The Great Lakes Pneumonia Front: A New Study of Land-Sea Interactions

Jordan J. Gerth

Graduate Research Assistant

Coop. Inst. for Meteorological Satellite Studies

Department of Atmospheric and Oceanic Sciences

University of Wisconsin – Madison

Madison, Wisconsin

Previous Studies

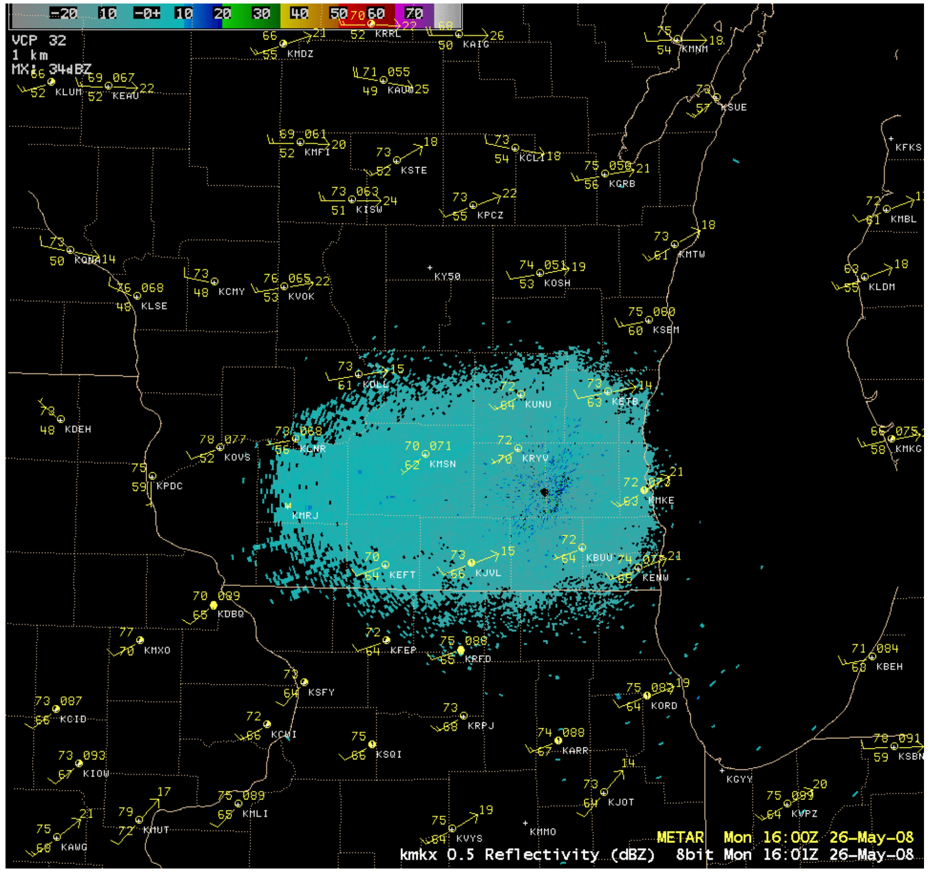
- Scott and Huff (1996) found net cooling as large as two degrees Celsius for locations within 80 kilometers of Lake Michigan due to marine influences.
- Laird et al. (2001) studied lake breezes influencing Milwaukee, Wisconsin, between 1982 and 1996, concluding that the mean number of lake breeze days rose from six to seven per month during May and June, to nine in July, twelve in August, and seven to eight in September.
- Arritt (1993) found compelling evidence that strong westerly flow during the spring and fall months displaces lake breezes which influence the western shore of Lake Michigan during the summer months when synoptic flow is weaker.

Previous Studies

- Laird et al. (2001) determined nearly 70% of all Lake Michigan lake breeze events reviewed occurred when the maximum air-lake temperature contrast was less than or equal to 12 degrees Celsius, and only about 15% of lake breeze days had temperature contrasts in excess of 20 degrees Celsius.
- Arritt (1987) found that there is strong stable stratification between water significantly colder than the ambient air temperature above, suppressing turbulent heat fluxes.
- A climatology produced by Laird et al. (2001) suggests that the days most favorable for lake breezes on the western side of Lake Michigan have synoptic westerly winds no stronger than 4.5 mph, requiring eastern United States high pressure.

Pneumonia Fronts

- There is a unique manifestation of the lake breeze from the southern shore of Lake Superior that occasionally impacts the western shore of Lake Michigan in the presence of a typically weak synoptic cold front. The resulting boundary produces a sharp wind shift to the northeast, an increase in surface wind speed, and a rapid decrease in surface temperature.
- Behnke (2005), the only known previous authority on pneumonia fronts, requires such features to produce hourly temperature falls between May and August of at least 16 degrees Fahrenheit at a lakeshore observing station with a drop of no more than 10 degrees at a station well inland.



26 May 2008 Memorial Day Pneumonia Front

Base radar reflectivity from the Milwaukee/Sullivan WSR-88D shows a sharp boundary developing and transgressing southern Wisconsin. Hourly METAR surface observations are plotted in yellow.

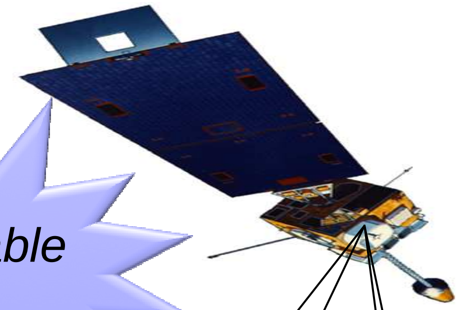
Animation credit: Scott Bachmeier

Motivation

- Lake breezes, specifically those developing in the Great Lakes region, have been a largely neglected area of study over the recent decade as the power and functionality of numerical weather prediction (NWP) models has significantly grown with faster, low-cost computing solutions.
- The Great Lakes have a substantial impact on life and commerce in the large industrial cities on its coasts.
- Pneumonia fronts are unique, high-impact manifestations of lake breezes which are not well understood.
- **Objective: Create a set of high-resolution initial conditions from satellite observations for use in local Weather and Research Forecast (WRF) model runs, specifically tailored for the Great Lakes.**

CIMSS Regional Assimilation System

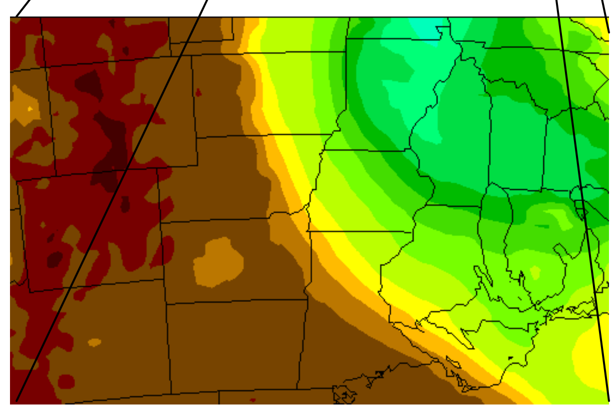
CRAS



Available for AWIPS

The Cooperative Institute for Meteorological Satellite Studies (CIMSS) uses the CIMSS Regional Assimilation System (CRAS) to assess the impact of space-based observations on numerical forecast accuracy.

CRAS is unique in that, since 1996, it's development was guided by validating forecasts using information from GOES.



Output online: http://cimss.ssec.wisc.edu/cras/

Slide credit: Robert Aune. NOAA/NESDIS

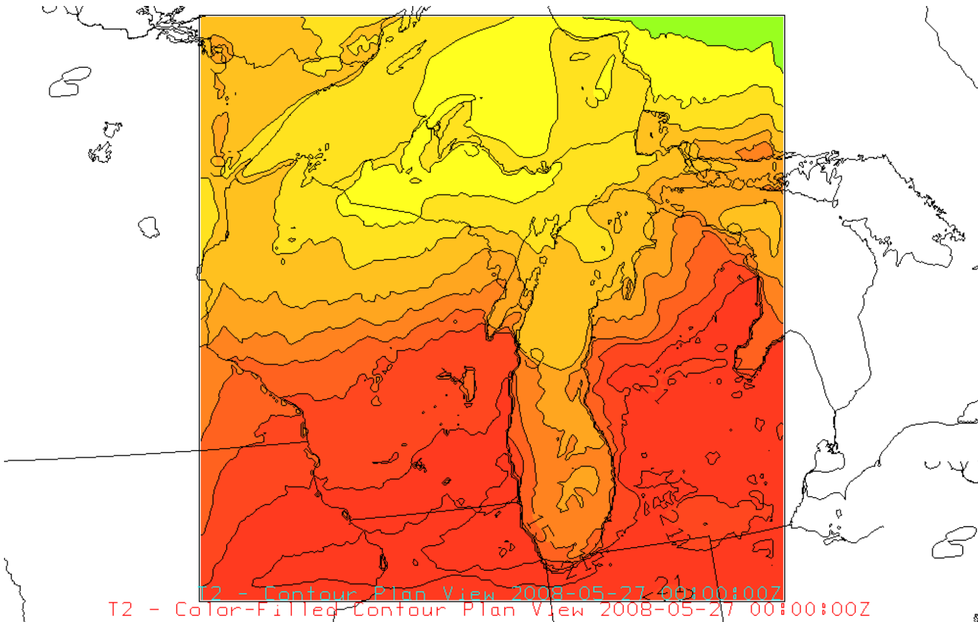
Transitioning to the WRF

- The most recent advances in numerical weather prediction have come with the advent and widespread distribution to the Weather Research and Forecast (WRF) model to both the field and academia. The WRF has two dynamical cores, one with customizable physics, and a 3-dimensional variational (3DVAR) assimilation system. The goal is flexibility.
- Concurrently, increases in personal computer capabilities and innovations in parallel processing have led to a realistic ability to run regional simulations on increasingly high-resolution mesoscale spatial and temporal grids with relative ease.
- An effort is underway to create initial conditions for the WRF using data from the GOES Sounder in a satellite-focused real-time mesoscale analysis system. WRF domains could then be provided boundary conditions from the CRAS to extend the analysis of satellite data in numerical weather predictions.

WRF Model of Pneumonia Front

- The WRF was employed in an attempt to accurately model the 26 May 2008 case.
- The model was run using the Advanced Research WRF (ARW) version 2.2.0 core to 24 hours from initialization on an 800 km by 800 km localized domain centered on Oconto, Wisconsin, with grid spacing of four kilometers.
- A similar WRF model was established in LaCasse et al. (2008) to study the impact of MODIS SST data on the nocturnal Floridian marine boundary layer.
- The model initialized with data from the 40-kilometer North American Mesoscale (NAM) model.
- The model used the Lin microphysics scheme, Dudhia shortware radiation scheme, Rapid Radiative Transfer Model (RRTM) longwave radiation scheme, Monin-Obukhov surface-layer scheme, Noah land-surface model, and the Yonsei University boundary-layer scheme. Cumulus and grid- scale convection was parameterized with the Kain-Fritsch scheme under vertical velocity damping and mixing terms evaluated in physical space. There were no vertical or horizontal diffusion constants.

