→ EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

30 July–10 August 2018 | ESA–ESRIN | Frascati (Rome) Italy

Ocean Colour and climate

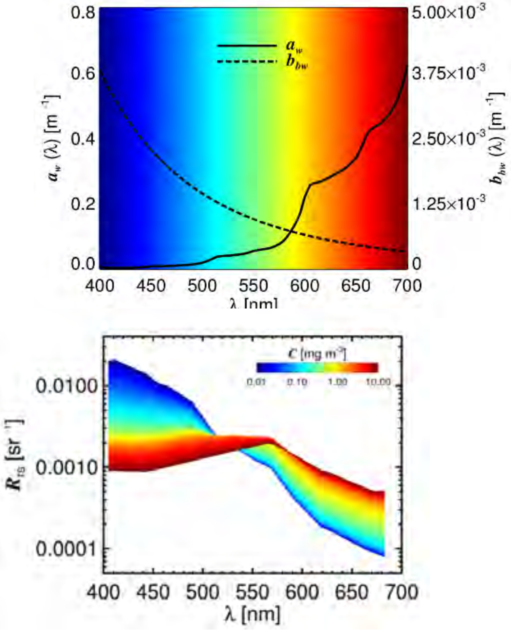
Bob Brewin[1,2]

[1] Plymouth Marine Laboratory (PML), Prospect Place, The Hoe, Plymouth PL1 3DH, UK

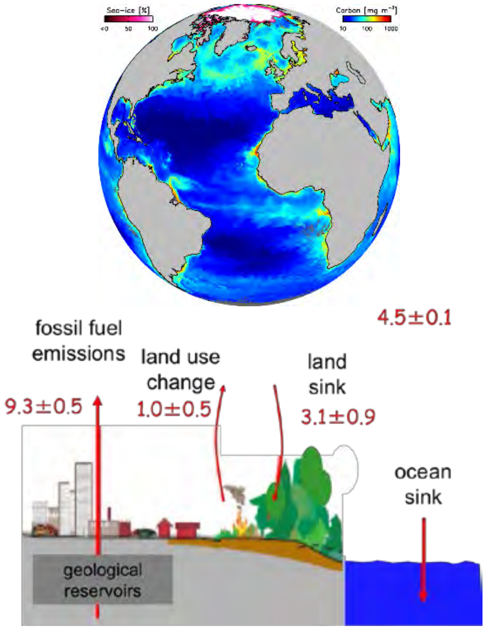
[2] National Centre for Earth Observation, PML, Plymouth PL1 3DH, UK

Overview of ocean colour lectures

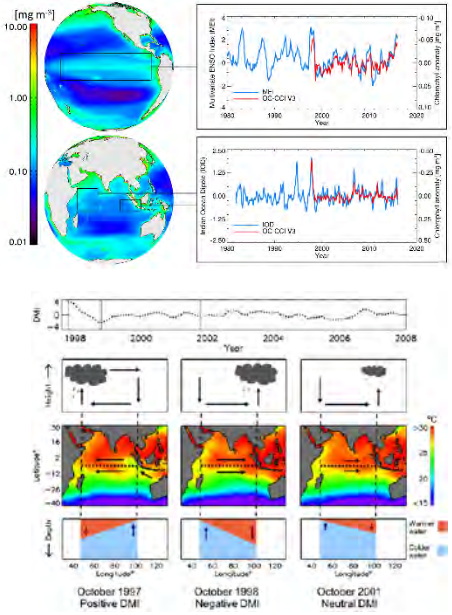
Ocean Colour theory
11:30 -12:30 1st August



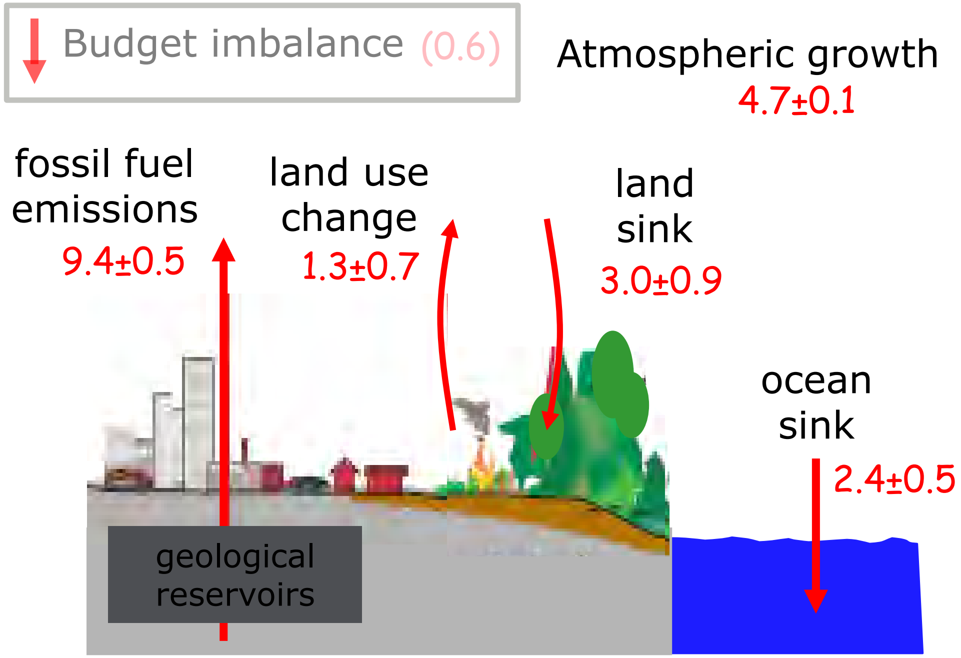
Ocean Colour and the marine carbon cycle
12:30 -13:30 2nd August



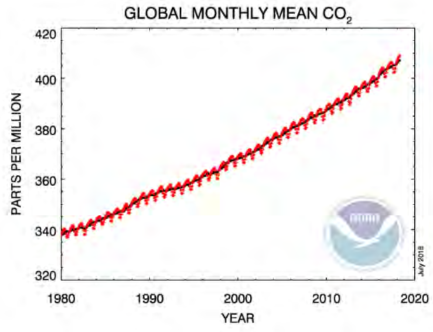
Ocean Colour and climate
11:30 -12:30 3rd August



2007-2016 Earth Carbon budget (GtC y^{-1})

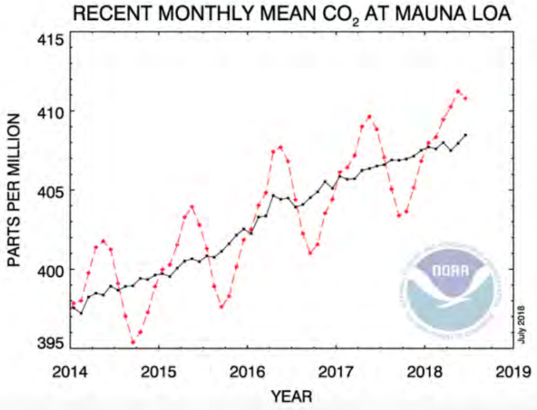


Sources: Le Quéré et al. (2018) Earth Syst. Sci. Data., 10, 405-448

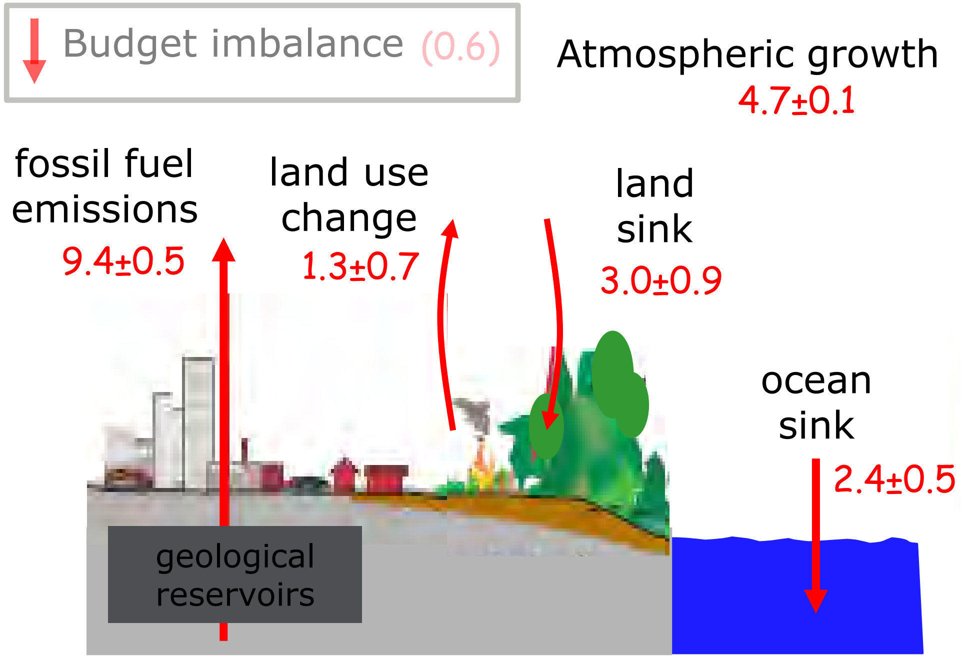


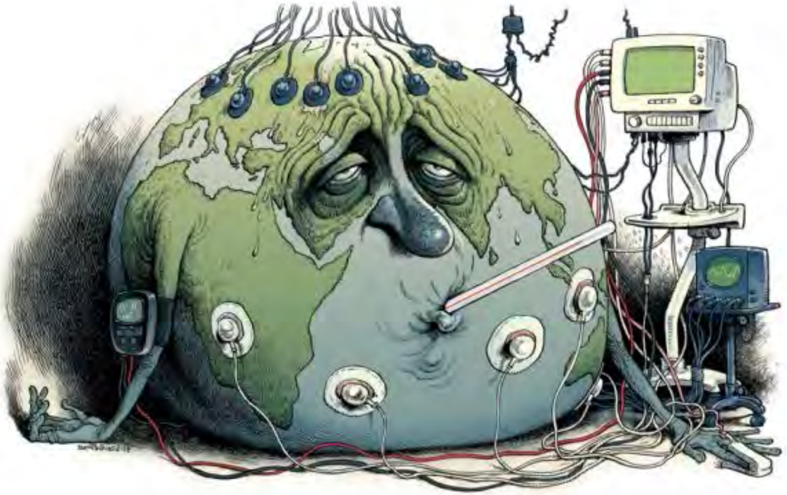
Recent Monthly Average Mauna Loa CO_2

June 2018: 410.79 ppm
June 2017: 408.84 ppm
Last updated: July 5, 2018



2007-2016 Earth Carbon budget (GtC y^{-1})





Victor & Kennel (2014) Nature

Sources: Le Quéré et al. (2018) Earth Syst. Sci. Data., 10, 405-448

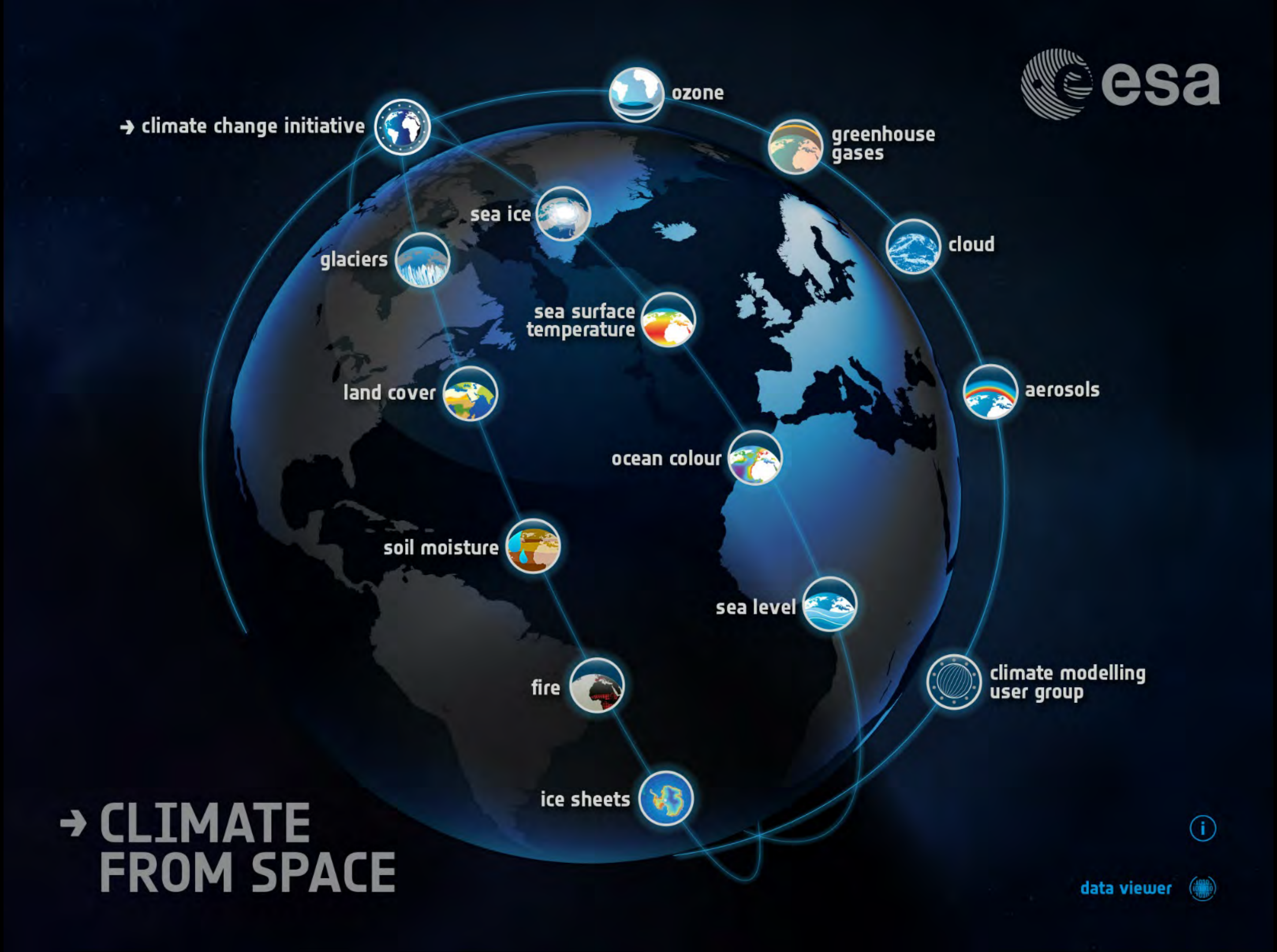
Datasets needed to monitor climate variability

Established in 1992, the Global Climate Observing System (GCOS) identified 50 Essential Climate Variables (ECVs) to support the work of the intergovernmental expert group on the evolution of climate, the UNFCCC and IPCC.

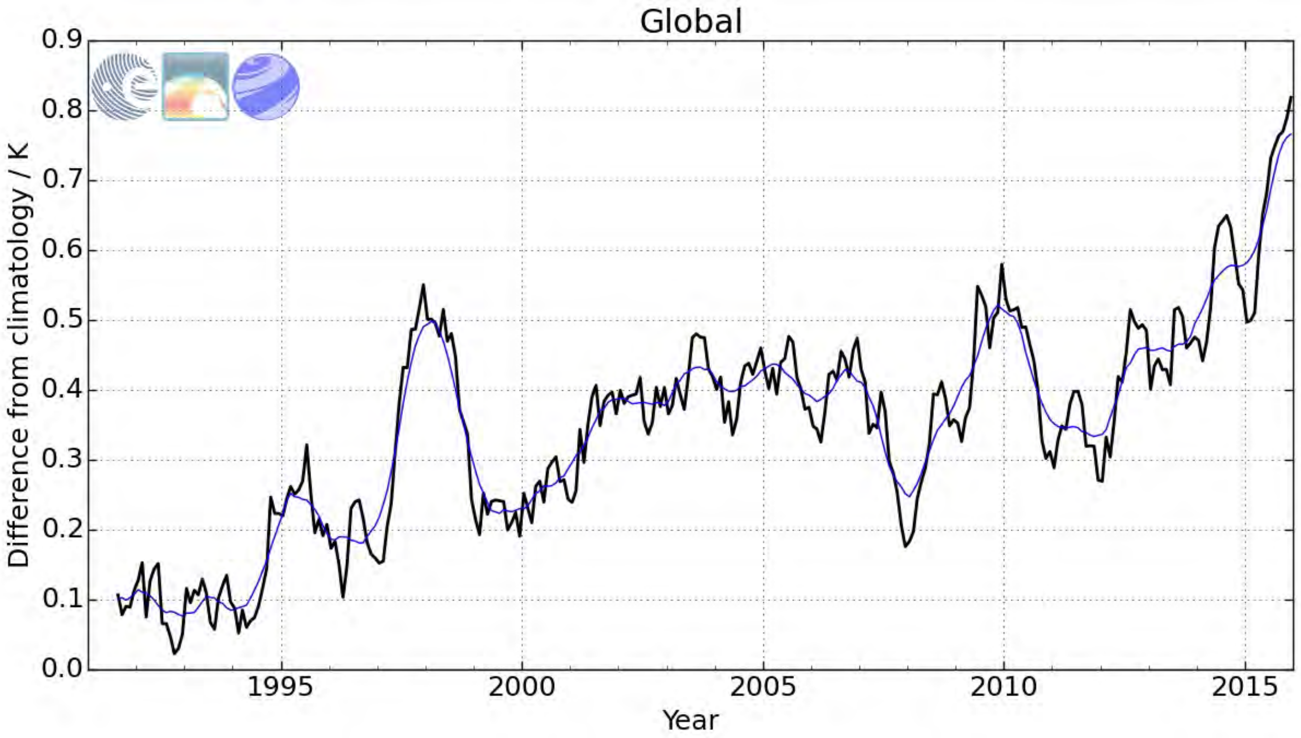
An ECV is a physical, chemical or biological variable, or a group of linked variables, that critically contributes to the characterisation of Earth's climate.

