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Satellite Based Retrievals of Chlorophyll, Dissolved Organic Carbon and Suspended Minerals for Lake Michigan

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State of Lake Michigan Conference

NASA

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GLERL
Great Lakes Environmental Research Laboratory

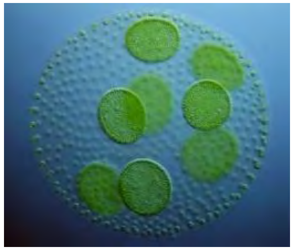
- Review Case II Color Producing Agent Algorithm
- Development of new hydro-optical (HO) models
  - Inherent optical properties (IOP) and in-situ measurement database
  - Compare lake to lake HO model parameters
- Lake Michigan examples and comparison
- Concluding Remarks

Motivation for Case II Color Producing Agent Algorithm

- Standard NASA retrieval is only for Chlorophyll concentrations
- Optimized for Oceans (Case I waters)
- Great Lakes (Case II) water color signatures are more complex (Chlorophyll, Dissolved Organic Carbon, and Suspended Mineral components)
- Primary productivity estimates for the Great Lakes require robust Chlorophyll concentration inputs

Chlorophyll (CHL) , Dissolved Organic Carbon (DOC), Suspended Mineral (SM) Algorithm

- Water color in inland and coastal water results mainly from three different parameters, known as color-producing agents (CPAs):
  - Chlorophyll (CHL): A green pigment found in plant cells. Algal cells that are suspended in water produce a green-yellow color.
  - Dissolved Organic Carbon (DOC): Organic carbons that are produced as part of micro-organism metabolism or are transported from decaying vegetation products via rivers and streams. DOC only absorbs light, it doesn't scatter it. It appears yellow to brown in color (CDOM).
  - Suspended Minerals (SM): Inorganic particulate matter. Scatters and absorbs light.



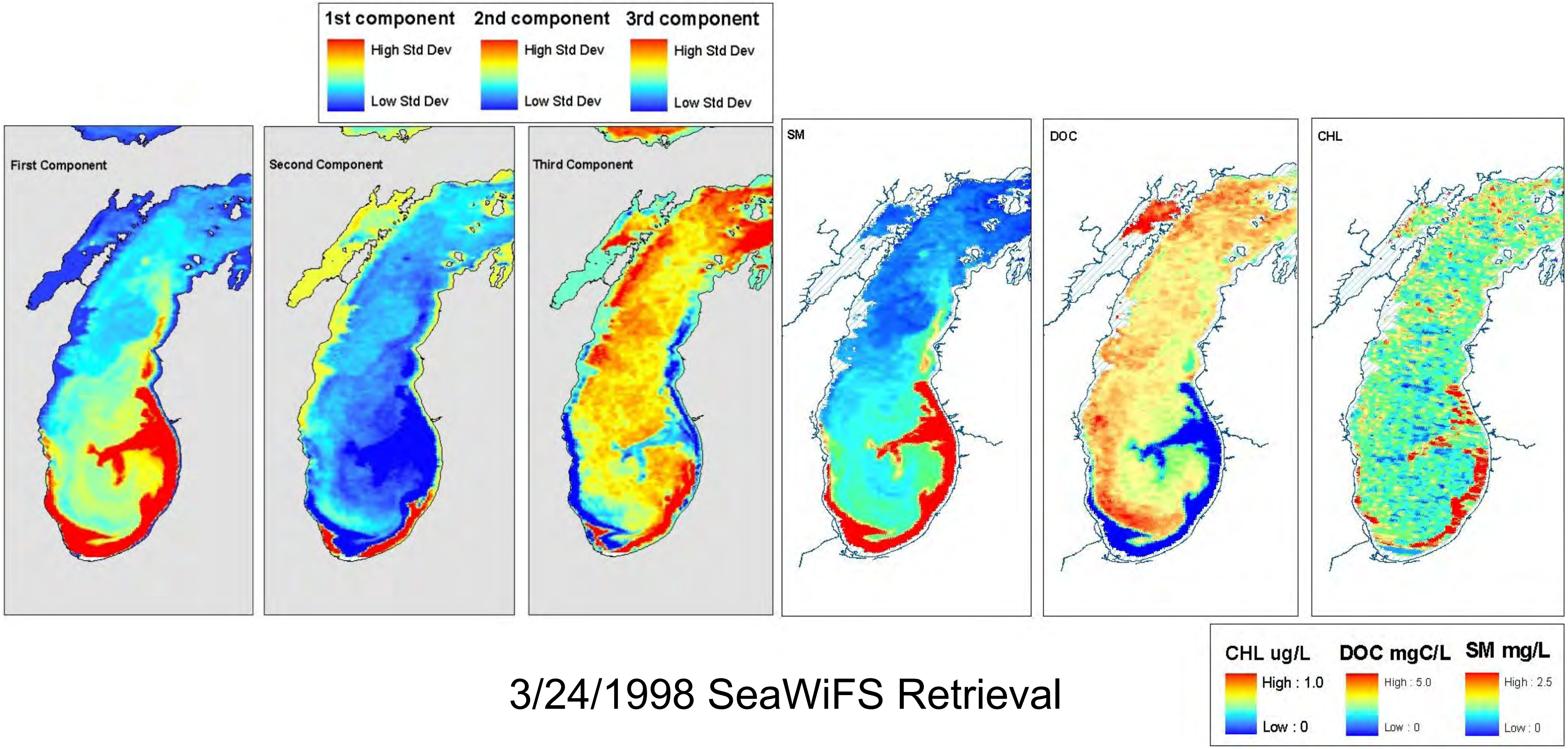
CHL

DOC

SM

Principal Component Analysis

- The standard NASA retrieval (OC3) assumes Chlorophyll is the primary and only significant CPA



3/24/1998 SeaWiFS Retrieval

CPA Algorithm

- The table of specific backscattering and absorption coefficients is also referred to as a Hydro-optical (HO) model
- Different bodies of water have different HO models
- Similar types of water bodies have similar HO-models, such as Lake Michigan and Lake Huron
- HO model depends of what type of CPAs are in the water

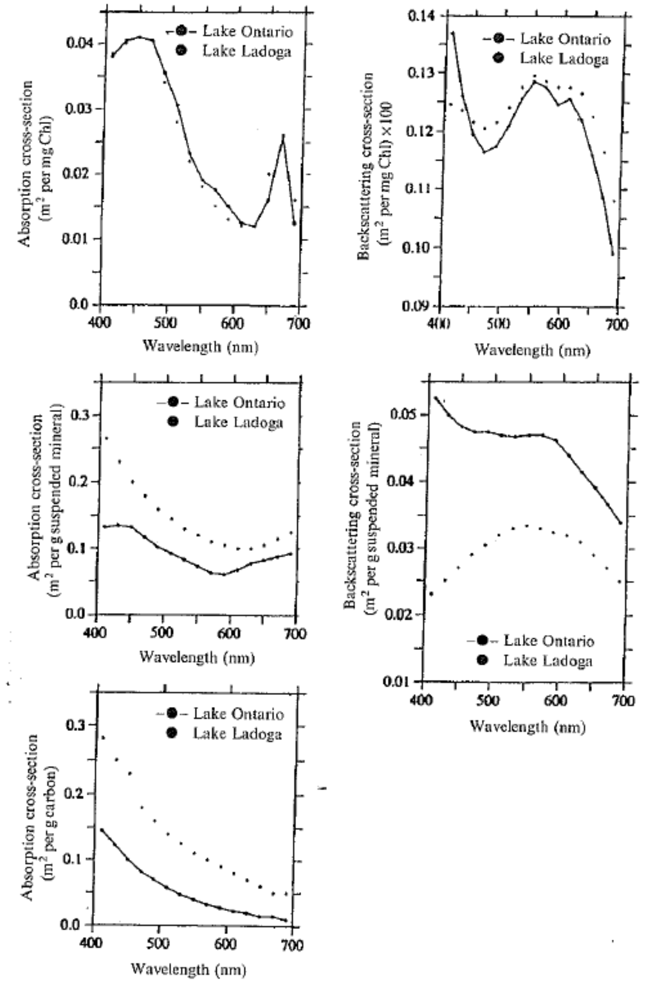


Figure 2.4. Specific spectral absorption and backscattering coefficients (cross-sections) for phytoplankton (*chl*), *sm*, and *doc* determined for Lake Ladoga (●) and Lake Ontario (-●-) waters (Bukata *et al.*, 1995).

