

Estimating Primary Productivity with WIM/WAM

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1 Introduction

Ocean primary production (PP) is a crucial component of the Earth's biogeochemical cycles of carbon and other major chemical elements. Net primary production (NPP, $\text{g C m}^{-2} \text{d}^{-1}$), i.e. total primary production minus the losses due to respiration of the phytoplankton, provides the upper bound for production at higher trophic levels. In situ measurement of PP or NPP is extremely time-consuming and not representative of a larger area due to high spatial and temporal variability. Obtaining estimates of PP at regional and global scales are therefore very difficult to make without the quasi-synoptic view provided by satellite data or numerical models. In this tutorial we try several ways of estimating NPP with WIM/WAM.

In situ primary production in the ocean is typically measured using one of the three techniques: (1) variations in oxygen concentration within a sealed bottle (developed by Gaarder and Gran in 1927); (2) incorporation of the radioactive C14 (in the form of sodium bicarbonate) into organic matter (developed by Steemann-Nielsen in 1951); (3) fluorescence kinetics (e.g. the FRRF = fast repetition rate fluorometry). Probably the most widely used is incubation (either in situ or on deck) with the C14 isotope due to its greater sensitivity compared to the oxygen methods.

The incubation time using methods 1 and 2 is typically 12 or 24 hours. In order to save ship time, bottles are often incubated on the deck of a ship under simulated light conditions instead of being lowered to a certain depth in the water column.

The best known satellite-based algorithm for NPP is VGPM = Vertically Generalized Productivity Model (Behrenfeld and Falkowski, 1997):

$$NPP = 0.66125 \times P_{opt}^B \times \frac{E_0}{E_0 + 4.1} \times Chl \times Z_{eu} \times DL$$

Chl sea surface chlorophyll a concentration [mg Chl m^{-3}];
 DL day length [in decimal hours];
 E₀ sea surface daily PAR [$\text{mol quanta m}^{-2} \text{d}^{-1}$];

Z_{eu} depth of euphotic zone [m];
 P_{opt}^B optimal daily carbon fixation rate [$\text{mg C (mg Chl)}^{-1} \text{ h}^{-1}$];

2 Prerequisites

We assume that you are familiar with the basics of WIM and of the command line programs. If not, please check out the WIM and WAM manuals. We also assume that you have a set of images that you can use. In our example 1 we use standard mapped (9 km) daily and monthly images of chlorophyll-a (CHLO_9) and photosynthetically active radiation (PAR) as well as 8-day and monthly images of SST. They should be on the WIM_WAM DVD under the *Sat* folder.

3 Using WIM interactively

Example 3.3 in [Practical Exercises with WIM and WAM](#) shows how you can calculate NPP using 3 sample images. The sample images of Chl and PAR are in `\Images\SeaWiFS\L3\Month` and the corresponding SST image is in `\Images\SST` on your DVD (or copied to `C:\Program Files\Wimsoft\Images`). As you can experience, it takes a long time to do that as you have to (1) manually find and load the **matching** images, (2) remap to the same projection if not all are in the same projection, (3) manually save the output to a file with a name that makes sense. In this example the SST image happens to be a 4 km resolution image and the Chl and PAR images are 9 km resolution images; therefore we need to remap SST to the same projection as Chl and PAR. It is important to find **matching** images of the same month and it is easy to make mistakes by performing these operations manually. Also, it is hard to reproduce the whole set of operations in case you need to change something and do it again. It is therefore obvious that running these operations in a batch mode is preferred.

4 Validating satellite estimates of NPP with *wam_npp_point*

As you experienced in the previous example, you can calculate NPP images interactively with WIM and create a set of NPP images. You can then validate NPP estimates by doing match-up analysis between a set of NPP images and a set of in situ NPP measurements (see the section on *wam_match* in [Practical Exercises with WIM and WAM](#)). There are several problems with this approach. First, NPP measurements are typically performed over a time period of 1 day, half day or less. Using monthly NPP data for validation of a daily NPP dataset is subject to big errors as NPP values change significantly depending on the daily radiation and Chl-a. It is therefore advisable to use daily satellite data for validation. This becomes a very time consuming task to do manually as the nearest daily image may be cloudy and you have to find another image. WAM includes a program *wam_npp_point* that automates this task.

wam_npp_point uses lists of images and finds the best matching images to calculate NPP data for a small neighborhood (typically 3 x 3 pixel window) centered at the in situ point of NPP measurement.