IPCC
INTERGOVERNMENTAL PANEL ON climate change

United Nations Framework Convention on Climate Change

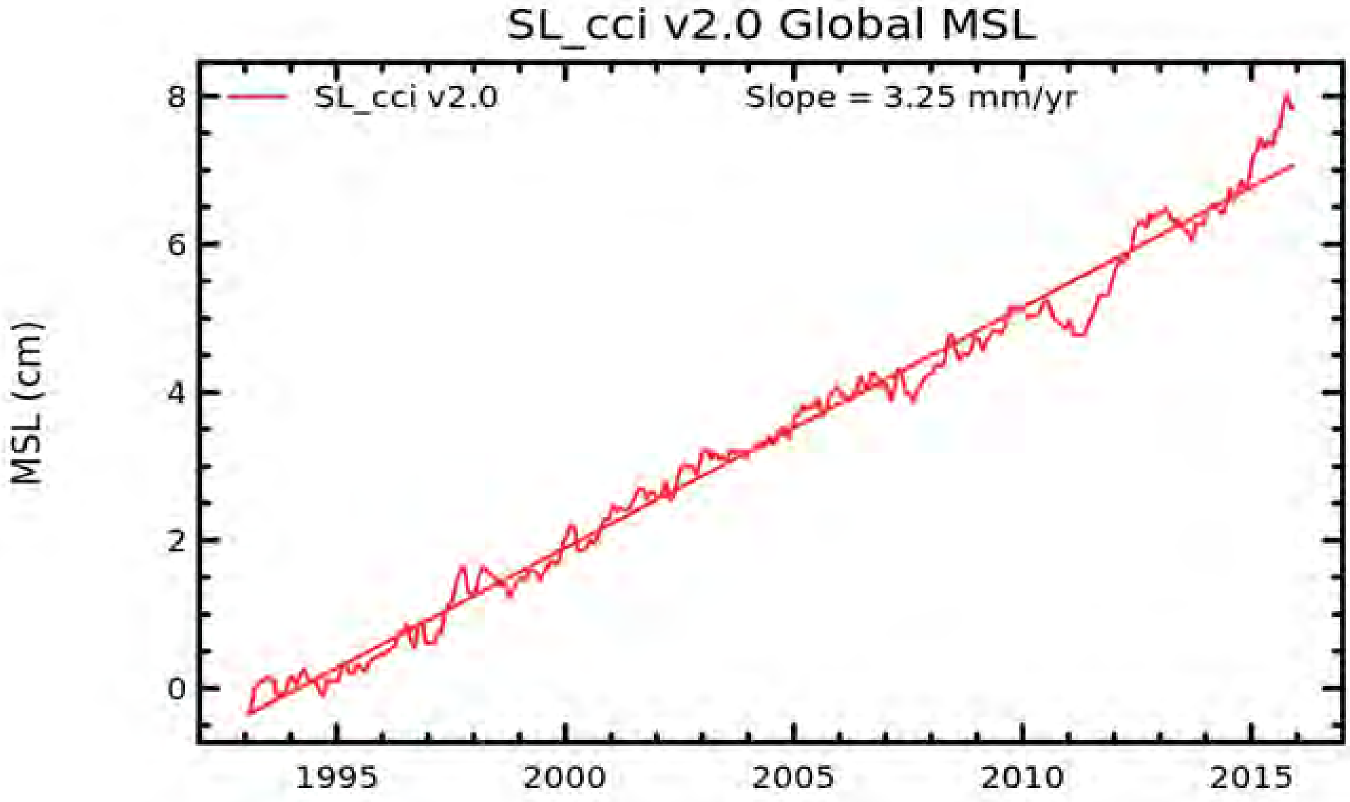

esa
climate change initiative
ozone
greenhouse gases
sea ice
glaciers
cloud
sea surface temperature
land cover
aerosols
ocean colour
soil moisture
sea level
climate modelling user group
fire
ice sheets
CLIMATE FROM SPACE
data viewer

Sea Surface Temperature CCI



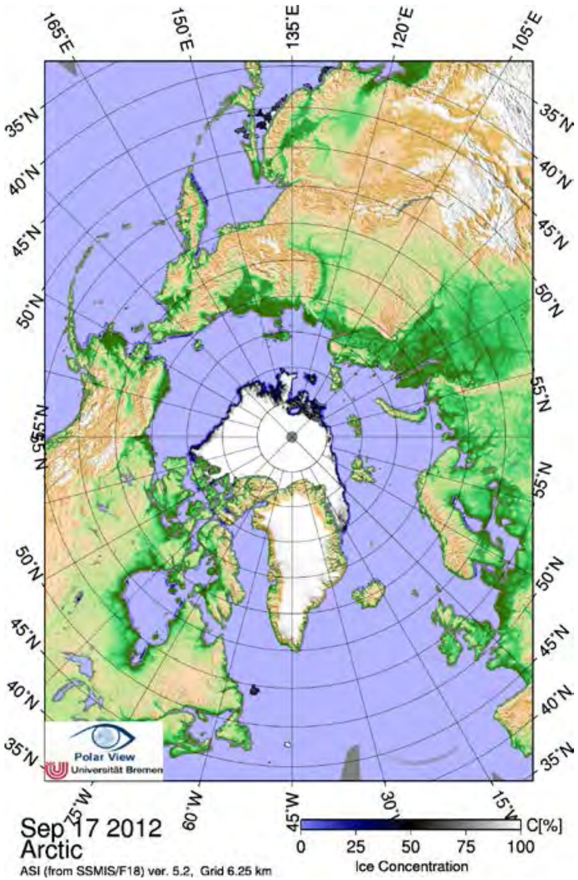
http://gwsaccess.ceda.ac.uk/public2/nceo_uor/sst/L3S/EXP1.2/

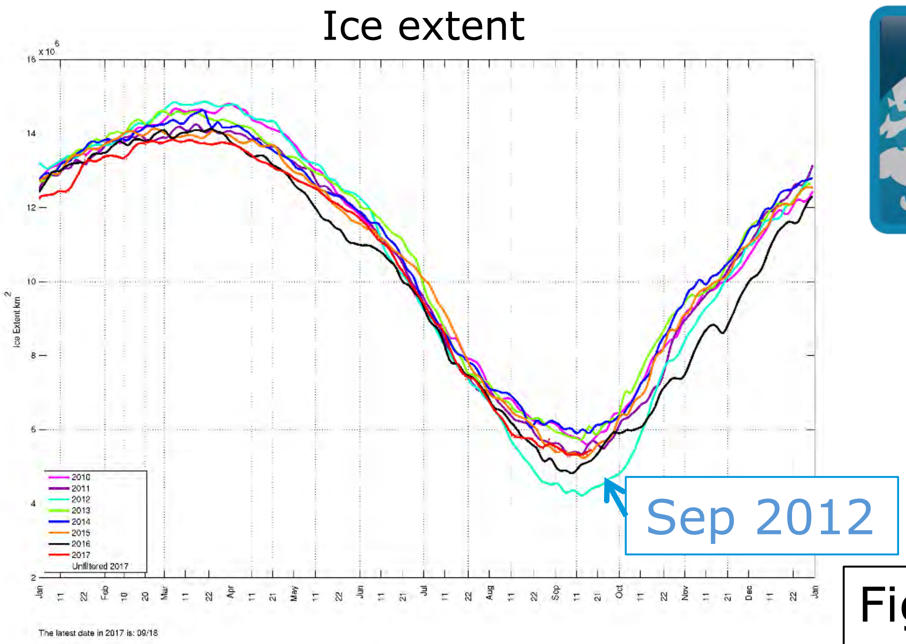
Sea Level CCI



http://www.esa-sealevel-cci.org/node/269?size=_original

Sea Ice CCI

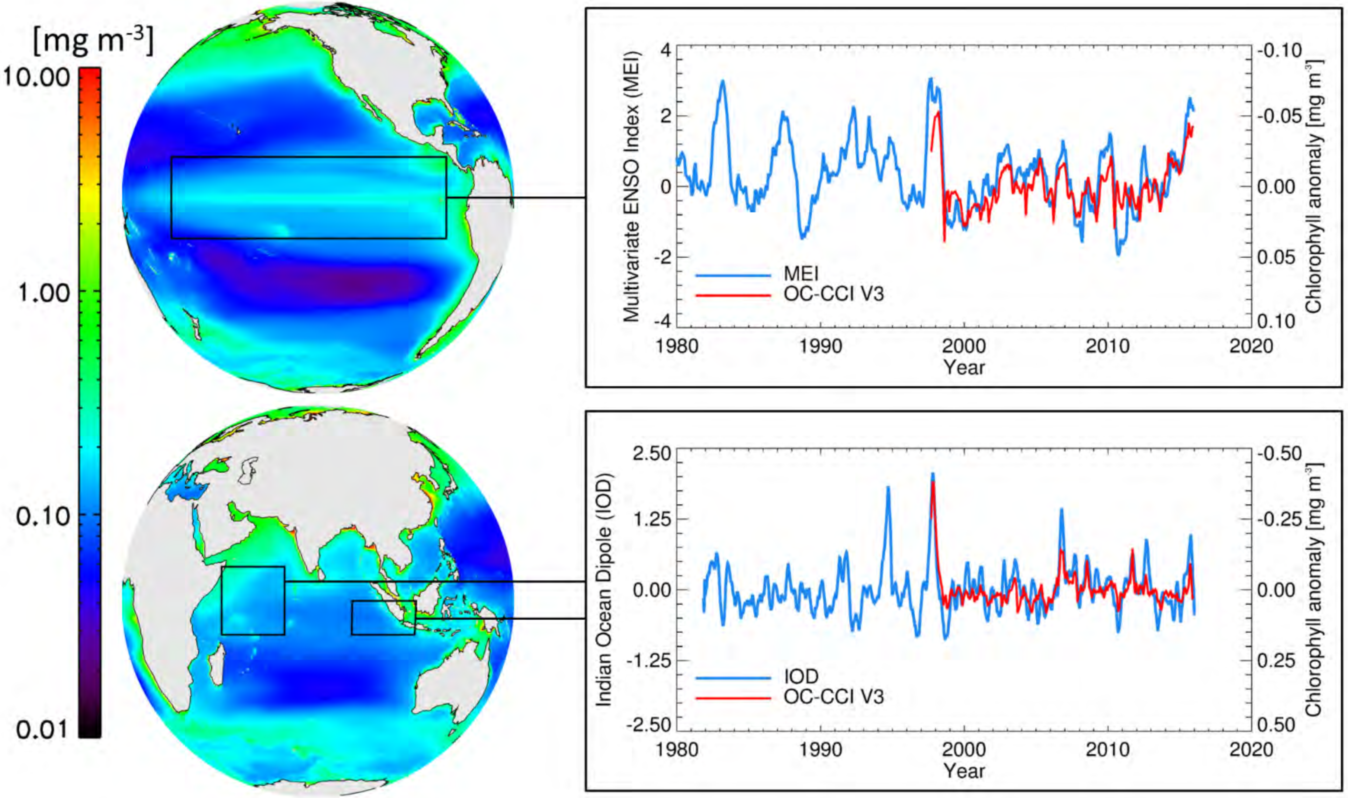




September shows the lowest ice area in the Arctic since satellite observation started in 1979.

Figure courtesy NERSC and http://arctic-roos.org

Ocean Colour CCI



von Schuckmann et al. (2016) Journal of Operational Oceanography

Overview

1) Datasets needed to monitor ocean colour climate variability

2) What are the potential responses of the marine ecosystem to a changing climate.
   - Total amount of phytoplankton (as indexed by chlorophyll-a concentration) might change
   - The community structure associated with the chlorophyll concentration might change
   - Other substances that absorb and scatter light in the visible domain might change, relative to chlorophyll-a
   - The phenology might change (e.g. timing, amplitude and duration of blooms)

3) Examples of climate variability observed in the ocean-colour data record

Overview

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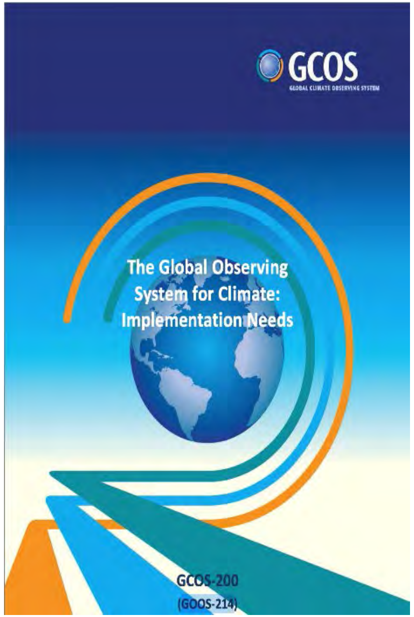
3) Examples of climate variability observed in the ocean-colour data record

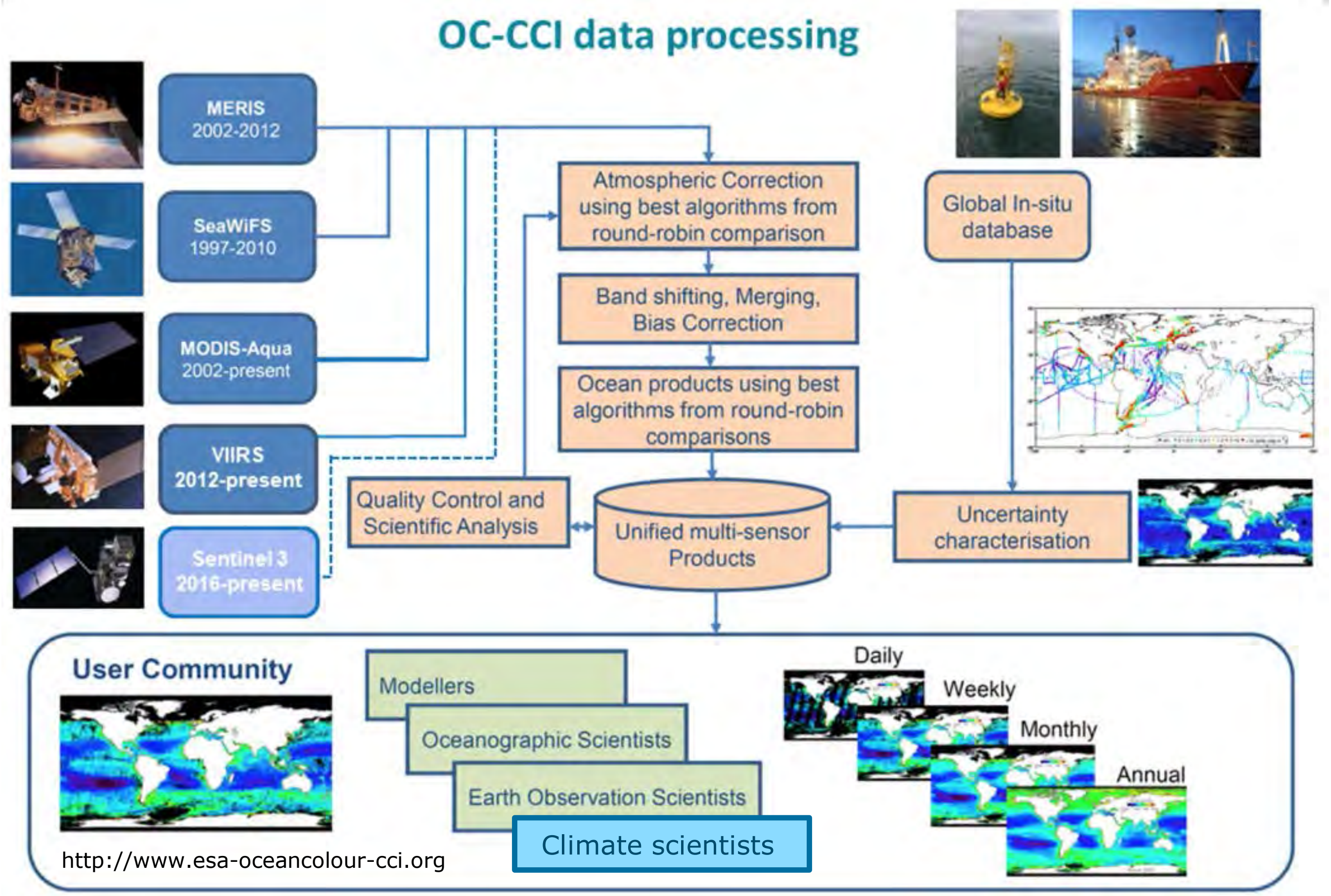
GCOS Ocean Colour requirements

Goal: create the most complete and consistent, error- characterized time series of multi-sensor global satellite ECV products for climate research and modeling meeting GCOS requirements

GCOS-200 October 2016					
Variable / Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Water Leaving Radiance	**4km**	**N/A**	**daily**	**5% (blue to green)**	**0.5%**
Chlorophyll-a concentration	**4km**	**N/A**	**weekly averages**	**30%**	**3%**



The Ocean Colour Climate Change Initiative



http://www.esa-oceancolour-cci.org

Inter-comparison Criteria

Sathyendranath et al. (2017) RSE

(1) Atmospheric correction or (2) In-water algorithms

Qualitative intercomparison
(Questionnaire)
Does the algorithm suit the requirements of OC-CCI?
Ranking

Quantitative intercomparison
(Validation)
How well does the algorithm perform?
Ranking

Additional criteria
Sensor specific performance? Algorithm tradeoffs?
Time-series comparsion?

