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Simple and efficient technique for spatial/temporal composite imagery

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ABSTRACT

Satellite ocean color remote sensing is plagued by loss of coverage due to cloud obscuring, glint contamination, atmospheric correction failures, and other issues. We have developed a simple and efficient technique for estimating missing remote sensing data by taking advantage of the inter-pixel spatial and temporal coherency of individual ocean color products. The technique first employs a limited iterative triangular interpolation procedure. This procedure attempts to select three neighboring pixels forming the tightest triangle enclosing the data point we are attempting to recover; and then interpolating. On failure to find three suitable neighbors, a second procedure is employed which attempts to recover missing data points by using a time dependent "latest pixel" replacement. This procedure replaces the missing data point with the most recent data point collected at that grid point within the last seven days. This technique has been applied to MODIS (MODerate resolution Imaging Spectrometer) ocean color products of phytoplankton absorption, back-scattering coefficient, and chlorophyll concentration to produce cloud free bio-optical products on a daily basis and provide a new capability for monitoring coastal processes. We demonstrate a new method on MODIS products and show how bio-optical properties change over a daily and monthly time scale.

Keywords: Coastal, Ocean Color, Remote Sensing, Composite, Cloud Removal

1. INTRODUCTION

Satellite remote sensing provides the benefits of wide spatial coverage and high temporal revisitation. This provides an advantage over other remote sensing platforms such as aircraft. The nature (it's in space) and in-flexibility (fixed look angle and time of over flight) of satellite remote sensing platforms cause them to be vulnerable to a few issues that other platforms can more easily avoid; namely cloud obscuring and sun glint. These two issues along with other common causes of data coverage loss such as atmospheric correction failure or product algorithm failure are a constant plague to the field of remote sensing.

The open and coastal ocean processes occur at different time and space scales. Satellite ocean color imagery captures the near surface properties of these processes at specific "windows" of opportunities based on the revisit time of the satellite and ability to see the ocean surface (cloud free, glint free, etc.). The revisit time for MODIS is fixed, however attempts to characterize the ocean processes are often limited as a result of clouds, producing data voids. These data voids hinder our ability to interpret the ocean processes. Specifically, the dynamic movements of ocean features are disrupted by these data voids and it is difficult to link the bio-optical properties as a response to circulation. Typically, to understand the changing structure, a 7-day latest pixel composite,[1] is used to fill in the data voids. Here the most recent valid pixel is used to represent the ocean surface. If the pixel is not valid, the previous day's value is used. If that day is not valid then the previous day's pixel is used. This procedure goes back for one week trying to find a valid pixel. If no valid pixel is found for a week, the value is not determined and the area remains black. Figure 1 shows an example of the Northern Gulf of Mexico indicating no retrieved data as black areas. Using this procedure, a daily image can be produced to represent the most recent satellite observations of the bio-optical properties. This procedure works well in open mesoscale processes which do not change too rapidly and where ocean processes have a residence time of $\sim 3-4$ days for

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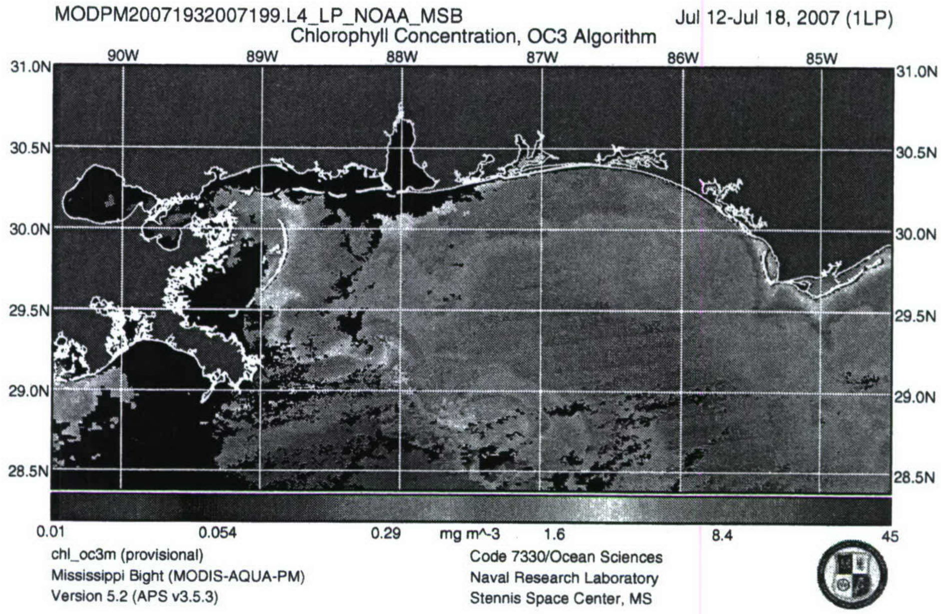