If a satellite-based NPP model needs 3 images (e.g. Chl-a, PAR and SST) then *wam_npp_point* needs 3 sets of images and a file with a list of in situ point measurements. This information is stored in a text file that looks like that:

```
# 1 - Chl
D:\Sat\Merged\L3\Daily\CHLO_9,A2007*9.hdf
# 2 - PAR
D:\Sat\SeaWiFS\L3\Daily\PAR_9,S2007*9.hdf
# 3 - SST
D:\Sat\Merged\L3\8day\SST_9,M2007*.hdf
# 4 - Points
C:\Sat\Merged\L4\qProdoPoint_2007.csv
```

The lines starting with # are comments and are ignored by *wam_npp_point*. As you can guess, we are listing the folder names of, respectively, Chl-a, PAR and SST files, and the path of the point file. Therefore, if the NPP model expects 3 types of images, we need 4 uncommented lines with paths (3 for the images and 1 for the point file). Also, for the image paths we can specify the matching filenames after a comma if we don't want to match all the files in that folder. For example, A2007*9.hdf would pick only those matching filenames. In the C:\Projects\WIM_add\Sat\Merged\L4 folder of the WIM_WAM DVD you can find a list file list_CalCOFI_VGPM_L3_2007_SWFAQU1_SWF1_MOD8.txt with contents similar to that above. Please notice that paths like C:\Sat\Merged\L3\Daily\CHLO_9 may need to be changed depending on the actual paths on your computer. You may be able to run *wam_npp_point* with the image files on the DVD but you may need to adjust the list file. As *wam_npp_point* will try to save the output to the path of the point file, you need to copy at least the point file to your hard disk where you have write permission, e.g. to C:\Sat\Merged\L4\qProdoPoint_2007.csv. The sample point file qProdoPoint_2007.csv has in situ NPP data from the CalCOFI 2007 cruises. It is a text file in the CSV format with the following content: Lon, Lat, Date, Time, Station, Chl_Depth_Integr, NPP_Depth_Integr. The first 4 columns are essential. Chl_Depth_Integr (vertically integrated Chl-a, mg m⁻²) is not actually required. NPP_Depth_Integr (vertically integrated NPP, mg C m⁻² day⁻¹) is the main variable that we are trying to match.

If you run *wam_npp_point* without arguments, you will see all possible arguments:

```
C:\Sat\Merged\L4>wam_npp_point
wam_npp_point vers. 2.5
Usage: wam_npp_point list_file [Algorithm] [AnyYear]
Algorithm:
missing equals VGPM (Behrenfeld & Falkowski, 1997)
VGPM (Behrenfeld & Falkowski, 1997)
VGPM-CAL - VGPM adjusted for CalCOFI PP data by Kahru et al., 2008
SPGANT - Southern Ocean version of VGPM; modified Pbopt and Euphotic depth
KI = Kameda & Ishizaka (2005) version of VGPM
CbPM = Behrenfeld et al, 2005 Carbon based Productivity Model
ESQRT = Eppley Square Root of Chl
```

Marra = Marra, Ho, Trees, 2003 model
Default Algorithm is VGPM
Extra option (argument2, AnyYear) must be a string of 0 or 1
1 in the Nth position means that the Nth image can be from any year, e.g.
a composite over many years;
0 in the Nth position means that for Nth image years and days are considered
when calculating the difference in days.
Default is to calculate difference in Days considering Years
Example: for VGPN 011 would use any years of the PAR and SST for a Chl image;
for CbPM 00101 would use any years of the PAR and MLD.

You can calculate satellite estimates of NPP corresponding to the in situ point values in file C:\Sat\Merged\L4\qProdoPoint_2007.csv using the following command:

```
wam_npp_point list_CalCOFI_VGPM_L3_2007_SWFAQU1_SWF1_MOD8.txt
```

As you can guess from the list file name, it uses merged daily SeaWiFS+Aqua Chl-a, SeaWiFS daily PAR and merged MODIS (Terra + Aqua) 8-day SST. As we are not specifying the NPP model here, it uses the default VGPM model.