CPA Algorithm

- Given an HO-model for a body of water, CPA concentration (Chl, SM, DOC) images can be produced from satellite reflectance images using multivariate inverse procedures
- Our algorithm uses the Levenburg-Marquardt (LM) procedure for finding a solution to the inverse problem
- A CPA concentration vector is found which minimizes the error between the measured and calculated RSR (Remote sensing reflectance)

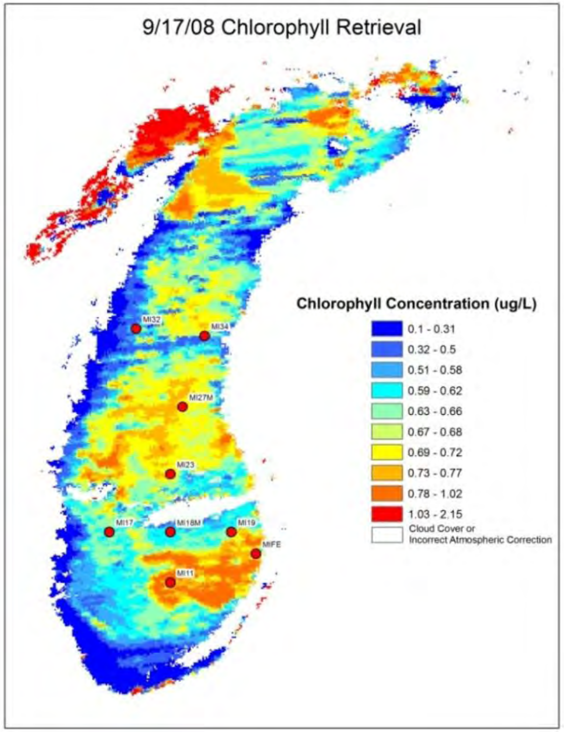
Application of Algorithm

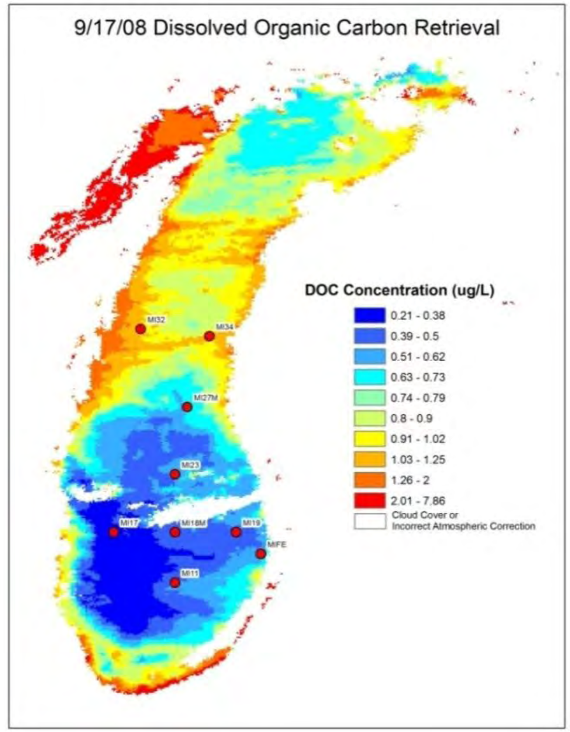
- The CPA retrieval algorithm has been applied to MODIS and SeaWiFS images of the Great Lakes, mostly using a HO-model for Lake Ontario developed over 20 years ago
- The most extensive analysis was performed in Lake Michigan:
  - Pozdnyakov, D., Shuchman, R.A., Korosov, A., Hatt, C. (2005) "Operational algorithm for the retrieval of water quality in the Great Lakes," Remote Sensing of Environment, Volume 97, Issue 3, pp. 352-370.
  - Shuchman, R.A., Korosov, A., Hatt, C. and. Pozdnyakov, D. (2006). "Verification and Application of a Bio-optical Algorithm for Lake Michigan Using SeaWiFS: a 7-year Inter-Annual Analysis." Journal of Great Lakes Research 32: 258-279.

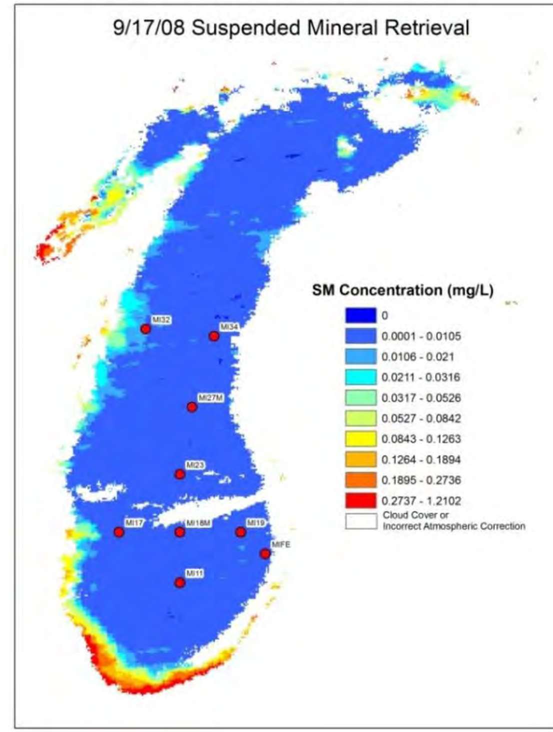
Initial 2006 Results of Algorithm

- Algorithm results for Lake Michigan have been shown to compare reasonably well with patterns obtained from sea-truth values – however absolute concentrations were either under predicted or over predicted as a function of concentration.
- More importantly, the images produced are able to capture important episodic events and temporal-spatial phenomena that scheduled field sampling cannot capture, such as the spring-time sediment re-suspension event in Lake Michigan
- Annual and inter-annual synoptic observations show changes in the Great Lakes that are a result of changing climate conditions and invasive species