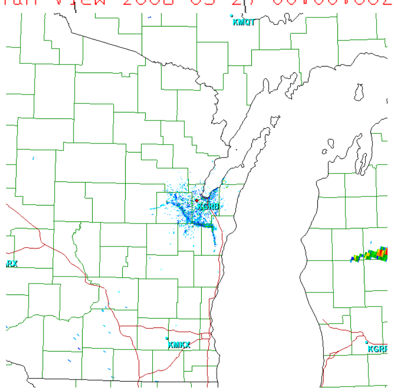
WRF Model of Pneumonia Front

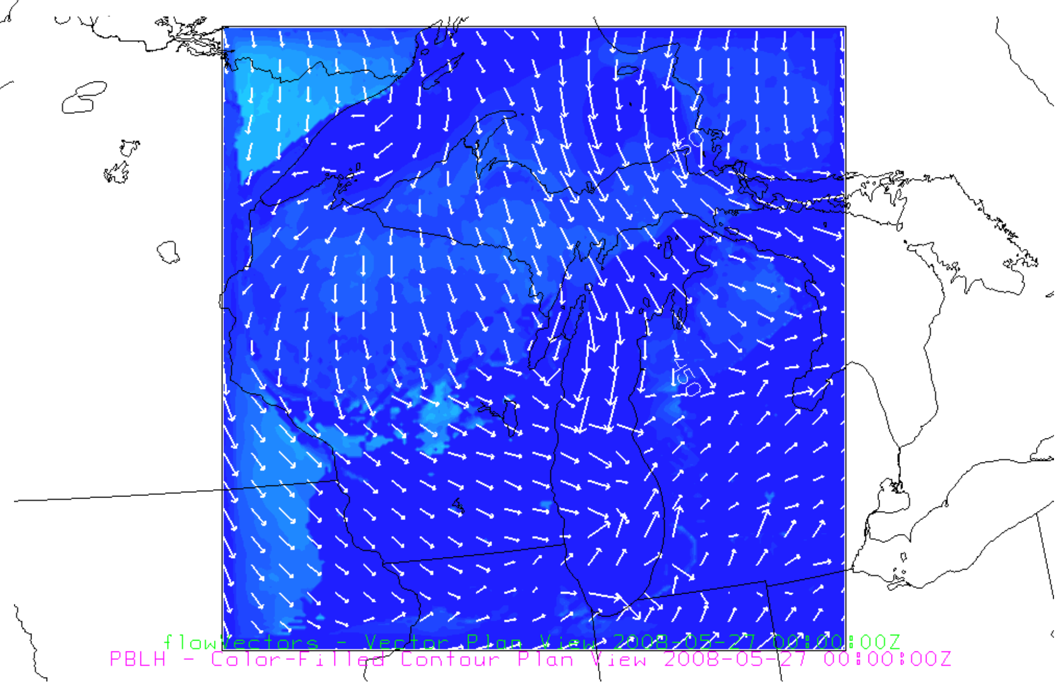


During the afternoon and evening hours of 26 May 2008, a strong convergence boundary descended south out of Lake Superior and accelerated down the western coast of Lake Michigan. There was no precipitation associated with this boundary, but the temperature and wind shift was significant, with coastal temperature declines of 20 degrees Fahrenheit and larger within an hour period. Reporting stations well inland did not experience significant temperature falls, though winds statewide become increasingly northeasterly during the late afternoon and evening.

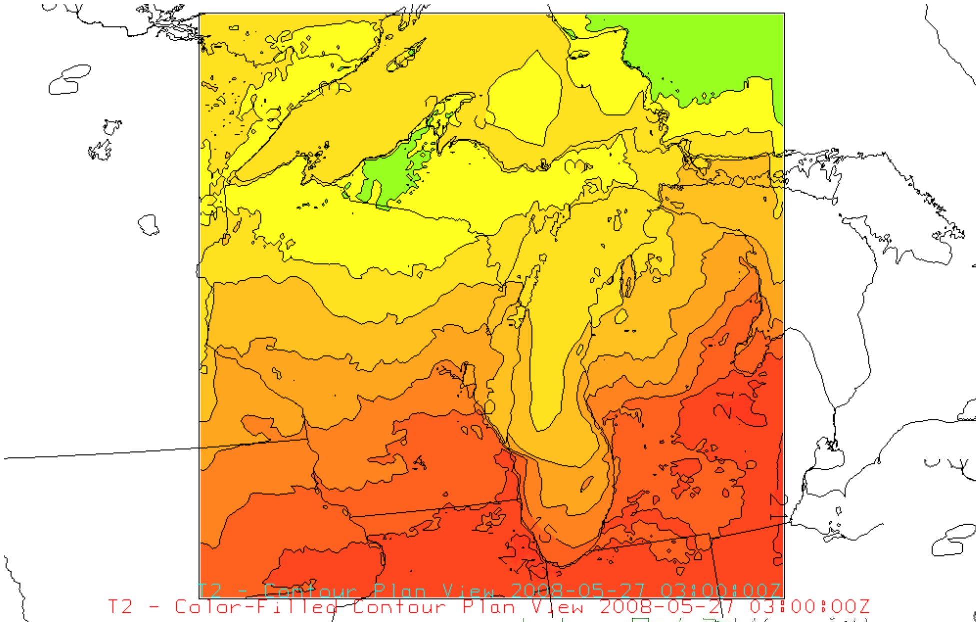
0000 UTC

27 May 2008





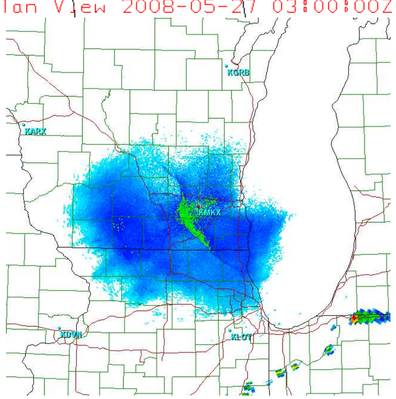
WRF Model of Pneumonia Front

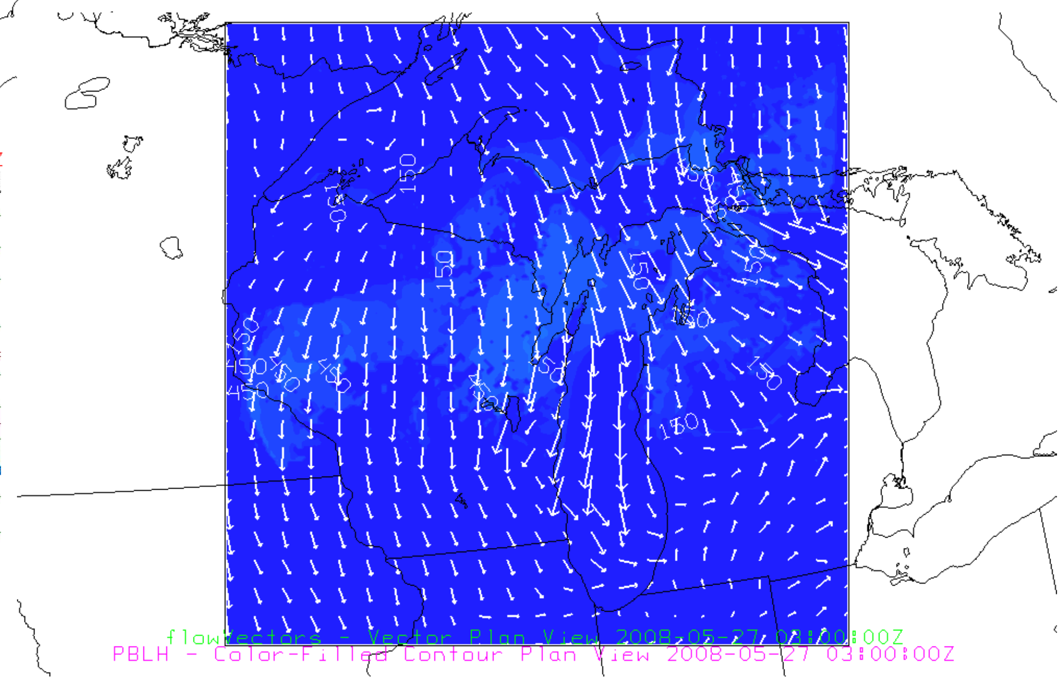


The National Weather Service in Milwaukee, Wisconsin, described this boundary as a pneumonia front. The boundary was first recognized on base reflectivity data from the Marquette, Michigan, (KMQT) Weather Surveillance Radar (WSR) as a hybrid of convective outflow and a lake breeze.