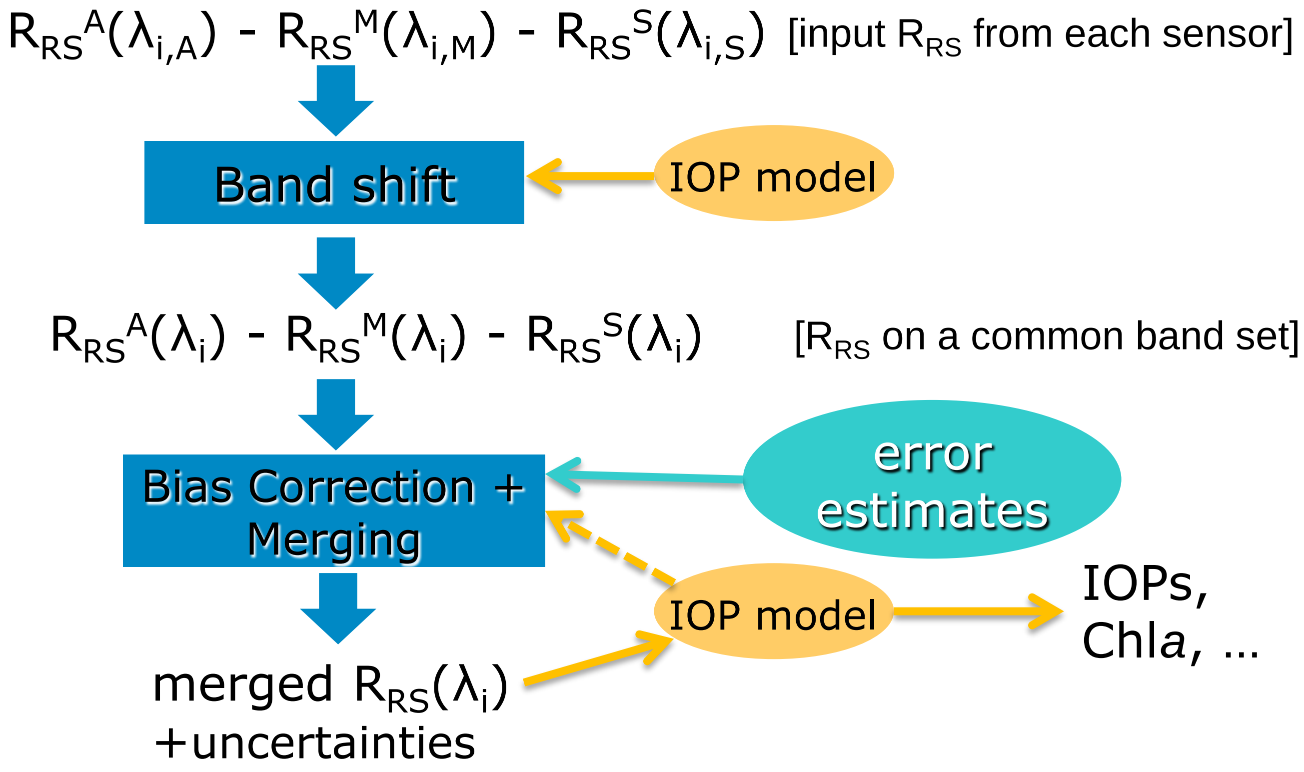
Algorithm selection

Brewin et al. (2015a) RSE
Müller et al. (2015a,b) RSE

Iterative loop

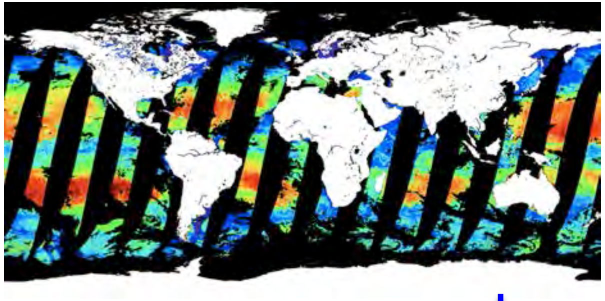
OC-CCI Data Merging Approach

produced of Frédéric Mélin

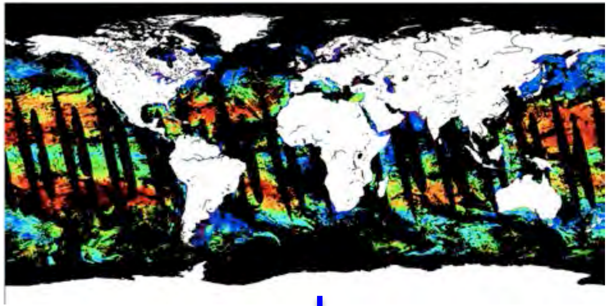


The Ocean Colour Climate Change Initiative

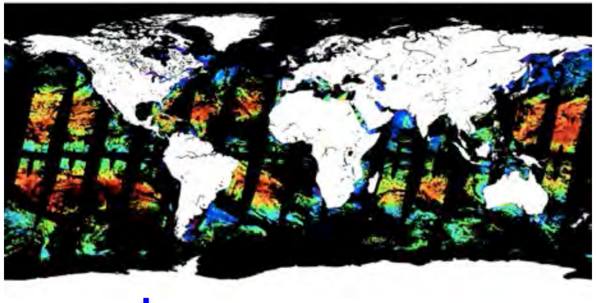
MERIS Radiance



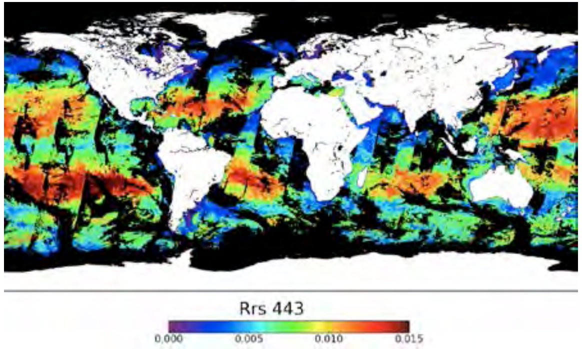
MODIS-A Radiance



SeaWiFS Radiance

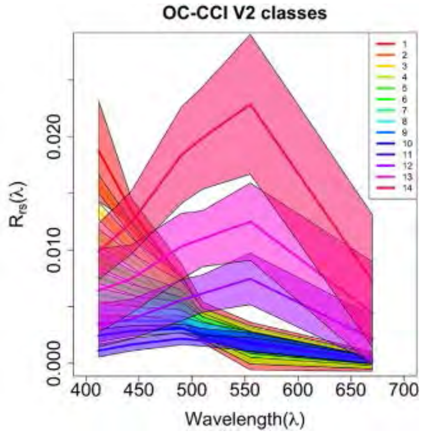


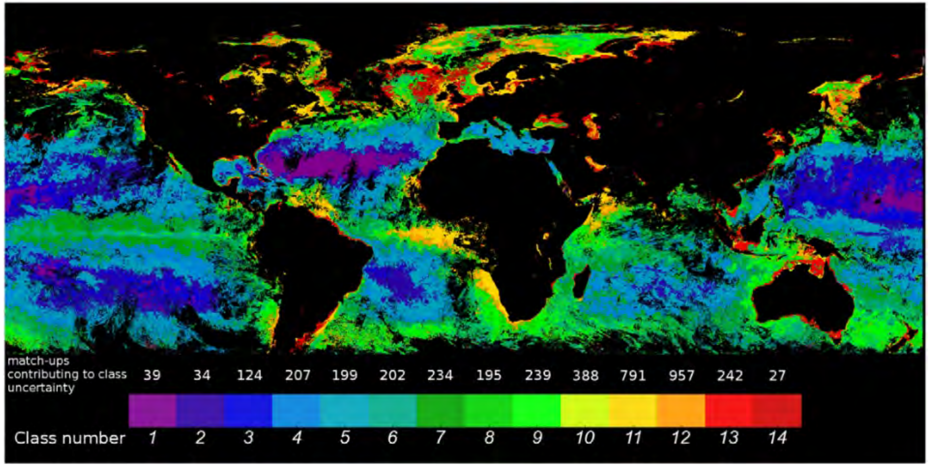
Band-shifting, bias correction and merging



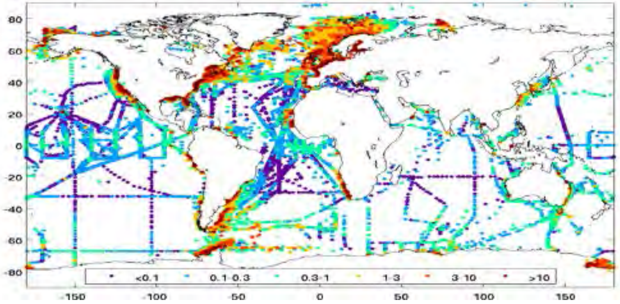
The Merged Product

The Ocean Colour Climate Change Initiative

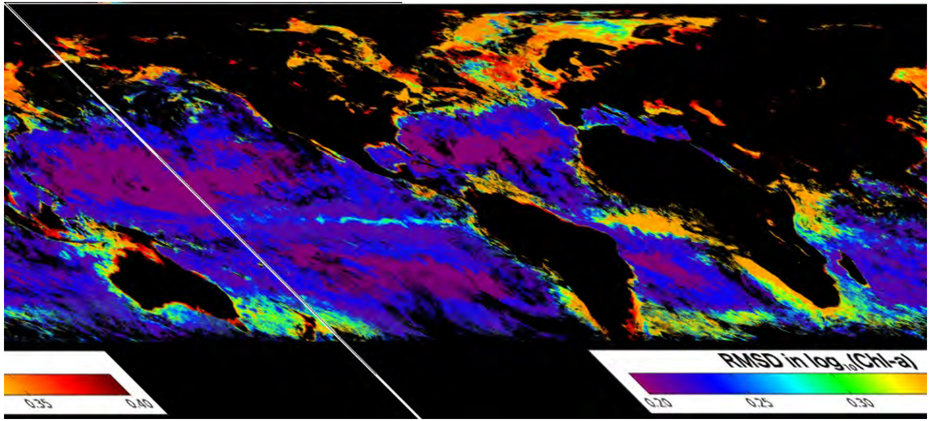




Moore et al. (2009) RSE

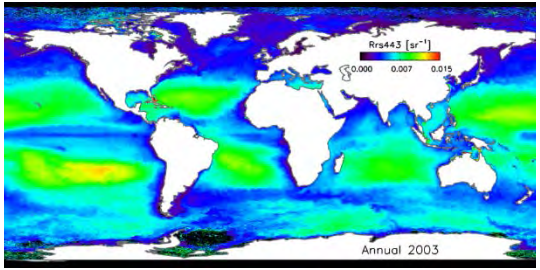


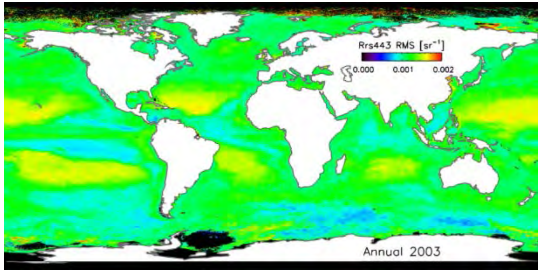
Chlorophyll database
Version 3.1: 79,924 observations

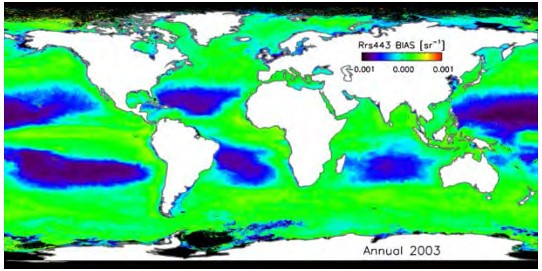


Jackson et al. (2017) RSE

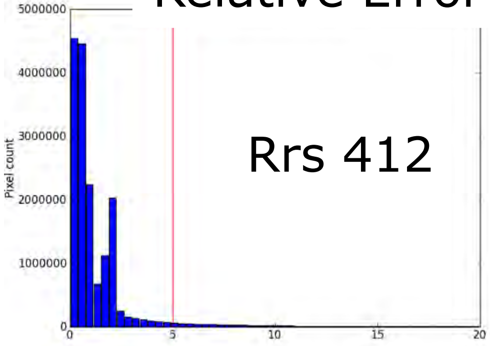
The Ocean Colour Climate Change Initiative

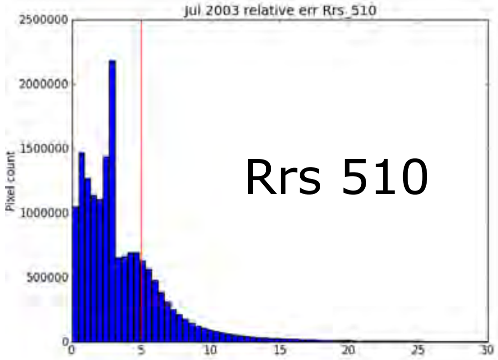






Relative Error

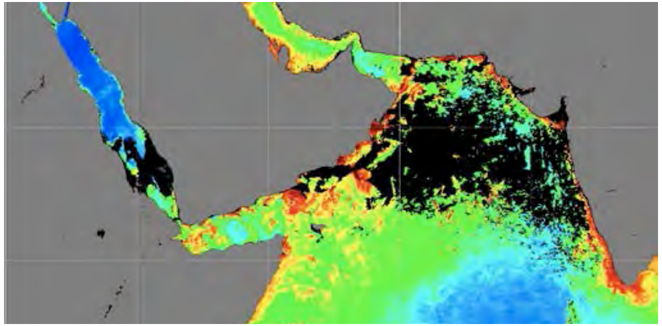




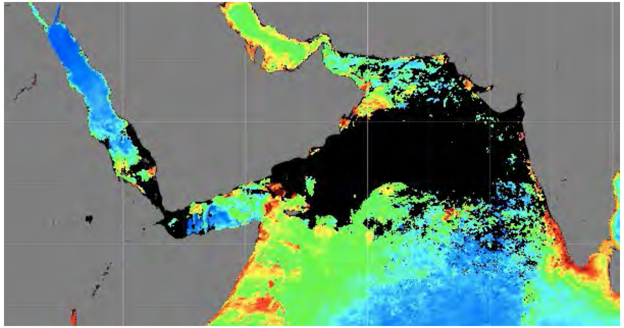
First of its kind, based on user feedback, according to a method that uses optical water classification (Moore et al. 2009).

Meeting current GCOS requirements for majority of ocean

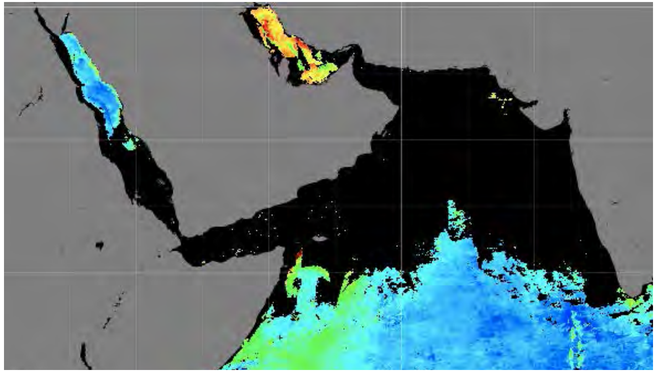
The Ocean Colour Climate Change Initiative



