

# 17. OCEAN COLOUR MEASUREMENTS OF THE PRODUCTIVITY IN THE BENGUELA CURRENT LARGE MARINE ECOSYSTEM

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## 17.1. Introduction and relevance of application

The Namibian coastline is about 1500km long with five coastal towns of which Walvis Bay and Lüderitz are the only two harbour towns. The entire coastline is relatively straight and unprotected, and strongly influenced by the cold Benguela Current flowing northwards. A major influence on the ecology of the region is the coastal upwelling of water from the shelf slope, caused by the long-shore wind regime. Strong southerly winds drive an offshore flow of coastal water, which is replaced by cold, nutrient-rich water from the continental slope. The high nutrient content gives rise to high primary productivity and supports rich commercial fisheries. The cold, productive upwelling water displays strong seasonal, interannual and decadal variability, which can easily be observed in satellite measurements of sea surface temperature (SST) and ocean colour.

Variation in fish recruitment growth and distribution is largely dependent on environmental conditions. Understanding the relationship between environmental variability, primary productivity, recruitment and abundance of commercially important fish species is necessary for ecosystem-based fisheries management. There is a lack of direct measurements of upwelling strength and phytoplankton production. However, marine ecologists in Namibia have over the past years developed a number of indirect indices; these include sea surface temperature (SST) and chlorophyll concentrations, wind speed and direction, and estimates of offshore transport of cold upwelling water. Much of the data used to develop these indices may be sourced from the Internet; this includes scatterometry wind data, low resolution chlorophyll-a concentrations from NASA MODIS and SeaWiFS, global SST from NCEP and Pathfinder. Higher resolution (1km) chlorophyll-a and SST are available through the DevCoCast channel on GEONETCast.

Namibia runs an intensive oceanographic monitoring programme, which relies on shipboard measurements of temperature, salinity and chlorophyll concentrations. Selected transects are monitored on a monthly/bi-monthly basis and the *in situ* measurements from these cruises can be used in conjunction with satellite data. The synoptic view of satellites makes it possible to detect fronts, upwelling filaments, plankton blooms, monitor the strength and extent of the coastal upwelling and detect intrusions of warm water from the boundaries of the system. The *in-situ* data taken at the surface provides a control on the satellite measurements and furthermore gives 3-dimensional information of the system.

## 17.2. Objective of the application

This application compares *in situ* measurements from one of the Namibian monitoring transects with 1 km spatial resolution satellite data of chlorophyll and sea surface temperature (SST) to assess the strengths and limitations of using satellite measurements of chlorophyll and SST to monitor primary productivity in the Benguela upwelling system.

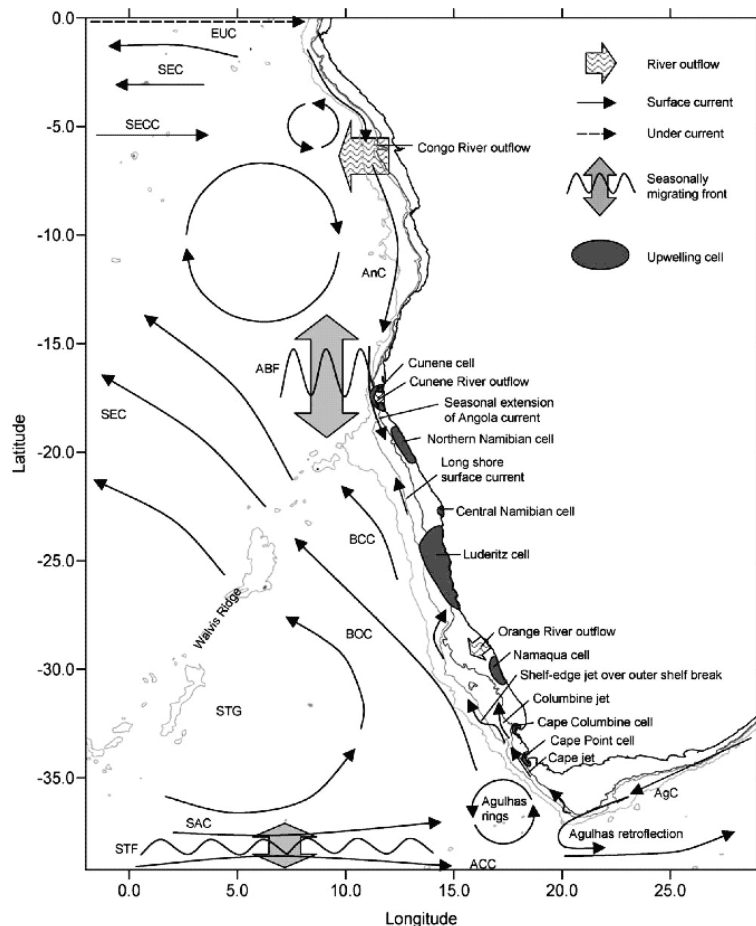
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### 17.3. Study Area

The Benguela system is one of the four major eastern boundary upwelling systems of the world. It spans three countries on the west coast of Africa from about 14°S in Angola, through the entire coast of Namibia to about 37°S off the southern tip of Africa. Figure 17.1 (after Hardman-Mountford et al., 2003) shows a schematic of the oceanography in the region. The Benguela system is the only eastern boundary upwelling system that is bounded by warm water at both ends: the warm Angola Current and Angola Dome to the north and the warm Agulhas Current in the south and east.



*Figure 17.1 Currents and upwelling cells in the Benguela system*

The cold waters of the Benguela Current itself originate in the Southern Ocean. The Benguela system has several ‘upwelling cells’ – regions where a change in the orientation of the coastline creates cyclonic wind-stress curl. The strongest of these is the strong Lüderitz cell in central Namibia, which divides the system into two. The northern Benguela shelf is a typical coastal upwelling system with equator ward winds, cool water, high plankton biomass and moderate to high fish biomass, which is currently in a depleted state. Widespread oxygen-depleted waters and sulphur eruptions restrict the habitat available for fish. The focus of this study is the upwelling cell near Walvis Bay, from the coast to a distance of 200-250 km – the maximum seaward extent of most upwelling filaments.

A typical feature of the central Namibian coastal ocean are the banks of fog that form when warm air from the Namib Desert flows seaward and cools as it crosses the cold Benguela Current. The location of these fog banks may vary, but it is often found in association with the coldest water of the central upwelling cells. The fog may prevent satellite measurements at visible and near infrared wavelengths. When less dense, it may not fully prevent measurements, but can still create problems for accurate atmospheric correction of ocean colour data.