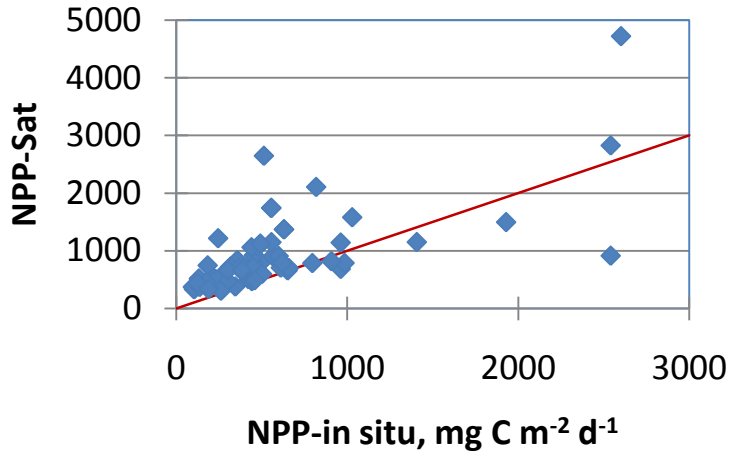
Try to understand the output of the *wam_npp_point* command. The basic idea is that *wam_npp_point* tries to find the closest matching satellite image for each input image. If the nearest image has not valid data (e.g. is cloudy), it tries the next following image. If that also has no valid data, it tries the next image in time and so on. The process is aborted if the time difference reaches 1 month. In nearly 60% of cases in the California Current a match in Chl-a is found with a difference in time of 0 or 1 day. For PAR the time difference is always 0 or 1 days as the measurement is not affected by clouds but only by orbit and swath. However, some matchups in Chl-a are not found until more than 10 days of time difference. As SST has a relatively weak influence on NPP, we use 8-day SST to improve coverage.

Assuming that the *wam_npp_point* command finished successfully, examine the output file. Before you actually do that, rename the output file to reflect the NPP model used:

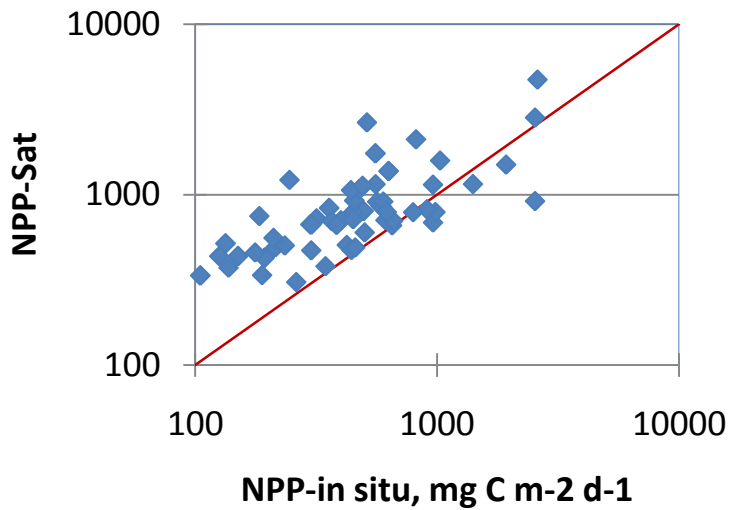
```
move list_CalCOFI_VGPM_L3_2007_SWFAQU1_SWF1_MOD8.txt_out.csv  
list_CalCOFI_VGPM_L3_2007_SWFAQU1_SWF1_MOD8.VGPM.csv
```

All this is in a single line. As you see, we added the name of the model (VGPM).

