An Operational Algorithm to Retrieve Chlorophyll, DOC, and Suspended Minerals from Satellite Data of the Great Lakes

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ABSTRACT

A set of algorithms have been developed for the five North American Great Lakes that utilizes MERIS, MODIS, or SeaWiFS satellite data to estimate chlorophyll (chl), dissolved organic carbon (doc), and suspended minerals (sm), the three primary Color Producing Agents (CPAs). The algorithms utilize a specific hydro-optical (HO) model for each lake. The HO models provide absorption functions for all three CPA components as well as backscatter relationships for the chl, and sm and were generated using in situ inherent /apparent optical (IOP/AOP) data collected with coincident water chemistry (concentration) measurements. These new algorithms provide more accurate chl values then those obtained using the standard OC3 NASA MODIS retrieval when compared to in situ cruise observations, as well as providing the additional information on doc and sm. The suite of atmospheric correction algorithms for MODIS was also evaluated. In general the standard NASA algorithm does an adequate correction all of the time.

1. INTRODUCTION

The Great Lakes account for approximately 20% of the Earth's surface fresh water and supply drinking water for 40 million United States and Canadian people [1]. Lakes Michigan and Huron in particular have undergone major changes in lower food web production as witnessed by decreases in average chlorophyll, primary productivity, Diporeia, and fish populations [2,3]. Lake Erie and to a lesser extent Lake Ontario continue to exhibit a multiple of Harmful Algal Blooms (HABs) each summer [4,5]. Remote sensing observations from satellites allow for the synoptic long term monitoring of all the Laurentian Great Lakes to document changes in water quality parameters and primary productivity as a result of the climate, anthropogenic, and invasive species forcing functions.

Waters in the Great Lakes and coastal ocean areas, known as the Morel and Prieur case II waters, have optical properties that are influenced not only by phytoplankton, but also inorganic terrigenous particulate matter in suspension (sm) and dissolved organics (doc). Note that the cdom color component retrieved by this set of algorithms is simply a portion (approximately half) and is not the same as doc. In the Great Lakes and in particular the nearshore, bays, river mouths, and areas of concern (AOCs) the content of sm and doc in the water column is abundant enough to compete with the phytoplankton in influencing the resultant composite optical properties, thus creating optically complex water [6]).

2. HYDRO-OPTICAL MODEL GENERATION AND ALGORITHM DESCRIPTION

When observing case II waters from space, it is impossible to retrieve the concentration of a single component like chl without also inferring the content of the other major water constituents determining the overall color, the so called color producing agents (CPAs) [7]. The new CPA algorithms presented here utilize a Levenburg-Marquardt (L-M) multivariate optimization procedure [8,9] to estimate chl, cdom, and sm based on hydro-optical (HO) models generated using cruise data from each of the Great Lakes. HO models were generated for each lake using simultaneously obtained optical water property data and measurement of chl, cdom, doc and sm using standard methods. The algorithms are non-satellite specific and the number of spectral bands utilized is variable depending on application. To avoid inadequate retrieval results, the algorithm identifies and discards pixels with poor atmospheric correction and/or water optical properties incompatible with the applied HO models. Thus pixels in optically shallow water (reflected light from the lake bottom) are discarded during the retrieval process. The algorithms are in the process of being modified to estimate CPAs in shallow water.

The overall algorithm and initial evaluation is well described by [7] and by [10] and will not be repeated here. In summary, the model assumes the remote sensing reflectance (RSR) can be calculated from the specific absorption and backscattering coefficients, along with concentrations of each CPA:

$$RSR_i = f(a_i,b_i)a_i = a_{H20,i} + C_{chl}a_{chl,i} + C_{doc,i}a_{doc,i} + C_{sm}a_{sm,I} \quad (1)$$

$$b_i = b_{H20,i} + C_{chl}b_{chl,i} + C_{doc}b_{doc,i} + C_{sm}b_{sm,i}$$

Where,
C = Vector representing concentration of each CPA
a_i = Bulk absorption coefficient for each CPA at band i
b_i = Bulk backscattering coefficient for each CPA at band i
$a_{i,j}$ = Specific absorption coefficient for each CPA j at band i.

$b_{i,j}$ = Specific backscattering coefficient for each CPA j at band i.

