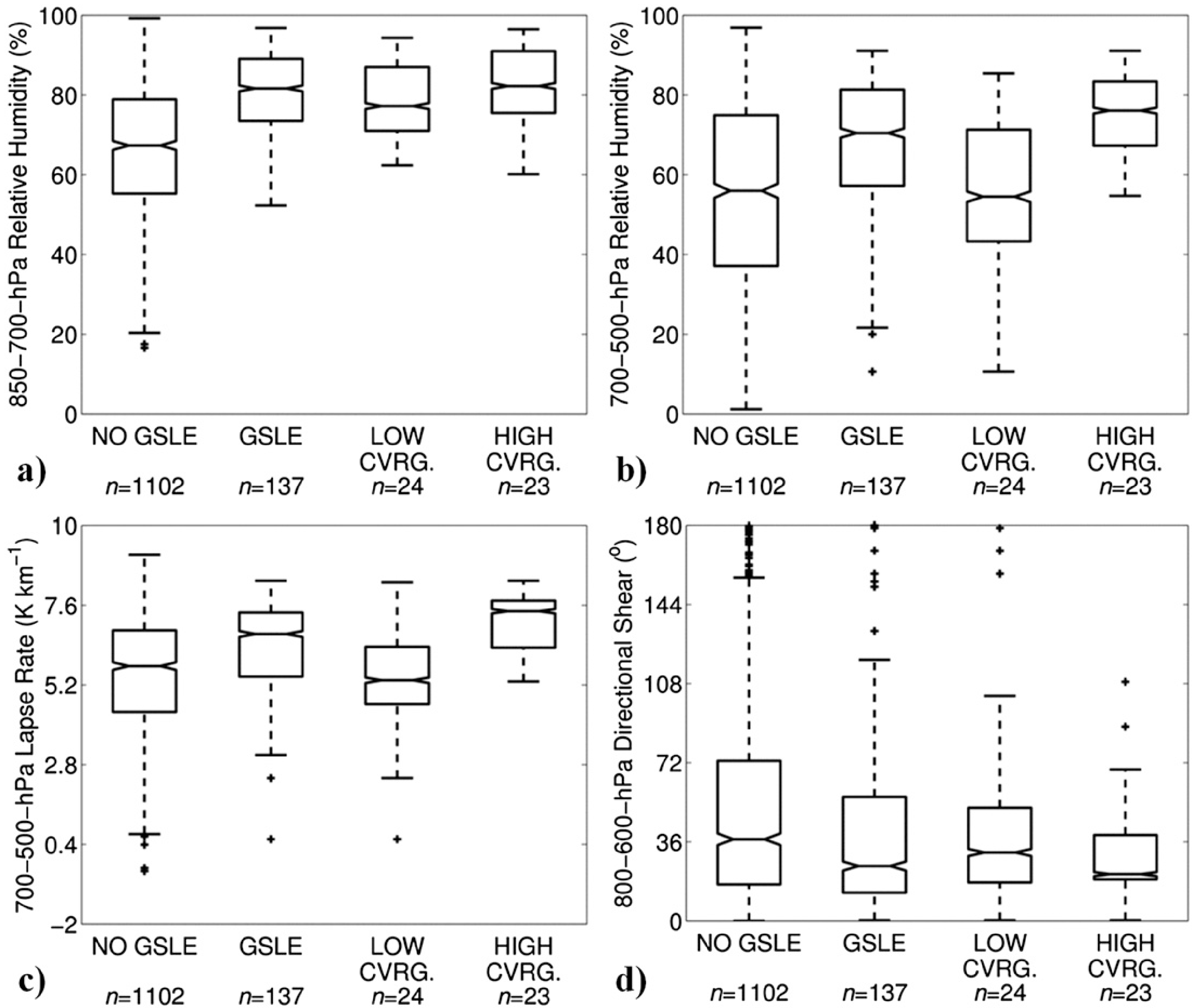


FIG. 10. Comparison of variables in the same categories of soundings as in Fig. 9, but for $\Delta T_{\text{excess}} \geq 0$: (a) 850–700-hPa mean layer RH (%), (b) 700–500-hPa mean layer RH (%), (c) 700–500-hPa lapse rate (K km^{-1}), and (d) 800–600-hPa directional shear (°). Box-and-whiskers plotting convention as in Fig. 9.