Lake Michigan CPA Retrievals

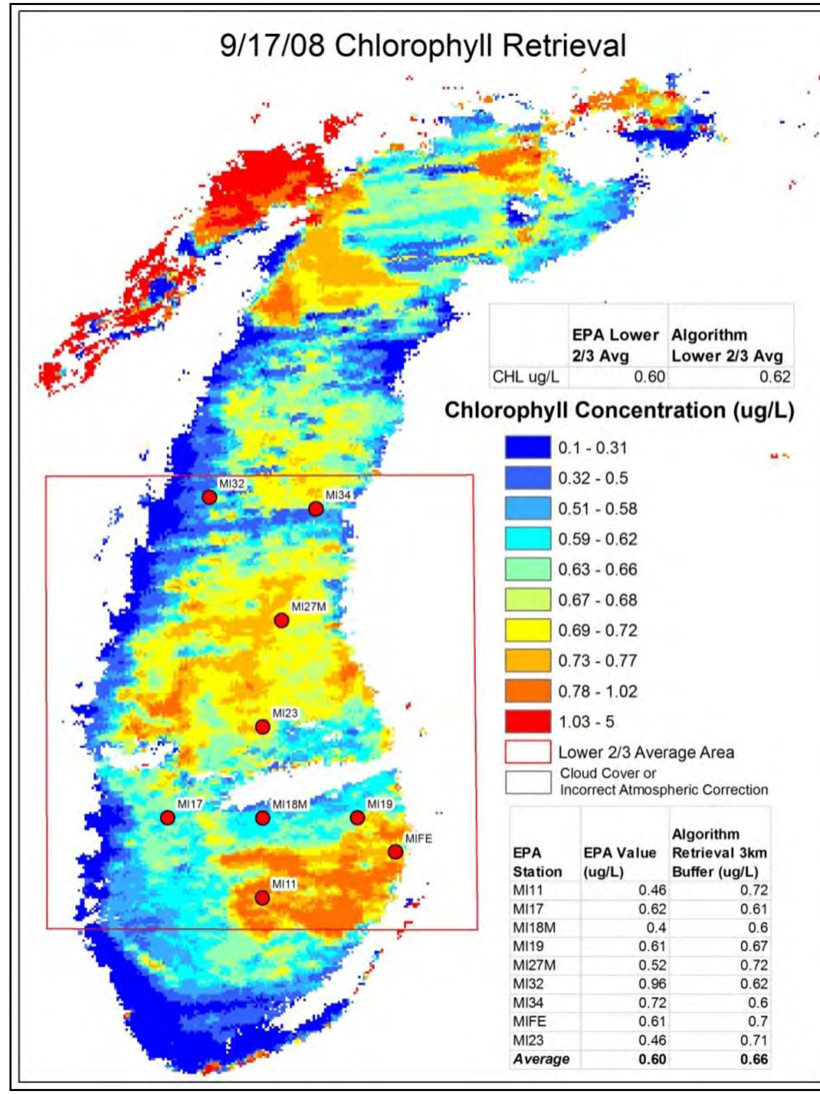






Chlorophyll Retrieval Comparison - Lake Michigan

- EPA sampling station average =.60 ug/L versus CPA algorithm (in boxed area) =.62 ug/L
- Individual station comparison (3x3 km buffer)
  - Max difference = .34 ug/L
  - Min difference = .01 ug/L
  - Avg difference = .17 ug/L
- Very good considering temporal and spatial differences between satellite retrieval and field measurements



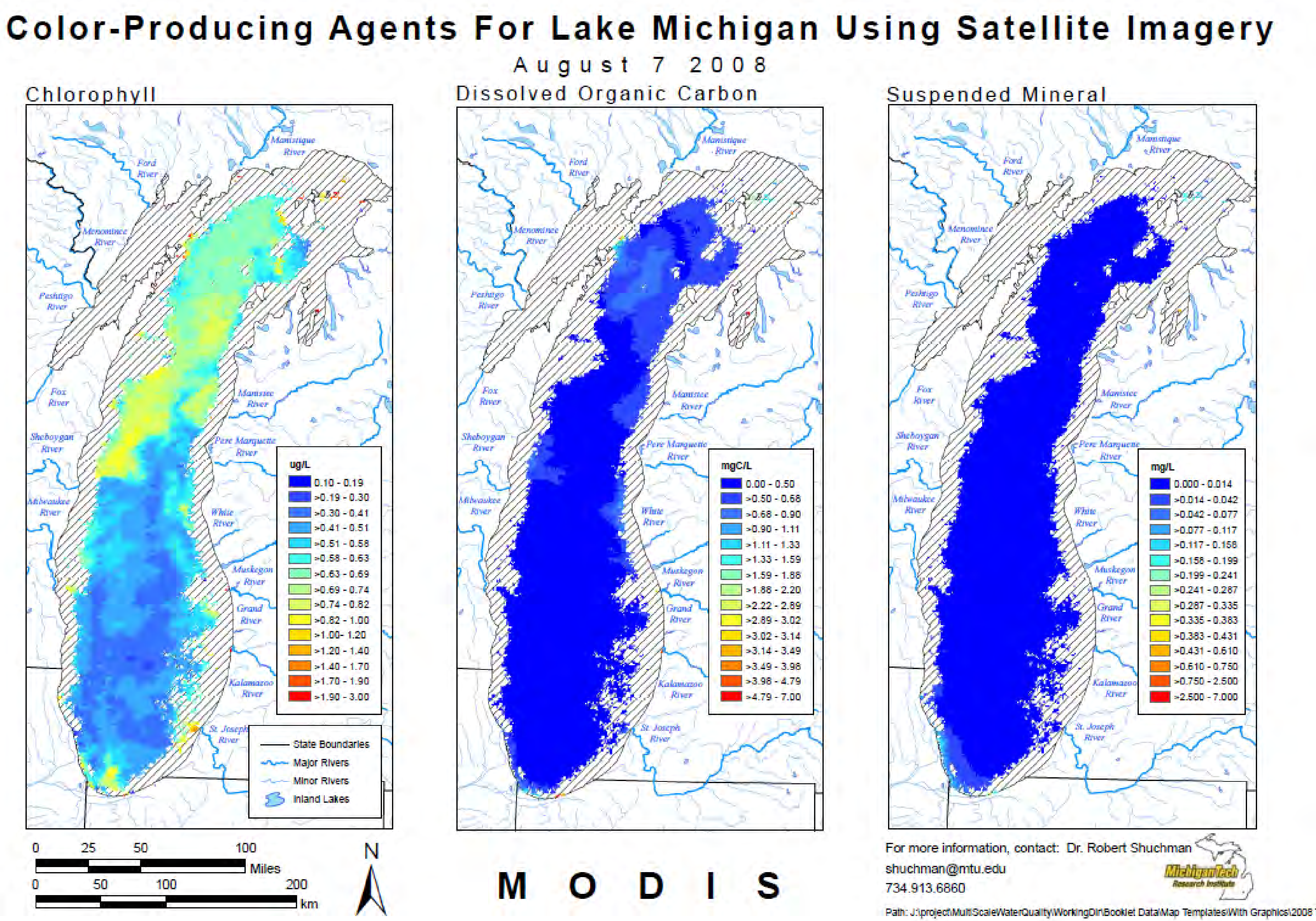
	EPA Lower 2/3 Avg	Algorithm Lower 2/3 Avg
CHL ug/L	0.60	0.62

EPA Station	EPA Value (ug/L)	Algorithm Retrieval 3km Buffer (ug/L)
MI11	0.46	0.72
MI17	0.62	0.61
MI18M	0.4	0.6
MI19	0.61	0.67
MI27M	0.52	0.72
MI32	0.96	0.62
MI34	0.72	0.6
MIFE	0.61	0.7
MI23	0.46	0.71
Average	**0.60**	**0.66**

