IOCCG Ocean Optics School 2014

Using satellite ocean colour data to investigate variability and climate change effects in phytoplankton

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NATURAL ENVIRONMENT RESEARCH COUNCIL

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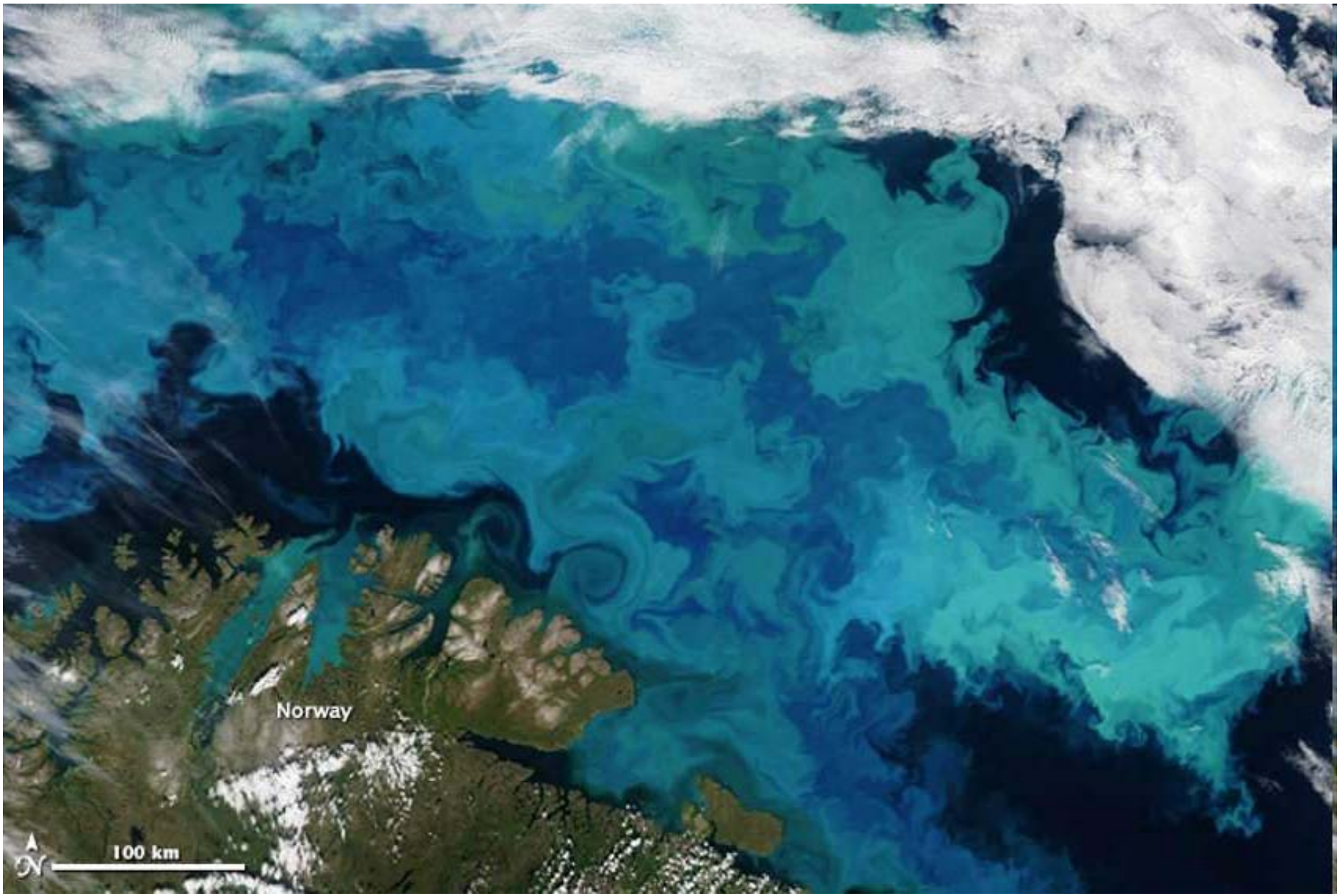


MODIS true colour image August 14th 2011, Barents Sea

Why is satellite ocean colour data useful for time series analysis?

Why is satellite ocean colour data useful for time series analysis?

- Frequent data
- High temporal and spatial resolution
- Continuous monitoring
- Multi-year records
- Chlorophyll concentration important to monitor for its relevance to coastal health and fisheries

Aims

- Learn about the temporal variability that occurs in phytoplankton populations
    - seasonal
    - interannual
    - decadal
    - long-term trends (climate change?)

- And how ocean colour data can be used to assess variability

- Understand how atmospheric and physical processes can create phytoplankton variability

- Learn about some techniques for analysing time series data

Lectures and practicals

- Wednesday 23rd July: 11.00 – 12.30

Lectures on seasonal, interannual and decadal variability: signatures and forcing factors

- Thursday 24th July: 14.00 - 15.30

Lectures on time series analysis: methods and metrics

- Friday 25th July: 13.45 - 15.45

Practical using online tool, Giovanni, following some examples and also using your own study region

A note

Here I focus on chlorophyll as the most widely used ocean colour product, but concepts & techniques equally applicable to all data

Here I ignore all technical aspects of atmospheric correction, case 2 problems etc. in favour of applying ocean colour data to answer interesting questions related to phytoplankton change

Terminology:

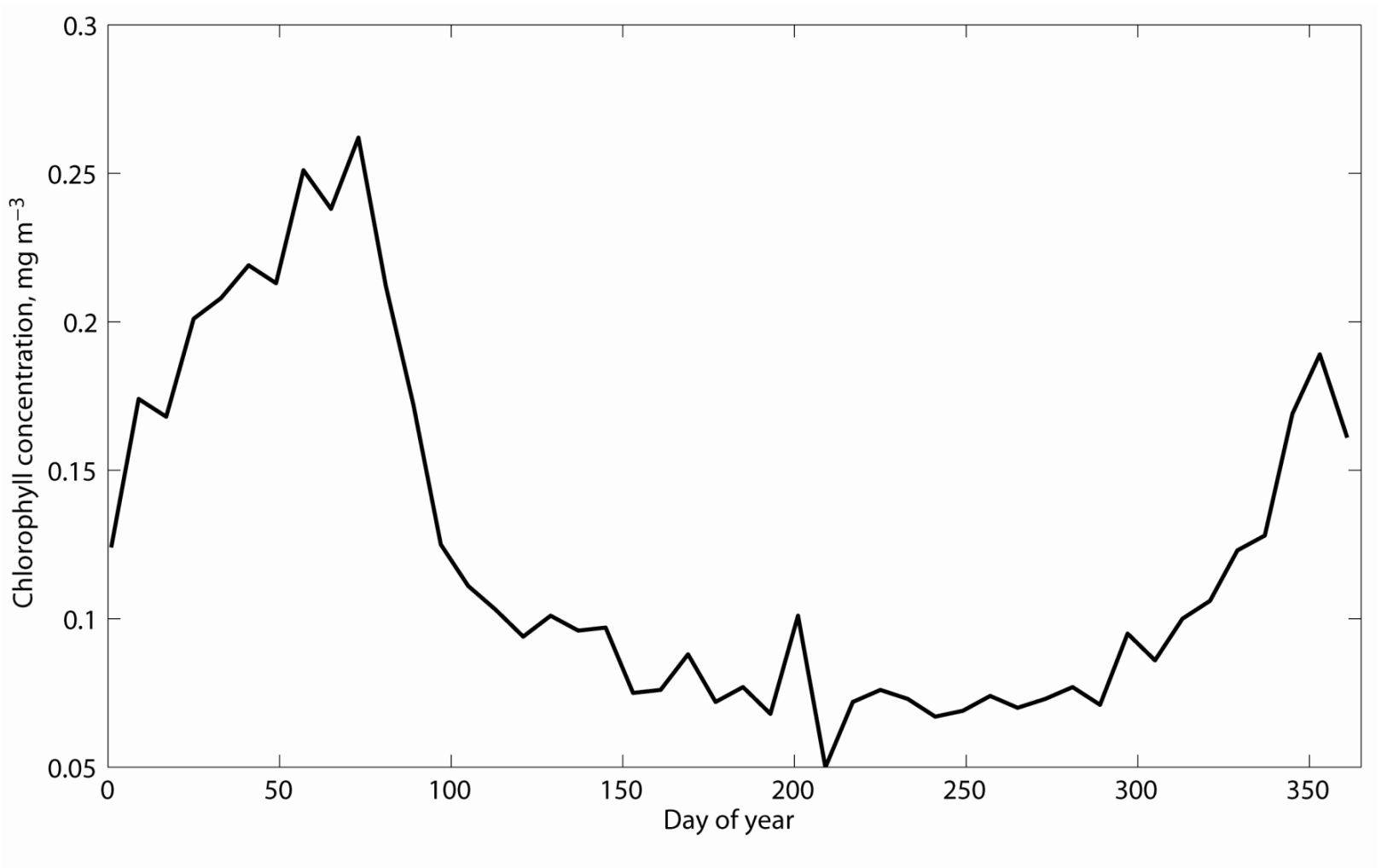
- Seasonal variability: within 1 year

- Interannual variability: over multiple years

- Decadal variability: over 10+ years

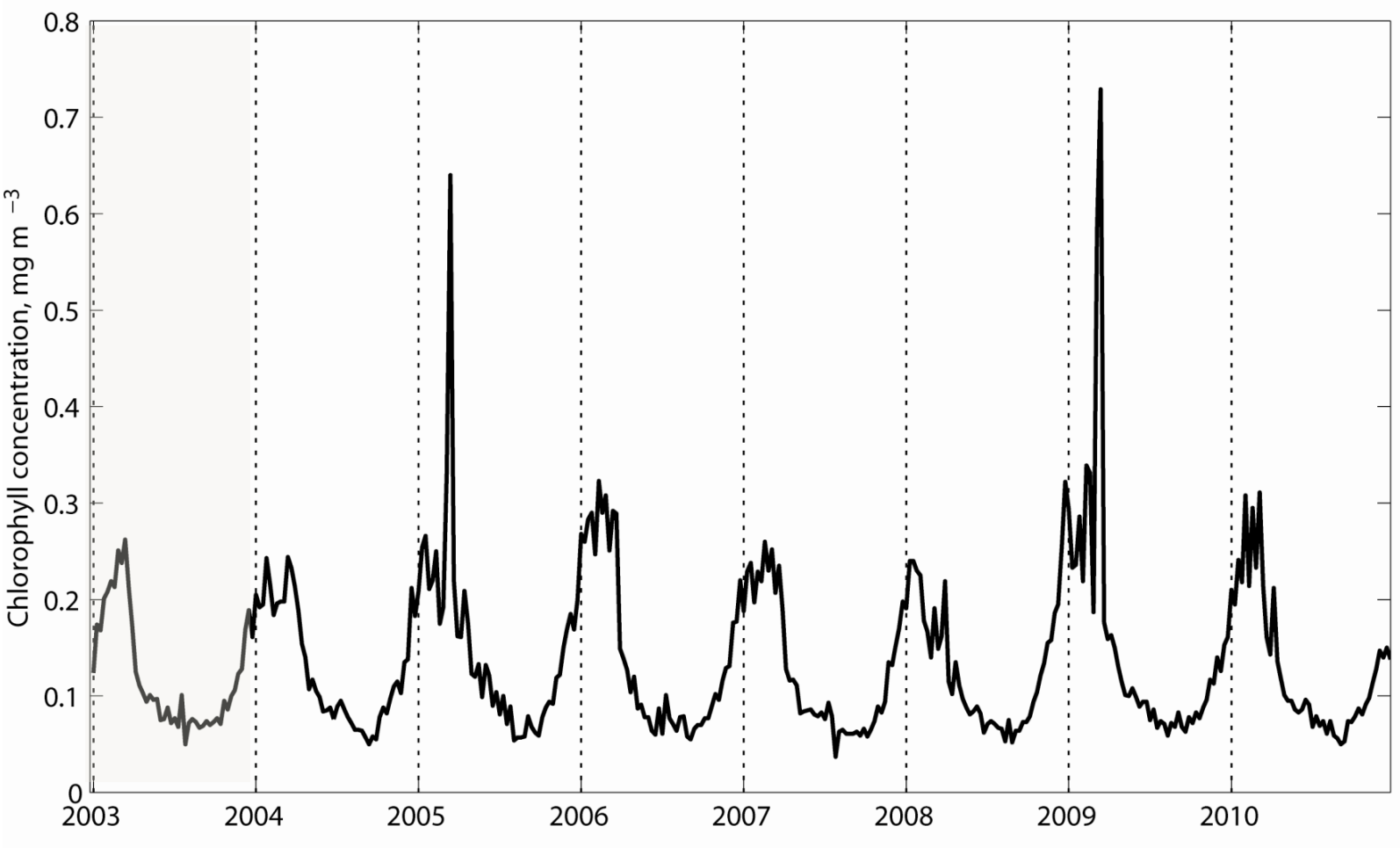
- Long-term trend: many, many years

Seasonal variability



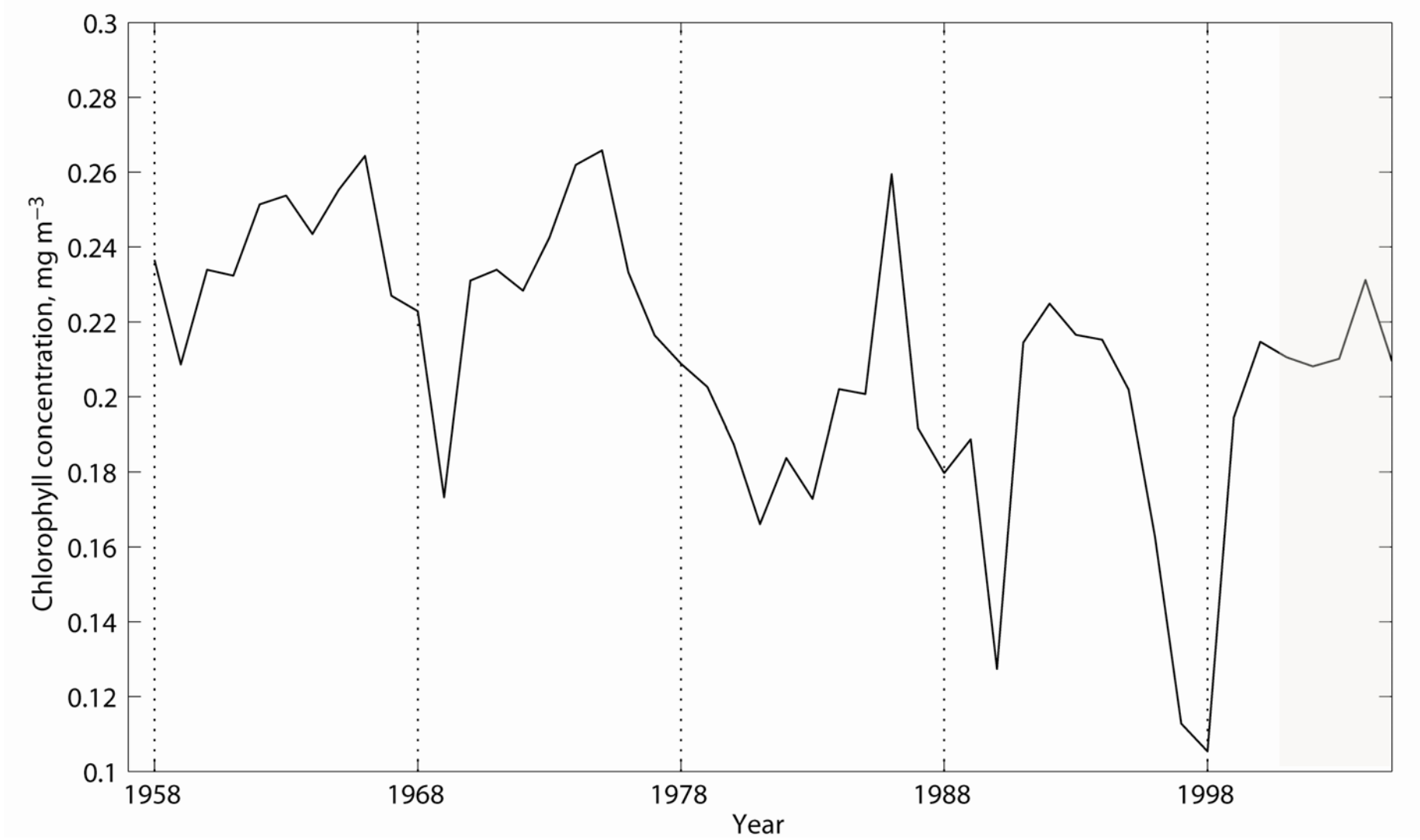
A typical year of data: MODIS 8-day mean chl in 2003 near El Jadida, Morocco

Interannual variability



MODIS time series of 8-day mean chlorophyll concentration near El Jadida, Morocco

Decadal variability



Annual mean modelled chlorophyll concentration shows variability over many decades

Long-term trends

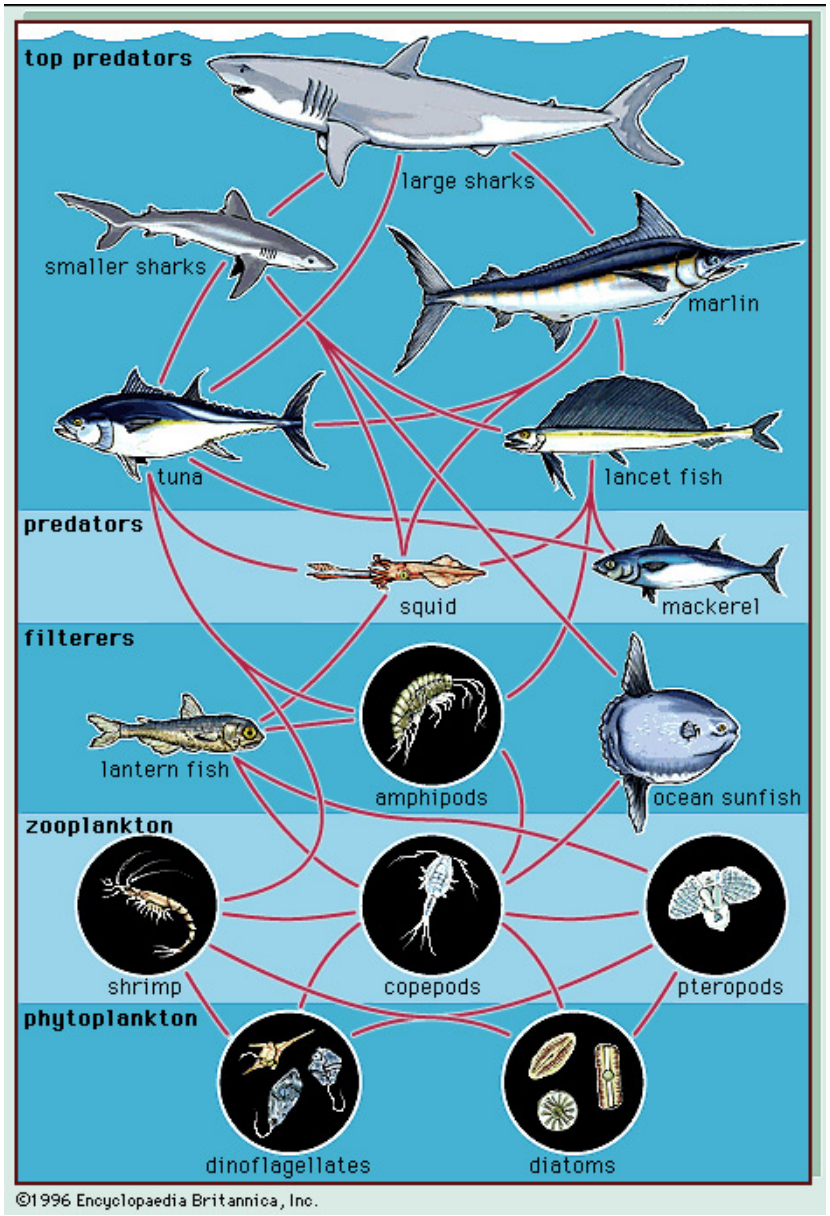
Annual mean modelled chlorophyll concentration shows a long-term declining trend, but with lots of decadal variability superimposed

Why is variability in phytoplankton important?

Why is variability in phytoplankton important?