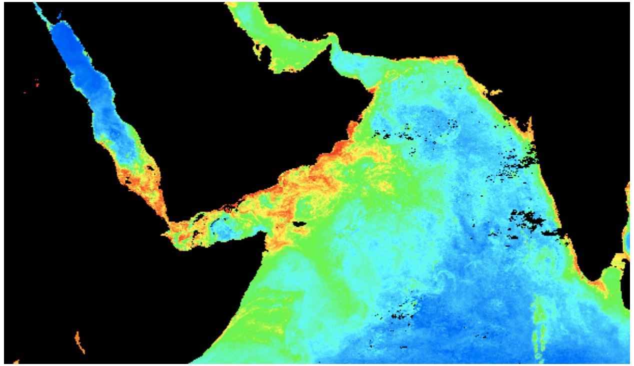
MODIS July Climatology from NASA



SeaWiFS July Climatology from NASA

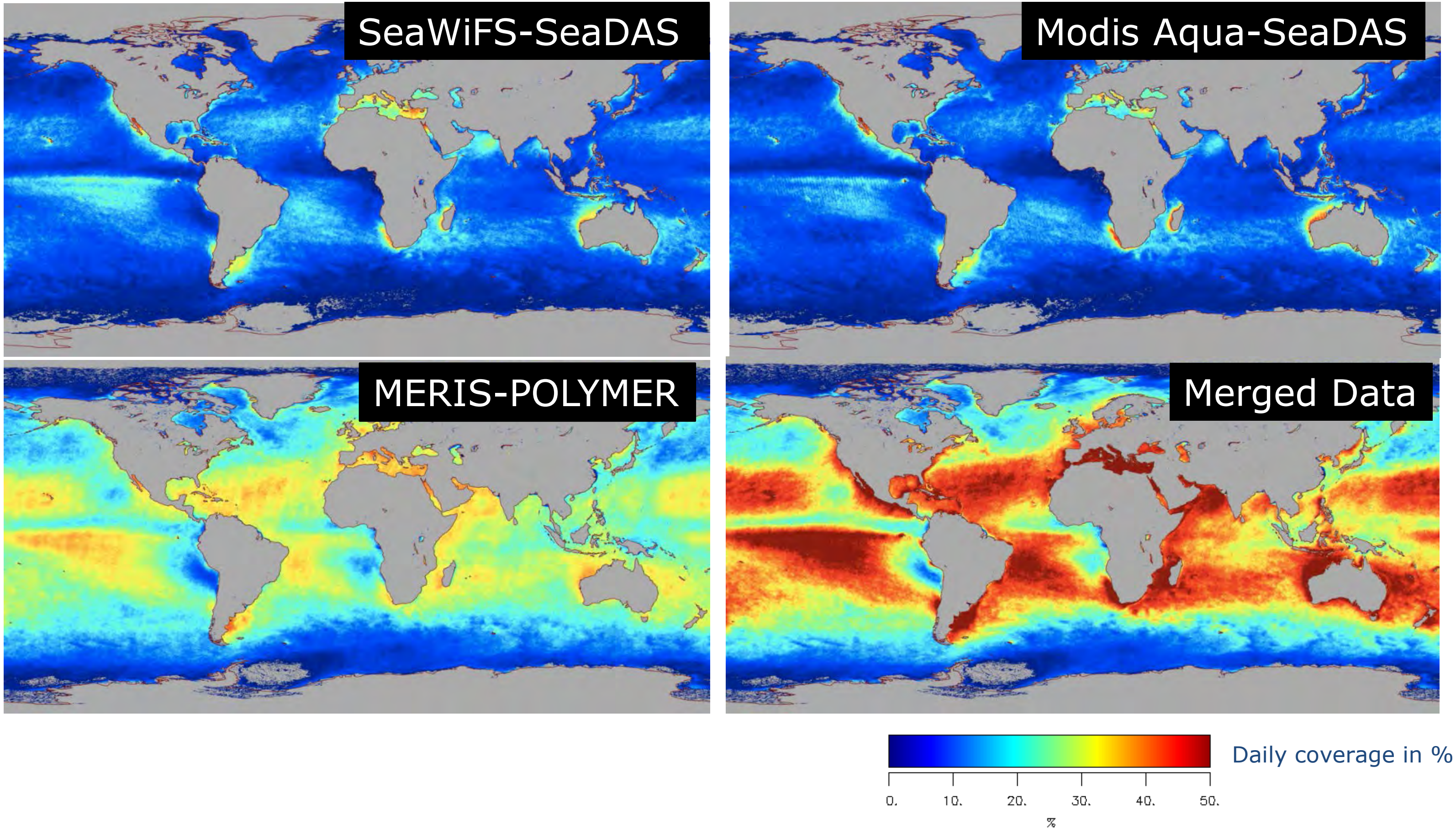


CZCS July Climatology from NASA

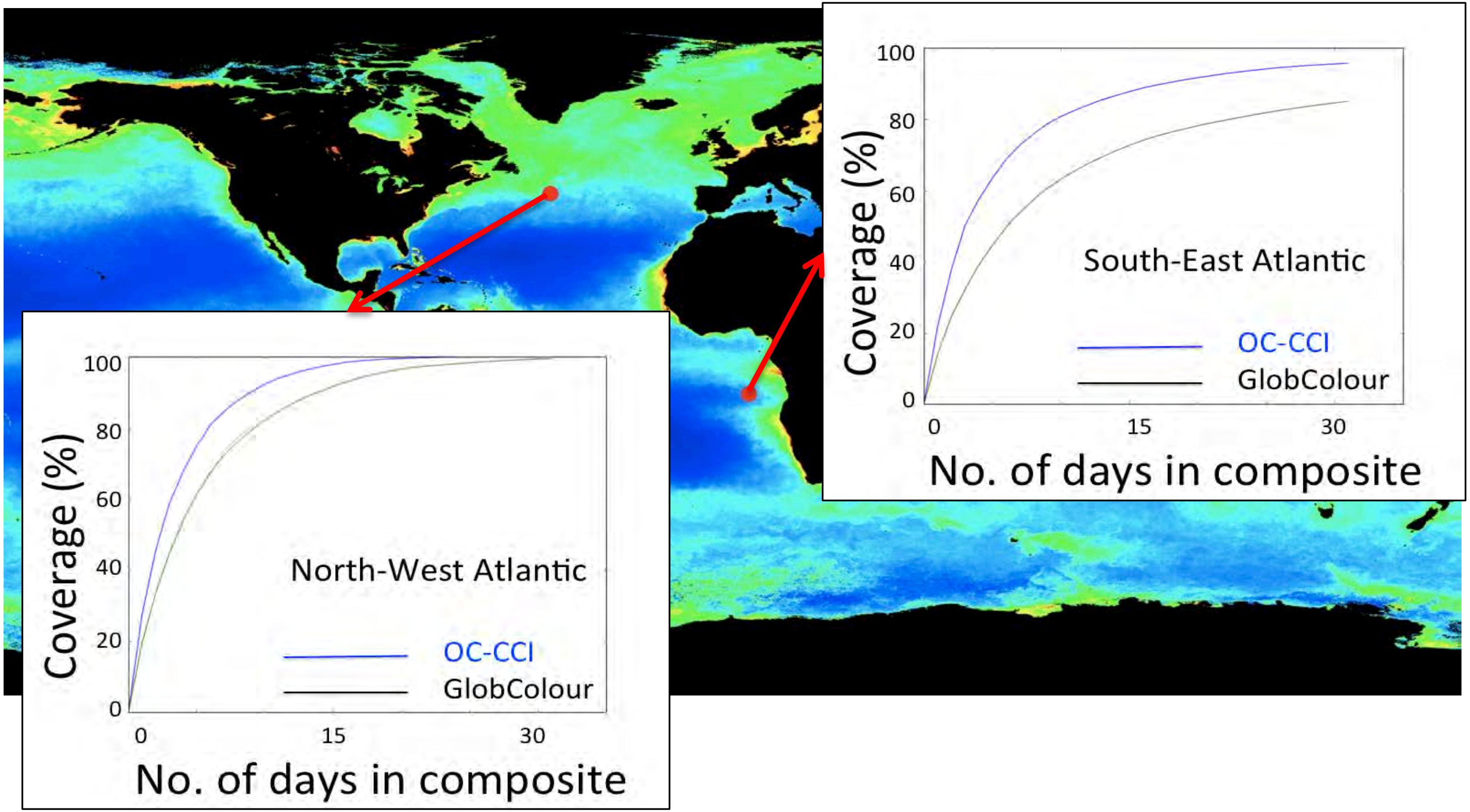


OC-CCI July 2003

The Ocean Colour Climate Change Initiative



The Ocean Colour Climate Change Initiative



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3) Examples of climate variability observed in the ocean-colour data record

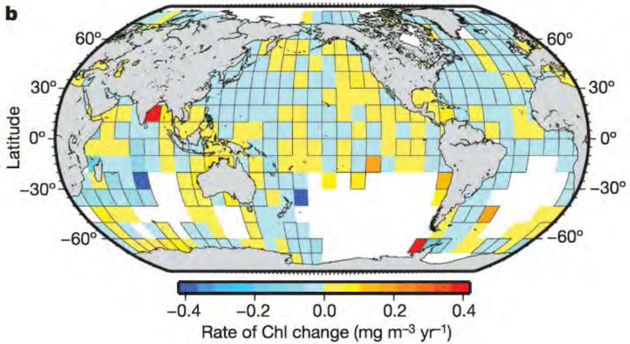
Total amount of phytoplankton might change

Vol 466 | 29 July 2010 | doi:10.1038/nature09268 nature

ARTICLES

Global phytoplankton decline over the past century

Da



LIMNOLOGY and OCEANOGRAPHY: METHODS

Limnol. Oceanogr.: Methods 10, 2012, 840–852

Integrating global chlorophyll data from 1890 to 2010

Daniel G. Boyce*, Marlon Lewis, and Boris Worm

nature International journal of science

Access provided by ESA-ESTEC European Space Agency

Communications Arising | Published: 13 April 2011

there a decline in marine

David L. Mackas

Nature 472, E4–E5 (14 April 2011) | Download Citation

Abstract

ARISING FROM D. G. Boyce, M. R. Lewis & B. Worm Nature 466, 591–596 (2010)10.1038/nature09268; Boyce et al. reply

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Natu

Ab

Contents lists available at ScienceDirect

ELSEVIER

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Estimating global chlorophyll changes over the past century

CrossMark

Daniel G. Boyce [a,b,c,*], Michael Dowd [d], Marlon R. Lewis [e], Boris Worm [a]

Total amount of phytoplankton might change

OCEANOGRAPHY

Century of phytoplankton change

David A. Siegel and Bryan A. Franz

Phytoplankton biomass is a crucial measure of the health of ocean ecosystems. An impressive synthesis of the relevant data, stretching back to more than 100 years ago, provides a connection with climate change.

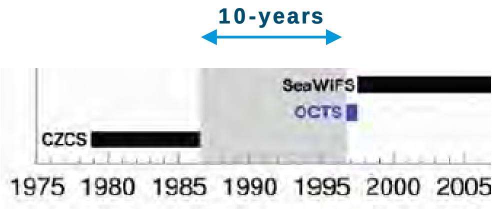
In 1865, Father Pietro Angelo Secchi was asked to map the clarity of the Mediterranean Sea for the Papal navy. He invented the simplest of oceanographic instruments: a 20-centimetre-wide white disk that is lowered until the observer loses sight of it, and for nearly 100 years determinations of Secchi depth were a routine part of oceanographic observations[1,2] (Fig. 1, overleaf). Secchi-depth determinations assess light penetration in the upper ocean, and can be related to phytoplankton abundance. Along with measurements of the upper-ocean concentration of chlorophyll, which is found in all phytoplankton, Secchi-disk depths provide the only data available for assessing changes in the global

“The analyses of Boyce *et al.* document the historical record. Looking into the future, however, satellite measurements will be the main source of data for assessing change in pelagic ecosystems.”

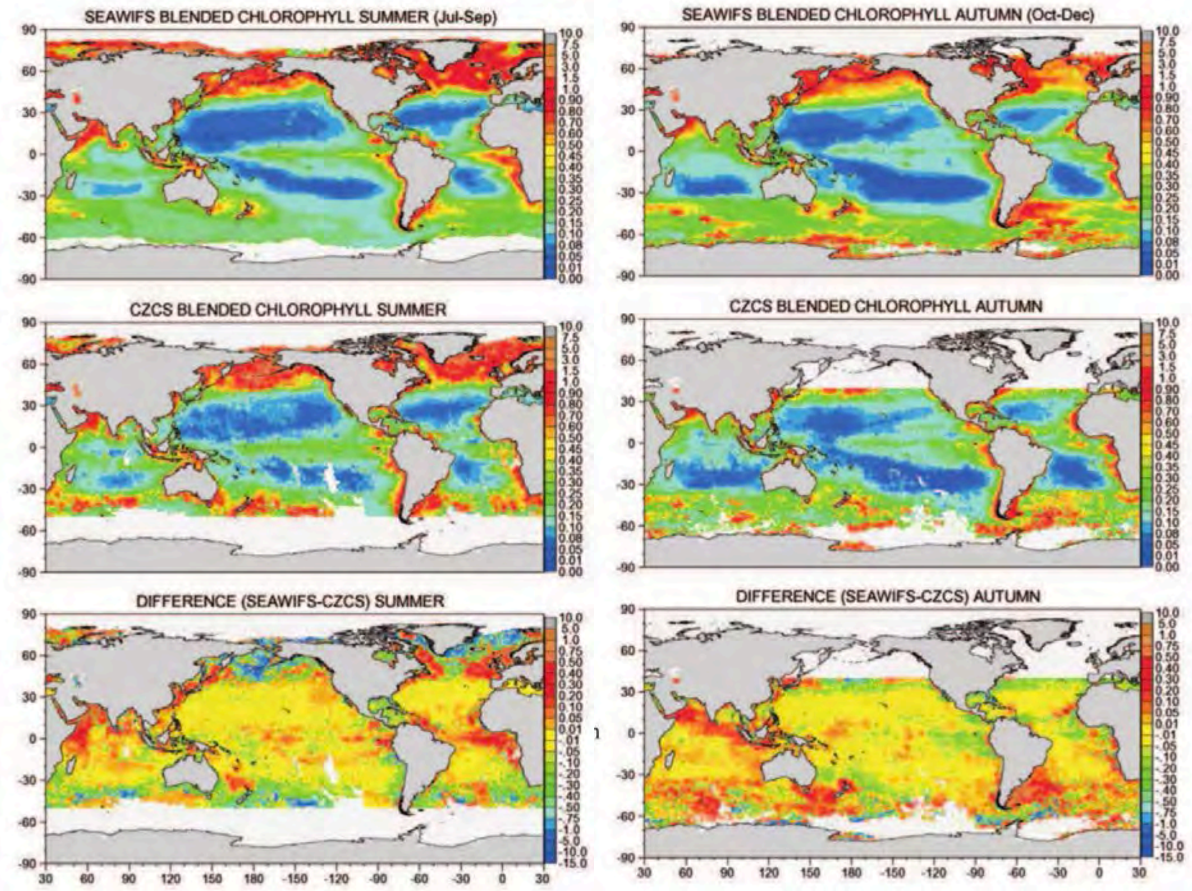
Total amount of phytoplankton might change

SeaWiFS
1997-2000

CZCS
1979-1986



Gregg et al. (2002)
GRL

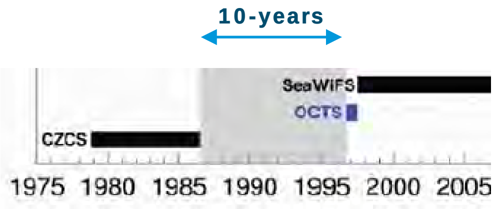


CHL

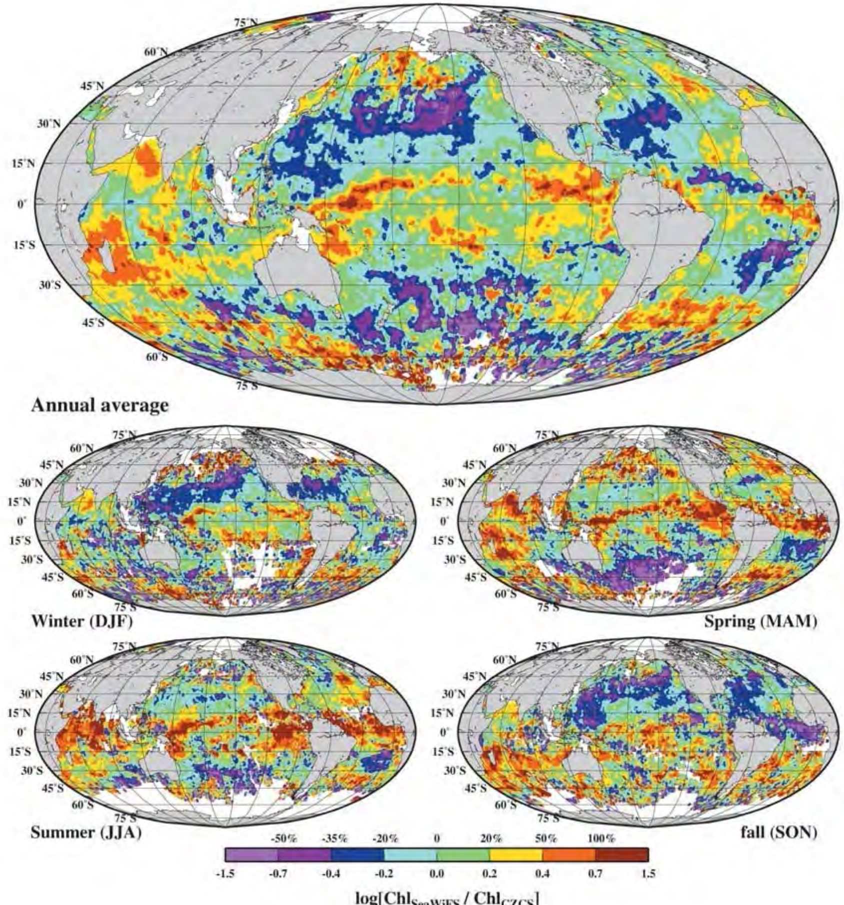
Total amount of phytoplankton might change

SeaWiFS
1998-2002

CZCS
1979-1983



Antoine et al. (2005)
JGR

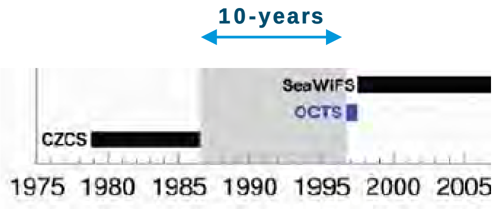


CHL

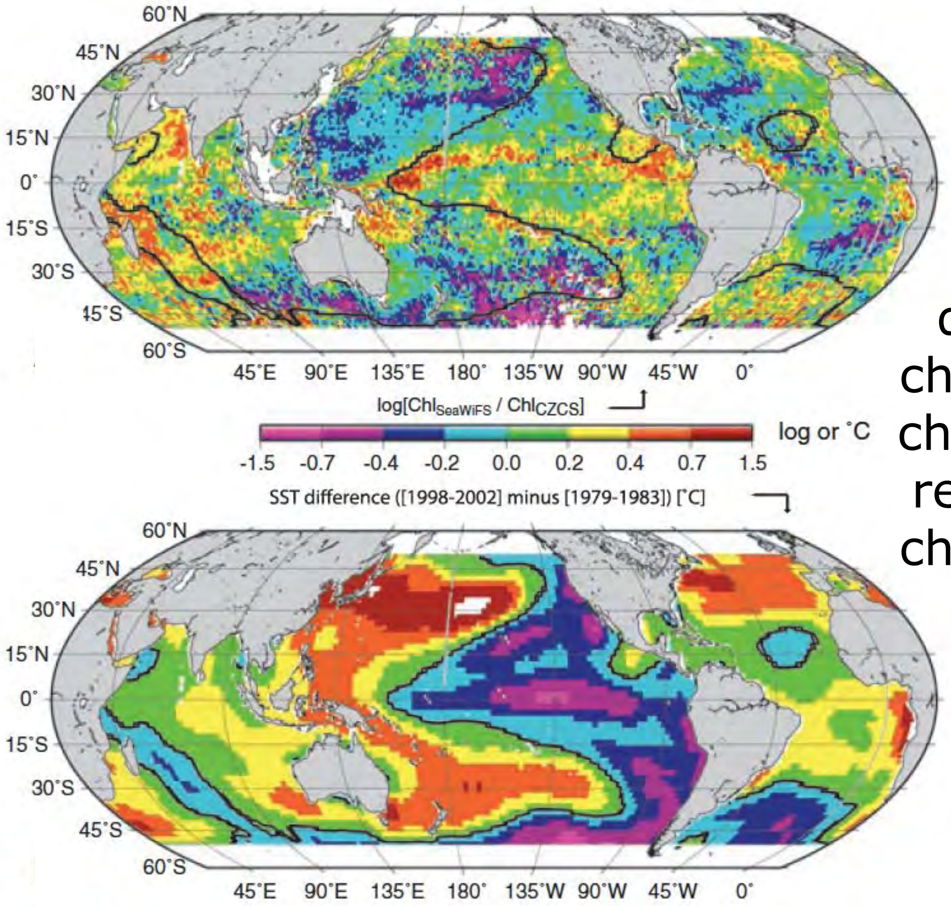
Total amount of phytoplankton might change

