The Influence of Surface Atmospheric Stability on Air-Water Interface Modeling over Lake Michigan

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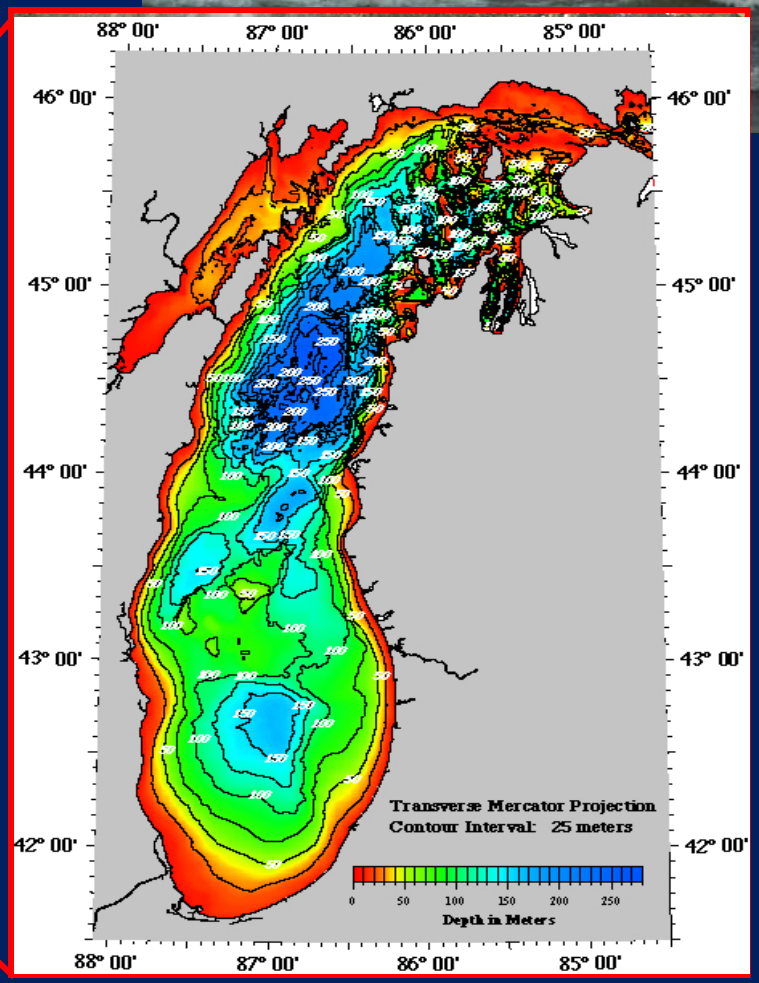
The Laurentian Great Lakes

- 6 quadrillion gallons of fresh water
- Covering more than 94,000 square miles
- 10,900 miles of total US and Canadian coastline

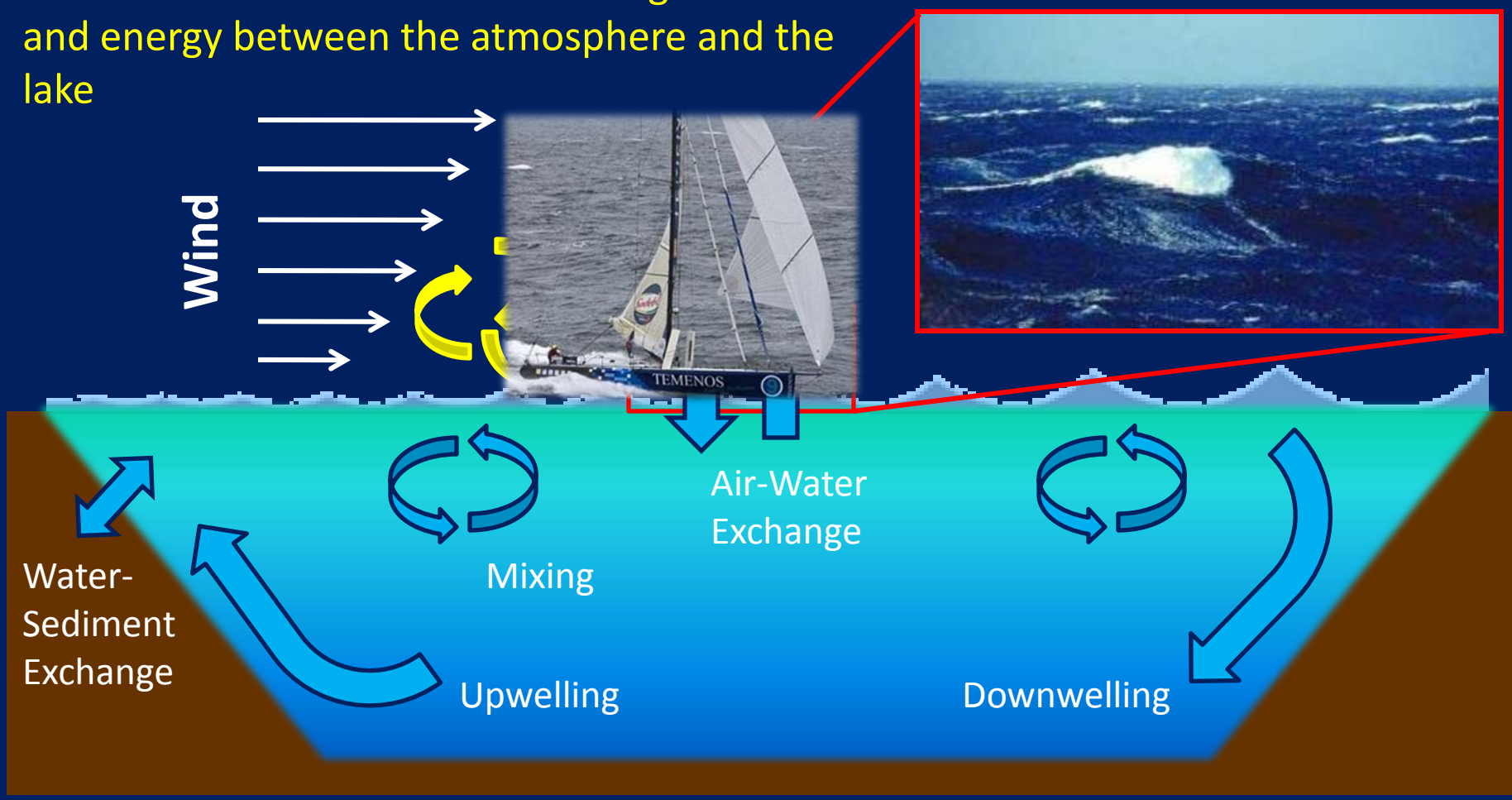
Lake Michigan

- 3rd largest freshwater lake by surface area
- 6th largest freshwater lake in the world
- 118 miles wide
- 307 miles long
- More than 1,600 miles of shoreline
- Average depth is 279 feet
- 925 feet deep at its deepest point



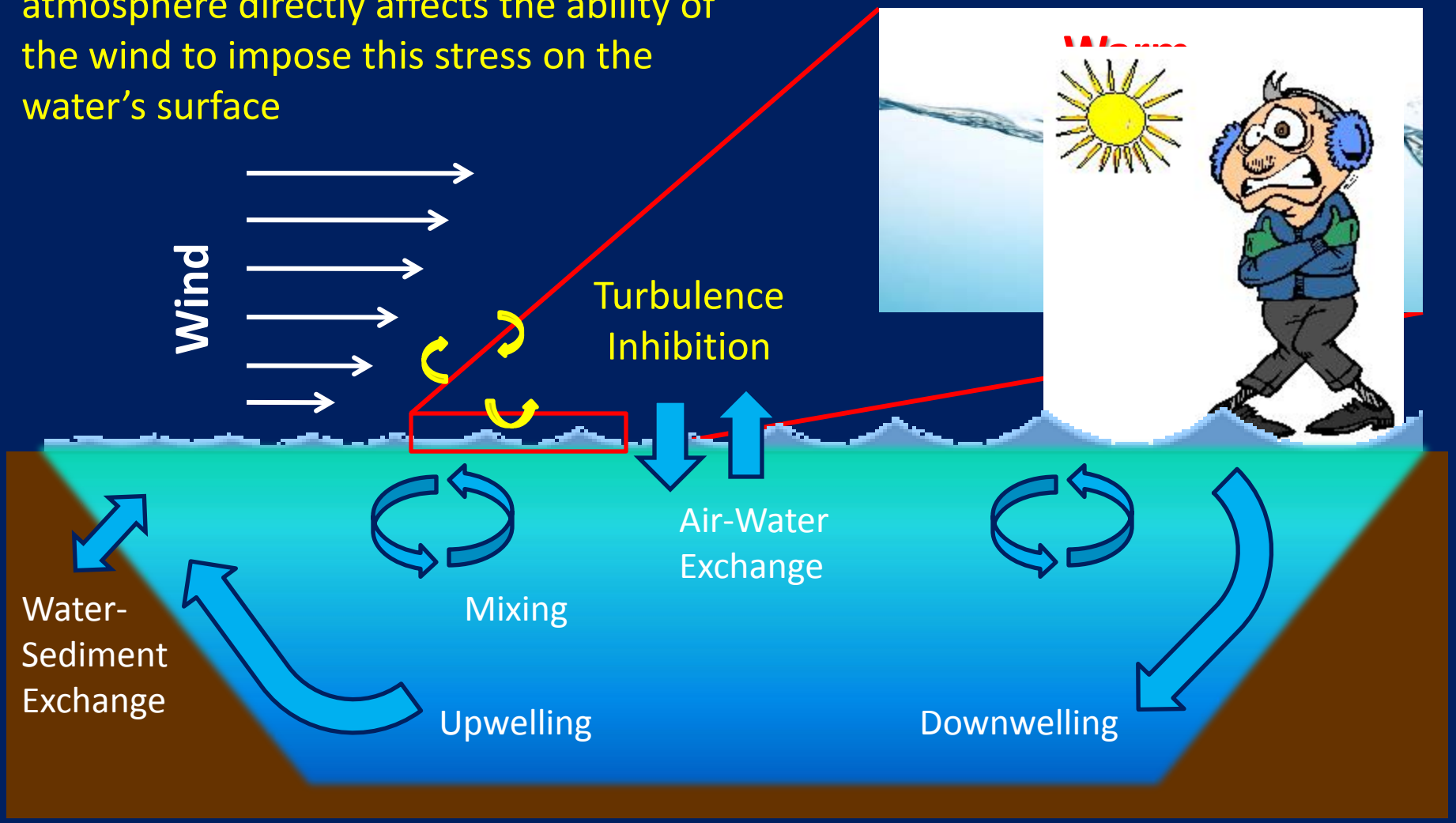
The Physical Environment

The vertical flux of horizontal momentum - or ***wind stress*** - develops waves on the water surface and accelerates the exchange of mass and energy between the atmosphere and the lake



The Problem

The stability of the near surface atmosphere directly affects the ability of the wind to impose this stress on the water's surface