- Phytoplankton are the base of the marine food web and are a food source for zooplankton and fish larvae
- Phytoplankton primary production results in a drawdown of CO_2 from the atmosphere and long-term sequestration of carbon
- They are a sensitive indicator of changing physical and atmospheric conditions
- Current mechanisms of variability may be an analogue for phytoplankton response to climate change

An example marine food web

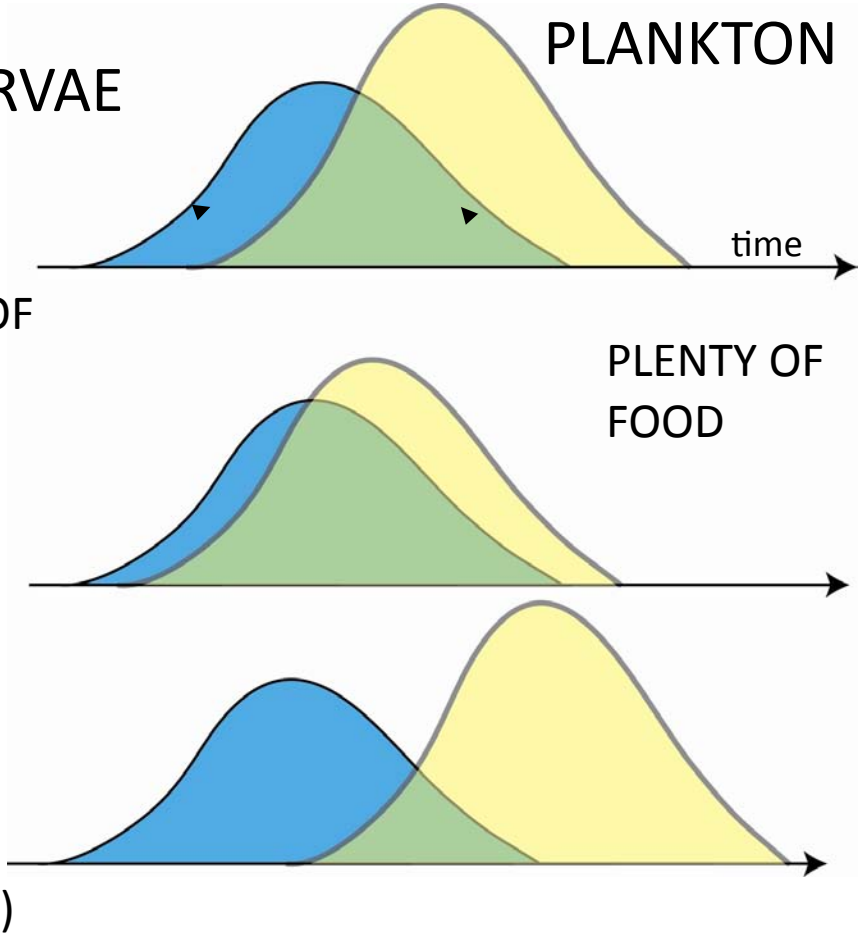


Phytoplankton form the base of the marine food web

Changes in phytoplankton abundance affect the entire chain

Match-mismatch hypothesis

Cushing's match-mismatch hypothesis: Abundance of fish year-classes determined by food availability during the critical period of larval development



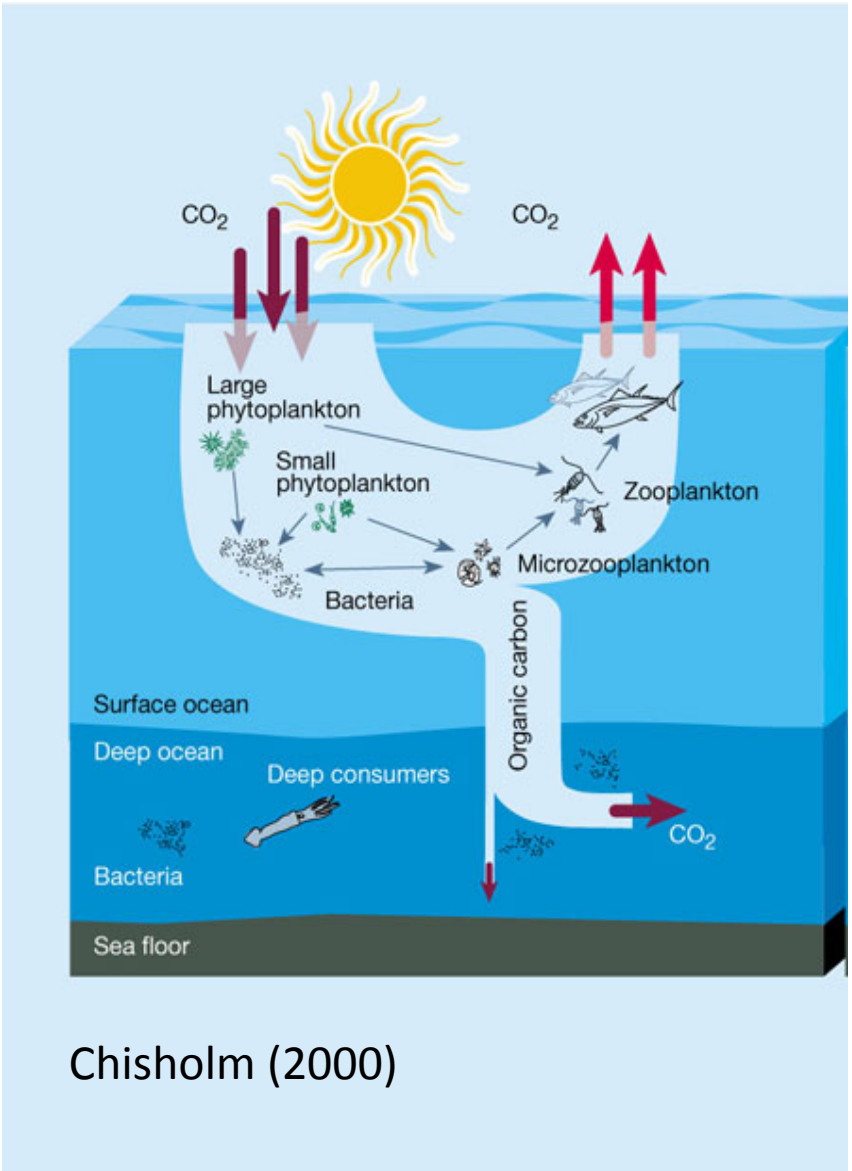
Cushing (1990)

Normal bloom timing – good overlap between food and prey, so both survive

Plankton develop **earlier** than normal - could increase larval survival

Plankton develop **later** than normal - could result in starvation and reduced survival

CO_2 uptake, export and storage



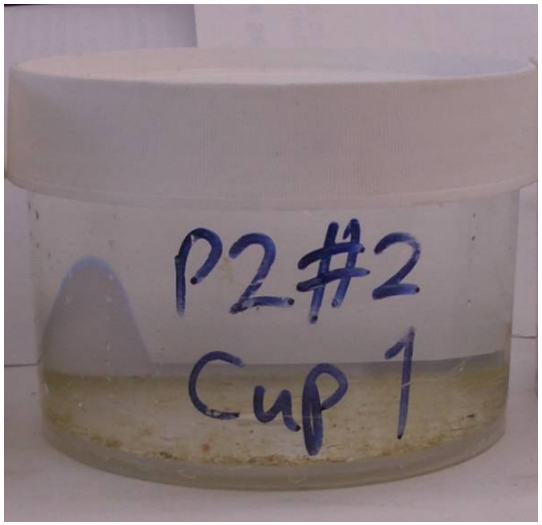
Chisholm (2000)

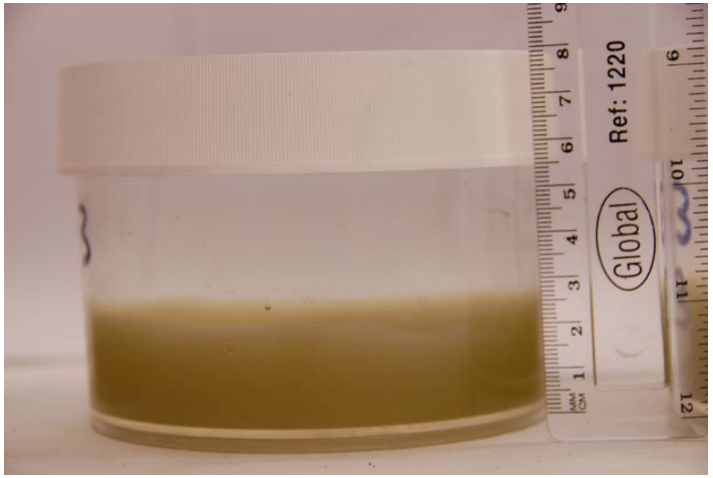
During photosynthesis, phytoplankton take up CO_2 and release oxygen

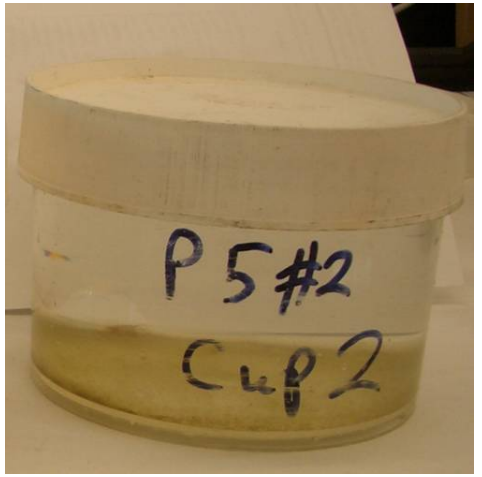
Almost half of the oxygen we breathe comes from phytoplankton!

Some of the carbon taken up by phytoplankton sinks into the deep ocean, where it's locked away for 1000's of years

CO_2 uptake, export and storage







7-11th May

14th May

17th May

Sinking material captured in a sediment trap in the Northern North Atlantic in 2008 at 600m depth

Enormous temporal variability in sinking carbon flux over the course of just 10 days

Courtesy R. Lampitt

Sensitive indicator of changing environment

Doubling rate once per day

Phytoplankton are heavily used as indicators for “Good Environmental Status”

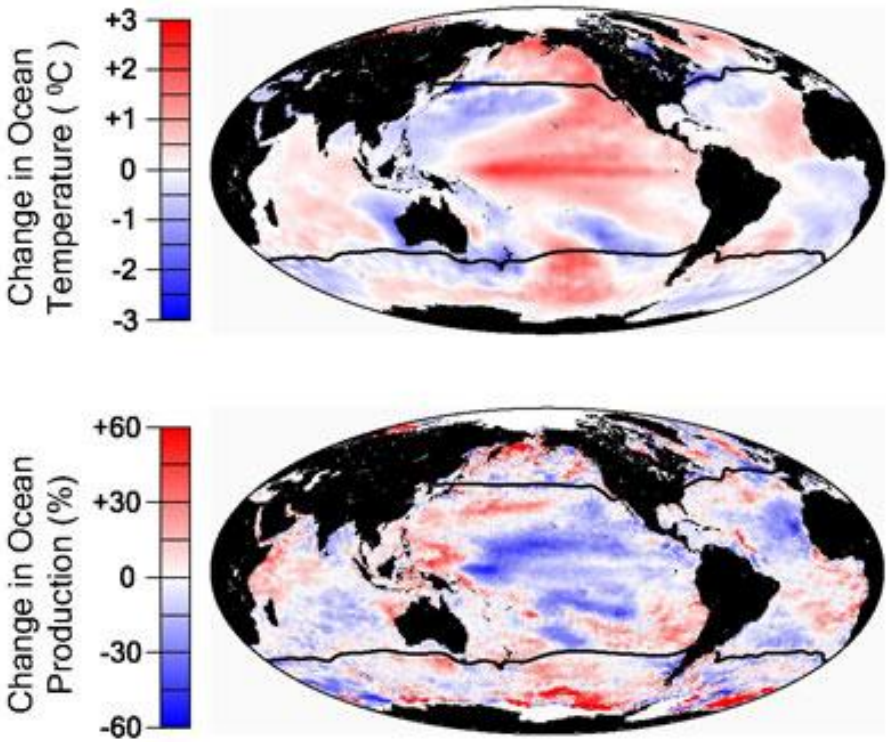
Biodiversity	Invasive species	Fish stocks
Contaminants in fish	Pollution	Marine food webs
Litter	Hydrographic conditions	Eutrophication
Noise	Sea floor integrity	

Variability now ≈ climate change response?

Phytoplankton variability we observe now may be an analogue for response to climate change

e.g. ocean temperature increased in the Pacific between 1999 and 2004 and ocean production went down

Would the same happen with increasing temperatures due to global warming??



Behrenfeld et al. (2006)

It's important to understand how and why phytoplankton vary with time

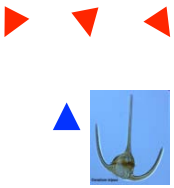
So, why does phytoplankton abundance vary with time?

Why does phytoplankton vary with time?

Because phytoplankton need 2 things to grow: **nutrients and light** and the supply of both changes over time

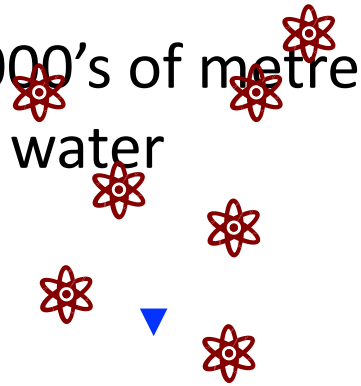
LIGHT

Ocean surface



?

1000's of metres of water

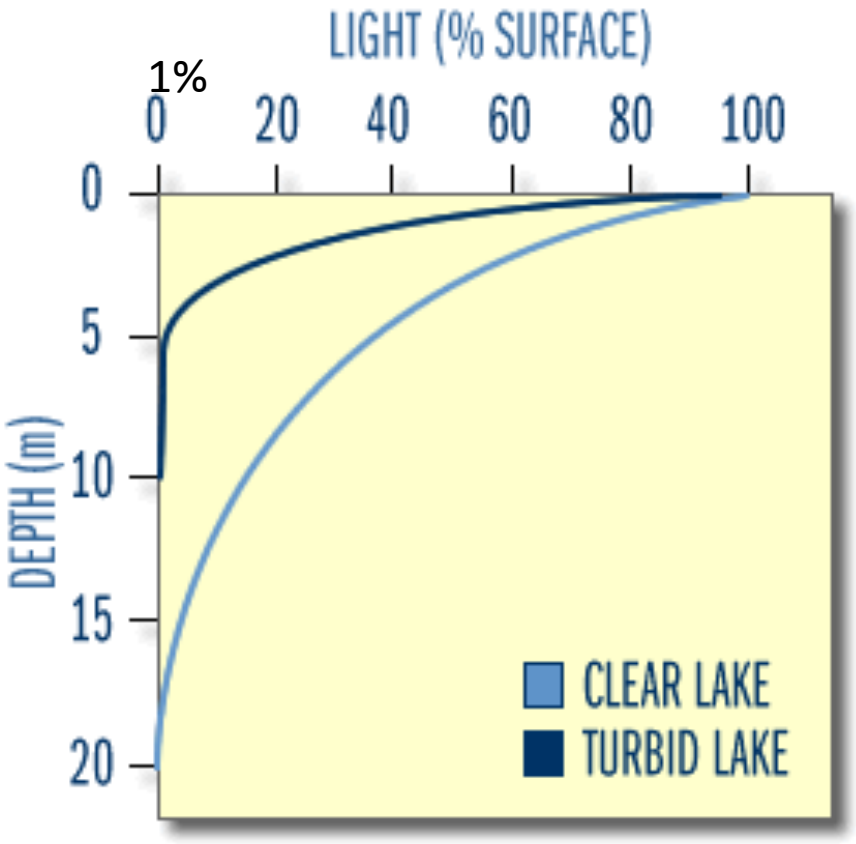


NUTRIENTS

Ocean floor

Light & phytoplankton

Amount of light dependent on latitude and time of year, but also water clarity

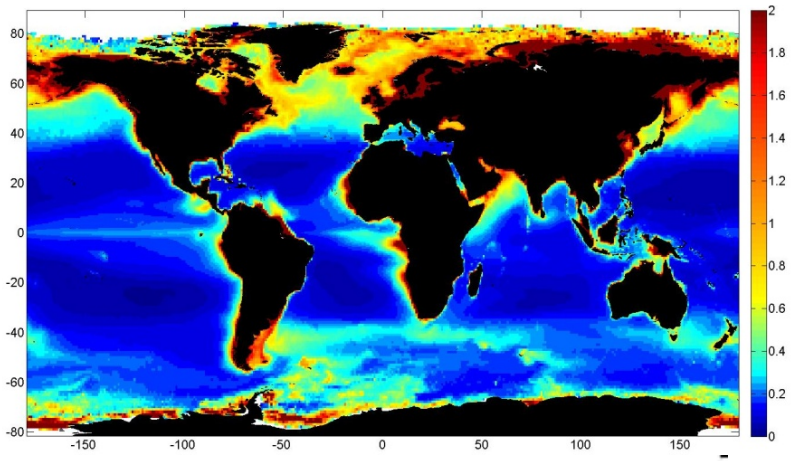


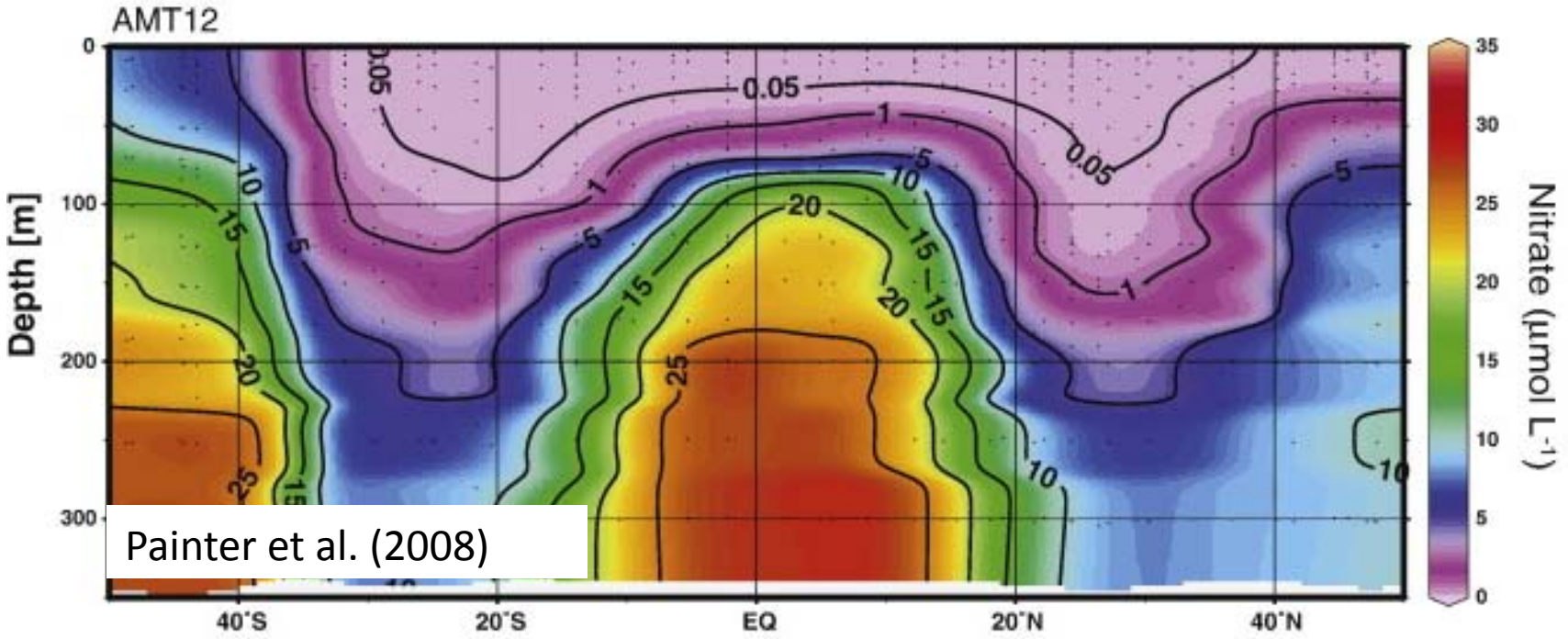
LIGHT VERSUS DEPTH PROFILES FOR A CLEAR LAKE ($k=0.2\ M^{-1}$) AND A TURBID LAKE ($k=0.9\ M^{-1}$).

Light levels decrease rapidly in the ocean. Light limits phytoplankton growth at ~ 1% of the surface value (the euphotic zone).

Nutrients & phytoplankton

Phytoplankton need macronutrients **nitrate**, **phosphate** & **silicate**. Also micronutrients: **iron**, cobalt, zinc, copper….





Most phytoplankton species need more than 1 µmol L^{-1} of nitrate

How do these factors combine to cause temporal variability in phytoplankton?

And how can we use ocean colour data to assess the variability?