SeaWiFS
1998-2002

CZCS
1979-1983



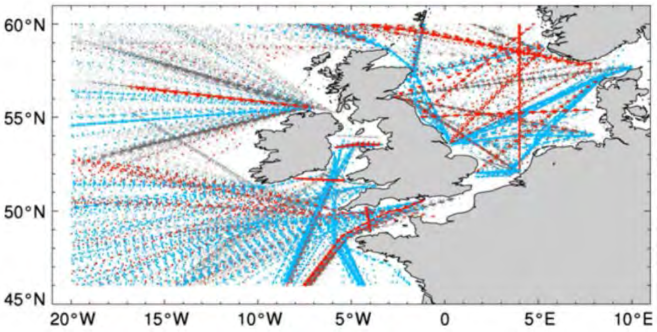
Martinez et al. (2009) Science

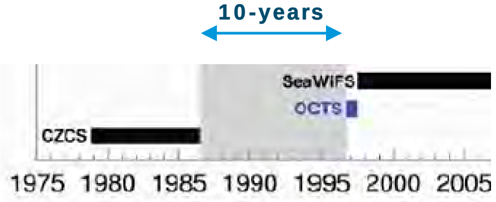


Multi-decadal changes in chlorophyll related to changes in SST

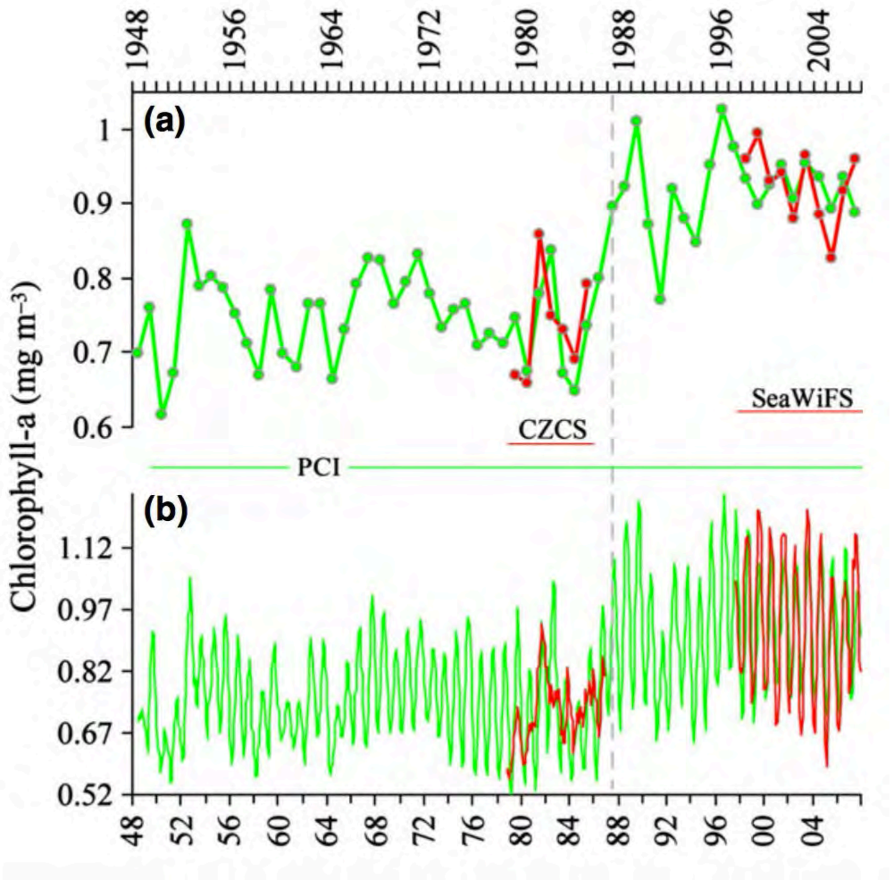
CHL

Total amount of phytoplankton might change





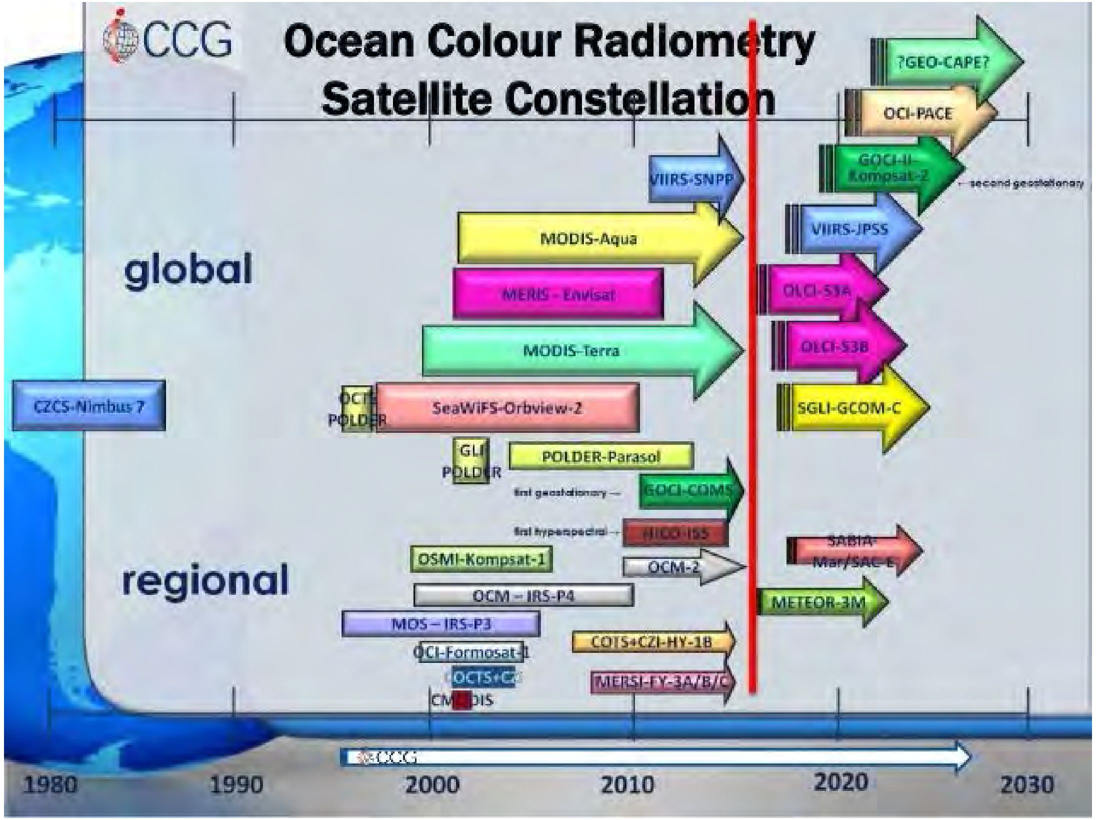
Raitsos et al. (2014)
GCB



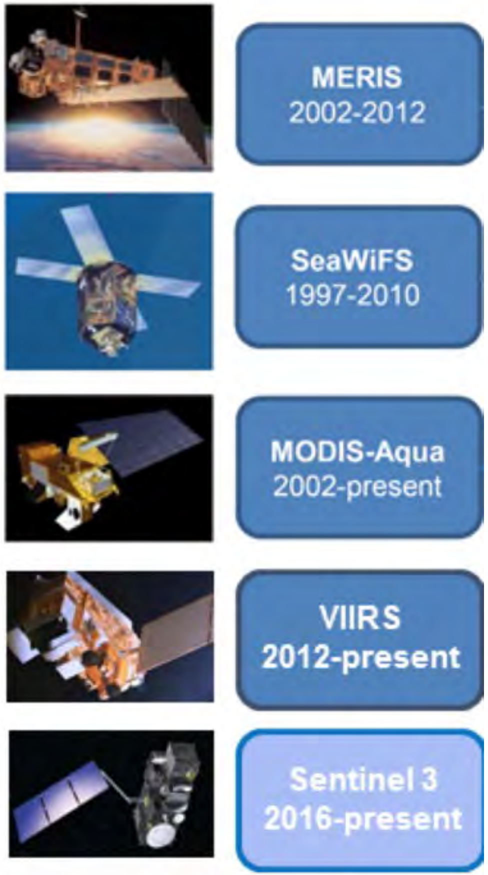
CHL

(NE Atlantic)

Total amount of phytoplankton might change



http://chlo4msfd.azti.es/products-and-services-for-satellite-chlorophyll-a-data/



Comparison of methodologies to produce trend maps from different sensors and time records

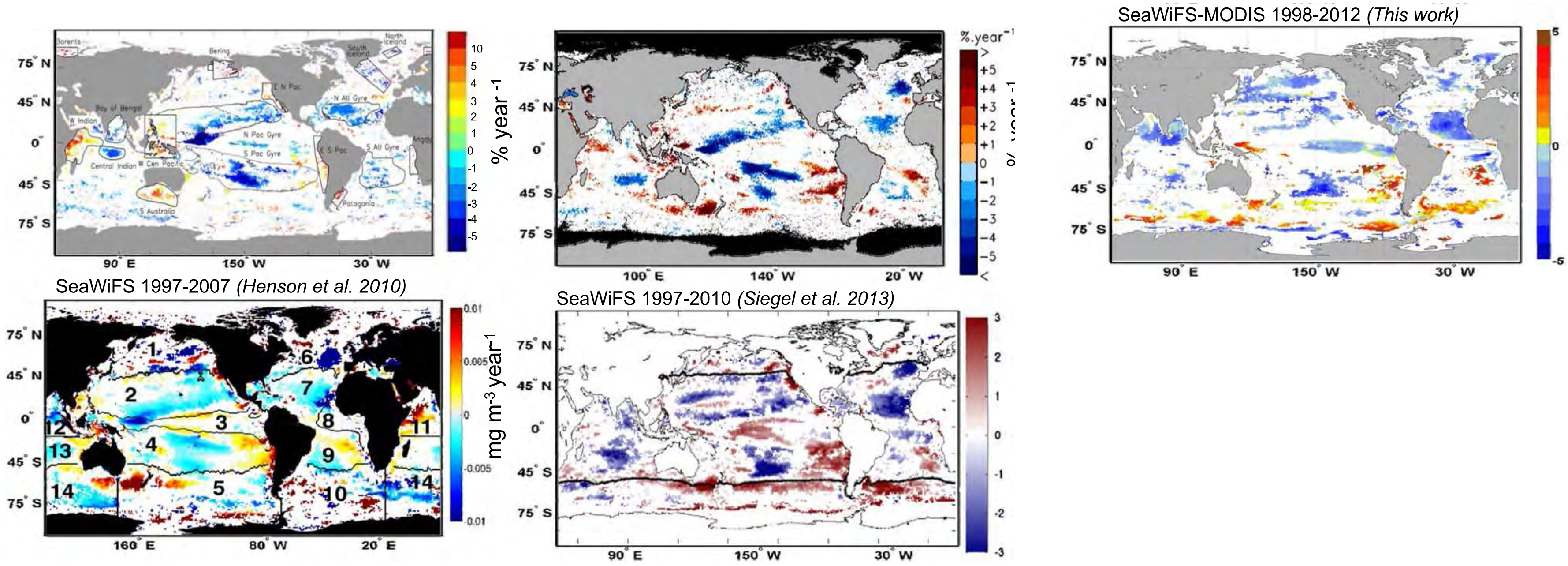
Table 2. Comparison of Methodologies by Previous and Present Efforts to Produce Trend Maps From Different Sensors and Time Records

Authors	Years	Sensor/Processing Version (PV)	Initial Data	Analysis Resolution	Special Treatment	Trend Analysis
Gregg et al. [2005]	1998–2003	SeaWiFS PV: 2003	9 km monthly means	25 km Annual mean anomalies (n = 6)		Linear regression
Henson et al. [2010]	1997–2007	SeaWiFS PV: V5.2	9 km monthly means	Spatial resolution unknown Monthly mean anomalies (n = 124)		Linear regression
Vantrepotte and Melin [2011]	1997–2007	SeaWiFS PV: R2009	9 km monthly means	27 km at equator Monthly means (n=120)	Selective data removal, gap filling (PCA)	Census X-11
Siegel et al. [2013]	1997–2010	SeaWiFS PV: 2010	9 km monthly means	$1^\circ \times 1^\circ$ Monthly mean anomalies (n = 154)	Logarithmic transformation, treatment of detrital material	Linear regression
This effort	1998–2012	SeaWiFS 1998–2002 PV: 2010 MODIS 2003–2012 PV: 2013	$1.25^\circ \times 0.67^\circ$ monthly means (after bias correction and data assimilation)	$1.25^\circ \times 0.67^\circ$ annual medians (n = 15)	Bias correction, data assimilation, end point bias removal, medians, treatment of aerosols	Linear regression

Gregg & Rousseaux (2014)

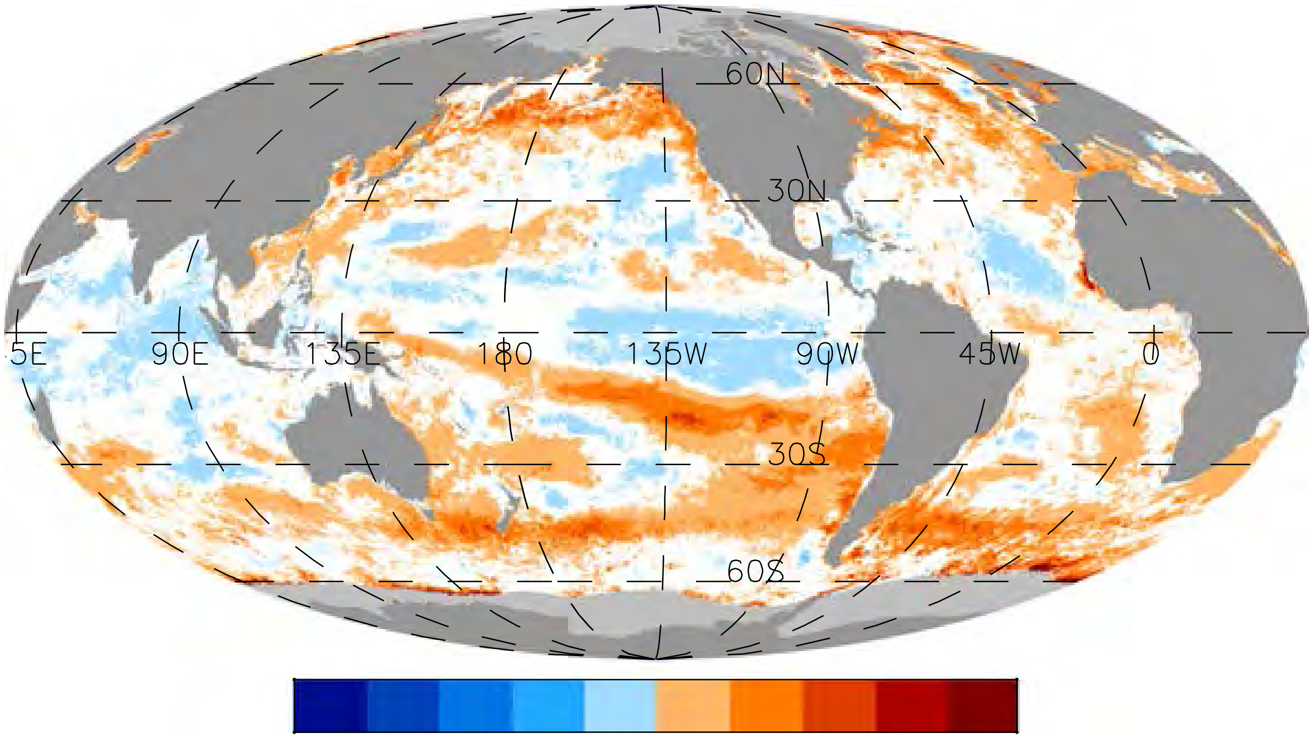
Total amount of phytoplankton might change

Comparison of methodologies to produce trend maps from different sensors and time records



Gregg & Rousseaux (2014)

Total amount of phytoplankton might change



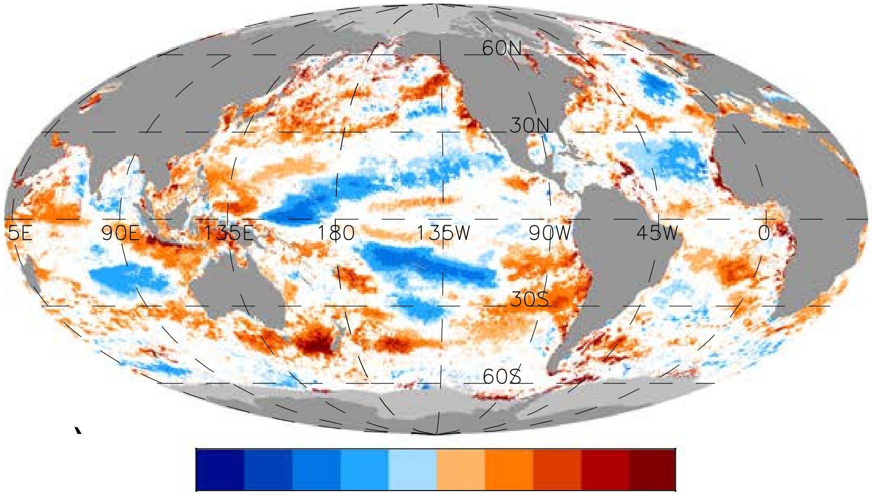
OC-CCI Chl-a
Oct 1997- Sep 2015

p<0.05

Mélin et al. (2017) RSE

Total amount of phytoplankton might change

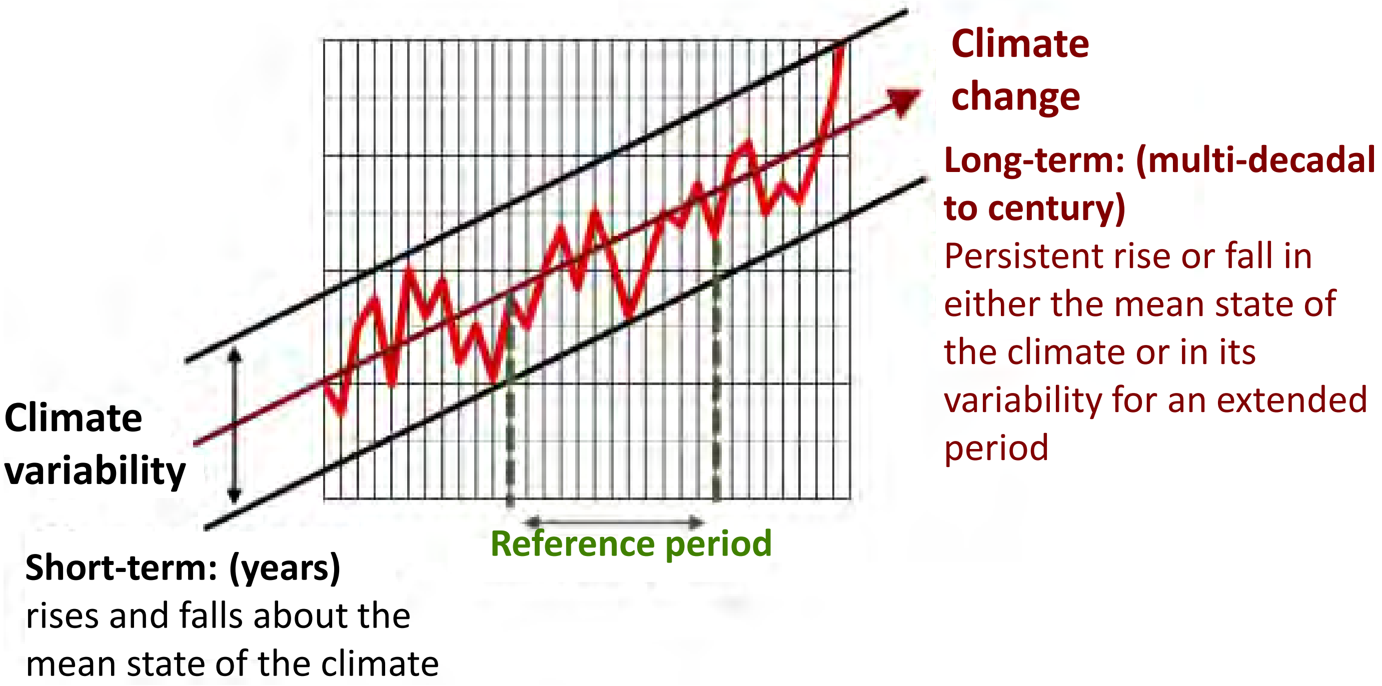
OC-CCI Chl-a
Jan 1998 – Dec 2007



OC-CCI Chl-a
Aug 2002 – Jul 2011

Mélin et al. (2017) RSE

Total amount of phytoplankton might change



Adapted from E. Barrow, http://www.cccsn.ec.gc.ca

Length of ocean colour time-series

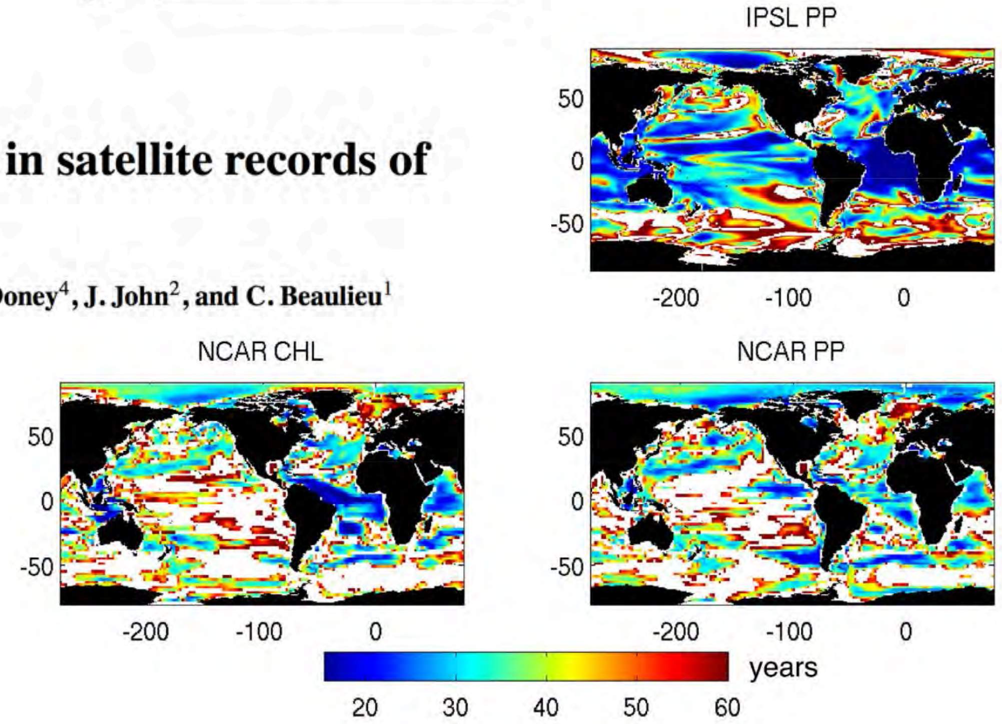
Biogeosciences, 7, 621–640, 2010
www.biogeosciences.net/7/621/2010/