As the above equations indicate, specific absorption and backscattering coefficients for each CPA are needed for each satellite spectral band utilized. The table of specific backscattering and absorption coefficients is referred to as the HO model. Given an accurate HO model can be generated for a body of water, CPA concentration images can be produced from satellite reflectance images using a multivariate inverse procedure. As mentioned previously this algorithm approach uses the Levenburg-Marquardt procedure for finding a solution to the inverse radiative transfer problem. In this procedure a CPA concentration vector is found which minimizes the error between the measured and calculated RSR. After an initial educated estimate for the CPA concentrations, the L-M procedure converges on a minimum in the error function using:

$$\sum_{i=1}^{total\_bands} \left(\frac{S_i - RSR_i}{S_i} \right)^2 = \text{Error} \qquad (2)$$

Where,
S_i = Measured remote sensing reflectance from satellite for band i
RSR_i = Calculated remote sensing reflectance from CPA concentrations, HO-model for band i.

3. ALGORITHM RESULTS

Based on the IOP measurements it was determined that a lake specific HO model was needed for each of the five Laurentian Great Lakes. In this section we present example results of the CPA algorithm for Lake Michigan and compare the retrievals to the Environmental Protection Agency (EPA) in situ observations of chl and where available cdom/doc and sm. The EPA does not routinely measure doc, cdom or sm. In the case of cdom we utilized the Upstate Freshwater Institute (UFI) measurements not used in the HO model development to show that CPA produces reasonable values. The new algorithm results were also compared to the standard NASA OC3 retrievals.

Fig.1 is an example of the new Lake Michigan CPA algorithm applied to a 1 km spatial resolution MODIS image collected on August 8, 2010. Hatched areas on the CPA retrieval image indicate no retrieval information, which is a result of clouds, poor atmospheric correction, or significant lake bottom return in optically shallow water. The figure shows the comparison of the CPA chl map to the standard NASA OC3 chl retrieval for the same MODIS image. The NASA OC3 algorithm was selected because this is the default chl model for case II waters. The EPA stations from a cruise (August 2 to August 5, 2010) are shown as red dots on the images. This August 8, 2008 image pair was the closest cloud free observation corresponding to the cruise dates. The maximum chl values generated by the CPA algorithm was 3.0 µg/L while the maximum value for the OC3 chl estimate was 400 µg/L. NASA cautions users to discard all retrievals in excess of 100 µg/L. Further examination of the NASA and CPA retrieval of chl indicates lower chl values are produced by the NASA OC3 algorithm in the open water portion of the lake, when compared to the CPA values. The CPA algorithm in its present form does not produce retrievals in optically shallow water, hence the high OC3 chl values along the shore in optically shallow water are not visible in the CPA product. Close examination of the OC3 retrieval reveals that the nearshore chl estimates are artificially very high, ranging upwards to 400 µg/L. These high values are most likely a result of the NASA algorithm interpreting high shallow water reflectance values as phytoplankton in the water column whereas these high reflectance values are actually the result of reflection off the lake bottom (sand and benthic algae) and contributions of cdom and sm in the water column.

Table 1 compares the EPA in situ chl values (red dots on Fig. 1) to the CPA and OC3 derived estimates. For both the CPA and OC3 estimates the same 3 X 3 km area was averaged over the EPA/GLERL locations. The table of values confirms the visual observations in Fig. 1, namely the OC3 produces chl estimates that are consistently lower than the EPA/GLERL cruise measurements. On the table, negative values indicate an under prediction from either of the two satellite retrieval methods. The average difference between the EPA/GLERL truth and CPA chl retrieval was 0.03 µg/L and 0.24 µg/L for the OC3. Minimum and maximum differences as well as the range of chl values produced by each algorithm are also presented in the table indicating improved accuracy for the CPA approach. A large box (see red outline on Fig.1) was drawn around the EPA/GLERL stations to compare the average chl value for this portion of the lake. The EPA/GLERL station average was 0.66 µg/L versus 0.69 µg/L for the CPA results and 0.42 µg/L for the OC3 results.

Fig. 2 shows a MERIS true color image of Lake Michigan taken on August 28, 2011. Fig. 3 is an example of the CPA algorithm applied to the MERIS satellite data collected over Lake Michigan. In this August 28 image, with a spatial resolution of approximately 330 meters, finer detail in the chl, doc, and sm concentration maps can be observed. The higher chl values along the Lake Michigan shore are typical for this time of year [11]. The sm concentration is relatively low throughout the lake with the exception of re-suspension as the result of wave action around the southern shore (red area). The doc values are also quite low at this time of year with the exception of the nearshore areas of the lake and Green Bay.

4. CONCLUSION

A comprehensive set of IOP measurements with corresponding in situ measurements of chl, doc, cdom, sm, and total suspended solids (TSS) have been assembled into a database for all the Great Lakes. This data set developed over several years of research cruises indicated the need for separate HO models for each of the Great Lakes to obtain the required retrieval accuracy. The database that spans nearly two decades of observations also provides insight into how the optical properties of the Great Lakes have changed due to anthropogenic, invasive species introduction and climate change forcing.