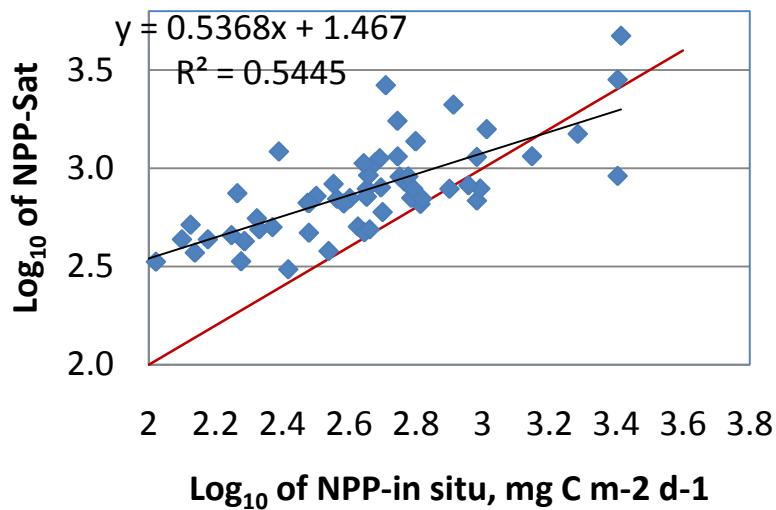
Now open the renamed output file in Excel and plot satellite NPP versus in situ NPP. You can make a graph that looks something like that:



You can see that the standard VGPM algorithm is over-estimating in situ NPP, especially in the low and middle range. Due to the large range of variability it is better to use log-log plot instead of the linear plot:



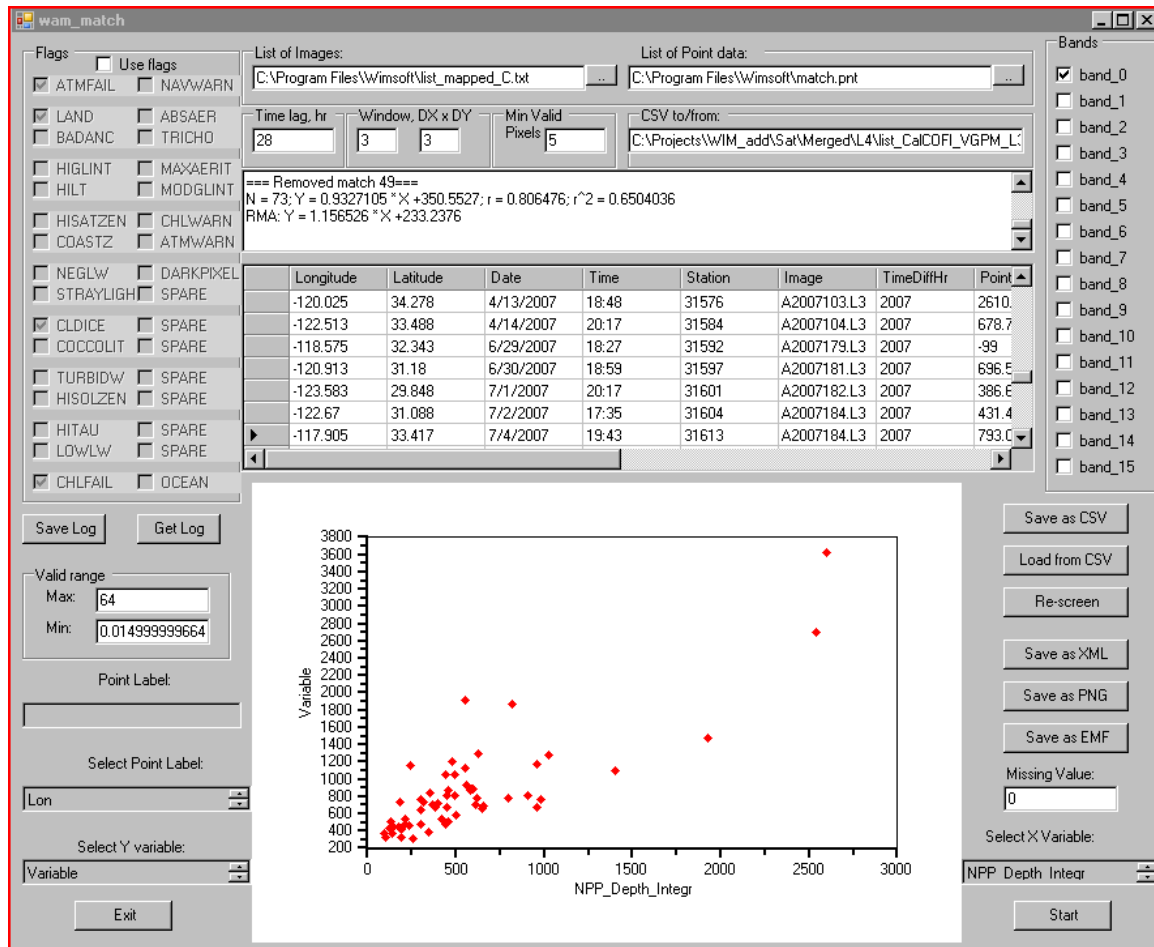
We can take log₁₀ of the variables in Excel make a new plot:



