What Colour is the Ocean?

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The fascination of ocean colour

Over the centuries, the colour of the ocean has inspired poets, artists, geographers, sailors, fishermen and explorers

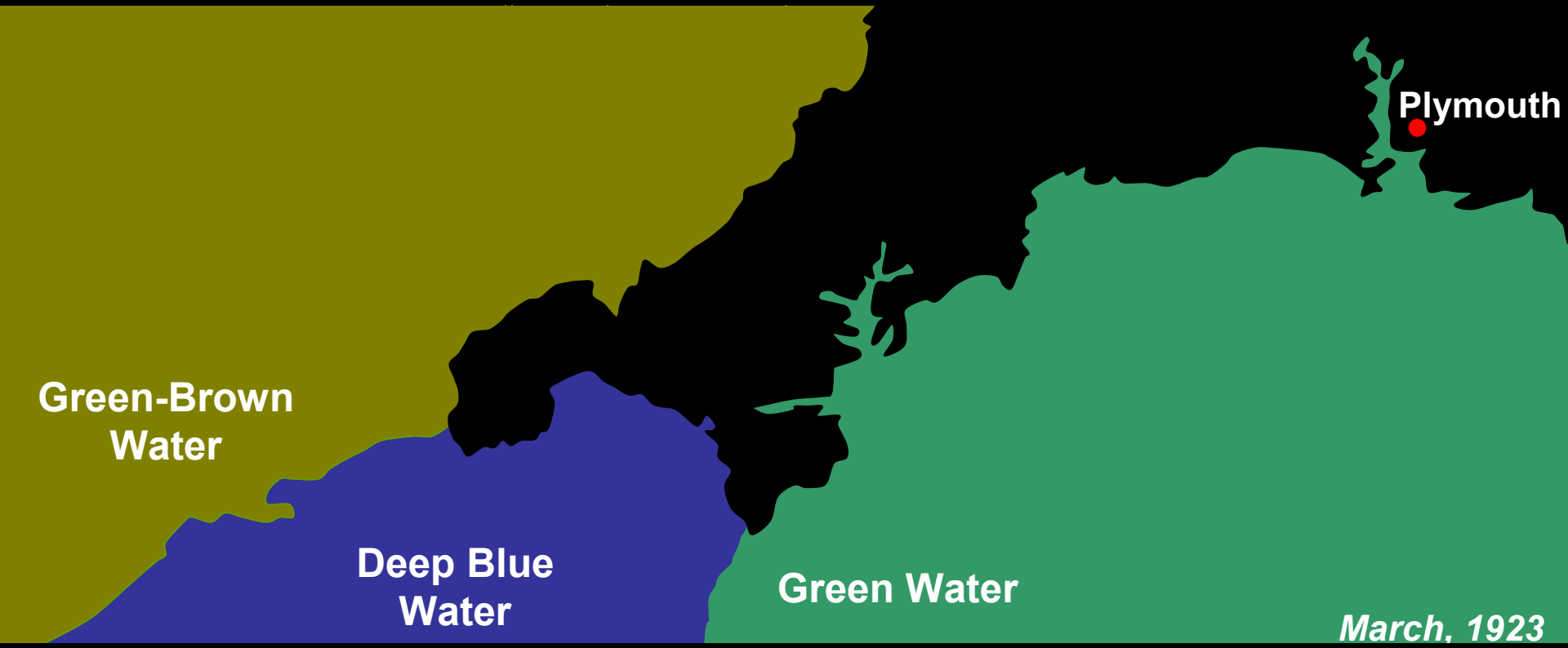
Alister Hardy

Alister Hardy

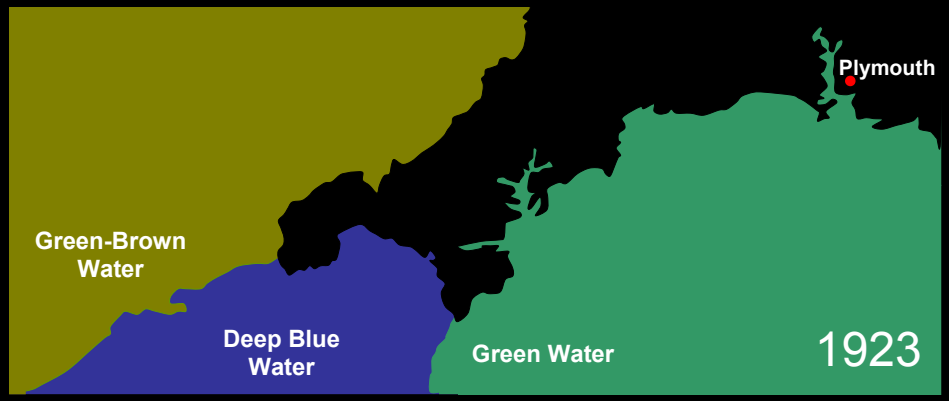
Colour of ocean as seen from ship at different times and places

Mariners have known for centuries that such differences in ocean colour provide important information for fishermen: whaling captains, notably William Scoresby, were particularly observant

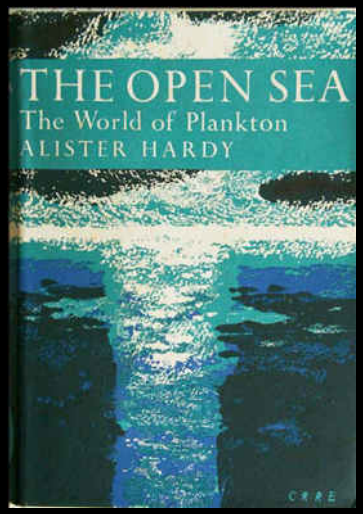
Alister Hardy (1923): Pioneering steps in Ocean-colour remote sensing



