# Satellite Oceanography: Ocean colour

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UNIVERSITY OF MIAMI
ROSENSTIEL SCHOOL of MARINE & ATMOSPHERIC SCIENCE

ESA EARTH OBSERVATION SUMMER SCHOOL
ON EARTH SYSTEM MONITORING & MODELLING
30 July - 10 August 2012

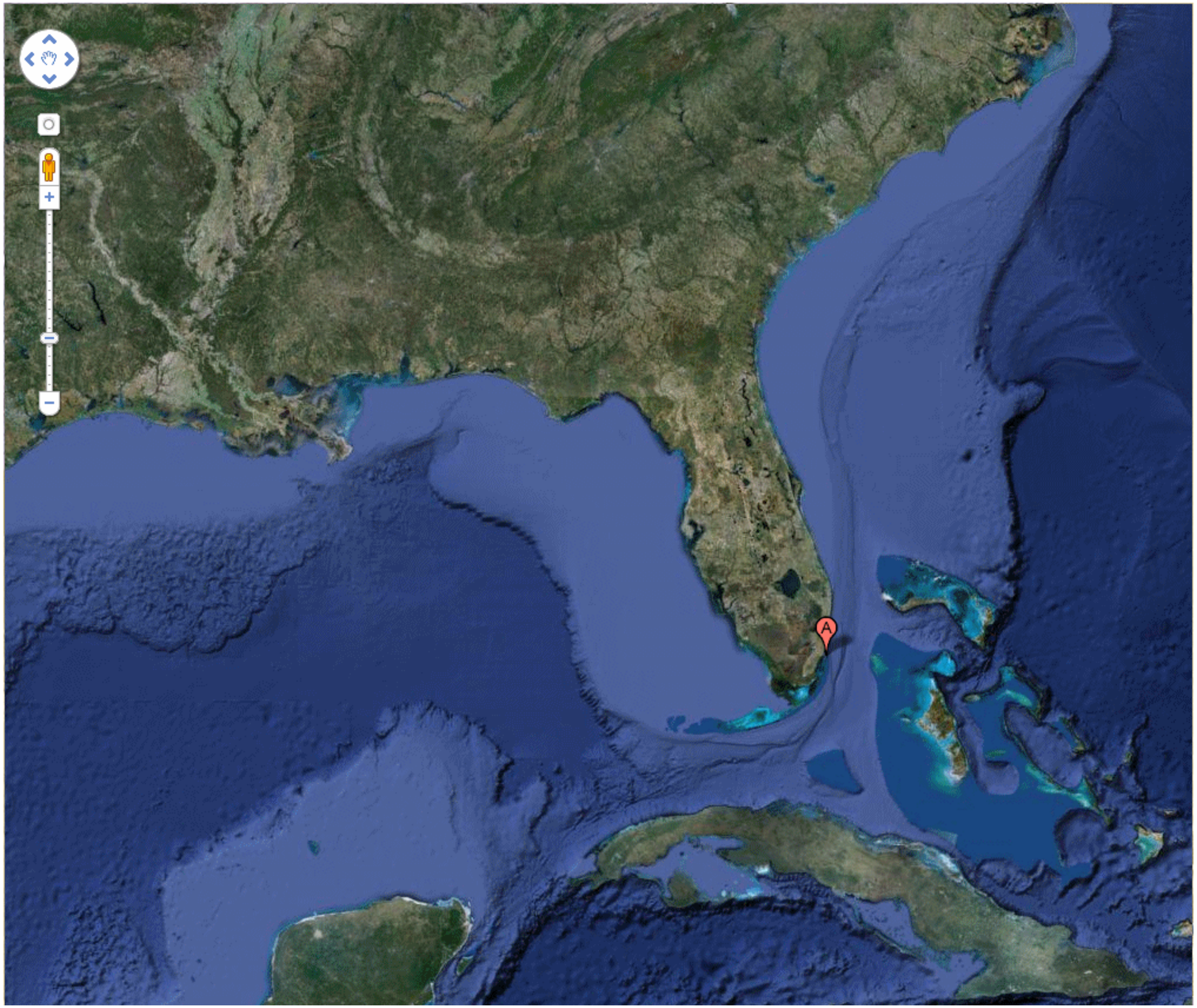
esa

# Outline

- Why try to measure ocean colour?
- What is ocean colour?
- Remote sensing of ocean colour.
- Ocean colour sensors.
- Chlorophyll retrievals.
- Primary productivity retrievals.

- But first, something about the University of Miami, and the Rosenstiel School of Marine and Atmospheric Science….


Welcome to
Florida
We are here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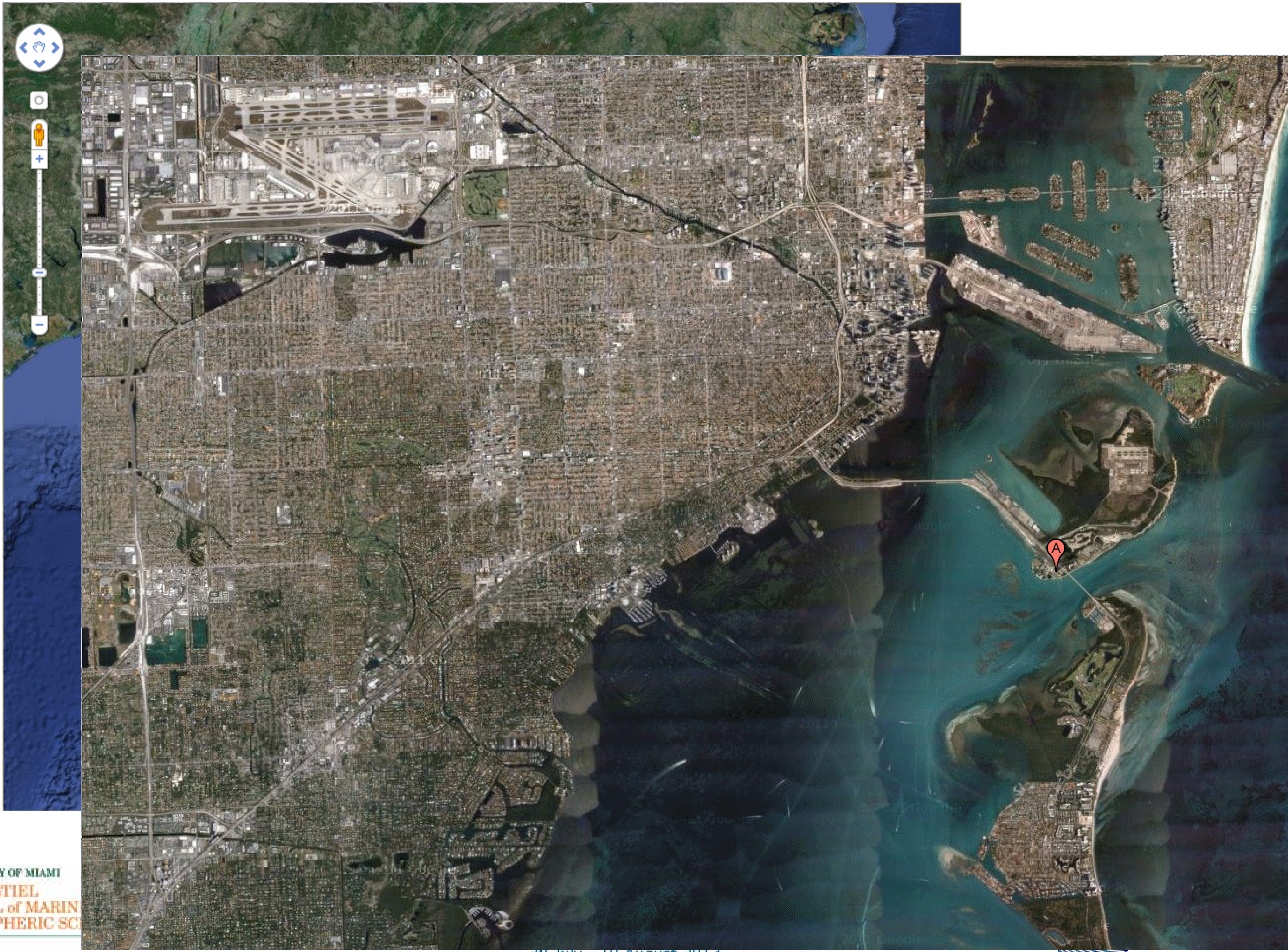

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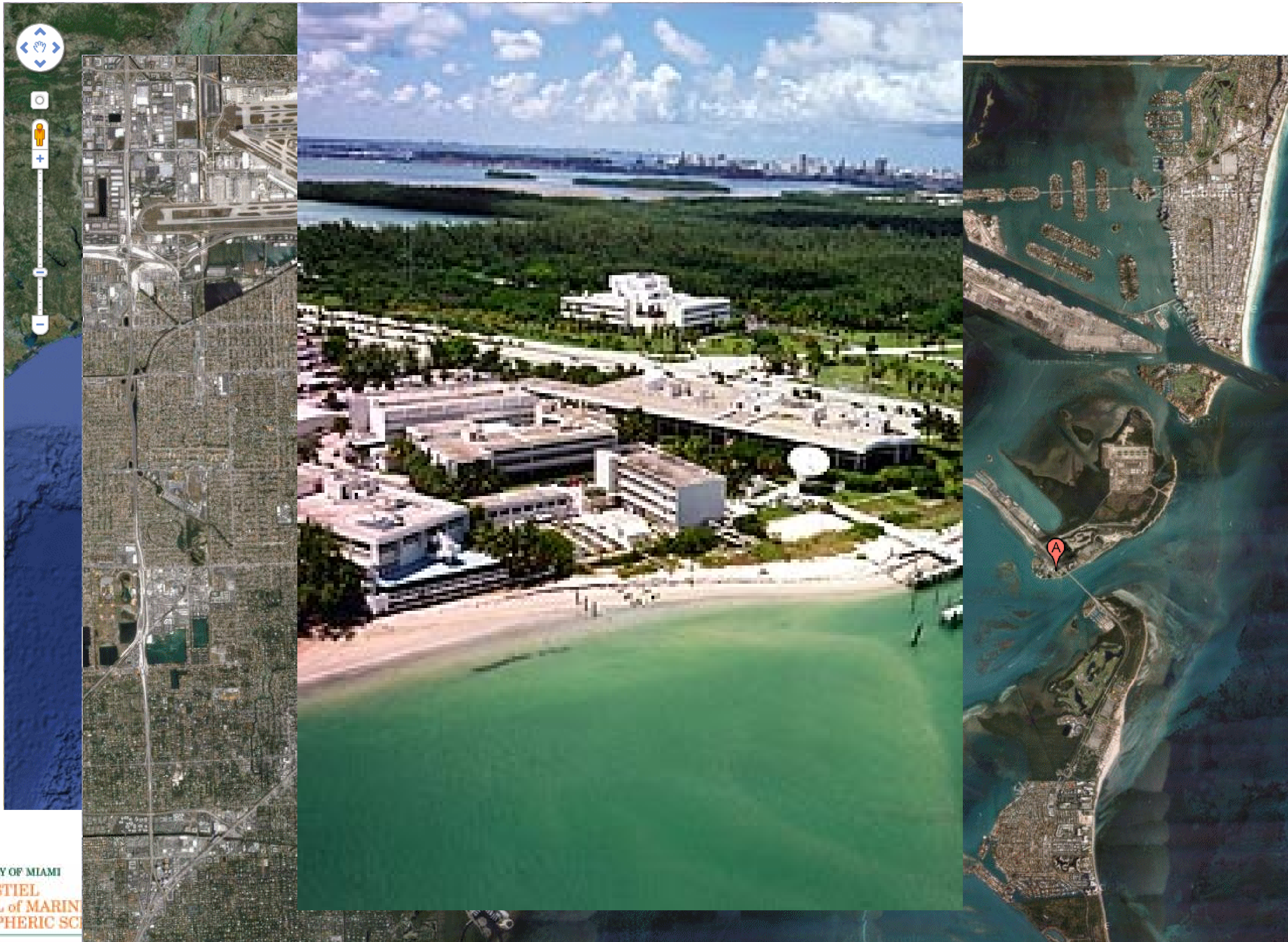
ATMOSPHERIC SC



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Ranked 38th university in the USA, by US News and World Report (out of ~1600)

Ranked 13th in the world for Geosciences by Thomson Reuters from its Essential Science Indicators

Ranked 5th university in the USA for Geosciences by Thomson Reuters from its Essential Science Indicators

CSTARS: Facility - Mozilla Firefox

http://cstars.rsmas.miami.edu/cstars-info/facility

THE WORLD FROM ANOTHER PERSPECTIVE

Center for Southeastern Tropical Advanced Remote Sensing

ROSENSTIEL SCHOOL OF MARINE AND ATMOSPHERIC SCIENCE

UNIVERSITY OF MIAMI

CSTARS





## Facility

The CSTARS receiving and analysis complex is located on the former U.S. Naval Observatory Secondary National Time Standard Facility, which the University of Miami purchased in 2000. The Richmond Campus consists of 78 acres with several buildings, two 11.3 m antennas, and a 20 m antenna. The 11 m antennas are used for X-band data collection from low-earth orbiting satellites, while the 20m antenna is used to facilitate geosynchronous satellite communications with the Antarctic, supported by the National Science Foundation.

CSTARS was designed and developed as a highly automated, near real-time, multi satellite reception and processing facility. The CSTARS facility consists of three components: Ingest Archive System (IAS); Product Generation System (PGS); Data Exploitation System (DES). The facility is based on two antennas for redundancy and conflict resolution and includes dual units of all key components of the IAS and PGS systems for redundancy and backup. This approach permits highly automated operation and seamless transition to backup units in case of sudden component failure.

Continuous electrical power to the facility is supported by an uninterruptible power supply (UPS) unit for all CSTARS critical systems such as the capture, processing and archiving computers and hardware and then a 400 KVA diesel generator will provide backup power for more than a week in the event of loss of power. Dark fiber optics cables are available and connect the CSTARS site with the University of Miami campus-wide network as well as to the Internet 2. CSTARS, one of four campuses of the University of Miami (UM) is connected to UM's redundant network ring. This means CSTARS is connected to the world on alternate, independent networks running OC-48 bandwidth. The University of Miami is one of the charter members for the development of the National Lambda Rail (NLR) and Florida Lambda Rail (FLR) that has provided 10 Gbit/s internet connectivity since 2004.

For more photos of the facility click here.

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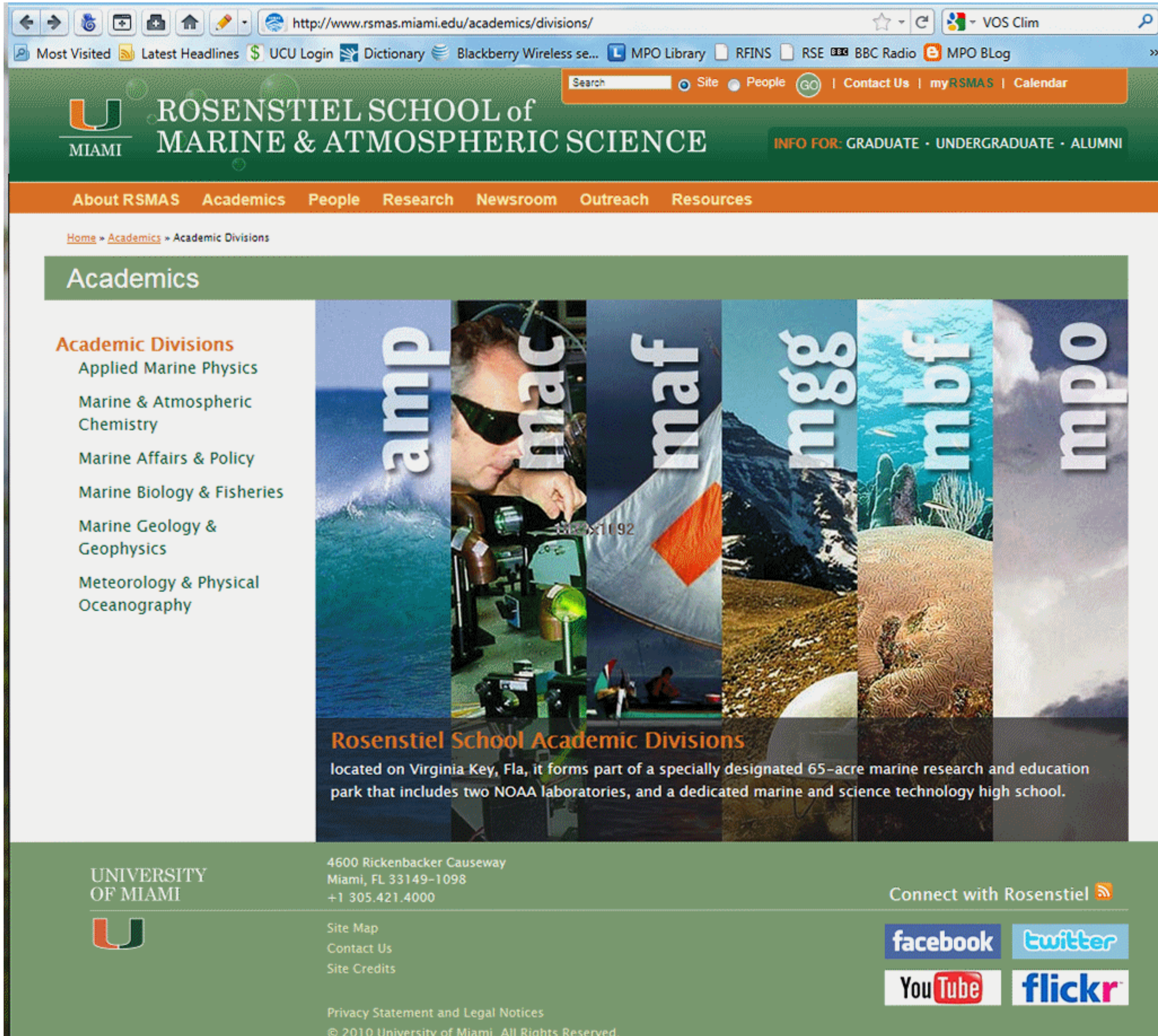


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ON EARTH SYSTEM MONITORING & MODELLING

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# RSMAS-Meteorology & Physical Oceanography (MPO)

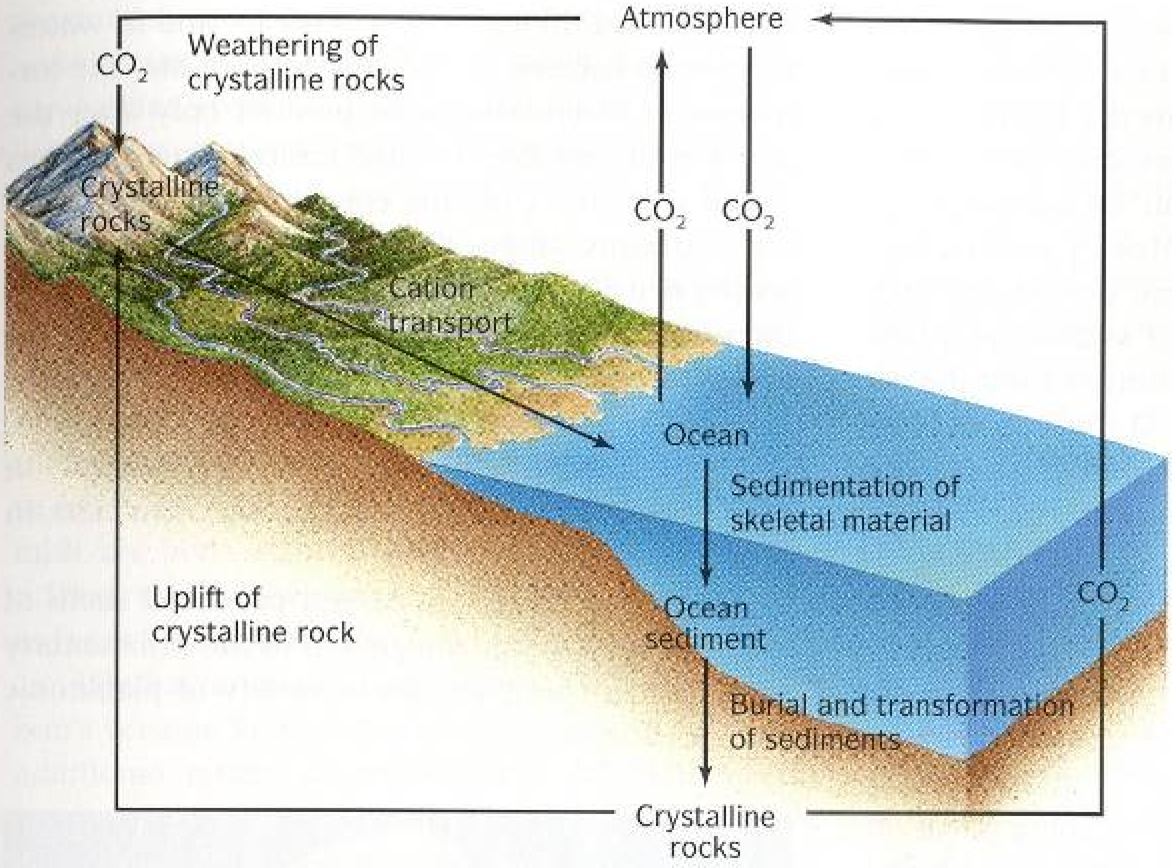
- RSMAS:
  - ~95 Faculty
  - ~325 Undergraduate students
  - ~250 Graduate students
- MPO:
  - 26 Faculty
  - ~40 Research staff
  - 56 grad students