As you can see, r^2 is 0.5445 which is not bad but is not great either.

This is the validation of the VGPM model with actual NPP measurements collected by the CalCOFI cruises in 2007 using half-day on deck incubations.

Sometimes you can see a few outliers that have obvious problems and which you may want to exclude. You can easily find the outliers and evaluate the effect of this interactive exclusion if you load the output CSV file into *wam_match* with the *Load from CSV* button. For example, after I eliminated 2 worst outliers, I get the r^2 of 0.650 in the *Linear* plot with the following screenshot:



The above test of *wam_npp_point* used the well-known Behrenfeld-Falkowski Vertically Generalized Production Model (VGPM) Behrenfeld and Falkowski [1997]. The other models available in *wam_npp_point* are:

Eppley Square Root (ESQRT) model [Eppley et al., 1985] that estimates depth-integrated primary production ($\text{g C m}^{-2} \text{d}^{-1}$) as the square root of surface chlorophyll-a concentration (Chl-a, mg m^{-3}). This purely empirical relationship represents the baseline of NPP prediction accuracy. If a complicated NPP model does not improve on the accuracy of the simple ESQRT model then it obviously has serious flaws.

The *Vertically Generalized Production Model* (VGPM) by Behrenfeld and Falkowski [1997] is the best-known NPP model. VGPM uses satellite estimates of Chl-a, photosynthetically active radiation (PAR) and sea-surface temperature (SST) as input.

The *Kameda and Ishizaka* [2005] model (KI) is a modification of VGPM that uses an assumption that both Chl-a and NPP can be partitioned into a stable part due to a small phytoplankton fraction and a variable part due to the large phytoplankton fraction. It also assumes that the chlorophyll-specific productivity is inversely proportional to phytoplankton size.

The *Marra et al.* [2003] model (MARRA) uses the same inputs of Chl-a, PAR and SST but is based on chlorophyll-specific phytoplankton absorption, which is parameterized

empirically as a function of SST. Absorption by photosynthetic pigments is distinguished from total absorption; the former is used to calculate productivity and the latter is used to estimate light attenuation in the water column. The depth profile of Chl-a is estimated assuming a Gaussian shape with parameters determined by the surface value.

The *Carbon-based Production Model* (CbPM) [Behrenfeld et al., 2005] is a new approach to NPP assessment that uses satellite-derived carbon to Chl-a ratio to predict phytoplankton growth rate. It utilizes the GSM01 semi-analytic algorithm to invert satellite-detected radiance into surface Chl-a and particulate backscatter coefficient (b_{bp} , m^{-1}) at 443 nm. The backscatter coefficient is then converted into phytoplankton carbon biomass (C) and NPP is calculated as the product of C and the specific phytoplankton growth rate (d^{-1}). Five input datasets are used, including the coefficient of attenuation of downwelling irradiance at 490 nm (K_{490} , m^{-1}).

As the VGPM, KI and MARRA models use the same input (Chl-a, PAR, SST) you can run them all with the same list file by adding an extra argument specifying the model (VGPM, VGPM-CAL, KI, MARRA). VGPM-CAL is another modification of VGPM that is adjusted to fit the California Current CalCOFI data. The ESQRT model needs just one satellite input field and you can just comment out the PAR and SST lines.

The CbPM model needs 5 input fields (Chl-a or a_p443 , $bbp443$, PAR, K_{490} , MLD) and these sample data are not provided on the WIM_WAM DVD.