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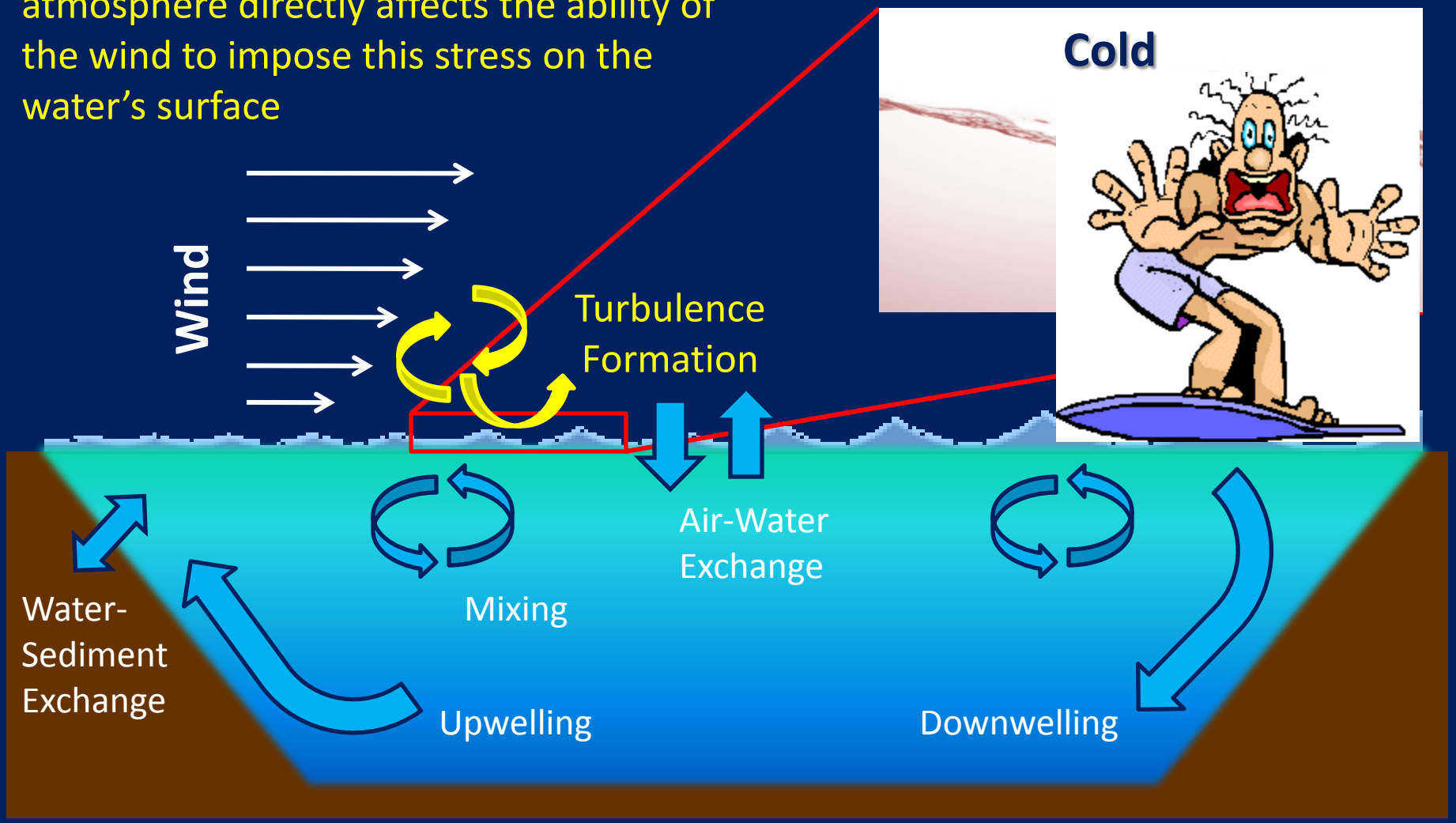
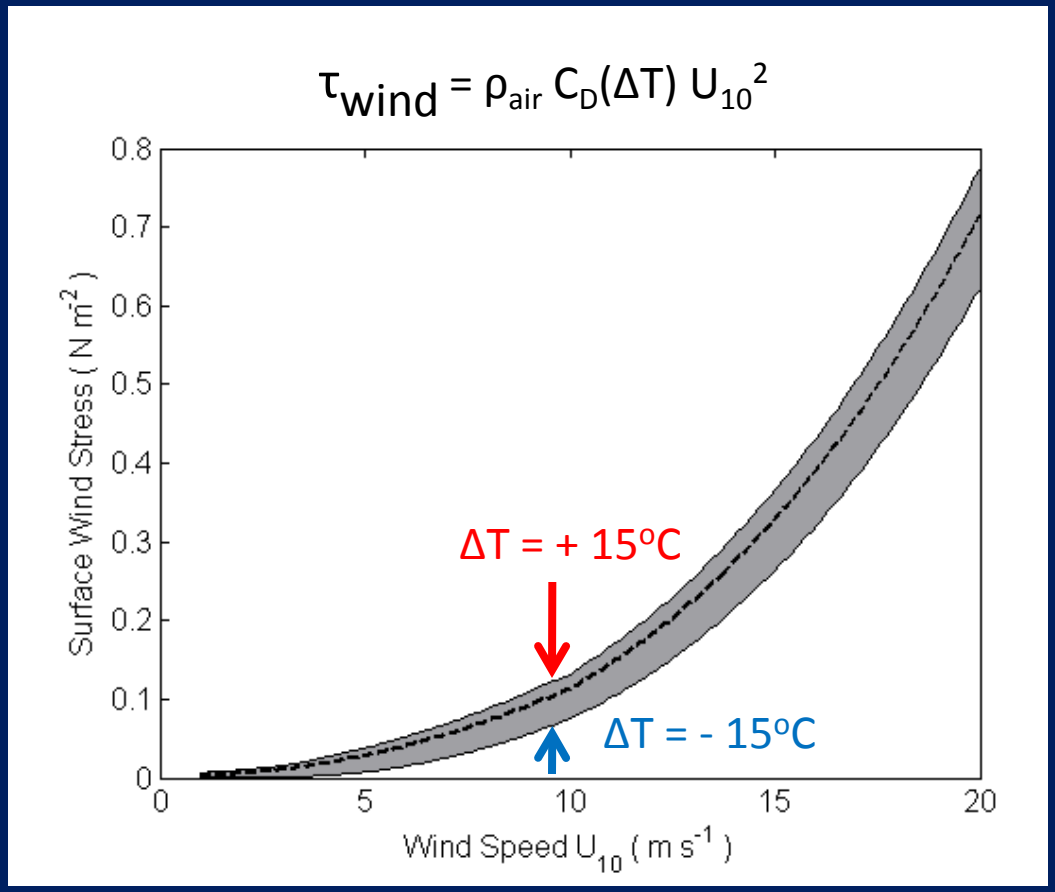


Background

The difference in wind stress based on the stability of the near surface atmosphere can be substantial!



Stability Conditions:

$\Delta T = T_{water} - T_{air}$

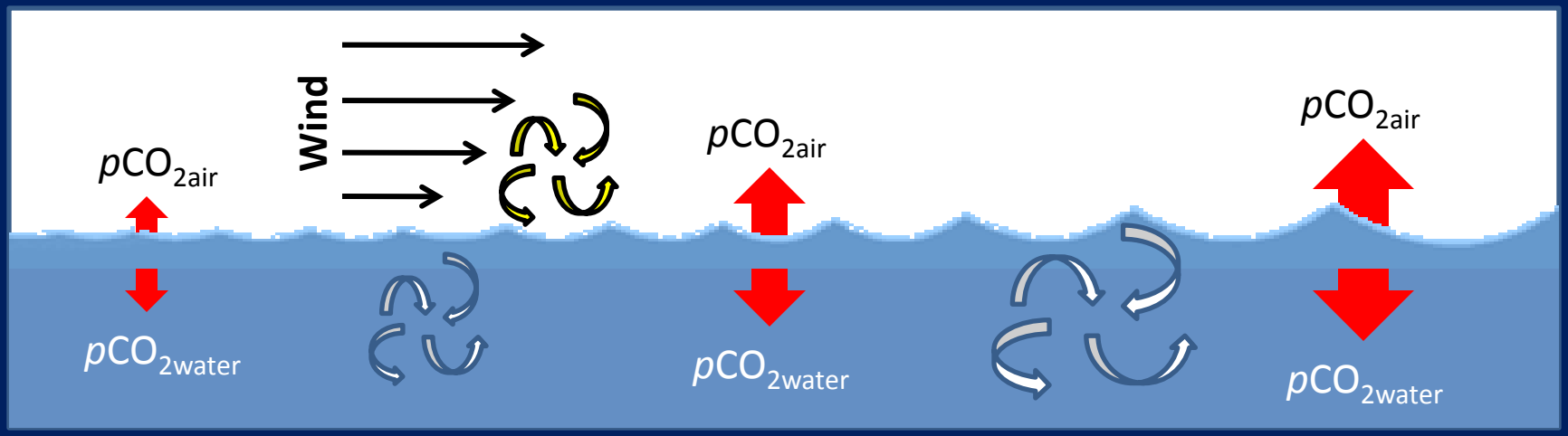
$\Delta T = +15^{o}C \longrightarrow 15\ \%$

Increase in τ

$\Delta T = -15^{o}C \longrightarrow 33\ \%$

Decrease in τ

Background



- The flux of CO_2 across the air-water interface is dependent on the vertical gradient of CO_2 across the interface and the transfer velocity at the interface

$$\textbf{Flux} = k\,(pCO_{2\,water} - pCO_{2\,air})$$

- Turbulent motions on the water side of the interface (waves and white caps) control the rate, k, at which CO_2 diffuses across the interface
- Therefore k is a function of:
  - Wind speed / Wind stress /Stability
  - Wave Height / White caps

