Remote Sensing of Harmful Algal Blooms

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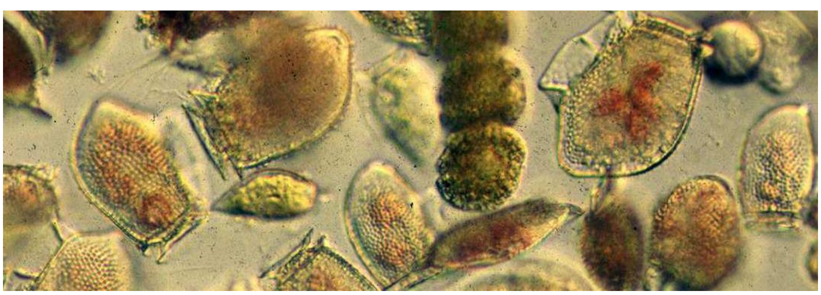
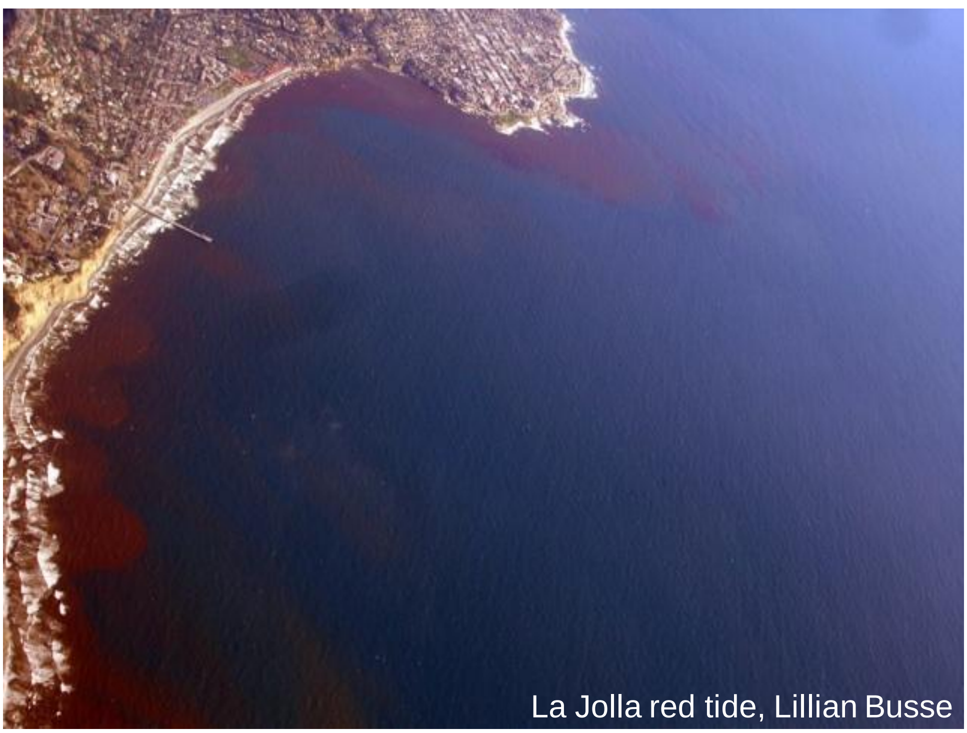
Harmful Algal Blooms

The definition of a HAB is not clear-cut, since it is a societal term, not a scientific term, that describes a diverse array of blooms (both macroscopic and macroscopic) that can cause detrimental effects to national economies.



Red Tides

- Blooms of single-celled microorganisms (phytoplankton) that attain such densities that they discolor the seawater; the most common ‘red tides’ are motile, **dinoflagellates**


La Jolla red tide, Lillian Busse

Most Red Tides are harmless

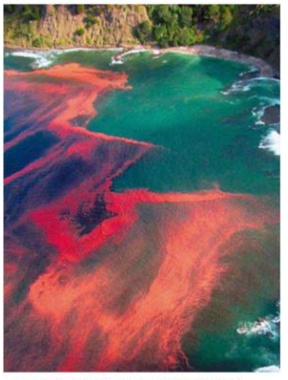

Santa Barbara News-Press (non-intensified digital camera photo)


October 6, 2009

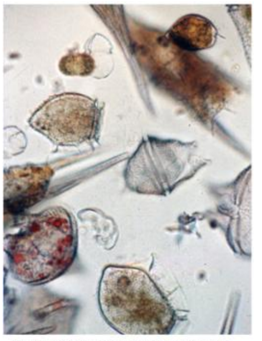
Harmful Algal Blooms

It is useful to differentiate between “high biomass” HAB blooms, such as red tides, and toxic HAB events, which can cause problems with no obvious change in the environment….

This cyanobacterial bloom has the typical appearance of a thick layer of green paint. The bloom was found to consist of toxic species in the genus Microcystis. (Photo by W. Carmichael)

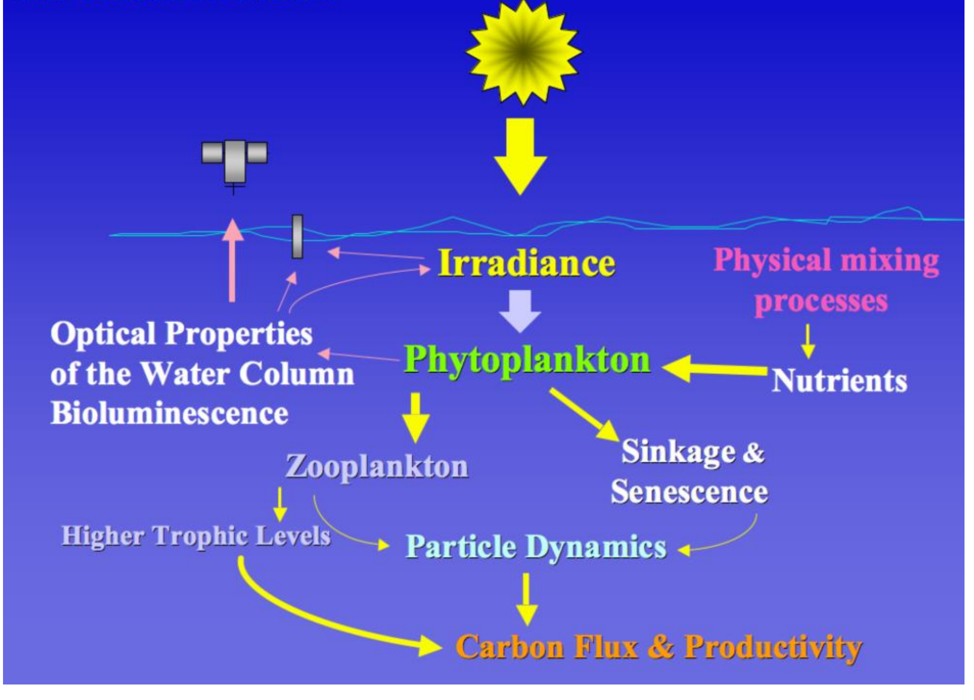


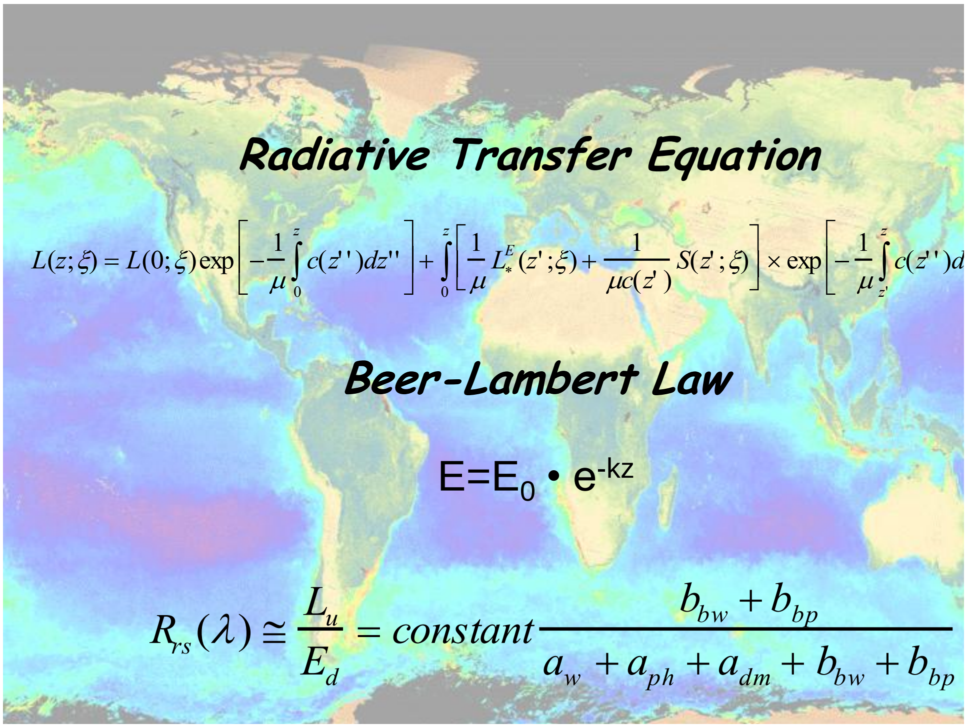
A spectacular "red tide" bloom (non-toxic) of *Noctiluca scintillans* in New Zealand. (Photo by M. Godfrey)