Three other upwelling-related phenomena may also prevent accurate atmospheric correction and subsequent calculations of chlorophyll concentration:

- The intensity and high particle scattering of some upwelling blooms can produce high signal returns in the near infrared channels used to calculate the various parameters used for atmospheric correction. When this occurs, there may be an over-correction in the visible channels, or a failure to establish the spectral characteristics of the aerosol contribution. Since chlorophyll concentrations are typically calculated from spectral ratios in blue and green channels, this will produce over-or under-estimates of chlorophyll, depending on the exact nature of the problem.
- ‘Sulphur eruptions’ from low oxygen regions of the sea floor have a similar effect to that of very high concentrations of plankton cells, by producing highly scattering ‘white’ water.
- Finally dust plumes from the Namib Desert produce absorbing aerosols that also create difficulties with establishing the spectral characteristics of the aerosol contribution and therefore reduce the accuracy of the atmospheric correction.

## 17.4. Data used for the study

### 17.4.1. Local *in-situ* data

*In-situ* measurements of upwelling diffuse attenuation, Ku440, chlorophyll-a, and temperature from two dates in 2009 were selected for use in the exercise. The first data set, from 1 April represents upwelling and bloom conditions during late summer; the second, from 20 August, were obtained during a winter period when the water was homogeneously mixed. The *in-situ* data for this exercise from the 20th of August is shown in table 17.1. These samples were taken on stations from inshore to offshore along the 23.00 °S line in Namibian waters off Walvis Bay.

Date	Satellite Time	In-situ Time	Time Difference	Latitude	Longitude	Station (nm)	<i>In-situ</i> SST	<i>In-situ</i> Chl-a
20/08/2009	12:55	12:07	-00:48	-23.00	14.37	2	12.08	4.00
20/08/2009	12:55	13:10	+00:15	-23.00	14.32	5	12.23	4.00
20/08/2009	12:55	14:23	+01:28	-23.00	14.23	10	12.56	4.41
20/08/2009	12:55	16:20	+03:25	-23.00	14.05	20	13.08	2.35
20/08/2009	12:55	17:59	+05:04	-23.00	13.86	30	13.30	2.47
20/08/2009	12:55	19:37	+06:42	-23.00	13.69	40	13.12	3.70
20/08/2009	12:55	21:25	+08:30	-23.00	13.51	50	13.35	1.88
20/08/2009	12:55	23:05	+10:10	-23.00	13.33	60	13.55	2.70
21/08/2009	12:55	01:45	+12:50	-23.00	13.15	70	13.72	2.35

**Table 17.1 *In-situ* sampling satellite overpass times for the match-ups used in the exercise**

### 17.4.2. Satellite data

The study uses 1 km spatial resolution MODIS-Aqua ocean colour and sea surface temperature (SST) data of the Namibia region, processed by the Plymouth Marine Laboratory (PML), which is available through the DevCoCast channel on GEONETCast. The data sets include level 2 processing flags, which are important for selection of valid chlorophyll concentrations. Two different days were chosen: the first shows an upwelling event centred on 29 March 2009 (late summer) and clearly illustrates some of the atmospheric correction issues associated with fog and very high plankton concentrations; the second, from 20 August, 2009 (southern winter) represents less problematic conditions and a reasonable match-up with *in-situ* chlorophyll and SST measurements from the Namibian monthly monitoring programme.

## 17.5. Methodology and data pre-processing

A flowchart of the overall methodology is provided in the figure below. Yellow squares indicate steps carried out in BILKO (<http://www.noc.soton.ac.uk/bilko/index.php>), green steps carried out in ILWIS, and blue steps carried out in Excel.

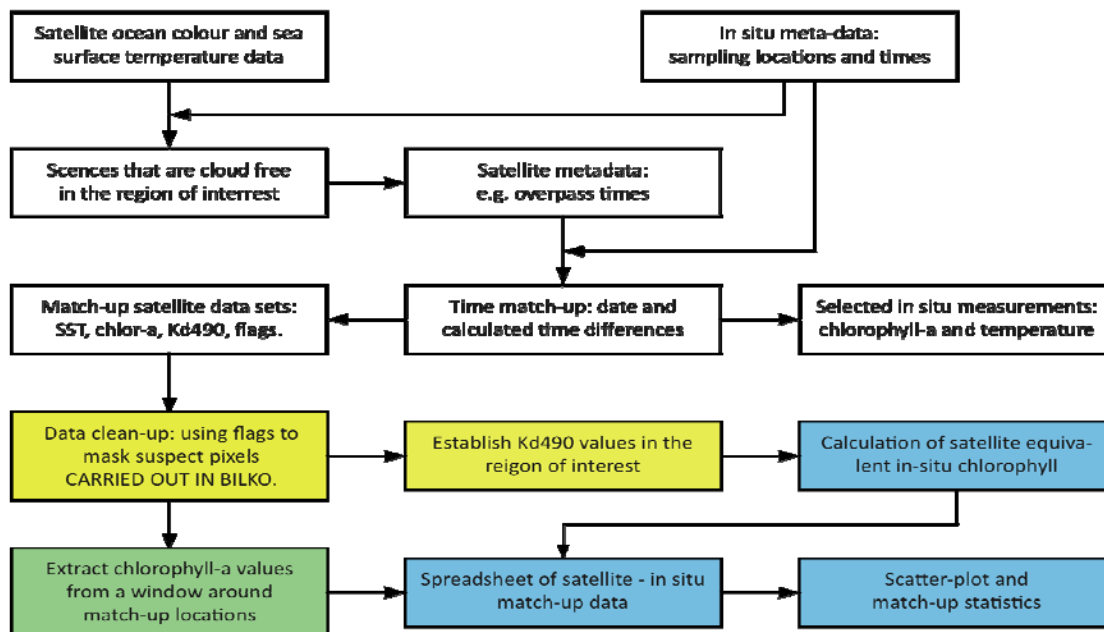


Figure 17.2 Flowchart showing the key data selection and processing steps

#### 17.5.1. Selection of satellite and in-situ match-ups

Figure 17.2 also gives an overview of the data selection and pre-processing steps. Satellite data are selected for dates corresponding to the Namibian *in-situ* monitoring programme along 23°S. Initial cloud free scenes from these dates are identified based on web-archives of browse-images. A further sub-selection was based on the time difference between satellite overpass time and the closest set of *in situ* measurements.