The new CPA algorithms for Lakes Michigan, Huron, and Superior are quite robust, with the estimates of chl comparing favorably to the near coincident EPA chl values. The cdom and sm derived values produced simultaneously during the retrieval process are within the correct range, and where coincident data are available, they are in good agreement. Although not shown here, the Lake Erie CPA produced estimates of chl, doc, and sm are good for the central and eastern portion, but under-estimated chl in the Western Basin. To achieve a more accurate retrieval in the western basin, a separate HO model maybe required or the existing Erie HO model updated with new backscatter coefficients for the chl and sm constituents. Also not shown in this paper, the Lake Ontario chl concentration values for the spring and late summer observations reveal the complexity of this Lake with low chl values reported by the EPA of approximately 1 µg/L in the spring to values of 4.5 µg/L in the late summer. The CPA algorithm under-predicted the chl in the spring, but did much better in late summer, correctly predicting the chl values as well as observing a whiting event via an increased value of the sm [12].

Overall, the CPA algorithm provides more accurate chl estimates than the standard NASA OC3 retrievals. The NASA estimates in the optically shallow water are not reliable, most likely the result of light being reflected off the lake bottom and the fact that nearshore waters of the Great Lakes are case II water, namely chl, doc, and sm constituents are in significant concentrations. Satellite derived primary productivity estimates will be more accurate using the new CPA algorithm than the OC3 algorithm based on the more robust chl estimates. The NASA chl estimates for Lake Erie are not particularly useful because this lake has major CPA elements in addition to chl.

5. REFERENCES

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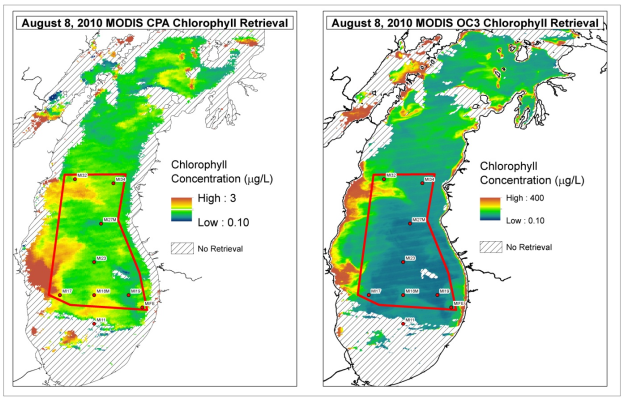

Figure 1. Comparison of CPA and NASA OC3 chlorophyll retrieval for a MODIS Aqua image of Lake Michigan on 8/8/2010

Table 1. Comparison between August 8, 2010 CPA and OC3 chlorophyll retrievals and EPA cruise observations for the same satellite image. For each EPA site (see figure 1) the CPA and OC3 derived chl value are presented along with the difference in respect to the EPA truth. Averages of the values and differences are also presented on the table. On the table, a negative indicates the given algorithm under predicted the chl value in respect to the EPA truth.

Station	EPA CHL (µg/L)	CPA CHL (µg/L)	CPA vs. EPA (µg/L)	OC3 CHL (µg/L)	OC3 vs. EPA (µg/L)
MI 17	0.51	0.81	0.30	0.37	-0.14
MI18M	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	-0.14
MI 23	0.55	0.59	0.04	0.30	-0.25
MI27M	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
Avg.	*0.66*	*0.69*	*0.03*	*0.42*	*-0.24*

Figure 2. MERIS true color image of Lake Michigan on 8/28/2011

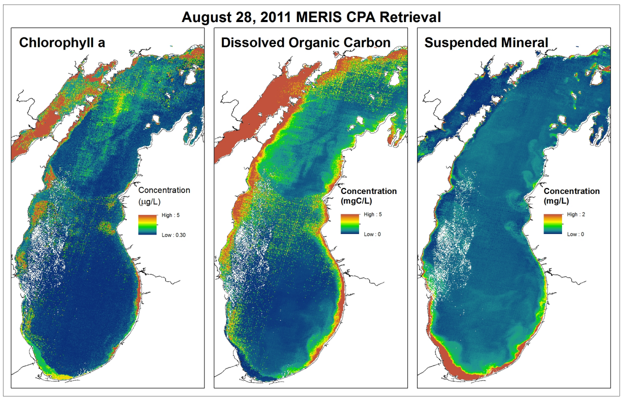

Figure 3. MERIS CPA (chl, doc, sm) retrievals for Lake Michigan on August 28, 2011.

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