Harmful algal blooms are caused by species of tiny plants—phytoplankton—some of which produce potent chemical toxins. Fueled by periodic abundances of nutrients in the ocean, these algae multiply and proliferate until they can cover tens to hundreds of miles of coastal ocean. (Photo by D. Anderson)

The research focus:





The Problem:

- We want to detect HAB events using optics (satellite, airborne, in-water sensors)…
  - BUT we only have access to water-leaving radiance
  - We can’t easily distinguish HABs from other organisms
  - We can’t detect anything below one optical depth
  - Not all HABs are high-biomass events
  - Most satellites are limited spectrally and spatially

Ocean Colour & Harmful Algal Bloom Working Group

International Ocean-Colour Coordinating Group
IOCCG

&

Global Ecology and Oceanography of Harmful Algal Blooms
GEOHAB

CoastColour 4a, Harwell, May 2011

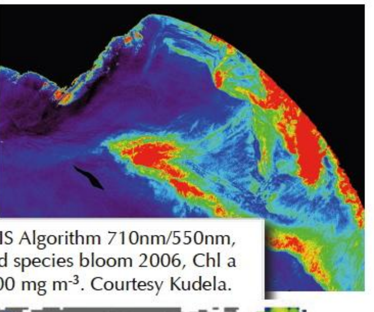
First Meeting, August 2010
Schulphoek, South Africa

Harmful Algal Blooms and Ocean Colour

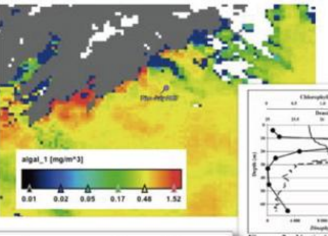
Ocean colour radiometry offers considerable potential for the observation of harmful algal blooms (HABs) – HAB-related observations are often seen as high impact motivating factors for ocean colour and/or bio-optical components of coastal observing systems.

However, effective HAB detection, monitoring and analysis requires an appreciation of the sizable uncertainties associated with ocean colour applications in the optically complex coastal zone.

Observation systems need to be cognisant of the ecological role of the wide variety of potentially harmful algal blooms across global coastal ecosystems - and information is needed regarding the suitability of available ocean colour techniques for HAB application to different ecosystems.



AVIRIS Algorithm 710nm/550nm, mixed species bloom 2006, Chl a >1000 mg m^{-3}. Courtesy Kudela.



Sub-surface Dinophysis bloom, Irish Sea. Courtesy Raine

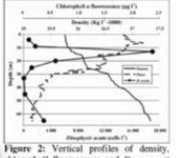


Figure 2: Vertical profiles of density, chlorophyll fluorescence and *D. acuta* at station 36 (51° 24' N, 09° 08' W) off the south coast of Ireland, 26th July. Note the high density thin layer at 13 m depth. Note the sizable population of viable cells near the seabed (water depth 68.5 m).

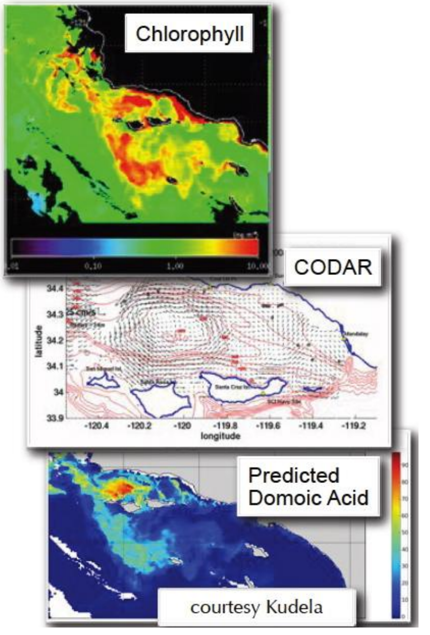
HABS and Ocean Colour: An Ecosystem-based Approach

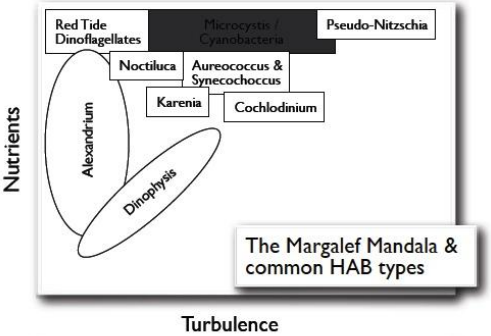
In many cases HABs are a normal part of ecosystem function - effective HAB observation & prediction systems must therefore be rooted in an understanding of system ecology.

Ocean colour likely to be most effective as part of a multi-sensor observation system allowing determination of ecosystem drivers - and response with regard to the phytoplankton dynamics of a system and ecological niches of phytoplankton communities.

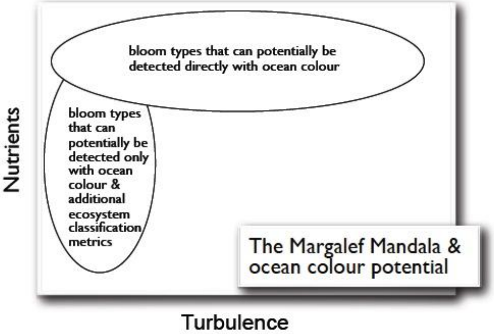
Different HAB species and conditions require specific observation systems and predictive models – many HAB types are not extreme biomass events and may not be amenable to OC-based observation.

Choice of ocean colour based method will depend on aims e.g. large differences in approach between operational detection and ecosystem analyses.





The Margalef Mandala & common HAB types



The Margalef Mandala & ocean colour potential

The Ecosystem Perspective

The Margalef mandala is a common way of examining algal succession by characterising the ecological niche in which different species or groups are most likely to proliferate.

Many harmful algal species can have impact at very low cell concentrations, as a minor component of the algal assemblage, or as subsurface blooms with no bio-optical surface expression.

Viewing the mandala from an ocean colour perspective, it is clear that only high nutrient-demand/biomass blooms are likely to be *directly* detectable using ocean colour - regardless of the algorithm type or technique used.

Using ocean colour as one component of a multi-parameter ecosystem classification - effectively using the mandala to create an earth observation based metric - will potentially allow the detection of some other bloom types.

Key Point:

To effectively detect or predict Harmful Algal Blooms using remote sensing, it is CRITICAL to treat remote sensing as one of many data sets, and to interpret the results in the ecological context of the region and organism.

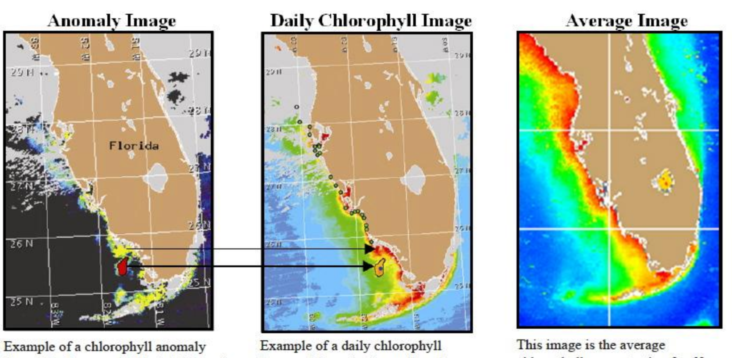
Detecting HABs

1) High Biomass events—chlorophyll and anomalies
2) Fluorescent Line Height (FLH) and Maximum Chlorophyll Index (MCI)
3) Backscatter from dense blooms
4) Inversion to identify specific organisms
5) Multi-spectral versus Hyperspectral
6) Integrating remote sensing with bloom ecology

Practical Applications--Detecting High-Biomass Events

- Chlorophyll is widely available from multiple satellite sensors
- Changes in chlorophyll (anomaly detection) should be a reasonable indicator of HAB events, and can be used for feature tracking, etc.
- Widely used in some areas
- Simple processing--calculate a running mean of chlorophyll and look for deviations

Practical Applications--Detecting High-Biomass Events



Example of a chlorophyll anomaly image (back page of bulletin). The red colored areas represent regions that have experienced a rapid increase in chlorophyll and have a high potential for containing *K. brevis* or have been confirmed to contain *K. brevis*.

Example of a daily chlorophyll image with marked sampling sites (front side of bulletin). The red polygons are chlorophyll anomaly areas that have high potential to contain *K.brevis* or have been verified to contain a *K. brevis* bloom.