#### 17.5.2. In-situ data pre-processing

Chlorophyll-a and temperature data is collected on the 23°00S line off Walvis Bay in Namibian waters in 2009 at different stations from inshore to offshore (2nm, 5nm, 10nm, 20nm, 30nm, 40nm, 50nm, 60nm and 70nm). Not all station measurements were done during the daytime (see table 17.1).

##### 17.5.2.1. Chlorophyll-a measurements

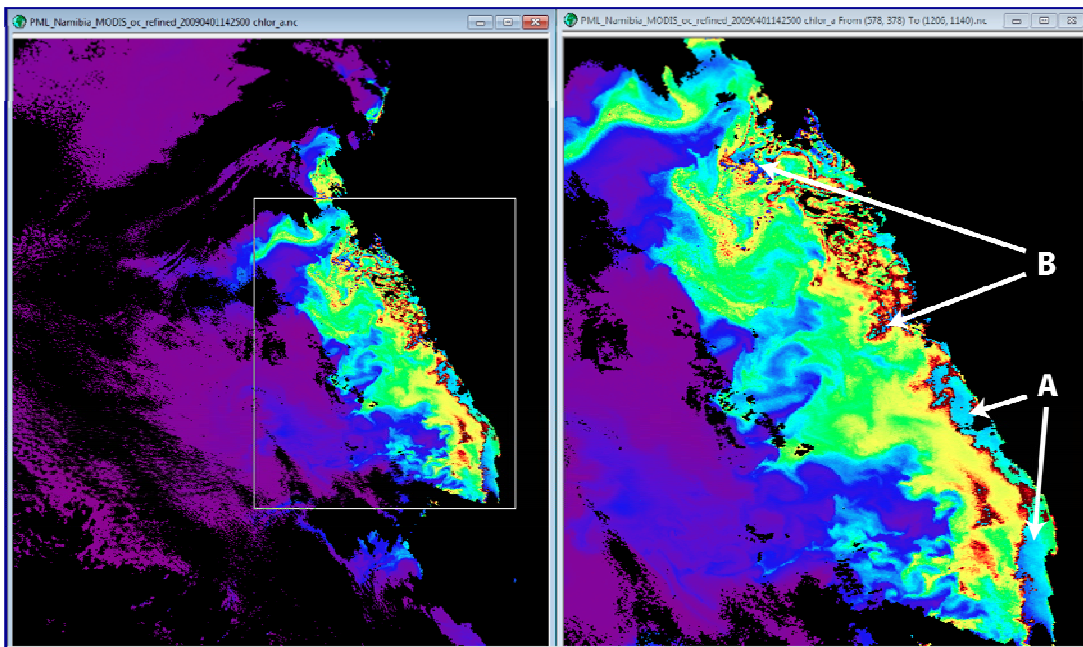
Sea water samples for chlorophyll-a are taken at different depth, close to the surface and approximately at 10m, 20m and 30m depth and filtered on a GF/F filter. In the laboratory, chlorophyll-a was determined fluorometrically, after extracting it for 24 hours in the dark at -20°C in 90% acetone. The Welschmeyer method was used to determine the fluorescence and chlorophyll-a concentrations was calculated as µg/l using the calibration factor obtained through preparing a set of dilutions and calculating the slope of the fluorometer readings versus chlorophyll-a concentrations.

##### 17.5.2.2. Temperature measurements

A Sea-Bird CTD (Conductivity-Temperature-Depth) mounted on a SBE32 12-position rosette was deployed at the stations at a descent rate of 1m/s to within 10m of the seabed. Through the SBE 11 deck unit and the Sea-Bird software four files are produced, namely a data file (DAT), a header file (HDR), a configuration file (CON) and a mark file (MRK), which are saved for further processing.

## 17.6. Satellite image processing

Visual screening of the 29 March chlorophyll data, using BILKO<sup>1</sup> (figure 17.3) shows clearly that some of the pixels contain invalid data, which must be masked. Anomalously low chlorophyll values in (A) are likely to be the result of fog; in (B) the atmospheric correction has most likely failed due to scattered cloud or the intensity of the plankton bloom or a combination of both.



*Figure 17.3 Chlorophyll data for Namibia displayed in BILKO.*

### 17.6.1. Creating a mask using BILKO software

Algorithms used to calculate chlorophyll-a from MODIS measurements are based on assumptions that do not always hold in highly productive regions such as the Benguela. During processing from level 1 to level 2 confidence flags are raised when these assumptions are violated. When a flag is raised, data in the corresponding pixel location must be considered less accurate or even invalid, depending on the seriousness of the problem. In some cases flagged pixels may still be useful, particularly when used with *in-situ* data that can provide independent verification, but care must be taken to check that spatial patterns are compatible with what would be expected from marine dynamics (currents, eddies, upwelling filaments, fronts, river plumes) in the region of interest. For the 1st April image a mask was created from selected flags, using the BILKO software and a bit-mask formula based on the flag values (figure 17.4)<sup>2</sup>. The mask was saved in GeoTiff format for import into ILWIS (see also figure 17.5).

<sup>1</sup> Bilko can be downloaded by registered users from the Bilko web site at [www.bilko.org](http://www.bilko.org). A detailed lesson explaining the level 2 processing flags, the thinking behind the Bilko formula document used for the masking process, and hints on how to recognize the spatial patterns characteristic of invalid data may be found at <http://www.noc.soton.ac.uk/bilko/eamnet/>.

<sup>2</sup> A detailed lesson describing the process of selecting suitable flags has been developed for the DevCoCast sister-programme EAMNet, and may be found on the Bilko web site at [www.bilko.org/eamnet/](http://www.bilko.org/eamnet/).

```

UNESCO Bilko - [MODIS_OC_flags_cstudy_apply.frm]
File Edit View Options! Window Help
# Flags normally used to mask invalid data
# ATMFIL (=1), LAND (=2) HIGLINT (=8), HILT (=16), HISATZEN (=32), CLDICE (=512),
# LOWLW (=16384), CHLFAIL (=32768), NAVWARN (=65536), NAVFAIL (=33554432)
const F1 = 1;
const F2 = 2;
const F3 = 8;
const F4 = 16;
const F5 = 32;
const F6 = 512;
const F7 = 16384;
const F8 = 32768;
const F9 = 65536;
const F10 = 33554432;
#Flags usually applied before processing to level 3 (composite images)
# CHLWARN Warning of unlikely (out of range) chlorophyll values (may be omitted if in-situ values exceed 100mg/m3)
const F11 = 2097152;
#Flags re NIR determination of epsilon ATMWARN (=4194304), MAXAERITER (=524288), FILTER (=67108864)
const F12 = 4194304;
const F13 = 524288;
const F14 = 67108864;

#Images used to create the stack (mask and masked are new, blank images)
const imagedata=@1;
const l2_flags=@2;
const mask=@3;
const masked=@4;

# THE IMAGE CALCULATIONS
# Setting the mask to 1
mask=1;

# Conditional statement to remove any negative values (negative nLw, Kd490 or chlor_a are meaningless)
if (imagedata < 0) mask=0 else mask=mask;

# Conditional statements to apply flags
if ((l2_flags&F1)==F1) mask=0 else mask=mask;
if ((l2_flags&F2)==F2) mask=0 else mask=mask;
if ((l2_flags&F3)==F3) mask=0 else mask=mask;
if ((l2_flags&F4)==F4) mask=0 else mask=mask;
if ((l2_flags&F5)==F5) mask=0 else mask=mask;