# What I am missing by being here…

And now back to Ocean Colour……

# Geochemical Carbon Cycle

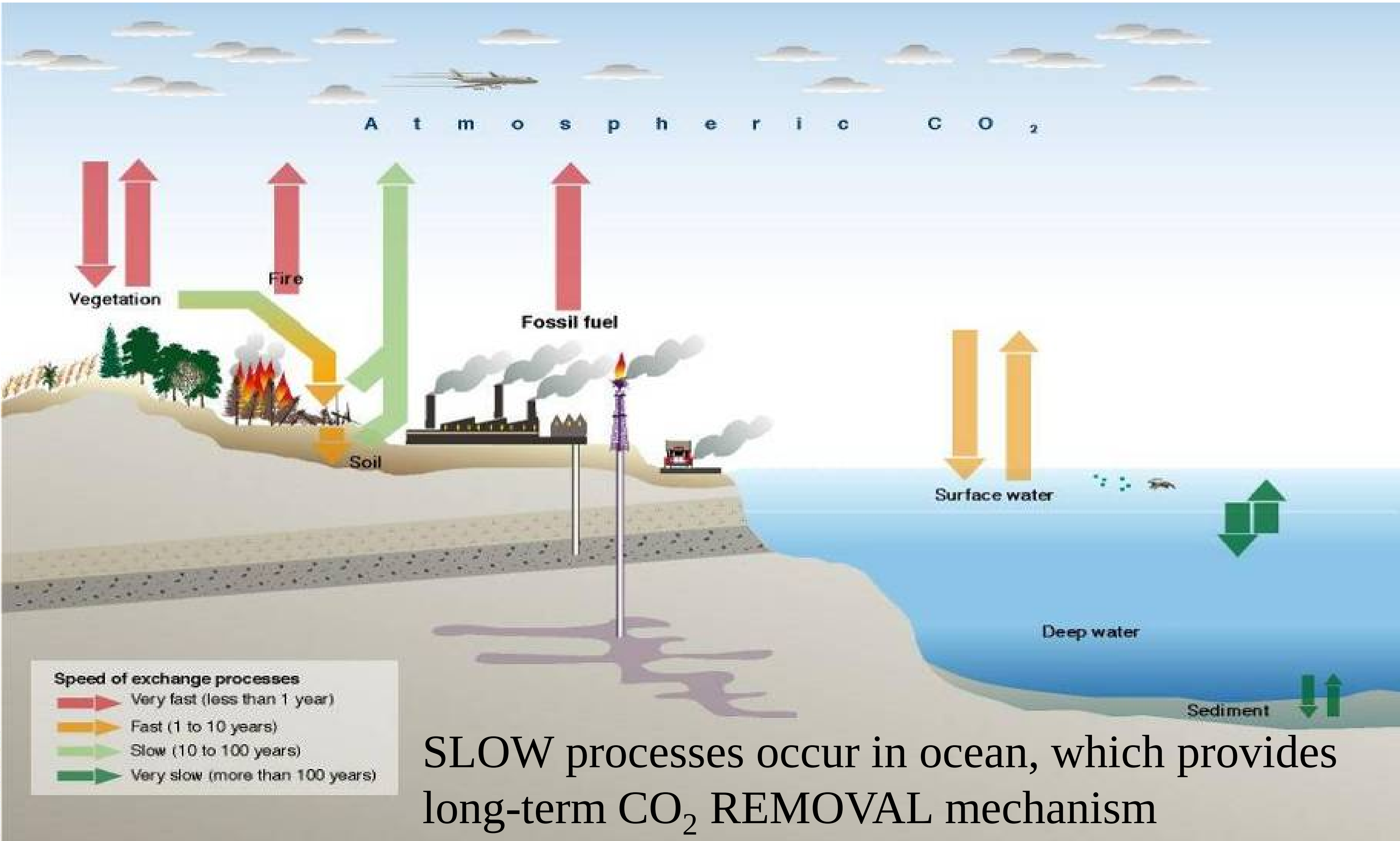





The geochemical carbon cycle is controlled by slow geomorphic and geotectonic processes, including the burial and transformation of sediments, the eventual uplift of crystalline rocks, and their subsequent weathering.

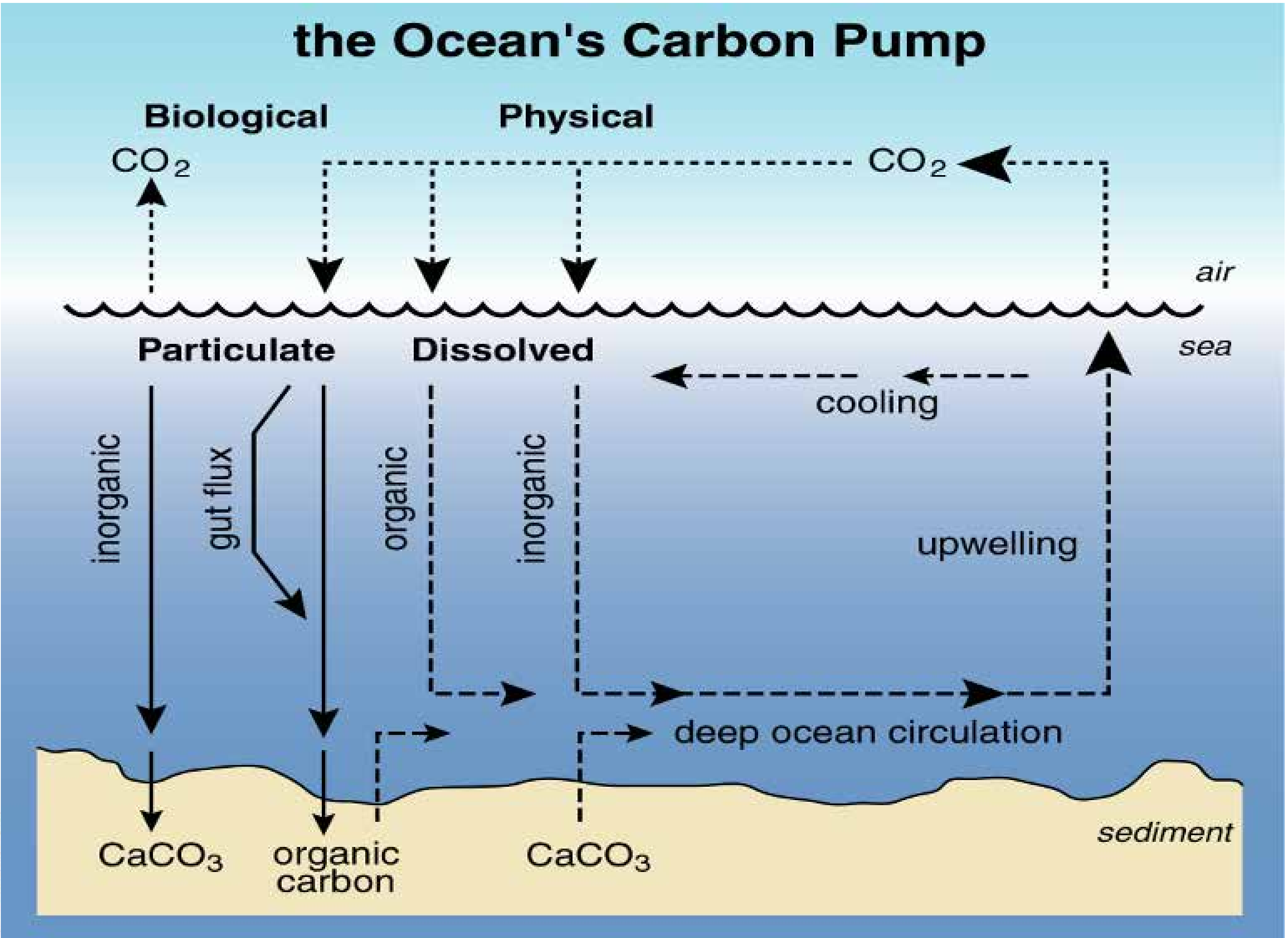
From Vaclav Smil, “Cycles of Life, Civilization and the Biosphere.” Scientific American Books, 1997

# Global carbon cycle: increase in atmospheric $CO_2$ contributes to global warming & climate change




SLOW processes occur in ocean, which provides long-term $CO_2$ REMOVAL mechanism

# Primary production is an important mechanism for carbon fixation

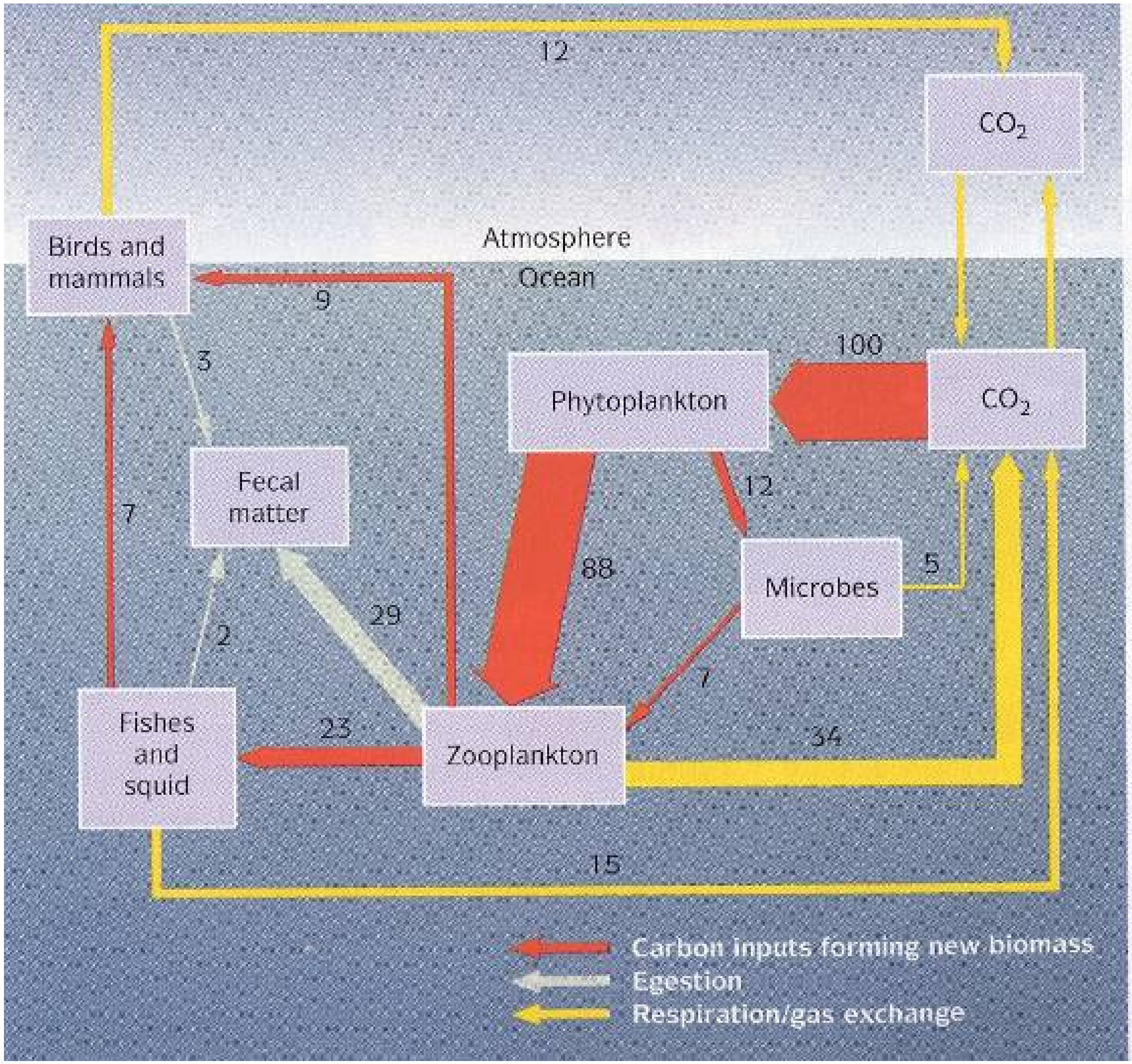



**Biomass?**

**Rates?**

**Feedbacks?**

# Quantifying the links




The respiration of birds and mammals is responsible for a substantial carbon "leak" in a great phytoplanktonic pump operating in Antarctic waters. In the depicted case, about one-eighth of all assimilated carbon is respired by these top predators. All values are shown as shares of the total carbon assimilated by phytoplankton.

From Vaclav Smil, "Cycles of Life, Civilization and the Biosphere." Scientific American Books, 1997

# Role of the Oceans in the Carbon Cycle

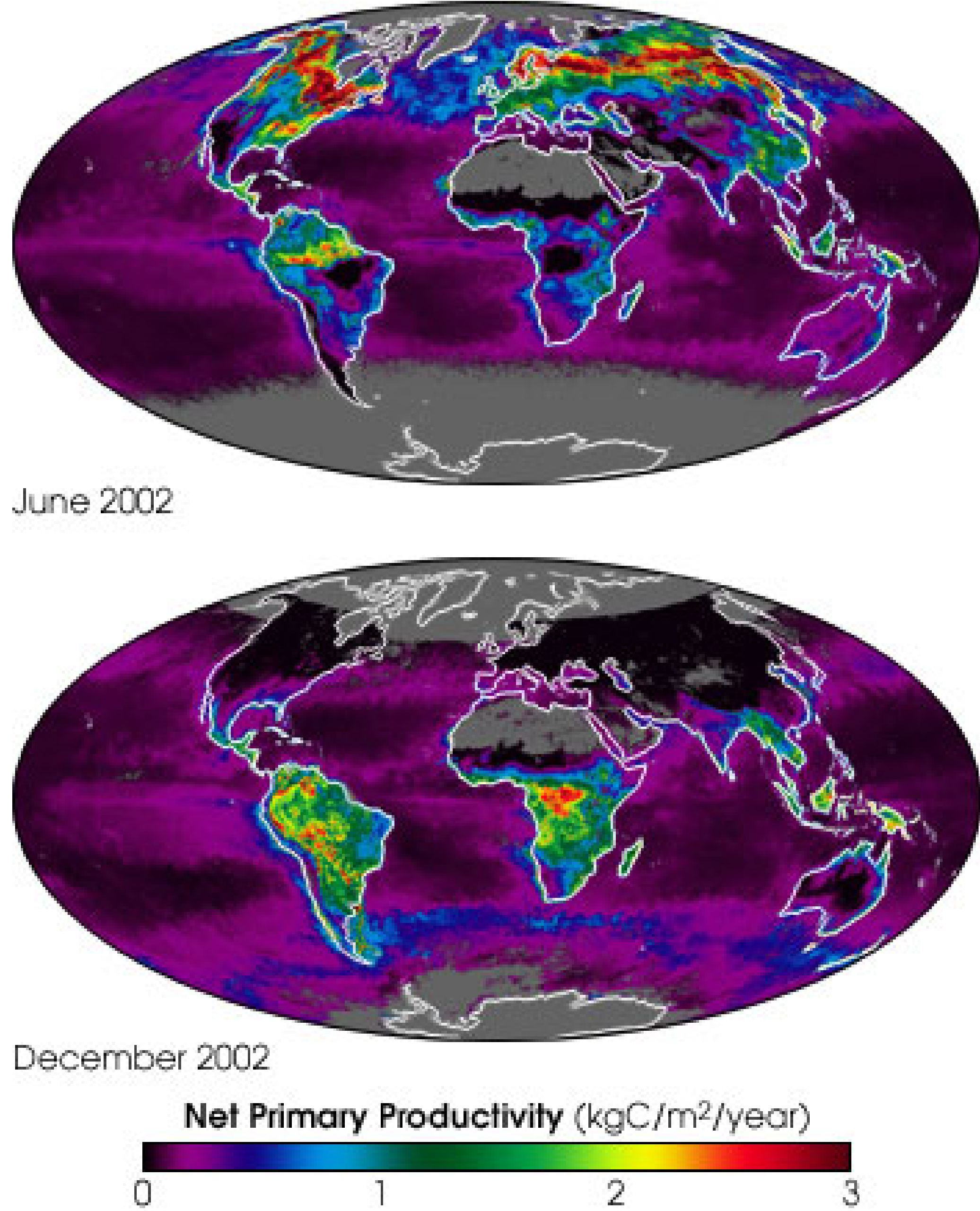
- What is the role of the oceans in the Carbon Cycle – net source or net sink?
- Will the ocean's role in carbon cycling change in terms of:
  - Changes in circulation and temperature
  - Shifts in ecosystem structure and carbon export

  (e.g., in analogy to vegetation shifts on land in response to precipitation changes)

# Primary Productivity

Only satellite remote sensing can give the global view.

But is it quantitative?



# What is ocean color?

- The color of the ocean gives an indication of the concentration of its optical constituents.

- In “clear” waters the main constituent influencing the ocean color is phytoplankton—the absorption by pigments such as the green pigment chlorophyll-a.
  - The higher the concentration of phytoplankton the greener the water.
  - If little phytoplankton is present, then the water will appear blue.

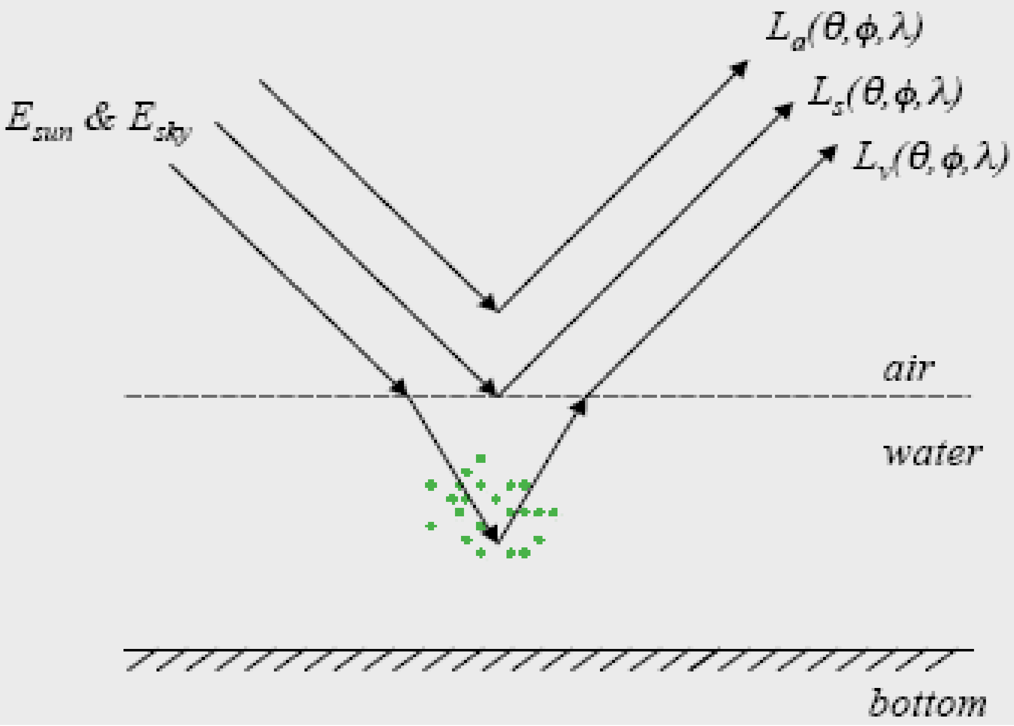
- In “turbid” waters (generally shallow, coastal waters) other constituents (such as suspended sediments, terrestrial run-off, colored dissolved organic matter - CDOM) influence the color.