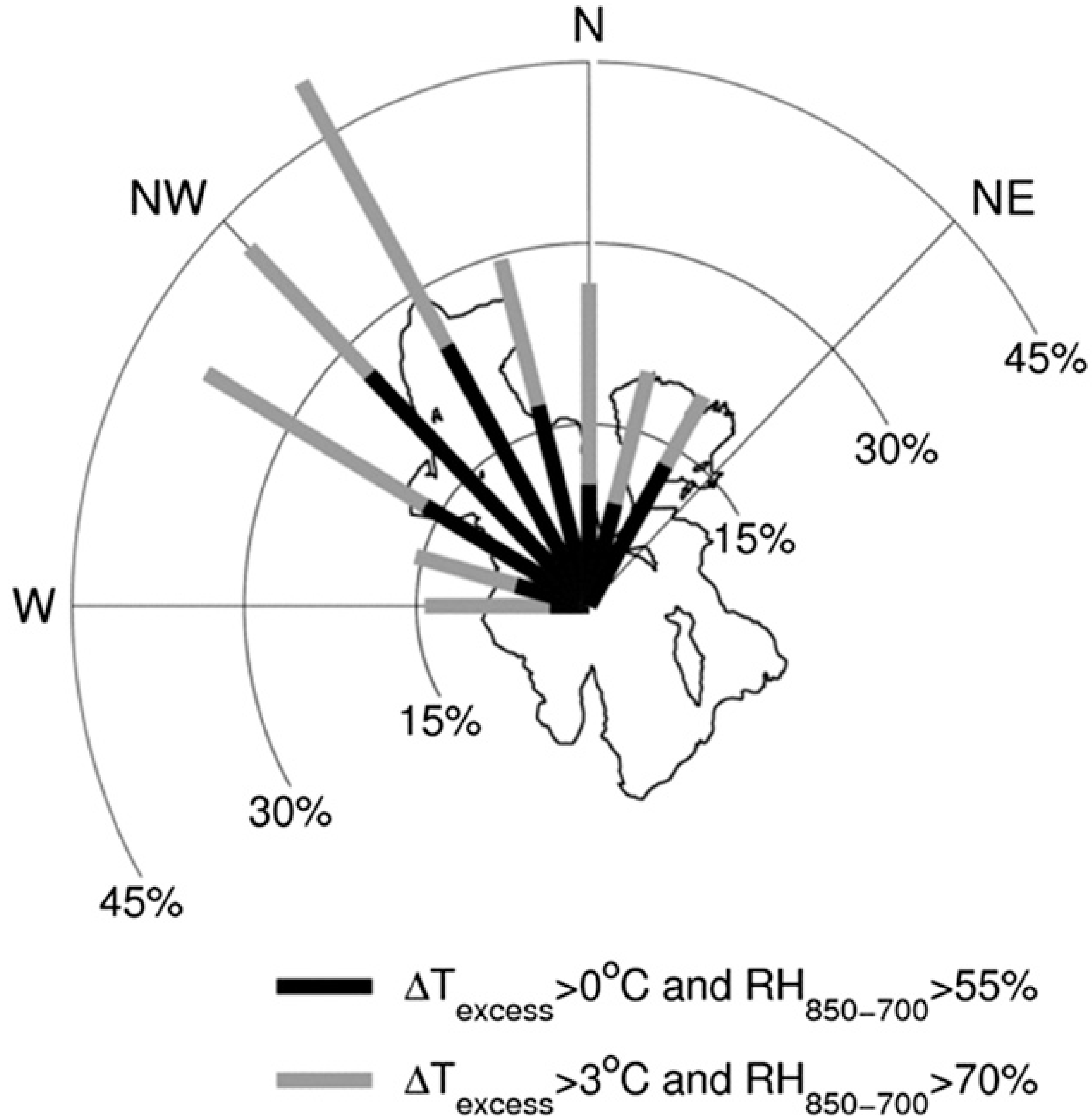


FIG. 11. Fraction of soundings (%) with GSLE vs 700-hPa wind direction, overlaid on GSL shoreline map, given $\Delta T_{\text{excess}} \geq 0$ and $RH_{850\text{–}700} \geq 55\%$ (black bars) or $\Delta T_{\text{excess}} \geq 3$ and $RH_{850\text{–}700} \geq 70\%$ (gray bars).