Figure 1. The latest pixel composite (LPC) for the Northern Gulf of Mexico for MODIS Aqua surface chlorophyll for July 18 with previous compositing beginning July 12. The black areas indicate that for the last seven days no valid pixels were available.

observable change. The dynamics of ocean processes become less stable in coastal areas as the processes become more dynamic with resident times approaching hours (tides, winds, etc.). For these coastal areas a more robust method is required to better represent the optimum replacement of "data voids".

To improve the satellite chlorophyll product, we have developed a (fairly) simple and (somewhat computationally) efficient technique for estimating missing remote sensing data points by taking advantage of the inter-pixel spatial and temporal coherency of individual ocean color products. We make the assumption that ocean color products, on any grid scale, possess a value similar in magnitude to their neighbors in nearby grid locations. We make a similar assumption in temporal space. These assumptions allow us to use these nearby data points to regenerate our missing data points.

2. MODIS PROCESSING

MODIS is a multi-spectral sensor with 36 discrete spectral bands. MODIS has nine bands at 1km resolution covering the visible spectrum between 412nm and 869nm, three bands at 500m and two bands at 250m. The MODIS data was processed using the Automated Processing System[2] Version 3.6 developed by the Naval Research Laboratory (NRL). The Automated Processing System (APS) is a collection of software programs assembled by NRL which handles the complete processing of satellite imagery after reception including atmospheric correction, the application of bio-optical algorithms to derive optical properties, and warping of the imagery to a standard map. APS implements a modification of the NASA SeaDAS (v5.1) atmospheric correction procedure.[3,4]

APS software identifies non-valid ocean pixels by screening for 1) Clouds 2) Glint contamination 3) negative radiances from errors in atmospheric correction i.e. epsilon failures 4) bio-optical algorithm failures. Data voids are numerous and unavoidable and extremely problematic in certain ocean regions. These voids can limit the utility of the satellite data especially for coastal applications.

APS implements a number of traditional compositing techniques such as weekly, monthly, and yearly averages. Pixels which have been identified as voids are excluded from the compositing methods. Additionally, APS implements a "latest pixel" composite (LPC). This composite method attempts to replace missing data points with data points at the same grid location collected in the recent past. This type of composite preserves good

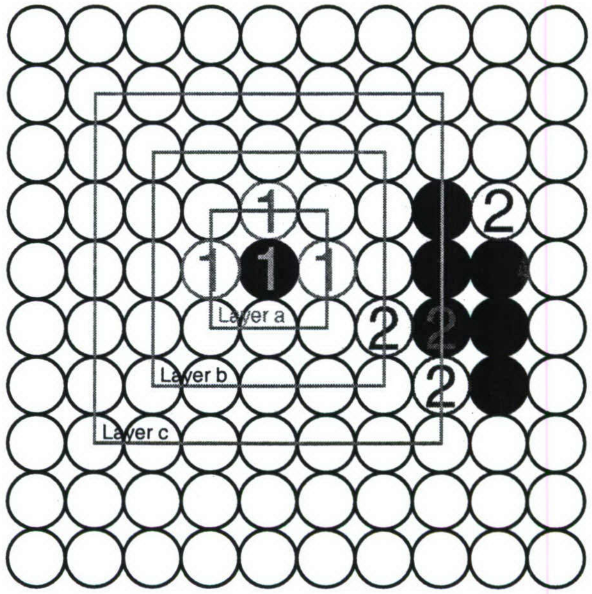

Figure 2. Example of how the triangular interpolation procedure works. The data voids (Black) are filled in using radius distances(referred to as layers a, b, c, ...).

data points, since a good data point is not mixed (averaged) with any other data point. The "7-day latest pixel" composite will search up to seven days into the past to find a good data point.