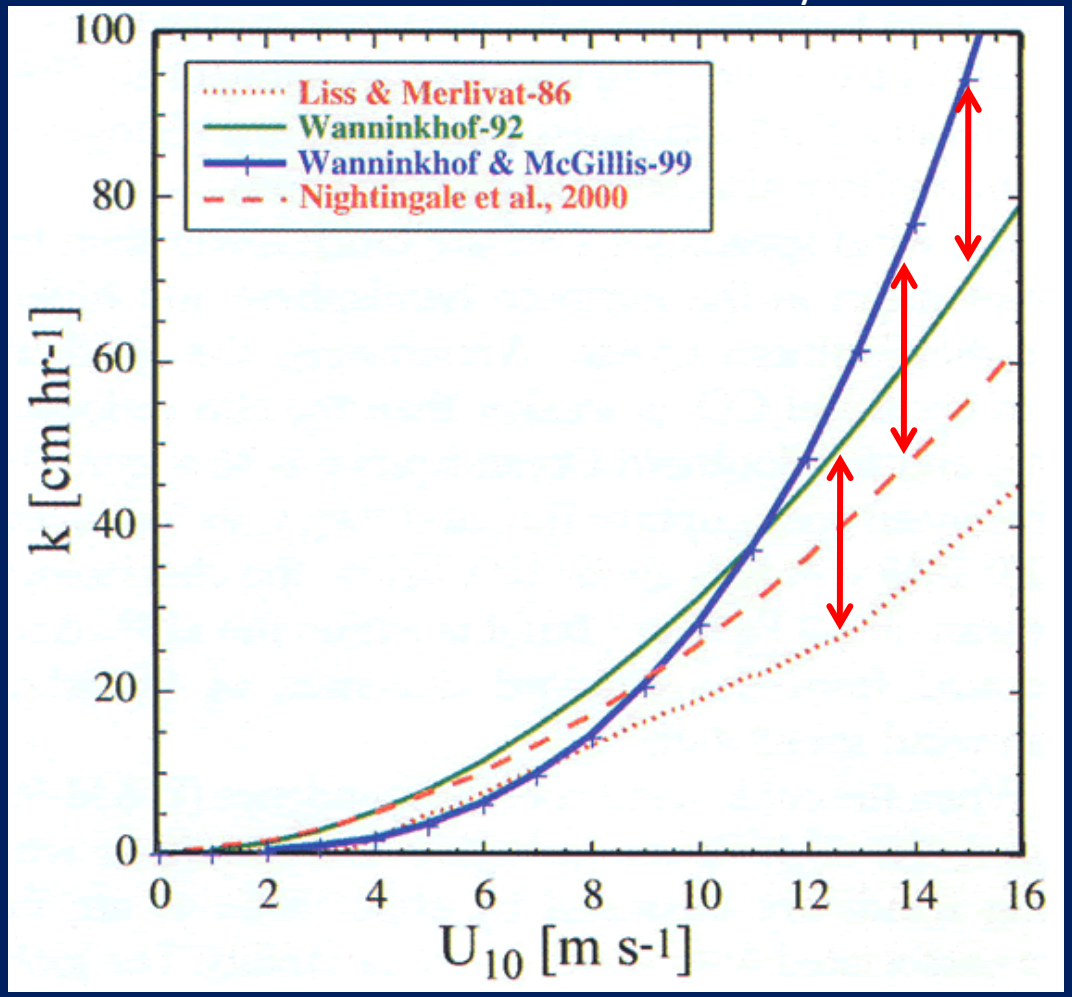
Background

Air-Sea Flux = k ($pCO_{2\ water} - pCO_{2\ air}$)

The transfer rate of CO_2 across the air-water interface has been parameterized based on the 10 meter wind speed (U_{10}) a relatively abundant variable at global scales

The difference between net, global CO_2 fluxes between the ocean and atmosphere calculated using different U_{10} based models is still an issue of discussion

Feely et al. 2001



Key Question

- How does the variability in wind stress based on surface atmospheric stability influence modeling of the air-water interface?
  - Wind wave development
  - Gas flux across the interface

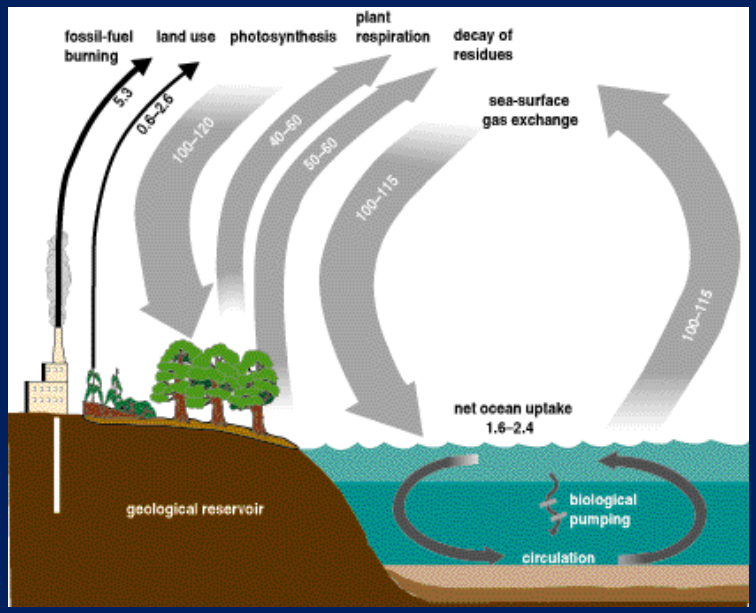
- Two studies were performed to:

  1. Quantify the influence of surface atmospheric stability on wind-wave modeling

  2. Quantify the influence of surface atmospheric stability and ***fetch*** on air-water CO_2 gas exchange modeling

Significance

- Wind-wave modeling and forecasting is an invaluable tool which helps to protect people and cargo across the Great Lakes and coastal oceans
- Air-water CO_2 gas exchange modeling will help answer important questions related to the local, regional, and global carbon cycle as it relates to the Great Lakes
- These two issues are interconnected through gas fluxes dependence on interface turbulence generated by waves and white caps

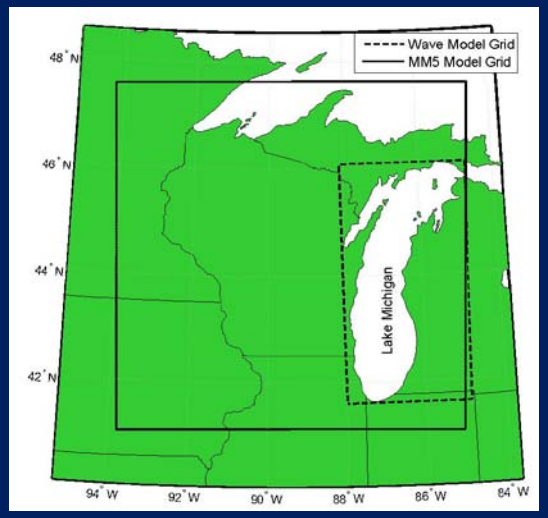


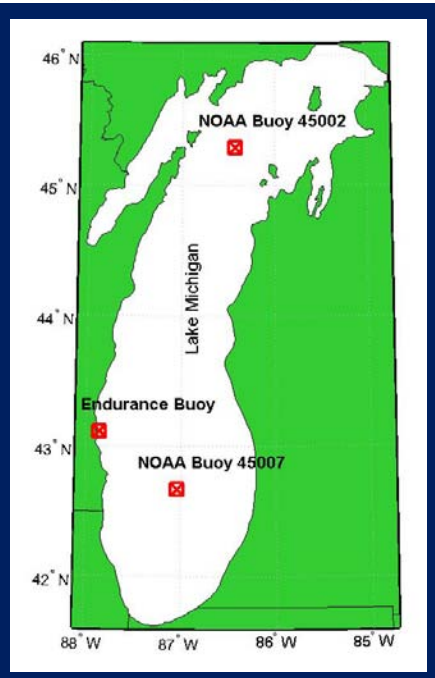
Methods

1. Wave Modeling

Wind-Wave Modeling

- Two, 120 hour simulations are run with the 2 km resolution GLERL-Donelan Wave Model
- Gridded, hourly 10m wind components are provided by the 3 km resolution MM5 Model
- A correction for near surface atmospheric stability is added to the wave model's aerodynamic drag coefficient
- Stability is calculated hourly as the difference between the average lake water temperature and the average over lake air temperature
- Ground truth data is provided by three buoys on Lake Michigan:
  - NOAA buoy 45002
  - NOAA buoy 45007
  - Great Lakes WATER Institute's Endurance Buoy





Methods

1. Wave Modeling

The bulk aerodynamic drag coefficient is corrected for atmospheric stability in the wave model:

If U_{10} is given and it is assumed that $C_D = C_N f(\Delta T)$,

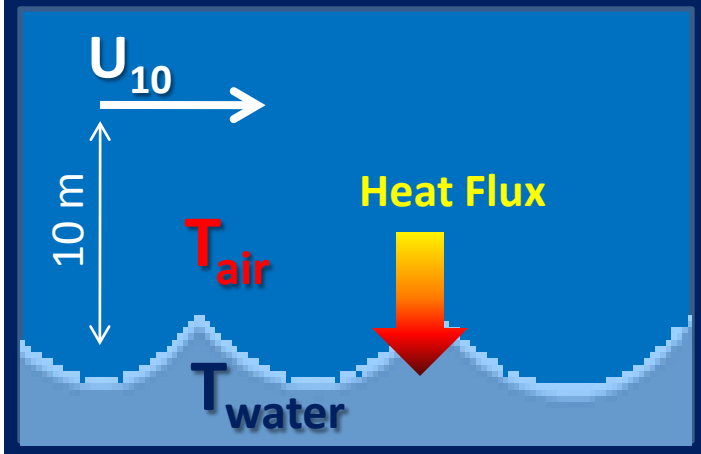
and $$C_N = \left[\kappa / \ln \frac{50}{\sigma}\right]^2$$ (Charnock's Law)

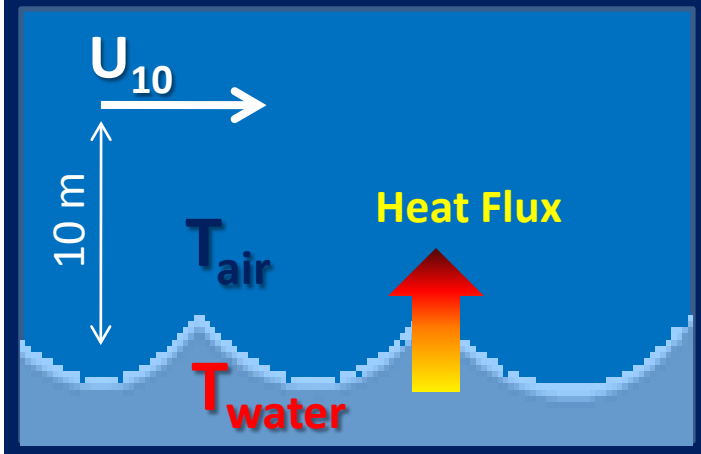
$$\tau = \rho_{air} C_D U_{10}^2 \qquad u_* = \sqrt{\tau / \rho_{air}}$$

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) + \frac{u_*}{\kappa} \psi\left(\frac{z}{L}\right)$$

than $$C_D = \frac{C_N}{\left\{1 + \frac{\sqrt{C_N}}{\kappa}\left(\ln\left(\frac{z}{z_0}\right) - \psi\left(\frac{z}{L}\right)\right)\right\}^2}$$

(Roll 1965; Large and Pond 1982; Erickson 1993)