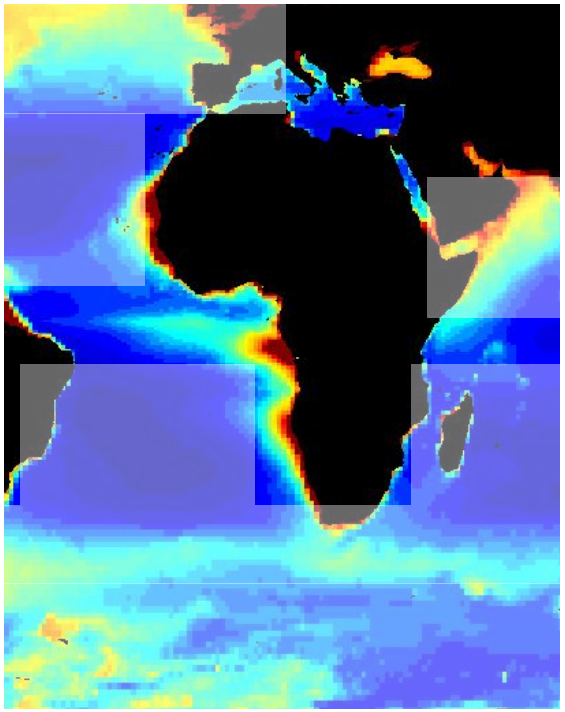
What other data can we use to figure out what causes the variability?

How do these factors combine to cause seasonal variability in phytoplankton?

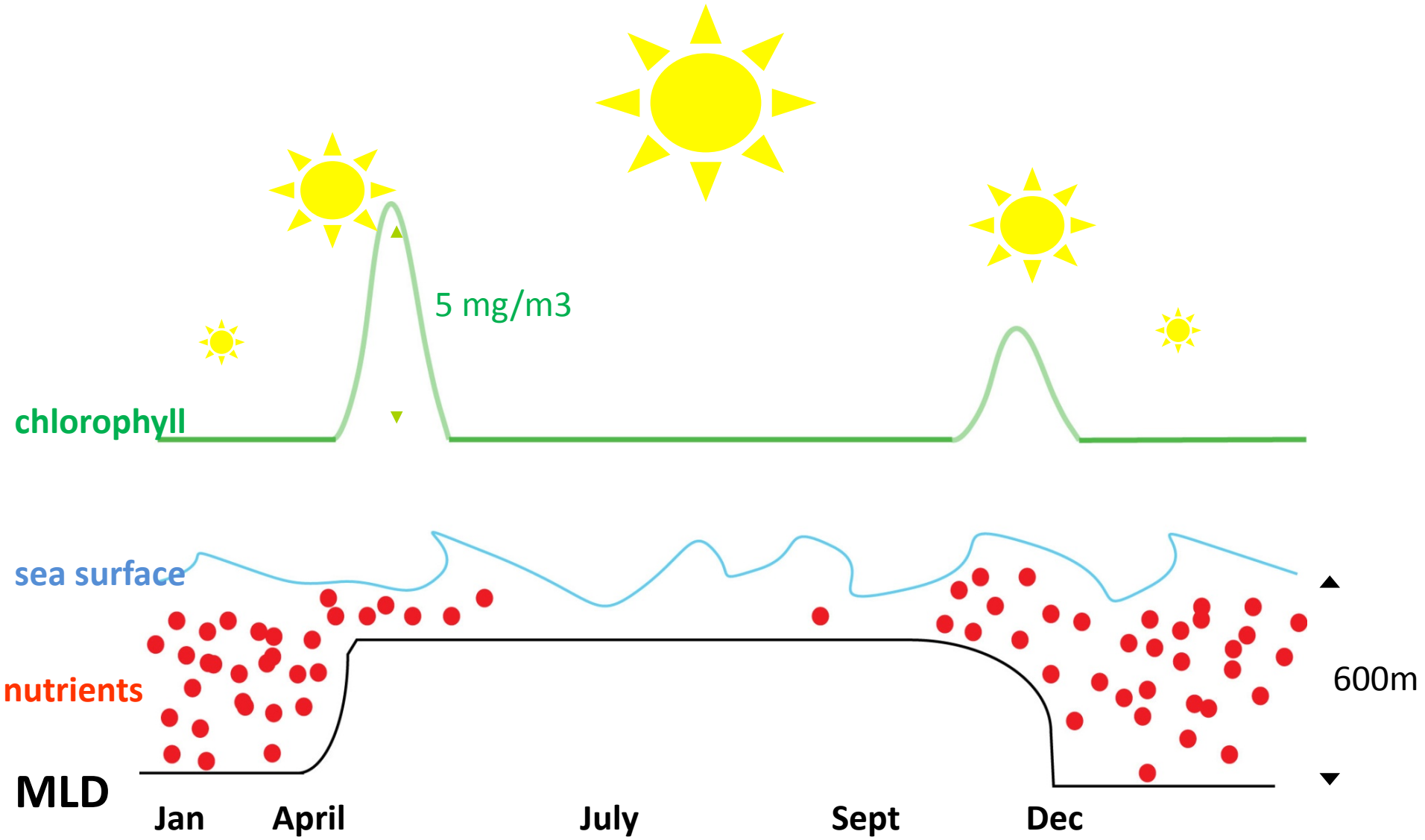
Nutrient limited regions, i.e. sub-tropics

Very nutrient limited regions, i.e. oligotrophic gyres

Light limited regions, i.e. high latitudes

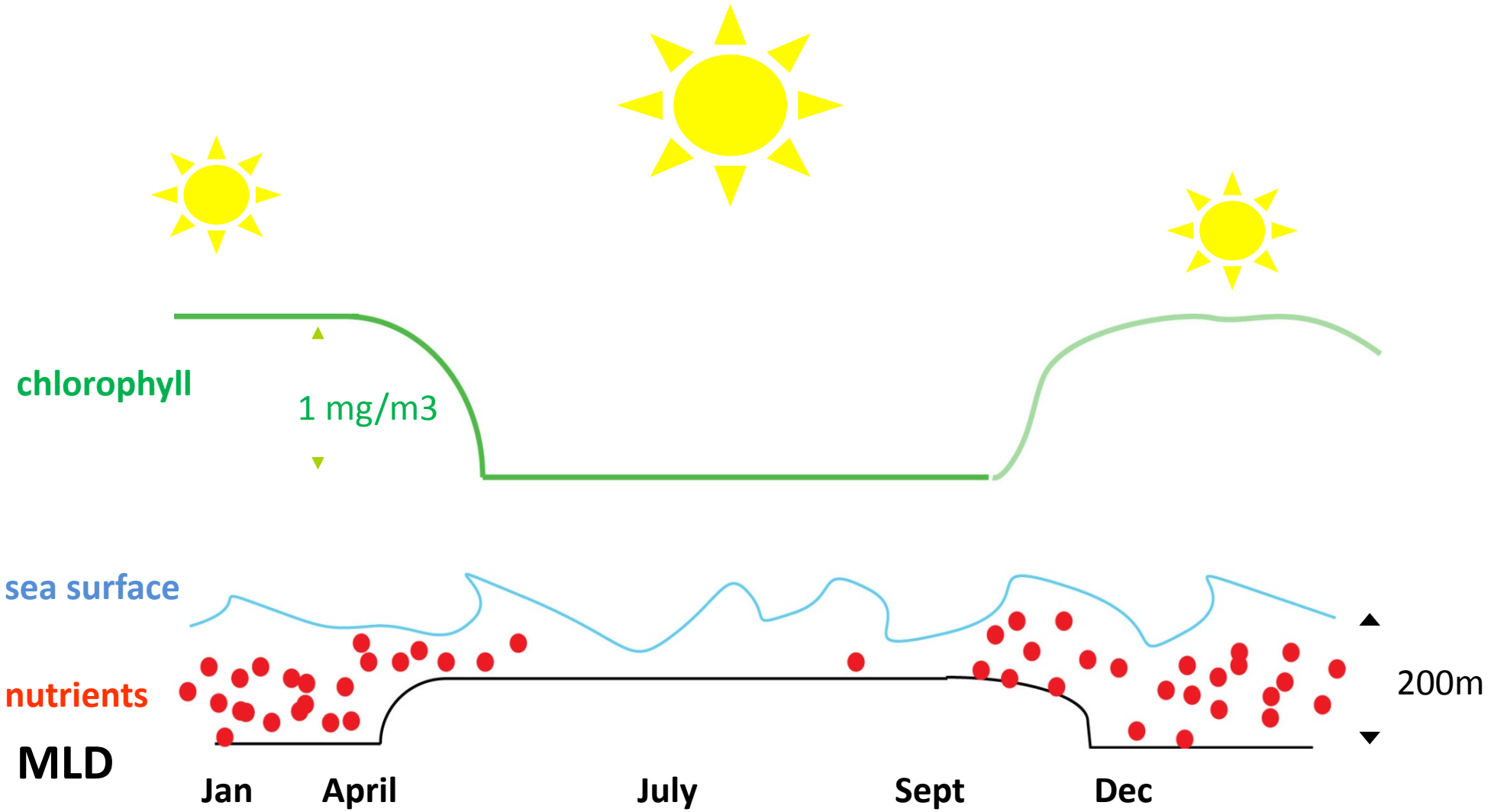


Seasonal cycle in light limited regions



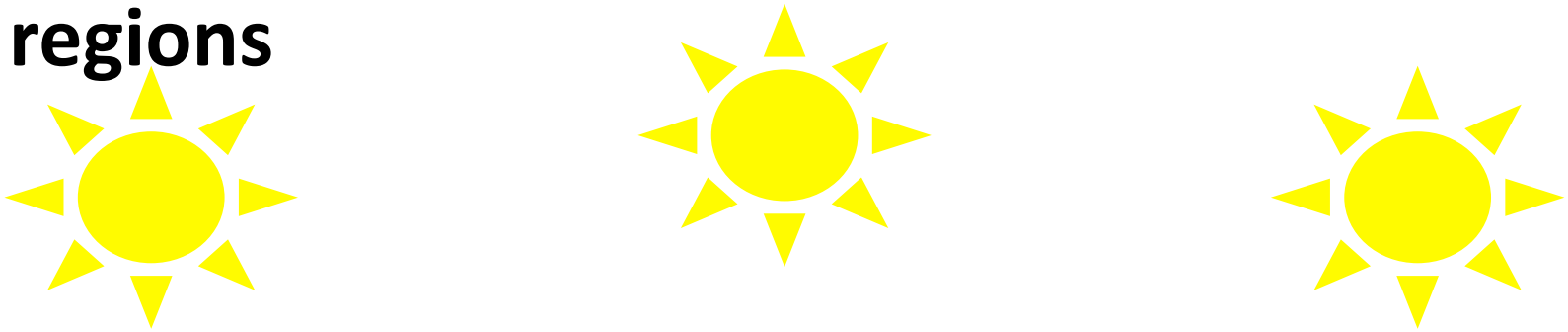
High latitude regions

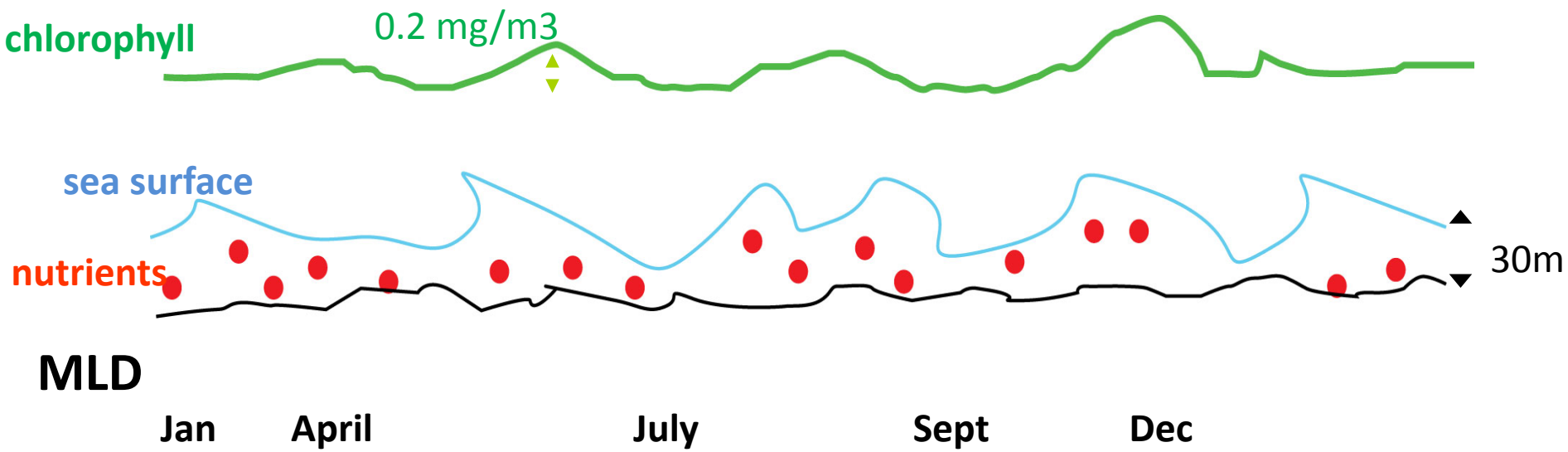
Seasonal cycle in nutrient limited regions



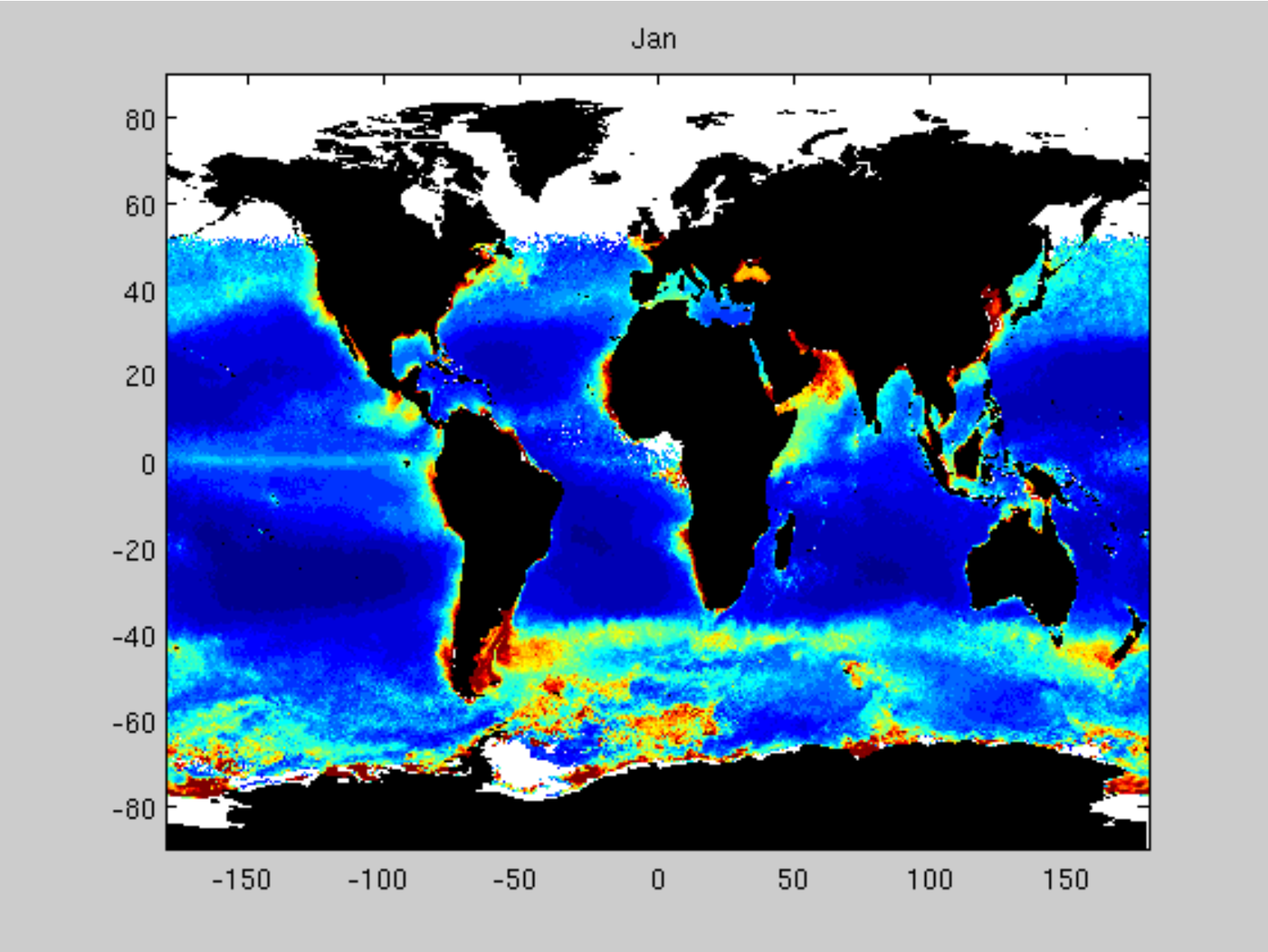
Sub-tropical regions

Seasonal cycle in very nutrient limited regions



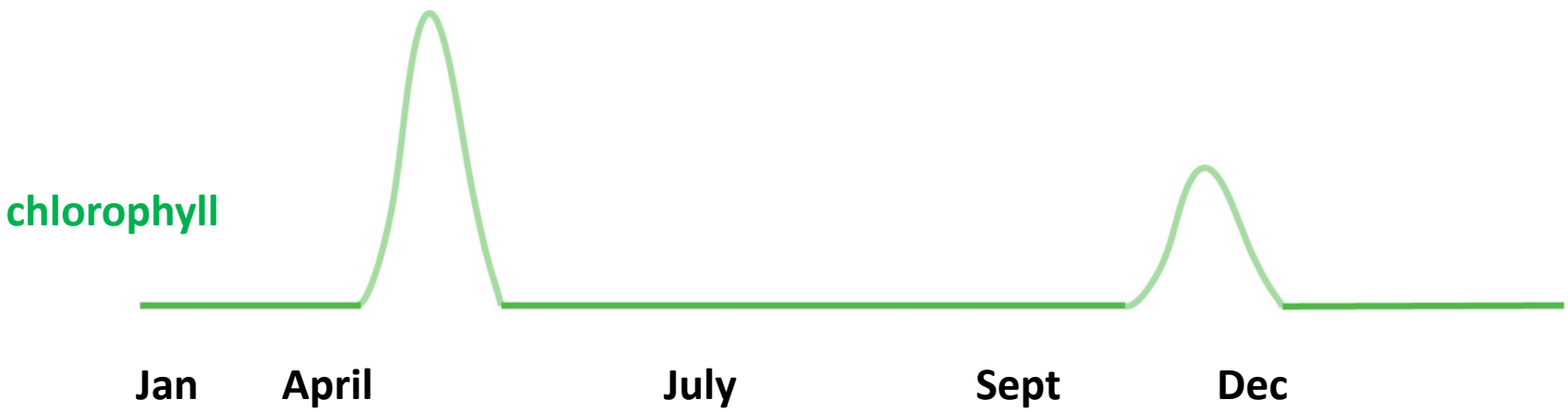


Oligotrophic gyres

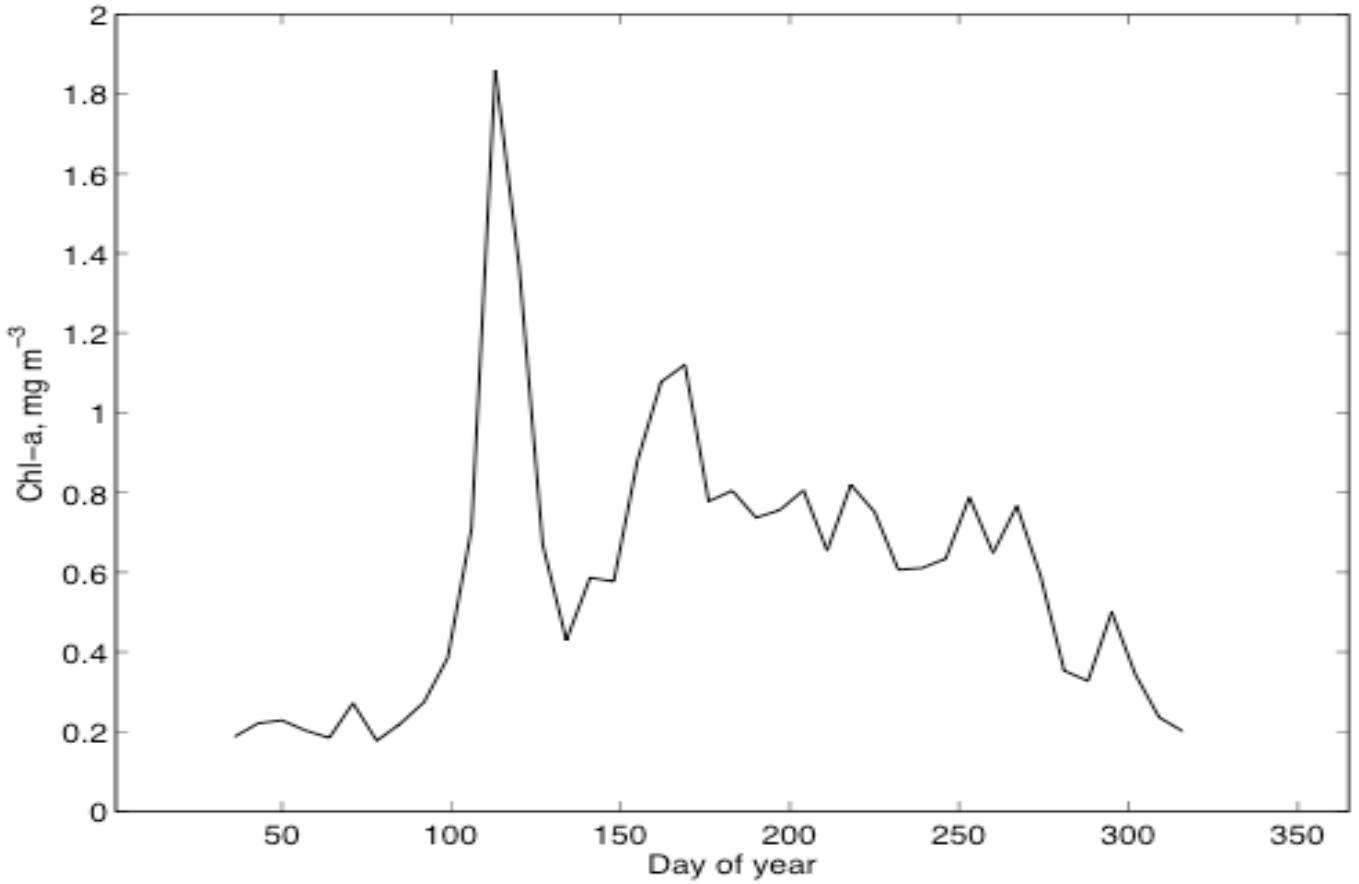

Jan
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150

Seasonal variability

What characteristics of seasonal variability in phytoplankton can we quantify with satellite data?