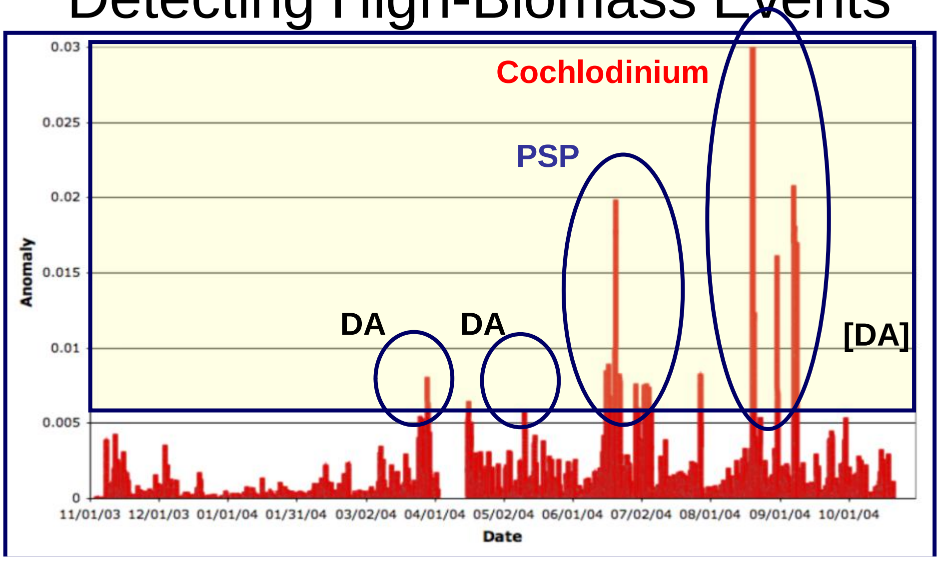
This image is the average chlorophyll concentration for 60 days prior to the image on the left. This image is not provided on the bulletin but is used to calculate the daily chlorophyll anomaly.

The top arrow indicates a region of high chlorophyll associated with a non-harmful bloom (colored yellow in the anomaly image).

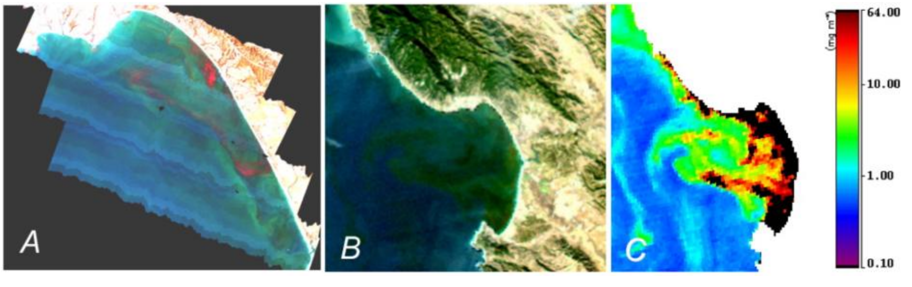
The bottom arrow indicates an anomaly area (left image) that has been verified as a *K. brevis* bloom (middle image), shown as a red polygon.

Cloudy areas are shown in gray. Cell count data may fall outside of an anomaly polygon in areas of cloud coverage.

Practical Applications--
Detecting High-Biomass Events

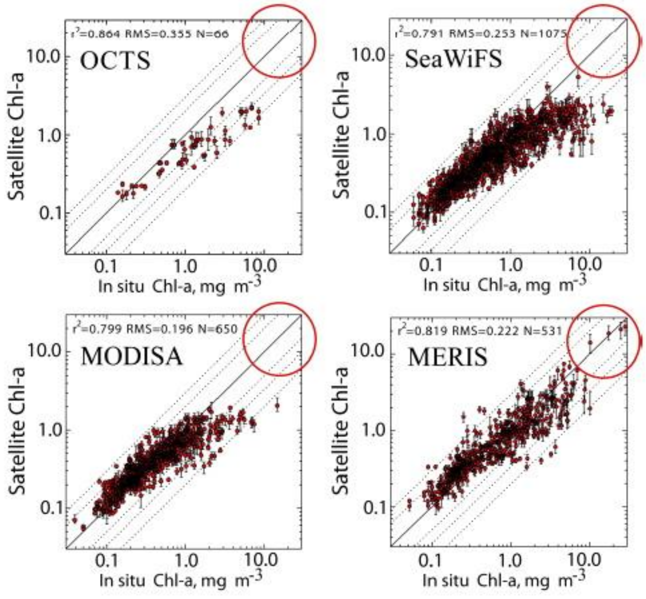


The Problem with Satellites…

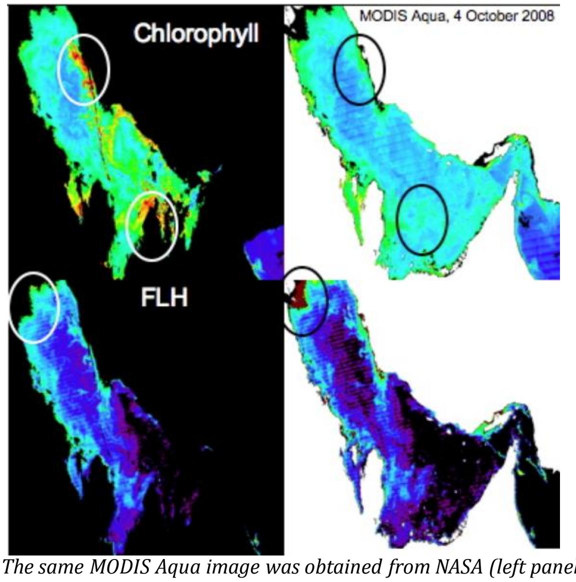


MODIS and MERIS provide reasonably high resolution (between 250-1000 m pixels), but the bands are not well chosen to detect red tides.

Standard chlorophyll algorithms “fail” in red tides, making the imagery look like it was a cloudy day….



Kahru et al. 2011, submitted

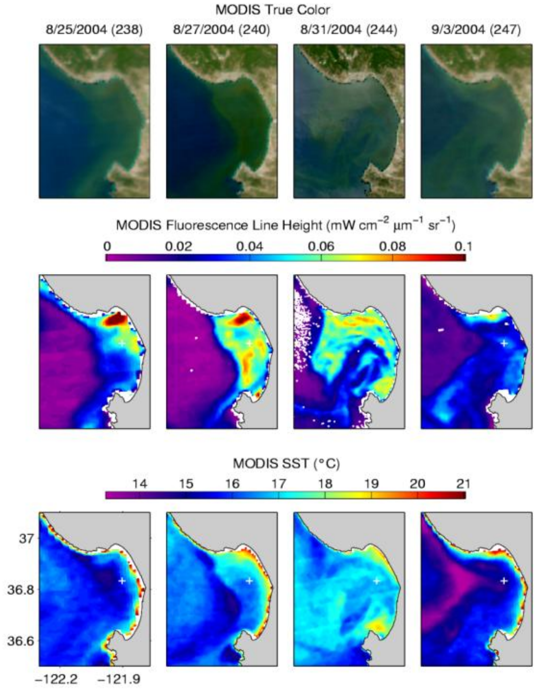


The same MODIS Aqua image was obtained from NASA (left panels) and reprocessed using a modified atmospheric correction (right panels) for chlorophyll and fluorescence line height (FLH). The circled regions show discrepancies between the two sets of images. The reprocessed file reduces the total chlorophyll in the Gulf, and fills in "missing" imagery caused by atmospheric correction failures. The reprocessed FLH suggests there was a large bloom in the northern Gulf, with patches of dense biomass distributed along much of the coastline throughout the region.

Arabian Gulf waters need to be processed with modifications from the standard global imagery—the occurrence of dust and aerosols significantly contaminates the ocean color imagery.

Fluorescence Line Height: Fixes the problems?

- Sediments, etc. don't interfere
- Fewer atmospheric correction problems
- Available on MERIS, MODIS, etc.



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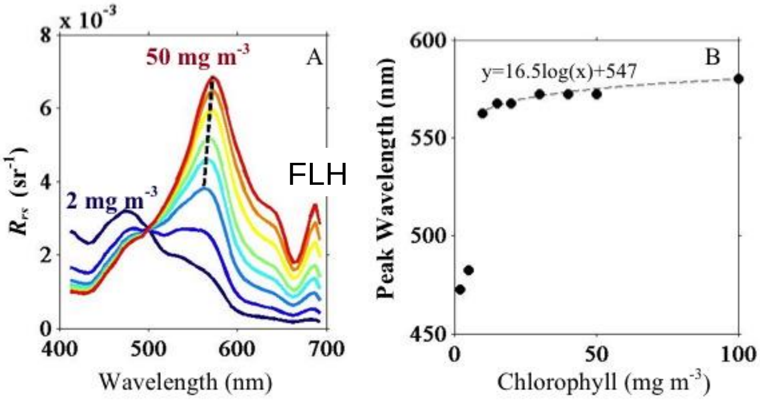
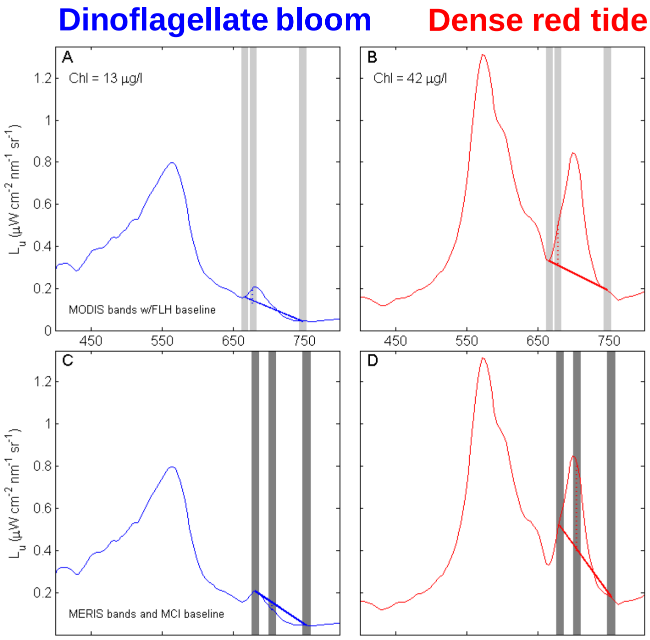