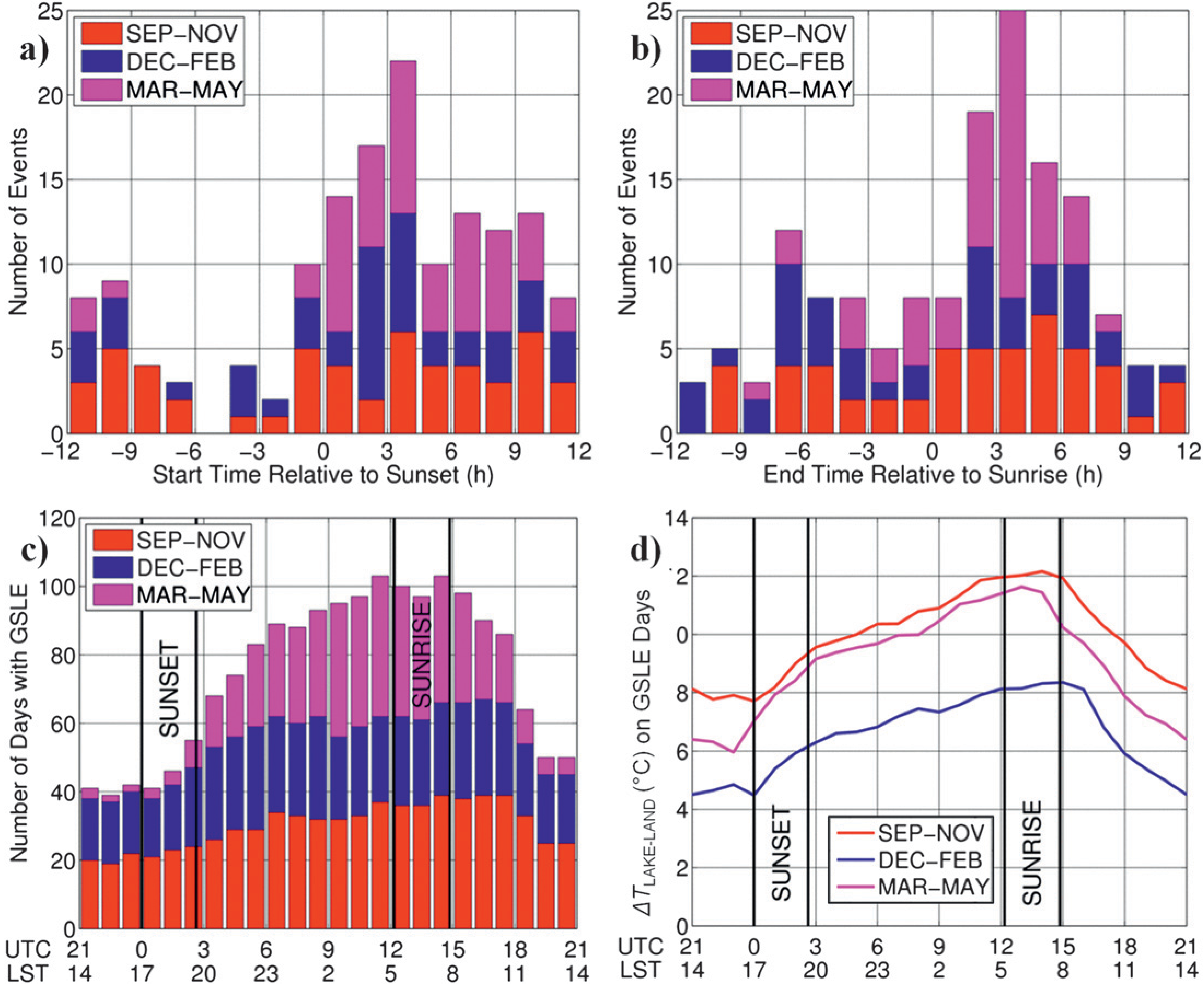


FIG. 12. Timing of GSLE events: (a) event start time relative to sunset (h); (b) event end time relative to sunrise (h); (c) number of days with GSLE at a given time of day (h, UTC and LST), where vertical bars indicate the ranges of sunrise and sunset times (16 September–15 May); and d) hourly median $\Delta T_{\mathrm{LAKE-LAND}}$ on days with GSLE.