```

Figure 17.4 BILKO 'formula' to create a mask from selected MODIS flags

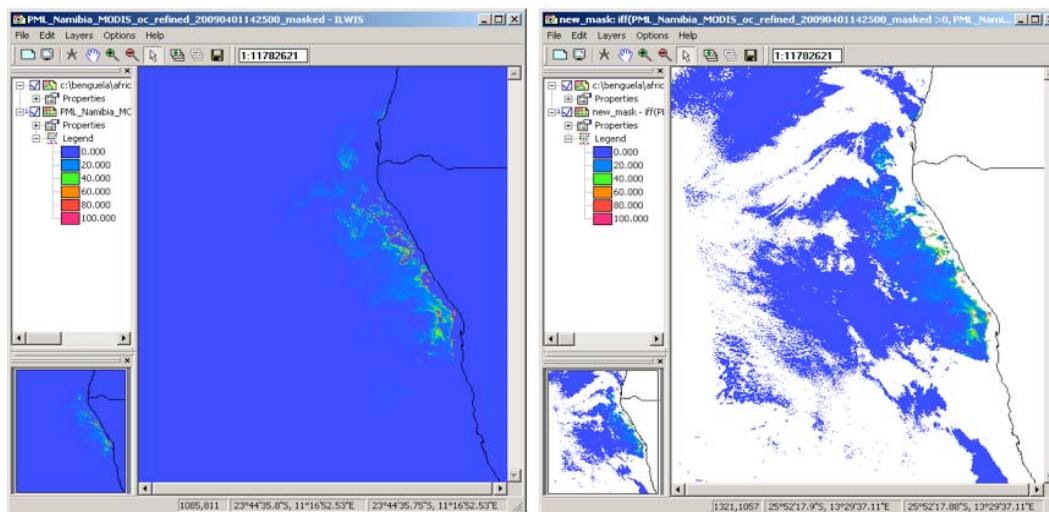


Figure 17.5 Original chlorophyll data (left) and after application of the mask with coastline and borders superimposed (right) imported in ILWIS

## 17.7. Comparing satellite and in situ data

Unzip the exercise data into your working directory. Here “C:\Data\Benguela” is used. Open ILWIS and navigate to this directory. Close ILWIS and open it again. The ILWIS catalogue should now show the content of the active working directory. Note that for this exercise all data needed still has to be imported.

### 17.7.1. Obtaining satellite-equivalent chlorophyll values from the in-situ measurements

*In situ* measurements of chlorophyll-a are made at different depths. From this it is necessary to calculate ‘satellite equivalent chlorophyll’ – the signal ‘seen’ by the satellite. According to bio-optical theory, 90% of the water leaving

signal in Case 1 waters<sup>1</sup> comes from first optical depth i.e.  $1/Kd_{490}$ . This means the  $Kd_{490}$  data provided by MODIS may be used to decide on how to calculate satellite equivalent chlorophyll. In clear open ocean waters, with very low concentrations of plankton cells in surface layers, the one optical depth can be several 10s of metres; in productive systems such as the Benguela it may be 5-10 m and sometimes less.

On 1 April satellite  $Kd_{490}$  values in the region of interest ranged from 0.2 to over 2.5  $m^{-1}$ . One optical depth ( $1/Kd_{490}$ ) was thus between 0.4 m and 5 m. *In-situ* measurements of upwelling diffuse attenuation at 440nm ( $Ku_{440}$ ) were comparable, (0.5 - 1.3  $m^{-1}$ , optical depths 0.7 - 1.9m). Chlorophyll data from the deeper samples (10m, 20m and 30m) therefore contributed only 0.5 - 5% to water-leaving radiance, and could thus be considered irrelevant<sup>2</sup>. Unfortunately no chlorophyll samples were taken near the surface. For this reason, and due to the problem with satellite data quality discussed in section 1.6, satellite - in situ comparison will only be carried out for 20 August, when *in situ*  $Ku_{440}$  ranged from 0.18 to 0.31  $m^{-1}$ , (optical depths: 3.1 - 5.6 m) and vertical profiles of temperature and chlorophyll revealed a well-mixed water column. Average *in situ* chlorophyll concentrations used for the comparison are given in Table 17.1 above.

### 17.7.2. Importing the 20 August chlorophyll-a map in ILWIS

The PML MODIS data comes in NetCDF format, which contains normalised water-leaving radiances at different wavelengths,  $nLw_*$ , chlorophyll concentrations,  $chl_{a}$ , and diffuse attenuation at 490 nm,  $Kd_{490}$ . These sub-datasets can be extracted using the GEONETCast Toolbox before you can display them in ILWIS. Another way to do this is using the DOS Command Prompt, which can be opened from the Accessories folder of the Program menu.

In the Command window, navigate to your working directory which contains the exercise data. In the figure 17.6 example, the data is kept in “*C:\data\benguela*”; note that you may have the data in a different directory.