Biogeosciences

Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity

S. A. Henson[1,*], J. L. Sarmiento[1], J. P. Dunne[2], L. Bopp[3], I. Lima[4], S. C. Doney[4], J. John[2], and C. Beaulieu[1]

“Our analyses suggest that a time series of ~ 40 years length is needed to distinguish a global warming trend from natural variability”



Total amount of phytoplankton might change

Implications for satellite Chl-*a* algorithms

- Retrievals of properties of the ecosystem should be independent of each other (CDOM, b_{bp}, Chl). Use of empirical relationships in the algorithms should be minimal.

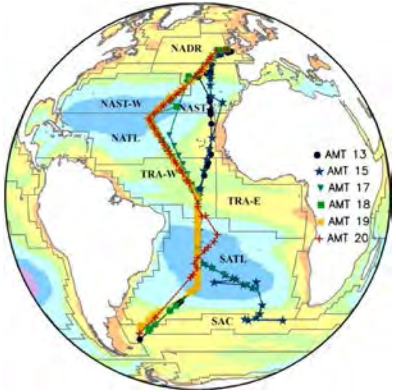
- Uncertainties in observations required to detect significant trends

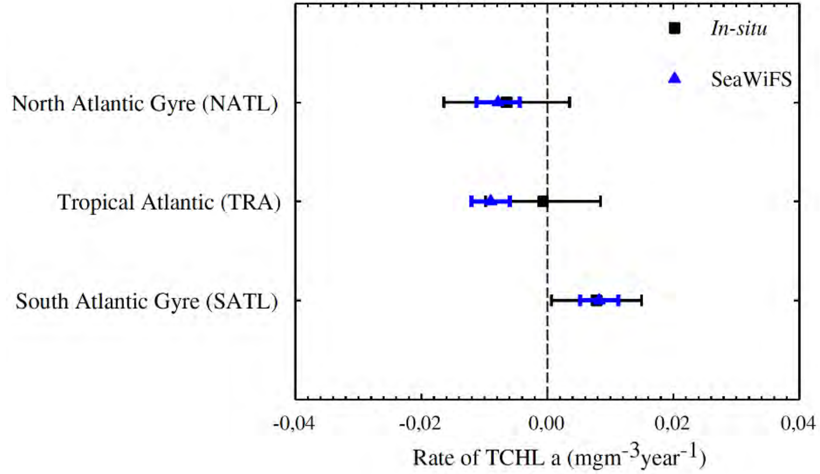
- We want an ocean-colour record with minimal gaps (Henson et al. 2010, BGS; Cole et al. 2016 JGR)

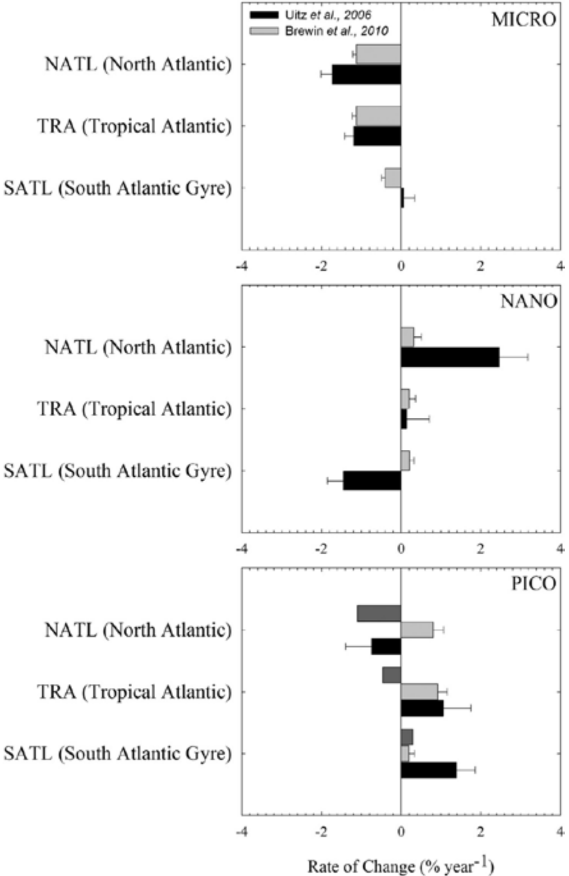
- Algorithms should be robust in a changing environment. For example, if phytoplankton community structure changes, these alterations should not interfere with the performance of the algorithm for estimating chlorophyll-a.

Sathyendranath et al. (2017) RSE

The community structure might change



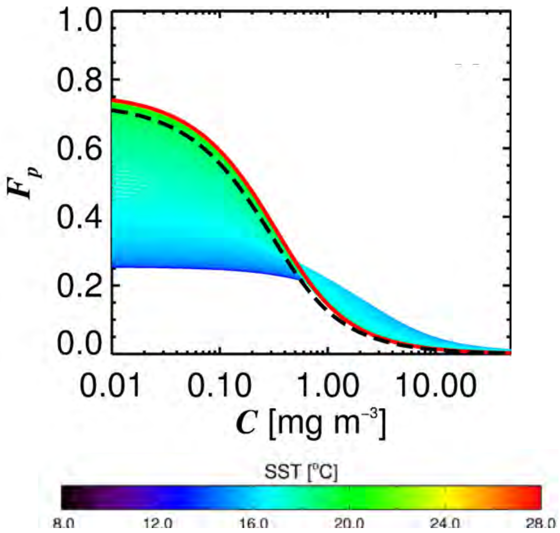


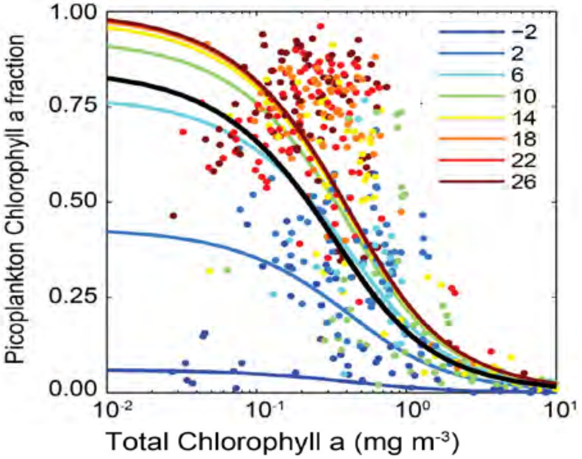


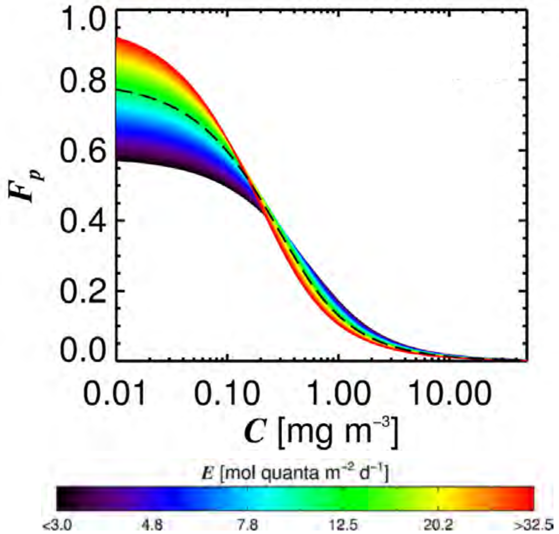
No significant changes in Chl-a in northern and equatorial provinces of the Atlantic, but significant changes in size-structure over a 7-year period

Agirbas et al. (2014) JMS

The community structure might change







Fraction of picoplankton to total chl-a in the North Atlantic as a function of SST.

Brewin et al. (2017) FMS

Fraction of picoplankton to total chl-a in the Global Ocean as a function of SST.

Ward et al. (2015) PLoS One

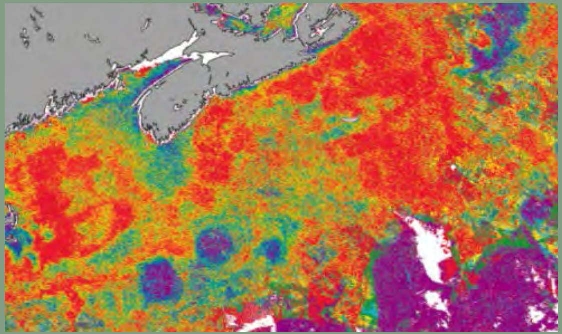
Fraction of picoplankton to total chl-a in the Global Ocean as a function of light

Brewin et al. (2015) RSE

The community structure might change

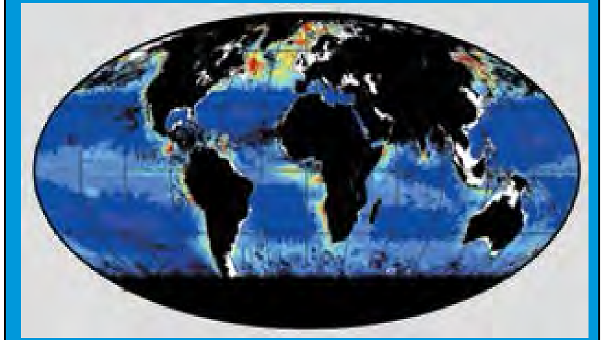
Implications for phytoplankton community structure algorithms

Detection-based



Sathyendranath et al. (2004) MEPS

Extrapolation-based



Uitz et al. (2006) J. Geophys. Res.

Bio-optical algorithms that allow retrieval of spectral variations in phytoplankton optical properties, are key to detection of phytoplankton types from ocean-colour data, especially in a climate-change context.

Sathyendranath et al. (2017) RSE

Other substance might change

$$a(\lambda) = a_w(\lambda) + a_B(\lambda) + a_{dg}(\lambda)$$

Water CONSTANT

Phyto-plankton

Detritus

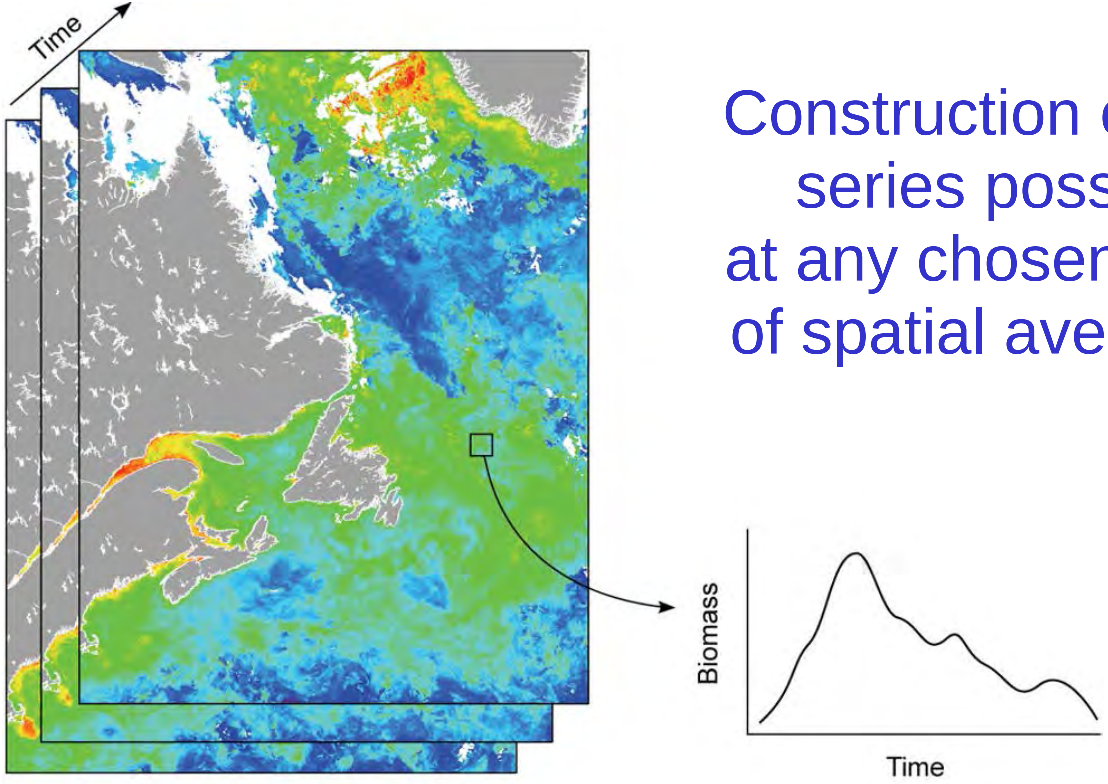
CDOM

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$$

Other substances that absorb and scatter light in the visible domain might change, relative to chlorophyll-a

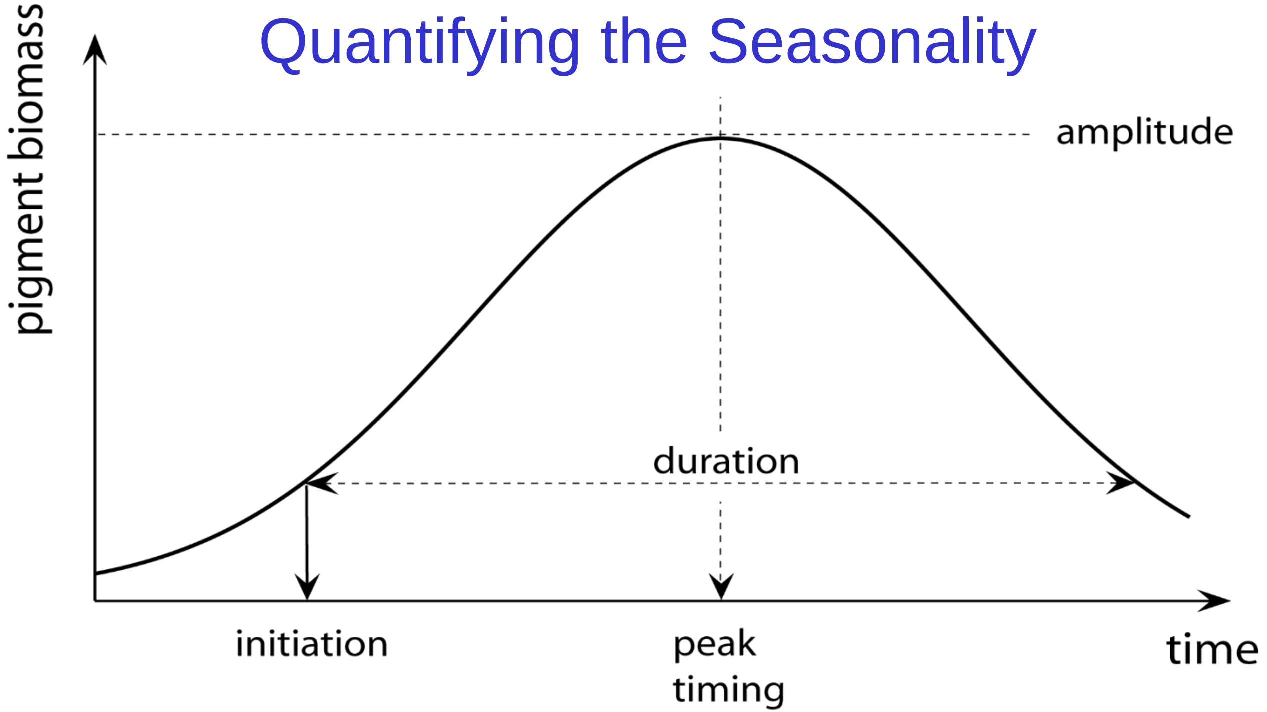
Implications for algorithms: Retrievals of ocean-colour properties should be independent of each other (CDOM, b_{bp}, Chl).