"…we passed over a sharp line separating the green water of the Channel from the deep blue of the Atlantic."



"If these marked colour-changes can be correctly interpreted we may in the future find aircraft being used to make rapid surveys of surface conditions in relation to fisheries."

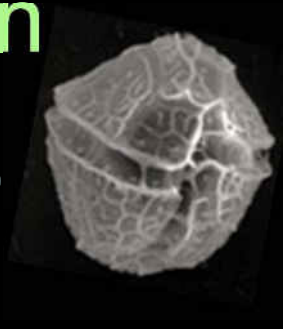


Ocean Colour: From Art to Science

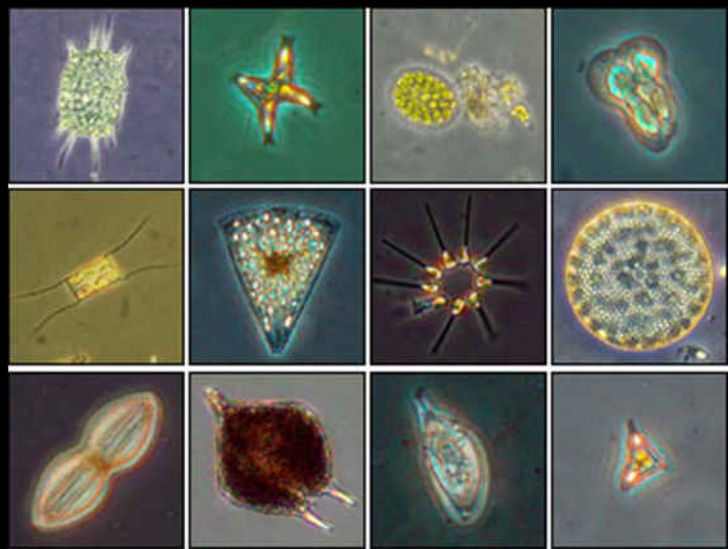
- But there are also scientific conclusions to be drawn from ocean colour
- Why is this so?
- Colour of the ocean contains latent information on the abundance of the marine microflora (phytoplankton)
- Invisible to the naked eye at close quarters, but huge collective impact visible from space.