3. METHODS AND RESULTS

The triangular compositing technique initially employs a limited iterative triangular interpolation procedure. This procedure attempts to select three neighboring pixels forming the tightest triangle enclosing the data point we are attempting to regenerate. The radius of the search, out from the center of the missing data point, is restricted to ten grid points (or ten layers, see figure 2). Once the three data points are found, a triangular interpolation is performed, and the result becomes the new value for the missing data point. If the three data points can not be found, then the value is left unchanged. Care is taken to avoid interpolating across obstructions such as land.

Figure 2 represents an example of the search procedure. Dark colored circles represent data voids, and light colored circles represent data points with known data values. The search is performed using a layered approach. For the case of the dark circle marked "1", the first layer marked "a", is made up of the eight circles immediately surrounding circle "1". These eight data points are added to a list of data points and for every combination of three data points, a triangle is created and a test is conducted to determine whether data point "1" falls inside the triangle. If the search fails at layer "a", then the search is expanded to include the data points from the next layer out: layer "b". The data points from layer "b" are added to the list of data points which already include those from layer "a", and again a triangle enclosing our target data point is searched for. This procedure is continued until three valid points forming a triangle around our point are found or the maximum search radius is reached. The red circles labeled "1" represent the three points selected for interpolation forming a triangle around point "1". The blue circles labeled "2" represent the three points selected for interpolation forming a triangle around point "2".

We have the ability to iterate so that the triangular interpolation procedure is performed repeatedly. Each successive iteration is able to make use of previously interpolated points when searching for the three neighboring pixels for the current triangular interpolation. The iteration can be performed a fixed number of times or repeatedly until no additional pixels can be interpolated. The iteration method can be used to gradually rebuild a section of an image and assists in reducing the neighbor search time by producing similar results with a smaller search radius.

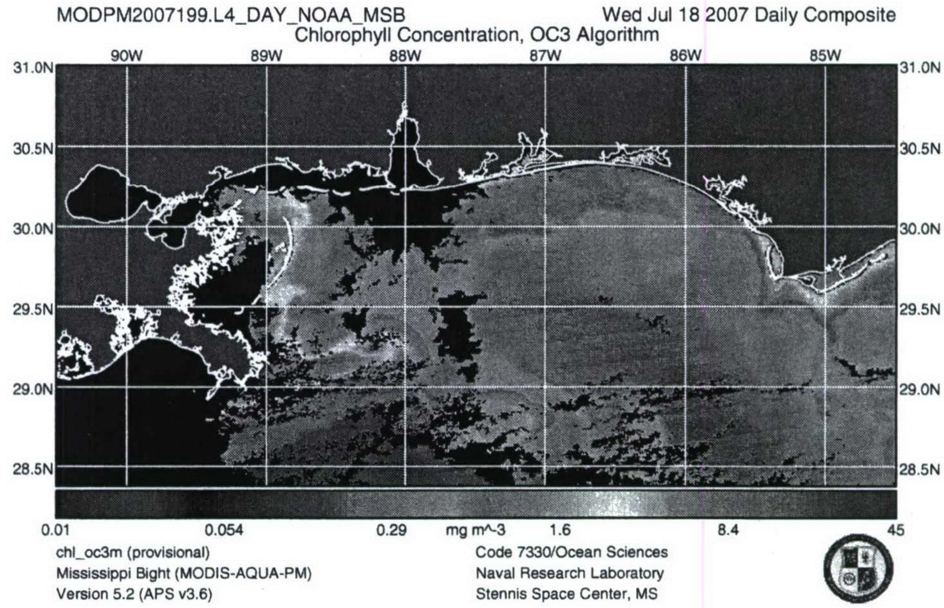

Figure 3. The original MODIS Aqua - surface Chlorohpyll image illustrating the data voids in black.

A nearest neighbor search is also implemented as a fall back method. As its name suggests this is simply a search, limited by the search radius, for the neighboring data point nearest to the data point we are attempting to regenerate.

Additionally, we make use of the image compositing capabilities of APS. We use APS's software to create the "7-day latest pixel" composite described above. We also make use of a feature which allows specifying a limit on the number of pixels that are averaged together to produce a data point. For example, if five scenes were supplied, and a valid non-obscured data point existed in each scene, then five pixels would be averaged together to produce the composited data point. If we limit the composite to two pixels, then only the first two encountered data points will be averaged, the others would be ignored.