Quantifying bloom timing



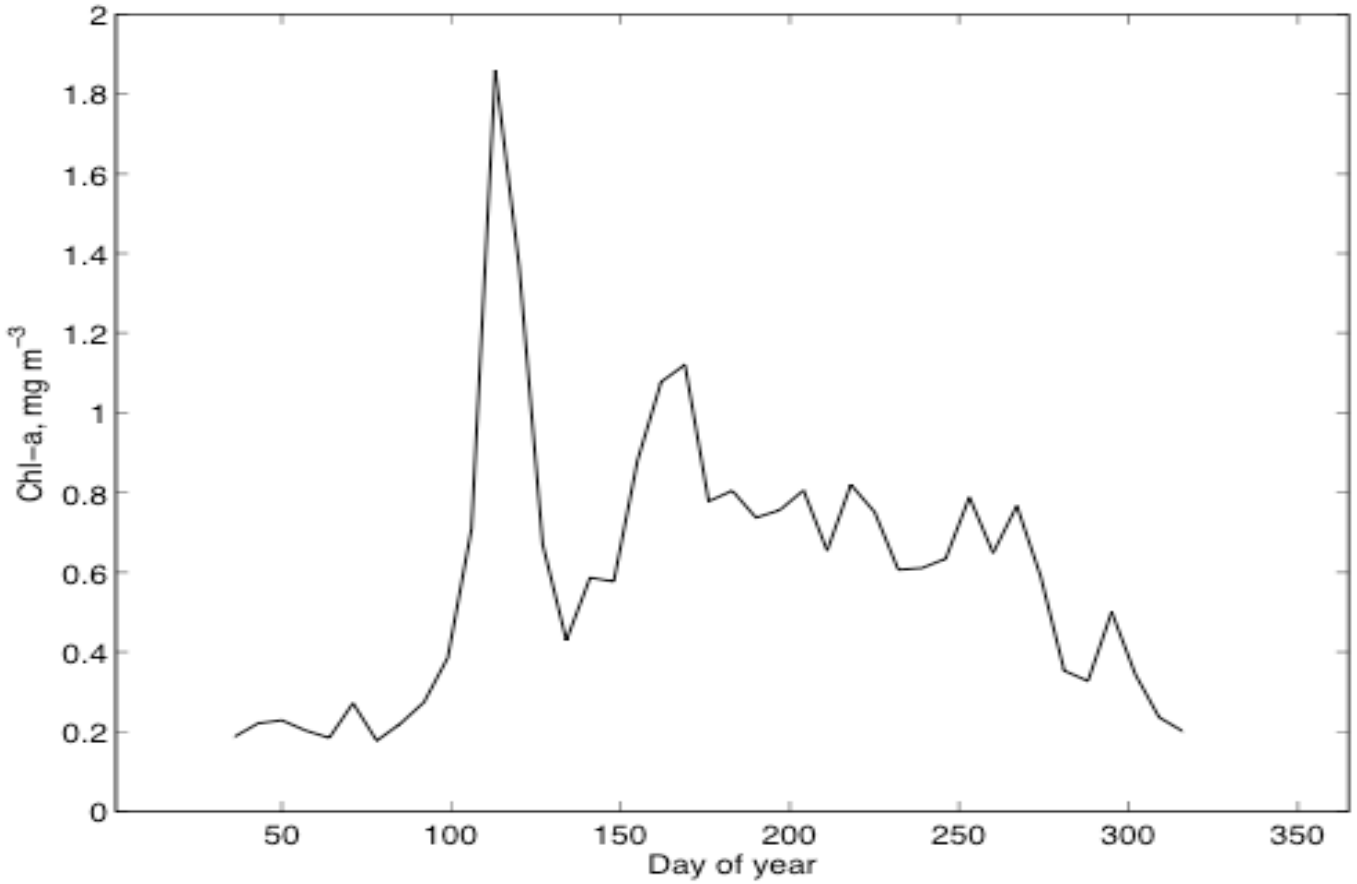
7-day mean SeaWiFS chlorophyll in Irminger Basin in 1998

Objective method

Spatially consistent

When would YOU say the bloom starts?

Quantifying bloom timing

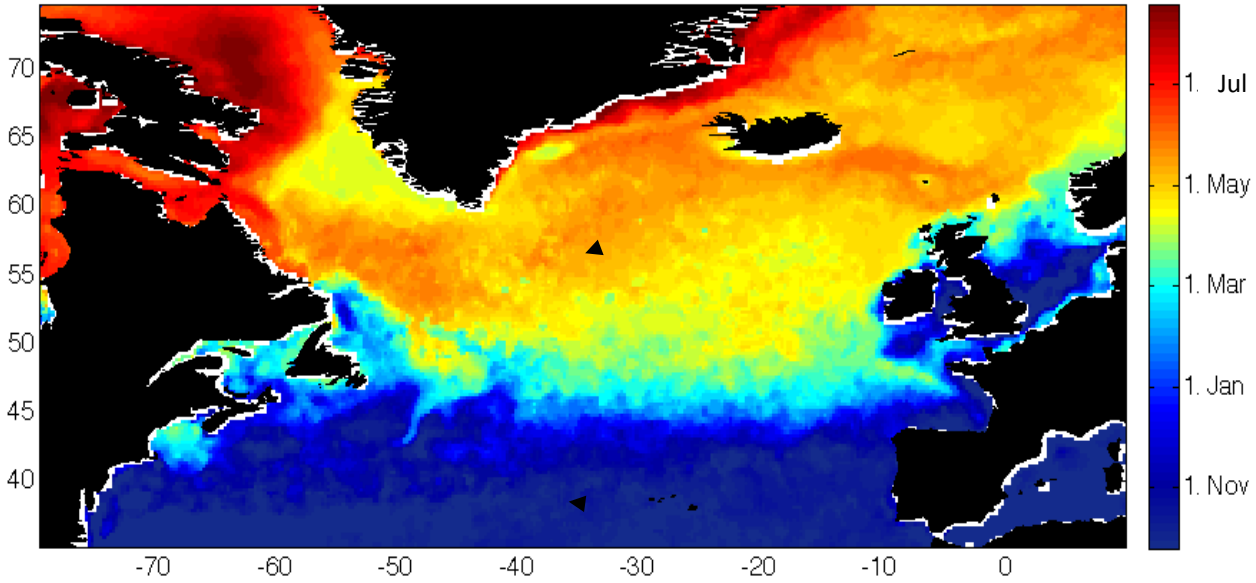


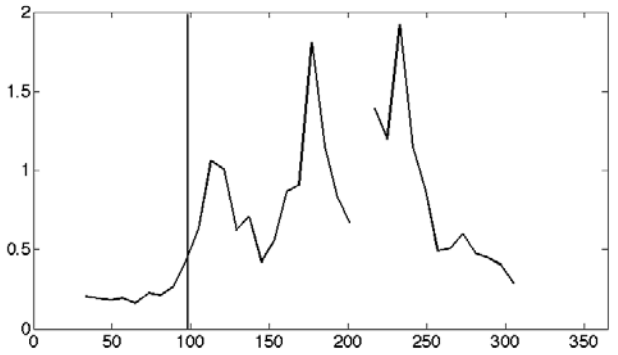
Day of year on which chlorophyll rises 5% above the annual median. Calculated separately for each pixel.

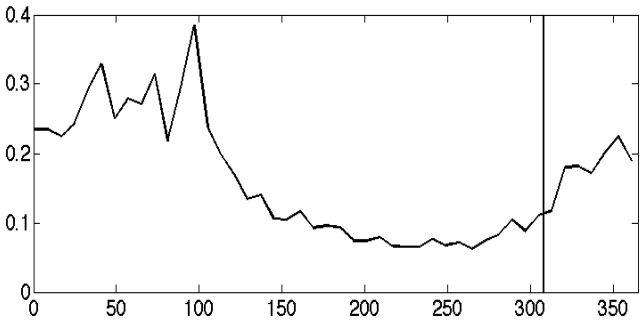
Siegel et al (2002)

Bloom timing from SeaWiFS

SeaWiFS mean start date (1998-2004)





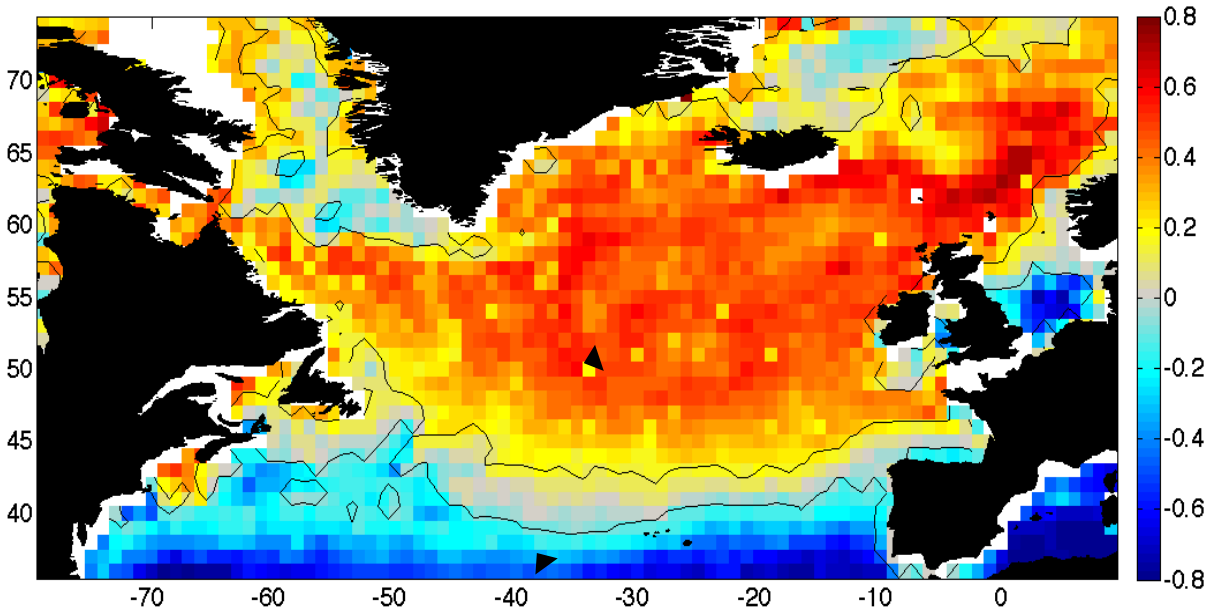


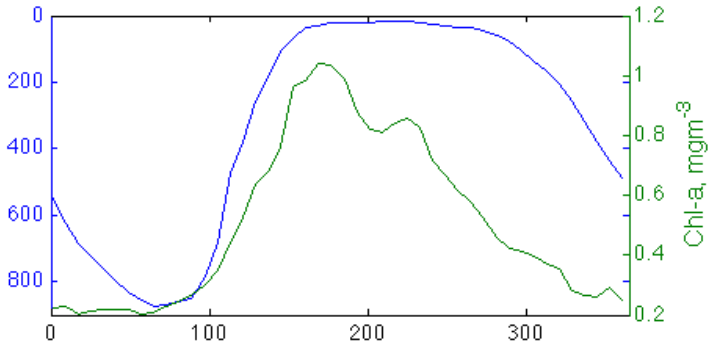
Why does the sub-polar bloom start in spring, but the sub-tropical bloom start in autumn?

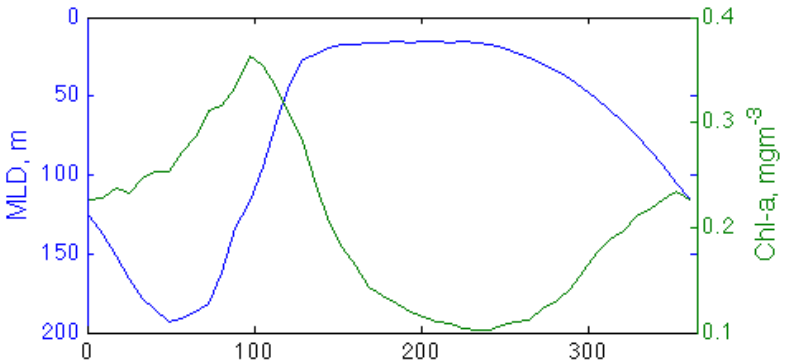
Henson et al. (2009)

Chl-a response to seasonal changes in MLD

Linear correlation MLD and chl







Green: SeaWiFS mean chl-a

Blue: Model mean MLD

Henson et al. (2009)

Physical drivers of bloom timing

We've seen that the depth of winter mixing and seasonal evolution of MLD is very important for bloom timing.

What controls the mixed layer depth?

- Increased heat into the ocean (both as you move equatorward, and transition from winter to summer)

  MLD response?

  Effect on bloom in sub-polar?

  Effect on bloom in sub-tropical?

- Increased wind speed (both as you move poleward, and transition from summer to winter)

  MLD response?

  Effect on bloom in sub-polar?

  Effect on bloom in sub-tropical?

Physical drivers of bloom timing

In regions away from the coast, the influences on water column stability are limited to heat buoyancy and wind mixing. But near the coast, also have to consider tidal mixing and freshwater input. These factors can be quantified in terms of potential energy anomaly.

Water column can stratify if:

Buoyancy > Mixing

Tidal

Wind

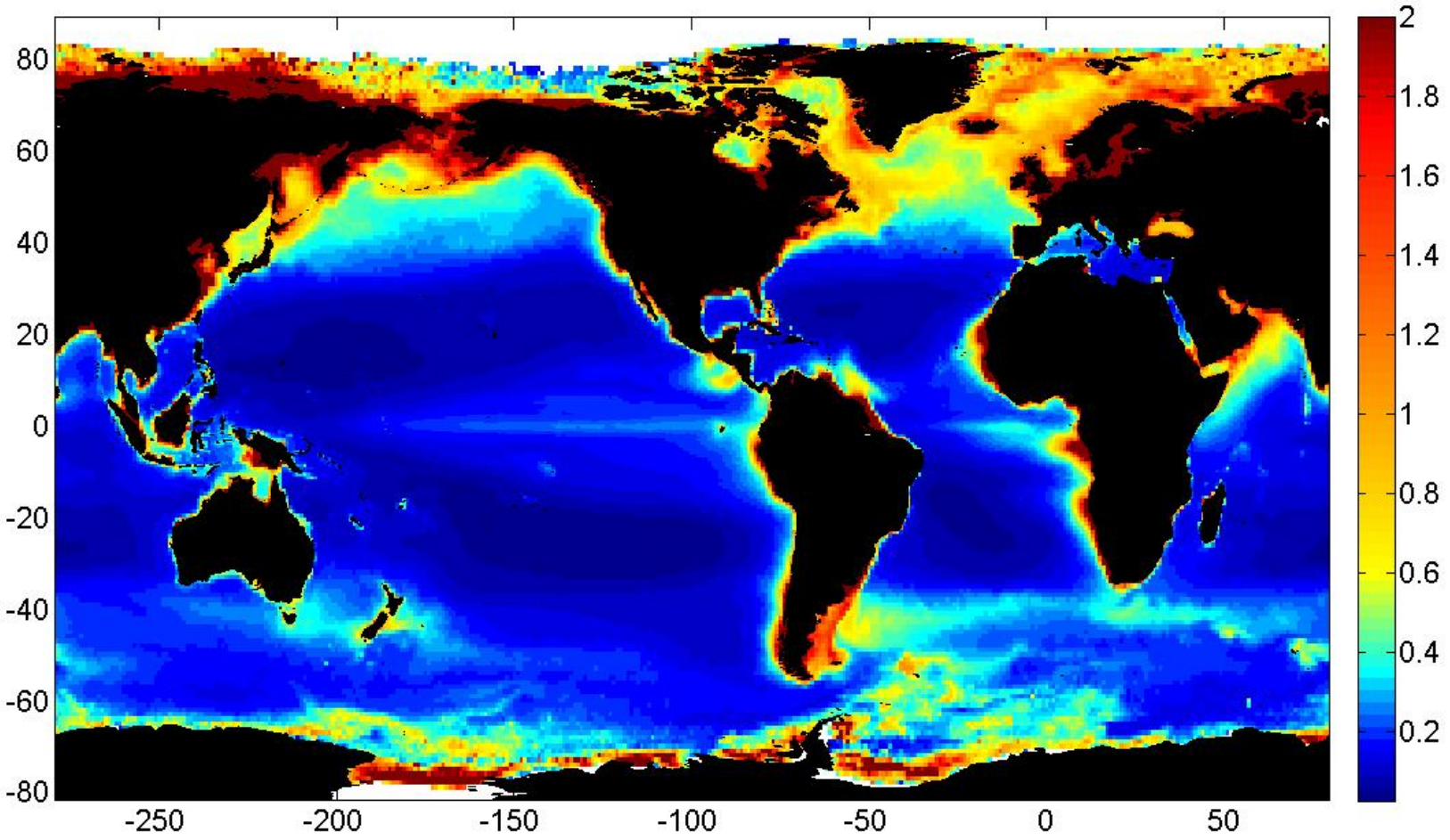
Freshwater

Heating

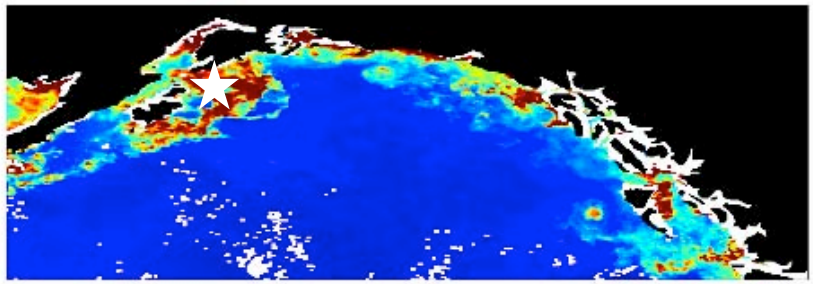
'Stability ratio': $\frac{\text{Buoyancy}}{\text{Mixing}} > 1$