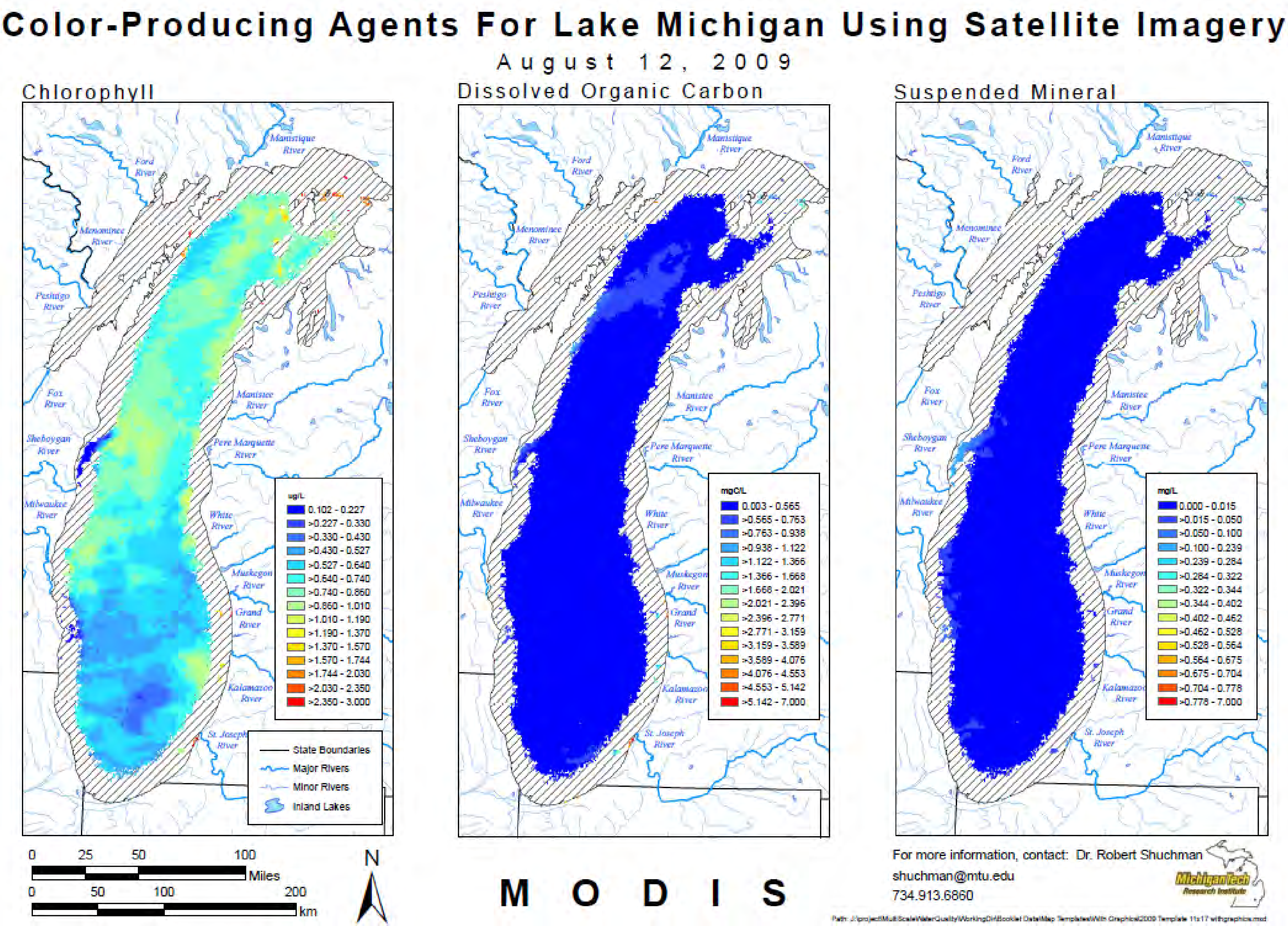
Lake Michigan CPA Retrievals

- Uses both MODIS (1 km resolution) and MERIS (300 m resolution) satellite imagery.
- Retrievals have been completed for entire MODIS Aqua archive (2002 – 2010) of cloud free imagery.
- Lake Michigan “sees” approximately 60-70 cloud free days a year between March and November.
- Retrieval results are optimal when the target is in the center of the swath.
- Approximately 520 MODIS images have been processed for Lake Michigan.
- Extensive archive facilitates analysis in Chlorophyll, DOC, and SM trends in relation to changes in anthropogenic forcing, invasive species, and climate change.

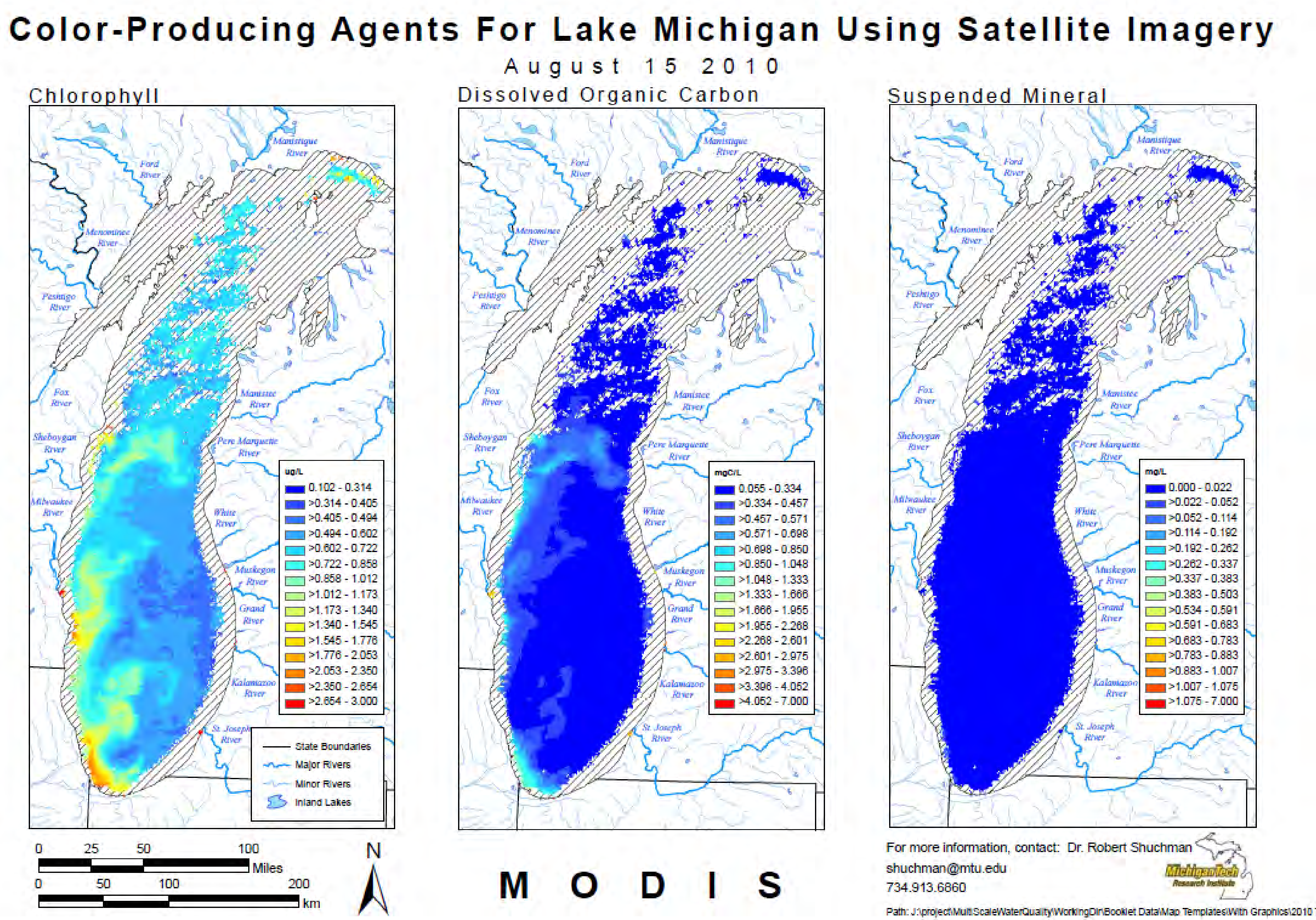
Lake Michigan CPA Retrievals Time Series – August 2008