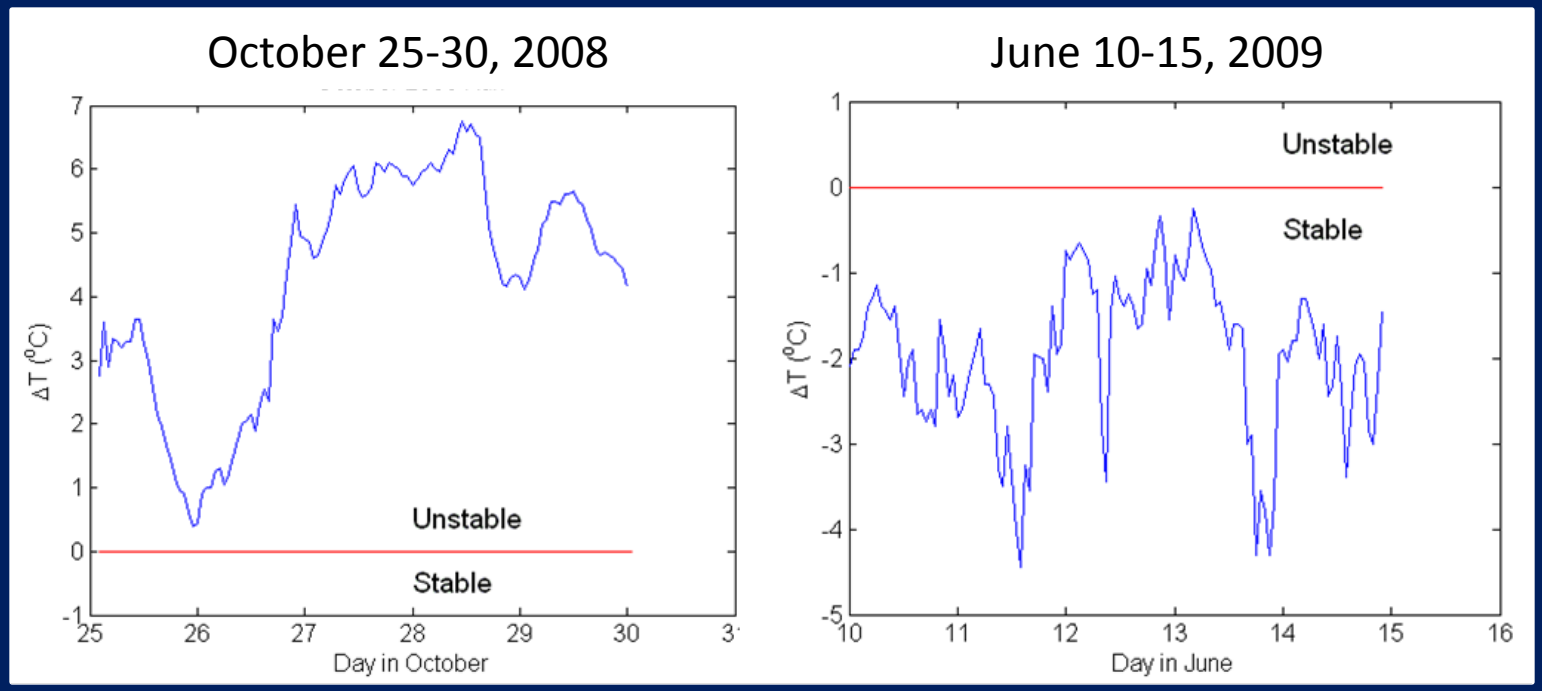




Methods

1. Wave Modeling

- The model is run twice for each 120 hour case:
  - Neutral – control – simulation
  - Stability – test – simulation
- Each case represents a different stability condition based on the spatially averaged water-air temperature difference ΔT (°C) over Lake Michigan:

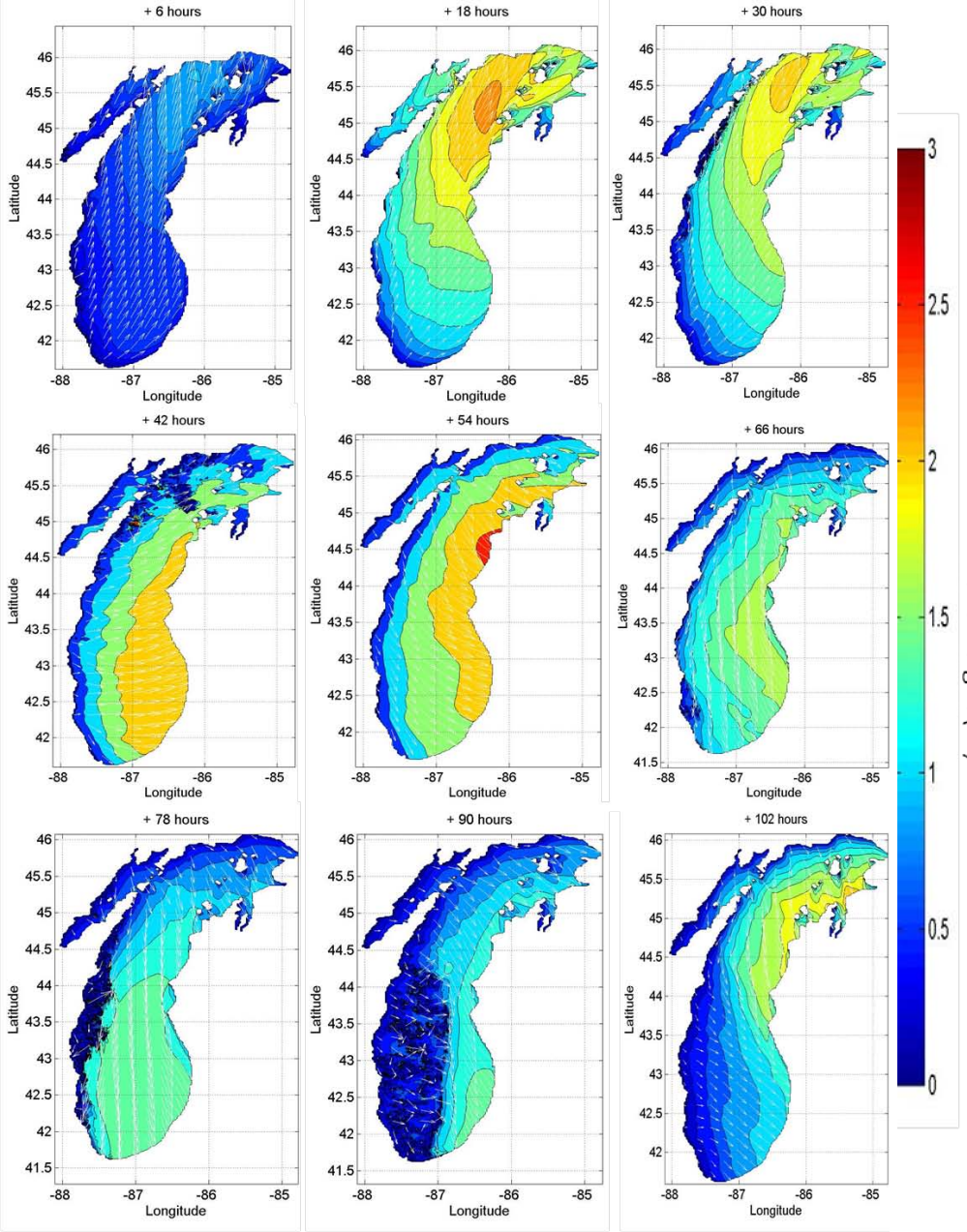


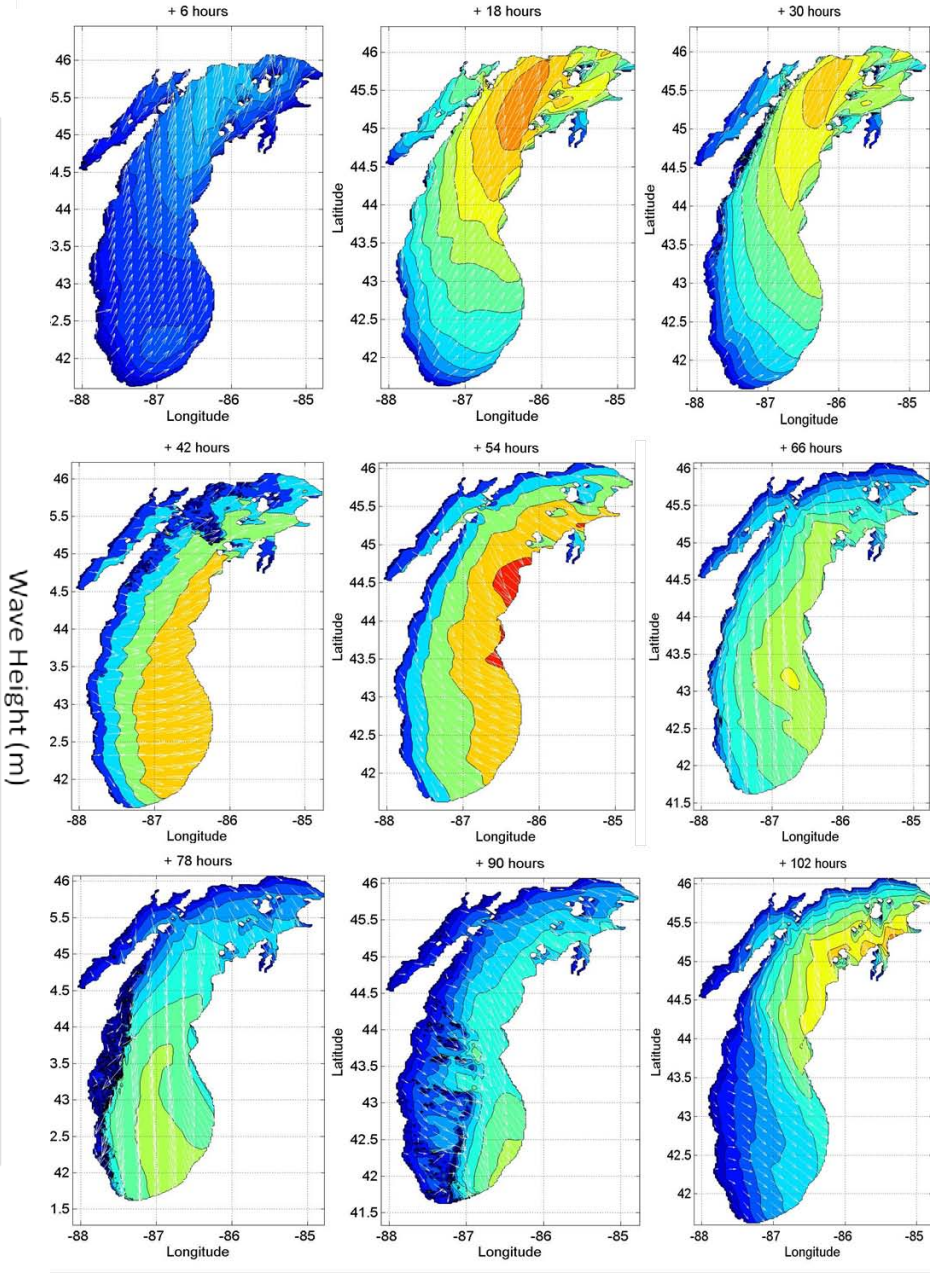
ΔT = Average Water Temperature – Average Air Temperature Over Water