The original MODIS Aqua image for the Northern Gulf of Mexico is shown in figure 3. The black areas offshore are clearly flagged as clouds and the coastal areas have failed due to atmospheric correction errors which produced negative radiances. This image is contrasted to the LPC image (figure 1) where a small amount of the black areas have been filled in. In this example the LPC is not the optimum since the previous seven days have collected few valid pixels in the region.

The new methods for filling in the void pixels on this image are performed in five steps.

1. The initial stage is to apply a triangular interpolation method to each data void, searching the necessary layers and iterating ten times. This is perhaps the most important step where the spatial interpolation fills in the majority of the data drop outs. The procedure propagates through the sequential data points filling in the data voids using a search radius of ten pixels or layers. Some of the data voids will remain after this procedure is performed on the entire image. The procedure is repeated ten times to continue to replace the data voids. The result shown in figure 4 clearly removes the cloud noise but still has large gaps in coastal areas.

2. The next step is to use a nearest neighbor search with search radius one to create a border around known pixels (figure 5). This procedure is similar to a dilation of known data values, and enlarges and extends known values into data void regions for bordering pixels. This is especially useful in near shore coastal regions and forms a transition of the bordering data with the next step.

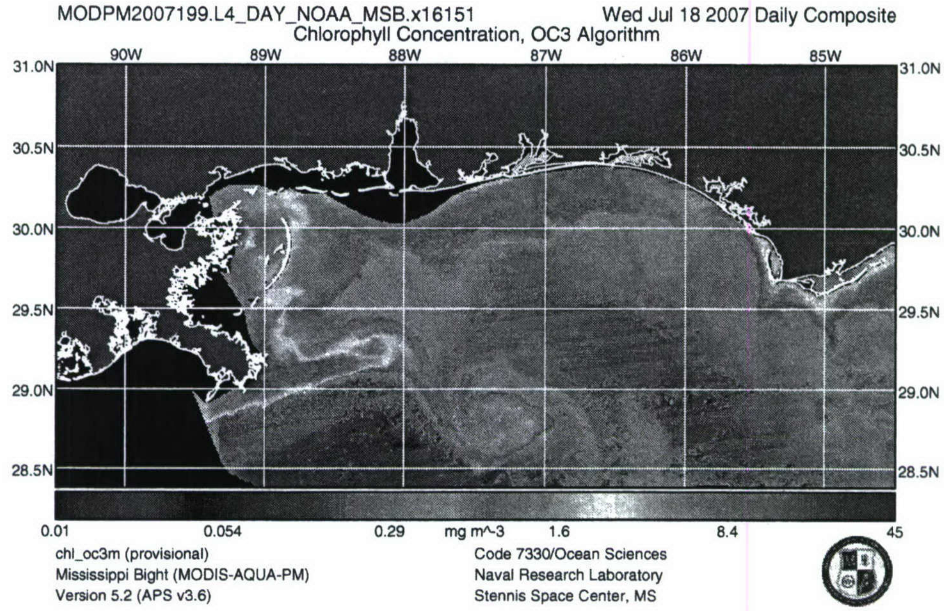

Figure 4. Step 1 of triangular interpolation of the data voids shows replacement of the majority of the cloud noise and data drop outs.