Peak reflectances shift to the **red** with increasing chlorophyll--most satellites don't have appropriate bands

Source: Dierssen et al., L&O 2006

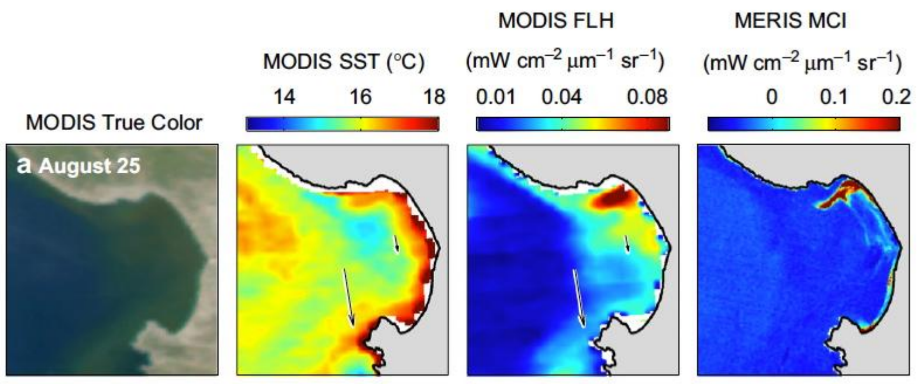


MODIS does well at low chlorophyll (<15 mg/m^3)

MERIS does well at high chlorophyll (>25 mg/m^3)

SeaWiFS has no FLH bands

MERIS MCI

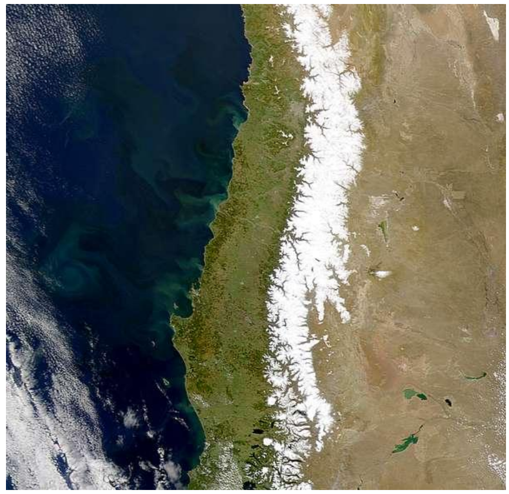


For true “red tides”, the MERIS Maximum Chlorophyll Index works really well, and is reasonably insensitive to atmospheric correction problems.

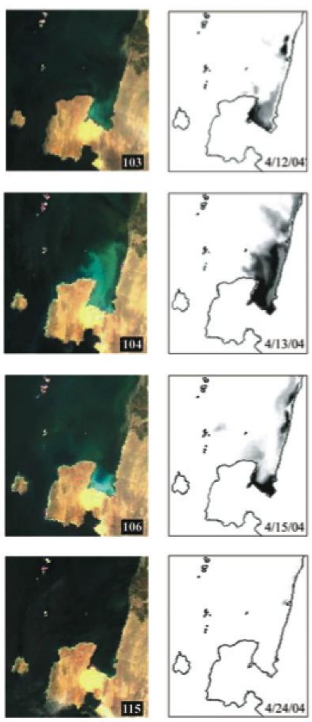
Ryan et al. 2009, Cont. Shelf Res.

Absorption plus Scattering

Red tide



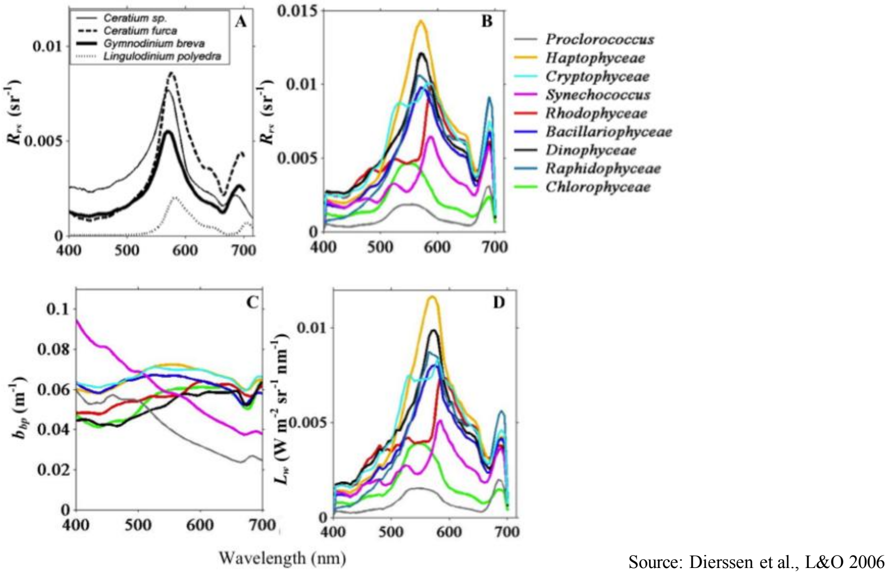
Eddies off the coast of Chile



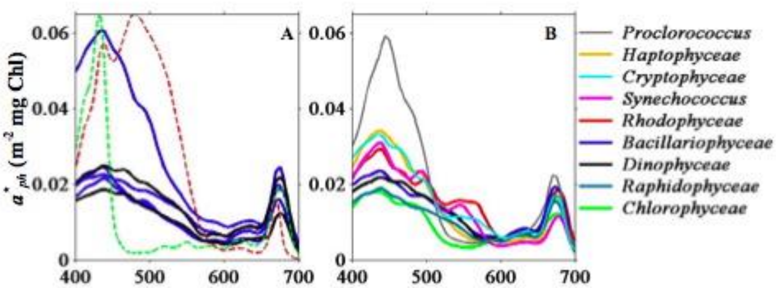
High-biomass blooms also result in elevated backscatter…

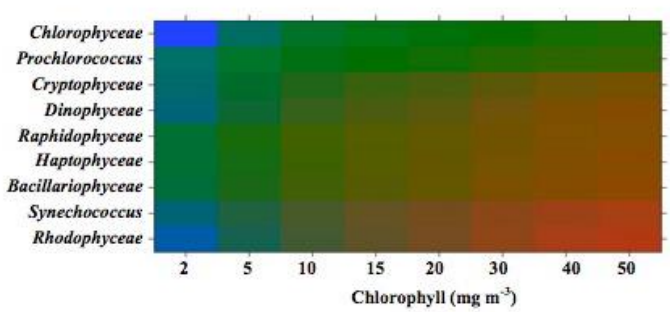
Gymnodinium sanguineum bloom in Paracas, Peru showing the potential advantage of increased spatial resolution (MODIS 250/500 m) for HAB event detection (source: Kahru, EOS 2004)

The problem… most HAB organisms are at low abundance or not distinguishable based on ocean color alone