Results

October Neutral Simulation

October Stability Simulation

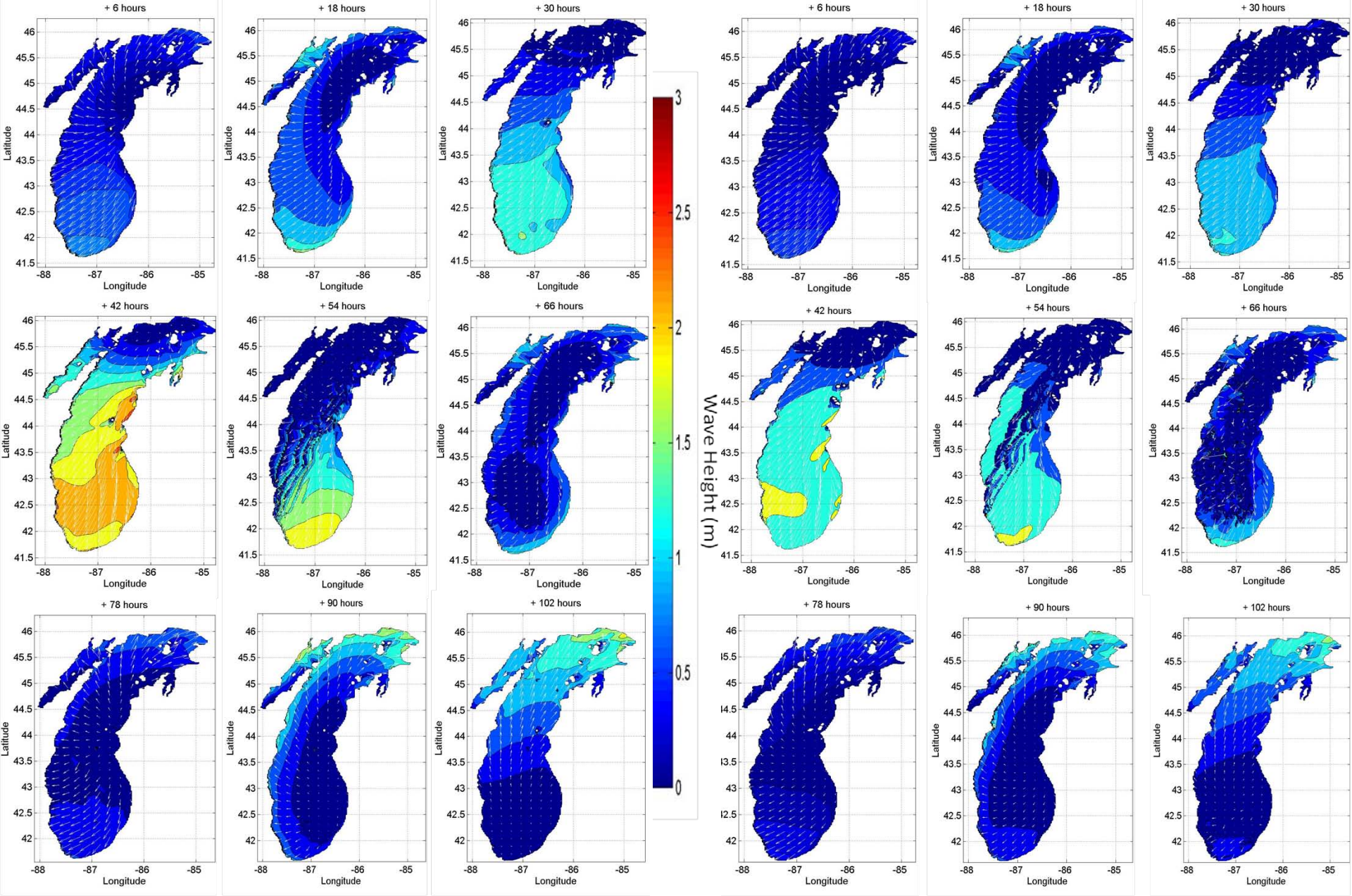




Results

June Neutral Simulation

June Stability Simulation

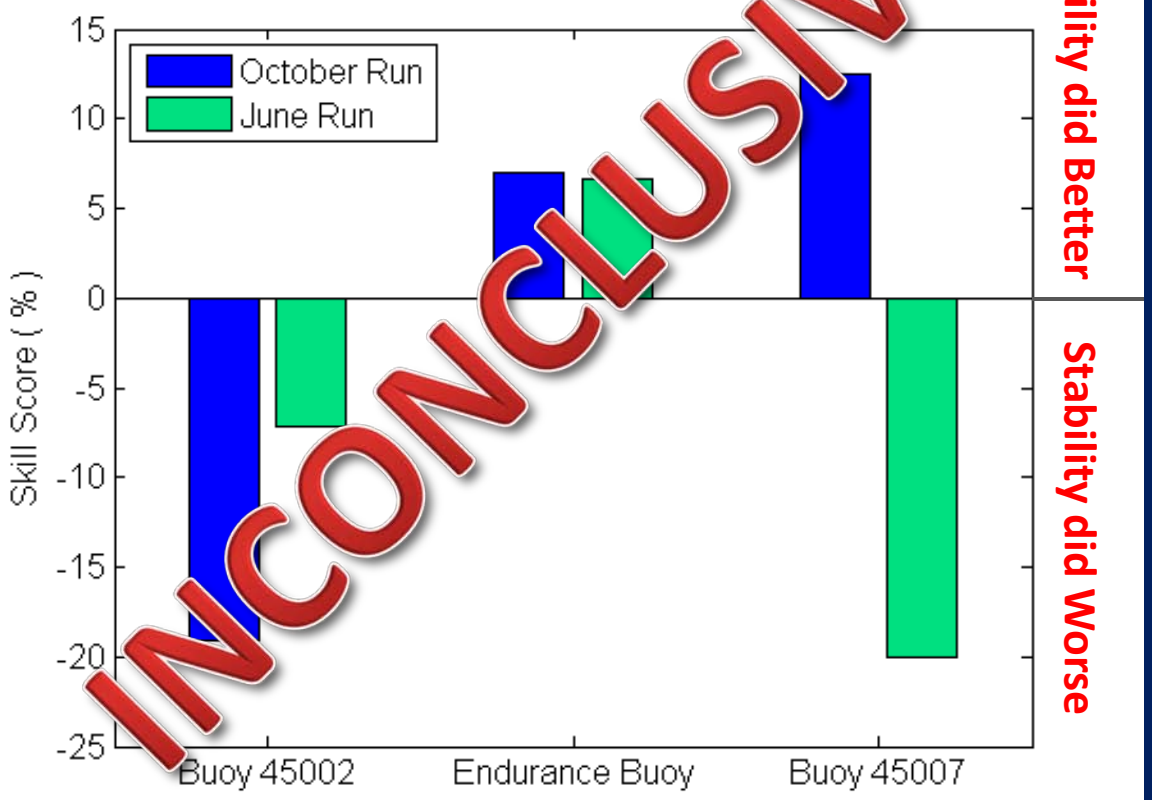


Results

1. Wave Modeling

The skill of the stability simulation compared to the neutral simulation calculated based on each simulations wave height RMS error at each buoy location

$$Skill = \left[1 - \frac{RMSE_{Stability}}{RMSE_{Neutral}}\right] * 100$$

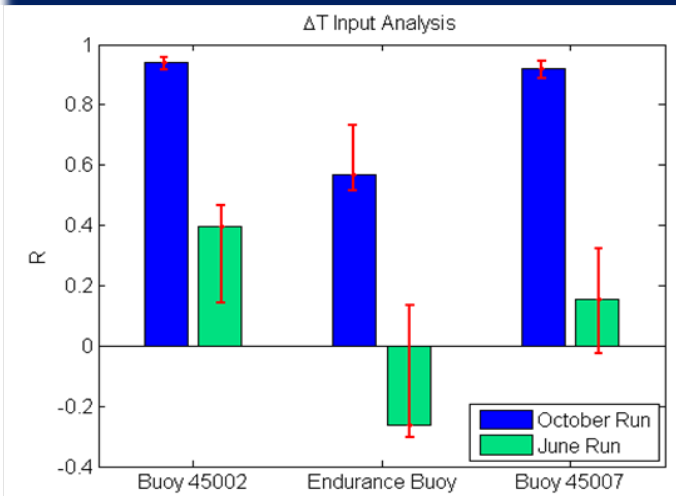


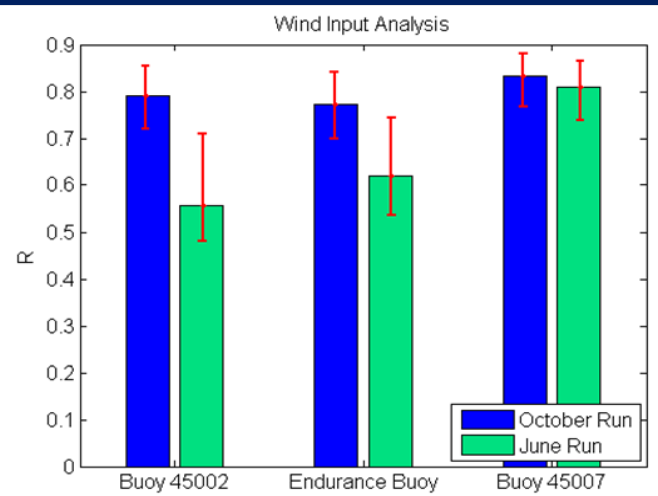
- The October case suggests the stability simulation was more skillful than the neutral
- The June case suggests that the stability simulation was less skillful than the neutral simulation
- Is the difference in skill between the two cases a function of method, or the quality of the input parameters?

Results

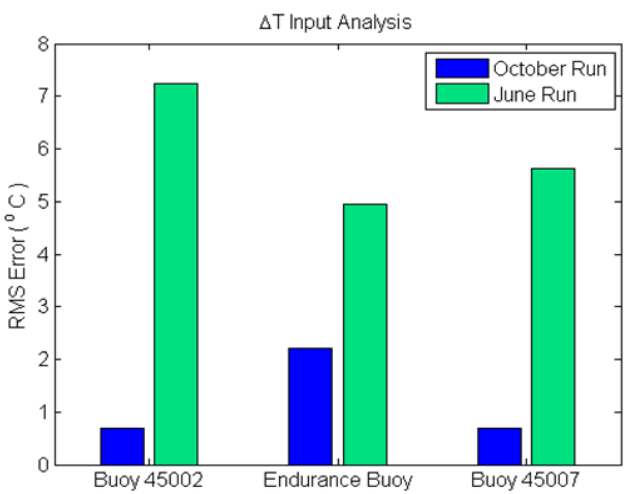
1. Wave Modeling

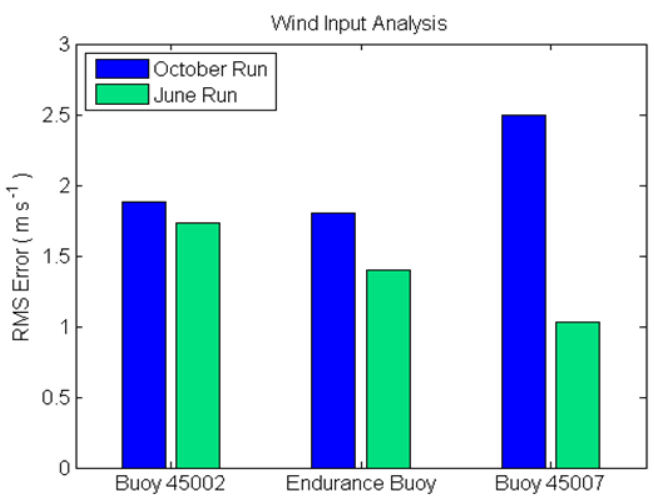
Evaluation of the input parameters, ΔT and wind speed, suggests that the spatially averaged ΔT input data for the June case is poor compared to that of the October case