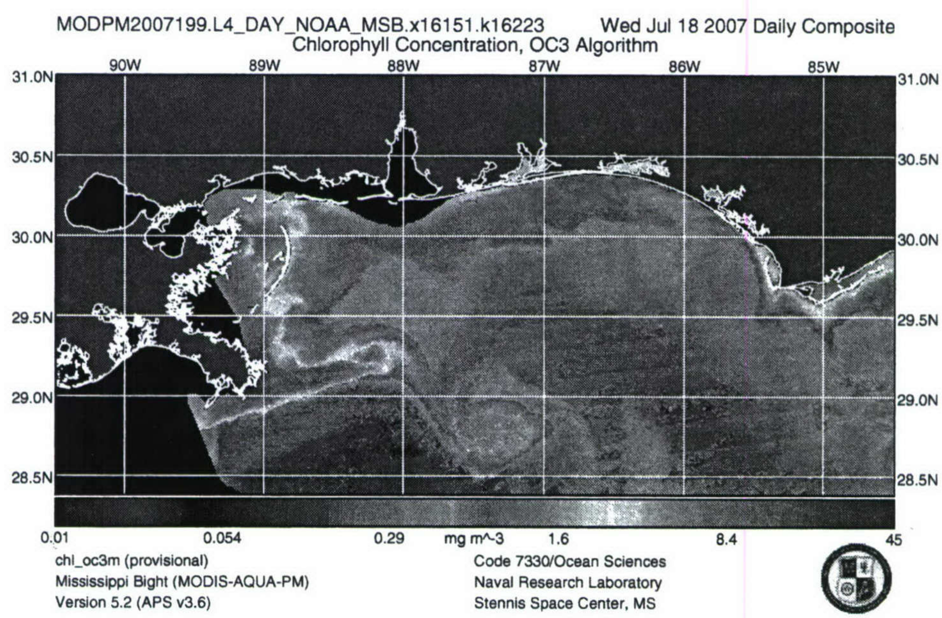

Figure 5. Step 2 creates a border around known data values to replace data voids; especially useful as a transition value when combined with the LPC in the next step.

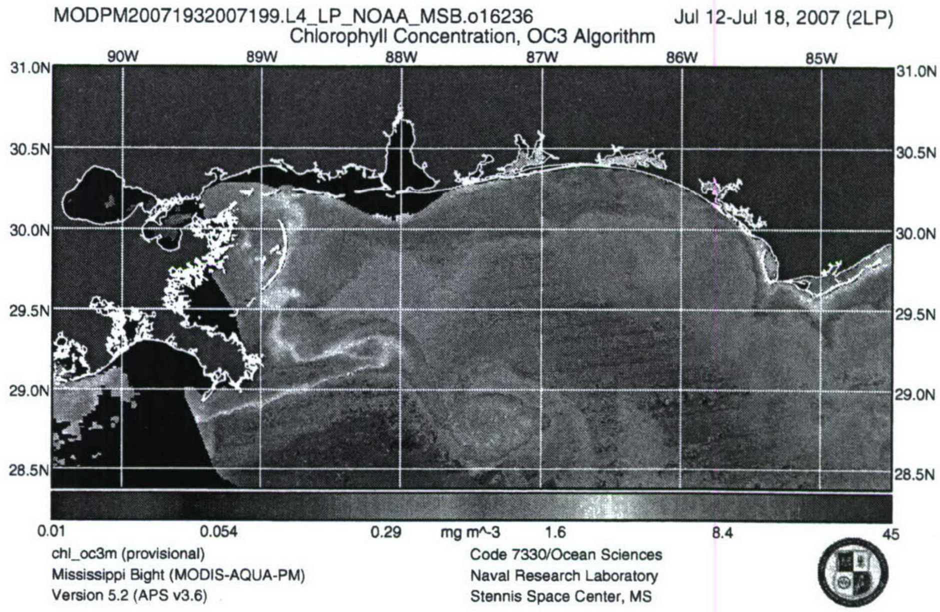

Figure 6. Composite of the 7-day LPC with the triangular interpolation methods (steps 1 and 2).

3. The next procedure is to create an "average" composite with a two pixel limit, of the results of steps 1 and 2 and the 7-day latest pixel composite. This will produce an image (figure 6) which will retain the results produced by step 1, and which will average the results of step 2 and the 7-day latest-pixel composite where they overlap. The 7-day latest-pixel composite will fill in areas for which there is no overlap.

4. The next step again applies the triangular interpolation method discussed in step 1 on the previous step 3. This image has now included additional temporal data voids from the previous seven days. The procedure again iterates ten times, similarly to Step 1. The result (figure 7) shows increased data inclusion in the West and in the Lake Pontchartrain. Note that the 7-day LPC did not show substantial increased data as is shown in figure 1.

5. The final step is used to remove all data voids and completely fill the data with the best estimate of the chlorophyll. (In certain instances a data value is required, for example in modeling the advection field or coastal monitoring where our best guess of the value is necessary). An estimate of the data points at every remaining grid point is produced by using a nearest neighbor search with search radius one pixel, and iterating until the image is completely filled in (figure 8). These continuously replicated values can produce significant errors. Note that the data replications in the western portion of the image have high uncertainty. Similarly the western side of Lake Pontchartrain has pixel replication.

4. CONCLUSION

A MODIS scene containing cloud obscured pixels for the Mississippi Bight region from MODIS Aqua on July 18, 2007, was used to illustrate the procedure. Here we followed the above enumerated procedure to replace the data voids for the Chlorophyll Concentration.