# Ocean Water Types - Jerlov

- Jerlov (1951) formally classified oceanic water types according to their optical attenuation properties:
  - Type I: extremely clear oceanic waters.
  - Type II: mostly clear coastal waters where attenuation >> oceanic waters of low productivity.
- However, many water bodies were found to lie between Types I and II and the former was subsequently split into Types IA and IB (Jerlov 1964).
- Type III waters are “fairly” turbid and some coastal regions are so turbid that they are “unclassified.”

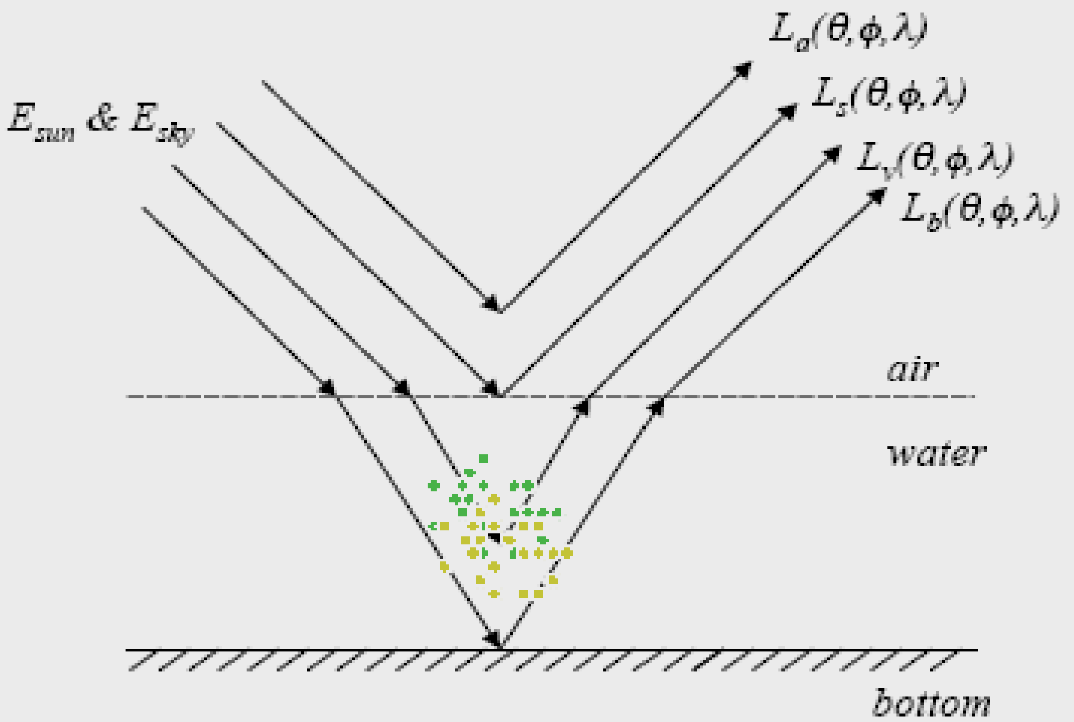
# Ocean Colour

- Water leaving radiance: Case 1
  - Need to remove the influence of the atmosphere
  - Atmospheric correction (H.R. Gordon and M. Wang)



# Ocean Colour

- Water leaving radiance: Case 2
  - Need to remove the influence of the atmosphere
  - Atmospheric correction (H.R. Gordon and M. Wang)

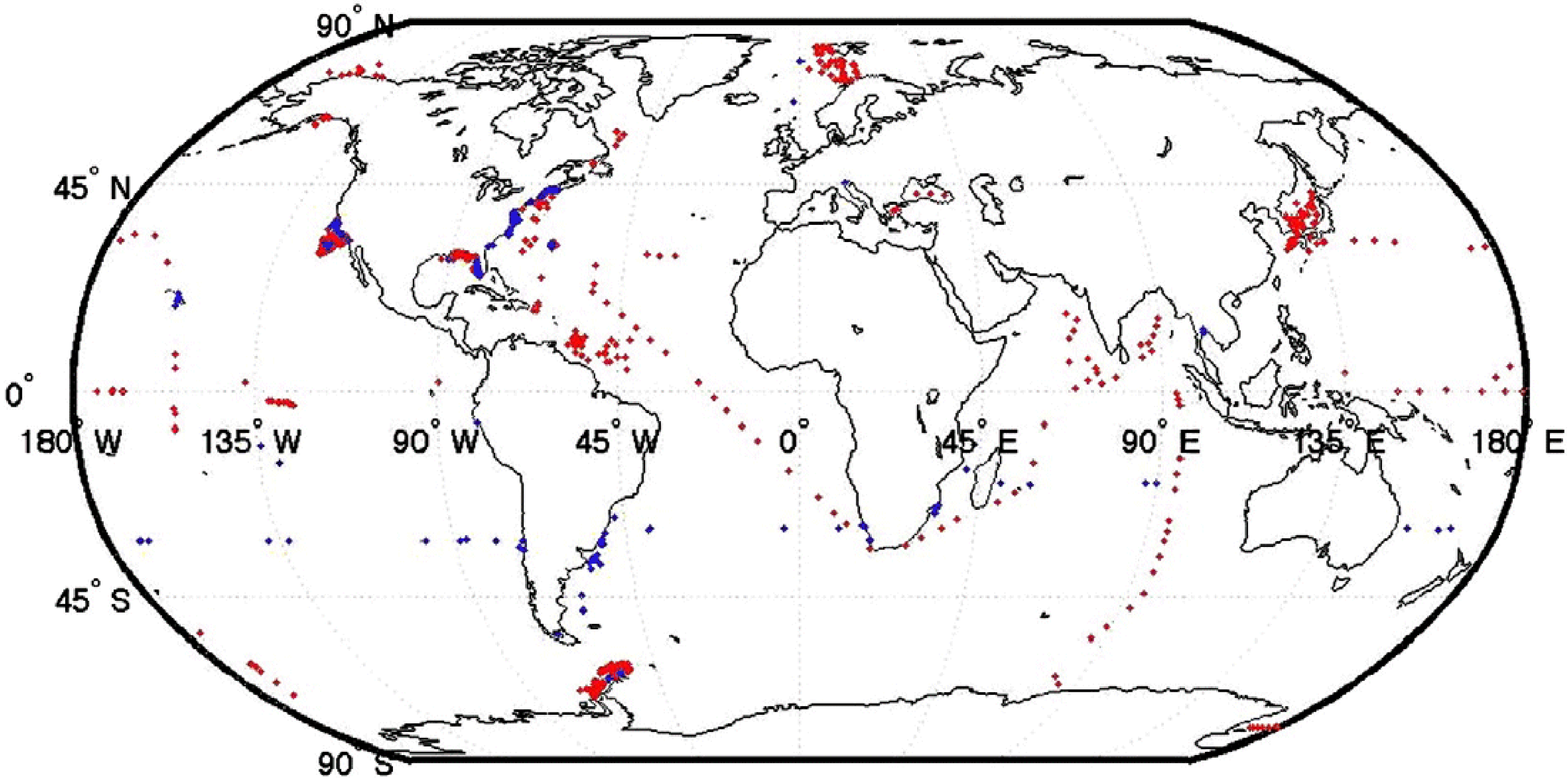


# Ocean Water Types - Moore

Moore et al (2009) used a Fuzzy Logic approach for quantitative ocean water classification according to spectral properties of Remote Sensing Reflectance.

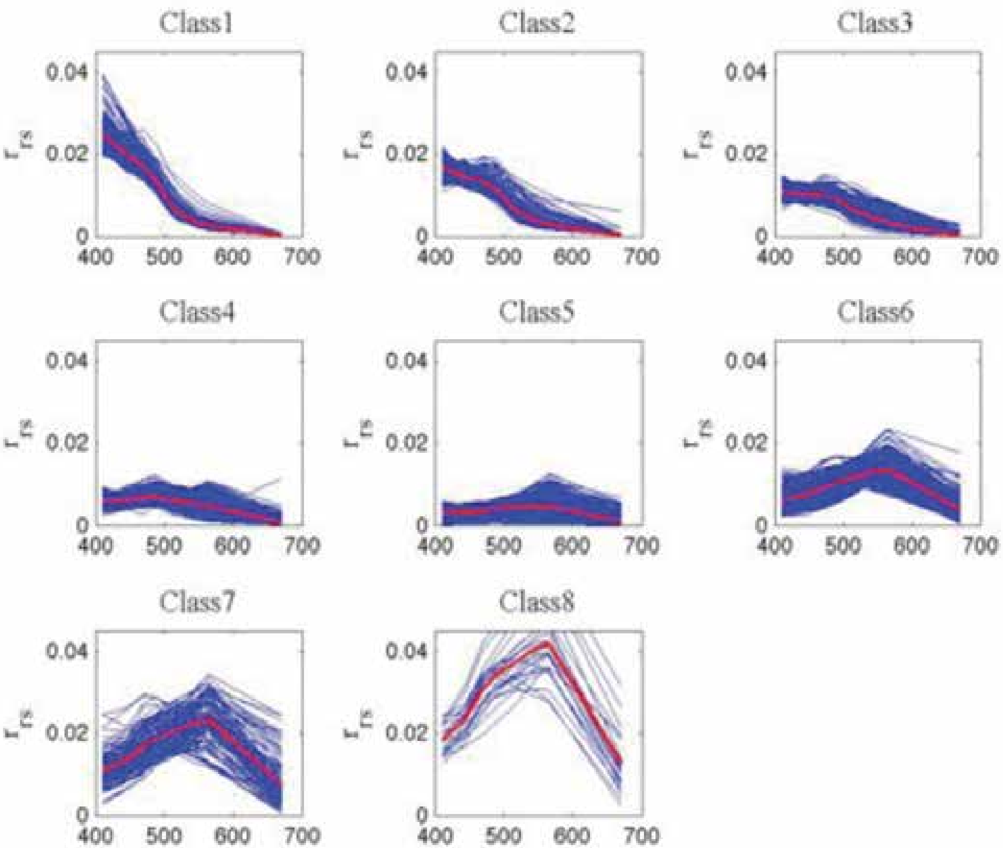
Moore, T. S., J. W. Campbell, and M. D. Dowell, 2009: A class-based approach to characterizing and mapping the uncertainty of the MODIS ocean chlorophyll product. *Remote Sensing of Environment*, ***113***, 2424-2430.

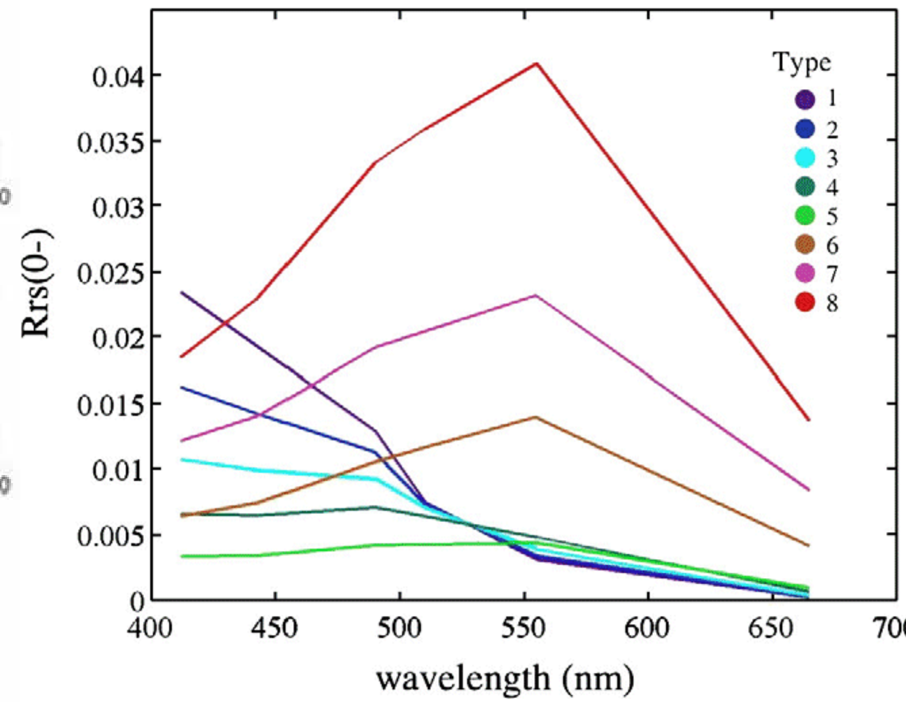
# Ocean Water Types – in situ data




Geographic distribution of the NOMAD V2 data set (red) and the Aqua validation data set (blue) used in the Moore et al (2009) analysis.

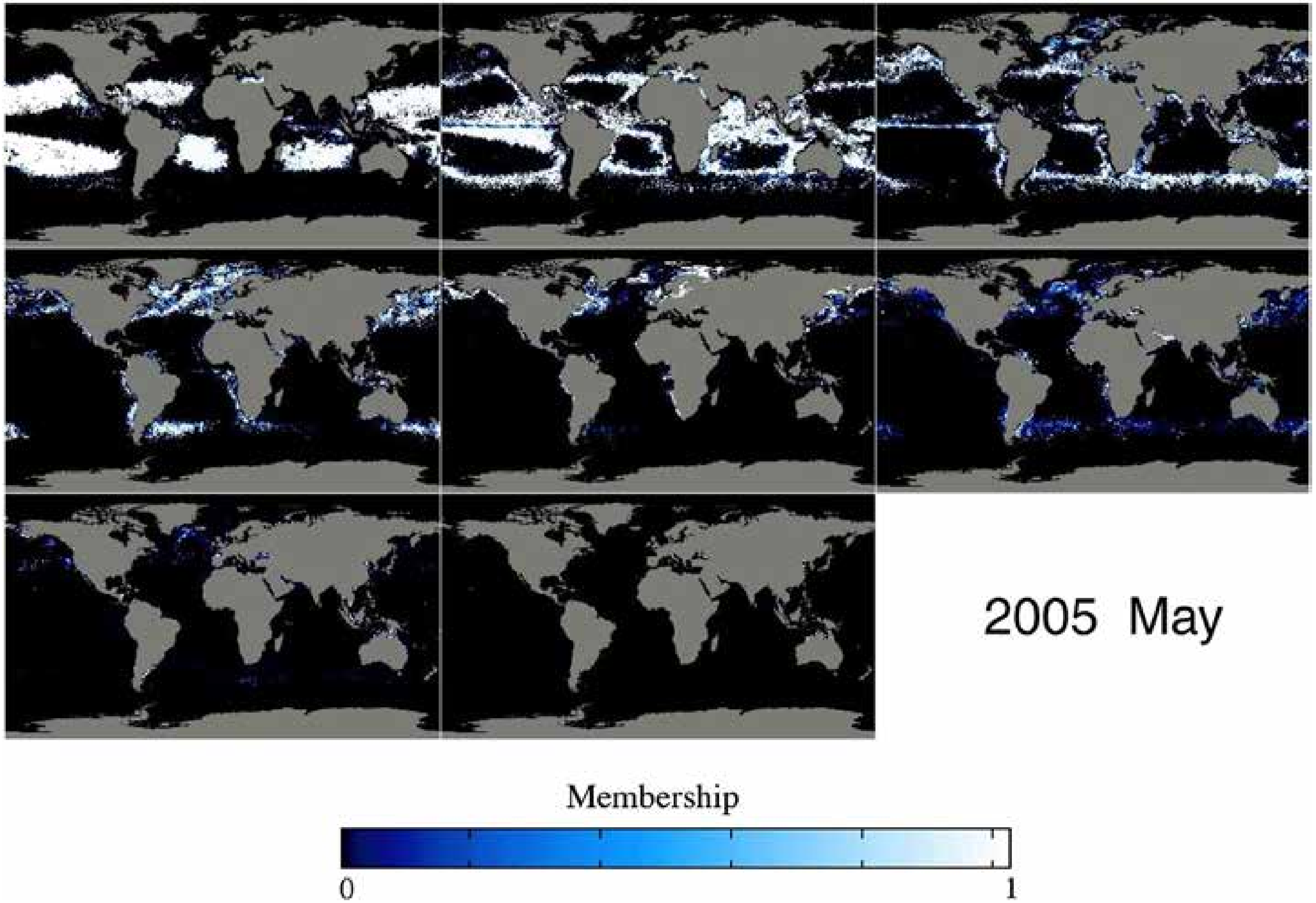
# Ocean Water Type Classification




Mean reflectance spectra for the eight optical water types.

# Ocean Water Types




The fuzzy membership maps of the eight optical water types for a monthly composite satellite image from MODIS Aqua for May 2005. Left to right, types 1–3 are top row; types 4–6 are middle row, and types 7–8 are bottom row. Memberships have been normalized by the sum.

# What can happen to a beam of radiation as it passes through the atmosphere ?

There are four processes that can alter the radiation as it passes through an elemental slab of the atmosphere:

- Radiation from the beam can be absorbed by the atmosphere
- Radiation can be scattered out of the beam into other directions
- ~~Radiation can be emitted by the atmosphere~~ (not in the visible)
- Radiation can scattered into the beam from other directions

# What can happen to a beam of radiation as it passes through the ocean ?

There are four processes that can alter the radiation as it passes through an elemental slab of the ocean:

- Radiation from the beam can be absorbed by the ocean (very wavelength dependent)
- Radiation can be scattered out of the beam into other directions
- ~~Radiation can be emitted by the ocean~~ (not in the visible)
- Radiation can scattered into the beam from other directions

# What can happen at the ocean surface ?

- Specular reflection of solar radiation
  - Polarization dependent
  - Solar zenith angle dependent
  - Roughness (wind, waves dependent)
- Reflection of sky-light
- Effects of white-capping

# Ocean colour measurements

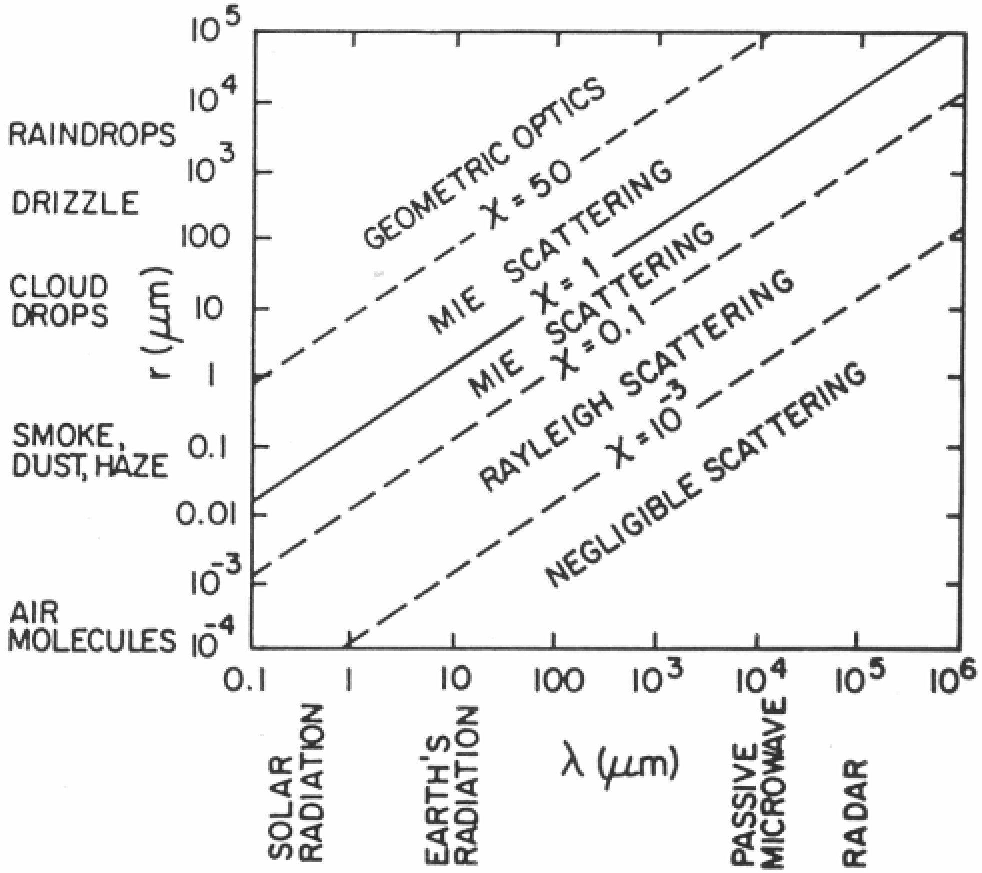
- Channel selection:
  - To measure pigments: chlorophyll, sediments, CDOM
  - Reference in Near IR channel where ocean is dark.
- Calibration:
  - Pre-Launch
  - On-orbit – solar diffuser, moon views
  - Vicarious – compare with surface or sub-surface sensors
- Atmospheric correction:
  - Rayleigh scattering - need $P_o$
  - Aerosol effects – modeling
  - Cloud cover – thresholding (daytime data only – that's fine as there's only daytime color data)
  - Ozone – requires ancillary data
- Surface corrections:
  - Reflected skylight
  - Sun glitter – need $U_o$
  - White caps – need $U_o$

# Atmospheric Correction

- We want to measure the "colour" of the ocean, but the satellite actually measures “ocean + atmosphere”. The atmosphere is 90% of the signal in the ‘blue’ segment of the spectrum, and it must be accurately modeled and removed.
- Some of the atmospheric effects that are included in visible “atmospheric correction” for retrieval of ocean water leaving radiance or reflectance include:
  - Gaseous absorption (ozone, water vapor, oxygen).
  - Molecular scattering (air molecules), also referred to as Rayleigh scattering. (reason for blue skies and red sunsets).
  - Aerosol scattering and absorption (haze, dust, pollution). Whitens or yellows the sky.