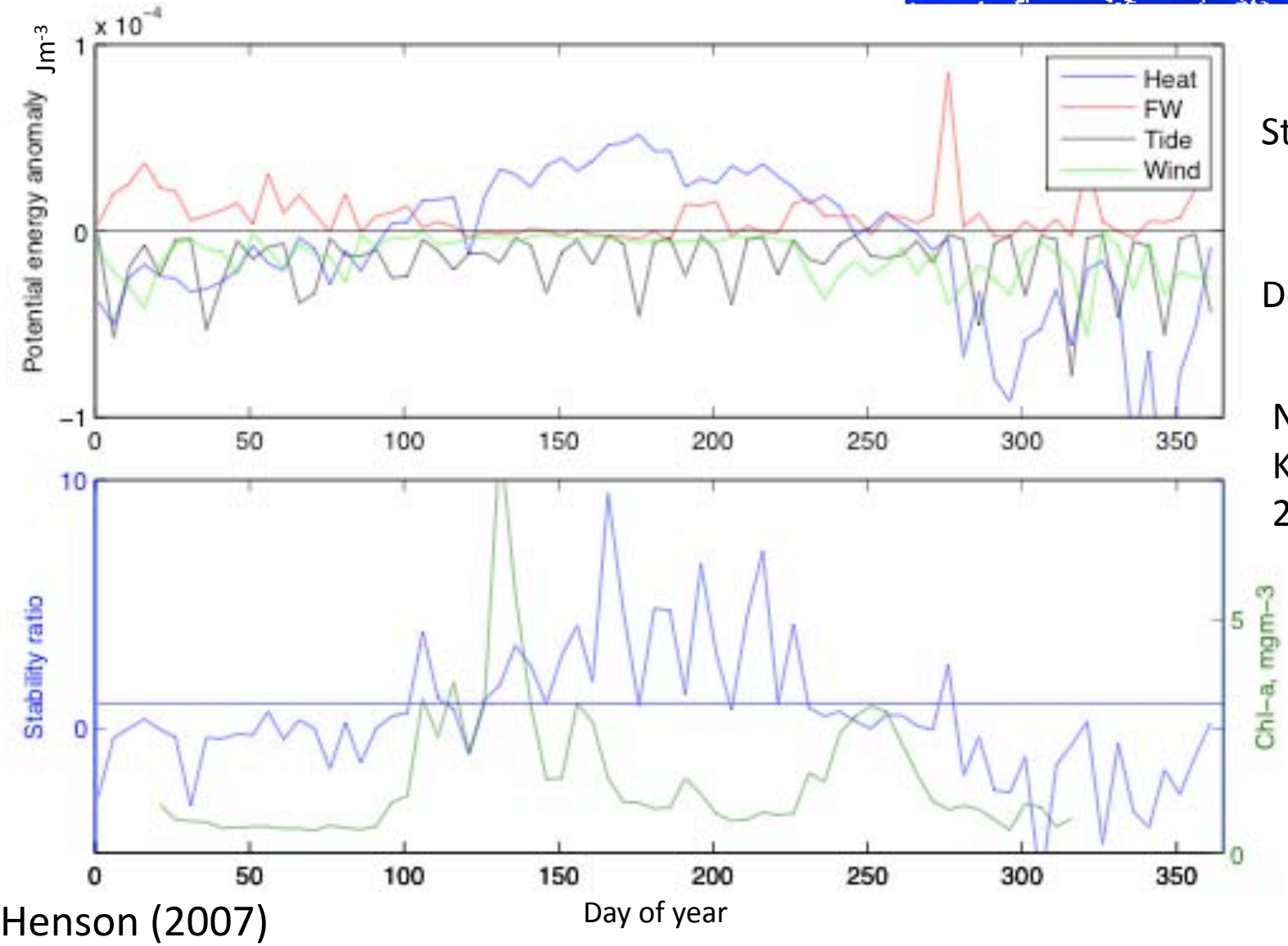
Simpson and Hunter, 1974; Simpson and Bowers, 1981, 1984

Gulf of Alaska



Stability ratio = $\frac{\text{Heat + Freshwater}}{\text{Wind + Tides}}$





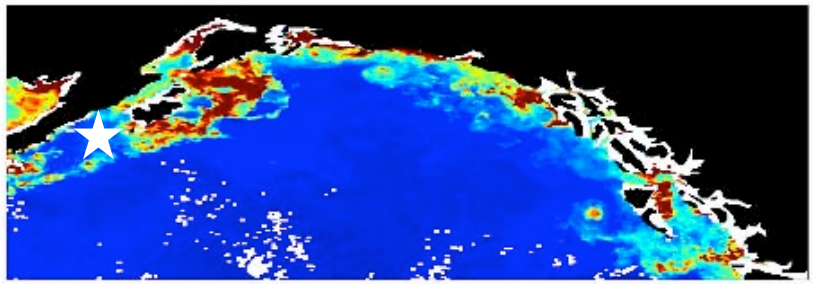
Stabilising

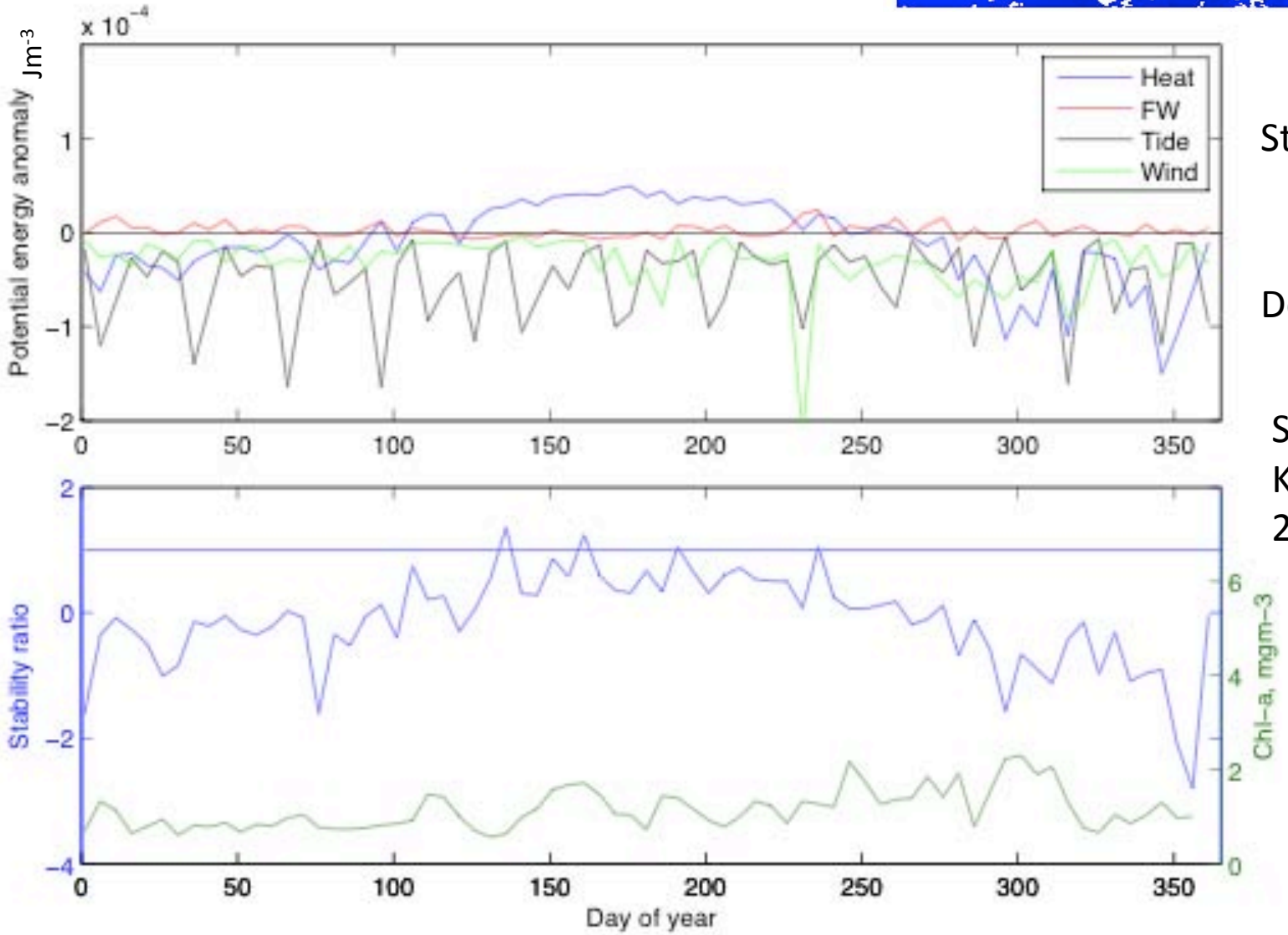
Destabilising

Northeast of Kodiak Island, 2001

Henson (2007)

Stability ratio = $\frac{\text{Heat + Freshwater}}{\text{Wind + Tides}}$



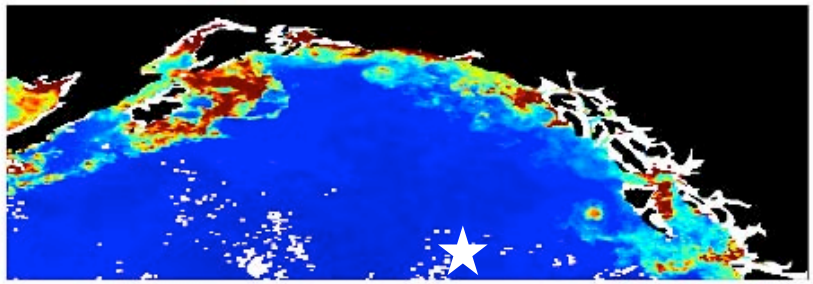


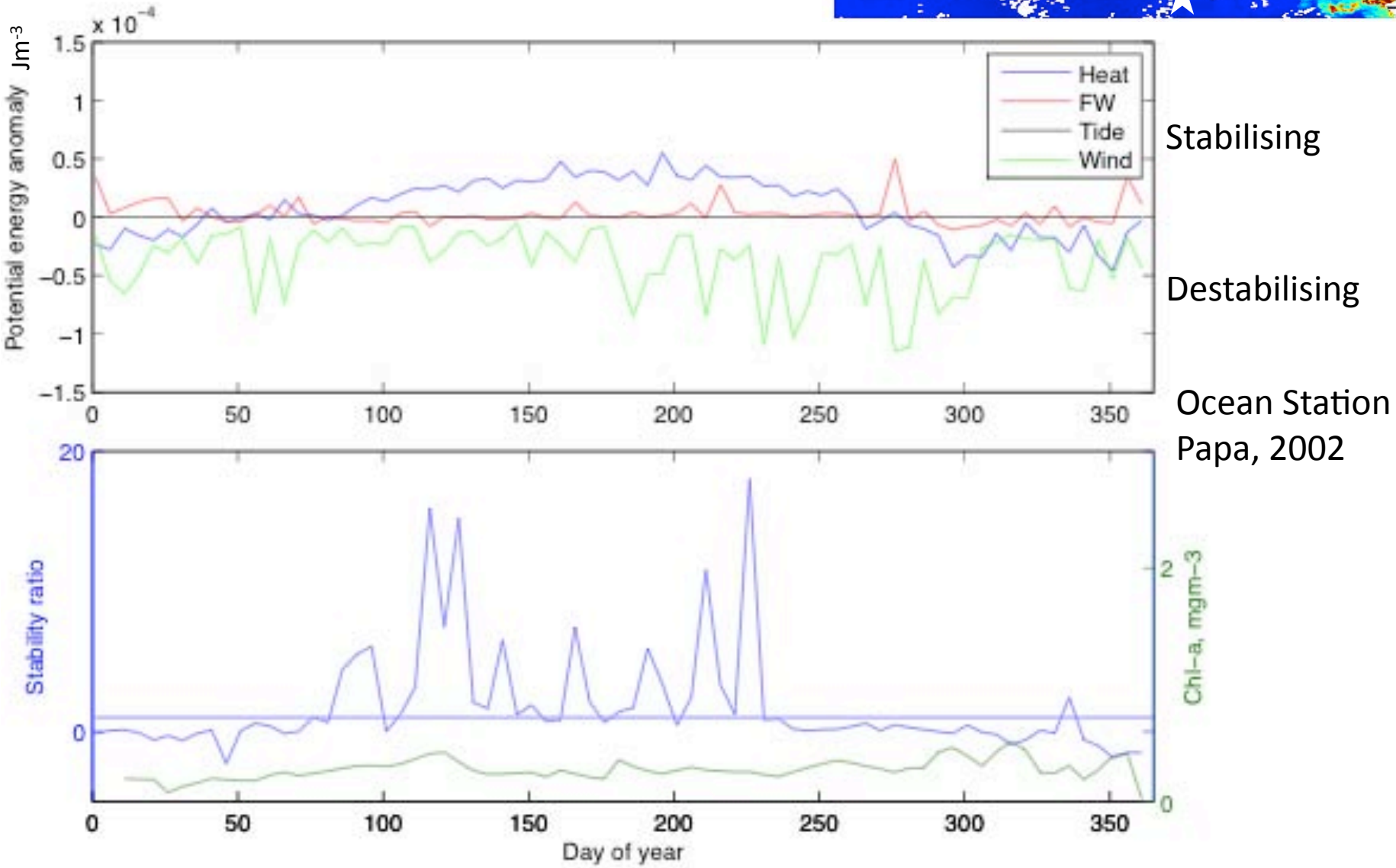
Stabilising

Destabilising

Southwest of Kodiak Island, 2001

Stability ratio = $\frac{\text{Heat + Freshwater}}{\text{Wind + Tides}}$





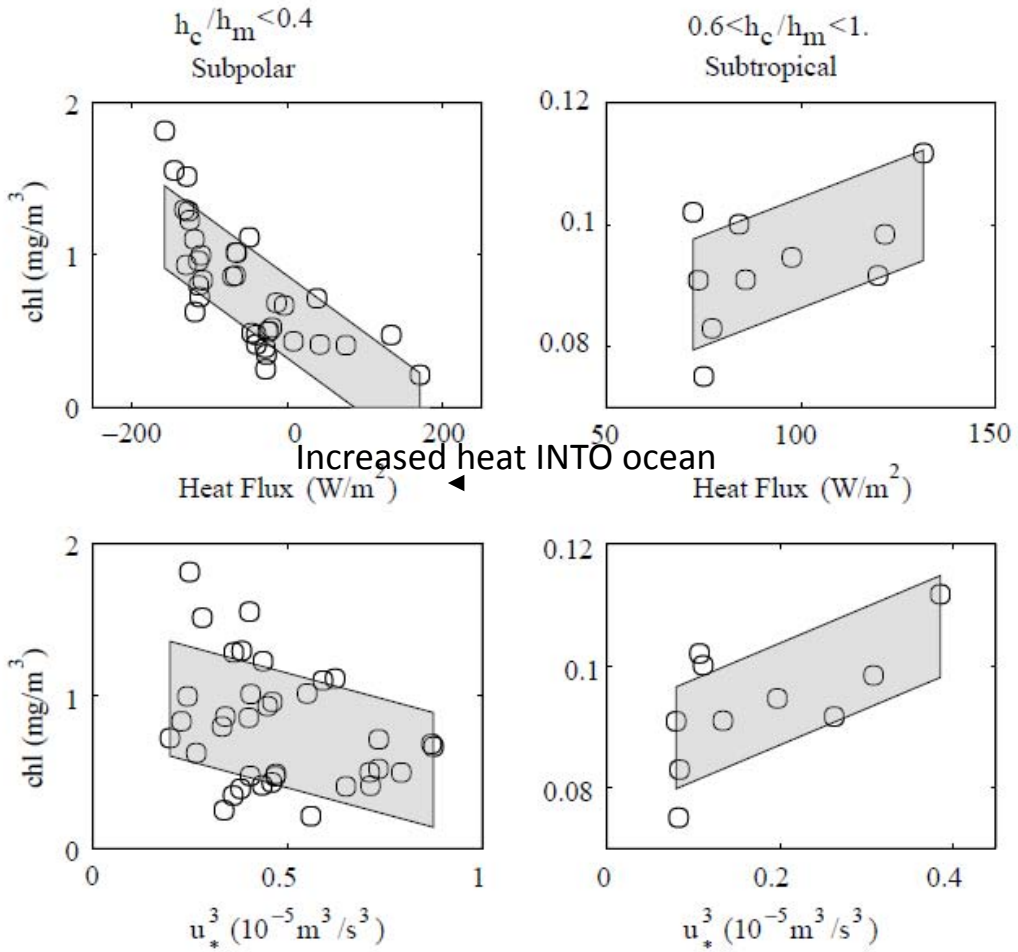
Stabilising

Destabilising

Ocean Station Papa, 2002

Bloom development

So far, we've focused on timing of the bloom. Let's have a quick look at how physical processes might affect the subsequent magnitude of the bloom.



North Atlantic: compare total chl-a to heat flux and wind mixing in sub-polar and sub-tropical regions

Note the opposite responses in bloom magnitude in the 2 regions to more mixing

Light limited vs nutrient limited again!

Follows and Dutkiewicz (2002)

Using ocean colour data for analysing seasonal variability

- Think quantitatively (particularly if you're studying a large region)
- Metrics to define start/end/duration of bloom
- What controls the start or development of the bloom? (combine colour data with other data)

Summary 1

- The seasonal variability in phytoplankton is dominated by the annual bloom
- Bloom onset is, generally speaking, either light limited (sub-polar) or nutrient limited (sub-tropical), which depends on winter mixed layer depth
- The onset of water column stability is crucial in light limited regions (determined by a balance of heating and freshwater buoyancy versus tidal and wind mixing)
- In nutrient limited regions, blooms may be stimulated by upwelling (or eddies or storms)
- The magnitude of the bloom is influenced by mixing (which alters nutrient and light availability) and biological processes (grazing, phytoplankton species succession)

How might interannual variability in bloom characteristics arise?

How might interannual variability in phytoplankton populations arise?

- Variability in physical processes:

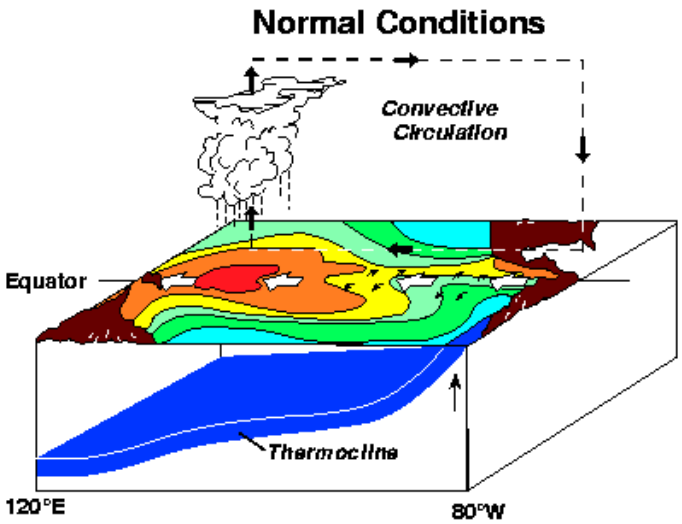
  Mixing/stratification. Heat flux, temperature, wind, storms, upwelling

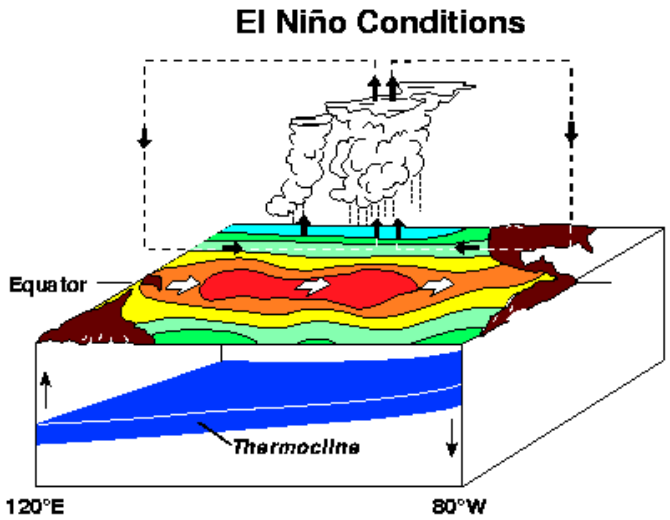
- Variability in biological processes:

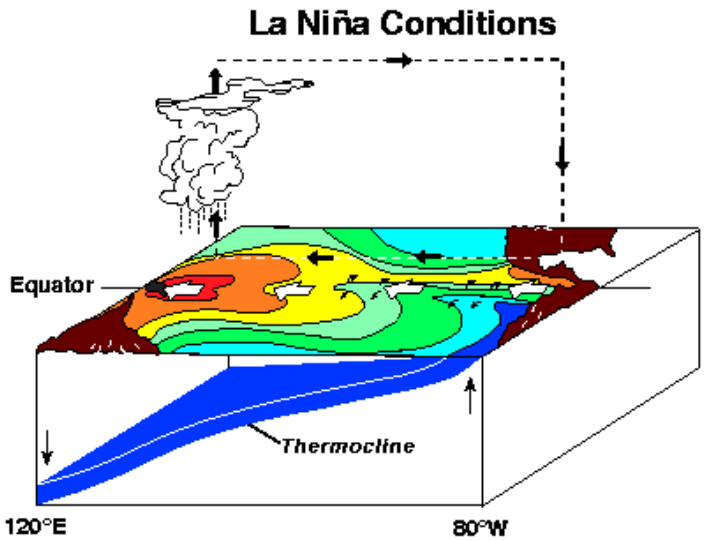
  Phytoplankton species composition, zooplankton grazing, viruses

These processes can be local-scale, or larger basin-scale effects. We're going to focus on how large-scale variability in physical atmospheric and oceanic conditions can cause variability in phytoplankton populations.