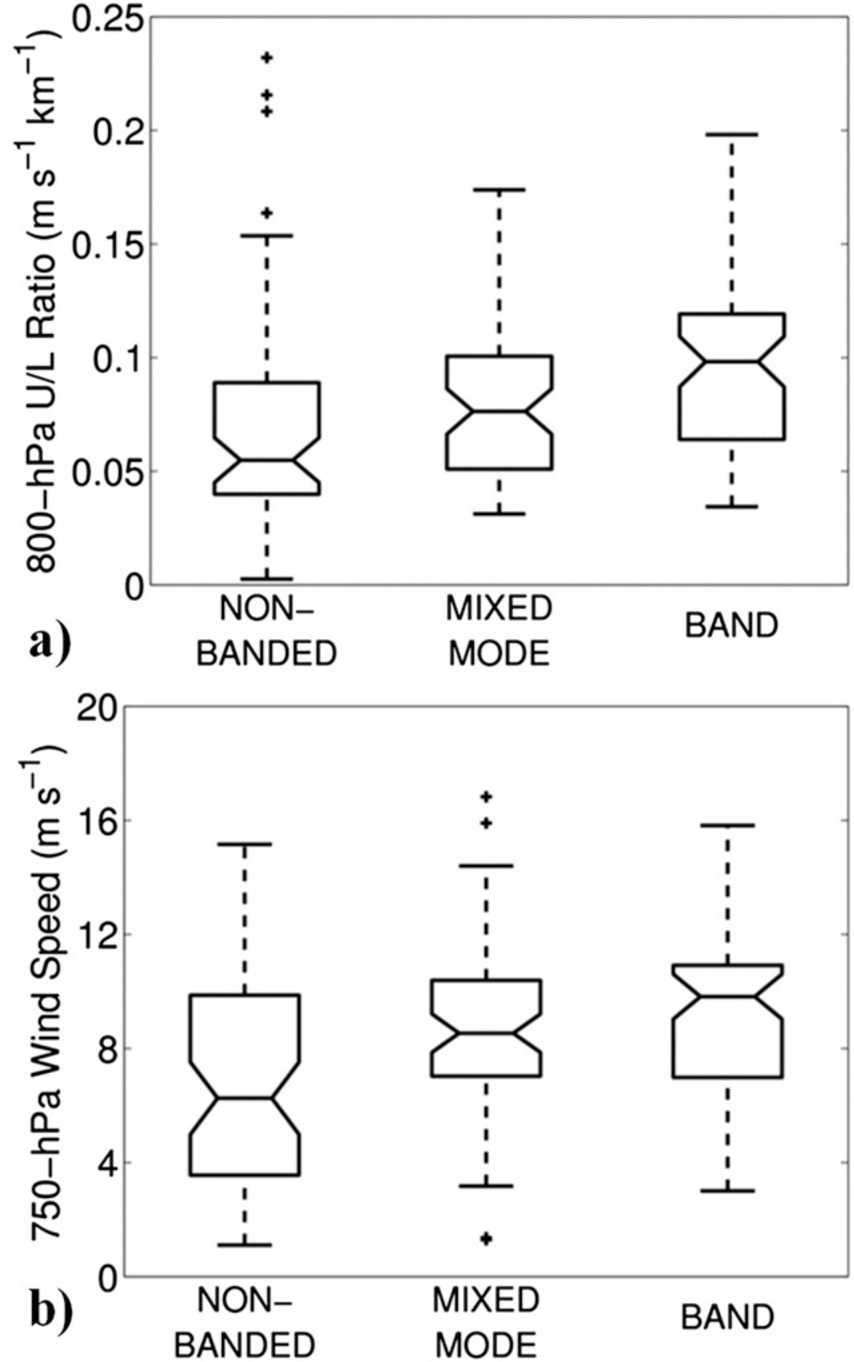


FIG. 14. GSLE mode vs (a) 800-hPa wind speed–fetch ratio (U/L; m s^{-1} km^{-1}), and (b) 750-hPa wind speed (m s^{-1}). Box-and-whiskers plotting convention as in Fig. 9.

TABLE 3. Utility of various forecast parameters, where $N_{soundings}$ is the total number of soundings that meet the given criteria, N_{GSLE} is the number of soundings that meet the criteria and are associated with GSLE, FO is the frequency of occurrence of GSLE, FAR is the false alarm rate, and POD is the probability of detection.