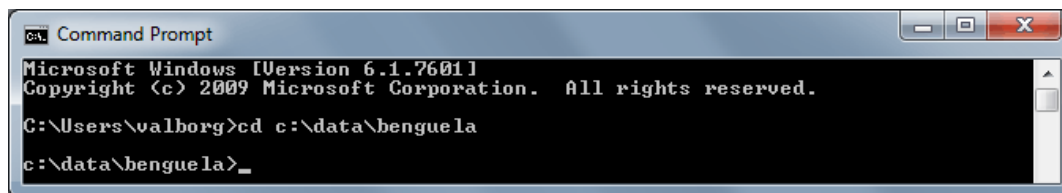


Figure 17.6 Command Prompt window showing navigation to the file containing the Benguela images

To check the content of the NETCDF files, type this command:

```
"C:\ilwis372_SEBS\Extensions\Geonetcast-Toolbox\GDAL\bin\gdalinfo.exe"
PML_Namibia_MODIS_oc_refined_20090820135500.nc
```

Note that in this example “*C:\ilwis372\_SEBS*” is used because the ILWIS software is installed directly on the C:\ drive in the folder “*ilwis372\_SEBS*”. If you have ILWIS installed in a different location you must use that. Press return to run the “*gdalinfo.exe*” application and take note of the listing of the content of the file “*PML\_Namibia\_MODIS\_oc\_refined\_20090820135500.nc*”. Note the names of the different sub-dataset; you will need these in the next step. Also see appendix 1 for the file content listing.

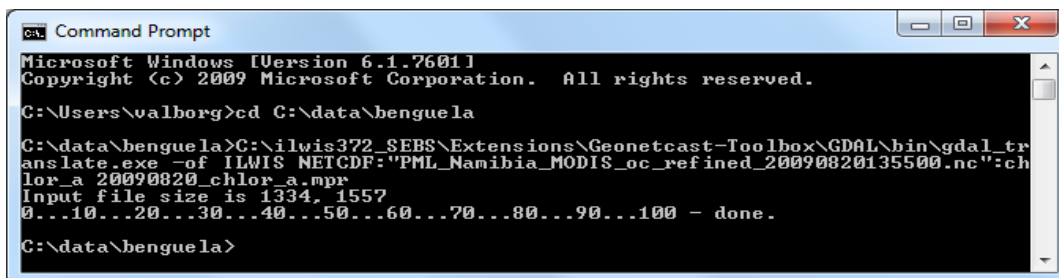
To import a sub-dataset into ILWIS you use “*gdal\_translate.exe*” from the Geonetcast Toolbox. For example, to import SUBDATASET\_8 “*chl<sub>a</sub>*” you type the following command:

```
"C:\ilwis372_SEBS\Extensions\Geonetcast-Toolbox\GDAL\bin\gdal_translate.exe" -of ILWIS
NETCDF:"PML_Namibia_MODIS_oc_refined_20090820135500.nc":chla 20090820_chla.mpr
```

<sup>1</sup> In Case 1 waters the optical characteristics are determined only by the optical properties of water, phytoplankton and associated plankton breakdown products, which are correlated with plankton concentrations. This contrasts with Case 2 waters, where optical properties also depend on concentrations of suspended sediment and coloured dissolved organic matter that enters the ocean from land, for example via rivers.

<sup>2</sup> On one station, no surface sample was taken, but the in situ measurements of temperature revealed a well mixed water column, so it was reasonable to assume that using an average in situ chlorophyll could be used for comparison with the satellite data.

This will run “*gdal\_translate.exe*” (found in the GDAL\bin directory of the Geonetcast Toolbox) to extract the sub-dataset named “NETCDF:”PML\_Namibia\_MODIS\_oc\_refined\_20090820135500.nc”:chlor\_a”. The output file is “20090820\_chlor\_a.mpr”. The expression “-of ILWIS” between the program and the image to be extracted specifies the output file format, here an ILWIS format is used. Execute the expression to import the chlorophyll-a map, an example is provided in figure 17.7 as well.



```


C:\Users\valborg>cd C:\data\benguela

C:\data\benguela>C:\ilwis372_SEBS\Extensions\Geonetcast-Toolbox\GDAL\bin\gdal_translate.exe -of ILWIS NETCDF:"PML_Namibia_MODIS_oc_refined_20090820135500.nc":chlor_a 20090820_chlor_a.mpr
Input file size is 1334, 1557
0...10...20...30...40...50...60...70...80...90...100 - done.

C:\data\benguela>

```

Figure 17.7 Import of SUBDATASET\_8 (chlor\_a) into ILWIS

After import, return to ILWIS, refresh the catalogue (select from the main ILWIS menu the option “Window” > “Refresh”) and select the GeoReference created, called “20090820\_chlor\_a” having the following icon: . Right click the icon with the mouse, from the context sensitive menu select the option “Properties” and change the coordinate system from “Unknown” to “LatlonWGS84” and press “OK” (see figure 17.8).

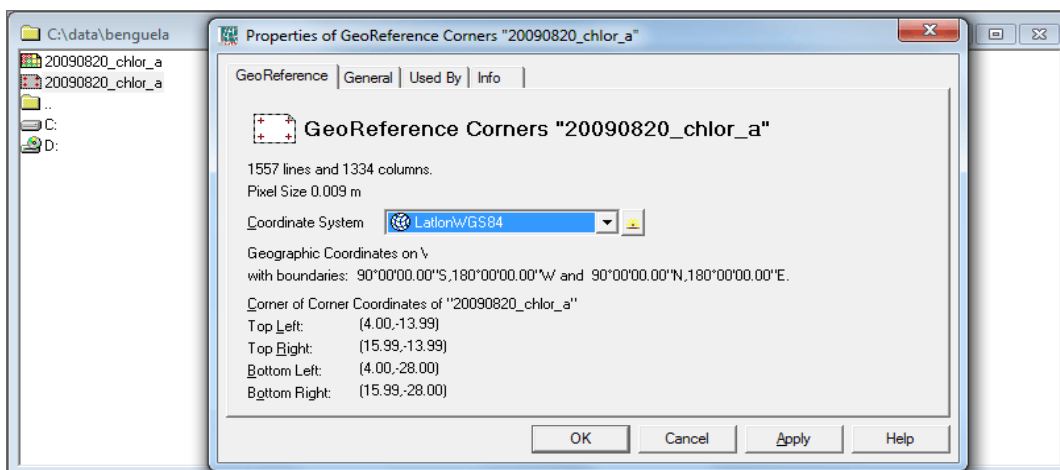
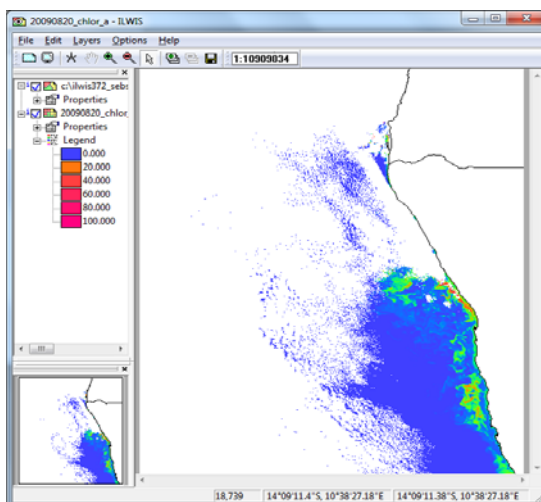


Figure 17.8 Changing the GeoReference information.