Your next task is to run the *wam_npp_point* with the other NPP models (ESQRT, KI, VGPM-CAL, MARRA) and compare the results. Remember to rename the output file according to the NPP model used. For example, when using the MARRA model, do

```
move list_CalCOFI_VGPM_L3_2007_SWFAQU1_SWF1_MOD8.txt_out.csv
list_CalCOFI_VGPM_L3_2007_SWFAQU1_SWF1_MOD8.Marra.csv
```

If you have your own NPP data then you should be able to compare the various NPP models versus your data. The WIM_WAM DVD has sample images for only 2007. Other years can be downloaded.

5 Creating satellite images of NPP with *wam_npp*

As you experienced in the previous example, you need a series of satellite data to calculate NPP. For most of the models you need 3 input images (5 images are needed for CbPM). Older versions of WAM used a list of individual filenames as input to calculate NPP. The current *wam_npp* saves you a lot of time and only needs a list of **paths** to the images and finds itself the best matching concurrent combination of images. As daily images are mostly empty (due to clouds or limited orbit coverage) we will use concurrent monthly data to create monthly NPP images. You can use almost any kind of images (e.g. in HDF format) that WIM can read. If the images are not in the same projection then they will be mapped to the first image (Chl-a) projection.

A sample list file *list_calc_NPP_VGPM_L3_Merged.txt* for *wam_npp* looks like that:

```
# 1 - Chl
D:\Sat\Merged\L3\Daily\CHLO_9,A2007001*9
# 2 - PAR
```



```
D:\Sat\SeaWiFS\L3\Daily\PAR_9,S2007*9.hdf
# 3 - SST
D:\Sat\Merged\L3\8day\SST_9,M2007*.hdf
```

As you can see, the first part is almost identical to the list file of *wam_npp_point* and the line for the point file is missing (the lines starting with # are comments and are ignored). As it takes a long time to calculate a global NPP image, this list file matches just the January 2007 image of Chl-a. If you have more time, you can edit the list file and use A*9 instead of A2007001*9.

To see all the options run *wam_npp* without arguments:

```
C:\Sat\Merged\L4>wam_npp
wam_npp vers. 2.6
Usage: wam_npp list_file [Algorithm] [AnyYear]
Available Algorithms:
missing equals VGPM (Behrenfeld & Falkowski, 1997)
VGPM (Behrenfeld & Falkowski, 1997)
VGPM-CAL - VGPM adjusted for CalCOFI PP data by Kahru et al., 2008
SPGANT - Southern Ocean version of VGPM; modified Pbopt and Euphotic depth
KI = Kameda & Ishizaka (2005) version of VGPM
CbPM = Behrenfeld et al, 2005 Carbon based Productivity Model
ESQRT = Eppley Square Root of Chl
Marra = Marra, Ho, Trees, 2003 model
Extra option (argument2, AnyYear) must be a string of 0 or 1
1 in the Nth position means that the Nth image can be from any year, e.g.
a composite over many years;
0 in the Nth position means that for Nth image years and days are considered
when calculating the difference in days.
Default is to calculate difference in Days considering Years
Example: for VGPN 011 would use any years of the PAR and SST for a Chl image;
for CbPM 00101 would use any years of the PAR and MLD.
```

As the output is recorded into the current directory where the command is issued from, you cannot issue this from the DVD where you cannot write. Therefore, create a folder like *C:\Sat\Merged\L4*, cd to that folder and issue the command from there.

The 2nd argument AnyYear is a sequence of 0s and 1s and is meant to match the corresponding image of any year. For example, when calculating NPP for OCTS we don't have SeaWiFS PAR data for the needed months (November-1996 to June-1997). We can create mean monthly PAR images for those months and use the mean monthly PAR for each particular month (or use SeaWiFS PAR from another year). In that case we would use the 2nd argument of 010. This means to use actual matching images for Chl-a and SST and the any year of that month for PAR (the 2nd image in the sequence).