Lake Michigan CPA Retrievals Time Series – August 2009

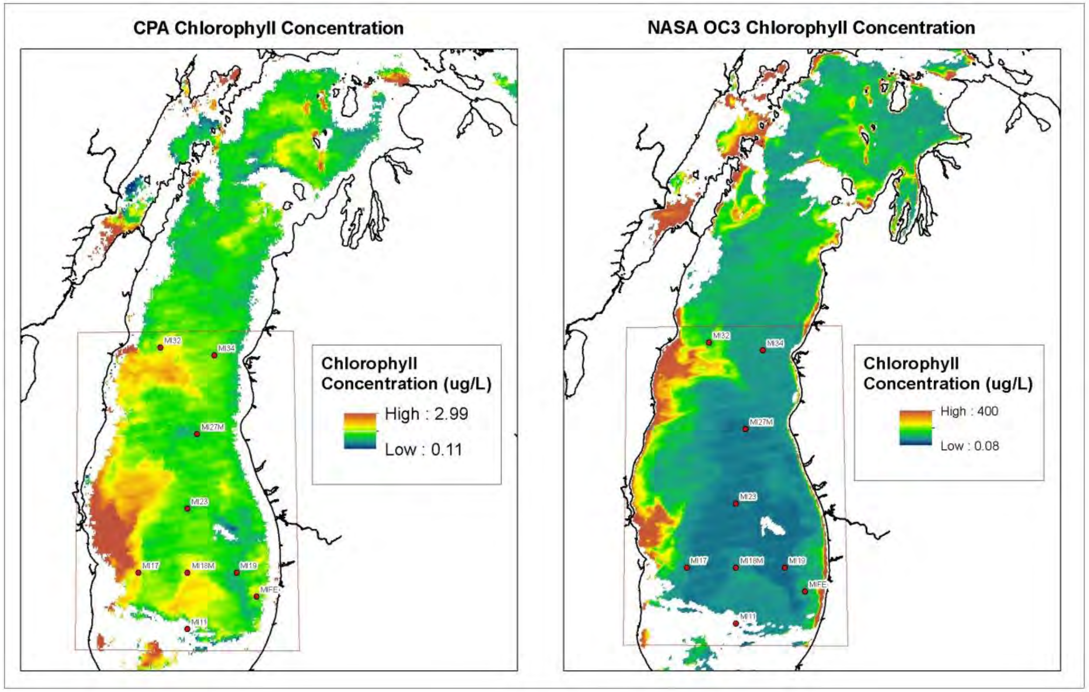


Lake Michigan CPA Retrievals Time Series – August 2010



Lake Michigan Chlorophyll Retrieval Comparison - Standard NASA OC3 Algorithm

- Cruise data from 8/6/2010-8/8/2010, Satellite image from 8/8/2010.
- GLERL sampling station average = .66 ug/L versus CPA algorithm (in boxed area) =.74 ug/L, OC3 = .76 ug/L
- Individual station comparison (3x3 km buffer)
  - Max difference
    - CPA = .51 ug/L
    - OC3 = .56 ug/L
  - Min difference
    - CPA = .01 ug/L
    - OC3 = .14 ug/L
  - Avg difference
    - CPA = .15 ug/L
    - OC3 = .24 ug/L

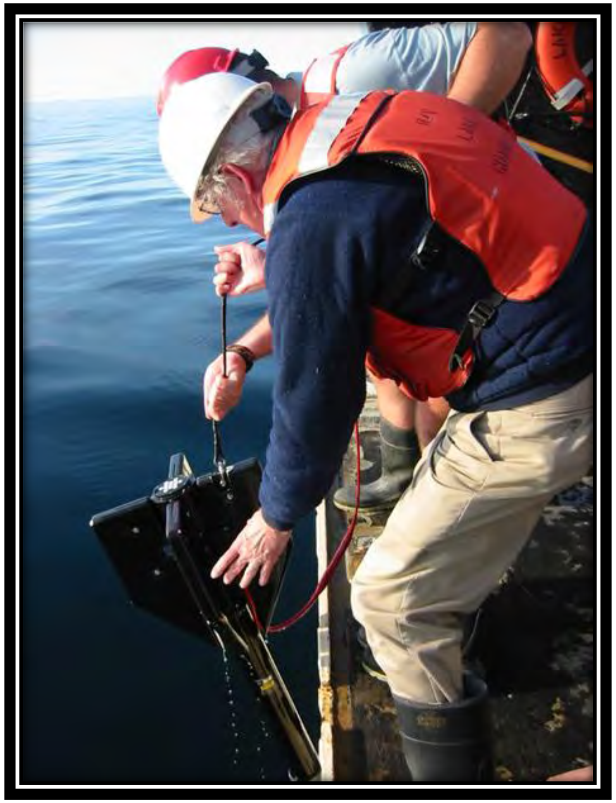


Station	In situ CHL (ug/L)	8/8/2010 CPA (ug/L)	CPA versus in situ (ug/L)	8/8/2010 OC3 (ug/L)	OC3 versus in situ (ug/L)
MI 17	0.51	0.81	0.30	0.37	0.14
MI 18M	0.61	0.80	0.19	0.43	0.18
MI 19	0.54	0.55	0.01	0.28	0.26
MI FE	0.63	0.73	0.10	0.49	0.15
MI 23	0.55	0.59	0.04	0.30	0.26
MI 27M	0.55	0.56	0.01	0.30	0.25
MI 34	0.60	0.68	0.08	0.44	0.16
MI 32	1.27	0.76	0.51	0.71	0.56

CPA Algorithm vs. Standard NASA OC3 Comparisons

- CPA retrievals are significantly more accurate than OC3 when compared to EPA in situ observations
- OC3 only provides Chlorophyll estimate, DOC and SM are not estimated
- Satellite based Lake wide primary productivity estimates require accurate Chlorophyll inputs

Database to Support HO Model Development for each Great Lake



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The Great Lakes IOP Geospatial Database: Design and Implementation

NOAA GLERL Great Lakes Environmental Research Laboratory

- **Objective**: Create an organized spatial representation of in-situ optical and lab concentration measurements.
  - We have created the ***Great Lakes Inherent Optical Properties (IOP) Geospatial Database***
  - Data was delivered in many different formats and styles (UFI & NOAA-GLERL).
  - Need a database development environment to be able to create data “importers” to make sure data is in standard format to facilitate accurate querying.
  - Need to rigorously test data importers to make sure data is imported correctly.
  - Data from many different years and cruises needs to be stored in a uniform structure
  - A spatially enabled database allows for spatial analysis of how much and where coincident field and lab data is present.