Linear correlation and 5% confidence interval between modeled and empirical time series at each location for each case



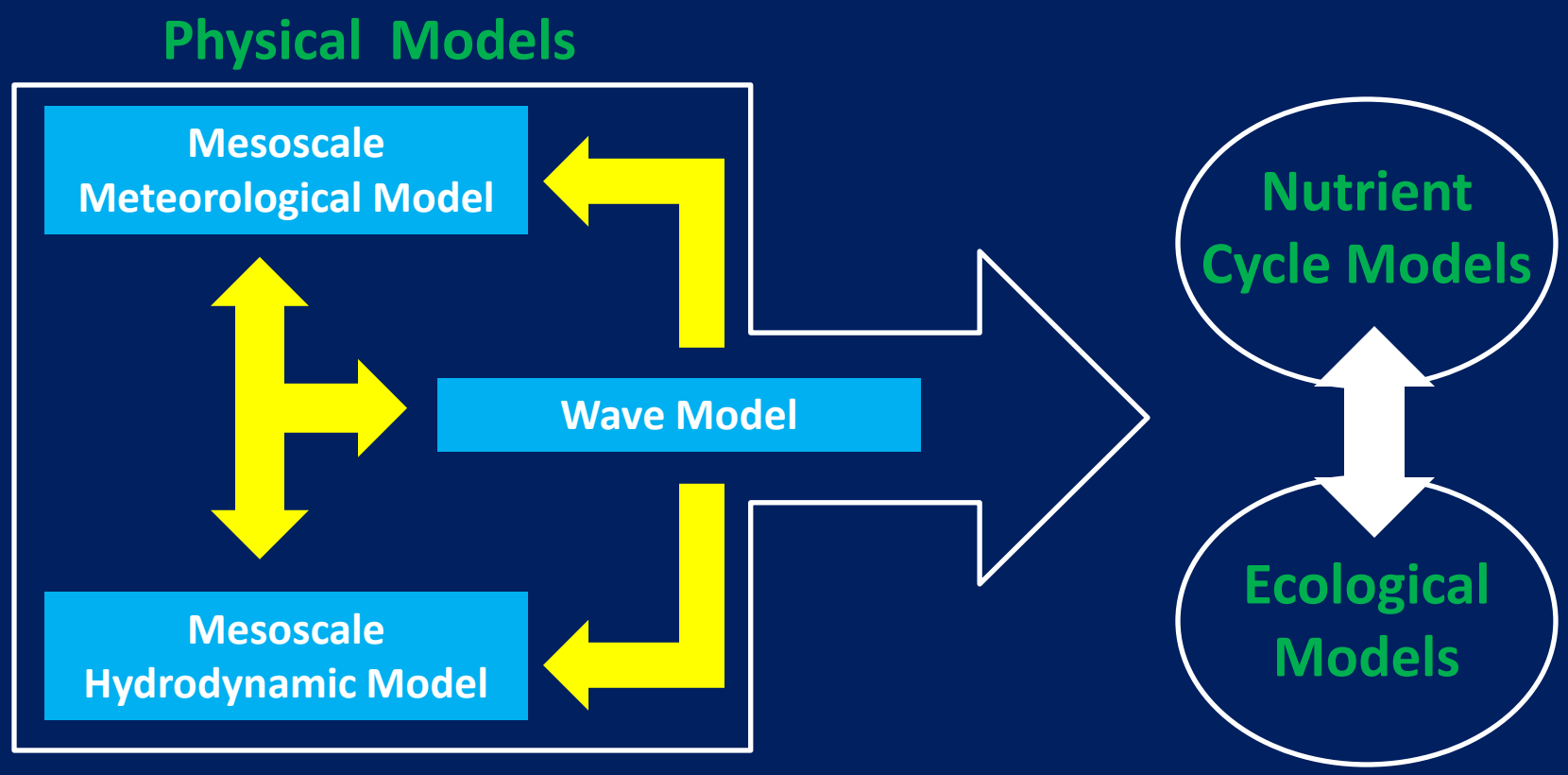


Root Mean Squared Error between modeled and empirical time series at each location for each case

Future Work

1. Wave Modeling

Integrating a hydrodynamic model into the atmosphere - wave model system would add gridded surface lake temperature data and could help in developing useful ecological models

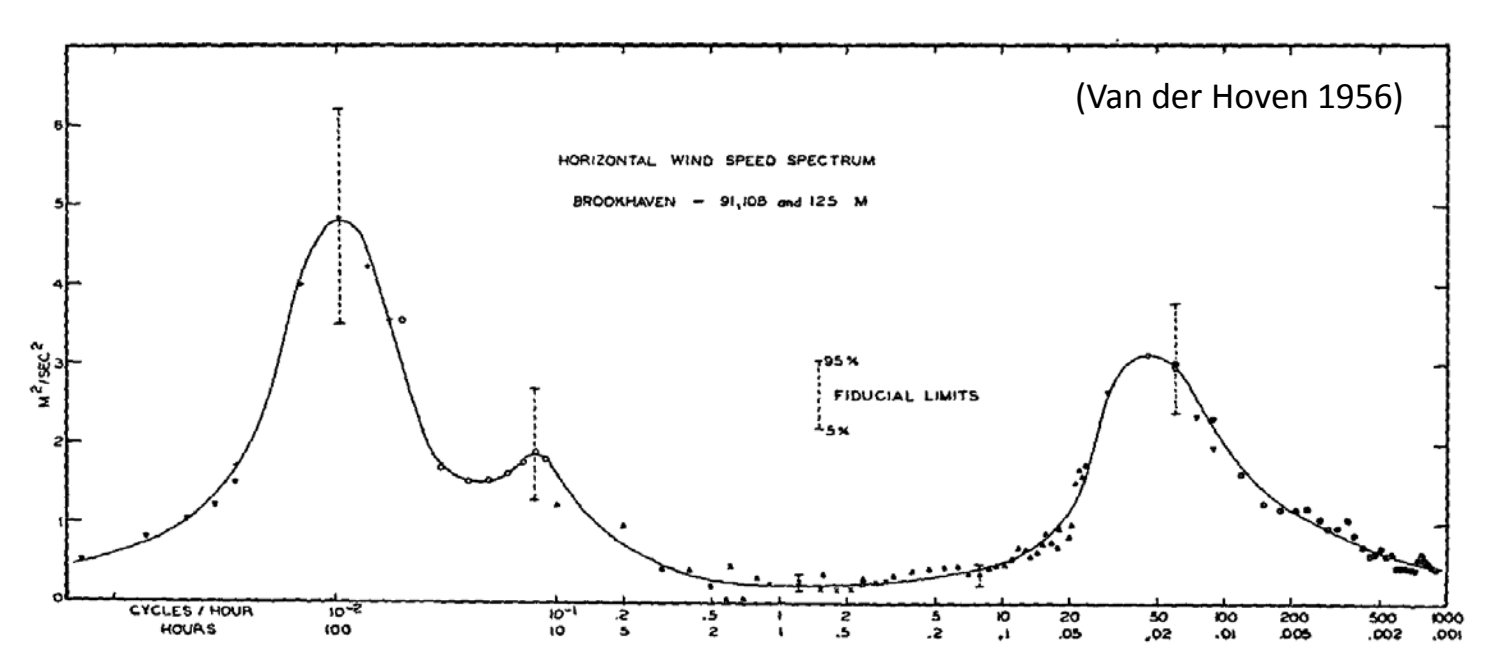


Future Work

1. Wave Modeling

Assess the quality of mesoscale meteorological models over water

- Able to resolve important mesoscale features
  - Sea Breeze Events
  - Frontal Passages, etc.
- Able to resolve necessary micro-scale turbulent features in the kinetic energy spectrum
  - Modeling the atmospheric boundary layer over the lakes
  - Applications in wind/hydrokenetic energy and weather forecasting



Methods

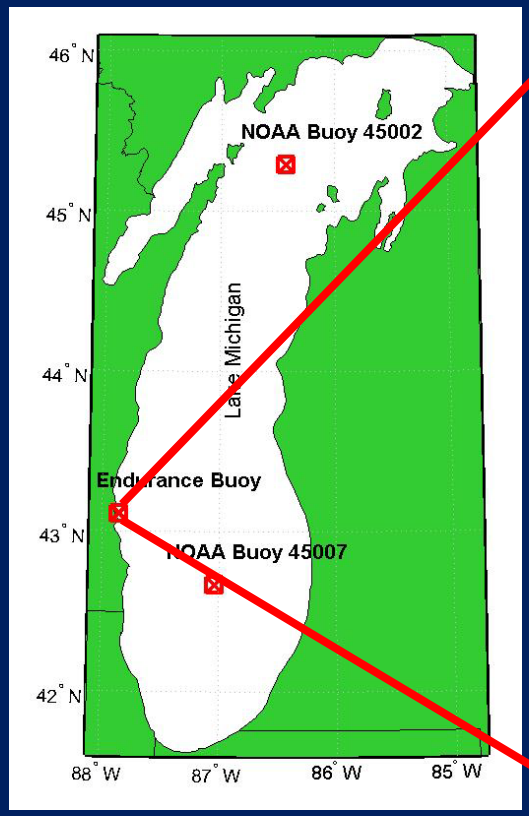
2. CO_2 Flux Modeling

- CO_2 gas transfer rate models from the literature are compared through their determination of net carbon flux across the air-water interface
  - Model 1 (k_1) ~ wind speed
  - Model 2 (k_2) ~ wind speed, stability, white cap coverage
  - Model 3 (k_3) ~ wind speed, stability, wave height, white cap coverage
- By comparing the three models over several cases, the influence of stability and fetch on air-water CO_2 gas exchange can be quantified
- Case Periods 1 – 5:
  - October 10-31, 2008
  - June 1-30, 2009
  - July 1-14, 2009
  - August 18-25, 2009
  - September 8-21, 2009

Methods

2. CO_2 Flux Modeling

In situ air and water pCO_2 data are collected every hour at the GLWI "Endurance" buoy which is moored in the coastal zone of Lake Michigan off the shore of Milwaukee, WI



Results

2. CO_2 Flux Modeling

- Air-water CO_2 gas exchange transfer rates:
  - Model 1 (k_1) ~ wind speed
  - Model 2 (k_2) ~ wind speed, stability, white cap coverage