Double click with the mouse the map “20090820\_chlor\_a” to open it. You can change the colour of the map using a Representation; here you can use the Representation “Pseudo”. For the chlorophyll-a map select a “logarithmic” stretch with the maximum set to “100”, and click “OK”. To add the boundaries for Namibia, select from the active map display window the option “Layers” > “Add Layer” and navigate to your ILWIS directory and select from there the sub-directory “\Extensions\Geonetcast-Toolbox\util\maps”, then select the vector map “Africa\_country”. In the subsequent Display Options dialog window check the box for “Boundaries Only” and uncheck the box “Info”. You can change the boundary colour to “Black”. The result should look similar to that of figure 17.9.



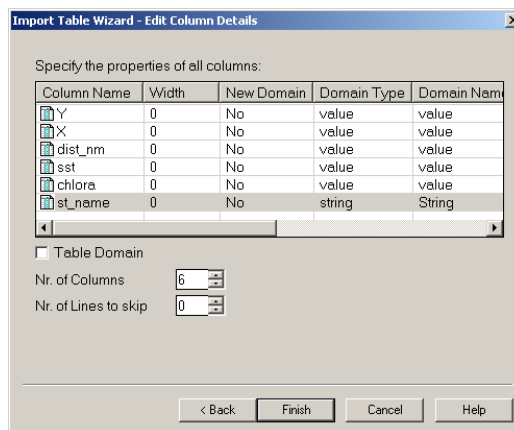


**Figure 17.9** Chlorophyll-a map of the Benguela region with coastline and borders superimposed

### 17.7.3. Import of *In Situ* sampling points and creating a Point Map

#### 17.7.3.1. Import of the In Situ observations

Open from your working directory the file “*in\_situ.txt*” by double clicking on it. There are 9 relevant records for the following attributes: latitude, longitude, distance in nautical miles, sea surface temperature, chlorophyll-a and the station name (see also table 17.1). To import this text file and create an ILWIS table conduct the following operation. Open from the main ILWIS menu the option “File” > “Import” > “ILWIS” > “Table” > “Space Delimited”, as input file select “*in\_situ.txt*” and as output file specify “*station\_data*” and press “OK” and “Next”. In the Edit Column Details window specify the settings as given in the figure below and press “Finish” and “OK”. Note that the Domain Type should be correctly specified, using a “value” domain, except for the column ‘st\_name’, which is having a “string” domain.



**Figure 17.10** Table column import settings

After import open the table “*station\_data*” and inspect the content. Note that there are two records, having as name ‘Base’ and ‘Return’, these are marking the start and end of the section. Close the table.

#### 17.7.3.2. Creating a Point Map

From the main ILWIS menu, select “Operations” > “Table Operations” > “Table to PointMap”. In the dialog window that opens choose as input the “*Station\_data*” table. The XY column (Coords) are automatically assigned, coordinate system is “*LatlonWGS84*”; as output point map use the name “*station\_data*”, keep the other settings default and press “Show” and “OK”.

Return to the chlorophyll map you opened earlier. To overlay the point map on this raster image, select “Layers” > “Add Layers” from the map display menu, and choose the newly created point map. The Display Options dialog allows you to select how the points are displayed. Check the Single Symbol box, and click on the tab to open the Symbol dialog. Choose from the option Symbol and select “Square”, using a symbol size of “3”, set the Fill Color to “Black” and press “OK” twice. You should now see the points on the chlorophyll map (figure 17.11). Use the zoom tool to get a better view of the sampling region. From the active map window select the option “File” > “Open Pixel Information” and move the mouse cursor over the sampling locations, check the map and table values!

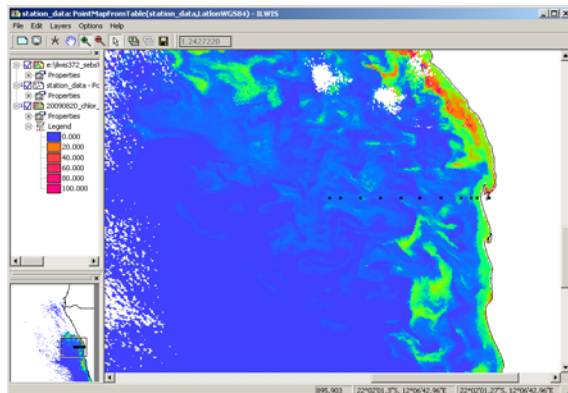


Figure 17.11 The chlorophyll-a image with the point map overlaid


#### 17.7.4. Extracting satellite data for statistical analysis

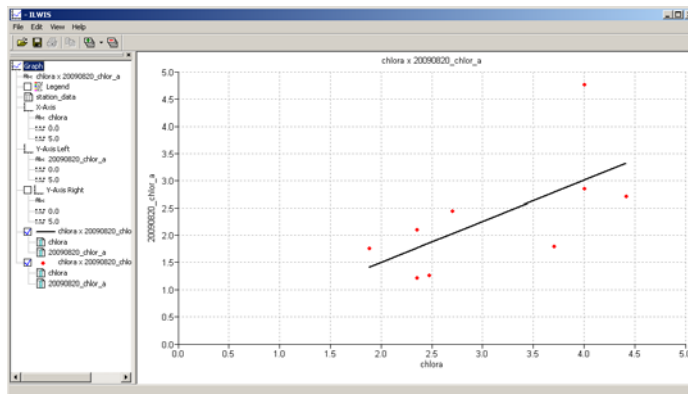
Before you can extract the information of the chlorophyll map you first have to rasterize the point map. From the main ILWIS menu, select “Operations” > “Rasterize” > “Point to Raster”, as point map select “station\_data” and as output map leave the default name “station\_data”, as georeference select “20090820\_chlor\_a” and press “Show”. In the new map display window, select from the menu “Layers” > “Add Layer” and select the “station\_data” point map. Zoom in on the observation locations to see the result of the operation.

Now select from the main ILWIS menu the option “Operations” > “Raster Operations” > “Cross”. As 1<sup>st</sup> map select “station\_data” and as 2<sup>nd</sup> map the “20090820\_chlor\_a” map. Specify as output table name “st\_chlor\_a” and press “Show”. Check the results given in the new table. For the sampling locations (except the ‘Base’) the chlorophyll-a values are extracted.