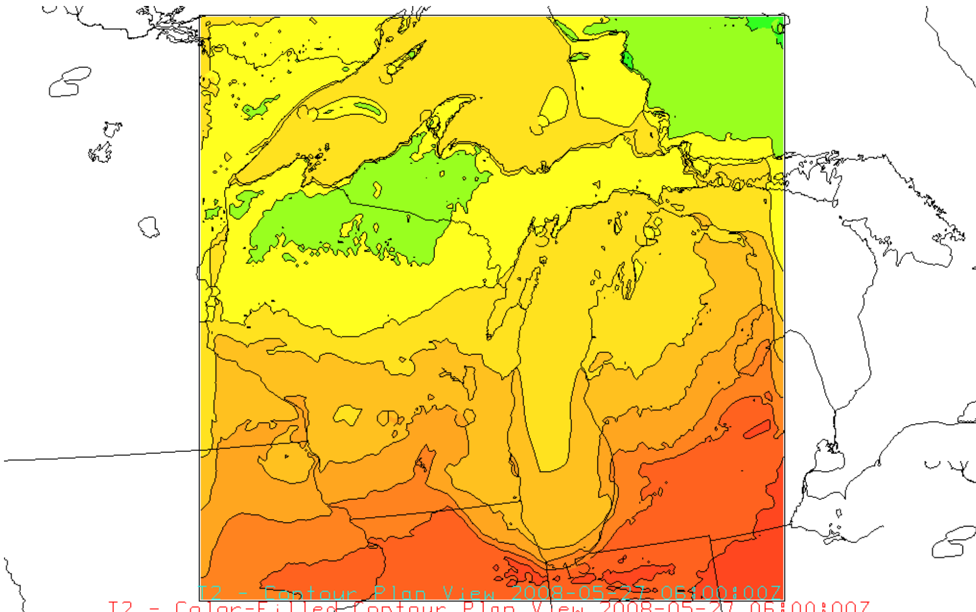
0300 UTC

27 May 2008





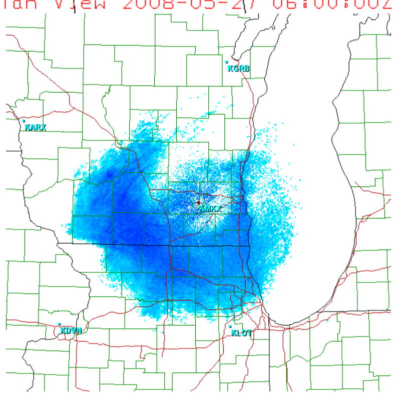
WRF Model of Pneumonia Front

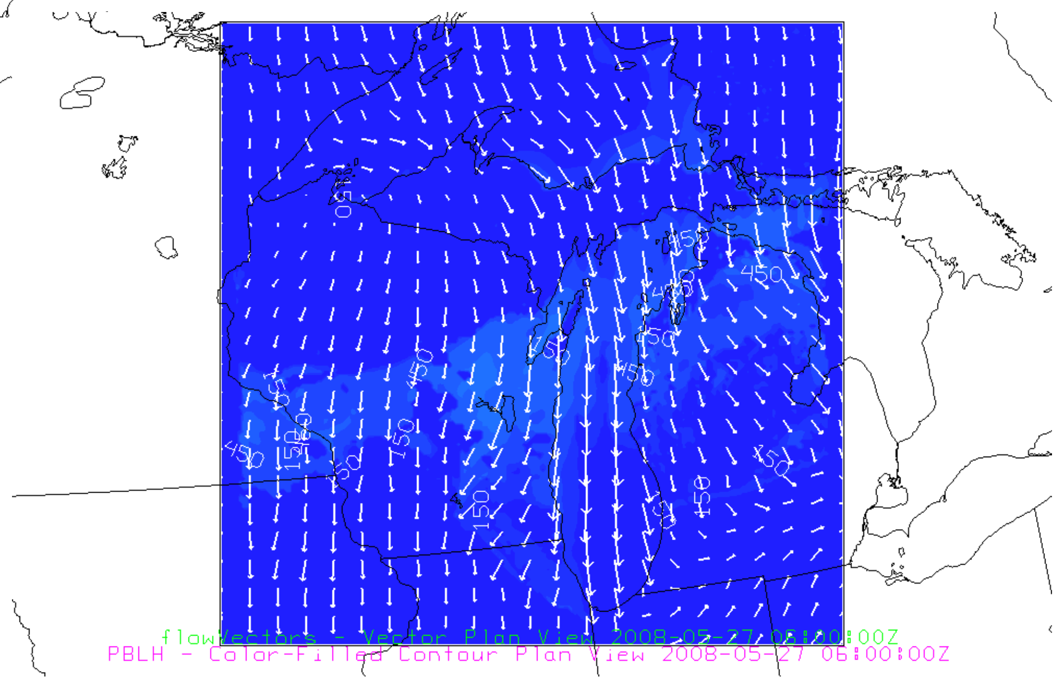


Milwaukee, Wisconsin, had partly cloudy skies during most of the day with temperatures similar to Green Bay in the upper 70s and lower 80s. Winds prevailed out of the southwest. At 1852 LST (0052 UTC), the temperature at KMKE was 78 degrees. At 1926 LST (0126 UTC), clouds had increased and the temperature had decreased to 55 degrees per NCDC reports. The Milwaukee observer reported a squall as winds changed from Southwest at 8 mph prior to the temperature drop to North at 29 mph gusting to 43 mph after. Winds remained strong with gusts in excess of 30 mph for the balance of the evening.

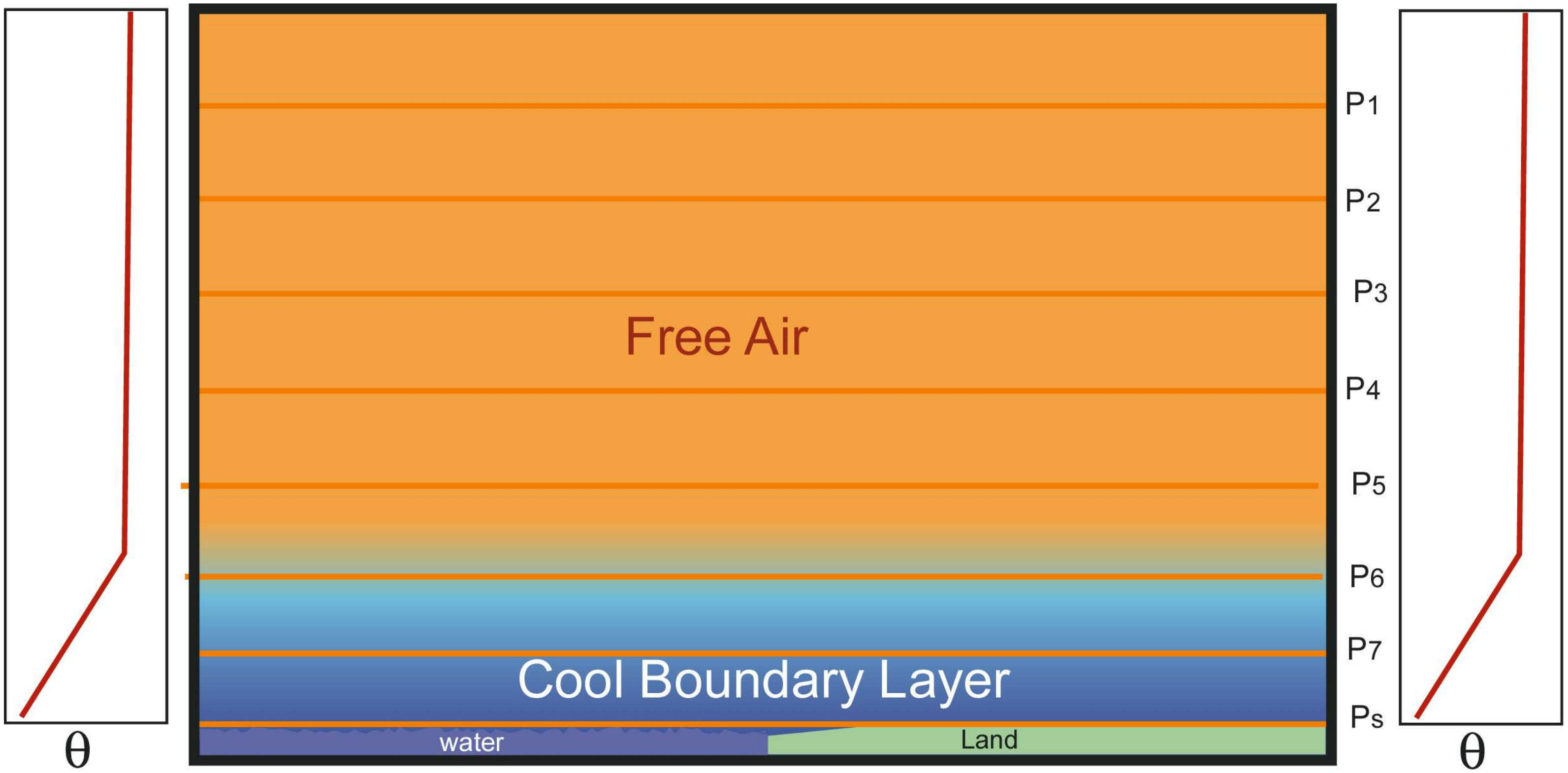
0600 UTC

27 May 2008





Sea Breeze Science

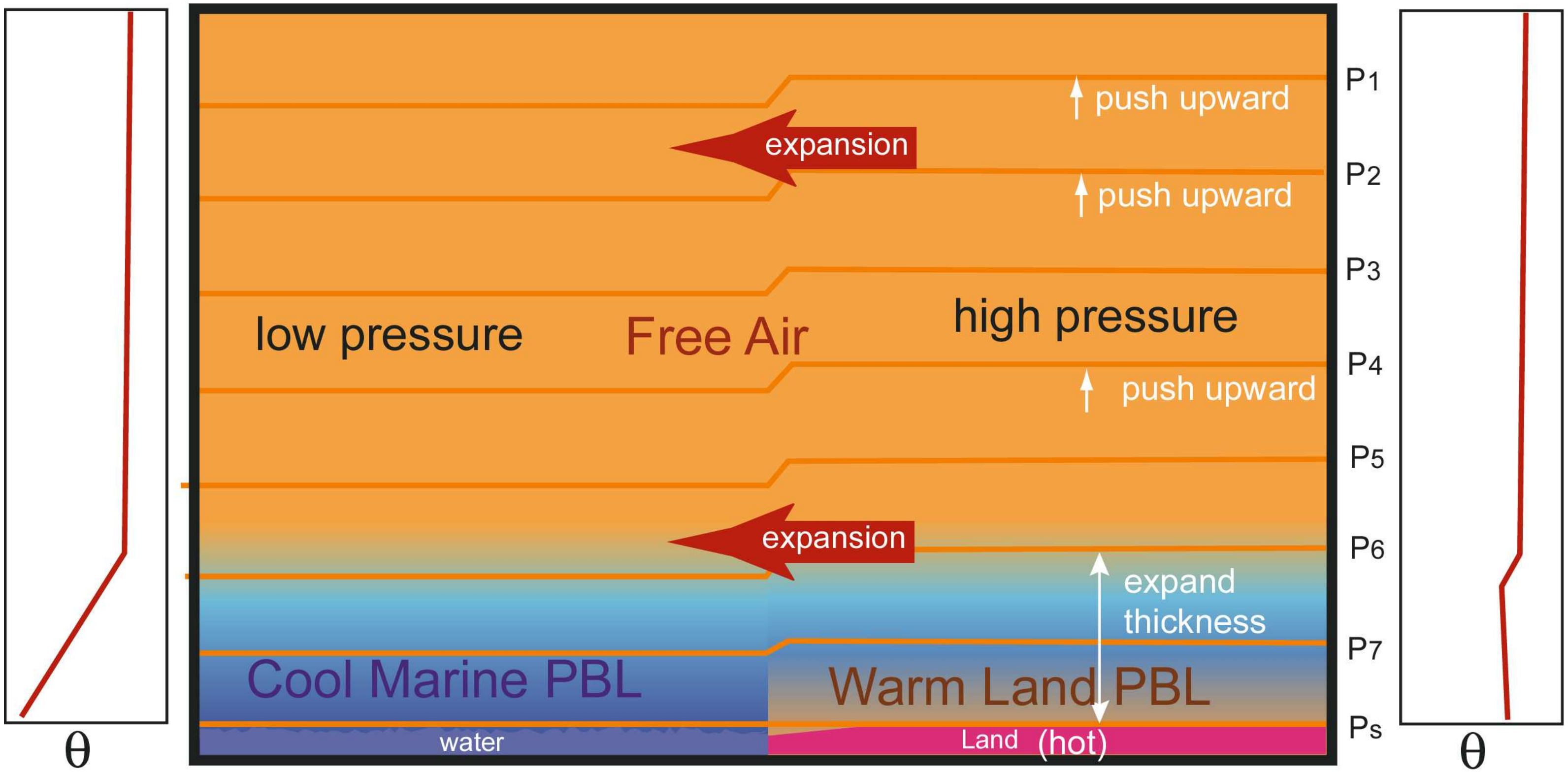


$$\theta = T\left(\frac{P_0}{P}\right)^{\frac{R}{c_p}}$$

where T is the absolute temperature (in K) of the parcel,
R is the gas constant of air,
c_p is the specific heat capacity at a constant pressure