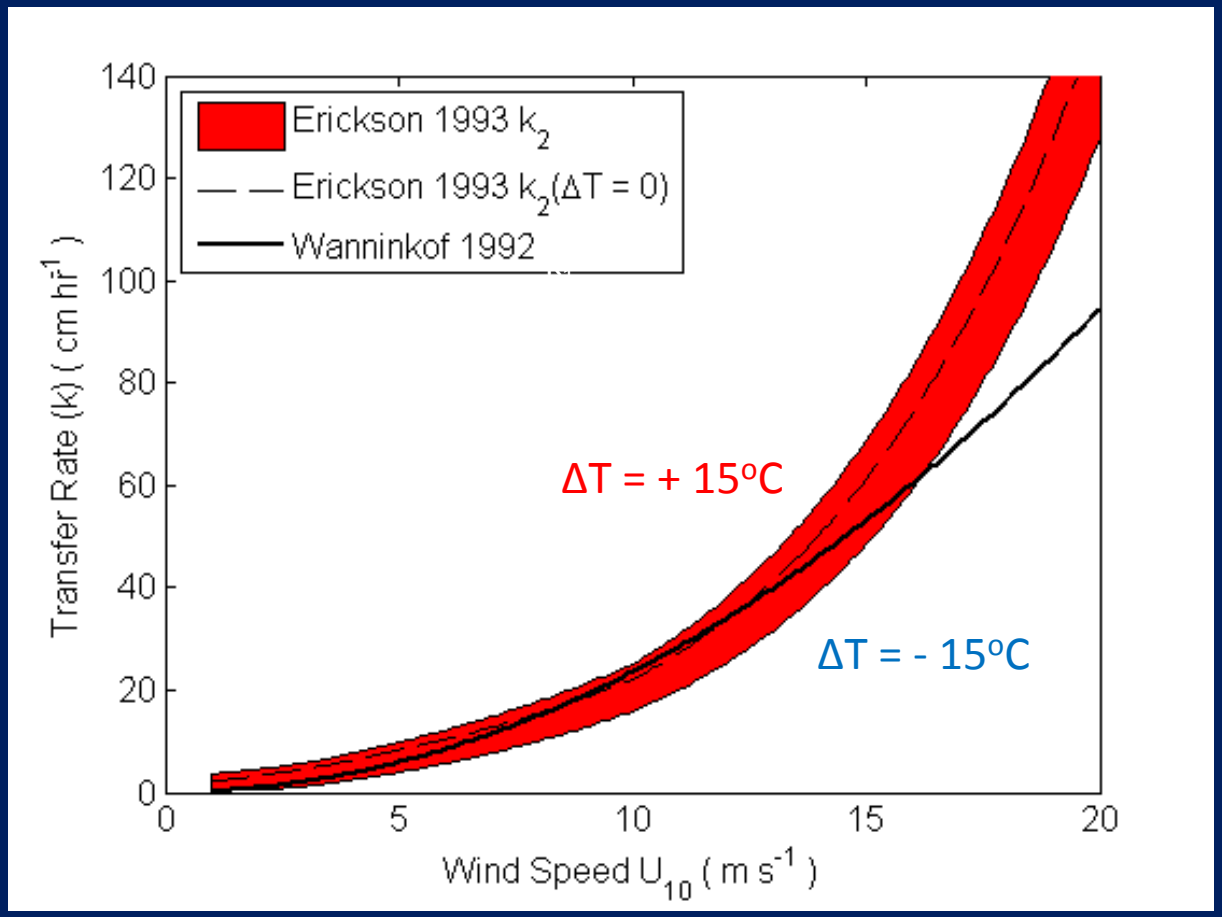
$$k_1 = 0.39U_{10}^2$$

$$k_2 = k_0(1-W_e) + 1300W_e$$

$$k_0 = 1.57\times10^{-4}\, u_*$$

$$W_e = 0.2u_*^3$$

$$u_* = C_D^{1/2}\, U_{10}$$



Results

2. CO_2 Flux Modeling

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  - Model 1 (k_1) ~ wind speed
  - Model 3 (k_3) ~ wind speed, stability, wave height, white cap coverage

$$k_1 = 0.39U_{10}^2$$

$$k_3 = k_0(1-W_w) + 1300W_w$$

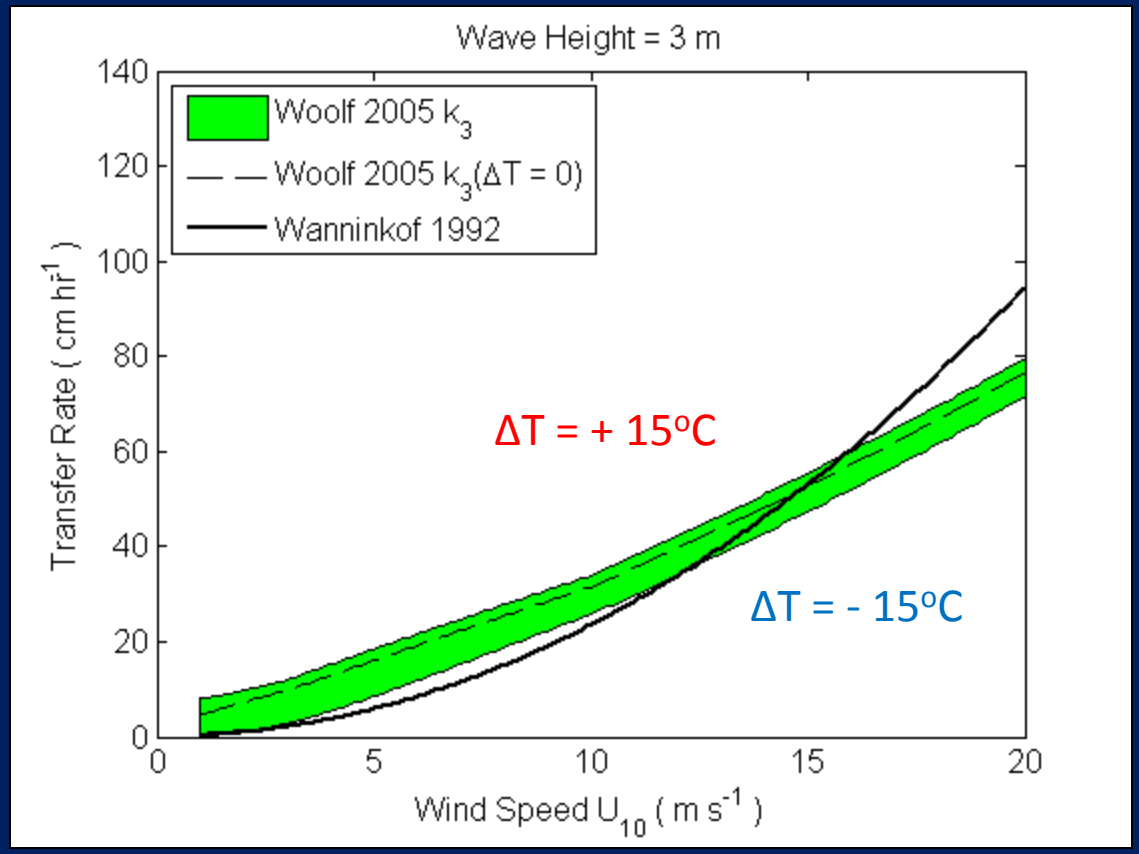
$$k_0 = 1.57\text{x}10^{-4}\ u_*$$

$$W_w = 4.02\text{x}10^{-7}R_H^{0.96}$$

$$R_H = u_*H/\nu_{air}$$

Wave Height ↔ Fetch

For the same wind speed and stability, the upwind side of the lake will have smaller waves than the down wind side

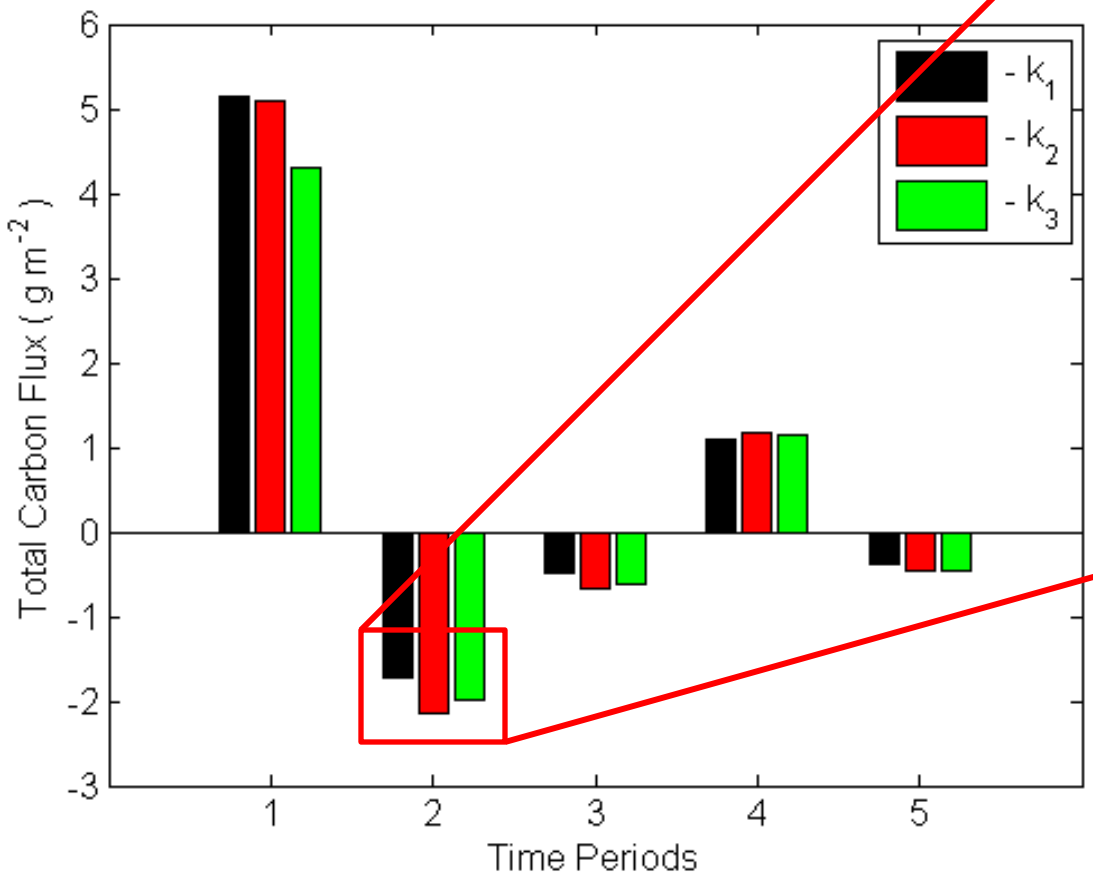


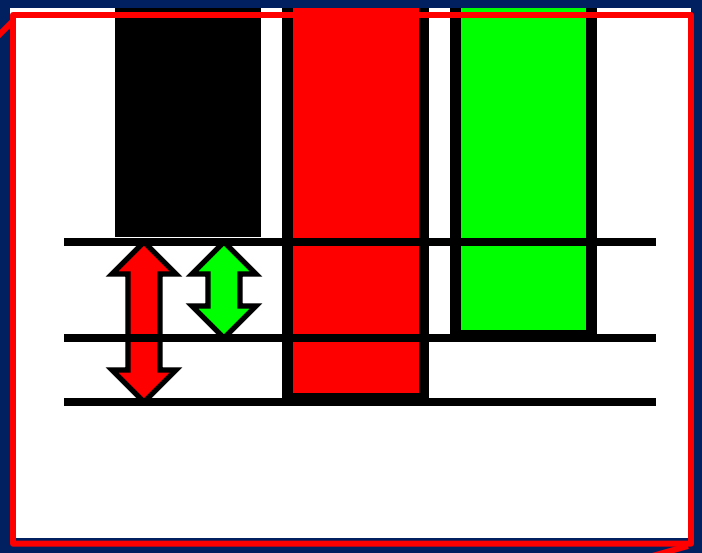
Results

2. CO_2 Flux Modeling

Net carbon flux across the air-water interface is calculated using each of the three transfer rate models