Open the table “station\_data”, from the main table menu, select the option “Columns” > “Join”, in the next ‘Join Wizard – Select input table and column’, select as input table “st\_chlor\_a” and as input column “20090820\_chlor\_a”, press “Next” three times, using the default settings, also the default output column name can be accepted and press “Finish” and “OK”. Inspect the content of the table and check the new column added.

To check the correlation between the *in situ* and satellite derived chlorophyll-a values, select from the table menu the option “Columns” > “Statistics”, as function select “Correlation” and as columns use “chlor\_a” and “20090820\_chlor\_a” and press “OK”. What can be concluded?

Select from the Table menu the graphics icon , and from the “Create Graph” menu, select as X-axis “chlor\_a” and as Y-axis “20090820\_chlor\_a”. Press “OK” to display the graph. You can modify the Graph properties by selecting the items in the left hand graph legend. E.g. unselect “Legend” and for the item “chlor\_a\*20090820\_chlor\_a”, by double clicking with the mouse on the item name, use as “Color” “Red”. Also change the Min-Max settings of the graph axis (X: from 0 to 5, interval of 0.5 and Y: from 0 to 5, interval 0.5). Proceed from the active Graph window, select from the menu “Edit”, “Add Graph” and select “Least Square Fit”. Select as X-column “chlor\_a” and as Y-column “20090820\_chlor\_a”, use as Function “polynomial” with “2” terms (1<sup>st</sup> order polynomial function) and press “OK”. From the Graph legend, select the item: “chlor\_a\*20090820\_chlor\_a - polynomial”, change the Color to “Black” and set the Line Width to “0.2”. Also note the regression formula, which is given on the lower left hand of this menu. Press “OK”. Your results should resemble those of figure 17.12.



**Figure 17.12** Scatter plot showing relationship

Close the graph window, eventually save the graph (select from the graph menu the option “File” > “Save”). Activate the table “station\_data” again and from the table menu select “Column”, “Least Squares” and for the X-column select “chlora” and the Y-column “20090820\_chlor\_a”, specify as output column “Calculated”. Use as function “Polynomial” as number of terms “2” and press “OK” to execute the operation. In the column properties window select the option “Additional Info”, here the function is given, leave the other options as default and press “OK”. A new column, called “Calculated” is now added to the table. Check the results obtained in the table and compare the differences between the observed, satellite derived and values obtained using the regression function.

### 17.7.5. Characterising chlorophyll variability in spatial windows around the sampling points

The ocean environment is highly dynamic and phytoplankton distributions are ‘patchy’ – that is highly variable over fairly short spatial and temporal scales. These patches drift, with currents and eddies, and may move by distances greater than a single pixel over a period of a few hours. For this reason it is not sufficient to compare the *in-situ* measurements to satellite data at a single point. You also need to characterise the spatial variability around each location. This may be done by selecting spatial windows of increasing size, centred on the pixel containing the sampling location. The mean or median chlorophyll concentrations, along with the standard deviation (or variance) needs to be calculated for several windows of increasing size (e.g. 3x3, 5x5, 7x7, even 9x9) around each sampling point. This process requires three steps before you can export the data for statistical analysis. Here only the average and median spatial variability are considered to serve as an example of the procedures to be followed.

#### 17.7.5.1. Step 1. Filtering

From the main ILWIS menu select the option “Operations” > “Image Processing” > “Filter”. In the Filter dialog set the filter type to “Average”. The rows and columns should change to 3x3; accept this. Specify as input map “20090820\_chlor\_a” and enter an appropriate name for the Output Raster Map. Note: it is important to choose a name which you will recognise immediately, because you need to make several maps, e.g. ‘chlor\_a\_3\_avg’ and ‘chlor\_a\_3\_med’, etc. Change the Precision to three digits, and click “Show”. To create the other filtered maps you can simply repeat the procedure and change the dimension of the filter kernel size (e.g. to 5 by 5). Repeat the procedure also for the 5x5, 7x7 and 9x9 average filter sizes. For median filtering, select as filter type “Median” and also create these maps using different filter sizes. Note that various other filters are at your disposal and if required you can create them yourselves, consult also the ILWIS Help if more assistance is needed.

#### 17.7.5.2. Step 2. Create a Map List

From the main ILWIS menu select the option “File” > “Create” > “Map List”. In the Create MapList window enter a name for the new Map List, e.g. “avg”. Select the different filtered raster images maps created by the average filtering in sequential order and move them to the right pane by clicking the “>” tab between the panes. Click “OK”. Repeat this procedure to create the Median filtered maps and call this map list “med”.

### 17.7.5.3. Step 3. Creating a Table from a Map List

From the main ILWIS menu, select the option “Operations” > “Point Operations” > “Point Map Cross”. In the Point Map Cross dialog select again the point map that contains the *in situ* stations, here called “station\_data”. Choose the Map List “avg” you have just created in step 2 above, specify as output point map “avg” and press “Shon” to execute the operation. You can close the newly created point map, open the newly created table “avg”. Repeat the procedure for the median filtered map list and call the output point map “med”. Open both tables you have just created and inspect the values of the different windows around your sampling point. For further analysis you can copy the values with station data into an Excel spreadsheet.

## 17.8. Statistical Analysis of the match-up data

The data extracted is summarised in the table below, which also includes the average *in-situ* chlorophyll. Statistical analysis may now be done in Excel, R or another suitable statistical package and will typically include plotting *in situ* chlorophyll-a against the satellite-derived concentrations as demonstrated above (see figure 17.12). More detailed analysis is outside the scope of this exercise.