The phytoplankton phenology might change



Construction of time series possible at any chosen scale of spatial averaging

The phytoplankton phenology might change



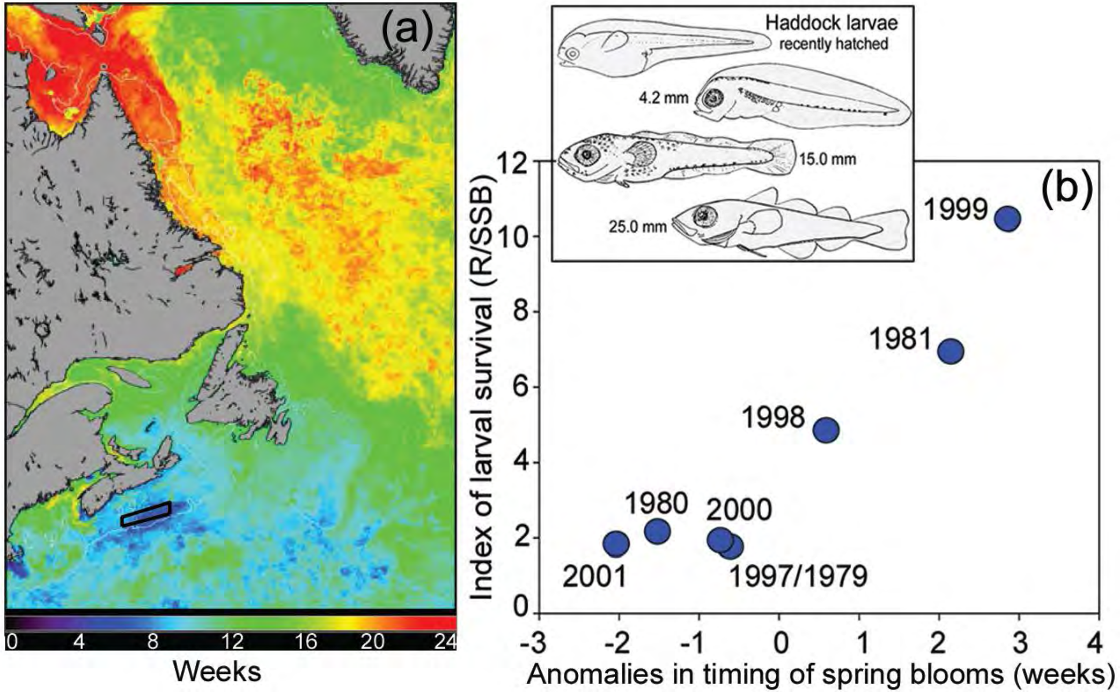
Any or all of these indices may vary between years
(at any or all of the pixels in the region of interest)

Platt, Sathyendranath & Fuentes-Yaco (2007)

The phytoplankton phenology might change

Inter-annual variations in the timing of the spring bloom impacts survival of larval fish

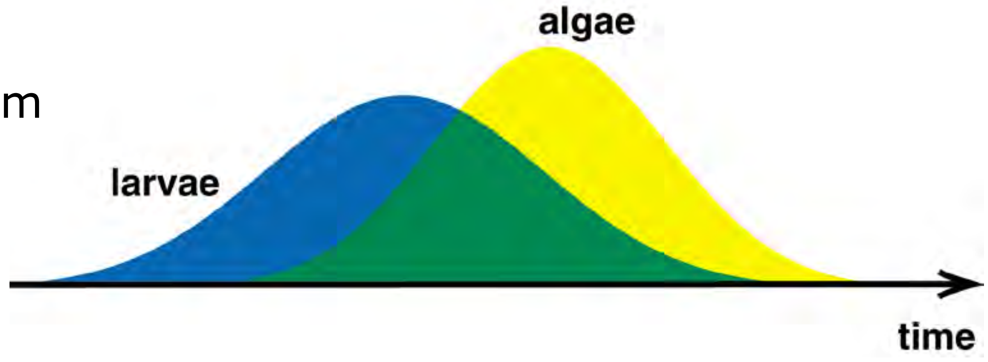
(*Platt et al. 2003 Nature*)



Unusually early spring blooms in 1981 & 1999 resulted in exceptional haddock year-classes

The phytoplankton phenology might change

Possible mechanism favouring early bloom of phytoplankton



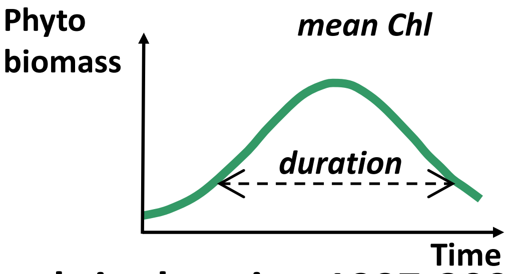
Where number of haddock larvae and biomass of phytoplankton overlap, larvae have food supply adequate for survival.

Where this is not so, larvae are vulnerable to death by starvation.

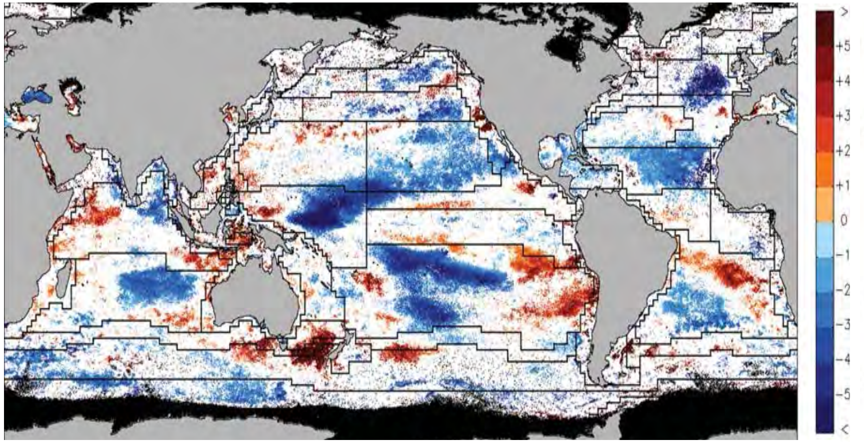
Early blooms imply a smaller proportion of the total larvae produced at risk from inadequate food supply.

Cushing (Match-mismatch) Hypothesis

The phytoplankton phenology might change

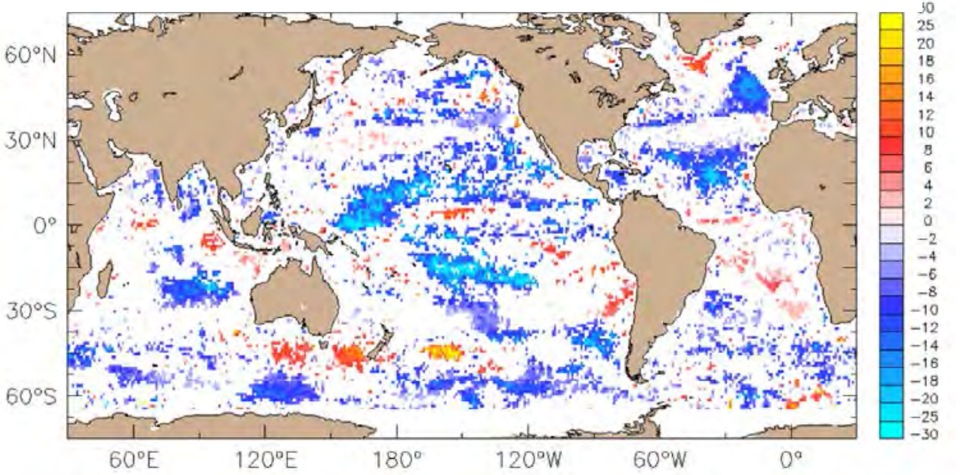


Trends in Chlorophyll 1997-2007



Vantrepotte and Mélin (2009)

Trends in duration 1997-2007



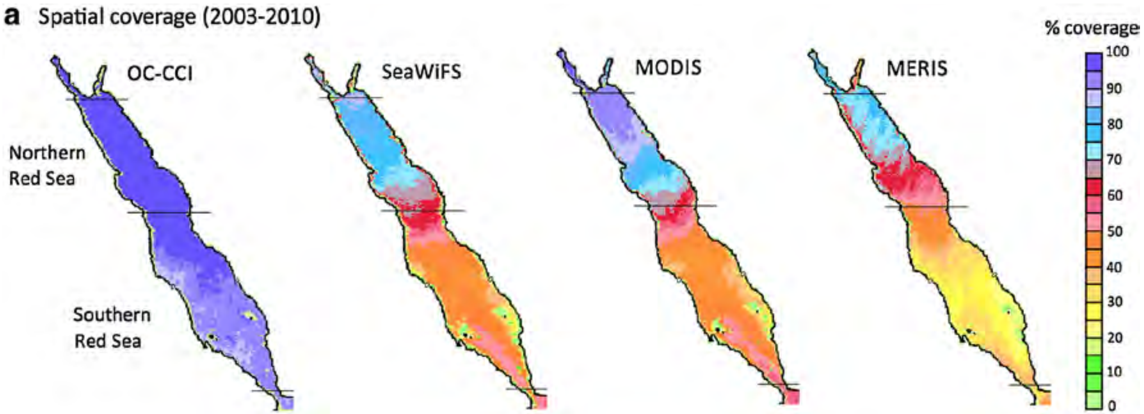
Racault et al. (2012)

The phenology might change

Implications for phenology algorithms

- We want an ocean-colour record with minimal gaps (Henson et al. 2010, BGS; Cole et al. 2016 JGR)

- We want an ocean-colour record with maximal temporal frequency (e.g. merged-ocean colour products)



Racault et al. (2015) RSE

Sathyendranath et al. (2017) RSE

Overview

1) Datasets needed to monitor ocean colour climate variability

2) What are the potential responses of the marine ecosystem to a changing climate.
   - Total amount of phytoplankton (as indexed by chlorophyll-a concentration) might change
   - The community structure associated with the chlorophyll concentration might change
   - Other substances that absorb and scatter light in the visible domain might change, relative to chlorophyll-a
   - The phenology might change (e.g. timing, amplitude and duration of blooms)

3) **Examples of climate variability observed in the ocean-colour data record**

Climate Indices

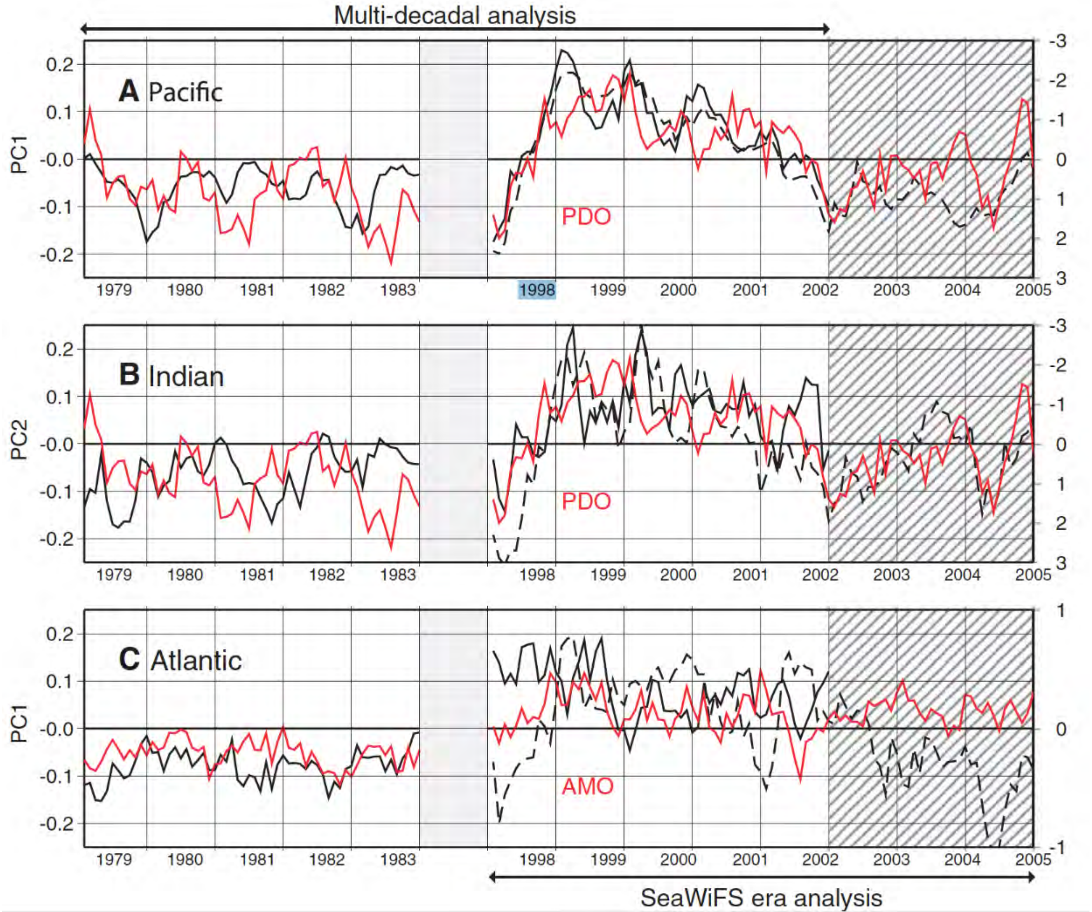
- **Definition**: A climate index is a simple diagnostic quantity that is used to characterise an aspect of a geophysical system such as a circulation pattern.

- A **variety of methods** have been used to derive climate indices: selected station, grid point or regional average data, and empirical orthogonal functions (EOFs).

- A **climate base period** is used for calculation of some climate indices. It is a reference period, which should include 30 years of data on the recommendation of the World Meteorological Organization (WMO).

- Most **commonly used climate indices** include the El Nino Southern Oscillation (ENSO), the Indian Ocean Dipole Mode Index (DMI), the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO), the Southern Annular Mode (SAM), and the Southern Oscillation Index (SOI).

Climate variability

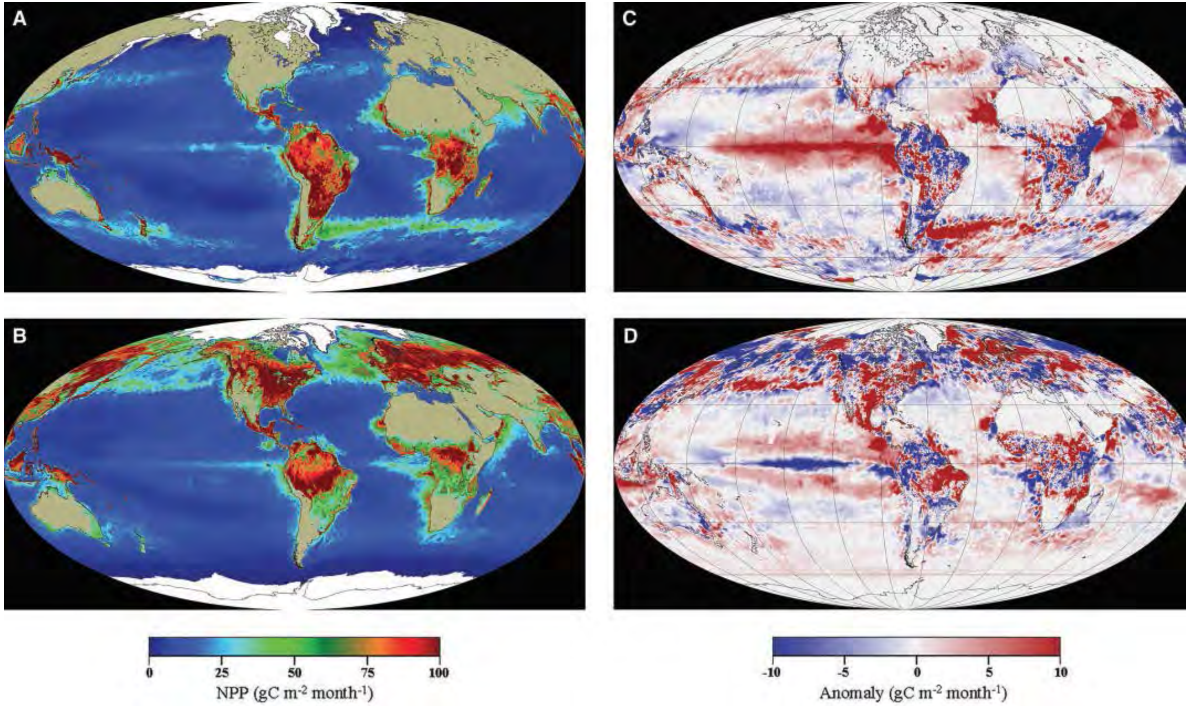


Multi-decadal changes in chlorophyll related to indices

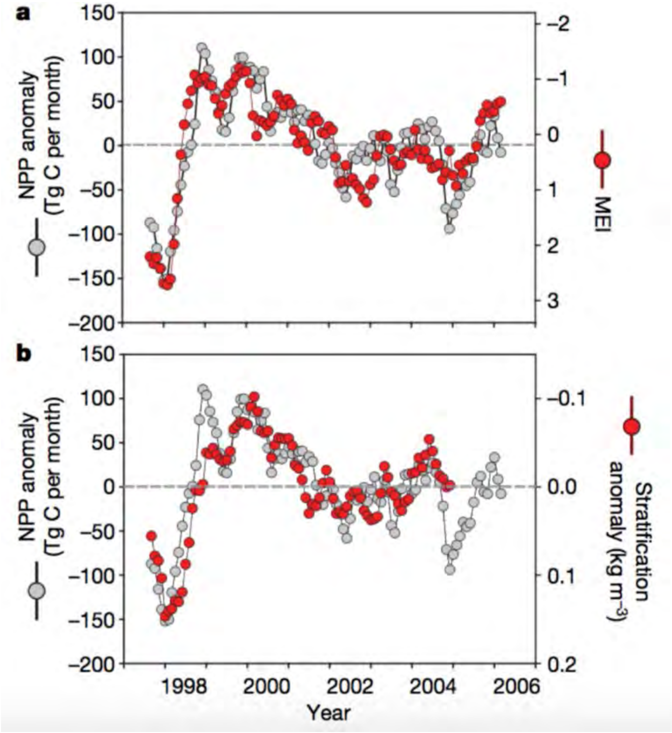
Martinez et al. (2009) Science

Climate variability

El Nino Southern Oscillation (ENSO)