Source: Greg Tripoli, http://www.aos.wisc.edu/~aos453/lectures09.html

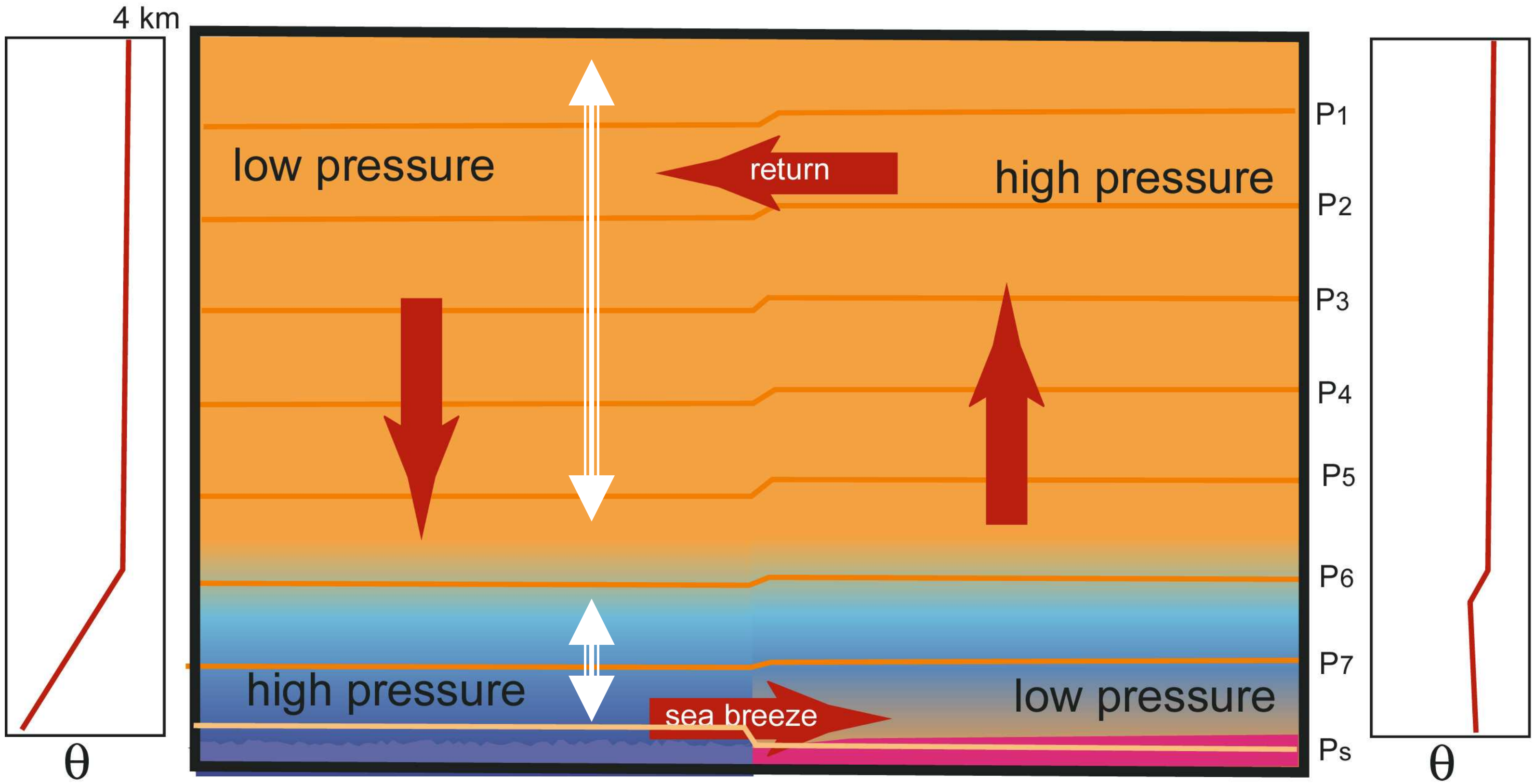
Sea Breeze Science



$\frac{\partial \theta}{\partial z} > 0$ **Static Stability** $h = z_2 - z_1 = \frac{R \cdot T}{g} \cdot \ln\left[\frac{P_1}{P_2}\right]$ **Unstable to Convection** $\frac{\partial \theta}{\partial z} < 0$

Source: Greg Tripoli, http://www.aos.wisc.edu/~aos453/lectures09.html

Sea Breeze Science



In terms of wind, the response is stronger near the surface because of maximized horizontal skin temperature gradient and minimized volume.

Source: Greg Tripoli, http://www.aos.wisc.edu/~aos453/lectures09.html

Sea Breeze Science

- In order to establish equilibrium following the differential surface heating, the atmosphere's behavior, especially near the surface, is largely summarized using the hydrostatic response.

$$F_{total} = F_{top} + F_{bottom} + F_{weight} = P_{top} \cdot A - P_{bottom} \cdot A + \rho \cdot g \cdot A \cdot h$$

- There is no net force on a parcel of air that is not moving. Thus, the size of the parcel is arbitrary; only the density is important:

$$\frac{\partial p}{\partial z} + \rho g = 0.$$

What satellite resources can help improve assessment of differential surface heating?

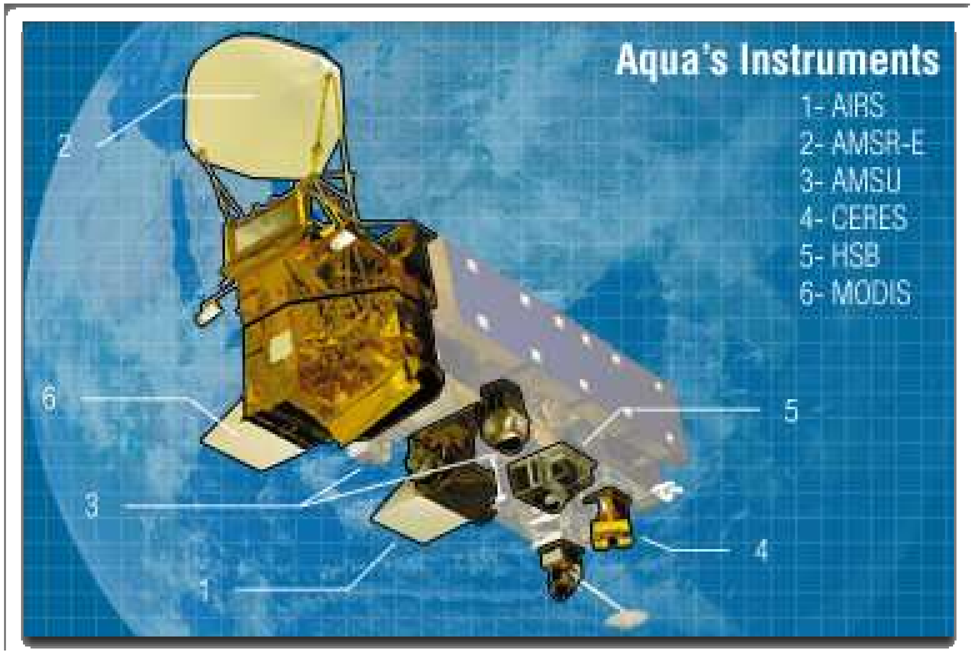
MODIS

MODerate resolution Imaging Spectroradiometer

On the Terra and Aqua satellites

36 spectral bands in both the visible and infrared

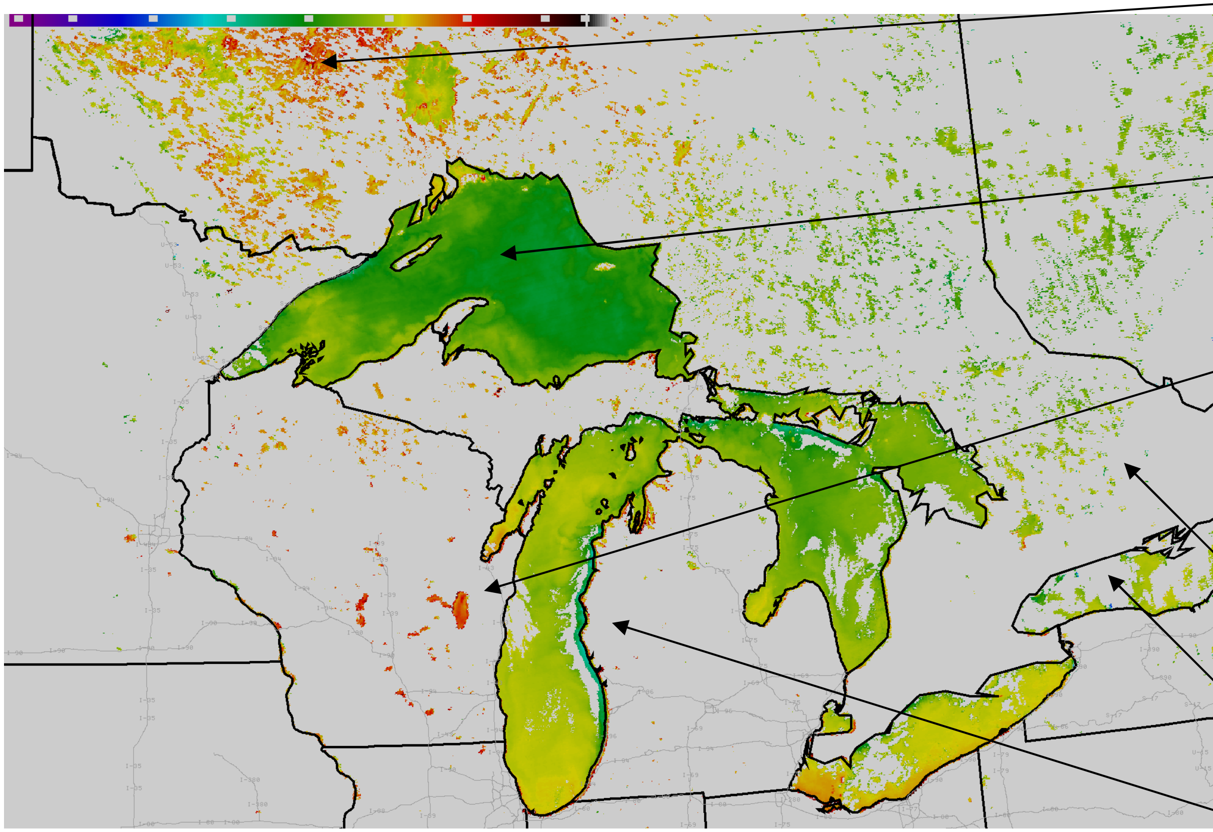
250 / 500 / 1000 m spatial resolution



MODIS Derived Products

- Combinations of MODIS bands can be used to derive land and sea skin surface temperatures.
- In scenes with no clouds, these derived surface skin temperatures can be included in NWP analyses as static surface data sets as part of the initial conditions.
  - How do we account for changes in surface skin temperature as part of the diurnal cycle?
- There are many sea surface temperature data sets available, but low resolution and quality control typically removes real gradients.
  - For example, GOES cannot resolve near-shore upwelling well due to diffraction resulting from the satellite-to-earth distance.
- NWP model nests also need atmospheric initial conditions and boundary conditions.