Adapted from **http://seawifs.gsfc.nasa.gov/SEAWIFS/TEACHERS/CORRECTIONS/** *Bryan Franz, SeaWiFS Project*

# Scattering regimes




Scattering regimes. [Adapted from Wallace and Hobbs (1977).

$\chi = 2\pi a / \lambda$

$= q$

# Optical properties of water

- Inherent Optical Properties (IOPs): properties of the medium, including absorption & scattering coefficients, and Fresnel reflection coefficients at the air-water interface.
- Apparent Optical Properties (AOPs): depend on IOPs and directional properties of the ambient light field, include diffuse attenuation coefficient, reflectance (at the surface and subsurface).

# Some definitions

- $L_w(\lambda)$ – Water Leaving Radiance: the radiance leaving the sea surface (excluding the direct reflection of skylight and sunlight) in the direction of the sensor
- $nL_w(\lambda)$ – Normalized Water Leaving Radiance: $L_w(\lambda)$ for the sun at zenith
- $R_{rs}(\lambda)$, $\rho(\lambda)$ – Remote Sensing Reflectance: $L_w(\lambda)$ divided by incident irradiance.

**Radiometric quantities**

| | | |
|---|---|---|
| $L(\lambda, \theta_s, \theta_v, \Delta\phi)$ | Spectral radiance | W m$^{-2}$ sr$^{-1}$ nm$^{-1}$ |

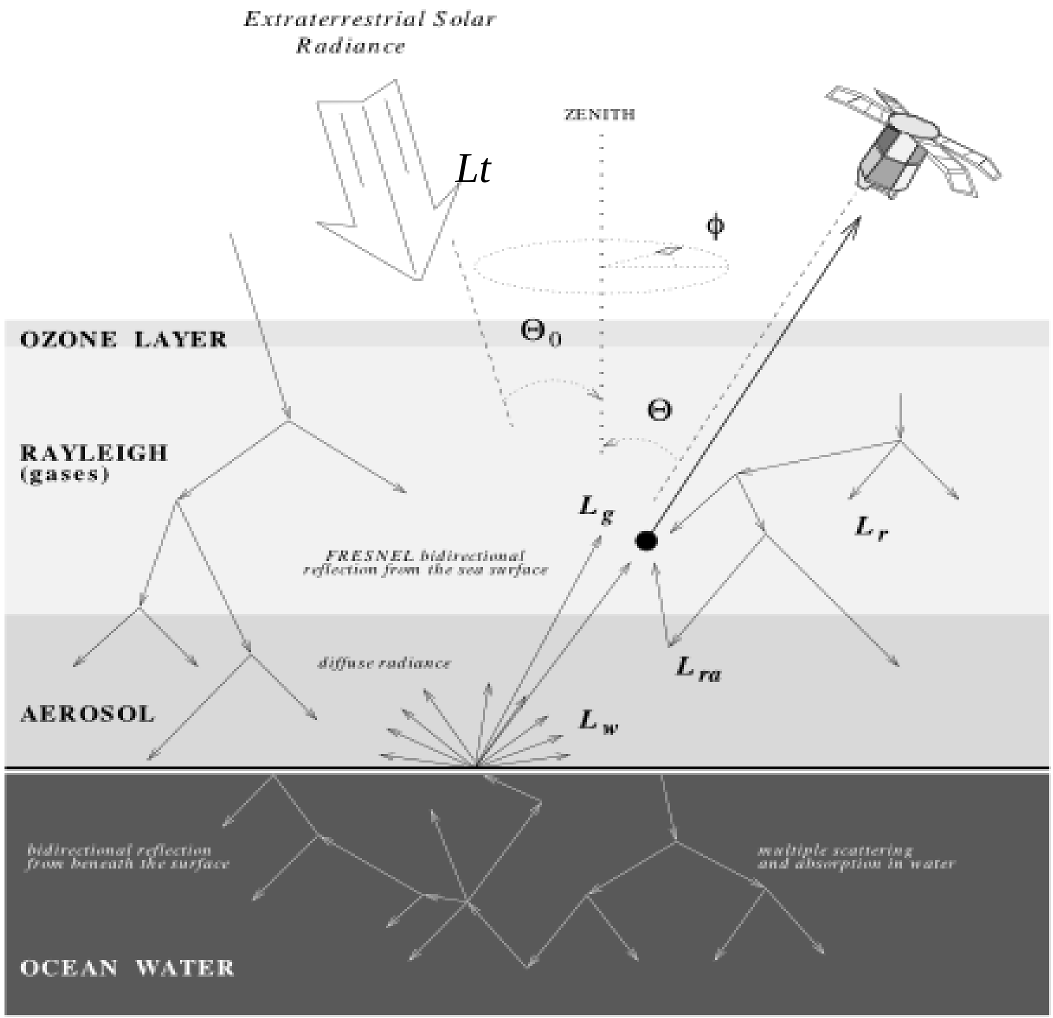
**Inherent Optical Properties (IOPs)**

| | | |
|---|---|---|
| $\beta(\theta, \lambda)$ | Volume scattering function (VSF) | sr$^{-1}$ |
| $\tilde{\beta}(\theta)$ | Normalised volume scattering function | sr$^{-1}$ m$^{-1}$ |
| $a(\lambda)$ | Absorption coefficient | m$^{-1}$ |
| $b(\lambda)$ | Scattering coefficient | m$^{-1}$ |
| $c(\lambda)$ | Attenuation coefficient for wavelength $\lambda$ | m$^{-1}$ |
| $b_b(\lambda)$ | Backscattering coefficient | m$^{-1}$ |

**Apparent Optical Properties (AOPs) and derived quantities**

| | | |
|---|---|---|
| $\rho_w(\lambda, \theta_s, \theta_v, \Delta\phi)$ | Reflectance | dimensionless |
| $\rho_{wn}(\lambda)$ | Normalised water reflectance (i.e. the reflectance if there were no atmosphere, and for $\theta_s = \theta_v = 0$) | dimensionless |
| $E_u(\lambda)$ | Upwelling irradiance | W m$^{-2}$ nm$^{-1}$ |
| $E_d(\lambda)$ | Downwelling irradiance | W m$^{-2}$ nm$^{-1}$ |
| $E_s(\lambda)$ | Total downwelling irradiance just above the sea surface, denoted also as Ed(0+). | W m$^{-2}$ nm$^{-1}$ |
| $R(\lambda, 0^-)$ | Diffuse reflectance at null depth, or irradiance reflectance ($E_u$ / $E_d$) | dimensionless |
| $F_0(\lambda)$ | Mean extraterrestrial spectral irradiance | W m$^{-2}$ nm$^{-1}$ |
| f | Ratio of $R(0^-)$ to $(b_b/a)$; subscript 0 when $\theta_s = 0$ | dimensionless |
| f' | Ratio of $R(0^-)$ to $(b_b/(a + b_b))$; subscript 0 when $\theta_s = 0$ | dimensionless |
| $Q(\lambda, \theta_s, \theta_v, \Delta\phi)$ | Factor describing the bidirectionality character of $R(\lambda, 0^-)$ Subscript 0 when $\theta_s = \theta_v = 0$; $Q = E_u/L_u$ | sr$^{-1}$ |

# Atmospheric processes and correction equation




At-satellite radiance
*e.g.* MODIS, SeaWiFS, MERIS, VIIRS…

$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_a(\lambda) + \rho_{ra}(\lambda) + t(\lambda)\rho_{wc}(\lambda) + t(\lambda)\rho_w(\lambda) + t(\lambda)\rho_g(\lambda)$$

# Atmospheric Correction Equation

$$\rho_t = \rho_r + (\rho_a + \rho_{ra}) + \tau\rho_{wc} + \tau\rho_g + \tau\rho_w$$

Expressed in terms of reflectance. <u>All terms are wavelength dependent</u>.

$\rho_w$ is the quantity we wish to retrieve at each wavelength.

$\tau$ is the atmospheric transmissivity

$\rho_t$ is the total reflectance measured at the satellite

$\rho_r$ is the contribution due to molecular (Rayleigh) scattering, which can be accurately modeled.

$\rho_a + \rho_{ra}$ is the contribution due to aerosol and Rayleigh-aerosol scattering, estimated in NIR from measured radiances and extrapolated to visible using aerosol models.

$\rho_{wc}$ is the contribution due to "white"-capping, estimated from statistical relationship with wind speed.

$\rho_g$ is Sun glint, the diffuse reflectance of the solar radiance from the sea surface. This effect for SeaWiFS is minimized by tilting the sensor. MODIS, MERIS & VIIRS do not tilt and the sun glint must be removed.

# Sun glint

True colour image, with wild fires in red.

The Moderate-resolution Imaging Spectroradiometer (MODIS) acquired this true-colour image of Florida on May 19, 2001, revealing a lot of smoke and haze blanketing most of the state.

Bright sea to the west is sun glint.

# Sunglint

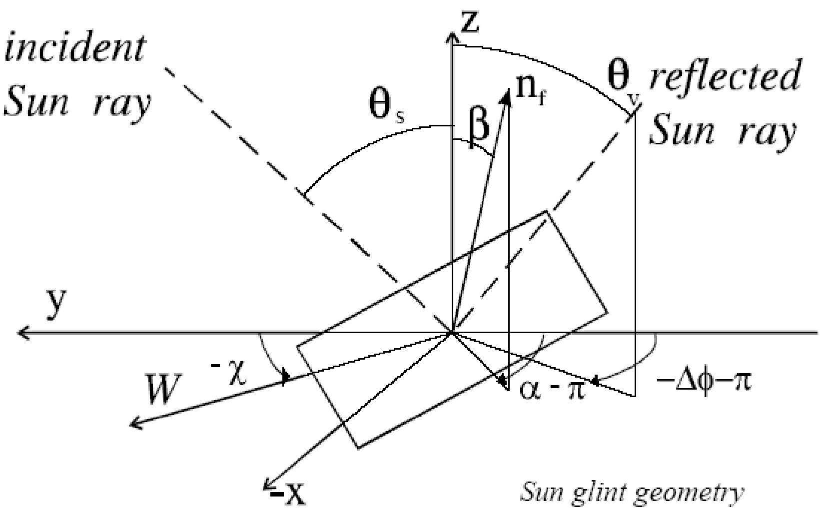
The intensity of sun-glitter can be calculated by the theory of Cox and Munk (1954), who showed, empirically, that for a uniform ocean surface roughness, there is a near-Gaussian distribution of surface wave slope with a probability function:

$$P(b, s) \approx (2ps^{2})^{-1} (\exp - (\tan^{2}(b))/s^{2})$$

Where s is the standard deviation of P, and is related, again empirically, to $U_{10}$, the near-surface wind speed (in $ms^{-1}$), by:

$$s^{2} = 0.00512\ U_{10} + 0.003$$

b is the zenith angle of the normal at the point on a surface wave at which reflection occurs.



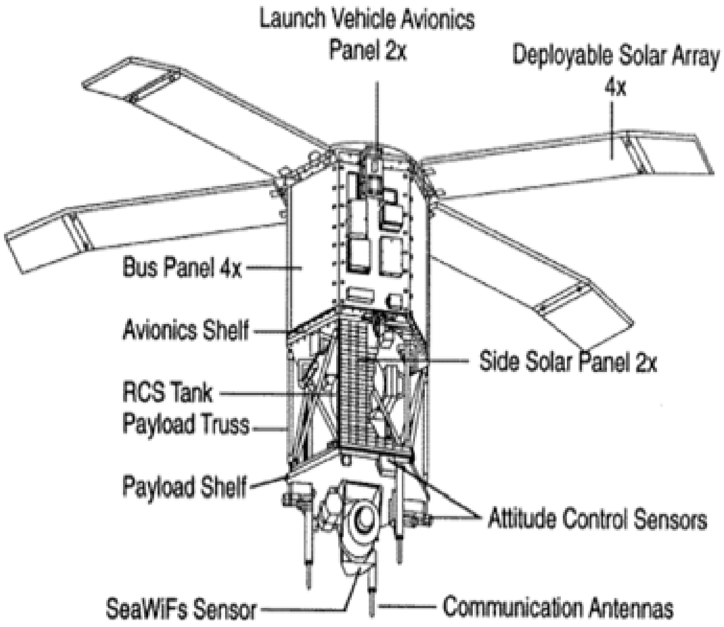
Sun glint geometry

# 15 years ago….

On August 1, 1997, an Orbital Sciences Corporation's L-1011 aircraft carrying a Pegasus XL rocket took off from Vandenberg Air Force Base. The rocket was released, the motor ignited and the SeaStar spacecraft carrying the SeaWiFS instrument was launched into orbit to begin a thirteen-year long mission.

http://www.youtube.com/watch?v=oEaz-W1h0A4

# SeaStar - SeaWiFS




| | |
|---|---|
| Orbit Type | Sun Synchronous at 705 km |
| Equator Crossing | Noon ±20 min, descending |
| Orbital Period | 99 minutes |
| Swath Width | 2,801 km LAC/HRPT (58.3°) |
| Swath Width | 1,502 km GAC (45°) |
| Spatial Resolution | 1.1 km LAC, 4.5 km GAC |
| Real-Time Data Rate | 665 kbps |
| Revisit Time | 1 day |
| Digitization | 10 bits |

| ***Band*** | ***Wavelength*** | ***Color*** |
|---|---|---|
| 1 | 402-422 nm | Violet |
| 2 | 433-453 nm | Blue |
| 3 | 480-500 nm | Blue-green |
| 4 | 500-520 nm | Green |
| 5 | 545-565 nm | Green |
| 6 | 660-680 nm | Red |
| 7 | 745-785 nm | Red-Near IR |
| 8 | 845-885 nm | Near IR |

# MODIS Bands - visible

About MODIS
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Data
Science Team
- Atmosphere
- Calibration
- Land
- Ocean

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MODARCH

| Primary Use | Band | Bandwidth[1] | Spectral Radiance[2] | Required SNR[3] |
|---|---|---|---|---|
| Land/Cloud Boundaries | 1 | 620 - 670 | 21.8 | 128 |
| | 2 | 841 - 876 | 24.7 | 201 |
| Land/Cloud Properties | 3 | 459 - 479 | 35.3 | 243 |
| | 4 | 545 - 565 | 29.0 | 228 |
| | 5 | 1230 - 1250 | 5.4 | 74 |
| | 6 | 1628 - 1652 | 7.3 | 275 |
| | 7 | 2105 - 2155 | 1.0 | 110 |
| Ocean Color/ Phytoplankton/ Biogeochemistry | 8 | 405 - 420 | 44.9 | 880 |
| | 9 | 438 - 448 | 41.9 | 838 |
| | 10 | 483 - 493 | 32.1 | 802 |
| | 11 | 526 - 536 | 27.9 | 754 |
| | 12 | 546 - 556 | 21.0 | 750 |
| | 13 | 662 - 672 | 9.5 | 910 |
| | 14 | 673 - 683 | 8.7 | 1087 |
| | 15 | 743 - 753 | 10.2 | 586 |
| | 16 | 862 - 877 | 6.2 | 516 |
| Atmospheric Water Vapor | 17 | 890 - 920 | 10.0 | 167 |
| | 18 | 931 - 941 | 3.6 | 57 |
| | 19 | 915 - 965 | 15.0 | 250 |

# MERIS on Envisat

- MERIS (Medium Resolution Imaging Spectrometer) is a programmable, medium-spectral resolution, imaging spectrometer operating in the solar reflective spectral range. Fifteen spectral bands can be selected by ground command.
- The instrument scans the Earth's surface by the so called "push-broom" method. Linear CCD arrays provide spatial sampling in the across-track direction, while the satellite's motion provides scanning in the along-track direction.
- The instrument's 68.5° field of view around nadir covers a swath width of 1150 km. Spatial Resolution:
  - Ocean: 1040m x 1200 m,
  - Land & coast: 260m x 300m
- Swath Width: 1150km, global coverage - 3 days
- VIS-NIR: 15 bands selectable across range: 390 nm to 1040 nm (bandwidth programmable between 2.5 and 30 nm)