Condition	$N_{soundings}$	N_{GSLE}	FO (%)	FAR (%)	POD (%)
$\Delta T \geq 16°C$	1432	275	19	81	91
$\Delta T \geq 22°C$	365	120	33	67	47
$\Delta T \geq 25°C$	38	19	50	50	12
$\Delta T \geq 16°C$ and shear $< 60°$	936	194	21	79	72
$\Delta T \geq 16°C$, shear $< 60°$, and no stable layers	619	145	23	77	55
$\Delta T_{excess} \geq 0$	1134	264	23	77	96
$\Delta T_{excess} \geq 2$	673	203	30	70	79
$\Delta T_{excess} \geq 0$ and $RH_{850-700} > 55\%$	884	236	27	73	94
$\Delta T_{excess} \geq 2$ and $RH_{850-700} > 55\%$	529	189	36	64	79

Great Salt Lake Effect

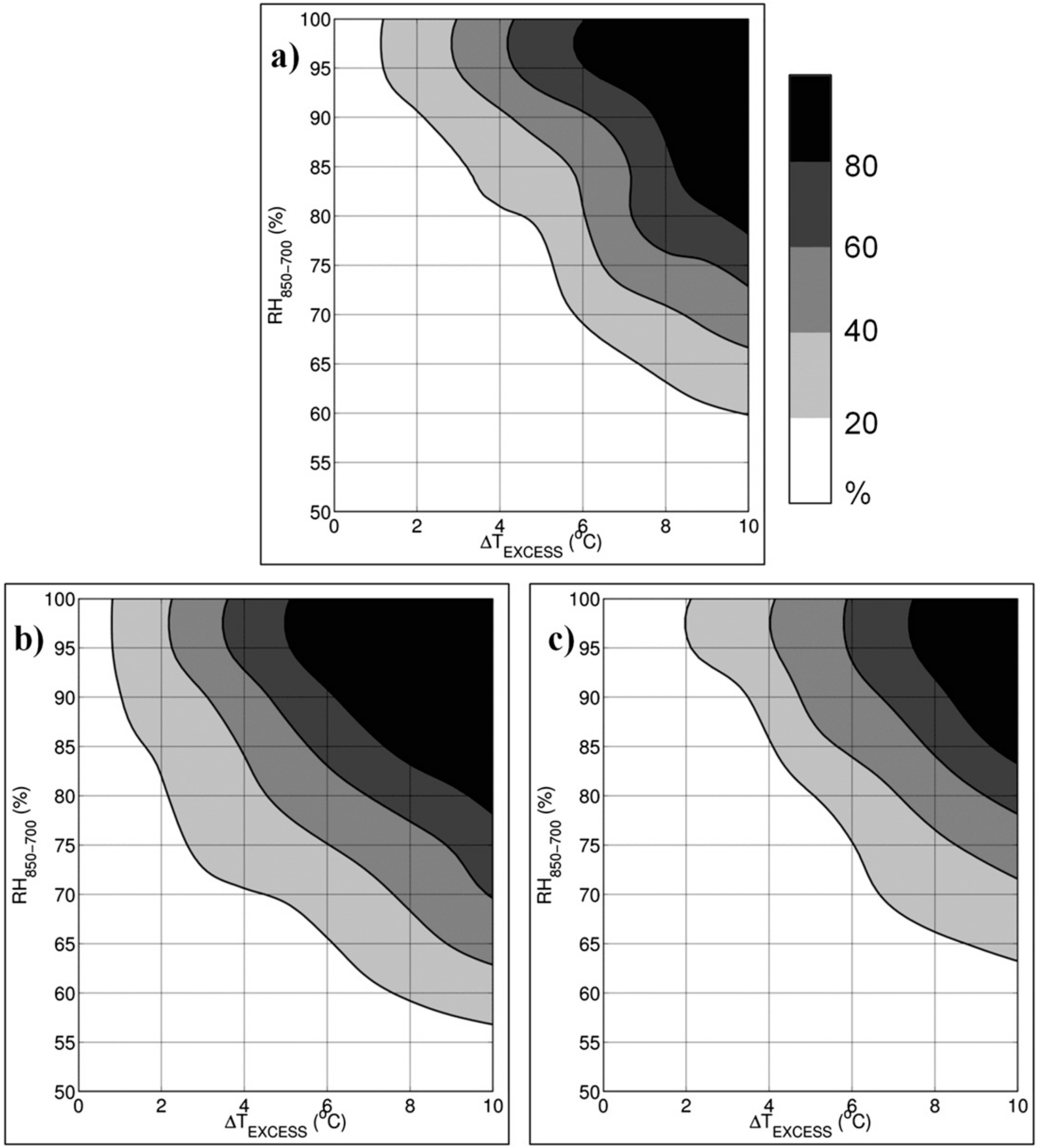
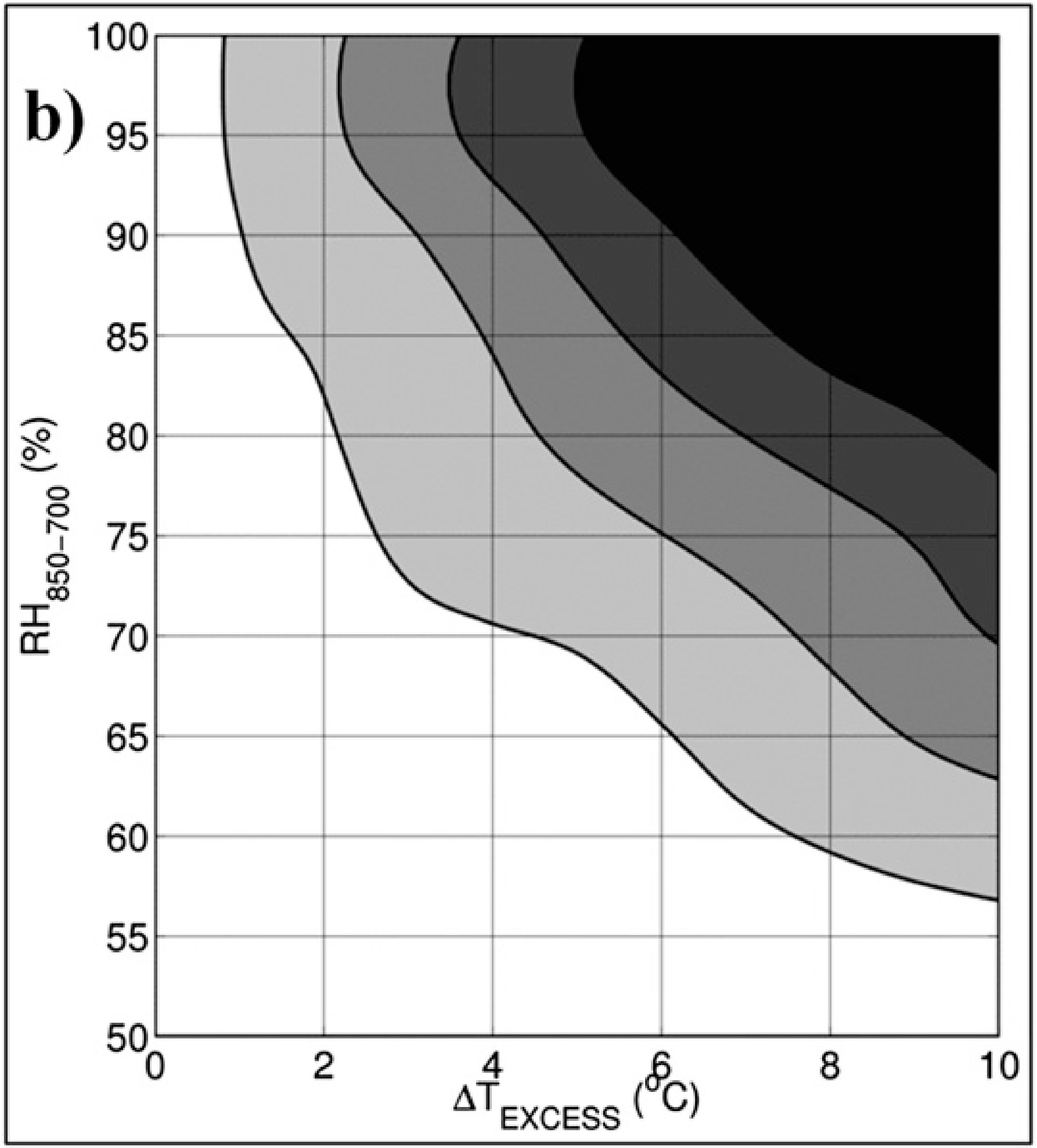


FIG. 15. (a) Fraction of soundings with GSLE (%, shaded according to scale at right) as a function of ΔT_{excess} (°C) and $RH_{850\text{–}700}$ (%). (b) As in (a), but for 700-hPa wind directions 290°–360°. (c) As in (a), but for 700-hPa wind directions 1°–289°.