Data Output Explain Messages History

	timestamp timestamp with time zone	height double precision	name character varying(255)	value double precision	name character varying(255)
1	2007-08-11 00:47:00+00	15	ON12	0.34433085	K_LU_hyperspectral_downcast
2	2007-08-11 00:47:00+00	4.7	ON12	1.58	Chl_fl
3	2007-08-11 00:47:00+00	4	ON12	0.647	scatter
4	2007-08-11 00:47:00+00	25.1	ON12	0.7	VSS_AH
5	2007-08-11 00:47:00+00	4	ON12	0.021	CDOM
6	2007-08-11 00:47:00+00	25.1	ON12	0.8	FSS_AH
7	2007-08-11 00:47:00+00	4	ON12	-0.062	particle
8	2007-08-11 00:47:00+00	1	ON12	0.9	TSS_AH
9	2007-08-11 00:47:00+00	4	ON12	-0.045	absorp
10	2007-08-11 00:47:00+00	25.1	ON12	1.5	TSS_AH
11	2007-08-11 00:47:00+00	4	ON12	0.645	atten
12	2007-08-11 00:47:00+00	1	ON12	0.8	VSS_AH
13	2007-08-11 00:47:00+00	4	ON12	0.645	scatter
14	2007-08-11 00:47:00+00	25.1	ON12	5.5	Chl_fl
15	2007-08-11 00:47:00+00	4	ON12	0.021	CDOM
16	2007-08-11 00:47:00+00	1	ON12	1.54	Chl_fl
17	2007-08-11 00:47:00+00	4	ON12	-0.065	particle
18	2007-08-11 00:47:00+00	1	ON12	0.1	FSS_AH
19	2007-08-11 00:47:00+00	4	ON12	-0.048	absorp
20	2007-08-11 00:47:00+00	15	ON12	0.34151024	K_LU_hyperspectral_downcast
21	2007-08-11 00:47:00+00	4	ON12	0.643	atten
22	2007-08-11 00:47:00+00	15	ON12	0.33200711	K_LU_hyperspectral_downcast
23	2007-08-11 00:47:00+00	4	ON12	0.643	scatter
24	2007-08-11 00:47:00+00	15	ON12	0.30769388	K_LU_hyperspectral_downcast
25	2007-08-11 00:47:00+00	4	ON12	0.02	CDOM
26	2007-08-11 00:47:00+00	15	ON12	0.31074586	K_LU_hyperspectral_downcast
27	2007-08-11 00:47:00+00	4	ON12	-0.068	particle
28	2007-08-11 00:47:00+00	15	ON12	0.33521512	K_LU_hyperspectral_downcast
29	2007-08-11 00:47:00+00	4	ON12	-0.051	absorp
30	2007-08-11 00:47:00+00	15	ON12	0.26708795	K_LU_hyperspectral_downcast
31	2007-08-11 00:47:00+00	4	ON12	0.641	atten
32	2007-08-11 00:47:00+00	15	ON12	0.22175645	K_LU_hyperspectral_downcast
33	2007-08-11 00:47:00+00	4	ON12	0.641	scatter
34	2007-08-11 00:47:00+00	15	ON12	0.22078695	K_LU_hyperspectral_downcast
35	2007-08-11 00:47:00+00	4	ON12	0.02	CDOM

Example of CHL, FSS, VSS, TSS, CDOM, absorption, & attenuation data now stored in relational IOP geospatial database

Field and Lab Data Summary

Data provided by the Great Lakes Environmental Research Laboratory (GLERL) and the Upstate Freshwater Institute (UFI)

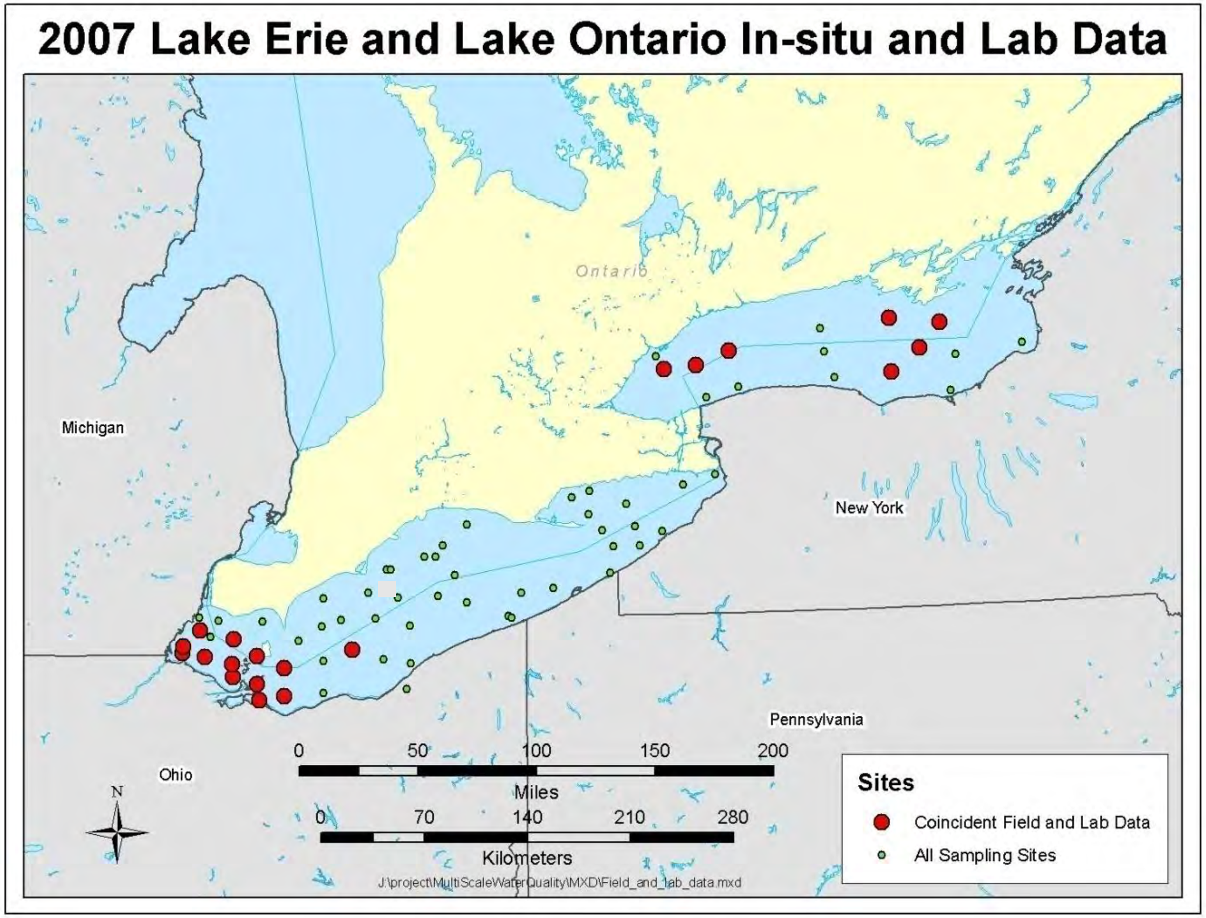
Great Lakes Inherent Optical Properties (IOP) Geospatial Database

		Field Measurements						Lab Measurements					
Year	Lake	Satlantic (AOPs)	Backscatter	Absorption	Attenuation	Scattering	CDOM	Chl	DOC	CDOM	SM	TSS	Locations
1997	Lake Michigan	■						■	■			■	■
1997	Lake Superior	■						■					■
1998	Lake Michigan	■						■	■			■	■
1998	Lake Erie	■						■				■	
2004	Lake Erie							■					
2005	Lake Erie	■						■	■	■	■		■
2006	Lake Superior	■	■	■	■	■	■	■		■	■	■	■
2006	Lake Huron	■						■	■				■
2006	Lake Erie	■						■	■				■
2007	Lake Superior	■						■	■	■	■	■	■
2007	Lake Erie	■	■	■	■	■	■	■	■	■	■	■	■
2007	Lake Ontario	■	■	■	■	■	■	■	■	■	■	■	■
2008	Lake Michigan	■	■	■	■	■	■	■	■	■	■	■	■
2008	Lake Huron	■	■	■	■	■	■	■	■	■	■	■	■
2008	Lake Erie	■	■	■	■	■	■	■	■	■	■	■	■
2008	Lake Ontario	■	■	■	■	■	■	■	■	■	■	■	■

Green cells indicate where there is available data, by year (1997-2008) & by lake