Net Flux of Carbon at the Endurance Buoy





- October 10-31 2008
- June 1-30, 2009
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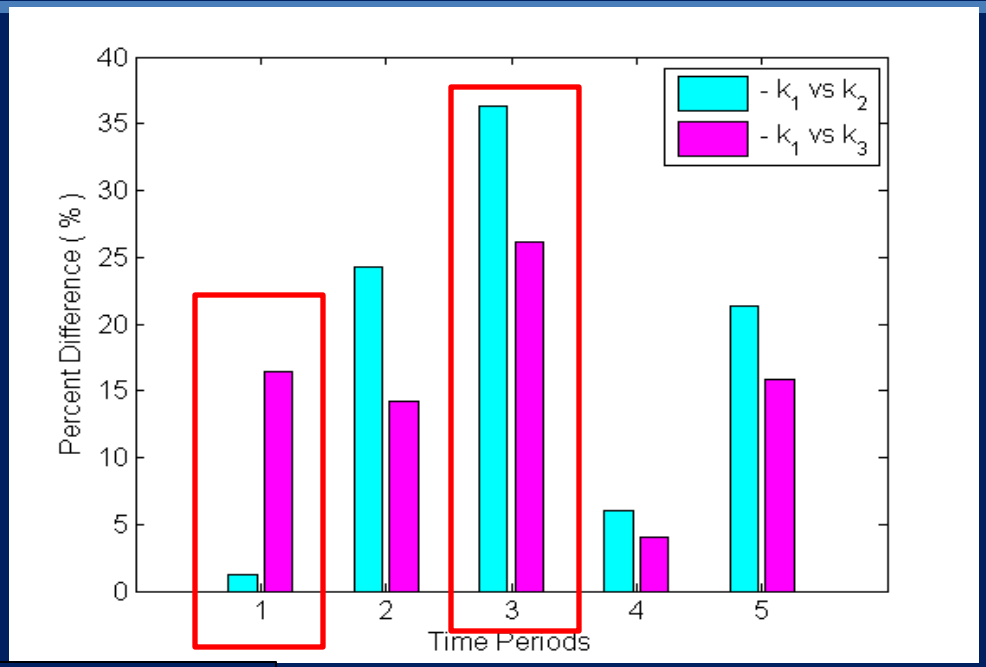
Results

2. CO_2 Flux Modeling

The difference in net flux between that associated with k_1, k_2, and k_3 is calculated as a percent of the net flux associated with k_1

The percent value represents the **potential error** associated with using k_1 over either k_2 or k_3 or by not accounting for stability and fetch



	Wind Speed (m s^{-1})			Wave Height (m)			$\Delta T = T_w - T_a$ (°C)		
Time Period	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
1	0.5	13.4	5.2	0.03	2.01	0.50	-8.5	10.9	2.1
2	0.1	9.9	3.6	0.01	1.19	0.15	-14.9	3.3	-1.9
3	0.3	9.1	3.2	0.02	0.43	0.10	-9.8	1.7	-1.9
4	0.6	7.8	4.1	0.03	0.9	0.3	-14.5	2.3	-6.5
5	0.3	8.2	3.7	0.01	1.01	0.18	-2.5	6.1	2.7

Time Periods 1 – 5:

- October 10-31 2008
- June 1-30, 2009
- July 1-14, 2009
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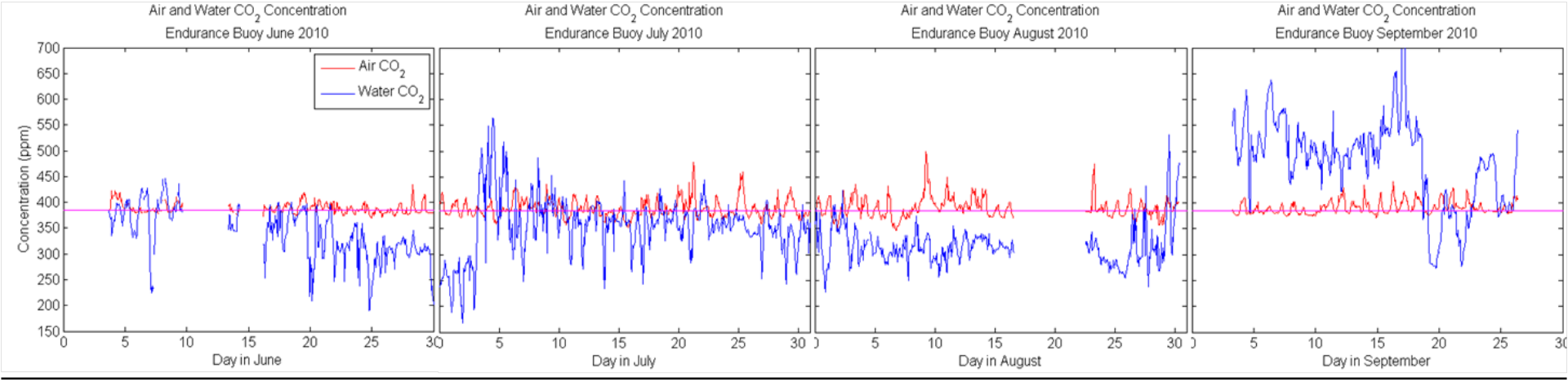
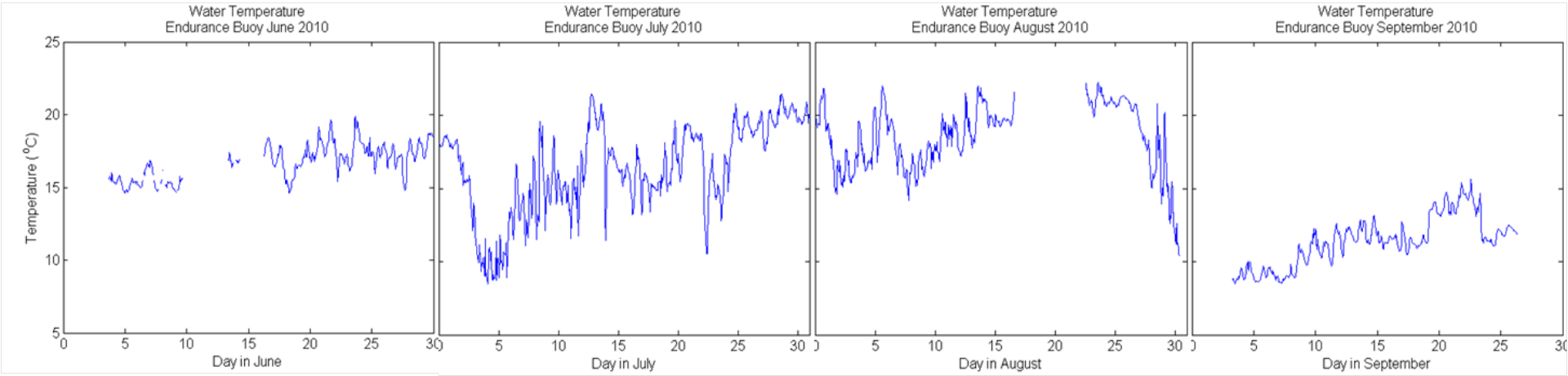
- September 8-21, 2009

Future Work 2. CO_2 Flux Modeling

To better compare these different CO_2 transfer rate models, they need to be evaluated over longer, more continuous data sets

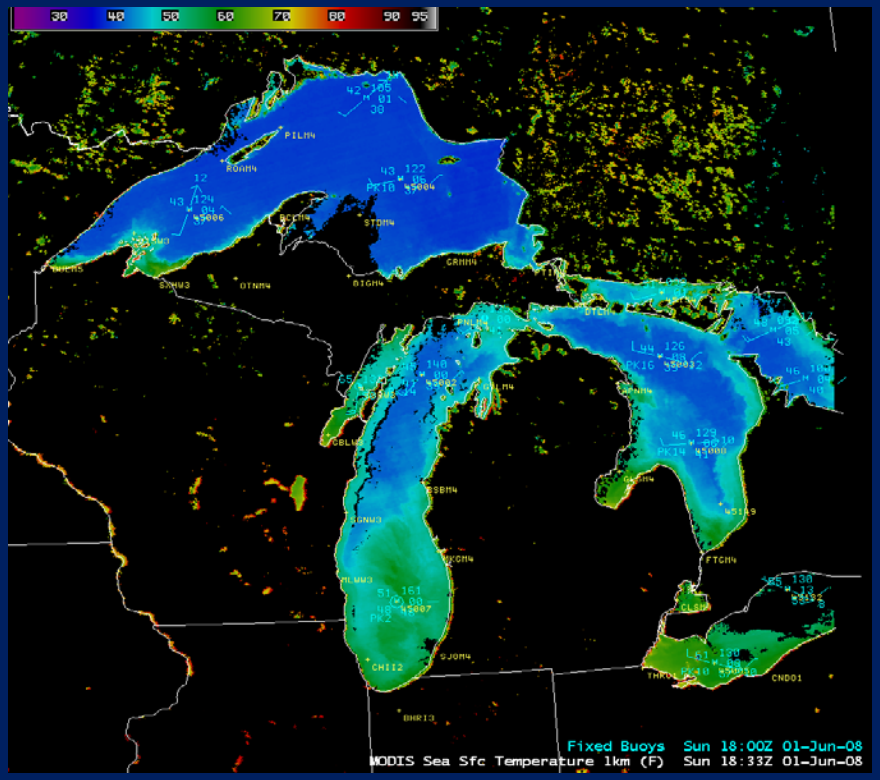




Future Work 2. CO_2 Flux Modeling

- Models need to be developed with emphasis put on the dynamic environment of the Great Lakes and coastal oceans
  - Revise transfer velocity to account for stability and fetch

- There are several methods for model development
  - Direct gas flux measurements – eddy covariance or floating chamber
  - Using heat as a mass tracer
    - Satellite data and Model output
  - Particle Imaging Velocimetry
    - Visualize and model the near surface water side boundary layer



Summary

- The variability in wind stress based on near surface atmospheric stability can be greater than 30% of the neutral wind stress
- Wave model experiments did not fully illustrate the effect of stability on wave modeling
  - Input surface water temperature data was not sufficient to accurately represent over lake stability conditions
  - With accurate high resolution input data, the process discussed here could improve wave model accuracy and effectively illustrate the physical significance of near surface atmospheric stability
- Differences in net carbon flux based on different CO_2 gas transfer rate models are substantial
  - This could result in large errors when modeling the carbon cycle of the Great Lakes and estimating its role in global systems

Questions?