El Niño/La Niña events



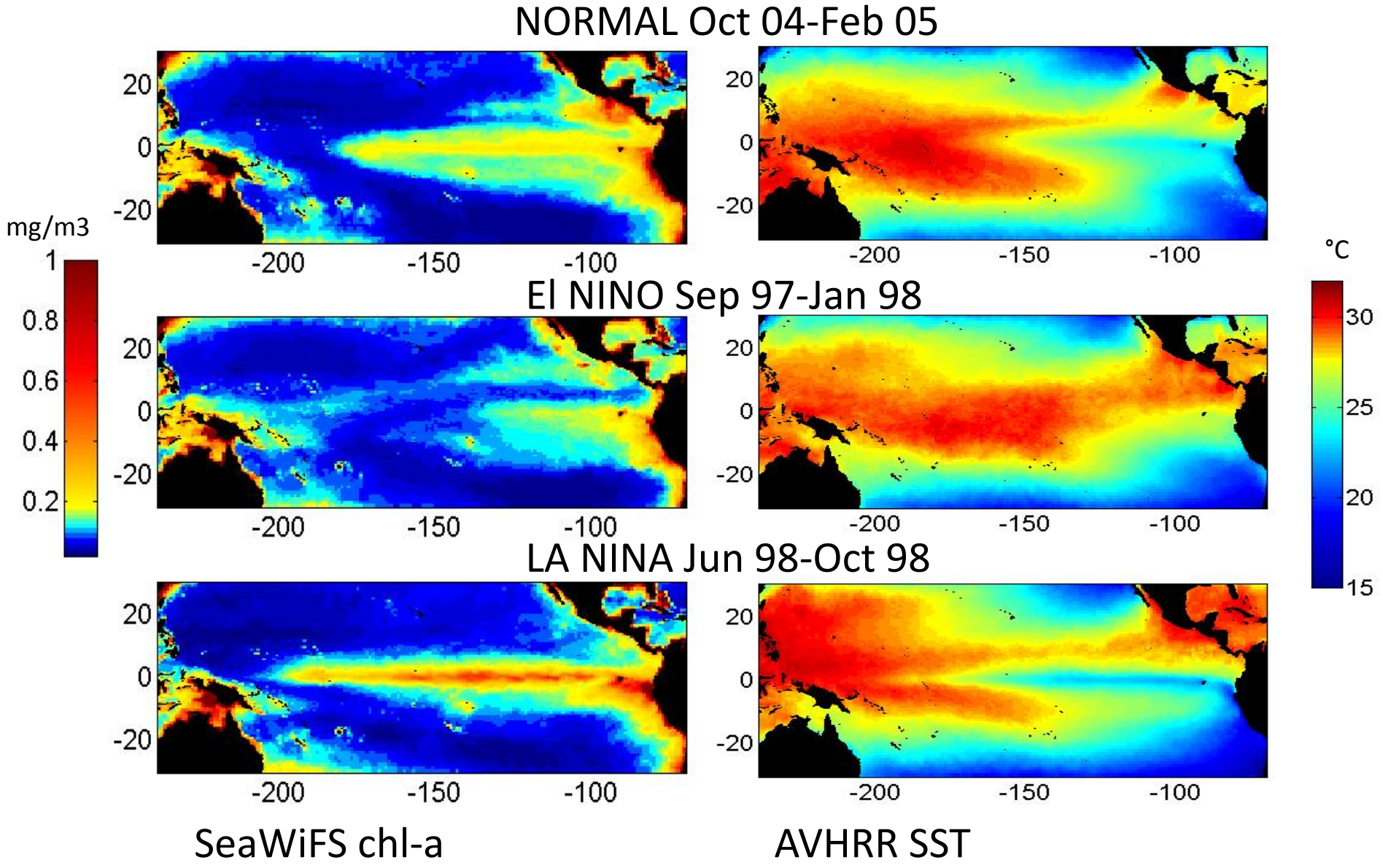




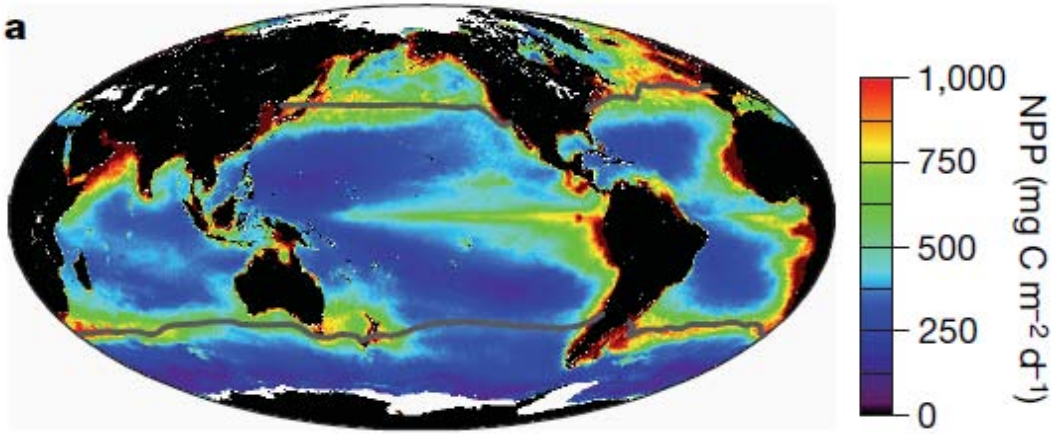
How do you expect El Niño/ La Niña to affect productivity in the Pacific?

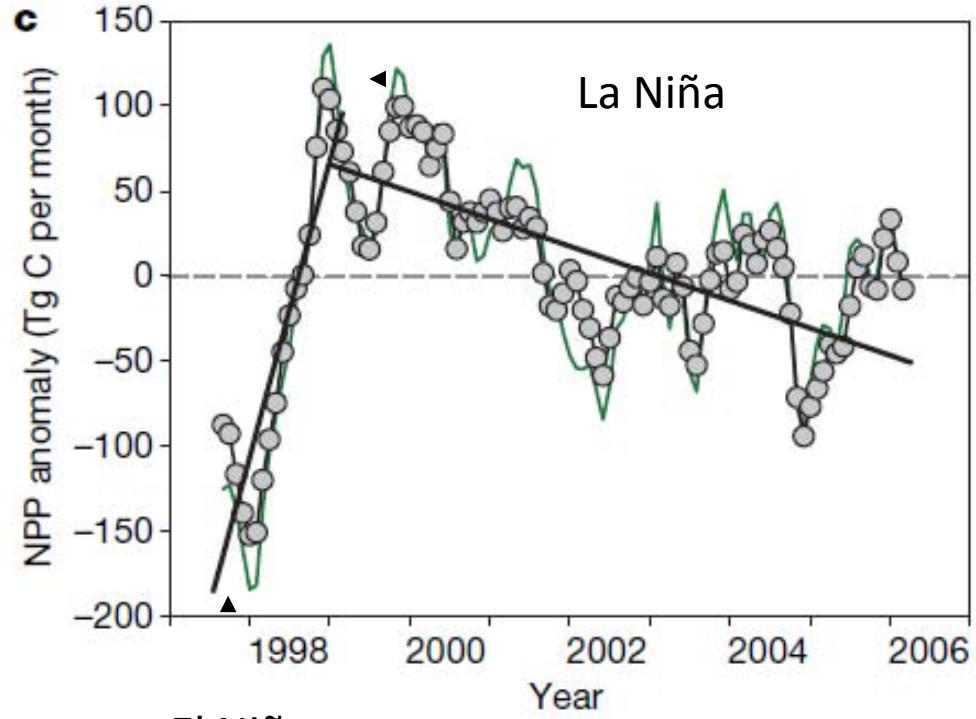
http://www.pmel.noaa.gov/tao/elnino/nino-home.html

El Niño/La Niña events



El Niño/La Niña events





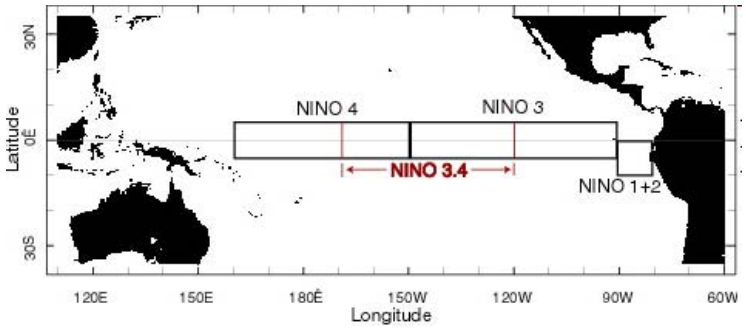
El Niño

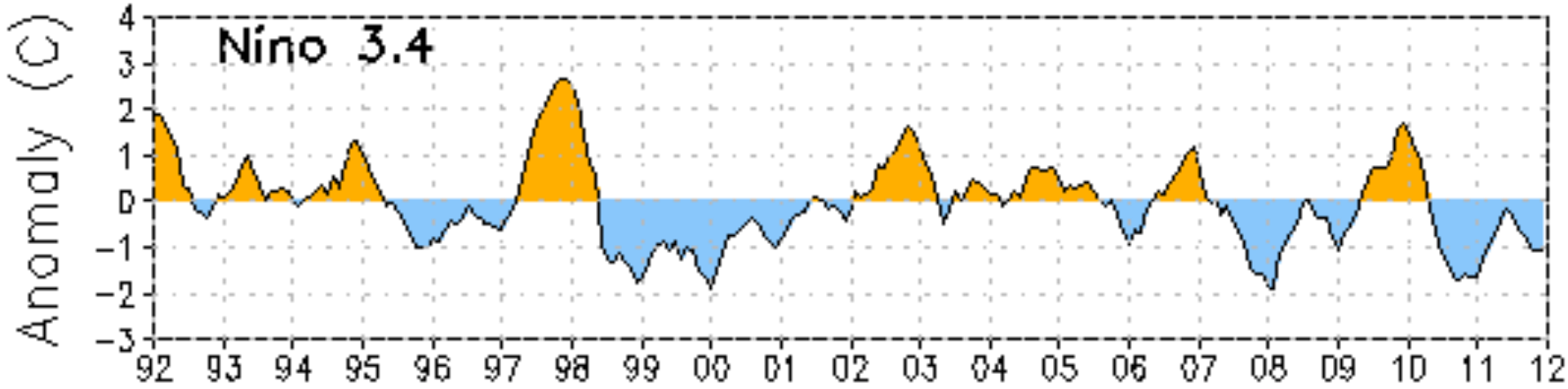
Time series of SeaWiFS-derived primary production averaged over the whole sub-tropics (not just Pacific)

Behrenfeld et al. (2006)

El Niño/La Niña events

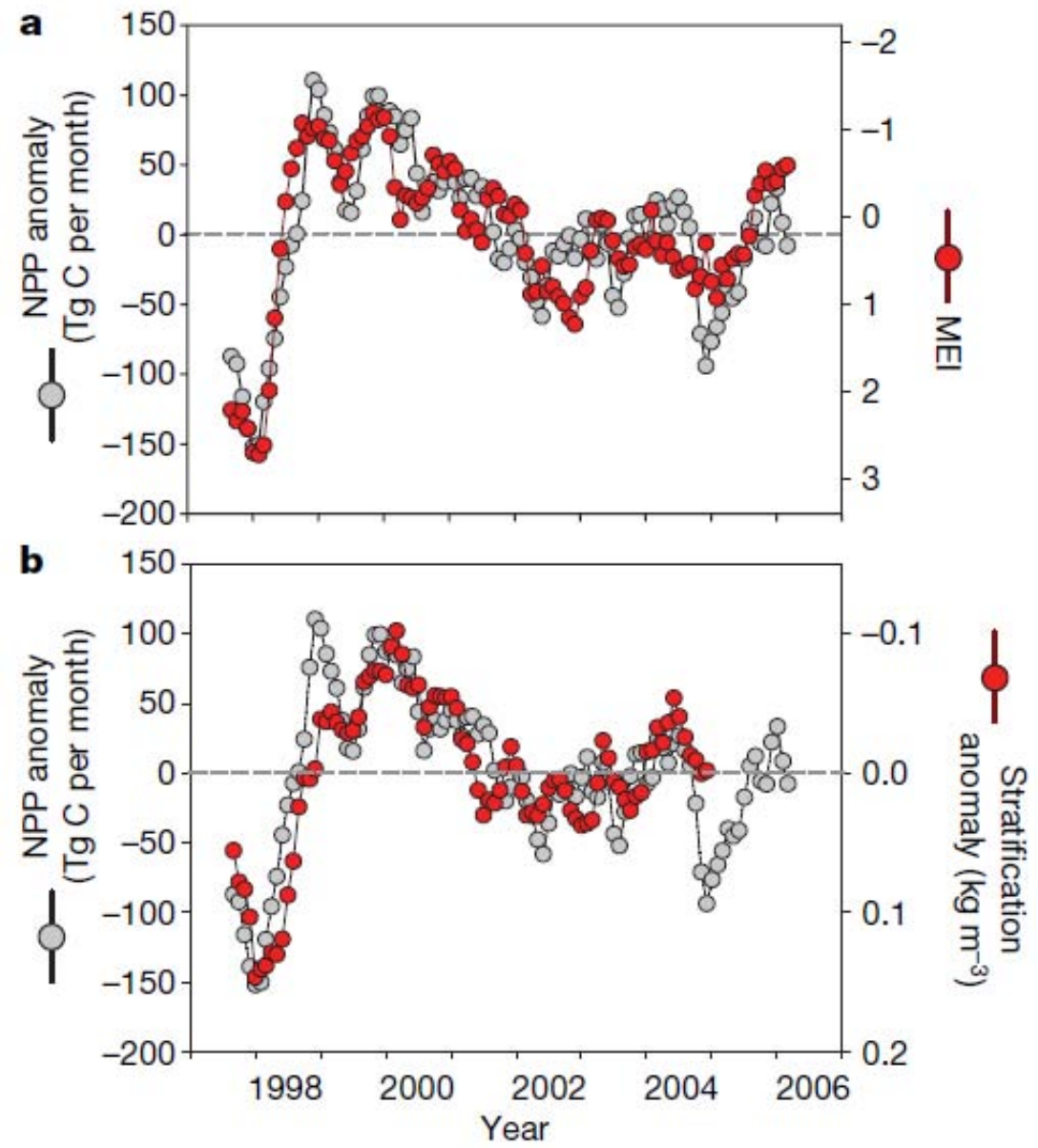
El Niño, La Niña and normal conditions are summarized by a 'climate index'. The Niño-3.4 index is the anomaly of sea surface temperature in the equatorial Pacific.





http://www.esrl.noaa.gov/psd/data/climateindices/

El Niño/La Niña events



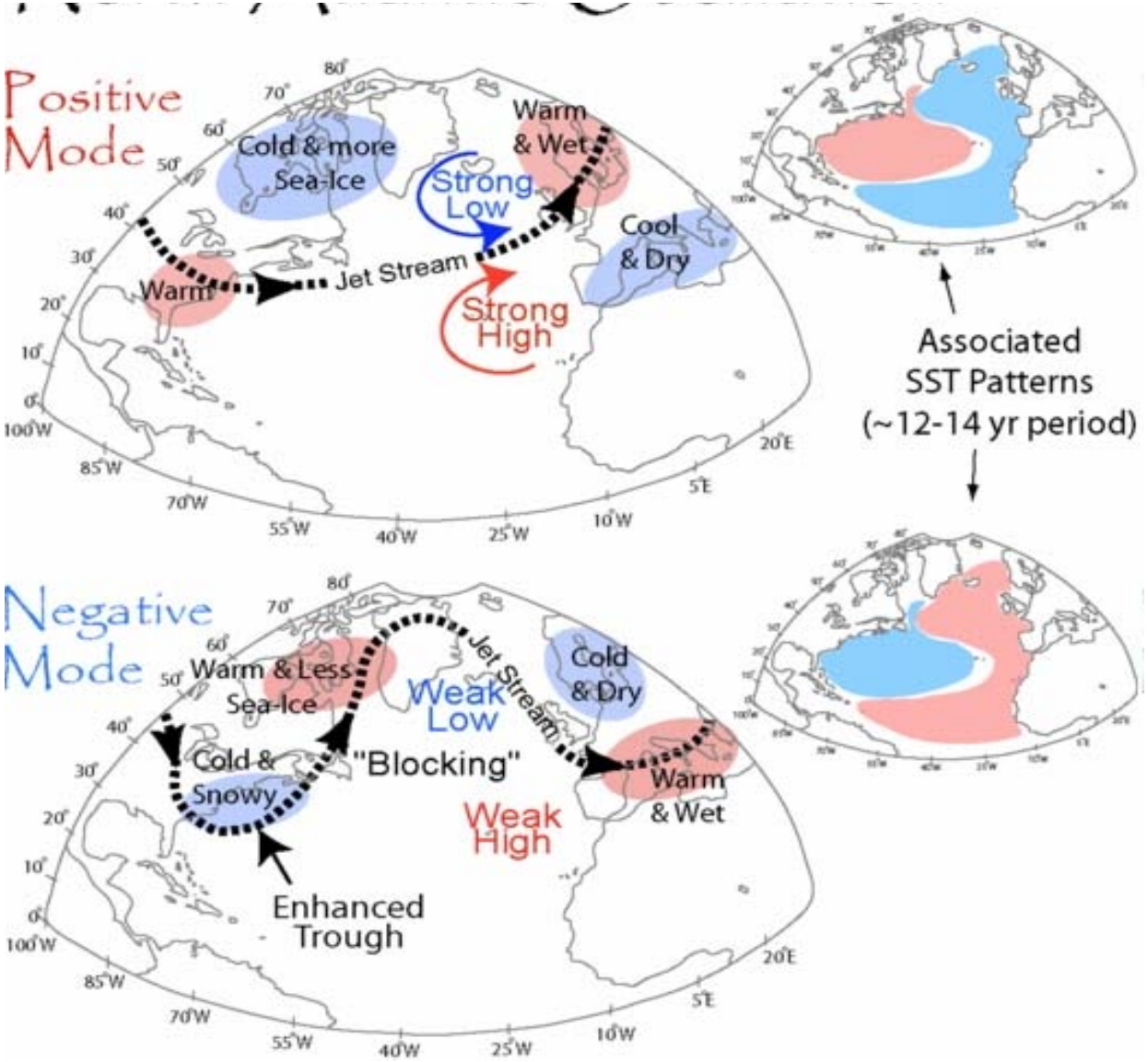
Behrenfeld et al. (2006)

The anomaly in sub-tropical primary production is anti-correlated with the El Niño index, i.e. EN = low PP, LN = high PP

WHY?

Because in EN years, stratification in the sub-tropics increases, imposing stronger nutrient limitation. In LN years, stratification weakens, resulting in increased nutrient concentrations in the euphotic zone.