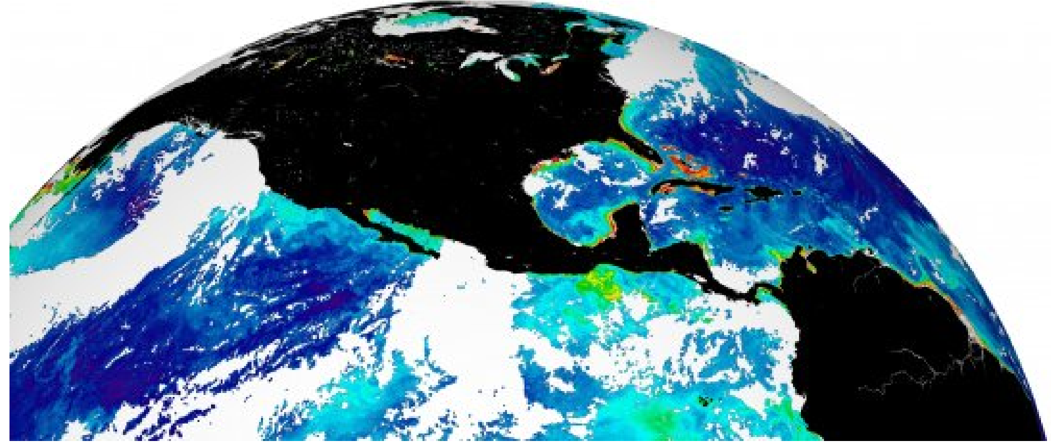
**MERIS Spectral bands**

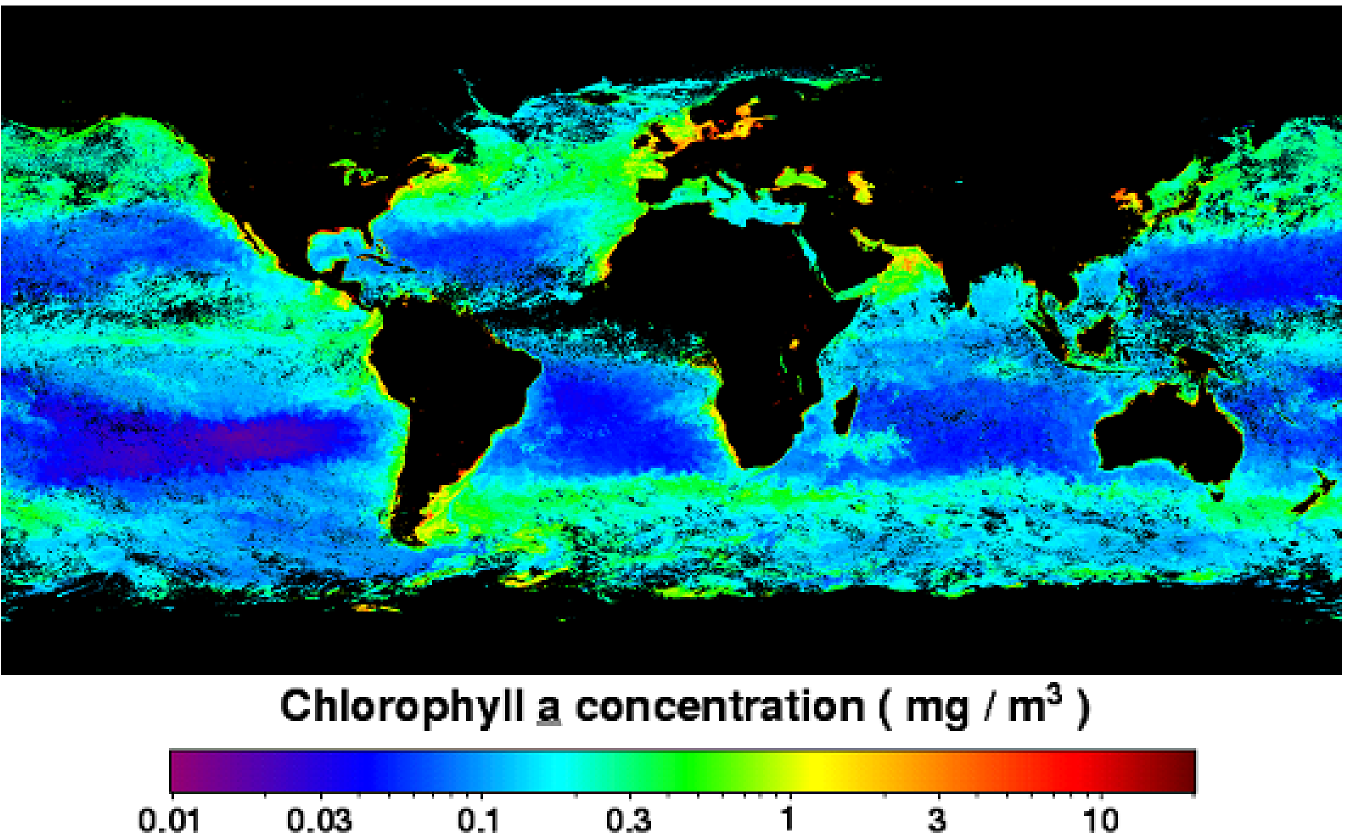
| Band number | Wavelength (nm) | Width (nm) |
|---|---|---|
| 1 | 412.5 | 10 |
| 2 | 442.5 | 10 |
| 3 | 490.0 | 10 |
| 4 | 510.0 | 10 |
| 5 | 560.0 | 10 |
| 6 | 620.0 | 10 |
| 7 | 665.0 | 10 |
| 8 | 681.25 | 7.5 |
| 9 | 708.75 | 10 |
| 10 | 753.75 | 7.5 |
| 11 | 761.875 | 3.75 |
| 12 | 778.75 | 15 |
| 13 | 865.0 | 20 |
| 14 | 885.0 | 10 |
| 15 | 900.0 | 10 |

# VIIRS spectral bands

| | | Band No. | Wave-length (mm) | Horiz Sample Interval (km Downtrack x Crosstrack) | | Driving EDRs | Radi-ance Range | Ltyp or Ttyp |
|---|---|---|---|---|---|---|---|---|
| | | | | Nadir | End of Scan | | | |
| VIS/NIR FPA | Silicon PIN Diodes | M1 | 0.412 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 44.9<br>155 |
| | | M2 | 0.445 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 40<br>146 |
| | | M3 | 0.488 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 32<br>123 |
| | | M4 | 0.555 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 21<br>90 |
| | | I1 | 0.640 | 0.371 x 0.387 | 0.80 x 0.789 | Imagery | Single | 22 |
| | | M5 | 0.672 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 10<br>68 |
| | | M6 | 0.746 | 0.742 x 0.776 | 1.60 x 1.58 | Atmospheric Corr'n | Single | 9.6 |
| | | I2 | 0.865 | 0.371 x 0.387 | 0.80 x 0.789 | NDVI | Single | 25 |
| | | M7 | 0.865 | 0.742 x 0.259 | 1.60 x 1.58 | Ocean Color<br>Aerosols | Low<br>High | 6.4<br>33.4 |
| CCD | | DNB | 0.7 | 0.742 x 0.742 | 0.742 x 0.742 | Imagery | Var. | 6.70E-05 |
| S/MWIR | PV HgCdTe (HCT) | M8 | 1.24 | 0.742 x 0.776 | 1.60 x 1.58 | Cloud Particle Size | Single | 5.4 |
| | | M9 | 1.378 | 0.742 x 0.776 | 1.60 x 1.58 | Cirrus/Cloud Cover | Single | 6 |
| | | I3 | 1.61 | 0.371 x 0.387 | 0.80 x 0.789 | Binary Snow Map | Single | 7.3 |
| | | M10 | 1.61 | 0.742 x 0.776 | 1.60 x 1.58 | Snow Fraction | Single | 7.3 |
| | | M11 | 2.25 | 0.742 x 0.776 | 1.60 x 1.58 | Clouds | Single | 0.12 |
| | | I4 | 3.74 | 0.371 x 0.387 | 0.80 x 0.789 | Imagery Clouds | Single | 270 K |
| | | M12 | 3.70 | 0.742 x 0.776 | 1.60 x 1.58 | SST | Single | 270 K |
| | | M13 | 4.05 | 0.742 x 0.259 | 1.60 x 1.58 | SST<br>Fires | Low<br>High | 300 K<br>380 K |
| LWIR | PV HCT | M14 | 8.55 | 0.742 x 0.776 | 1.60 x 1.58 | Cloud Top Properties | Single | 270 K |
| | | M15 | 10.763 | 0.742 x 0.776 | 1.60 x 1.58 | SST | Single | 300 K |
| | | I5 | 11.450 | 0.371 x 0.387 | 0.80 x 0.789 | Cloud Imagery | Single | 210 K |
| | | M16 | 12.013 | 0.742 x 0.776 | 1.60 x 1.58 | SST | Single | 300 K |

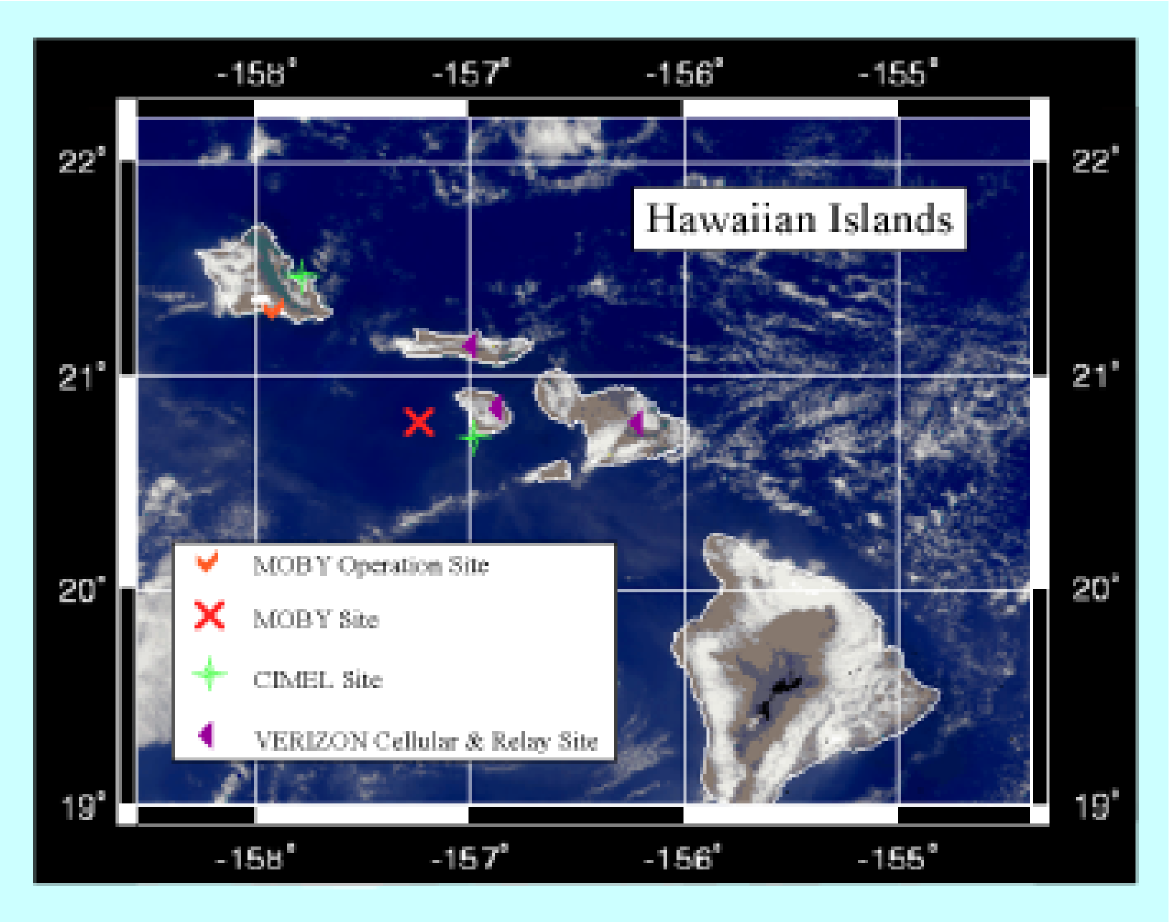
# VIIRS Ocean colour





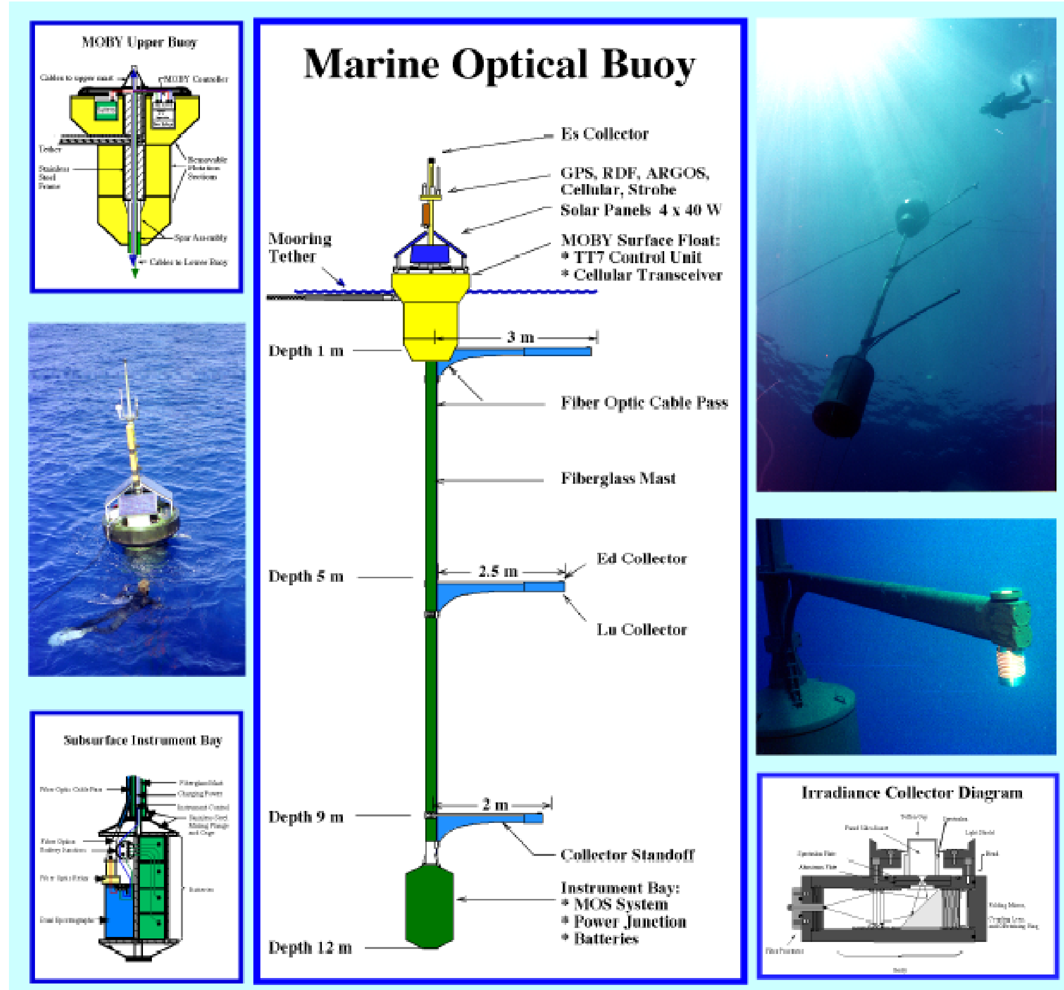

Level-3 composite of chlorophyll-a concentration is based on data taken from the VIIRS sensor for the entire month of March 2012. (Courtesy of NASA/GSFC OBPG).

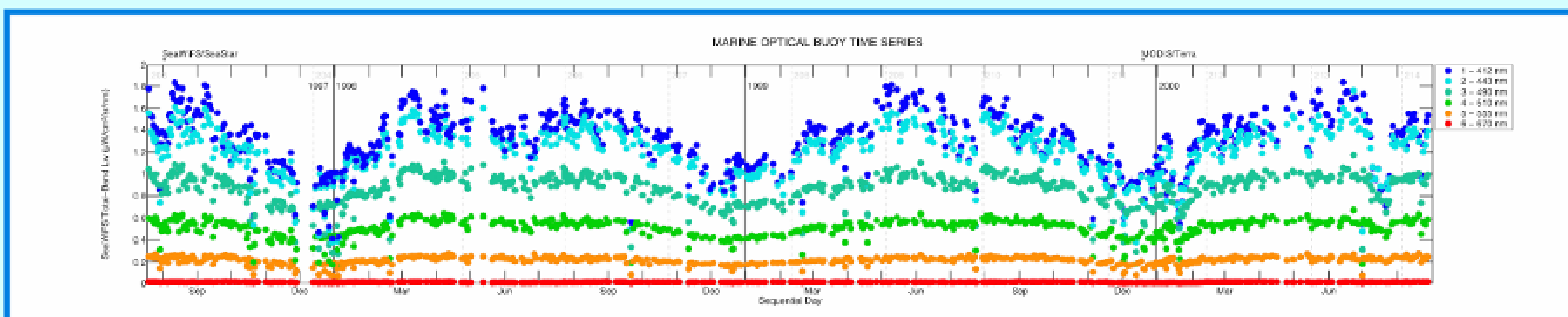
# MOBY Calibration Site – Hawaii



# MOBY Instrument

and spectral Time Series of MODIS ocean colour bands



# Description and Comparison of MODIS Chlorophyll Products

MODIS Chlorophylls:

- **Chlor_MODIS** **(MOD19: Dennis Clark)**
- **Chlor_a_2** **(MOD21: Janet Campbell)**
- **Chlor_a_3** **(MOD21: Ken Carder)**

SeaWiFS Chlorophyll serves as the reference product ……

SeaWiFS Chlorophyll:

- **OC4.v4** **John E. O'Reilly**

# What is the difference between MODIS chlorophylls?

- **"Jerlov Case 1" waters: Chlor_MODIS (Clark)**

This is an empirical algorithm based on a statistical regression between chlorophyll and radiance ratios.

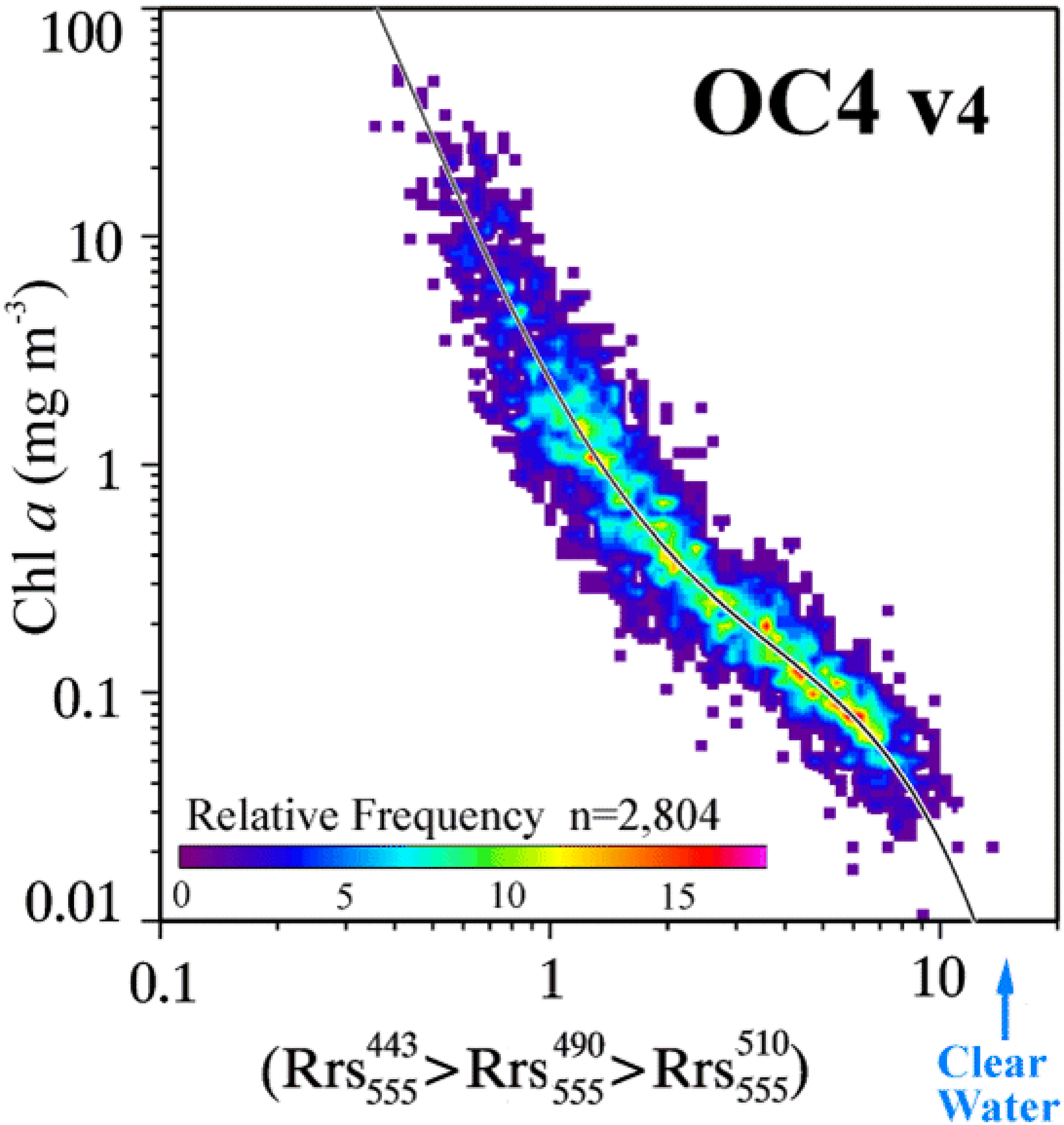
- **"Jerlov Case II" waters: Chlor_a_3 (Carder)**

This is a semi-analytic (model-based) inversion algorithm. This approach is required in optically complex "Case II" (coastal) waters.