MODIS Sea Surface Temperature



Ground contamination

Large, deep bodies of water take the longest to warm in the summer

Shallow bodies of water warm relatively quickly

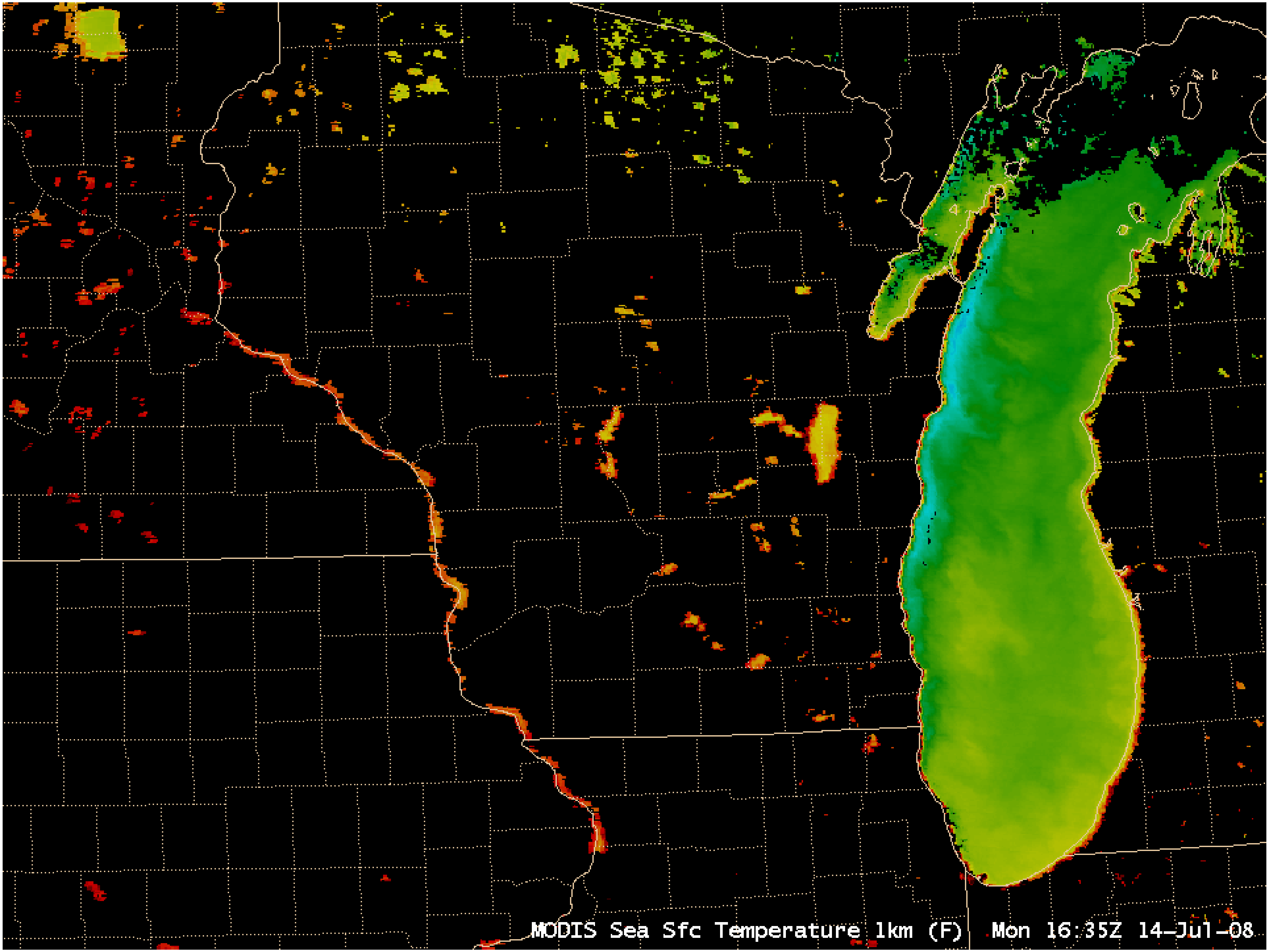
MODIS can determine sea surface temperature of water bodies at least one square kilometer in area

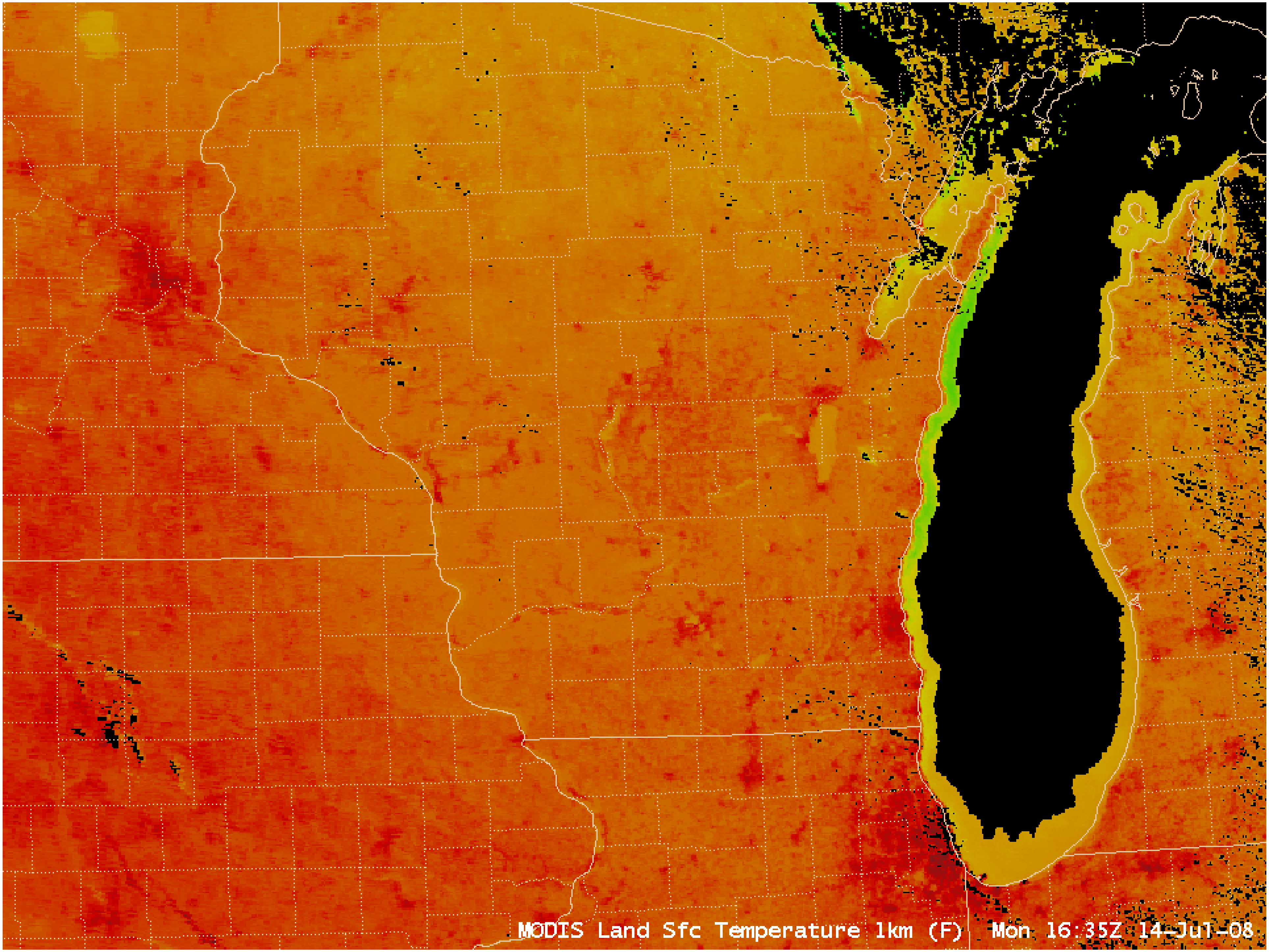
Clouds obstruct observation

MODIS Pass from 18:40Z
Monday, August 11, 2008

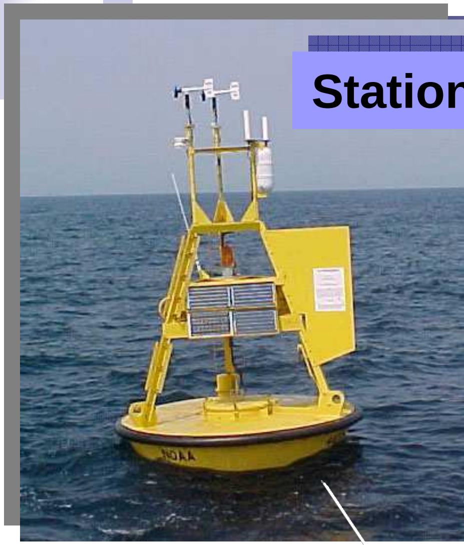
Mesoscale surface thermal features, such as upwelling, easily identifiable, usable