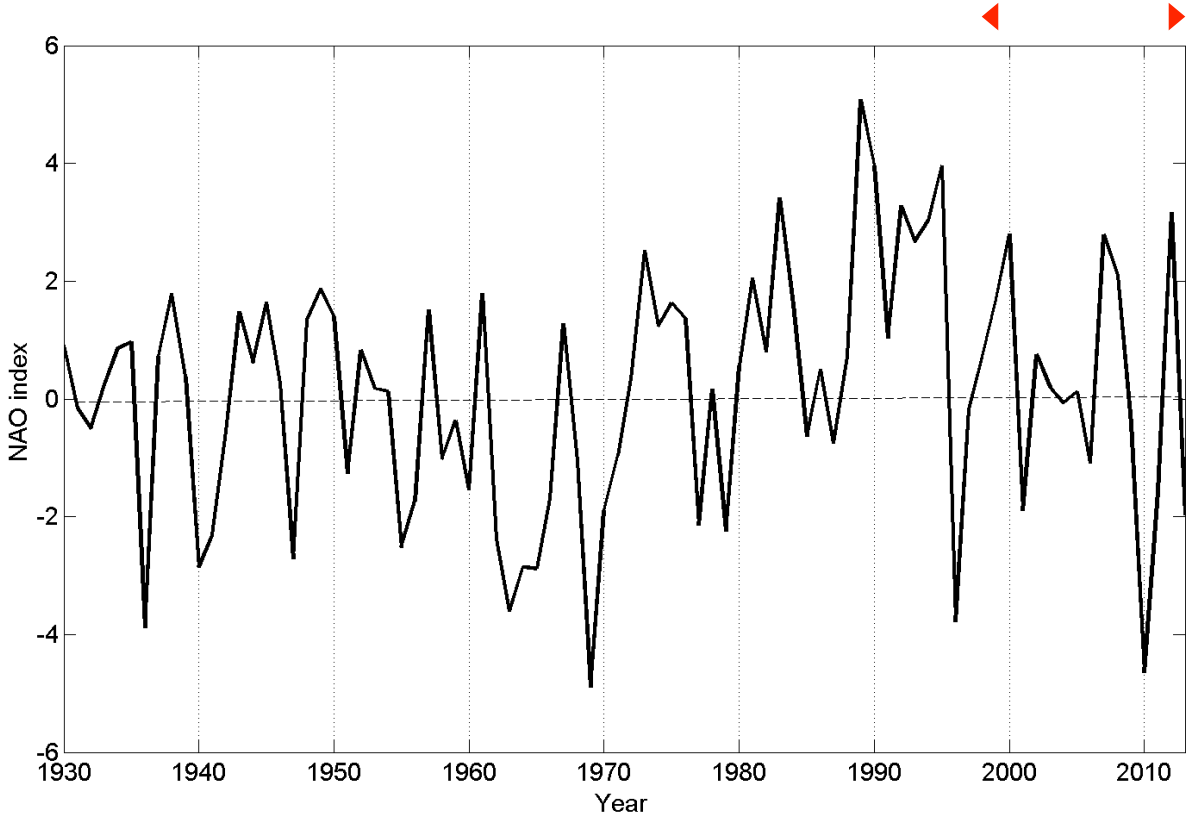
North Atlantic Oscillation



NAO index defined as the sea level pressure difference between Portugal and Iceland

http://www.newx-forecasts.com/nao.html

North Atlantic Oscillation

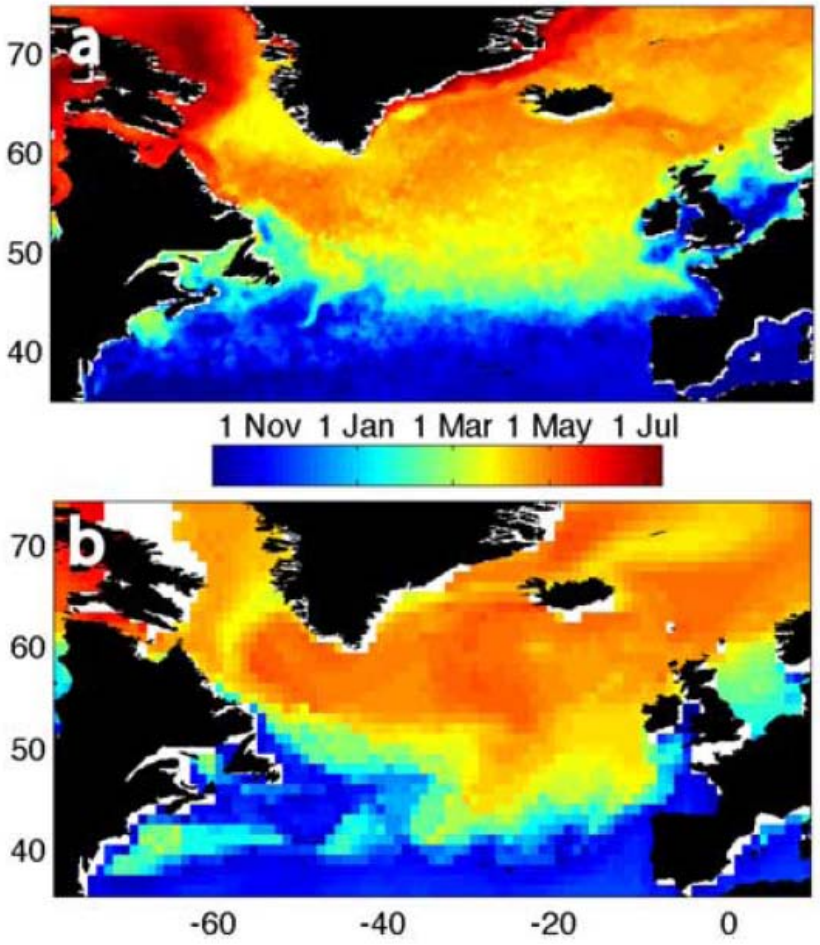


http://www.cgd.ucar.edu/cas/jhurrell/indices.html

Is the 16 years of ocean colour data sufficient to adequately represent the difference between positive and negative NAO phases?

North Atlantic Oscillation

To get at decadal variability, can also use a combination of satellite data and model output. Of course, we have to validate the model first!

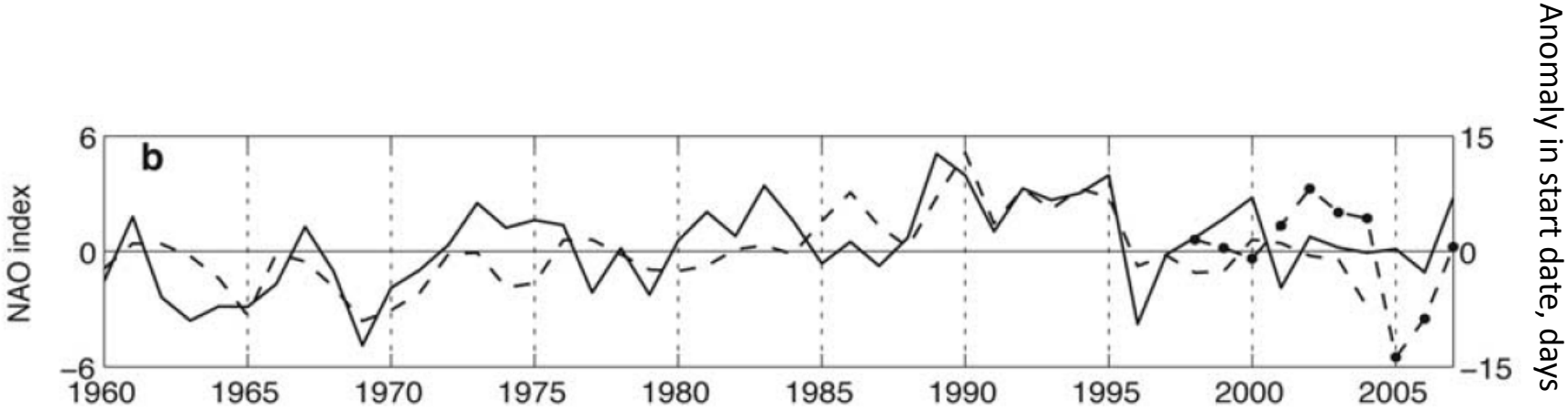


Mean bloom timing from SeaWiFS data

Mean bloom timing from a biogeochemical model

Henson et al. (2009)

North Atlantic Oscillation



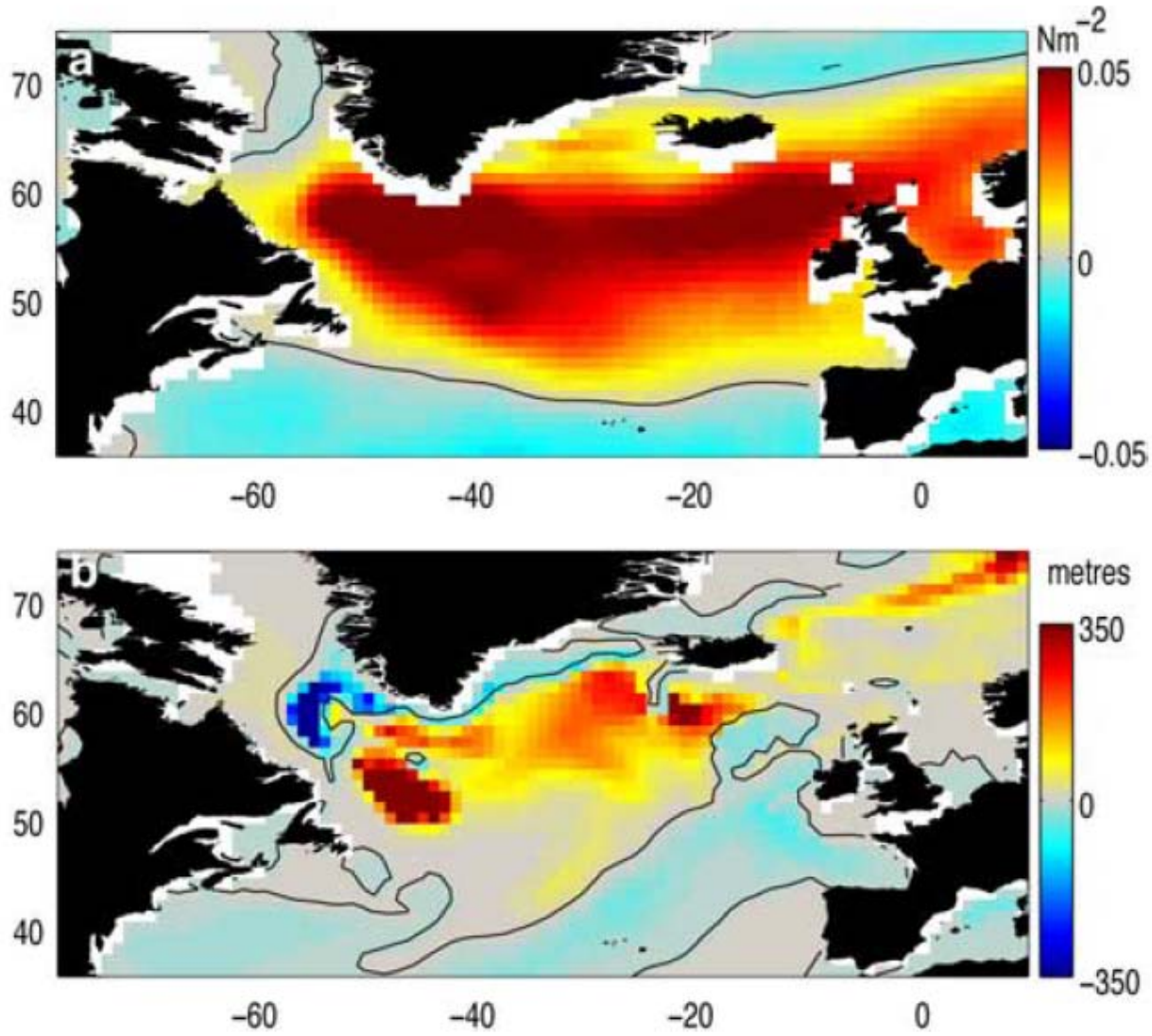
Solid line is NAO index; dashed line is anomaly in modelled start date in the sub-polar North Atlantic; dotted line is anomaly in satellite-derived start date.

In the sub-polar part of the North Atlantic, positive phase of the NAO corresponds to later start to the spring bloom.

WHY?

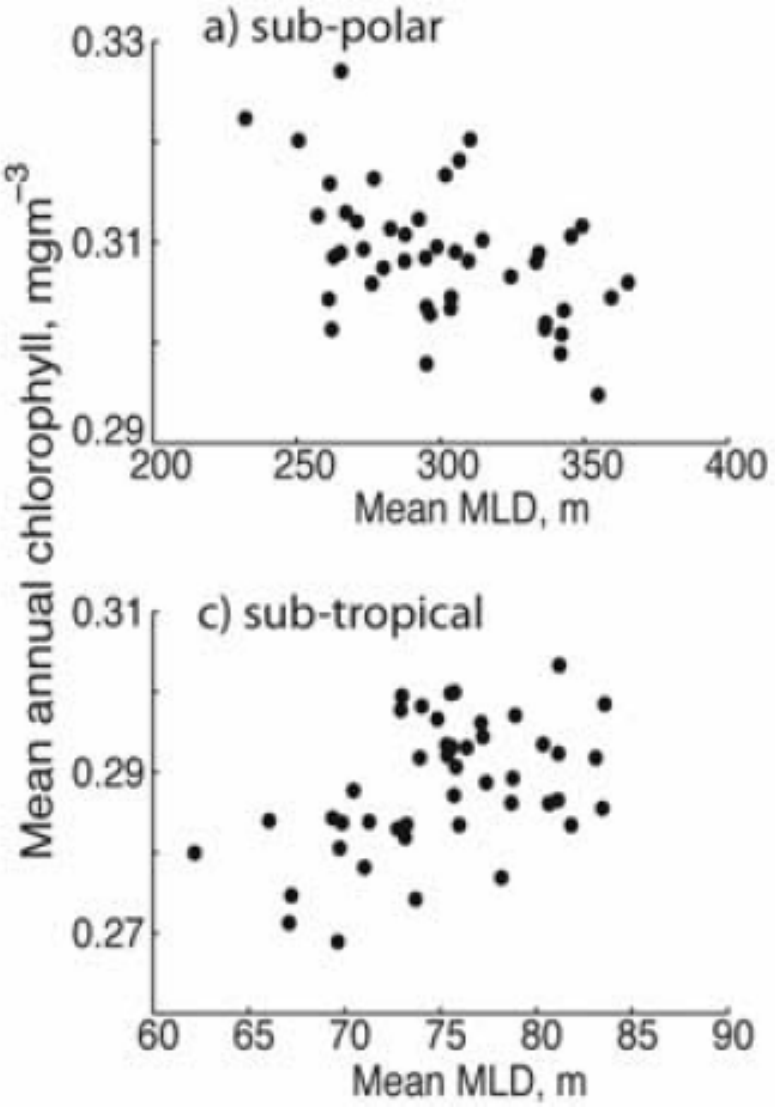
Henson et al. (2009)

North Atlantic Oscillation



Difference in westerly wind stress (top) and MLD (bottom) between negative and positive NAO phase

North Atlantic Oscillation



Henson et al. (2009)

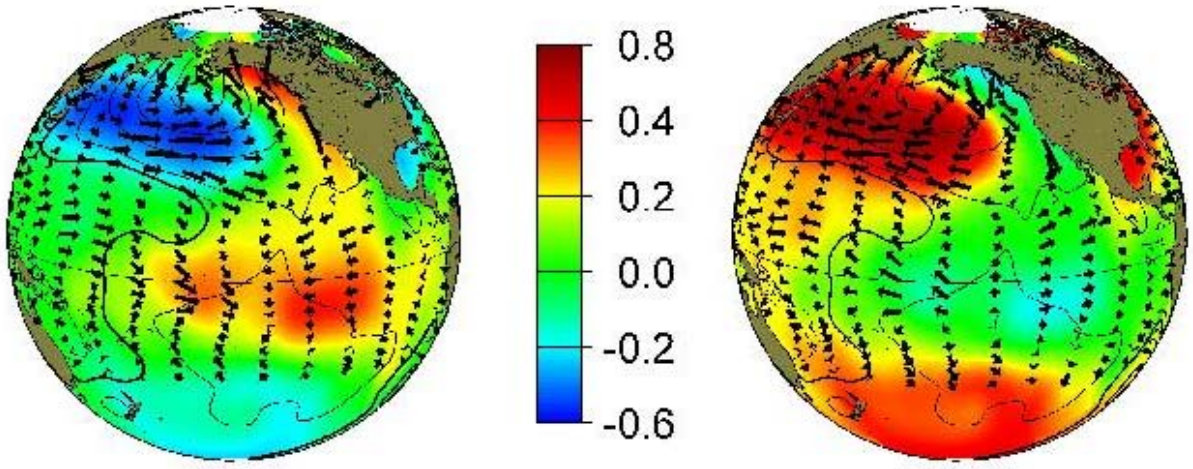
Relationship between interannual variability in modelled mean winter MLD and bloom magnitude

Why do we see these opposing relationships?

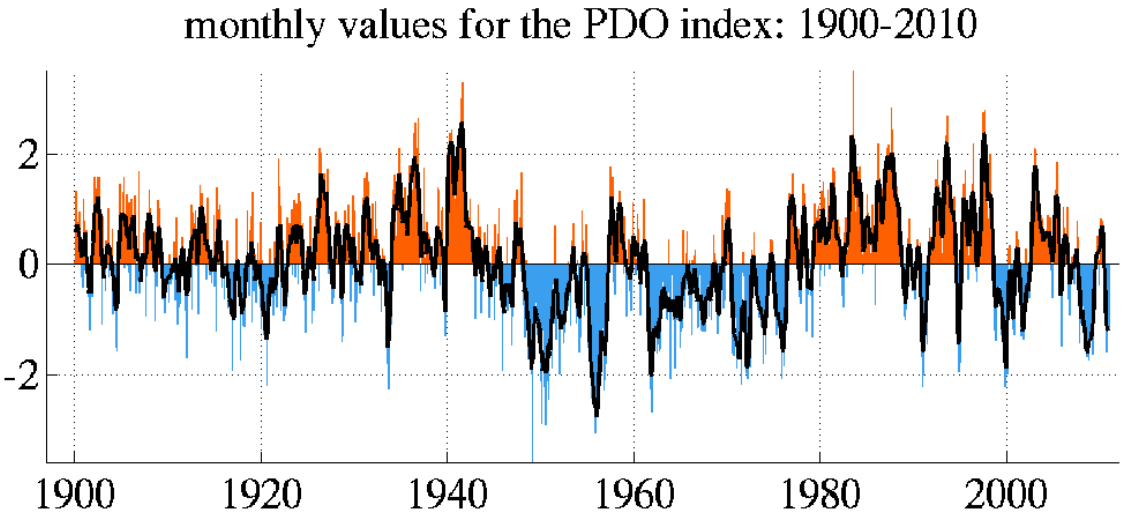
Pacific Decadal Oscillation

Warm phase

Cool phase

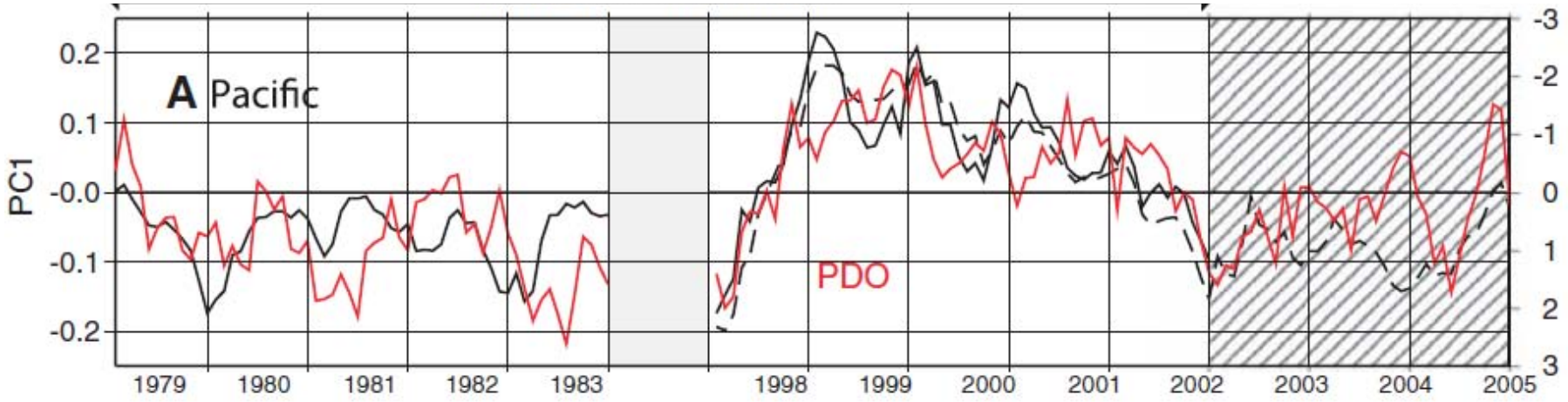


Typical wintertime SST (colours), wind stress (arrows) and sea level pressure (contours)



http://jisao.washington.edu/pdo/

Pacific Decadal Oscillation



Positive PDO associated with increased chlorophyll (averaged over whole North Pacific)

Martinez et al., 2009

Many other drivers of interannual to decadal variability in phytoplankton

For example…

Indian Ocean Monsoons which cause large regional changes in phytoplankton populations (e.g. Wiggert et al., 2006)

Southern Oscillation Index linked to variability in MLD and chlorophyll in the Southern Ocean (e.g. Lovenduski and Gruber, 2005)

North Pacific Index linked to variability in mixing, phytoplankton and salmon stocks (e.g. Gargett, 1997)

Using ocean colour data for analysing interannual variability

- Think quantitatively (particularly if you're studying a large region)
- Define variability in magnitude, location, start, length etc. of chlorophyll bloom
- What controls this variability? (combine colour data with other data)

Summary 2

- There is substantial interannual and decadal variability in phytoplankton – both in terms of magnitude and timing
- Phytoplankton variability arises from variability in atmospheric and physical oceanographic conditions
- Decadal variability in conditions is often encapsulated in various climate indices
- Several years of data are needed to see the effects of both the positive and negative phases of climate indices
- The variability in phytoplankton has knock-on effects on zooplankton and fish larvae survival

How do you think climate change could impact phytoplankton populations?