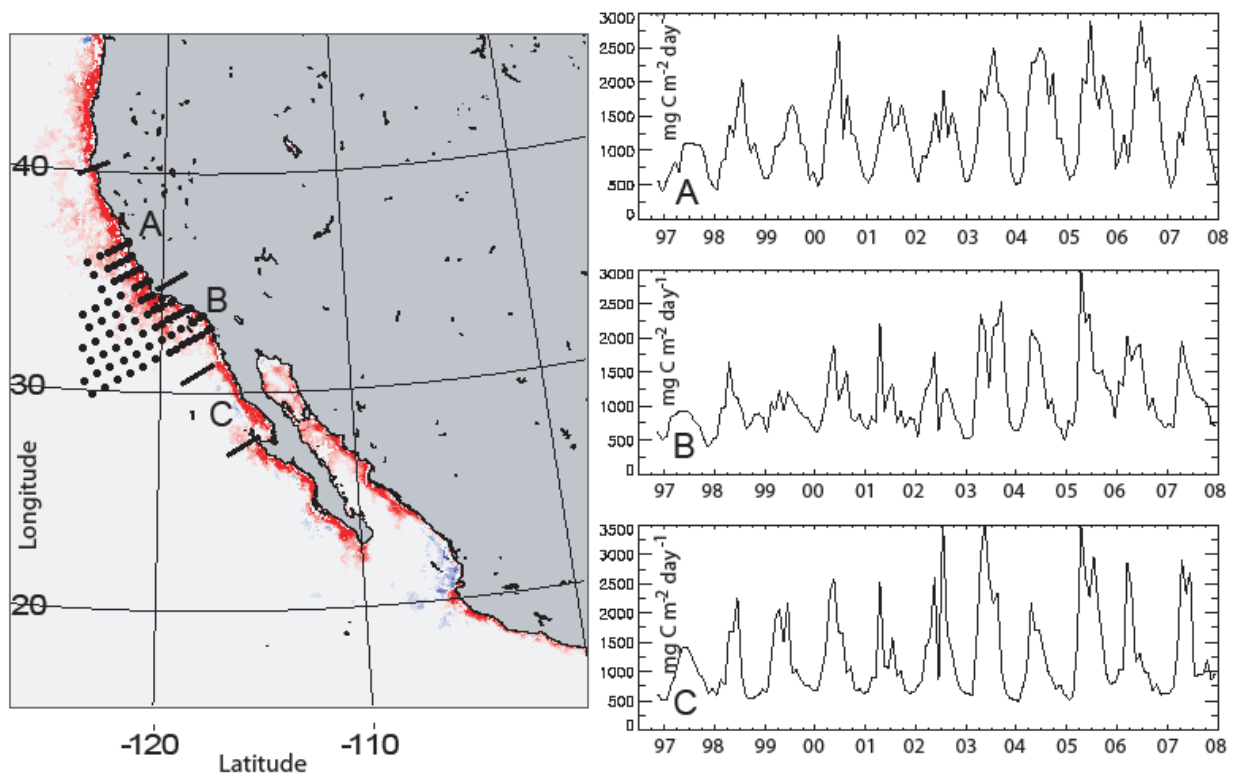
You may be able to download global NPP images from some websites but the advantage of using *wam_npp* is that you can create these images for your particular datasets with higher spatial and/or temporal resolution using the input data and model options that are most appropriate for your case. Also, it is possible to extend both *wam_npp_point* and *wam_npp* and add new NPP models and different options.

As you can see from the list file *list_calc_NPP_VGPM_L3_Merged.txt* the following input data are used: Chl-a data from the DVD \Sat\Merged\L3\month\CHLO_9, PAR data from \SatSeaWiFS\L3\Month\PAR_9 and SST data from \Sat\Merged\L3\month\SST_9.

After you have created a time series of monthly NPP images, you can apply a number of tools. You can detect trends in NPP with *wam_annual_max*, see [Tutorial Detection of Change.pdf](#) for details.

You can also create time series for your area of interest with *wam_statist* - see [Practical Exercises with WIM and WAM](#) for details on *wam_statist*.

For example, after running *wam_annual_max* and *wam_statist* for the 50 km near-shore band along the California coast we get the following:



The figure above shows a map of the change in annual maximum VGPM-CAL primary production during last 11 years (1997-2007). Red areas show significant increase, blue areas significant decrease and light gray areas have no detectable trend. The grid of the CalCOFI stations with in situ NPP measurements is shown as black filled circles. Right panel shows monthly time series of NPP in 50 km coastal strip off Central California (A), Southern California (B) and Northern Baja California (C).