CIMSS


MODIS Sea Sfc Temperature 1km (F) Mon 16:35Z 14-Jul-08

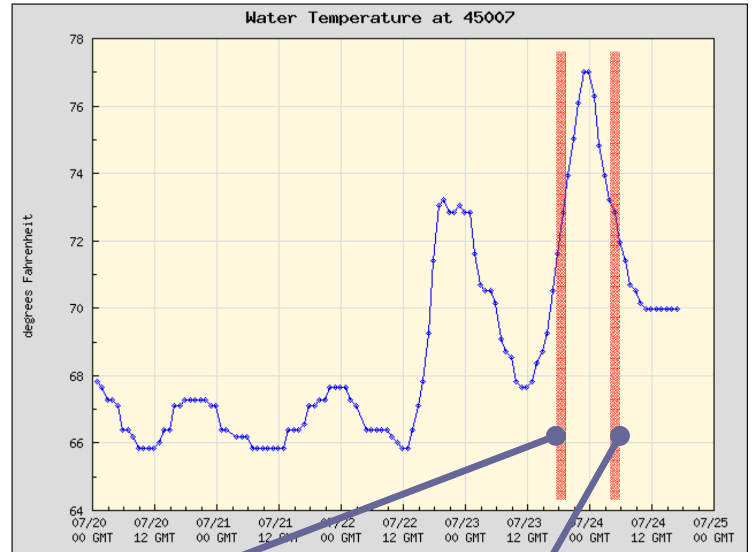

MODIS Land Sfc Temperature 1km (F) Mon 16:35Z 14-Jul-08

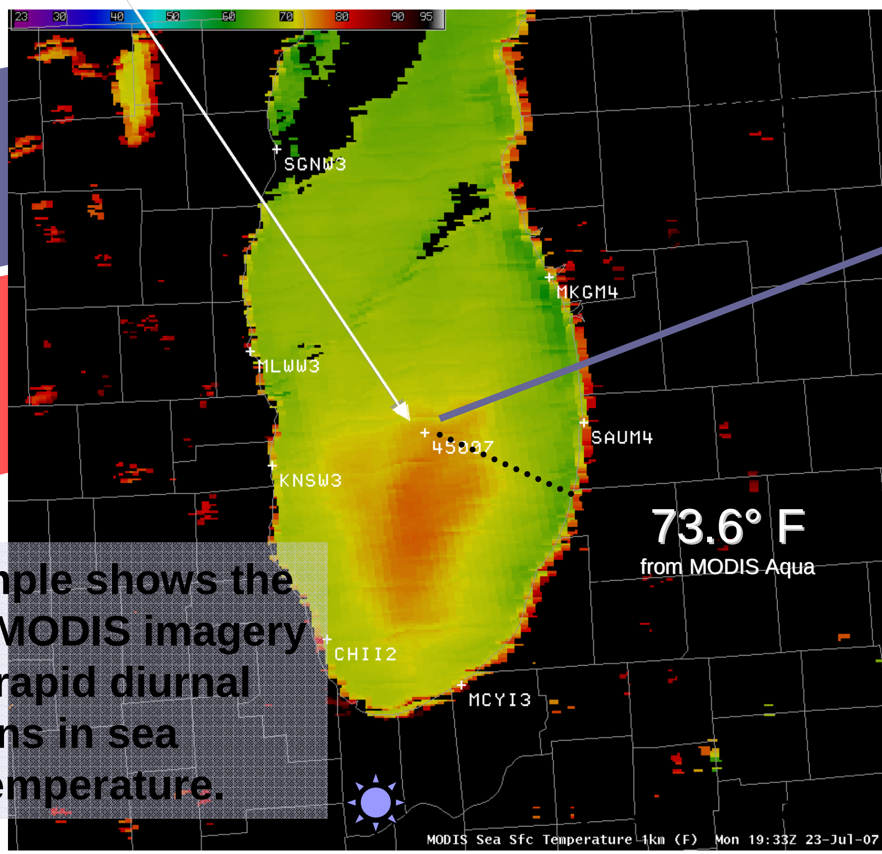
Station 45007 - S MICHIGAN 43NM East Southeast of Milwaukee, WI

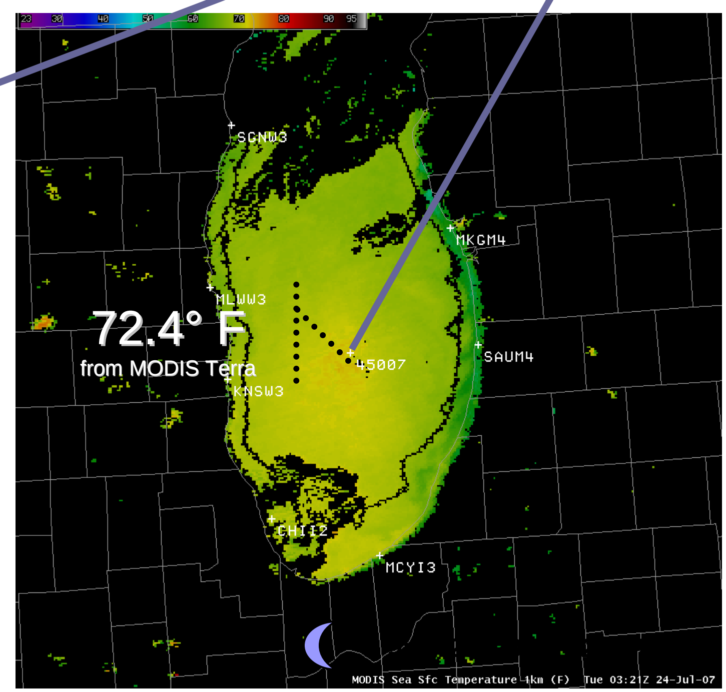


Owned and maintained by National Data Buoy Center
3-meter discus buoy
DACT payload
42.68 N 87.03 W (42°40'30" N 87°01'30" W)

Site elevation: 176.4 m above mean sea level
Air temp height: 4 m above site elevation
Anemometer height: 5 m above site elevation
Barometer elevation: 176.4 m above mean sea level
Sea temp depth: 0.6 m below site elevation
Water depth: 164.6 m
Watch circle radius: 245 yards







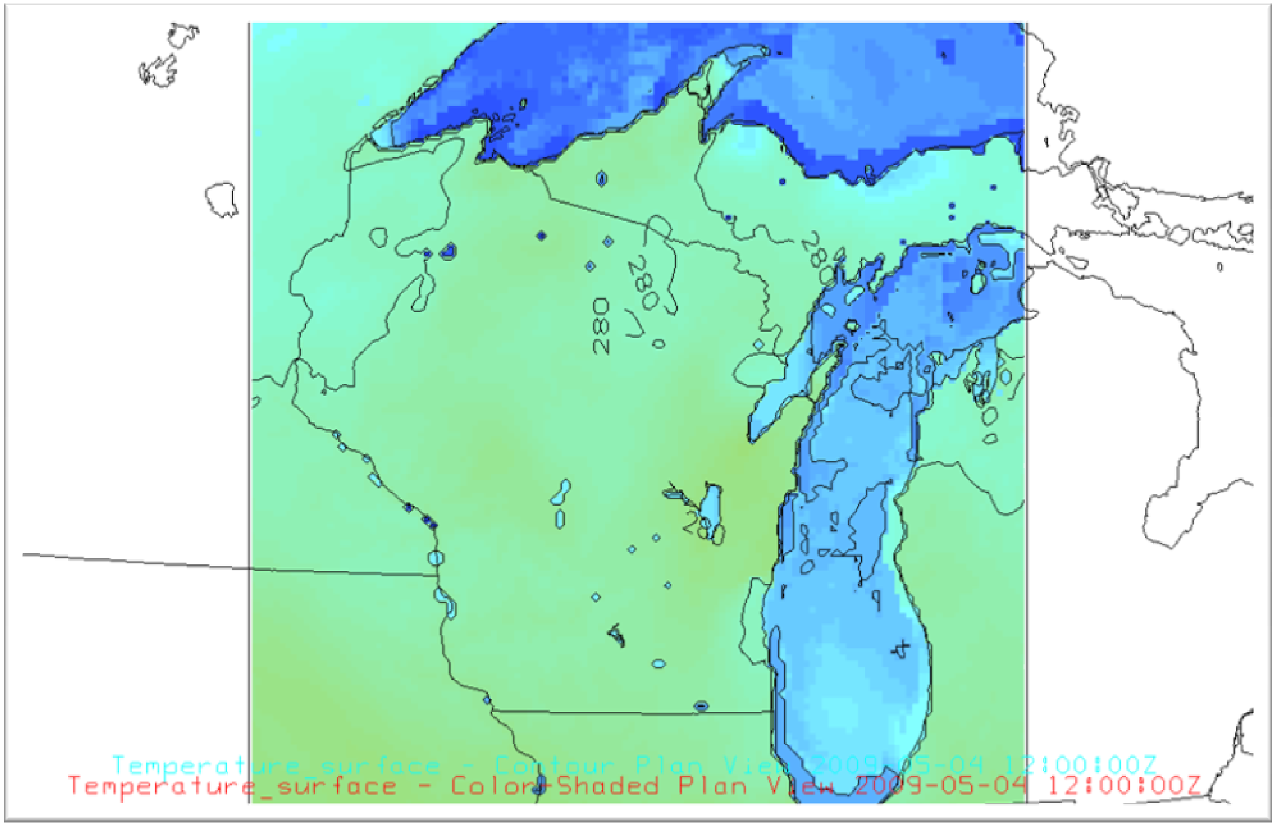
This example shows the ability of MODIS imagery to depict rapid diurnal fluctuations in sea surface temperature.

4 May 2009 Case Study

- In order to assess the value of high-resolution SSTs on NWP simulations of lake-induced mesoscale circulations, the WRF-ARW version 3 core was run twice out to 36 hours at a spatial resolution of five kilometers.
- The runs were identical aside from the initial surface skin temperature analysis: the control run, with the standard SST analysis from the RTG-SST, was compared with the experimental run, containing the improved-RTG static analysis with an additional set of cloud-filtered satellite observations from MODIS. The applied schemes were identical to those used in the case study.
- MODIS SST observations were used as truth over the RTG background; there is not a spatial variability or integrity check aside from among the MODIS SST data itself.
- Initial conditions and boundary conditions were provided from the Global Forecasting System (GFS) at approximately 40 kilometers spatial resolution.
- The 180 by 130 grid-point domain of the simulation covered all of Wisconsin, Lake Michigan, Lake Superior, and the Upper Peninsula of Michigan, as well as eastern Minnesota, northern Illinois, northeastern Iowa, and western Lower Michigan.