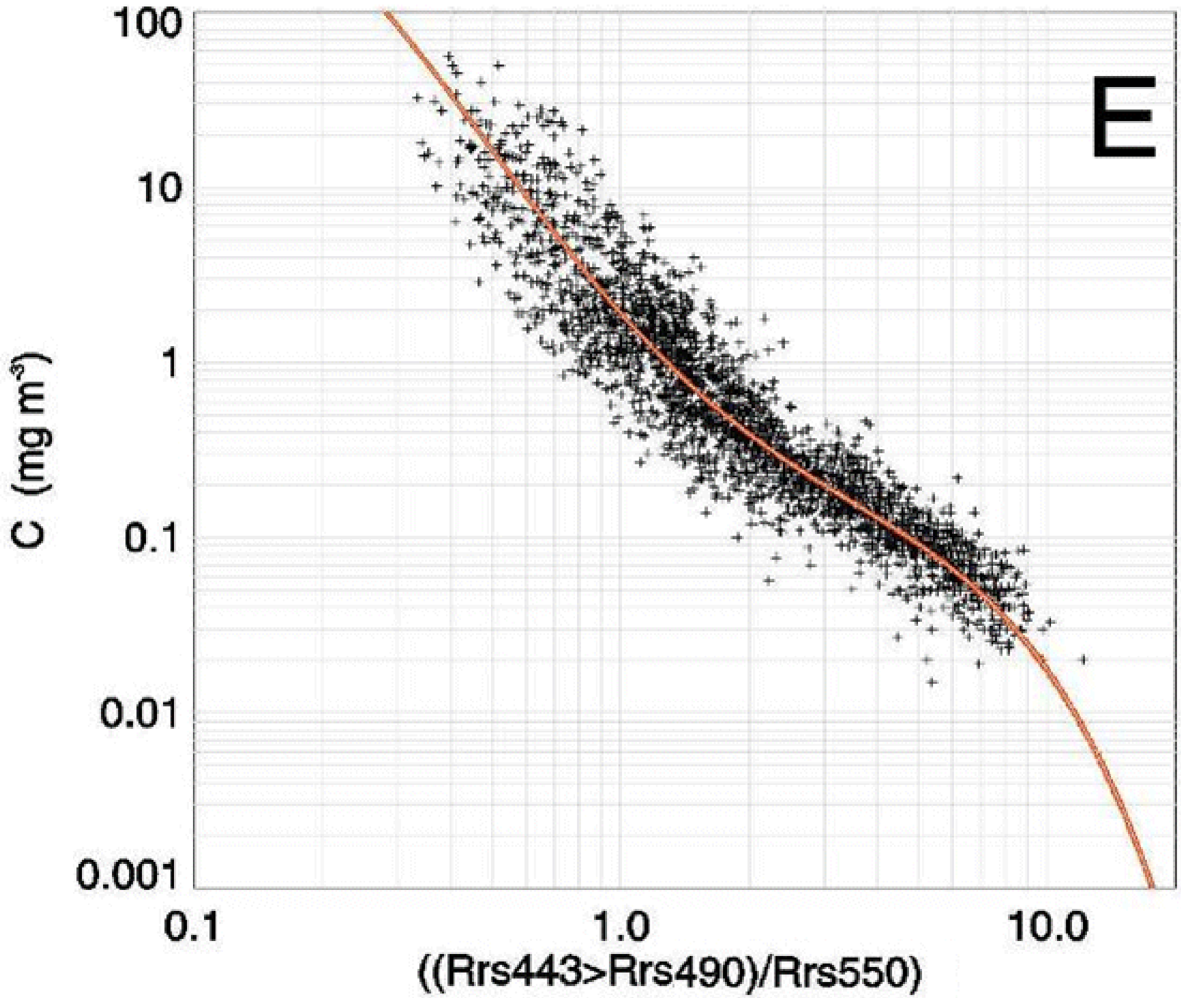
A 3rd algorithm was added to provide a more direct linkage to the SeaWiFS chlorophyll:

- **"SeaWiFS-analog" Chlor_a_2 (Campbell)**

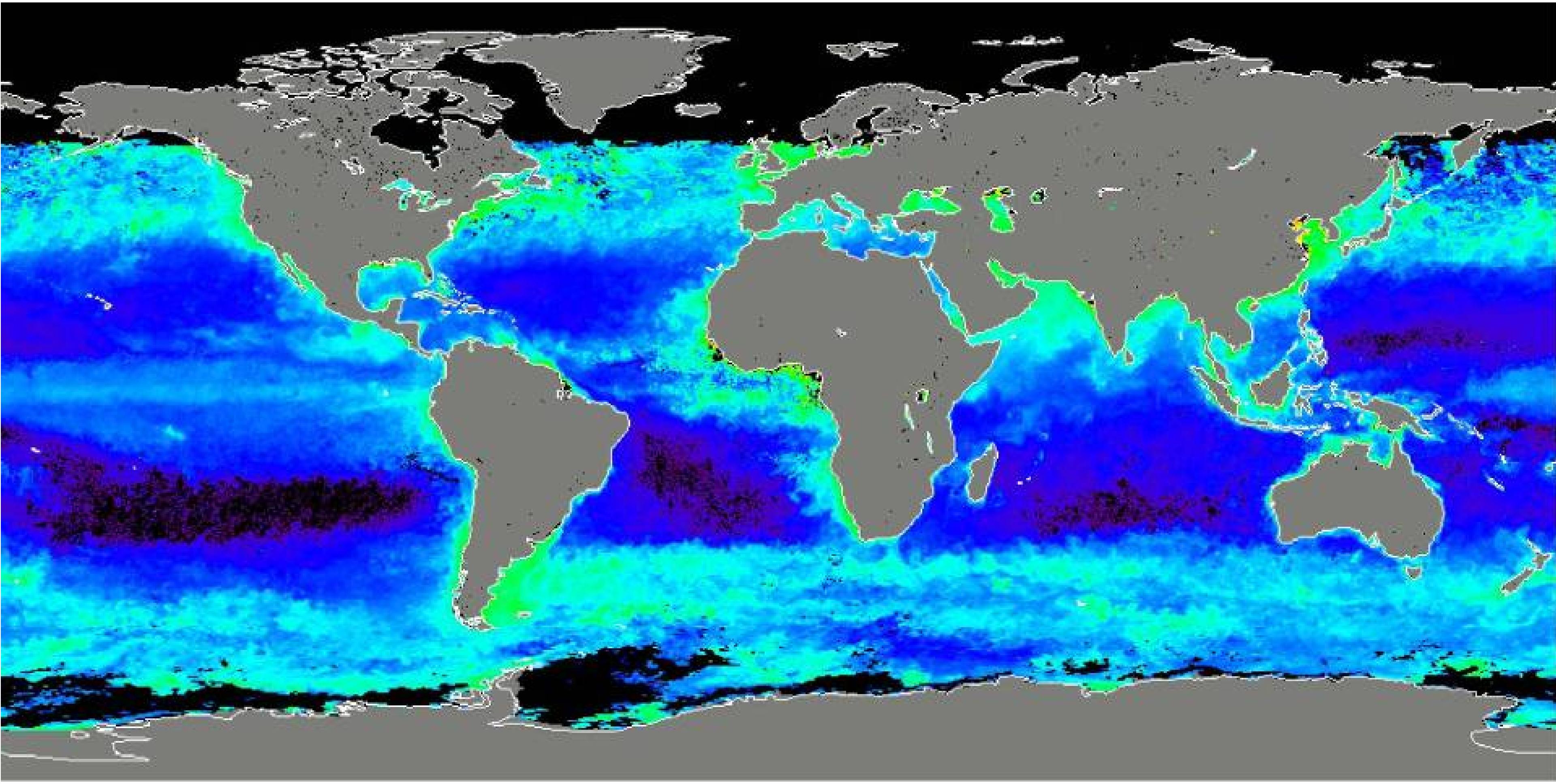
- **SeaWiFS algorithm OC4.v4 (O'Reilly)**


OC4 v4
100
10
1
0.1
0.01
Chl a (mg m-3)
Relative Frequency n=2,804
0
5
10
15
0.1
1
10
(Rrs443/555 > Rrs490/555 > Rrs510/555)
Clear Water

The Chlor_a_2 algorithm was proposed by the developers of the OC4.v4 SeaWiFS algorithm. It was called OC3M (3 band, M for MODIS)



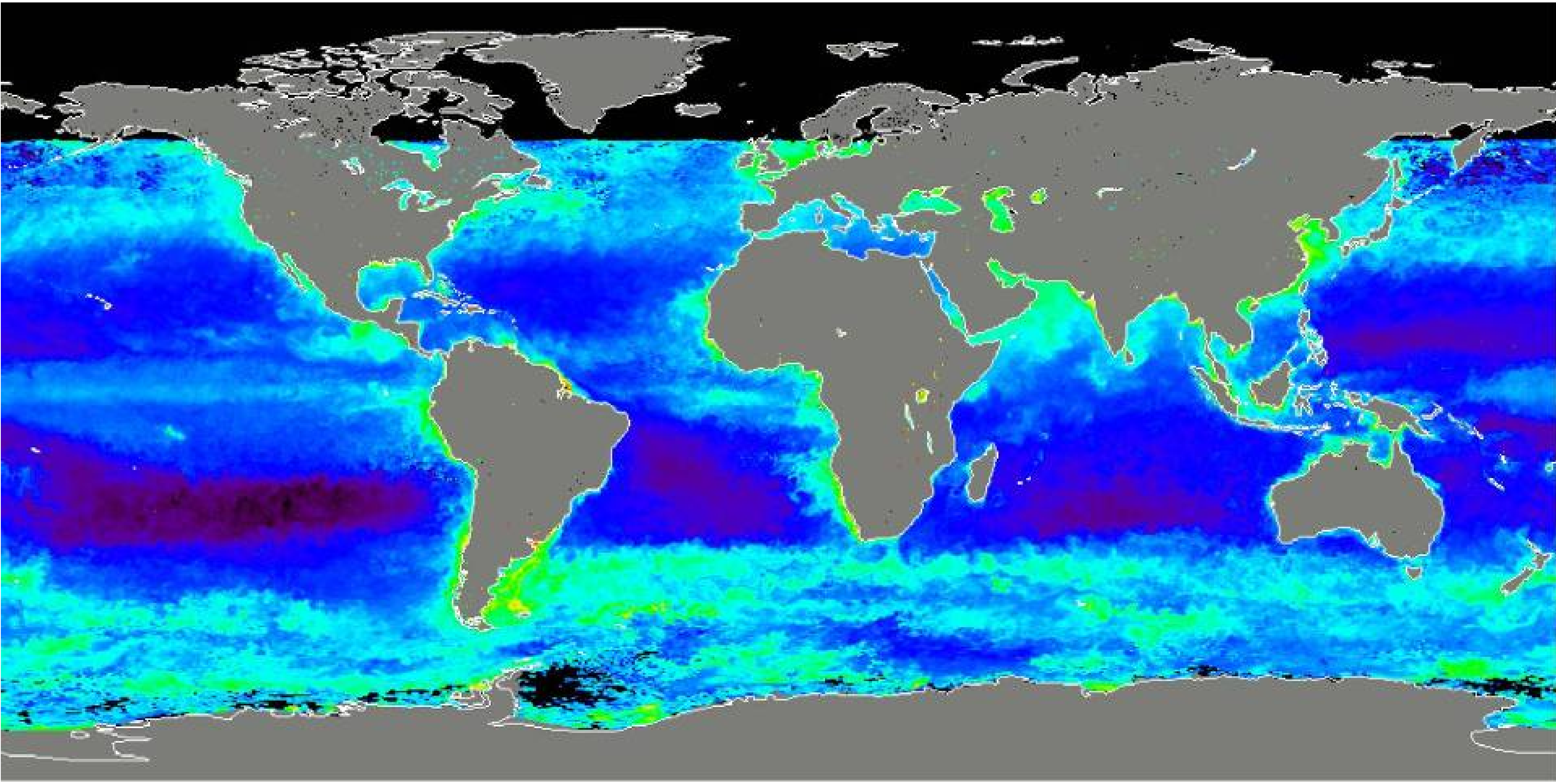
# Chlor_MODIS December 2000



This algorithm was based on regression involving HPLC chlorophyll(s). n=93, $r^2$=0.915, std error of estimate = 0.047.

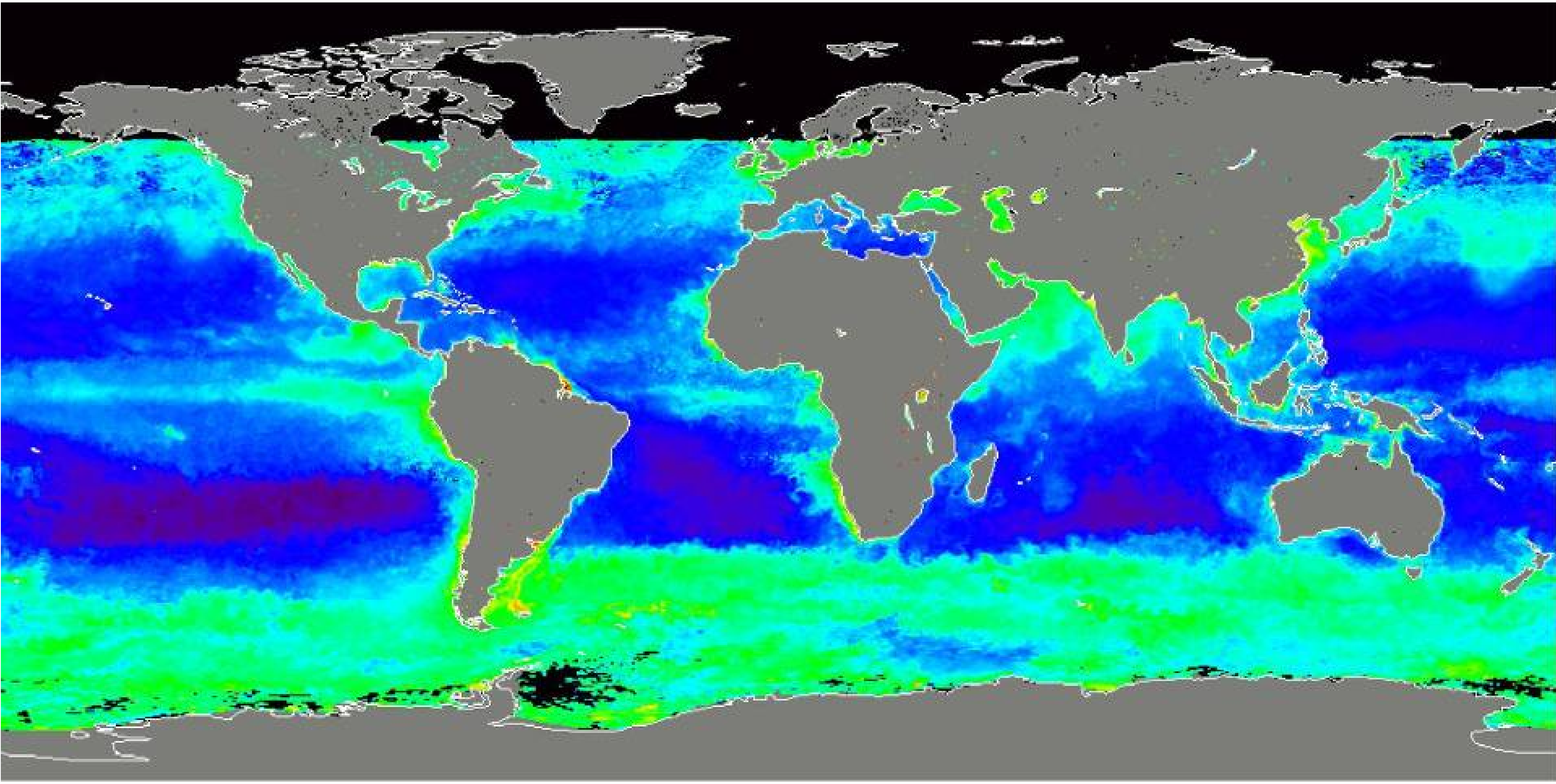
Collection 4: Based on ratio 443 or 488 to 551

# Chlor_a_2 December 2000



This "SeaWiFS analog" algorithm is based on the same data set used to parameterize the SeaWiFS algorithm.

# Chlor_a_3 December 2000



This “semi-analytic” algorithm accounts for pigment packaging effects in nutrient-replete and nutrient-deplete conditions.

Uses MODIS SST (daytime 11-12 mm) to determine nutrient deplete/replete status.

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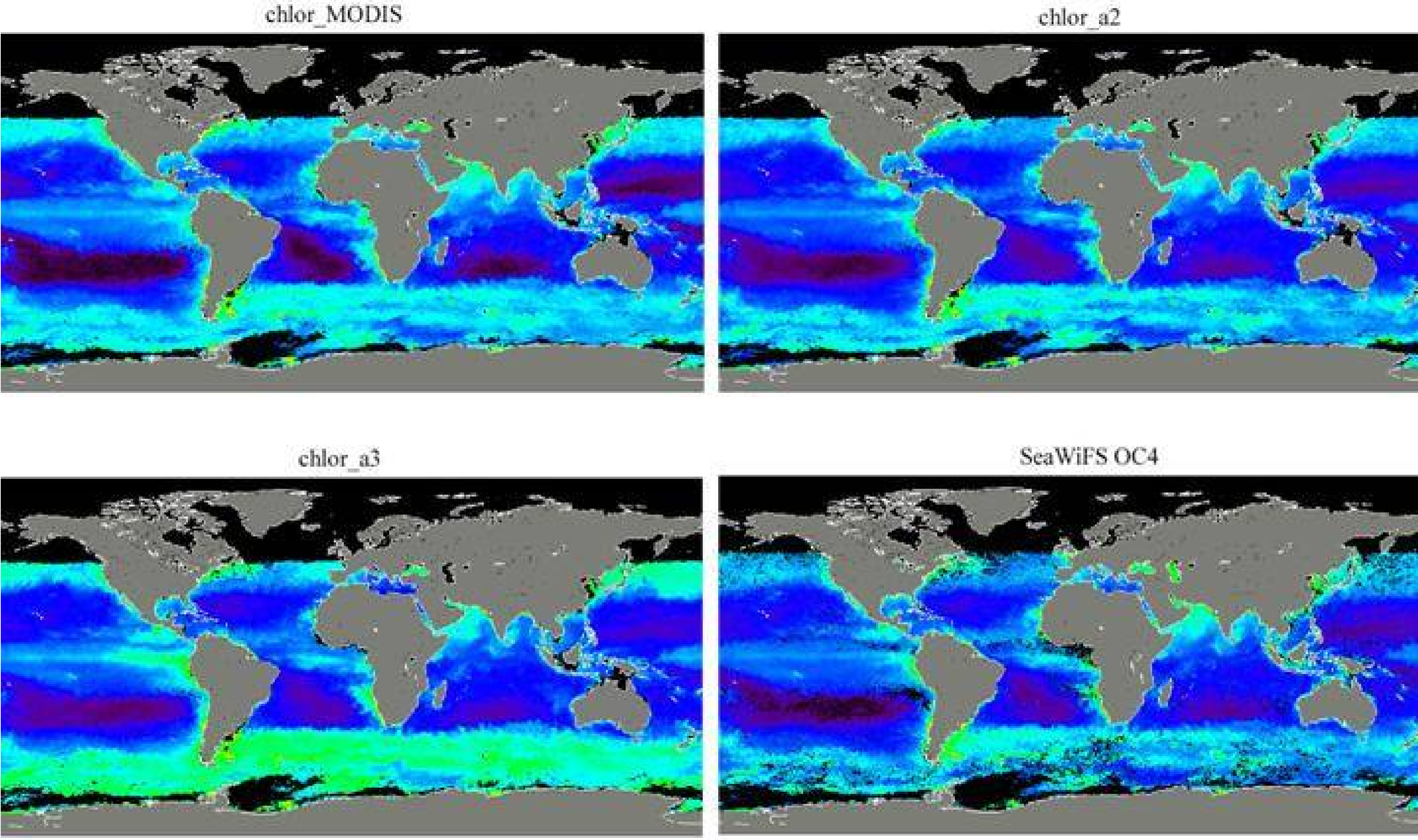
ON EARTH SYSTEM MONITORING & MODELLING
30 July - 10 August 2012

esa

# Comparison of MODIS Chlorophyll Products with SeaWifs Chlorophyll



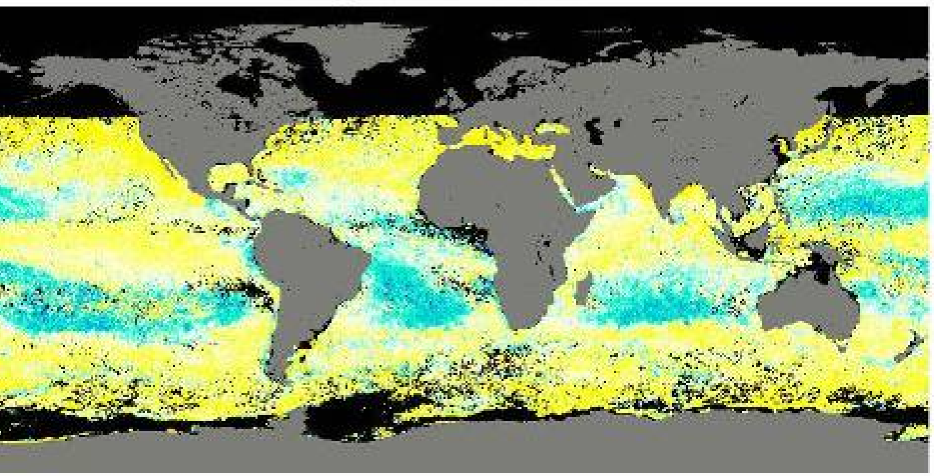
# MODIS Chlorophyll products - SeaWiFS OC4V4 comparison