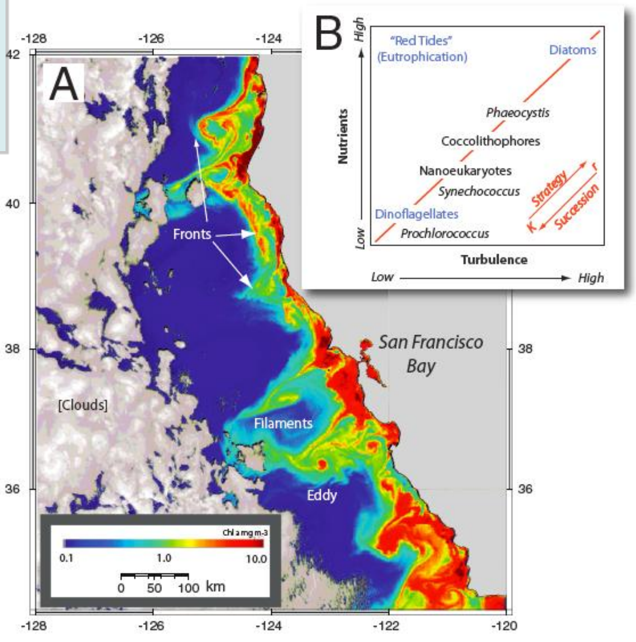


Source: Dierssen et al., L&O 2006

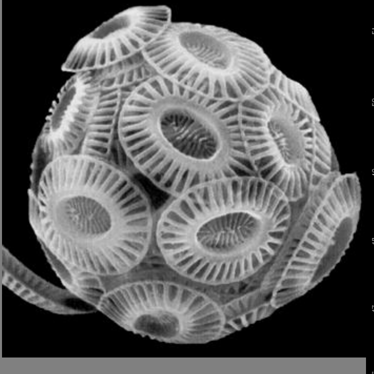


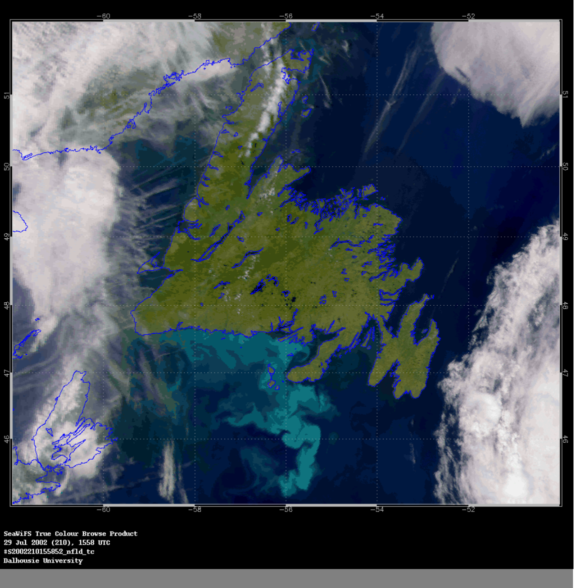


Combining Ecology With Ocean Optics To Identify "Phytoplankton Functional Types"



Scattering in the ocean

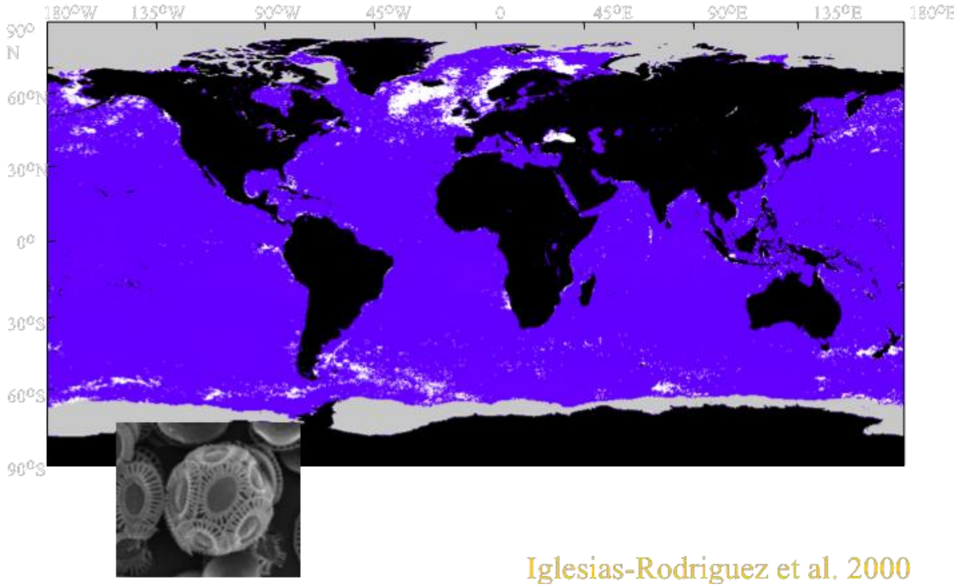




Coccolithophore
Emiliania huxleyi

http://earthguide.ucsd.edu/earthguide/imagelibrary/emilianiahuxleyi.html

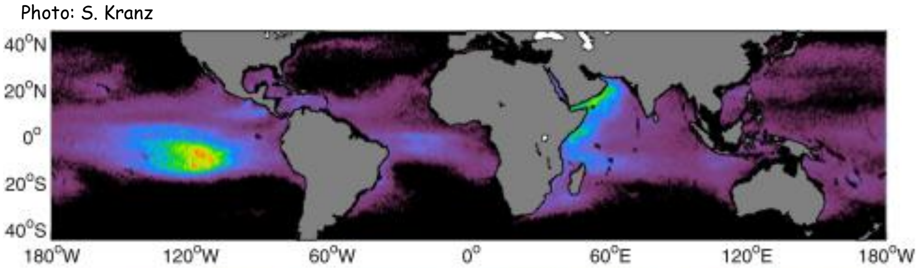
Coccolithophores—high backscatter



Iglesias-Rodriguez et al. 2000

Photo: S. Kranz

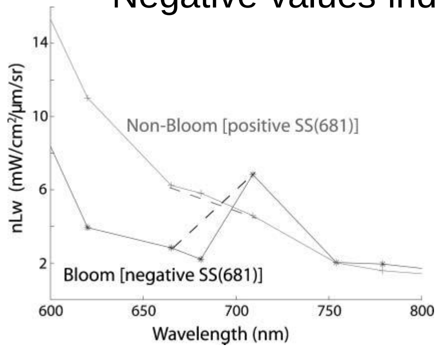
Nitrogen-Fixers Identified from Space



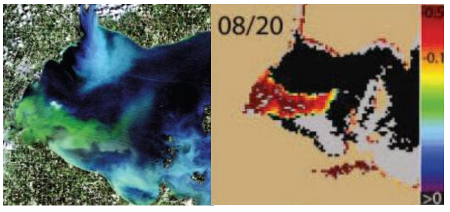
Westberry et al., JGR 2006

Spectral Signature: 680nm Line Height

- Wynne *et al.* used 680nm line height as a cyanobacteria index in MODIS data
  - Negative values indicated Microcystis

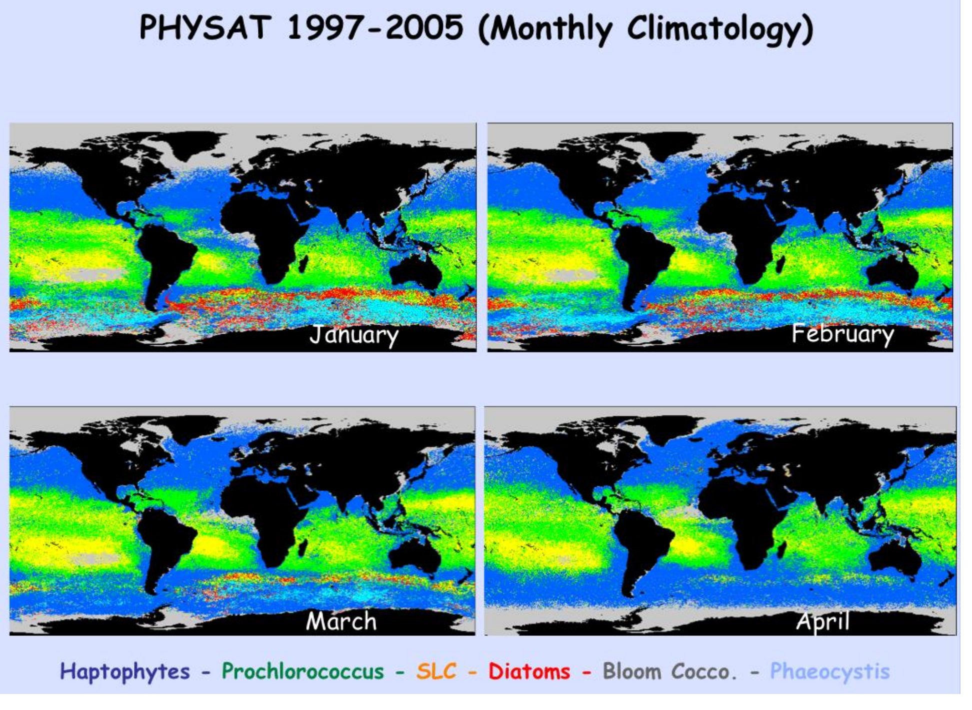


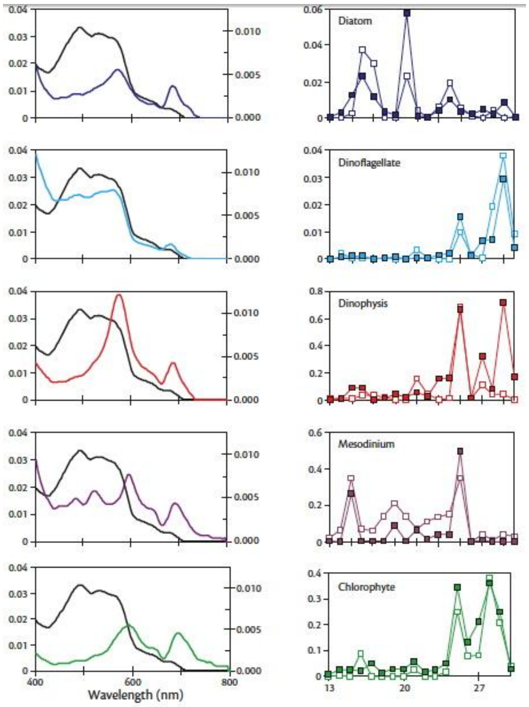
MERIS spectra of western Lake Erie:
8/21/2003 bloom conditions
8/17/2004 non-bloom conditions