Behrenfeld et al. (2001) Science

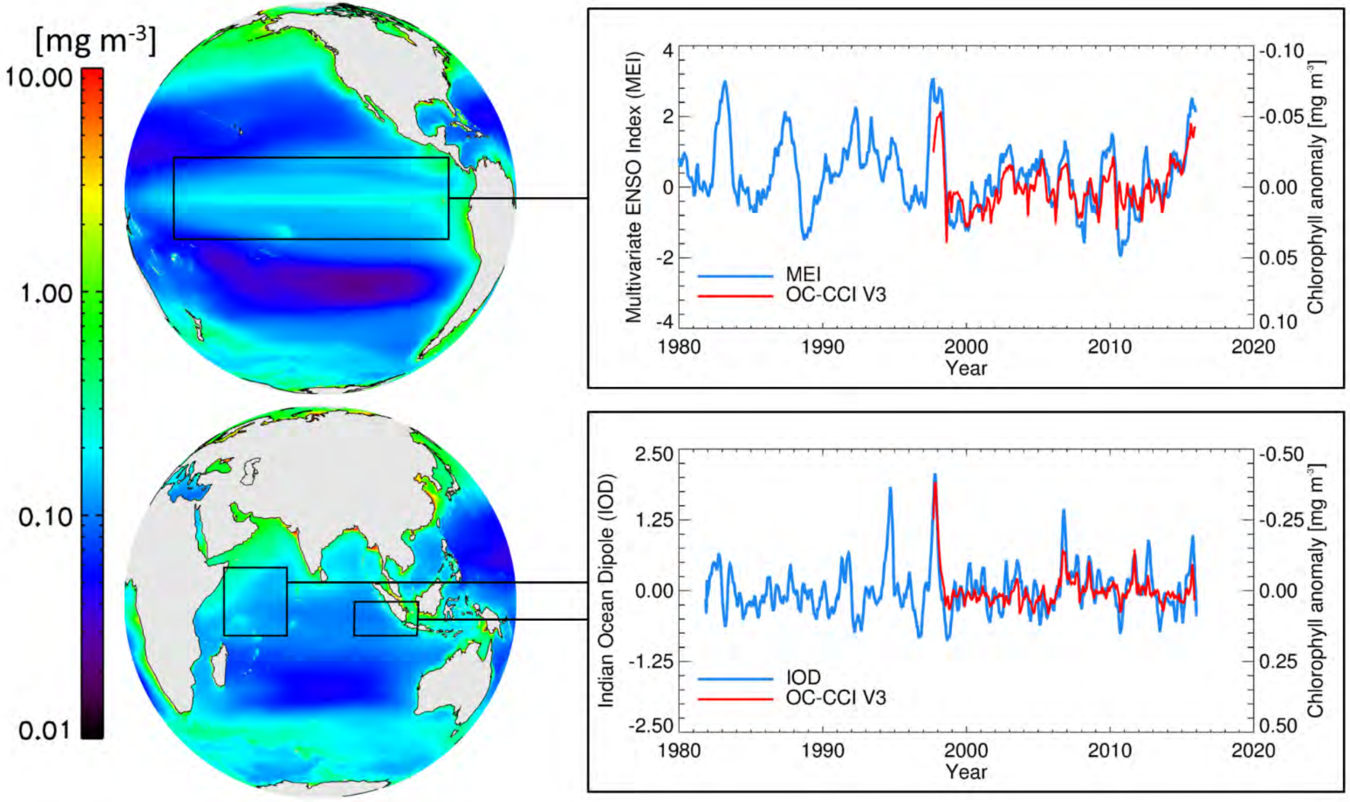


Behrenfeld et al. (2006) Nature

Climate variability

ENSO

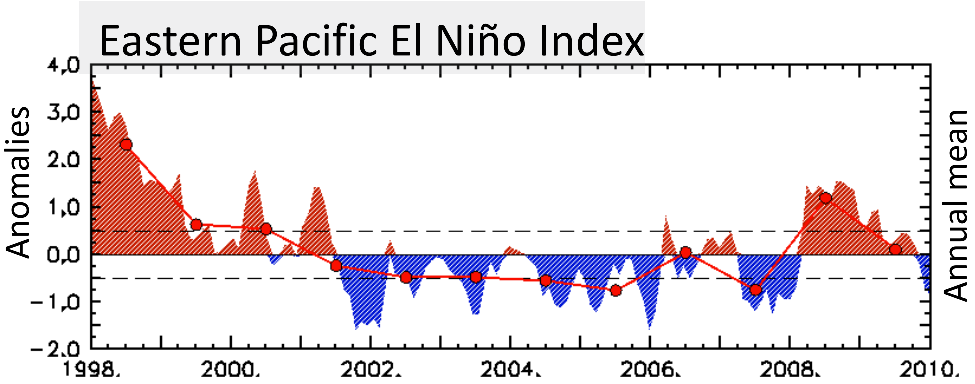
IOD

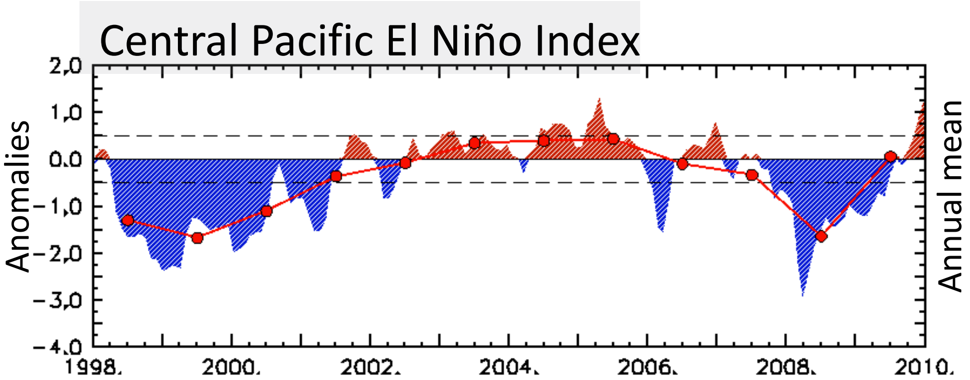


von Schuckmann et al. (2016) Journal of Operational Oceanography

Climate variability

EP and CP Indices





Method and data from Kao and Yu 2009; and Yu et al., 2012.

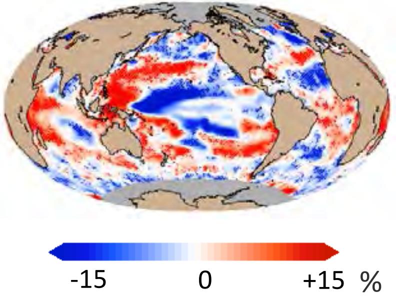
Use a regression-EOF analysis to identify the CP and EP types of El Niño from monthly SST data.

Racault et al. (2017) Front. Mar. Sci.

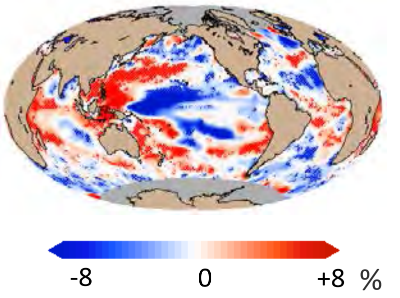
Climate variability

Central Pacific El Niño Impact on Biology

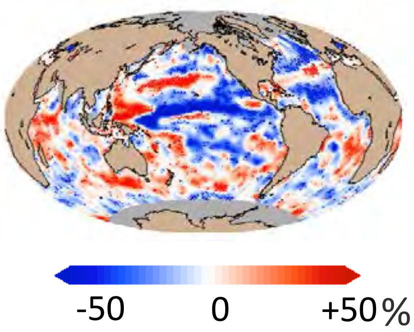
Chlorophyll



Primary Production

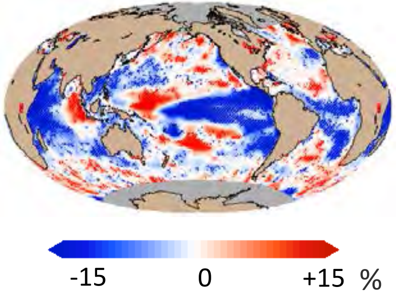


Growth duration

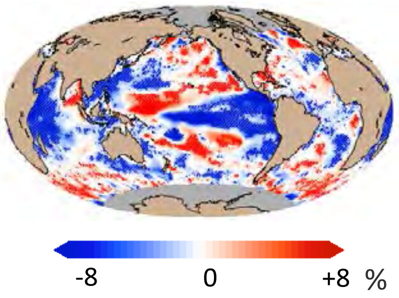


Eastern Pacific El Niño Impact on Biology

Chlorophyll

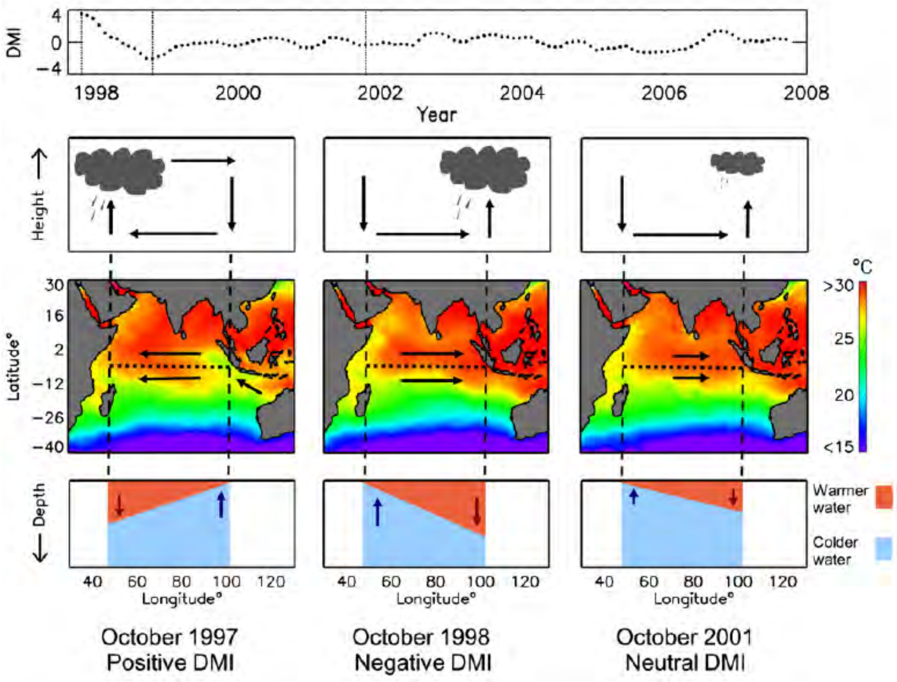


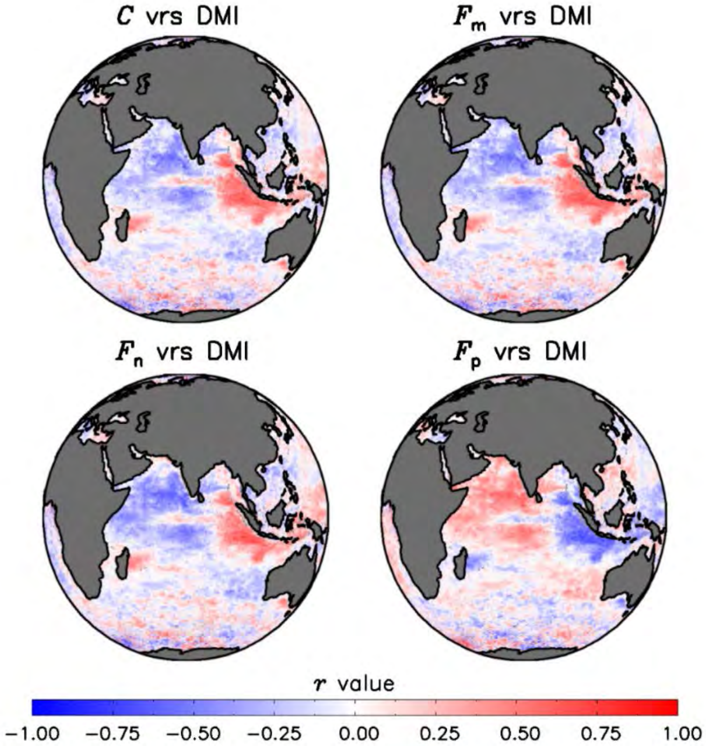
Primary Production



Racault et al. (2017)
Front. Mar. Sci.

Changes in phytoplankton size structure in relation to Dipole Mode Index



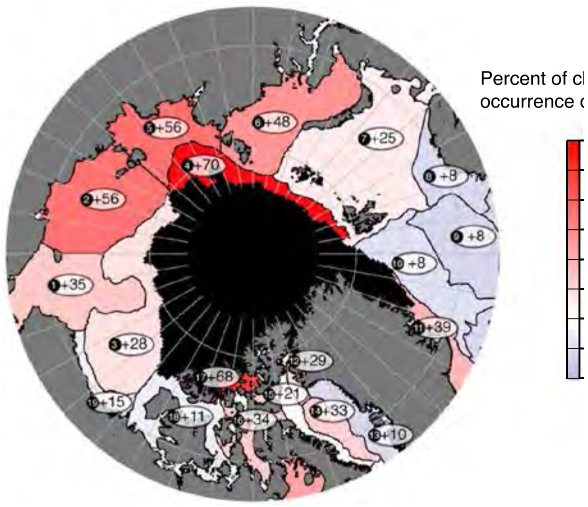


Brewin et al. (2012) DSRII

Effects of sea ice cover on satellite-detected primary producers in the Arctic Ocean

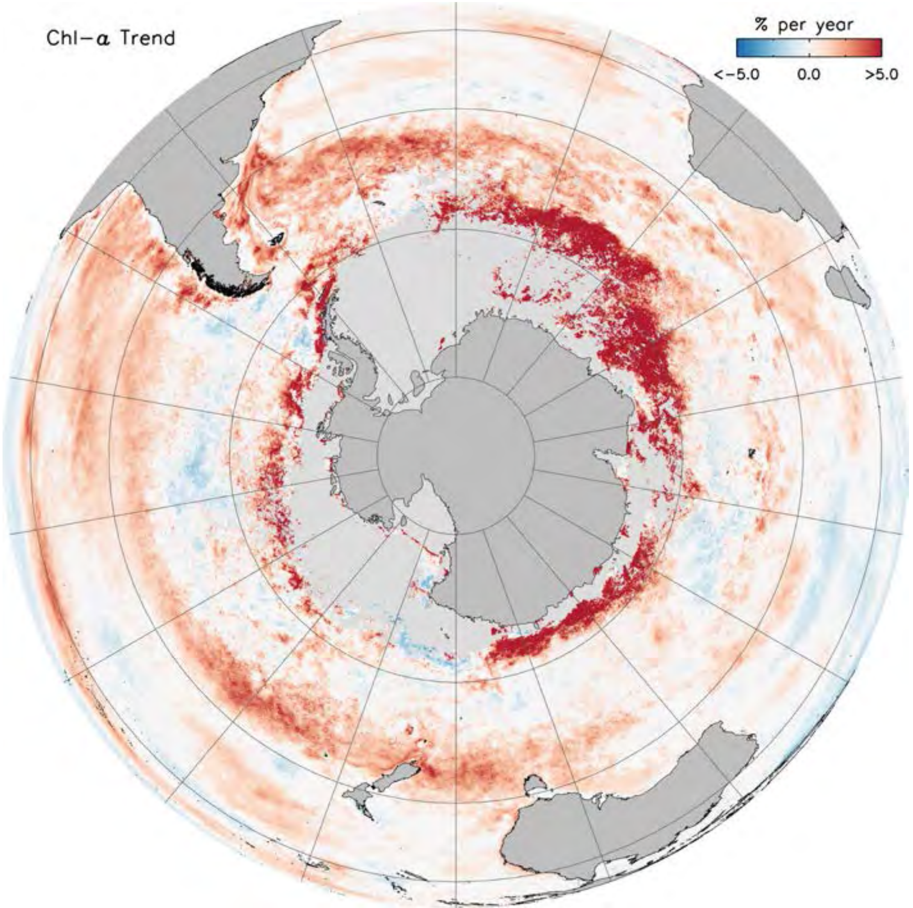
In a changing Arctic Ocean, a phenology of biological productivity with two phytoplankton blooms and two peaks of sedimentation may become prevalent

Phenological changes



Ardyna et al. (2014) GRL

Trends in Chl-*a* in the Southern Ocean from OC-CCI data (1997-2016)



Trend map produced using the standard OC-CCI Chl-a product following the methods described in Mélin et al. (2017). Only significant trends are shown ($p<0.05$).

Figure produced by Silvia Pardo at PML

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3) Examples of climate variability observed in the ocean-colour data record

Further reading

http://ioccg.org/what-we-do/ioccg-publications/

http://ioccg.org/resources/ocean-colour-bibliography/

http://ioccg.org/what-we-do/ioccg-publications/ioccg-reports/

Further reading

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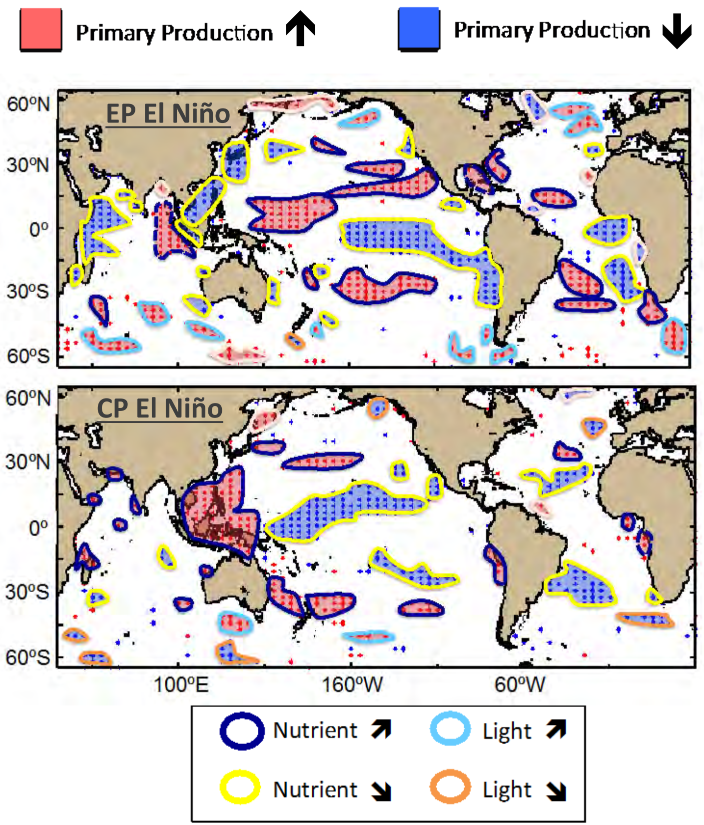
Further reading

El Niño impact on Primary Production



Atlas of impact of EP and CP El Niño on primary producers

Interpretation of the dominant mechanisms driving the diverse biophysical interactions: horizontal and vertical advection, stratification, wind, atmospheric dust deposition, riverine input

67% of the total affected areas are in the tropics and mid-latitudes and remaining **33%** being areas located in high-latitudes

Racault et al. Front. Mar. Sci., 2017