Chlor_a2 (SeaWiFS ‘like’) most closely agrees with SeaWiFS

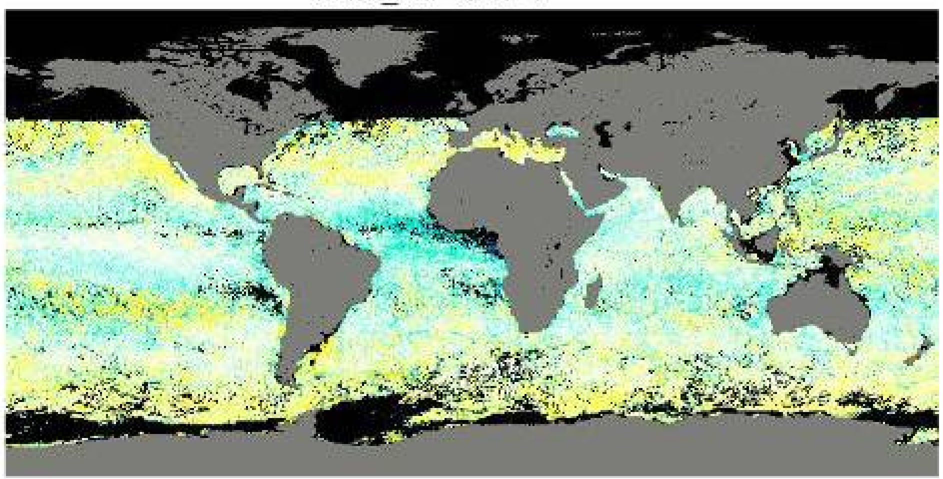
Chlor_MODIS differs more due to its use of HPLC pigments as a reference

Chlor_a3 shows significant difference in Antartic and equatorial Pacific due to use of the nutrient depletion temperature

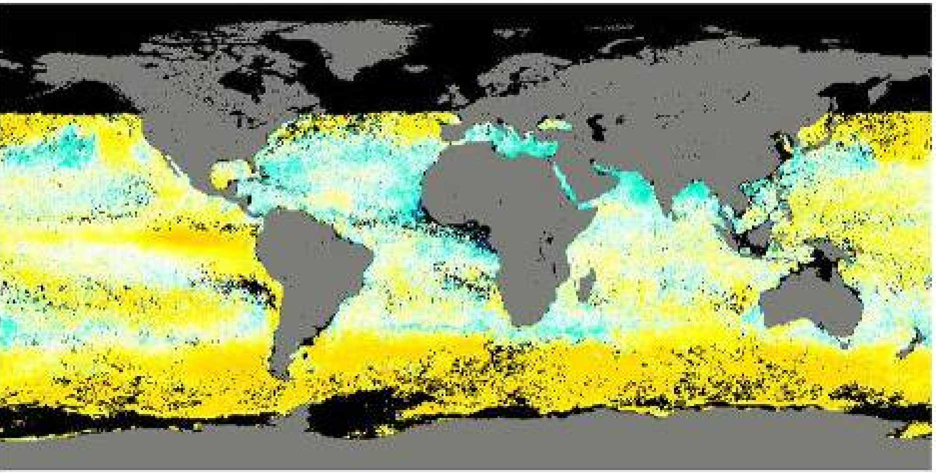
Chlor_MODIS - Oc4v4

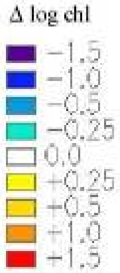


Chlor_a2 - Oc4v4

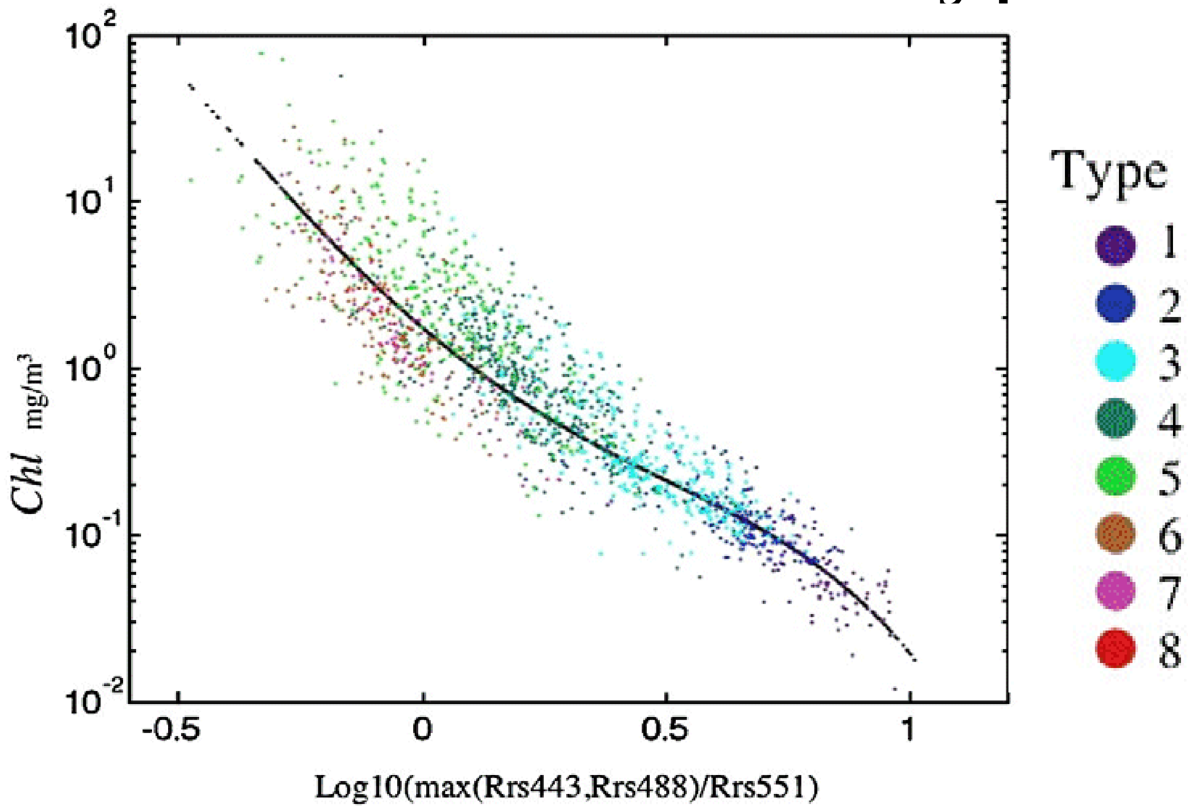


Chlor_a3 - Oc4v4



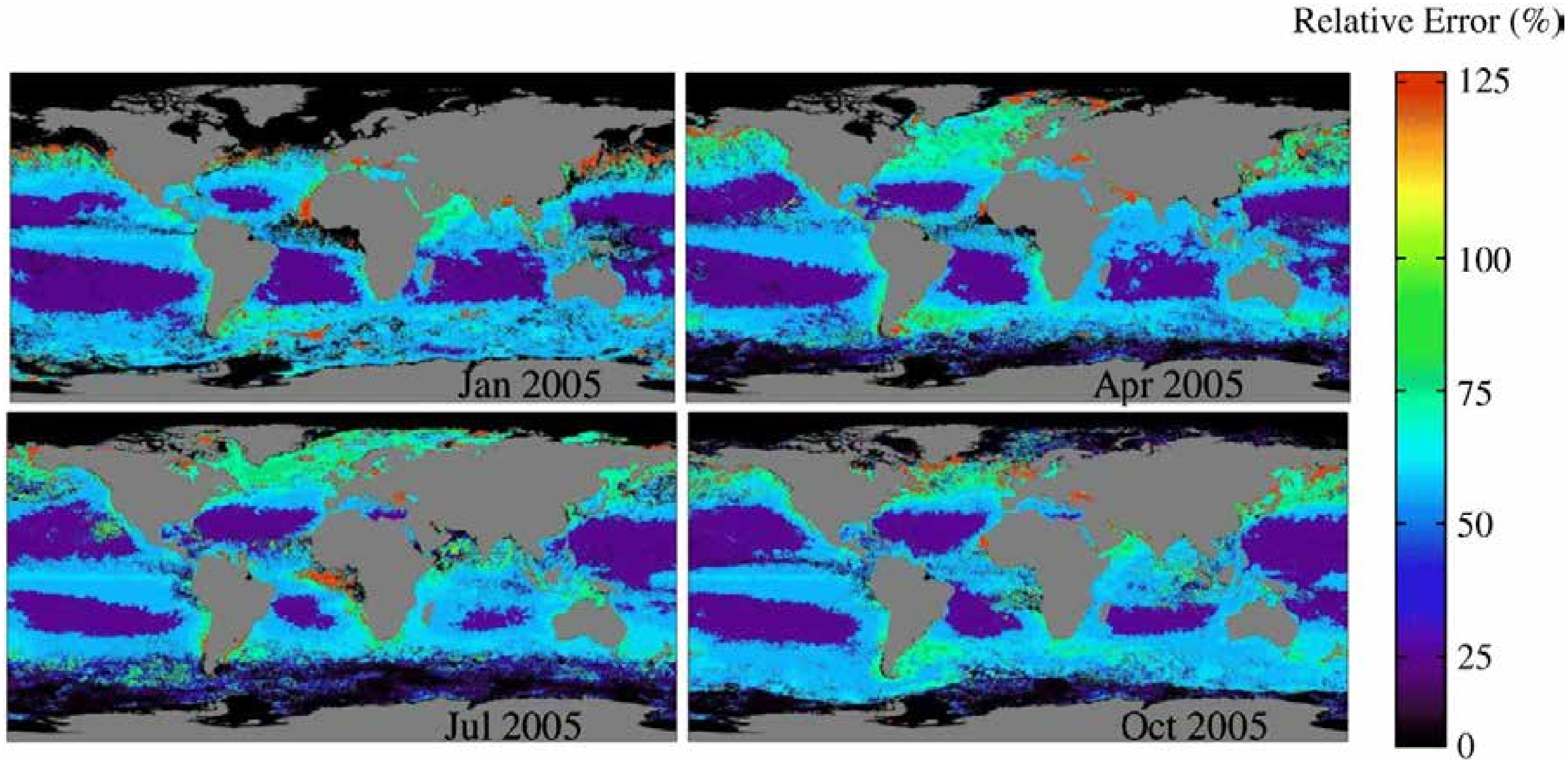


# Chlorophyll retrievals according to Ocean Water Types

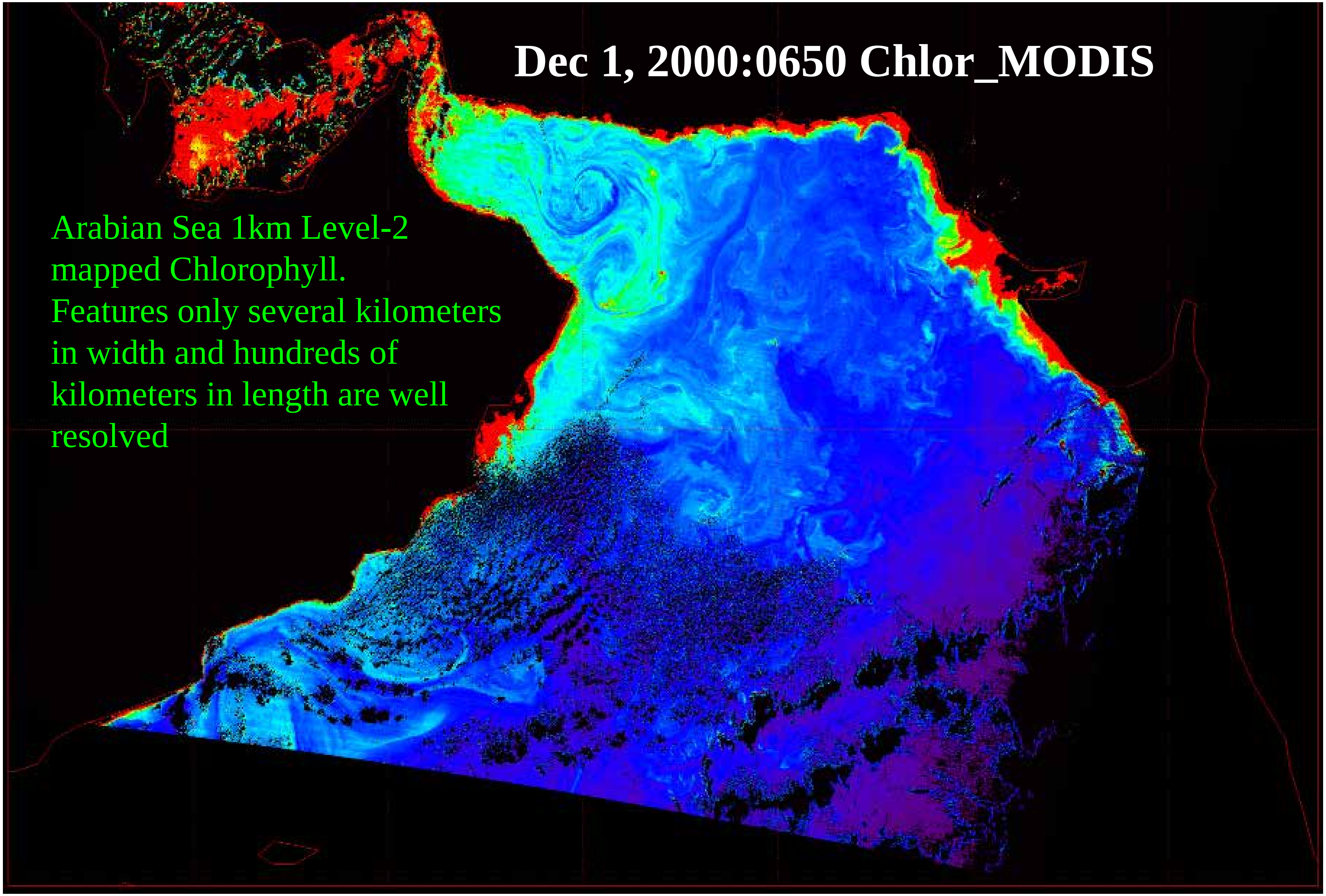



The statistical relationship between Chl and the reflectance ratio used to define the OC3M algorithm. The point data are from the NOMAD V2 data set, and the line is the OC3M algorithm. Points are color-coded according to the optical water type having the highest membership.

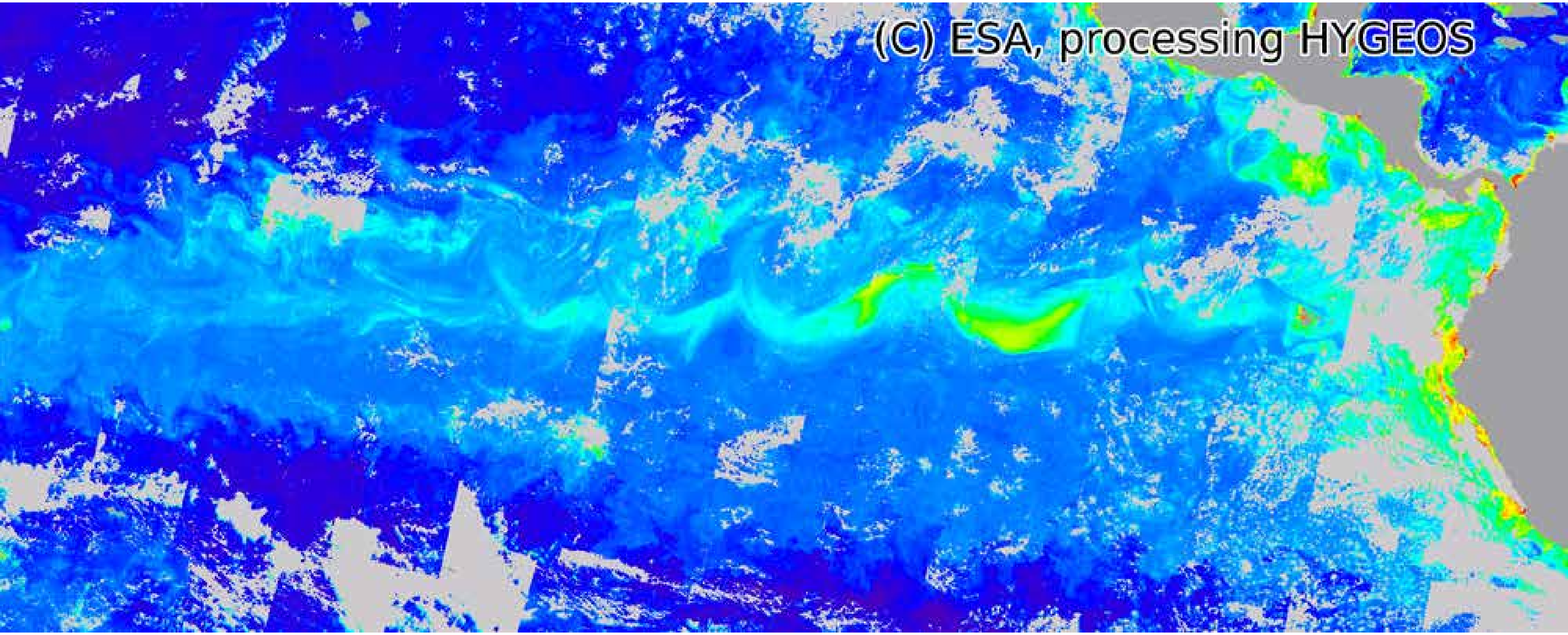
# Chlorophyll errors according to Ocean Water Types




Global maps of the MODIS Aqua chlorophyll uncertainty for January, April, July, and October 2005.