WRF-ARW Model Output

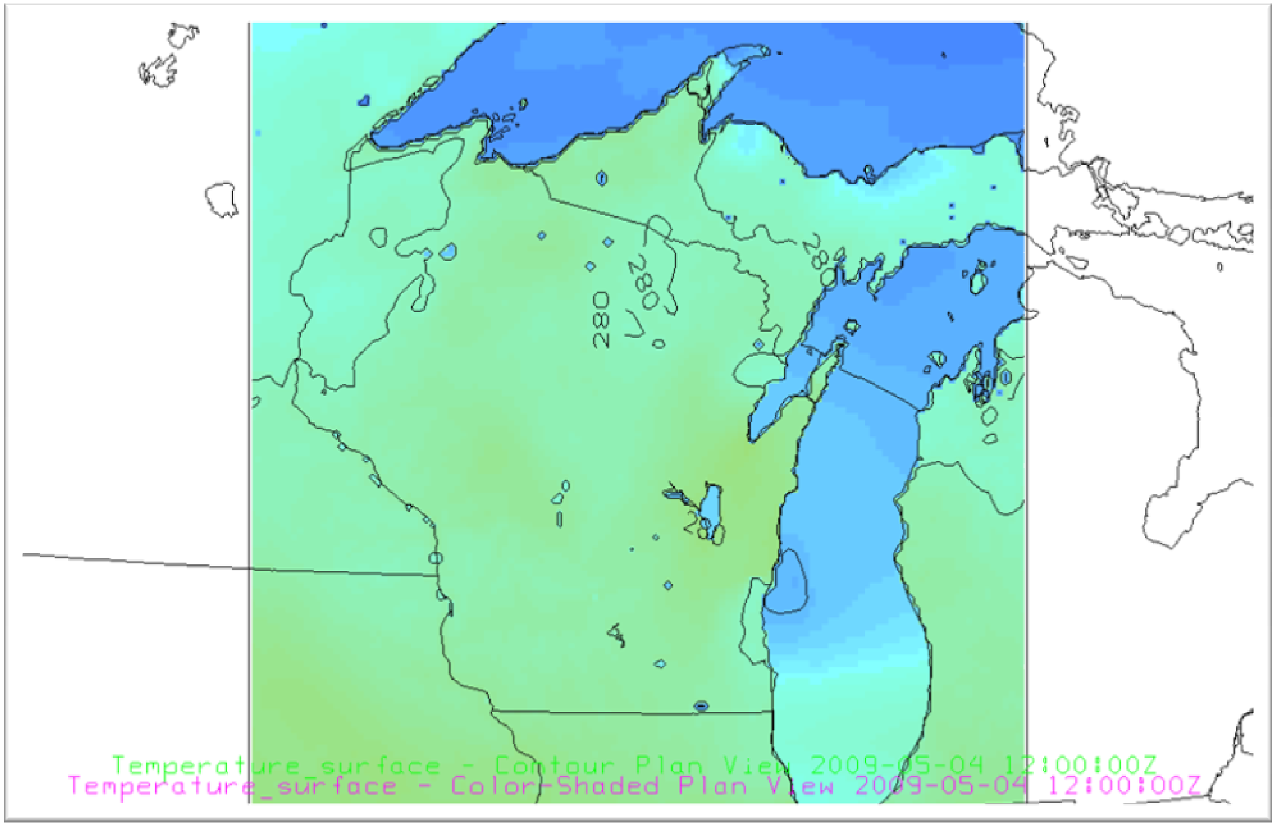
- Surface skin temperature (both land and water), 12:00 UTC on 4 May 2009 (+0)



WRF-ARW run containing the MODIS-influenced RTG sea surface temperatures

WRF-ARW Model Output

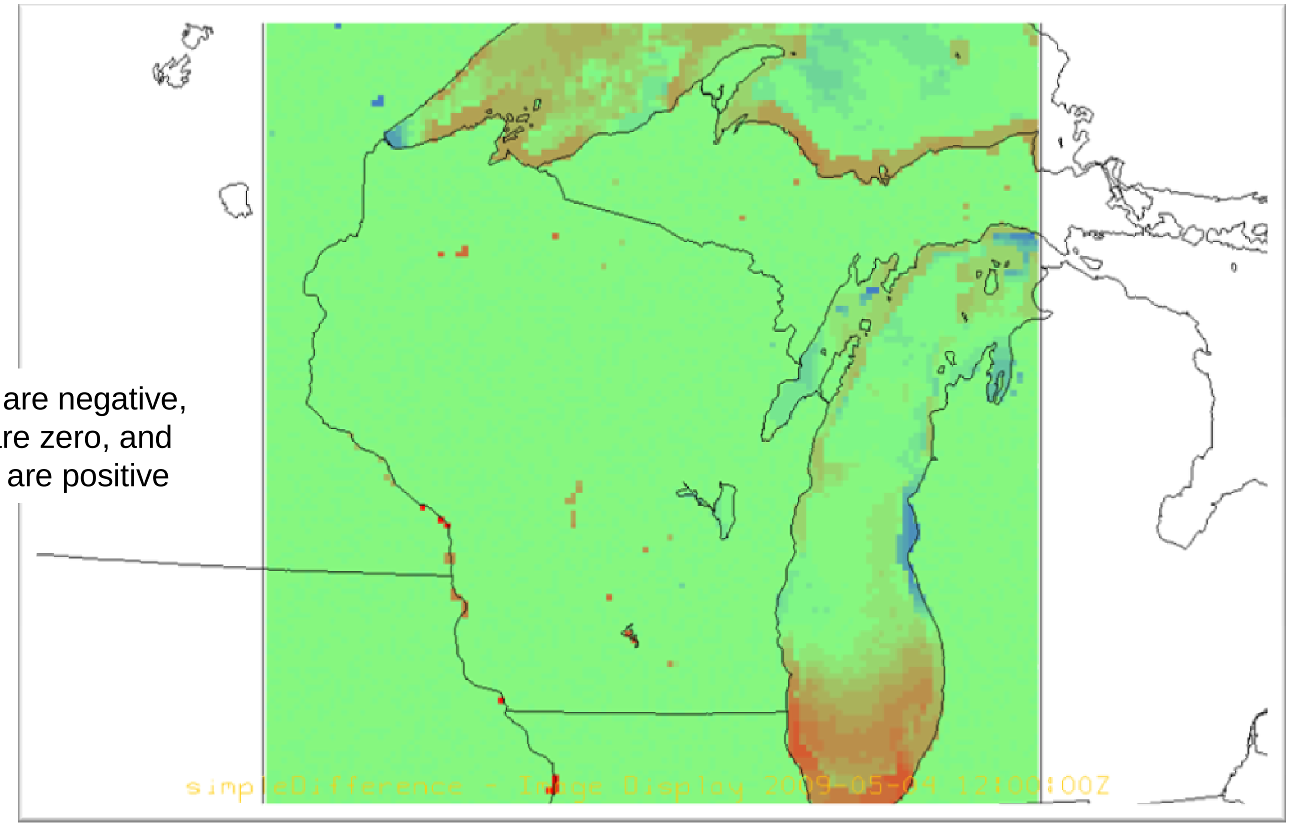
- Surface skin temperature (both land and water), 12:00 UTC on 4 May 2009 (+0)



WRF-ARW run containing solely the RTG sea surface temperature data

WRF-ARW Model Output

- Surface skin temperature (both land and water), -5 K to 5 K

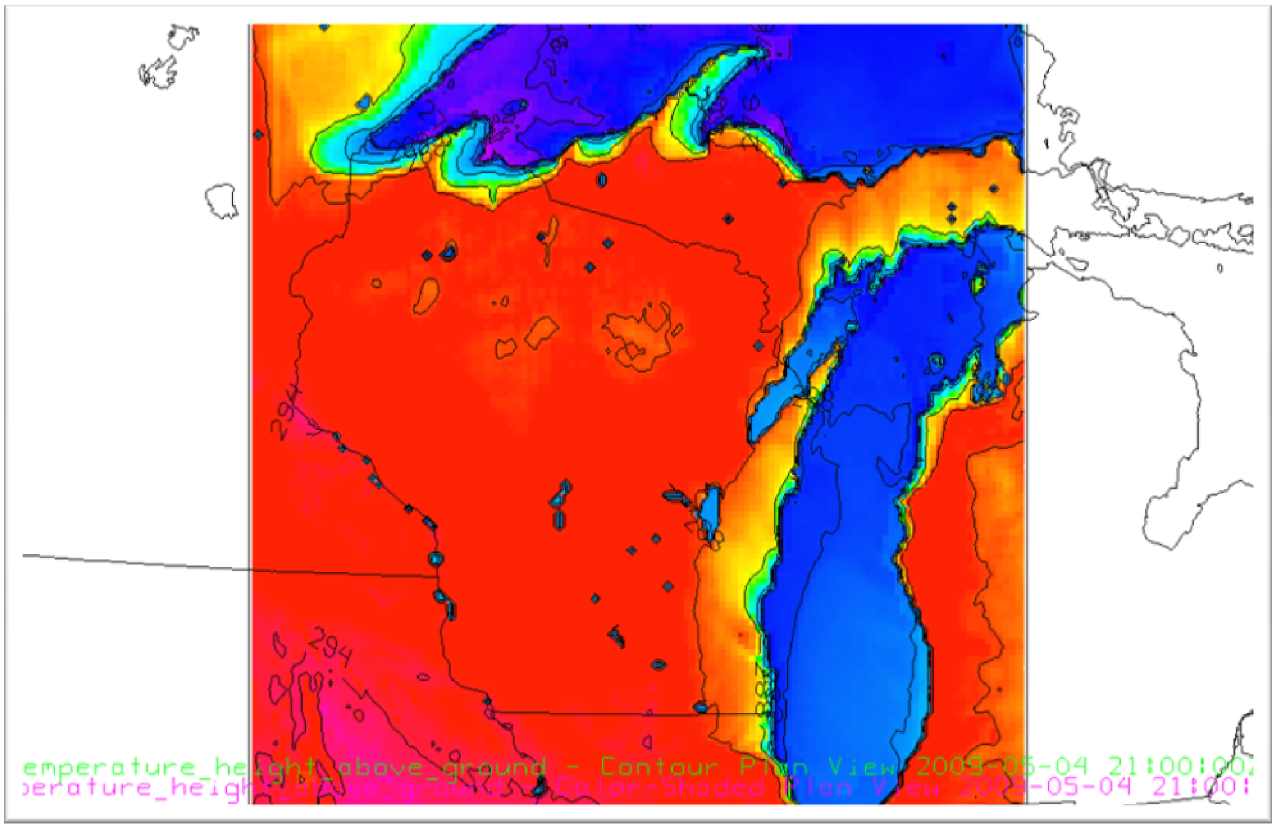


the blue shades are negative, pastel greens are zero, and the red shades are positive

A pixel-by-pixel difference subtracting the second image from the first image (the run without MODIS sea surface temperatures from the run with the sea surface temperatures)