Spatial Distribution of Coincident Field and Lab Data

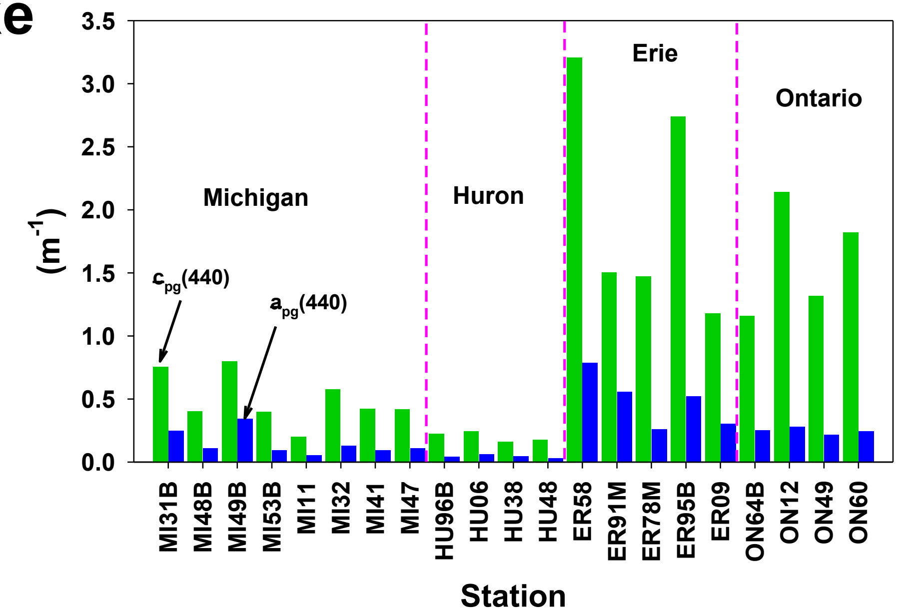
- Spatial data is easily accessed via open source & commercial GIS environments.
- Facilitates QA/QC activities as well as spatial analysis.
- Data can easily be distributed via online interactive websites as well.

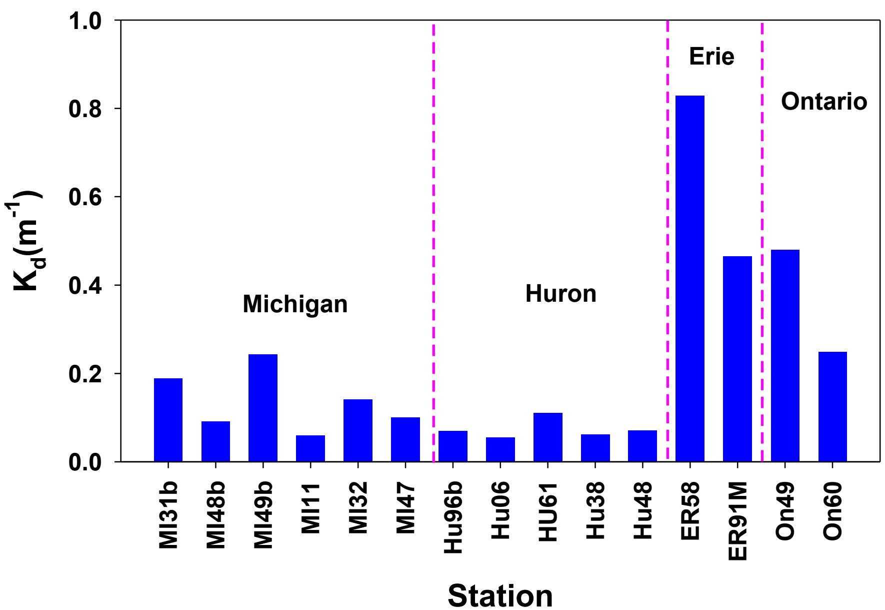


Upstate Freshwater Institute Inherent Optical Property Comparison

August 2008 Cruise on R/V Lake Guardian

Bulk attenuation, c_{pg}, and bulk absorption, a_{pg}, show water optical variability among lakes.



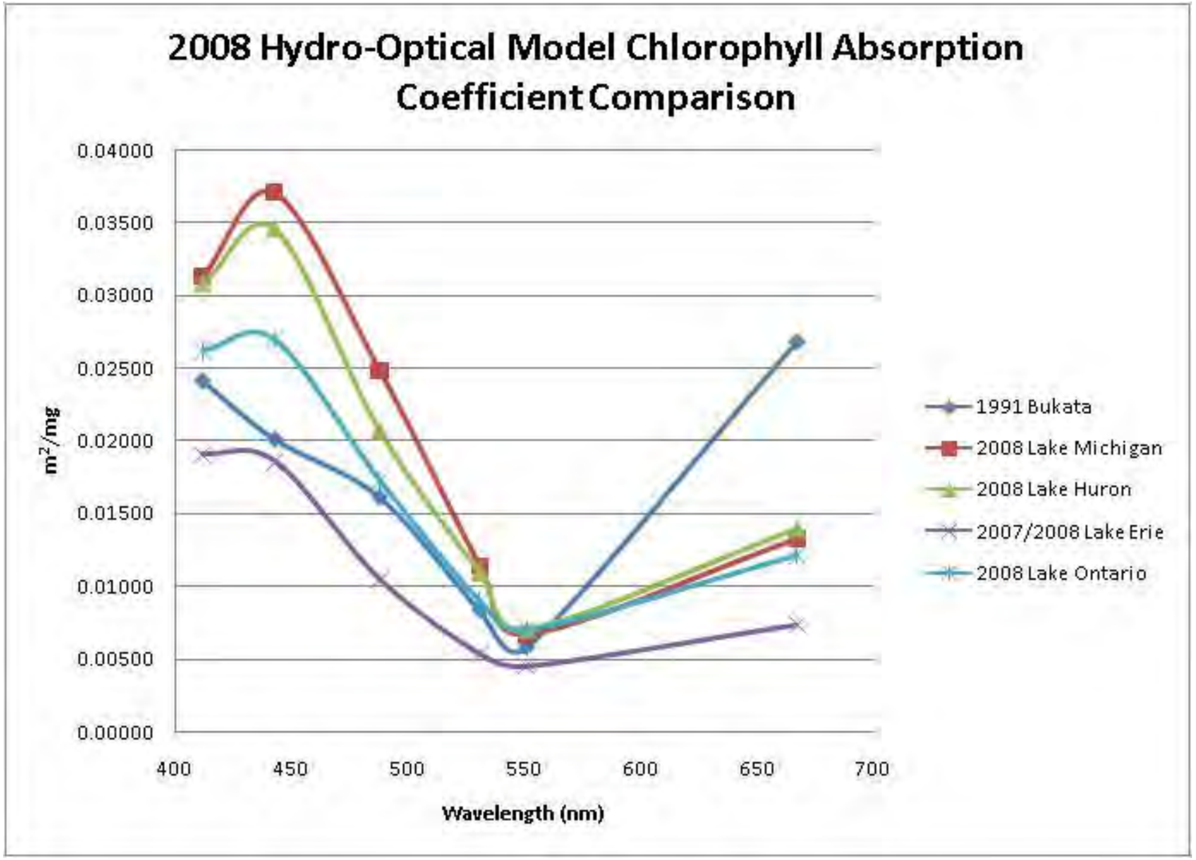


The diffuse attenuation coefficient @490nm, K_d, reaffirms that apparent optical properties among lakes is also quite variable, as expected.

From: O'Donnell, David et al. 2009 IAGLR Presentation: "*Spectral Measurements of Absorption, Beam Attenuation and Backscattering Coefficients, and Remote Sensing Reflectance in Four Laurentian Great Lakes*."