Above left: LandSat image Lake Erie, 8/19/2009
Above right: 681nm line height from MODIS, 8/20/2009

Wynne et al. 2009

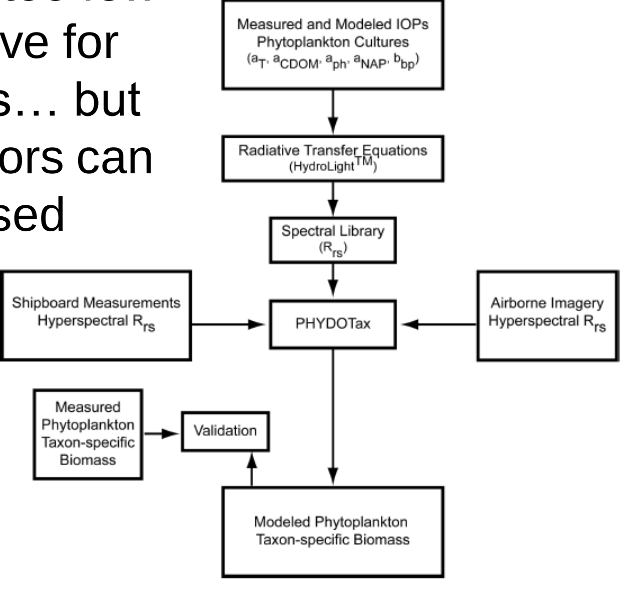




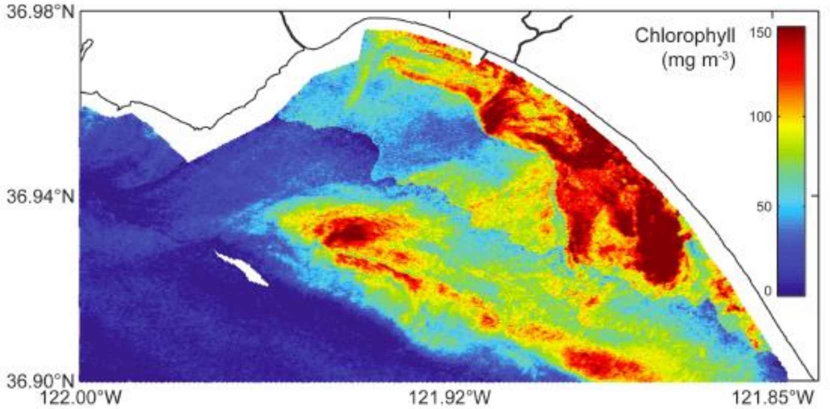
Spectral reflectance and modeled absorption for major functional groups from a red tide in the Benguela (source: Babin et al., *Oceanography* 2005)

Solid black line: pre-HAB reflectance

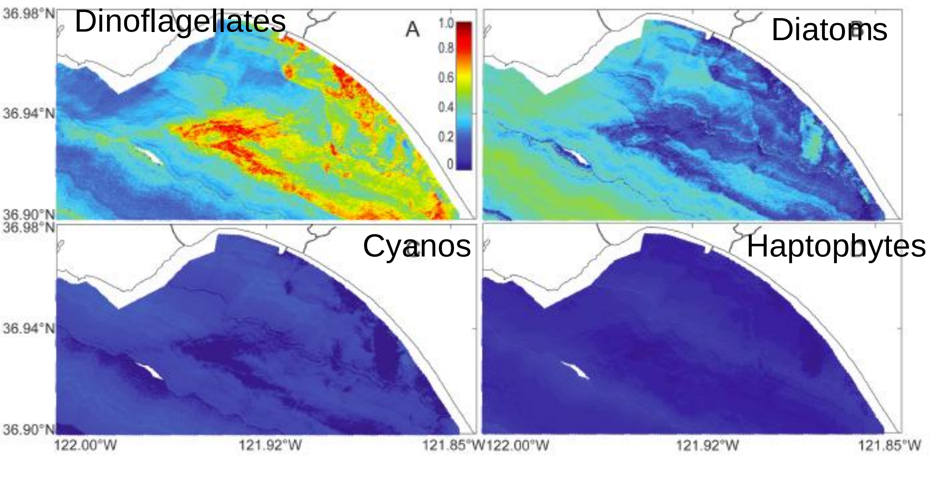
Most existing satellite sensors have too few bands to solve for multiple PFTs… but airborne sensors can also be used



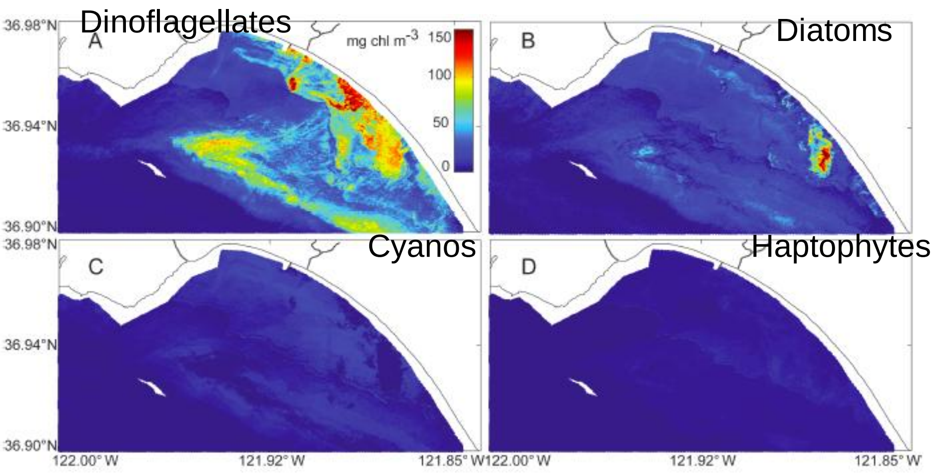
Monterey Bay, CA 2006



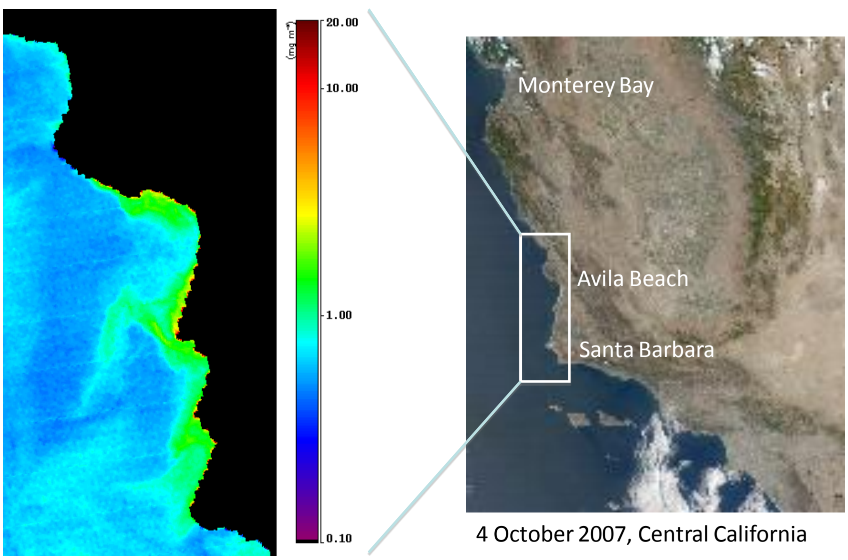
Relative proportion….



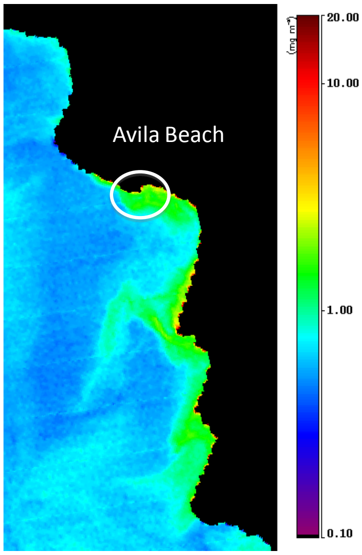
Mapped to CHL

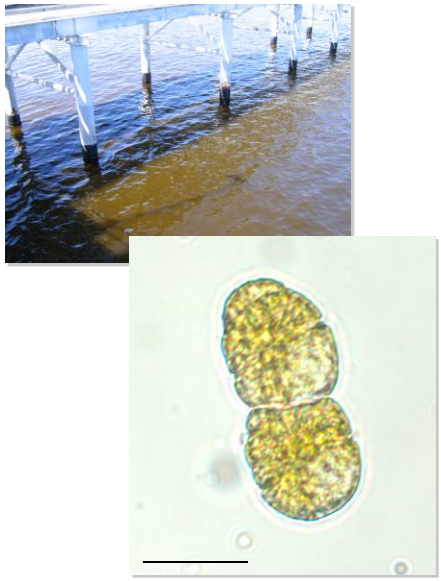


MODIS AQUA Satellite Imagery



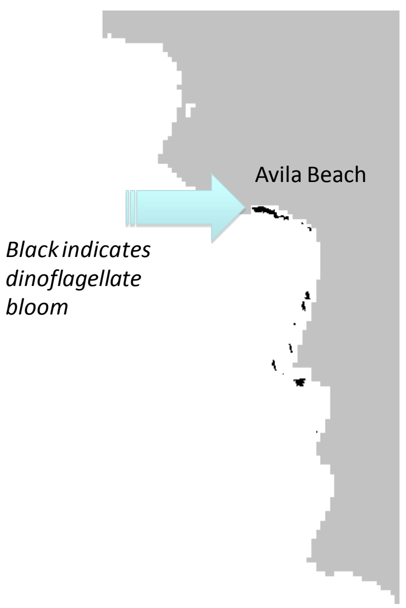
4 October 2007, Central California





October 3, 2007 (*C. fulvescens* bloom)