We have applied our compositing technique to additional MODIS ocean color products of phytoplankton absorption, back-scattering coefficient, and chlorophyll concentration to produce cloud free bio-optical products on a daily basis and provide a new capability for monitoring coastal processes. A visual comparison of our new composite product against our previous operational composite, the 7-day latest pixel composite, shows that the new process yields a cleaner, more representative picture of the oceanographic fields.

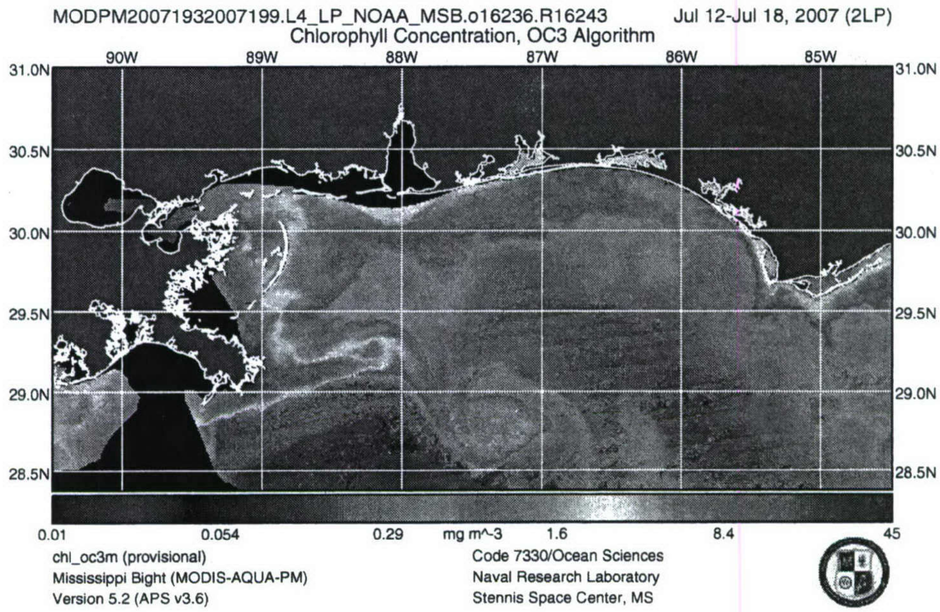

Figure 7. The merge and interpolation of the 7-day LPC and the previous three steps.

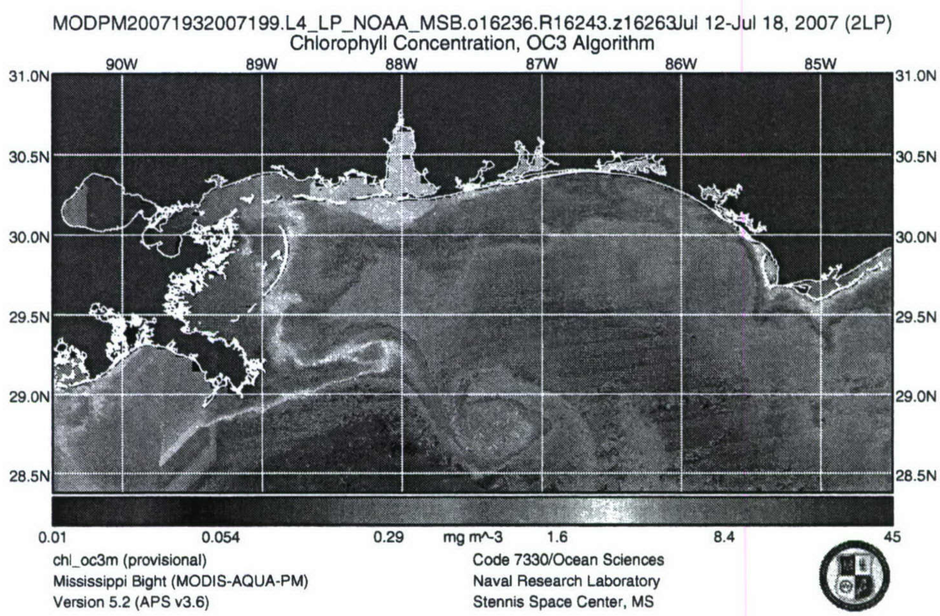

Figure 8. The final step of using the nearest neighbor fill results in a completely data filled chlorophyll image.

Cloud contaminated pixels are still an issue and produce some compositing artifacts. Additionally, selecting an overly large search radius can produce strange looking results when the triangular interpolation is performed over large distances.

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