Station	in situ	chlor_a Modis	avg 3x3	avg 5x5	avg 7x7	avg 9x9	med 3x3	med 5x5	med 7x7	med 9x9
ww23002	4.0	4.769	4.769	3.062	3.235	3.343	2.933	2.958	2.991	2.933
ww23005	4.0	2.862	2.862	2.817	2.824	2.826	2.715	2.715	2.819	2.715
ww23010	4.41	2.715	2.715	1.302	1.321	1.351	1.265	1.299	1.316	1.265
ww23020	2.35	1.216	1.216	1.177	1.2	1.237	1.186	1.188	1.194	1.186
ww23030	2.47	1.267	1.267	1.661	1.62	1.617	1.647	1.63	1.609	1.647
ww23040	3.7	1.795	1.795	1.664	1.573	1.541	1.686	1.588	1.562	1.686
ww23050	1.88	1.761	1.761	2.388	2.264	2.11	2.448	2.168	2.004	2.448
ww23060	2.7	2.456	2.456	1.904	1.827	1.837	1.878	1.799	1.835	1.878
ww23070	2.35	2.103	2.103	2.015	2.001	1.928	1.956	1.956	1.937	1.956

**Table 17.2** *In situ* average and satellite derived chlorophyll for various match-up windows

## 17.9. Processing the SST data

In your directory also a NETCDF file is available providing the satellite derived sea surface temperature (SST). Repeat the steps described before and analyse the *in situ* and satellite derived sea surface temperatures. First inspect the file using 'gdalinfo' and then import the file using 'gdal\_translate'. A sample import syntax string is provided below.

```
"C:\ilwis372_SEBS\Extensions\Geonetcast-Toolbox\GDAL\bin\gdal_translate.exe" -of ILWIS
NETCDF:"PML_Namibia_MODIS_sst_refined_20090820135500.nc":sst 20090820_sst.mpr
```

Upon completion of the import right click with the mouse the newly imported map, here called "20090820\_sst", from the context sensitive menu select the option "Properties" and now select as georeference the one used for the chlorophyll-a map "20090820\_chlor\_a". All other processing and analysis routines are identical to the procedures described above. If successful the results should resemble those provided in figure 17.13. The satellite SST is consistently higher than the corresponding *in situ* temperature. This is due to solar heating of the surface 'skin' of the ocean during the day. Satellites measure the 'skin temperature' - the top mm of the water. During the day this layer is heated by the sun, and becomes warmer than the underlying water. In-situ measurements are made at depths of 1 to 5 m. This 'bulk' temperature varies less between day and night than the 'skin' temperature seen by the satellite. The plot also shows that the location 2nm from the shore has a much greater difference between 'skin' and 'bulk' than indicated for the other 8 sampling points. The reason for this may be 'land contamination' (radiation from much warmer land contributes to the signal) or, perhaps more likely, calmer near-shore conditions (calmer waters have a greater difference between 'skin' and 'bulk' temperatures). Removing this outlier makes the SST – *in situ* relationship linear.

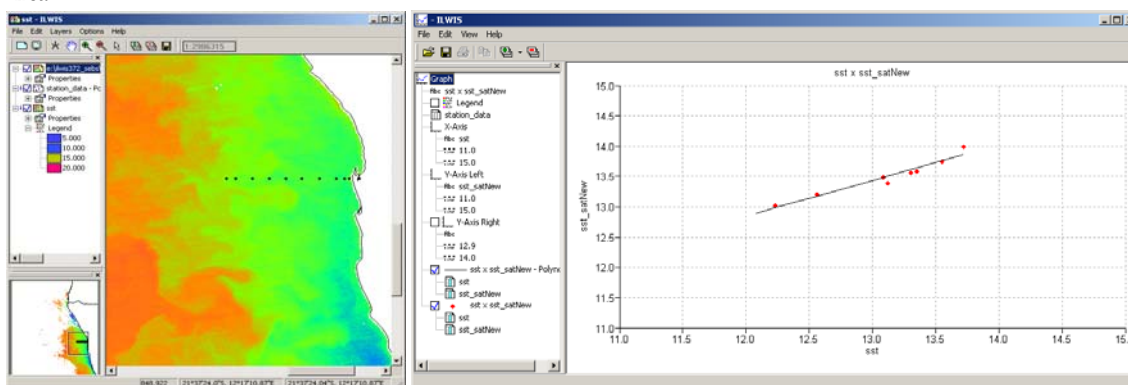


Figure 17.13 Results of the *in situ* and satellite derived SST comparison

## 17.10. Concluding remarks

Satellite measurements of ocean colour and sea surface temperature can provide valuable information about the dynamics of the Benguela coastal upwelling system. However, care must be taken to identify artefacts in the satellite data and exclude these from the analysis. The strength of satellite images lie in their synoptic view of the region and their regular repeated measurements, which make them a good tools for spatial and temporal variability and change in the region. However, absolute values of chlorophyll and SST are less reliable. The examples shown here indicate that *in-situ* measurements are still needed to 'calibrate' the satellite measurements - particularly close to the coast, or at times of strong upwelling when the satellite measurements are more problematic.

## REFERENCES

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Hardman-Mountford, A.J. Richardson, J.J. Agenbag E. Hagen, L. Nykjaer F.A. Shillington, and C. Villacastin (2003): Ocean climate of the South East Atlantic observed from satellite data and wind models, *Progress in Oceanography* 59, 181–221

Hutchings, L., C.D. van der Lingen, L.J. Shannon, R.J.M. Crawford, H.M.S. Verheye, C.H. Bartholomae, A.K. van der Plas, D. Louw, A. Kreiner, M. Ostrowski, Q. Fidel, R.G. Barlow, T. Lamont, J. Coetzee, F. Shillington, J. Veitch, J.C. Currie, and P.M.S. Monteiro (2009): The Benguela Current: An ecosystem of four components, *Progress in Oceanography*, 83, 15–32.

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## APPENDIX 1

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File content listing of the file *PML\_Namibia\_MODIS\_oc\_refined\_20090820135500.nc*

Driver: netCDF/Network Common Data Format

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Size is 512, 512

Coordinate System is ''

Metadata:

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NC\_GLOBAL#citation=If you use this data towards any publication, please acknowledge this using: 'The authors thank the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) for supplying data for this study' and then email NEODAAS (info@neodaas.ac.uk) with the details. The service relies on users' publications as one measure of success.

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NC\_GLOBAL#creator\_url=http://rsg.pml.ac.uk

NC\_GLOBAL#references=See NEODAAS webpages at <http://www.neodaas.ac.uk/> or RSG pages at <http://rsg.pml.ac.uk/>

NC\_GLOBAL#Metadata\_Conventions=Unidata Dataset Discovery v1.0

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NC\_GLOBAL#summary=This data is Level-3 satellite observation data (Level 3 meaning raw observations processed to geophysical quantities, and placed onto a regular grid).

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NC\_GLOBAL#institution=Plymouth Marine Laboratory Remote Sensing Group

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NC\_GLOBAL#geospatial\_lon\_min=4

NC\_GLOBAL#contact1=email: rsghelp@pml.ac.uk

NC\_GLOBAL#license=If you use this data towards any publication, please acknowledge this using: 'The authors thank the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) for supplying data for this study' and then email NEODAAS (info@neodaas.ac.uk) with the details. The service relies on users' publications as one measure of success.

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