Great Salt Lake Effect



Great Salt Lake Effect

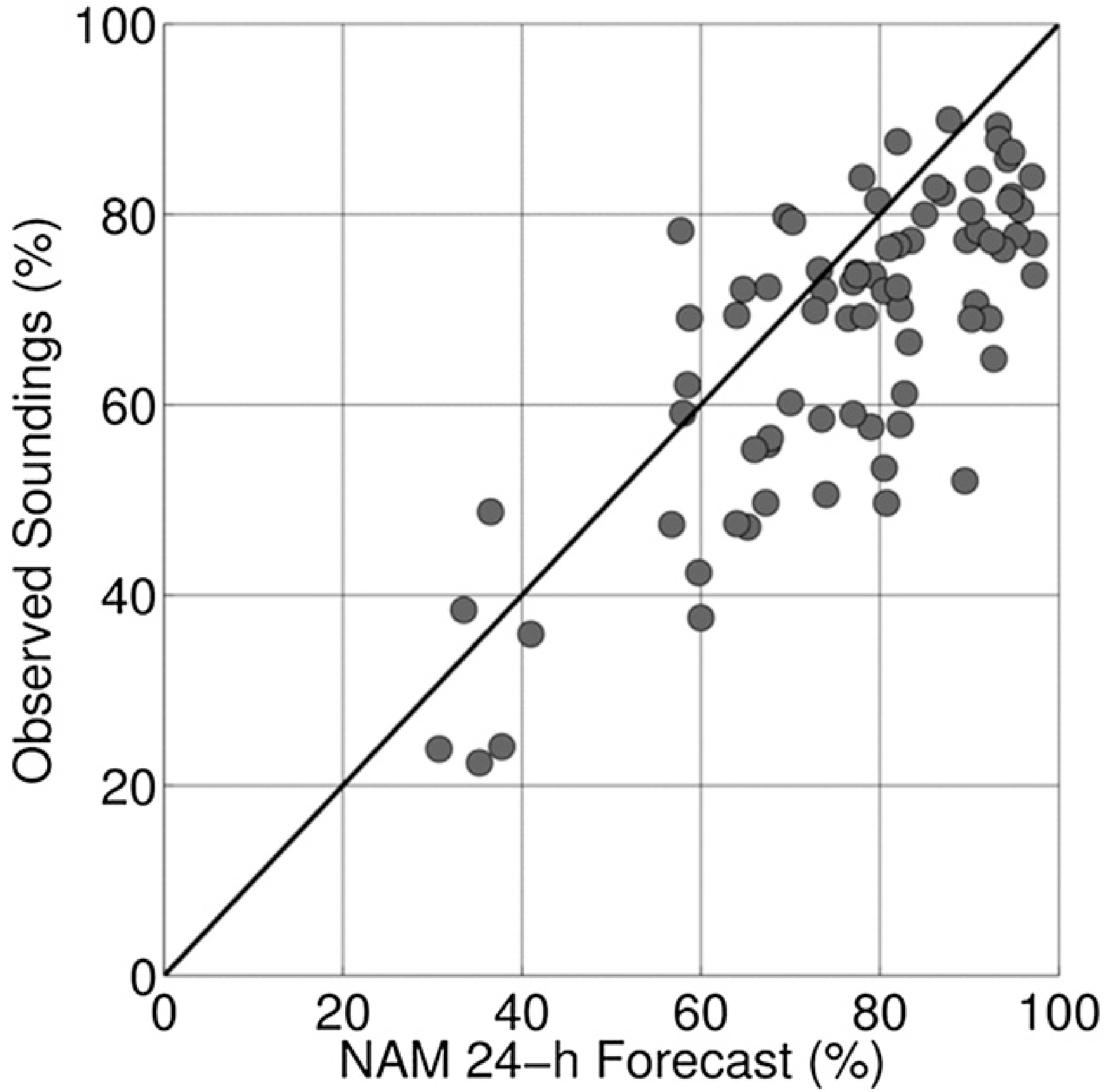
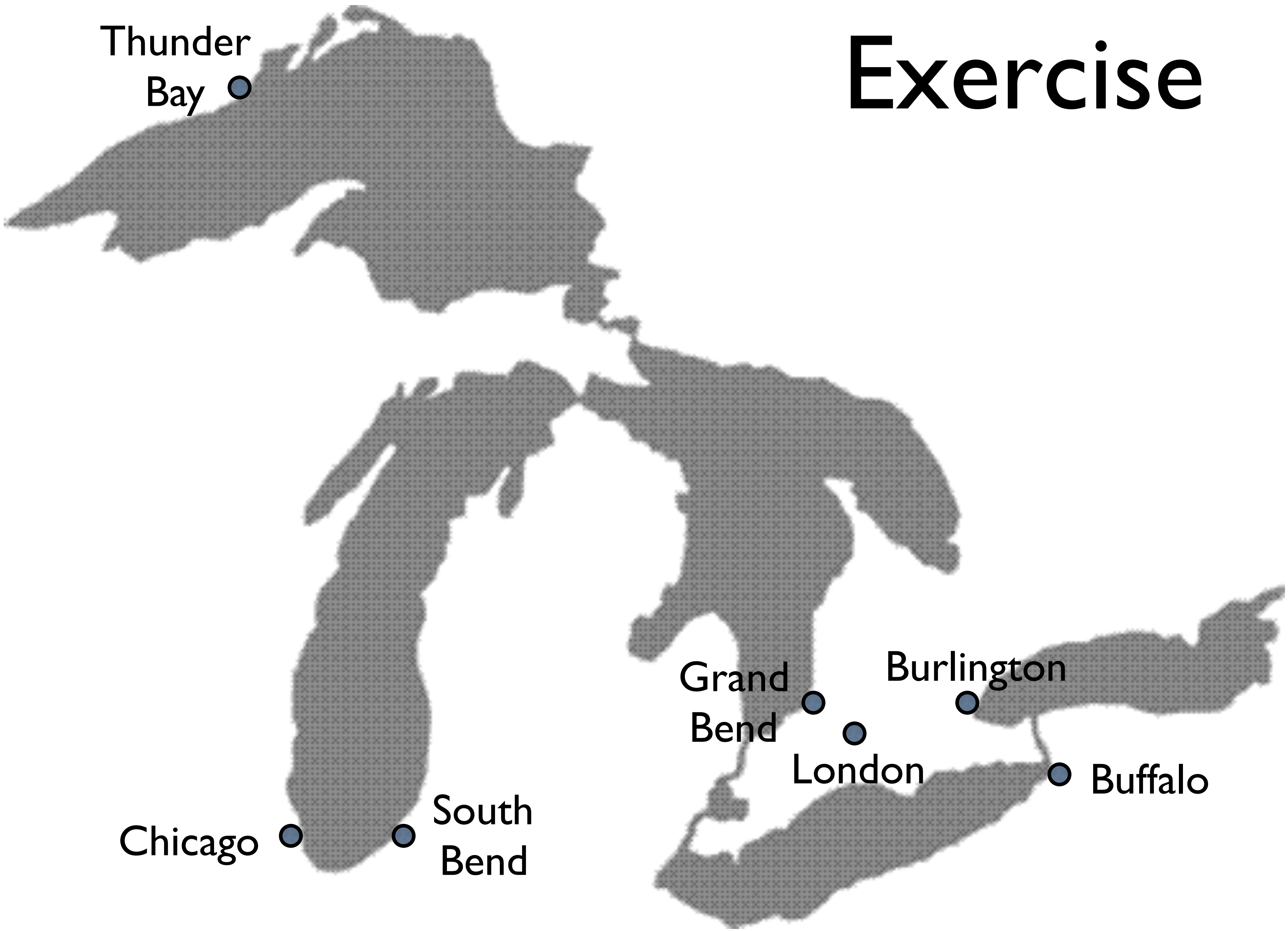


FIG. 16. Observed 850–700-hPa RH (%) from KSLC soundings vs 24-h NAM forecasts, from the 2008/09 and 2009/10 cool seasons. Diagonal line indicates a perfect forecast.

Exercise



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