WRF-ARW Model Output

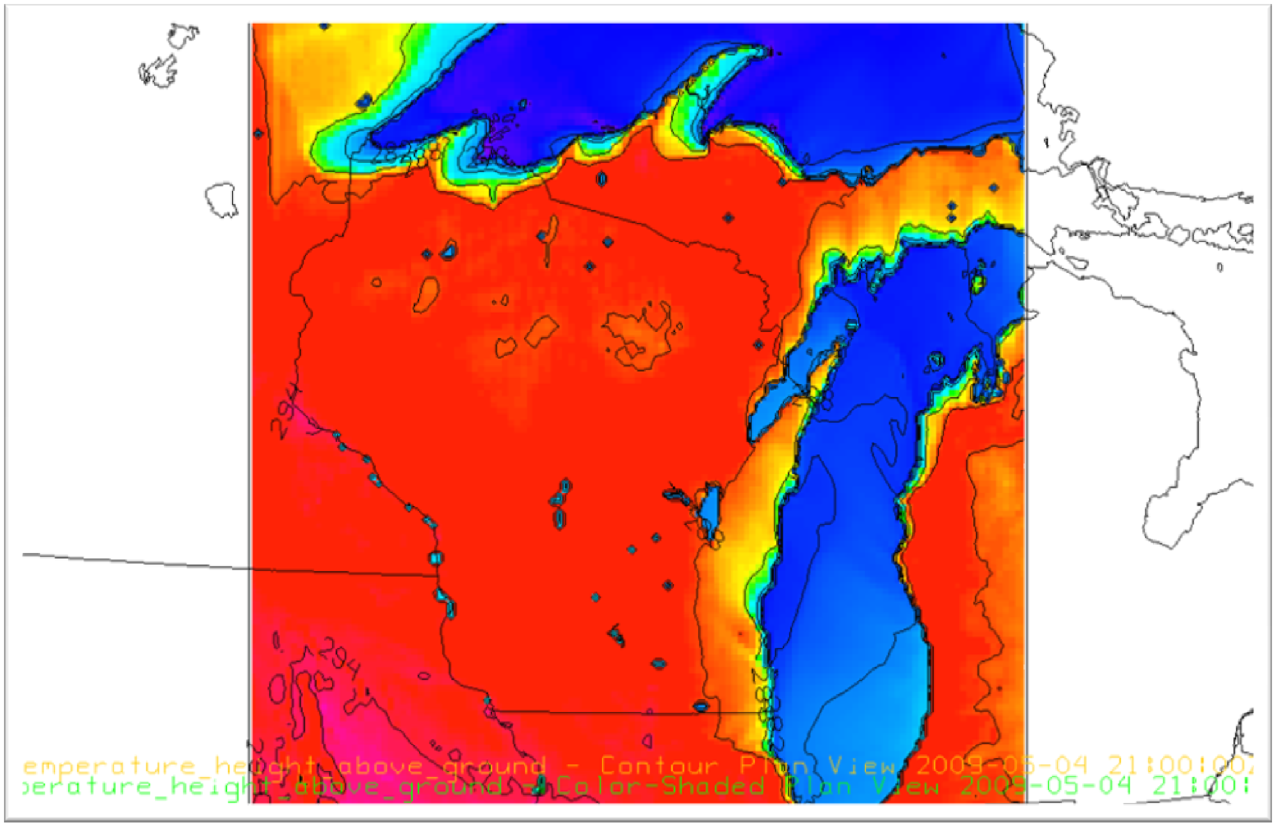
- Two-meter temperature, 21:00 UTC on 4 May 2009 (+9)



WRF-ARW run containing the MODIS-influenced RTG sea surface temperatures

WRF-ARW Model Output

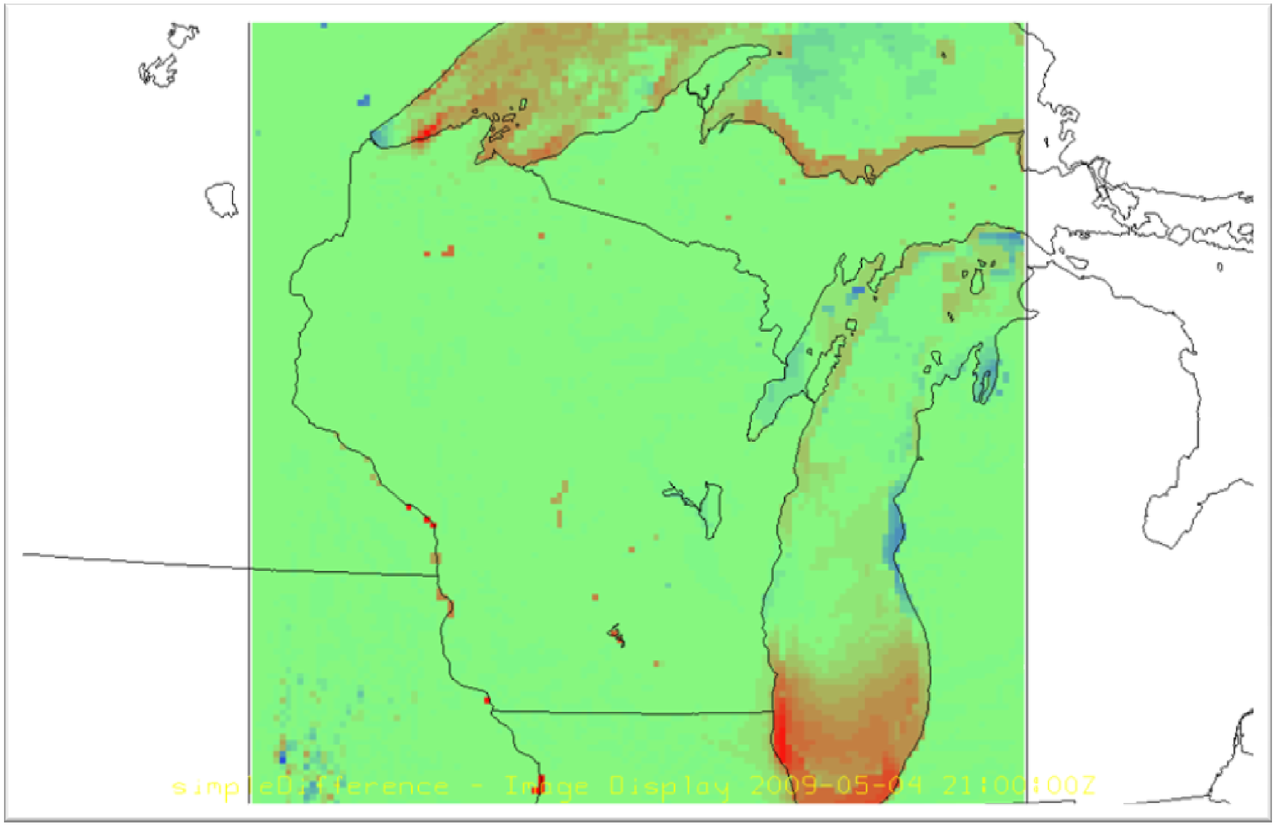
- Two-meter temperature, 21:00 UTC on 4 May 2009 (+9)



WRF-ARW run containing solely the RTG sea surface temperature data

WRF-ARW Model Output

- Two-meter temperature, -3 K to 3 K



A pixel-by-pixel difference subtracting the second image from the first image (the run without MODIS sea surface temperatures from the run with the sea surface temperatures)

Conclusions

- While the influence of sea surface temperatures determines the coastal over-land two-meter temperature as well as the over-water two-meter temperature, subtle changes to the SST and SST gradients both over open water and near shore do not greatly influence coastal air temperatures.
- Urban areas play an unknown role in lake breeze processes which are guided by latent heat fluxes.
- Small model domains with high spatial resolution will result in solutions with numerical noise.
- Despite the strong temperature gradients surrounding Lake Superior, no enhanced convergence boundary developed during the evening of 4 May 2009, consistent with the prevailing surface wind regime and observational data.
- A pneumonia front or lake breeze is not necessary to produce near-shore cooling; this can be achieve through substantial and sustained synoptic flow over the large bodies of water. This type of cooling is typically more horizontally disperse than the typical lake breeze gradient, resembling a density current with a sharp cross-boundary contrast.
- **Future work: Can AVHRR add additional spatial coverage through increasing the temporal resolution of polar-orbiter data?**

Summary

- Initial conditions should be the same spatial resolution as the model run resolution.
- Satellite-based instrumentation defeats traditional observation systems in accomplishing this task, but provides hurdles for data assimilation (what about cloudy observations?).
- Higher spatial resolution leads to a more precise solution among NWP models (accuracy depends on the initial, boundary conditions, and any parameterizations).
- Further attention needs to be given to the static data sets– *Should they be static?*

Questions? Comments?

- **Thank you for your attention.**
- Author information: Jordan Gerth, 1225 W. Dayton Street, Madison, WI 53706; Jordan.Gerth@noaa.gov
- Please contact me if you are interested in participating in our research to operations satellite product trials.
- I would like to thank the Wisconsin Space Grant Consortium (WSGC), the National Aeronautics and Space Administration (NASA), and the Space Science and Engineering Center (SSEC) at the University of Wisconsin (UW) for the ability to conduct this research. The WSGC has provided continued funding for this project since 2007, which has maximized use of post-mission NASA space-based assets for added value.

References

- Arritt, R. W., 1987: The effect of water surface temperature on lake breezes and thermal internal boundary layers. *Bound.-Layer Meteor.,* **40,** 101–125.
- ——, 1993: Effects of the large-scale flow on characteristic features of the sea breeze. *J. Appl. Meteor.,* **32,** 116–125.
- Behnke, C., 2005: Synoptic and Local Controls of the Lake Michigan Pneumonia Front.
- Biggs, W. G., and M. E. Graves, 1962: A lake breeze index. *J. Appl. Meteor.,* **1**, 474–480
- Chelton, D. B., 2005: The impact of SST specification on ECMWF surface wind stress fields in the eastern tropical Pacific. *J. Climate,* **18,** 530–550.
- Davies, J., 2004: The IMAPP MODIS Sea Surface Temperature Algorithm.
- Gallus, W.A., and M. Segal, 1999: Cold Front Acceleration over Lake Michigan. *Wea. Forecasting*, **14**, 771–781.
- Garratt, J. R., 1986: Boundary-layer effects on cold fronts at a coastline. *Bound.-Layer Meteor.,* **36,** 101–105.
- Kunkel, K.E., S.A. Changnon, B.C. Reinke, and R.W. Arritt, 1996: The July 1995 Heat Wave in the Midwest: A Climatic Perspective and Critical Weather Factors. *Bull. Amer. Meteor. Soc.*, **77**, 1507–1518.
- LaCasse, K.M., M.E. Splitt, S.M. Lazarus, and W.M. Lapenta, 2008: The Impact of High-Resolution Sea Surface Temperatures on the Simulated Nocturnal Florida Marine Boundary Layer. *Mon. Wea. Rev.*, **136**, 1349–1372.
- Laird, N.F., D.A.R. Kristovich, X.Z. Liang, R.W. Arritt, and K. Labas, 2001: Lake Michigan Lake Breezes: Climatology, Local Forcing, and Synoptic Environment. *J. Appl. Meteor.*, **40**, 409–424.
- Lyons, W. A., 1972: The climatology and prediction of the Chicago lake breeze. *J. Appl. Meteor.,* **11,** 1259–1270.
- Mass, C.F., D. Ovens, K. Westrick, and B.A. Colle, 2002: Does Increasing Horizontal Resolution Produce More Skillful Forecasts? *Bull. Amer. Meteor. Soc.*, **83**, 407–430.
- Scott, R. W., and F. A. Huff, 1996: Impacts of the Great Lakes on regional climate conditions. *J. Great Lakes Res.,* **22,** 845–863.
- Song, Q., T. Hara, P. Cornillon, and C. A. Friehe, 2004: A comparison between observations and MM5 simulations of the marine atmospheric boundary layer across a temperature front. *J. Atmos. Oceanic Technol.,* **21,** 170–178.
- Strabala, K., 2008: Personal interview.