Modified Hydro-Optical Model Chlorophyll Example

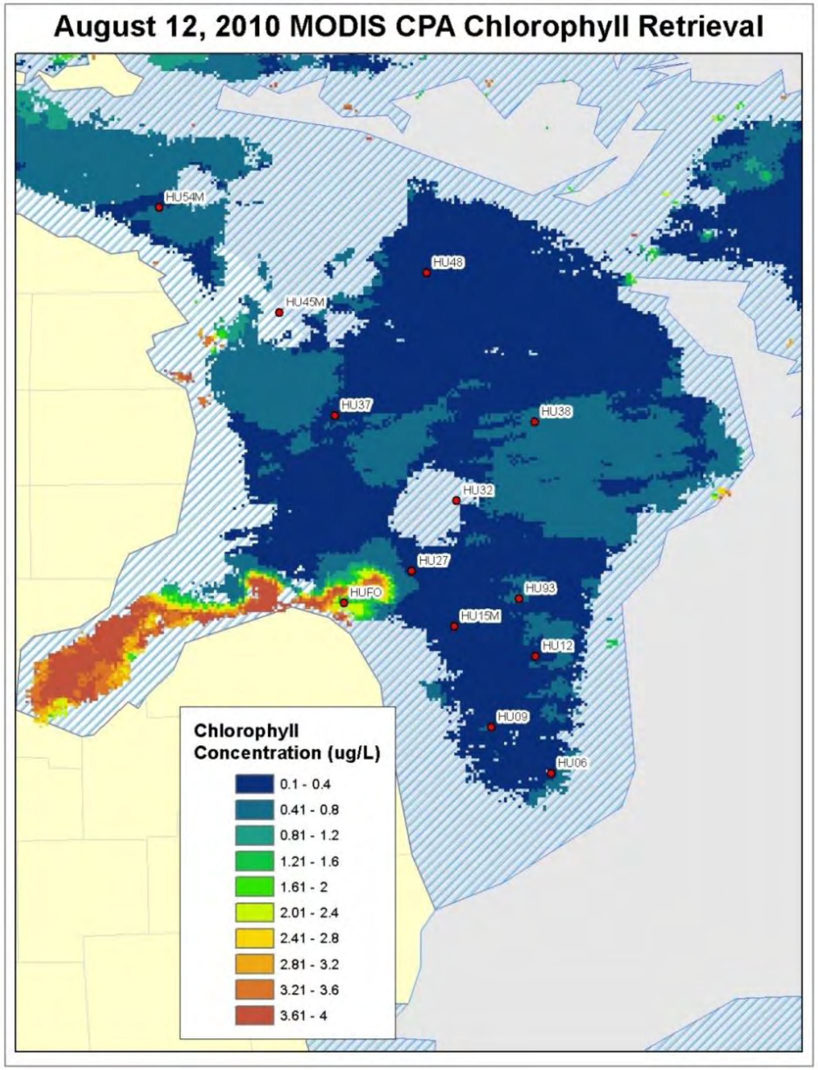
- Significant departure from over 20 year old Bukata Lake Ontario HO Model
- Results agree with analysis conducted by UFI.
- Indicates that different HO models will be necessary for individual lakes or groups of lakes for accurate retrievals.
- Further analysis will be done examining in-situ data from 2000-2007 to further strengthen HO model parameters.



Summary for Hydro-Optical Model

- A comprehensive set of IOP measurements with in-situ sampling exists for all the Great Lakes.
- This data set is providing input for updating the Hydro-optical (HO) models for each lake, which is necessary for correct retrievals.
- Preliminary results indicate each Lake will require its own unique HO model.
- The new HO models for Lakes Michigan and Huron are providing robust retrievals.
- CPA algorithm provides more accurate chlorophyll estimates than the standard NASA OC3 retrievals.

Chlorophyll Retrieval Comparison Lake Huron



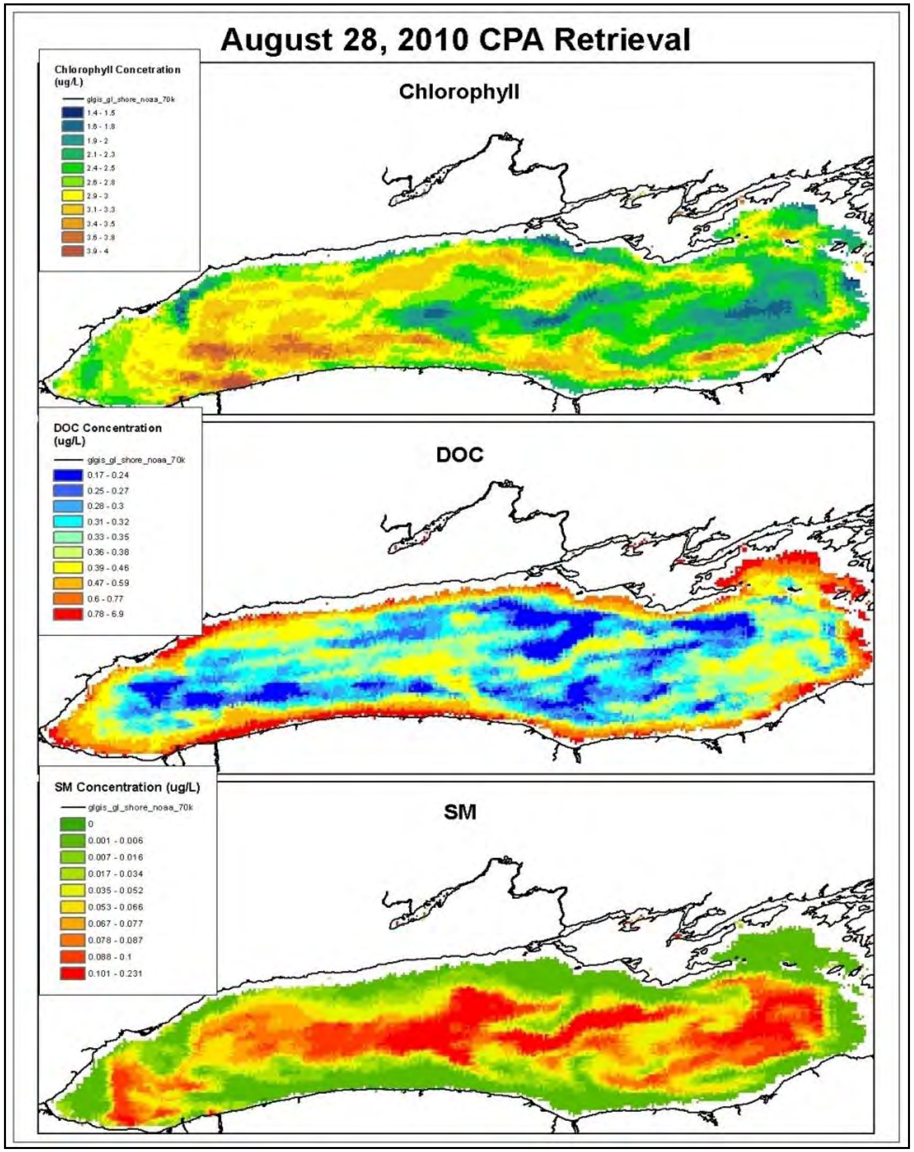
Station	Depth (m)	In situ CHL (ug/L)	CPA Retrieval (8/12/10)	CPA versus in situ (ug/L)
HU 48	1.6	0.33	0.28	0.05
HU 45M	1.8	0.71	0.41	0.30
HU 37	1.9	0.33	0.36	0.03
HU 38	2.1	0.31	0.47	0.16
HU 32	1.5	0.34	0.35	0.01
HU 27	2.1	0.33	0.36	0.03
HU 15M	2.1	0.32	0.18	0.15
HU 93	2.1	0.36	0.41	0.05
HU 12	1.9	0.41	0.36	0.05
HU 09	1.9	0.37	0.35	0.02
HU 06	2.1	0.53	0.35	0.18

Average Difference = .09 ug/L

- In situ measurements from NOAA GLERL cruise 8/6/2010 to 8/8/2010

Lake Ontario CPA Retrieval Example

- A work in progress
- Lake Superior and Lake Erie next



Questions?

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