How might climate change affect phytoplankton populations?

These are the processes identified as causing interannual variability:

- Variability in physical processes:

  Mixing/stratification. Heat flux, temperature, wind, storms, upwelling

- Variability in biological processes:

  Phytoplankton species composition, zooplankton grazing, viruses

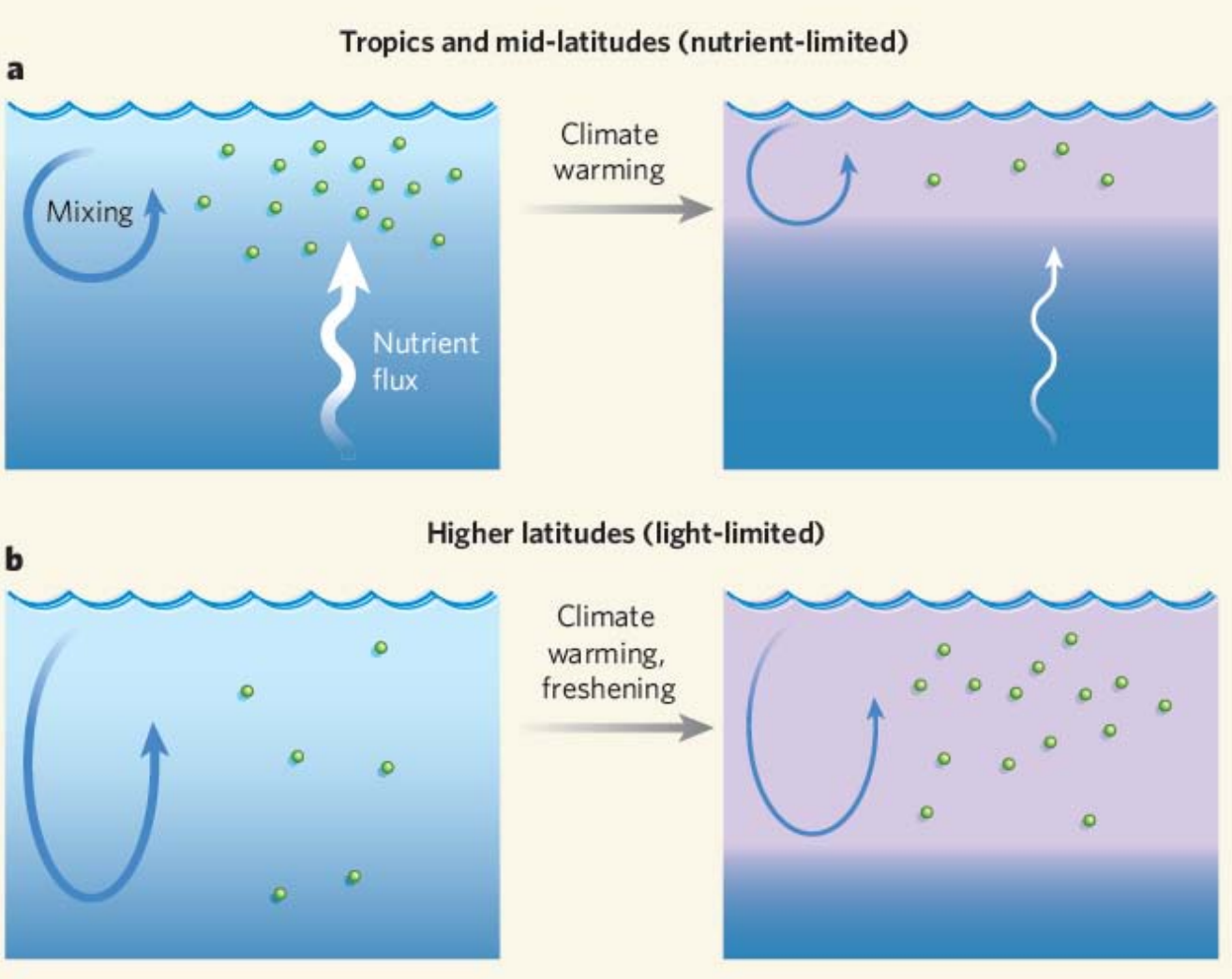
Detecting climate change effects on chlorophyll

Detecting climate change is important – policymakers, politicians, public

Potentially big impacts on fisheries, CO_2 uptake and storage

Important to detect trends and ascribe to climate change (not just variability)

How might climate change alter chl?

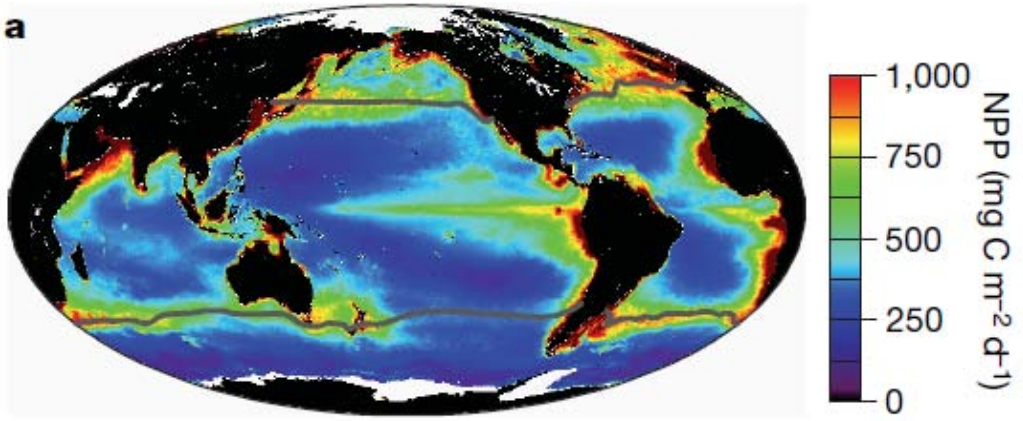


Reduced mixing + nutrient limitation -> lower PP

Reduced mixing + light limitation -> higher PP & earlier blooms

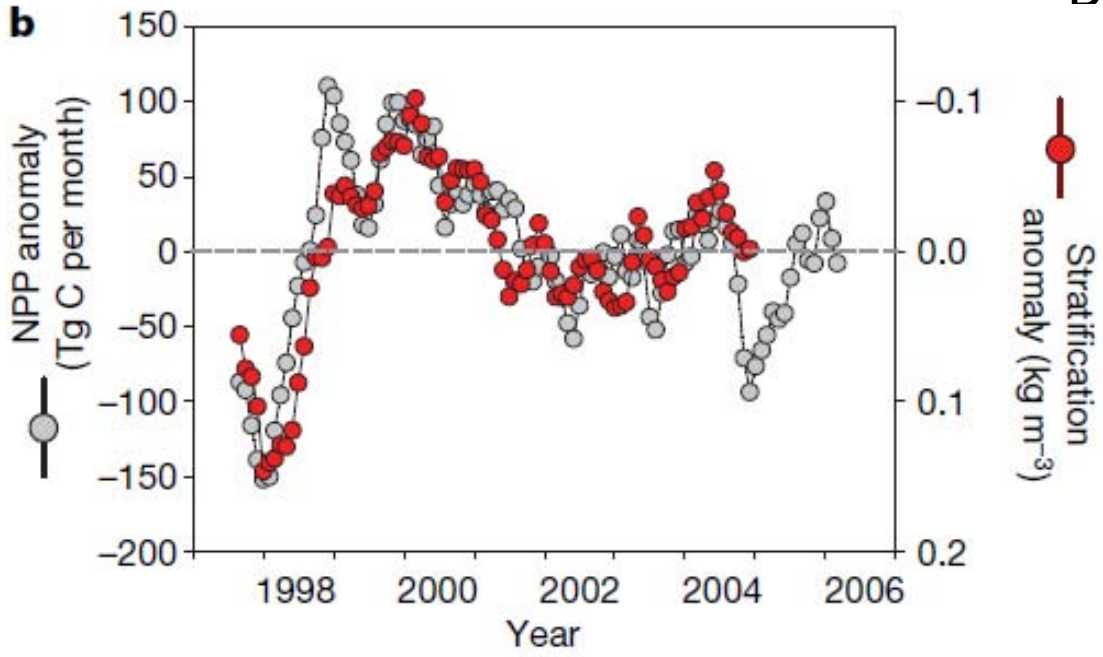
Doney, 2006

Can we already detect impact of climate change on phytoplankton?



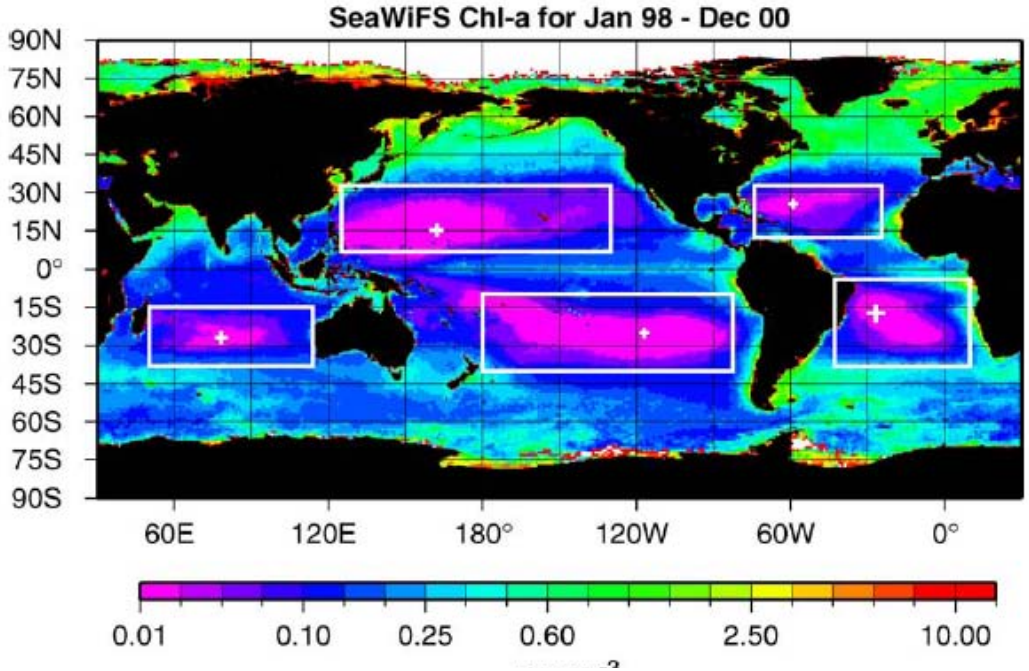
Sub-tropical decrease in satellite PP since 1999 attributed to increasing stratification

Behrenfeld et al. (2006)



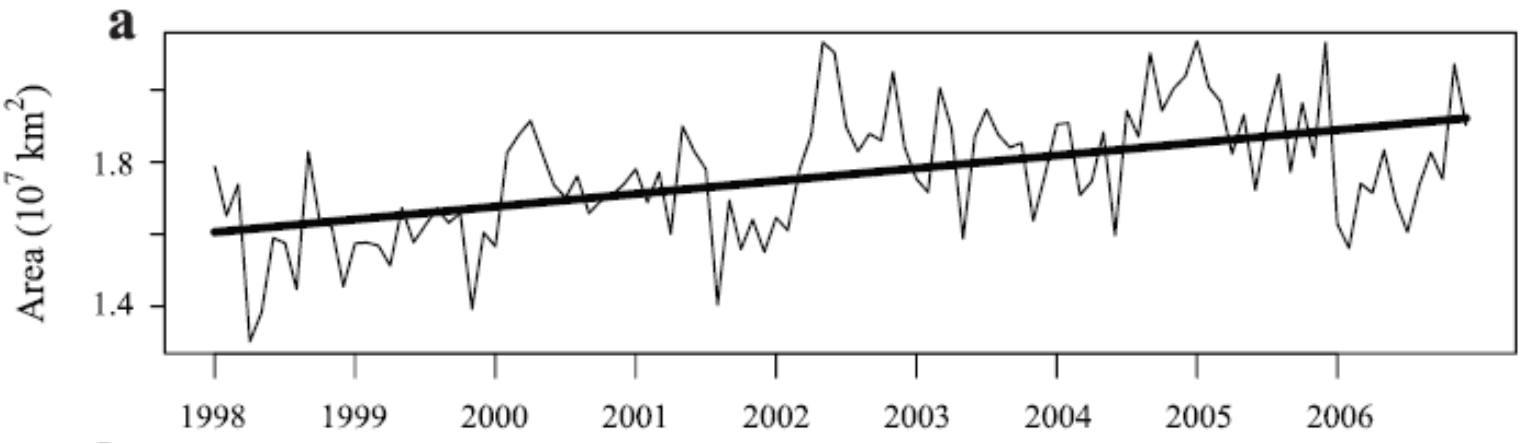
Does this reflect the impact of climate change?

Can we already detect impact of climate change on phytoplankton?



Size of oligotrophic gyres increased since 1998

Polovina et al. (2008)



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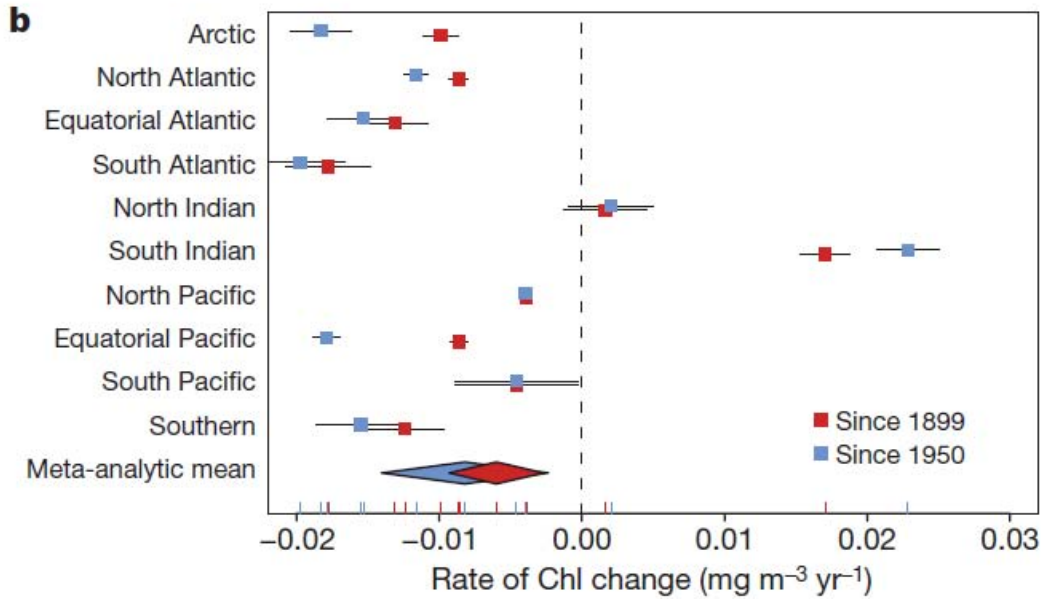
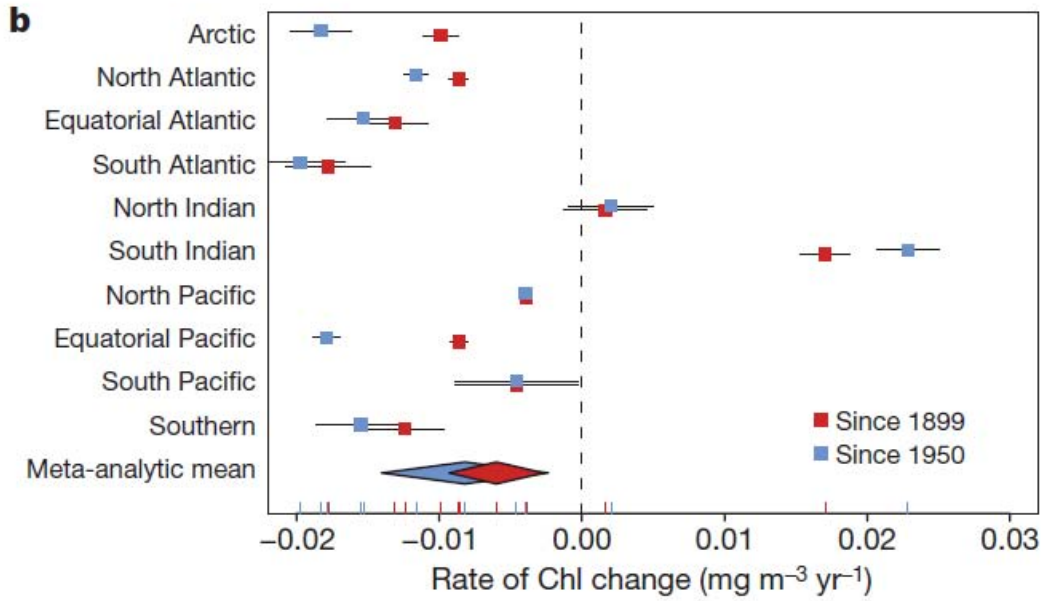
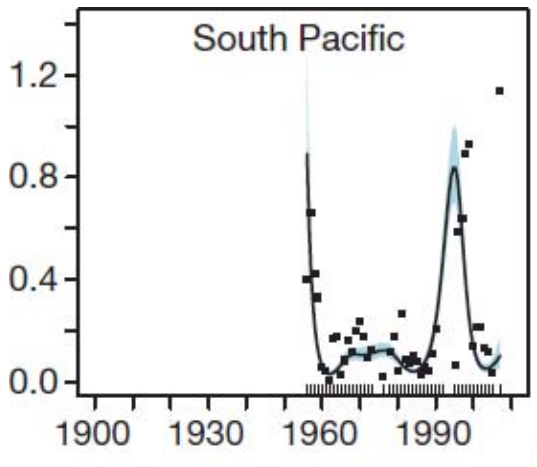
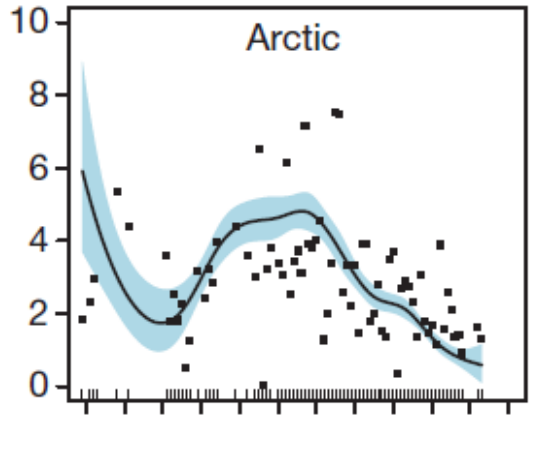
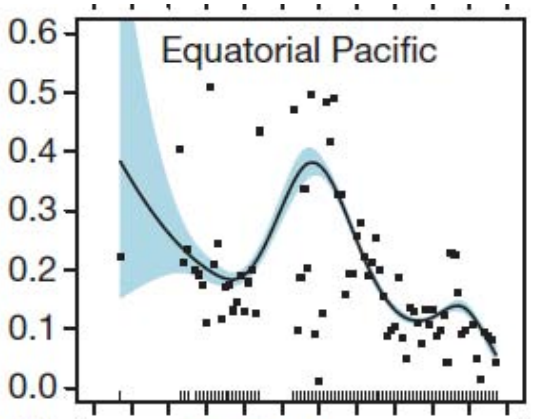
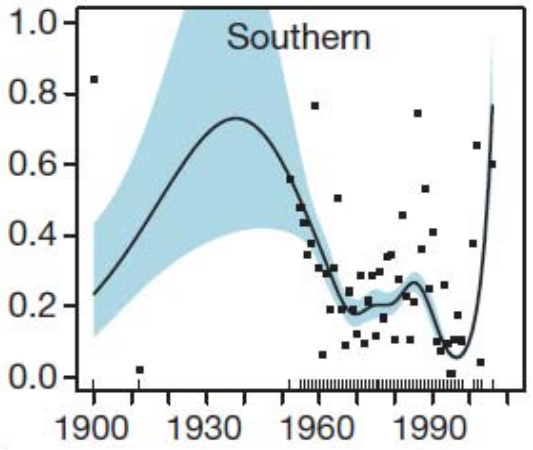


100 years of data combining *in situ* Secchi depth and chlorophyll measurements

Boyce et al. (2010)

Can we already detect impact of climate change on phytoplankton?

See also rebuttals in *Nature* 472 (7342)