Matrix Inversion Algorithm Optimized for Dinoflagellates



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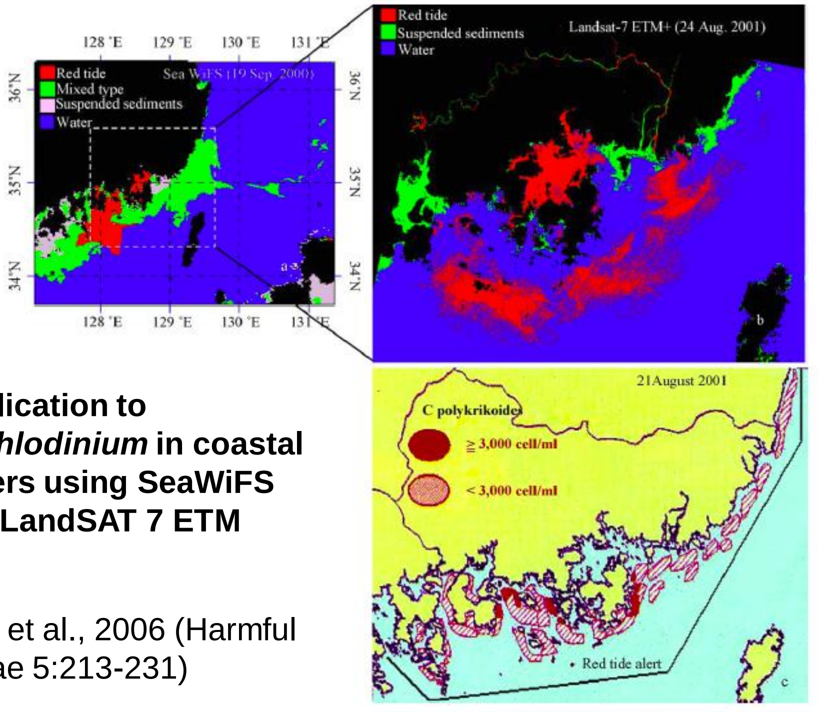


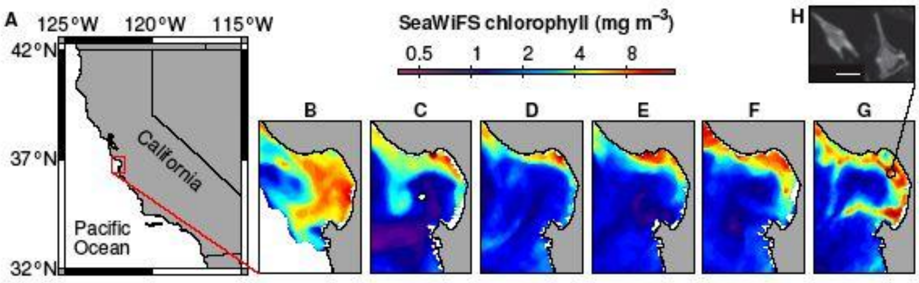
Application to *Cochlodinium* in coastal waters using SeaWiFS and LandSAT 7 ETM

Ahn et al., 2006 (Harmful Algae 5:213-231)

Key Point:

To effectively detect or predict Harmful Algal Blooms using remote sensing, it is CRITICAL to treat remote sensing as one of many data sets, and to interpret the results in the ecological context of the region and organism.

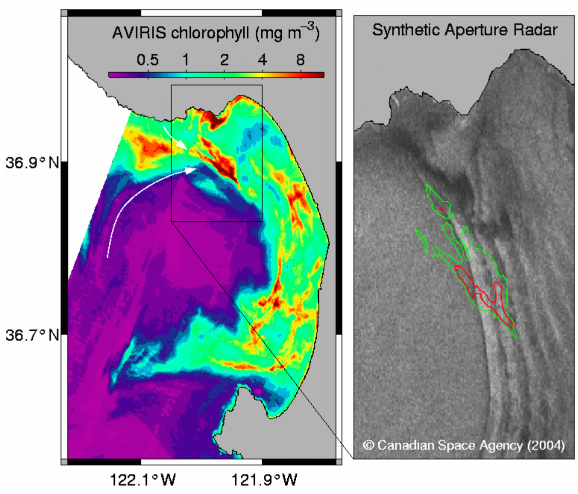
You can't ignore everything else!

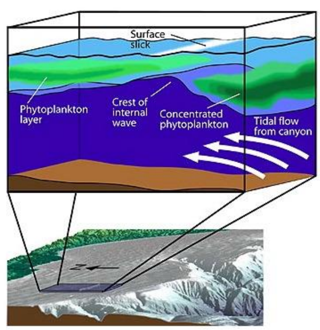


Sequential images of SeaWiFS chlorophyll showing the replacement of a diatom community by a red tide.

Ryan et al., 2005 (Oceanography)

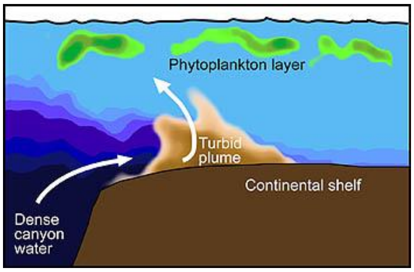
Internal Wave Modification of a Red Tide

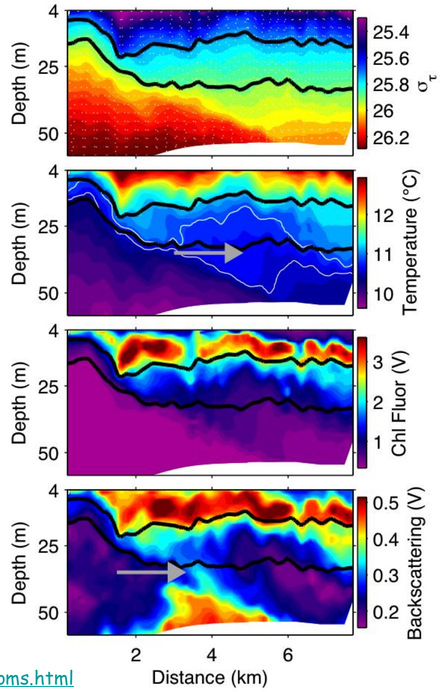




Source: Ryan et al. 2005

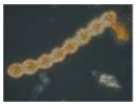
Towed and powered vehicles (not stuck in one place, but can't carry all the instruments)