Dec 1, 2000:0650 Chlor_MODIS
Arabian Sea 1km Level-2
mapped Chlorophyll.
Features only several kilometers
in width and hundreds of
kilometers in length are well
resolved

# Chlorophyll signature of TIWs




The Tropical Instability Waves are associated with equatorial upwelling that brings nutrients into the euphotic zone for consumption by phytoplankton.

http://www.hygeos.com/en/meris-polymer.php

# Ocean Net Primary Production Models (ONPP)

MODIS Ocean Net Primary Production (ONPP) provides measure of Carbon fixation by phytoplankton

Two models: P1 and P2

**P1** = Behrenfeld & Falkowski

NPP = f(Chl *a*, PAR, Pb opt)

Integrated over the Euphotic zone (1%)

Pb opt = f (SST) 7th order polynomial

**P2** = Howard, Yoder, Ryan

NPP = f (Chl *a*, PAR, Pmax)

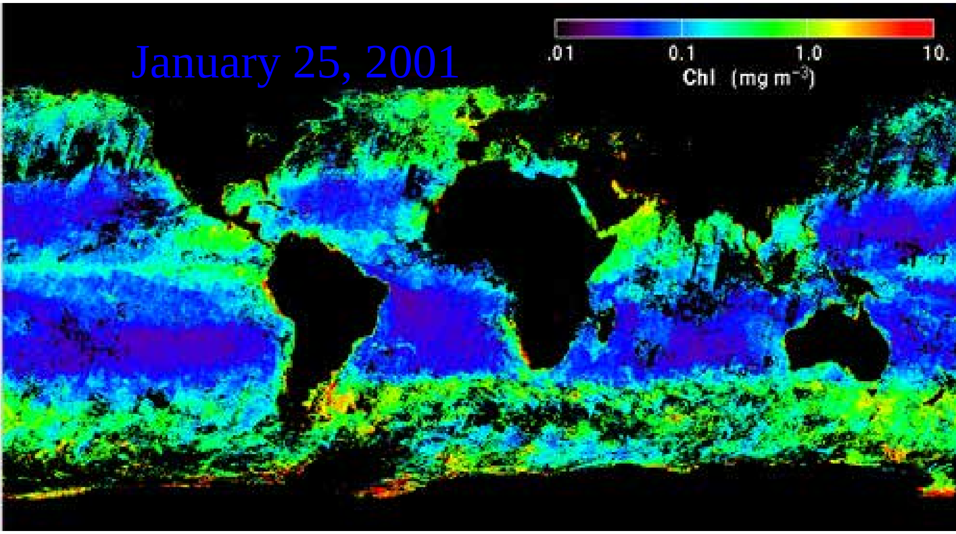
Integrated over the upper Mixed Layer Depth (MLD)

Pmax (Platt) = f (SST) Eppley Peterson exponential

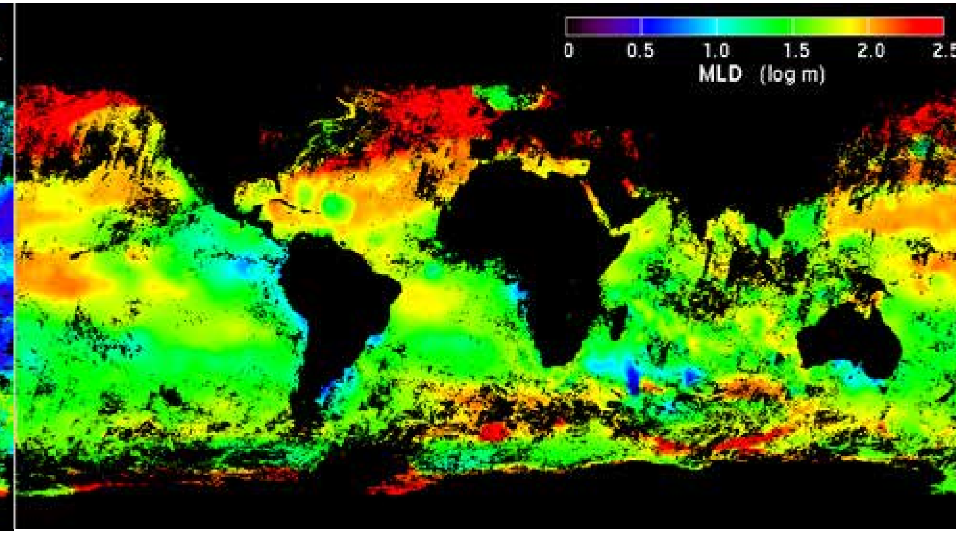
For a fuller discussion, see: Carr, et al, 2006, A comparison of global estimates of marine primary production from ocean color. Deep Sea Research Part II: Topical Studies in Oceanography, 53, 741-770.

# ONPP INPUT FIELDS

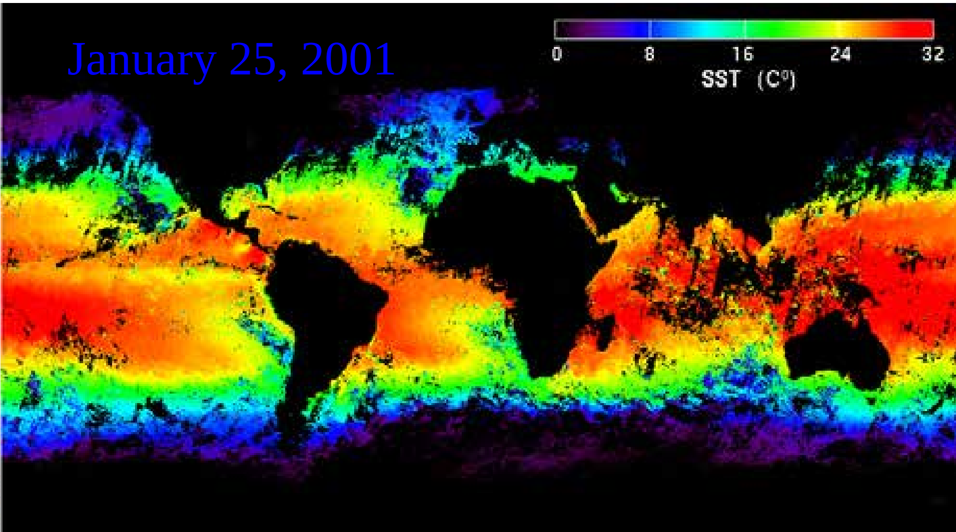
## Chlor_a_3 MODIS
Chlorophyll concentration



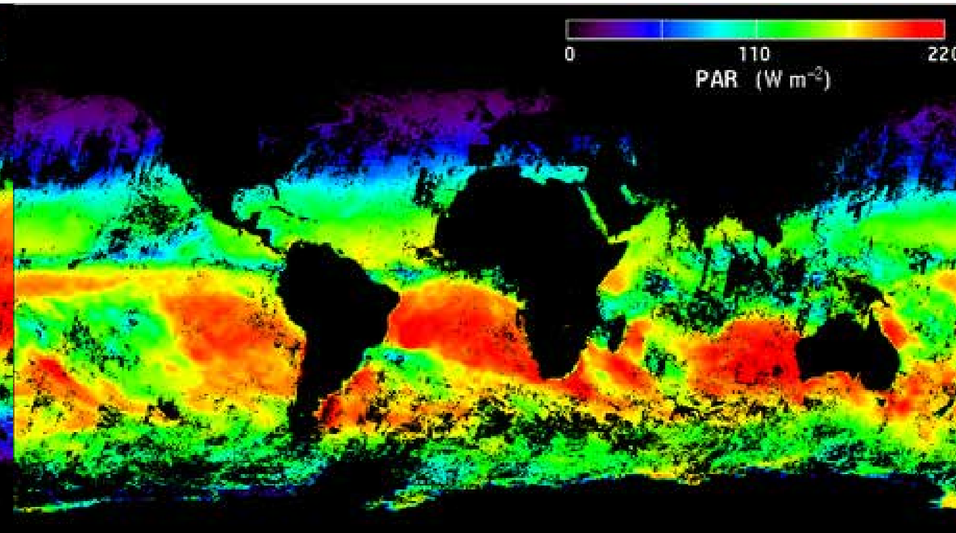

## MLD (FNMOC)
Mixed Layer Depth (for P2)




## SST MODIS
SST day




## PAR (GSFC DAO)
Photosynthetically Available Radiaiton



# P1= Behrenfeld-Falkowski:

Daylength (hrs)

$$P1 = 0.66125 \times H \times P^{b}_{opt} \times \frac{PAR}{PAR + 4.1} \times Chl \times Z_{eu}$$

**Optimal photosynthetic yield**

$$P^{b}_{opt}(T) = \begin{cases} 0 & if \quad T < -10 \\ 1.13 & if \quad T < -1 \\ \sum_{i=0}^{7} \frac{a_i \cdot T^i}{10^i} & if \quad -1 \le T \le 28.5 \\ 4 & if \quad T > 28.5 \end{cases}$$

**Depth of euphotic zone**

$$Z_{eu}(Chl) = \begin{cases} 68.89 \cdot Chl^{-0.125} & if \quad Chl < 0.0435 \\ 37.67 \cdot Chl^{-0.317} & if \quad 0.0435 \le Chl \le 1 \\ 36.12 \cdot Chl^{-0.378} & if \quad Chl > 1 \end{cases}$$

# P2 = Howard-Yoder-Ryan:

Depth of mixed layer

$$P2 = -Z_{ml} \times P_z$$

Carbon fixation/volume over depth of mixed layer

$$P_z = \frac{P^b_{max} \times \overline{E}_0}{P^b_{max} / a + \overline{E}_0} Chl$$

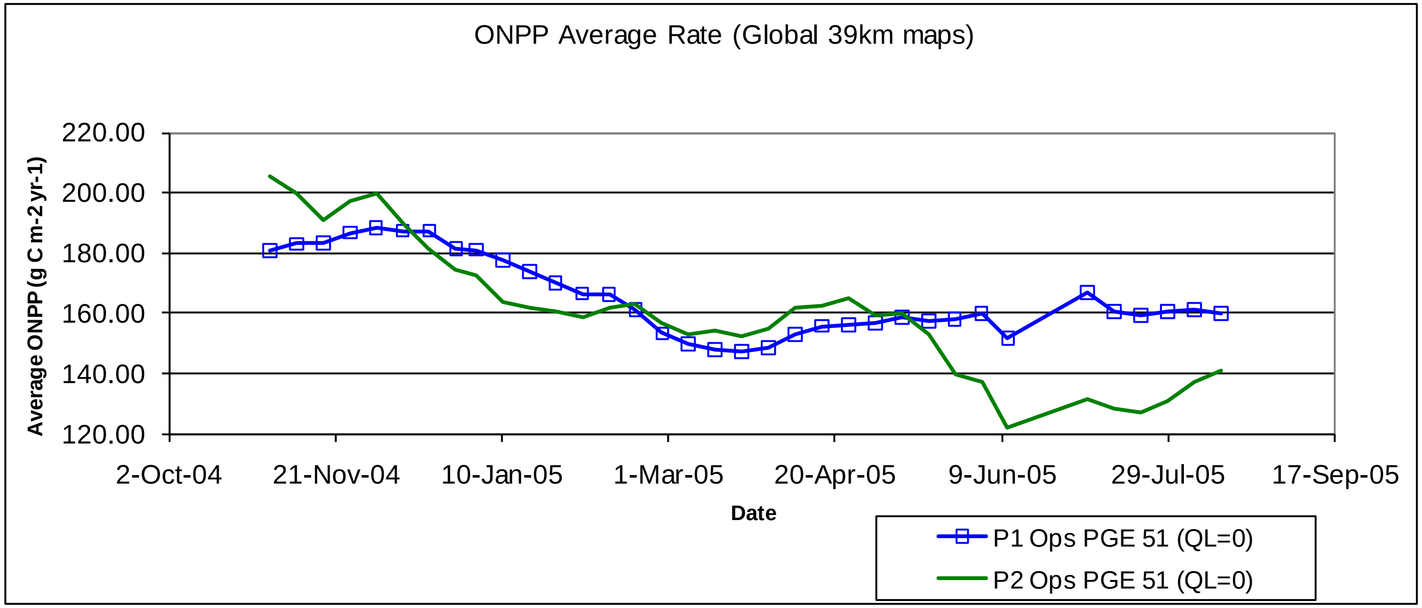
Avg radiative energy over mixed layer depth

$$P^b_{max} = 24 \times e^{0.09 \times T}$$

a = 0.11*24

$$\overline{E}_0 = PAR \times \frac{(1 - e^{K_{PAR} \times Z_{ML}})}{-K_{PAR} \times Z_{ML}}, \quad -K_{PAR} \times Z_{ML} > 0$$

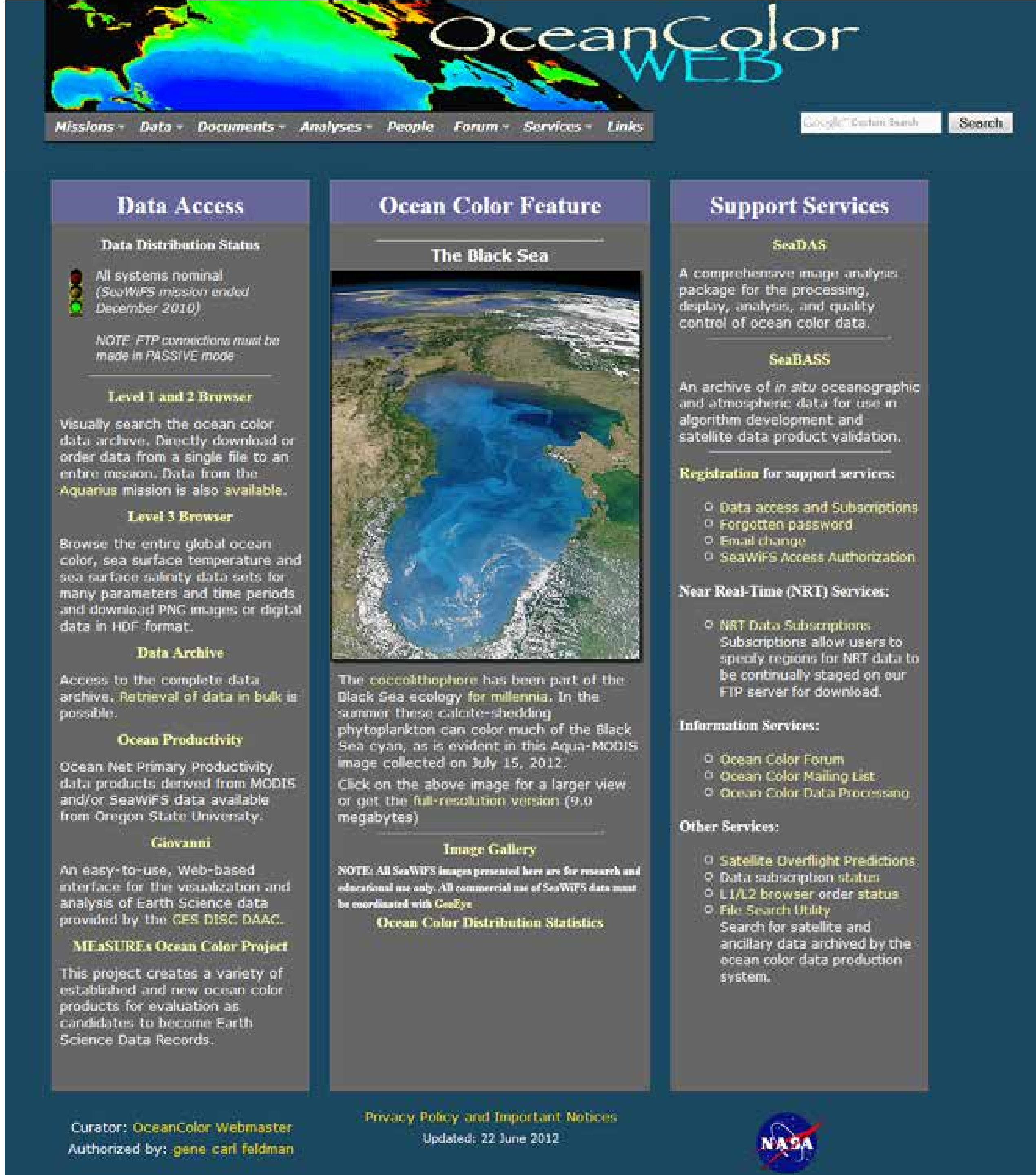
# Differences in PP estimates




**Difference between P1 & P2 primarily due to MLD effect in temperate zones & Southern Ocean**

# NASA ocean colour data access

http://oceancolor.gsfc.nasa.gov/

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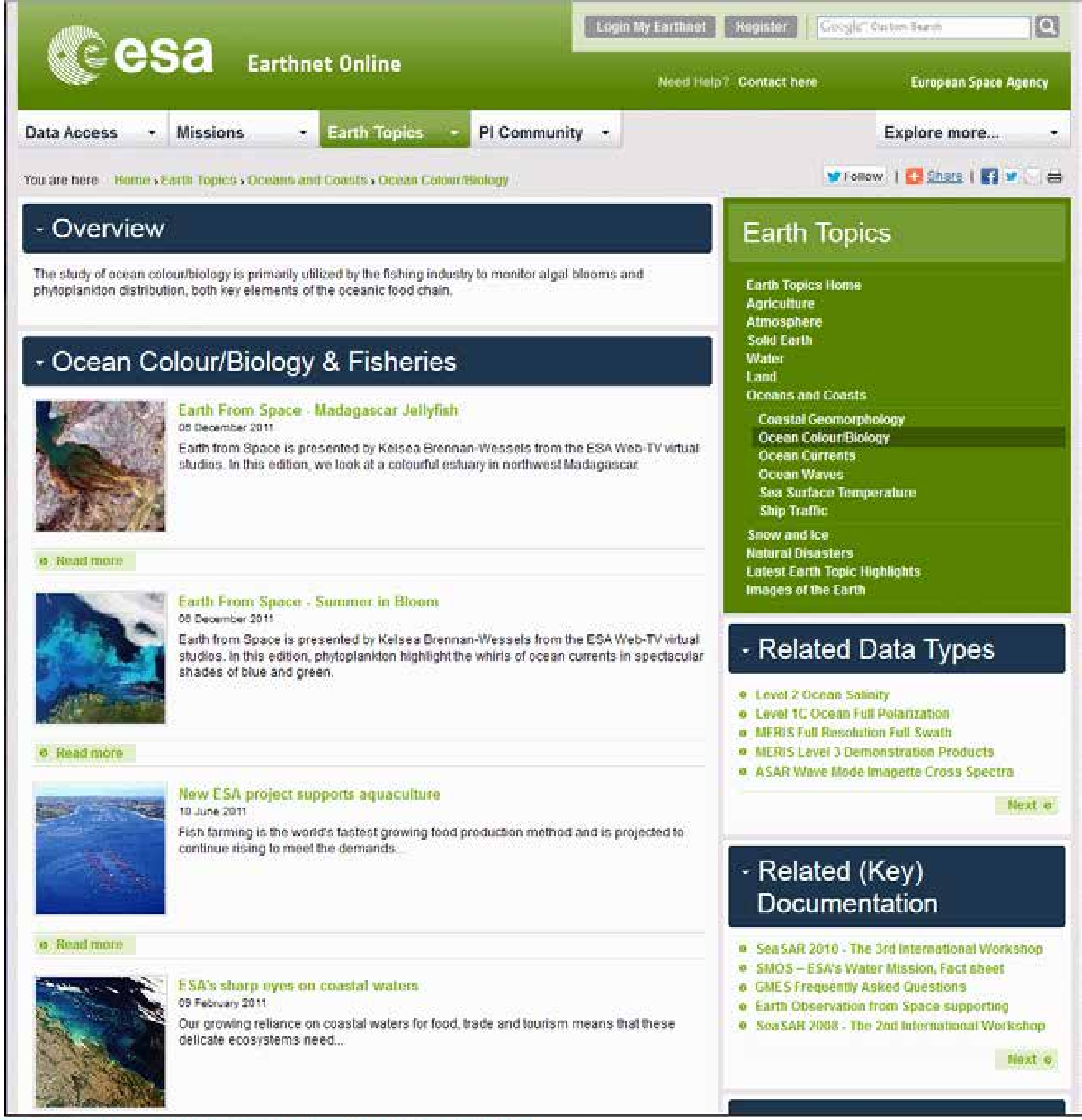
# ESA ocean colour data overview

https://earth.esa.int/web/guest/earth-topics/oceans-and-coasts/ocean-colourbiology-fisheries




Data available at

http://merci-srv.eo.esa.int/merci/welcome.do

All for now….

Questions?