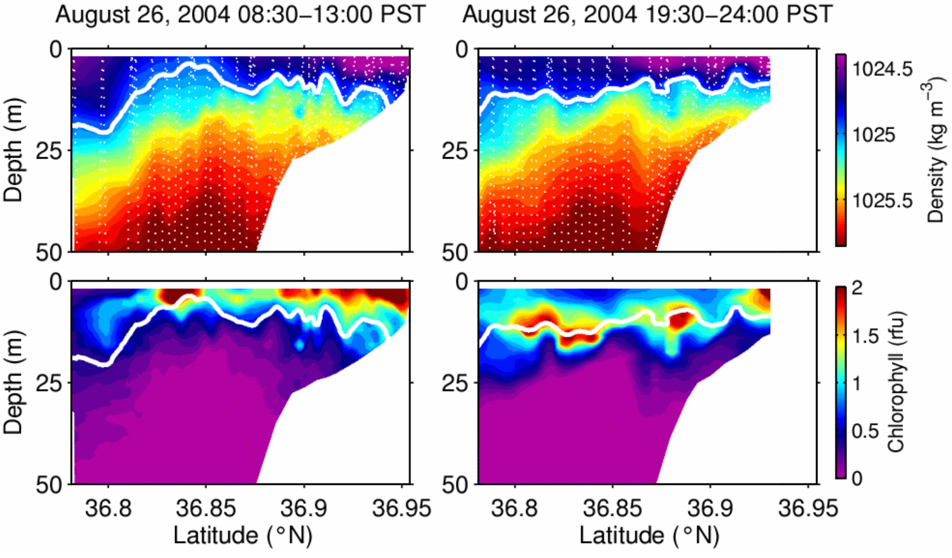


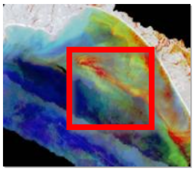


http://www.mbari.org/news/homepage/2005/ryan-blooms.html

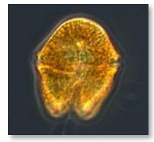
Vertical Migration

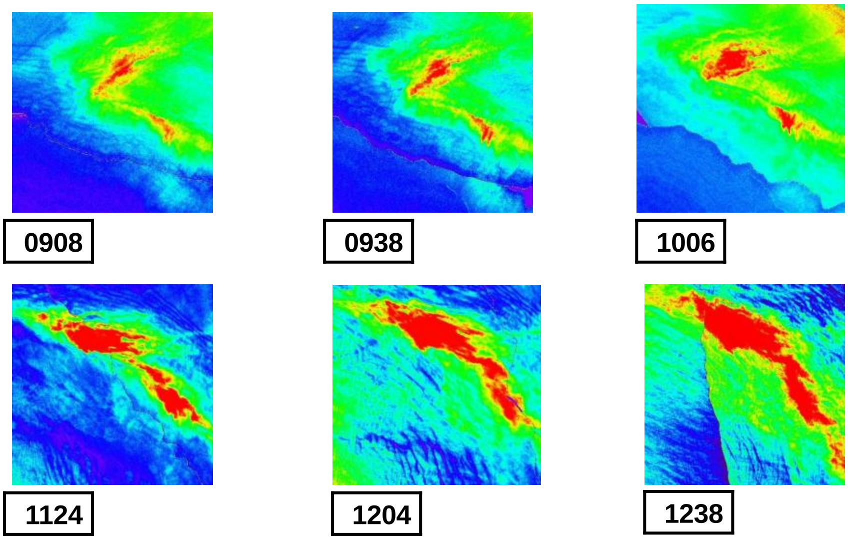


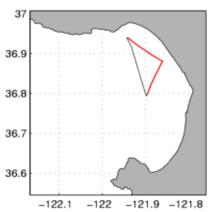




Physical: Vertical Migration

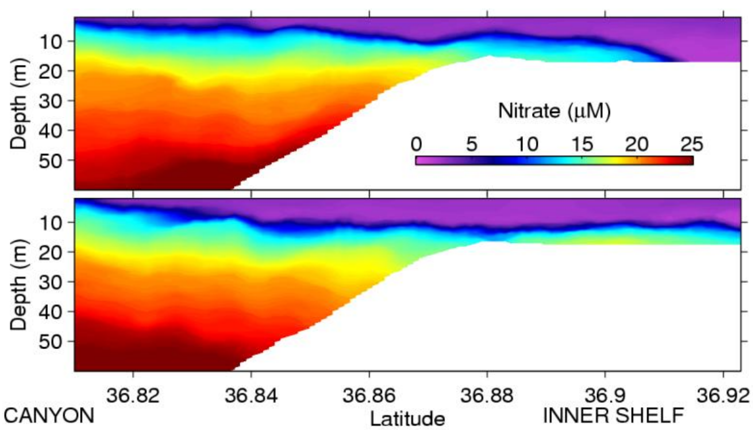






A sub-thermocline nutrient pump

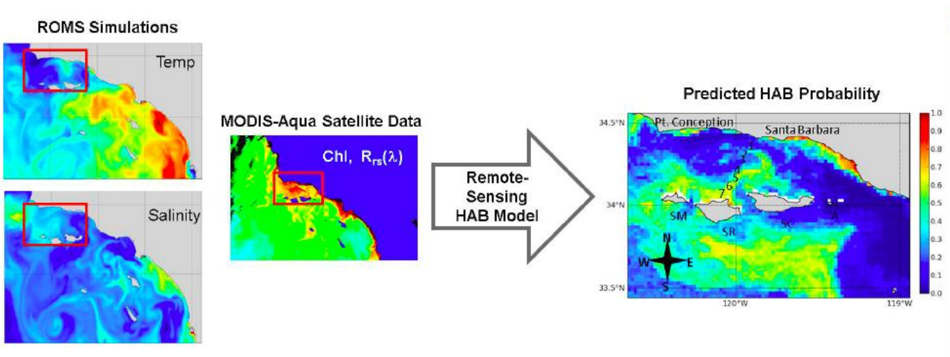
Shea and Broenkow (1982) showed how the large amplitude internal tide over the canyon can pump deep, cold water onto the shelf. We saw this process pumping nutrients into the hypothesized red tide incubator.



Source: John Ryan, MBARI

- *AUV sections 7 hours apart, each >180 profiles in < 4 hours*

Remote Sensing is only one data set…



Merging ROMS physical models with RS to produce statistical probabilities of HAB events.

Anderson et al. GRL 2011

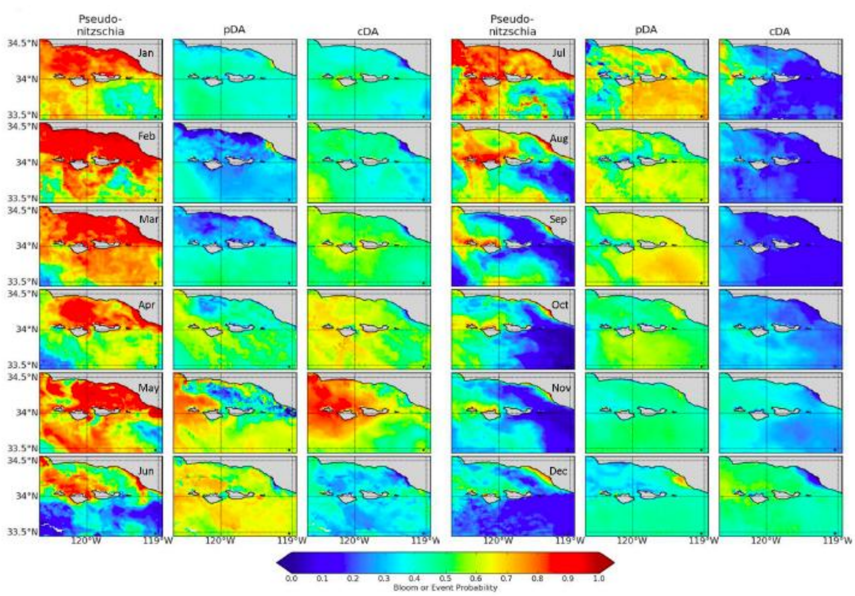


Figure 2. Monthly probability maps of *Pseudo-nitzschia* blooms ($\geq 10^4$ cells L^{-1}), elevated pDA (≥ 0.5 $\mu g\ L^{-1}$) and cDA (≥ 10 pg $cell^{-1}$) for January to December 2009.

Anderson et al., GRL 2011, L04603

The Future of HAB RS

HICO sensor Concepcion, Chile

SENSOR	AGENCY	SATELLITE	SCHEDULED LAUNCH	SWATH (km)	SPATIAL RESOLUTION (m)	# OF BANDS	SPECTRAL COVERAGE (nm)	ORBIT
VIIRS	NOAA /NASA (USA)	NPP	2011	3000	370 / 740	22	402 - 11,800	Polar
OLCI	ESA/ EUMETSAT	GMES-Sentinel 3A	Q1 2013	1270	300/1200	21	400 - 1020	Polar
HSI	DLR (Germany)	EnMAP	2013	30	30	228	420 - 2450	Polar
SGLI	JAXA (Japan)	GCOM-C	2014	1150 - 1400	250/1000	19	375 - 12,500	Polar
COCTS CZI	CNSA (Japan)	HY-1C/D (China)	2014	2900 1000	1100 250	10 10	402 - 12,500 433 -885	Polar
Multi-spectral Optical Camera	INPE / CONAE	SABIA-MAR	2015	200/2200	200/1100	16	380 - 11,800	Polar
OC Scanner Coastal Zone Scanner	ROSCOSMOS (Russia)	Meteor-3M(3)	2015	3000 800	1000 80	8 6	402 – 885 410 – 786	Polar
VIIRS	NOAA /NASA (USA)	JPSS-1	2015	3000	370 / 740	22	402 - 11,800	Polar
OLCI	ESA/ EUMETSAT	GMES-Sentinel 3B	2017	1265	260	21	390 - 1040	Polar
COCTS CZI	CNSA (Japan)	HY-1E/F (China)	2017	2900 1000	1100 250	10 4	402 - 12,500 433 - 885	Polar
GOCI-II	KARI/KORDI (South Korea)	KMGS-B	2018	1200 x 1500 TBD	250/1000	13	412 - 1240 TBD	Geostationary
OES	NASA	PACE	2019	*	*	*	*	Polar
OES	NASA	ACE	>2020	TBD	1000	26	350-2135	Polar
Coastal Ocean Color Imaging Spec (Name TBD)	NASA	GEO-CAPE	>2020	TBD	250 - 375	155 TBD	340-2160	Geostationary

Summary

- Remote Sensing of HABs is subject to all of the issues associated with RS (clouds, algorithm failure, etc)

- Although it would seem that true red tides would be easy to detect, most standard ocean color products are not designed for high biomass and complex coastal waters

- There are many (increasing) examples of HAB products, but they generally require specialized processing and are specific to the region/organism

- Given high quality data, it is possible to identify Phytoplankton Functional Types or even genera of algae

- RS is only ONE tool—the best results are obtained by putting the results in an ecological context!