Phytoplankton bloom in the North Sea off the coast of Scotland. Image captured by ESA's MERIS sensor on 7 May 2008.

Some properties of phytoplankton



- Predominantly single-celled and microscopic (0.5 to 250μm)
- Green plants (chlorophyll pigments, photosynthesis)
- Mostly confined to the surface (illuminated) layer
- Ubiquitous and abundant (up to 10^5 cells ml^{-1})
- Control colour of water (detectable from space)
- Consume carbon dioxide
  (ocean carbon cycle, climate change)
- Collective metabolism enormous
  (50 x 10^9 tonnes per annum)
- Slightly negatively buoyant

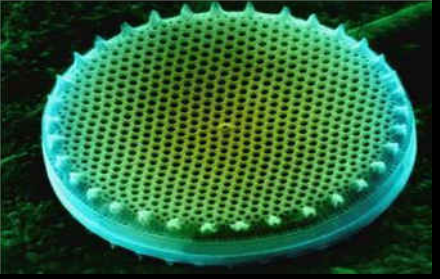


Ocean Ecosystem as Thermodynamic System

The pelagic ecosystem is an open, dissipative system sustained by regular energy supply from sun, to which it is coupled through the pigment molecules contained in phytoplankton. The light penetrating into the ocean allows biogeochemistry, where otherwise only geochemistry would be possible.

Furthermore, the light that escapes from the ocean (the basis of the ocean-colour signal), carries coded information on ocean biology and biogeochemistry.

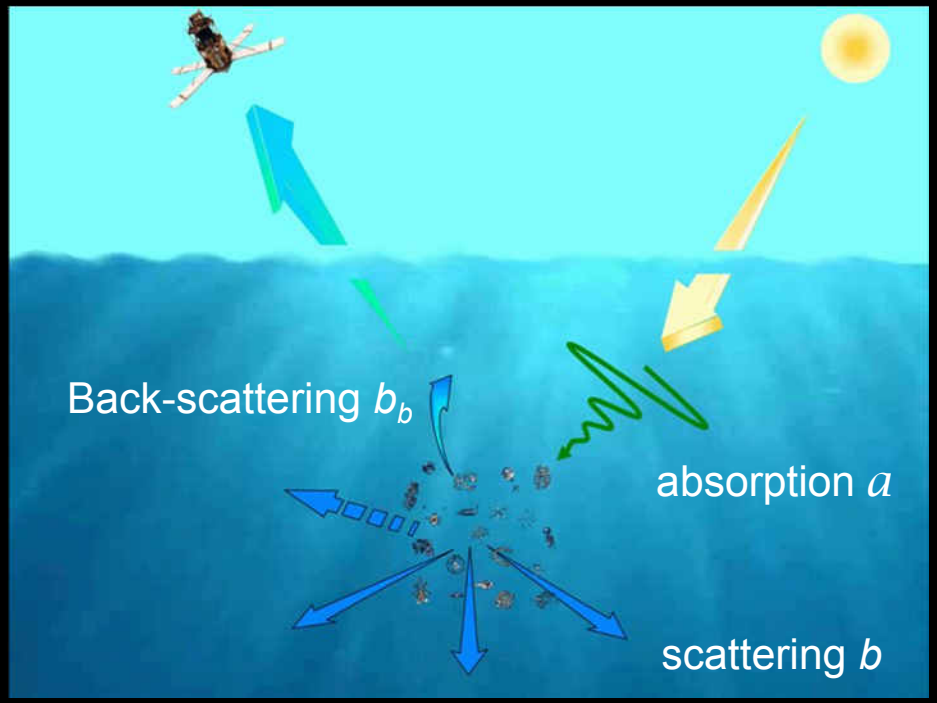
Emil Nolde

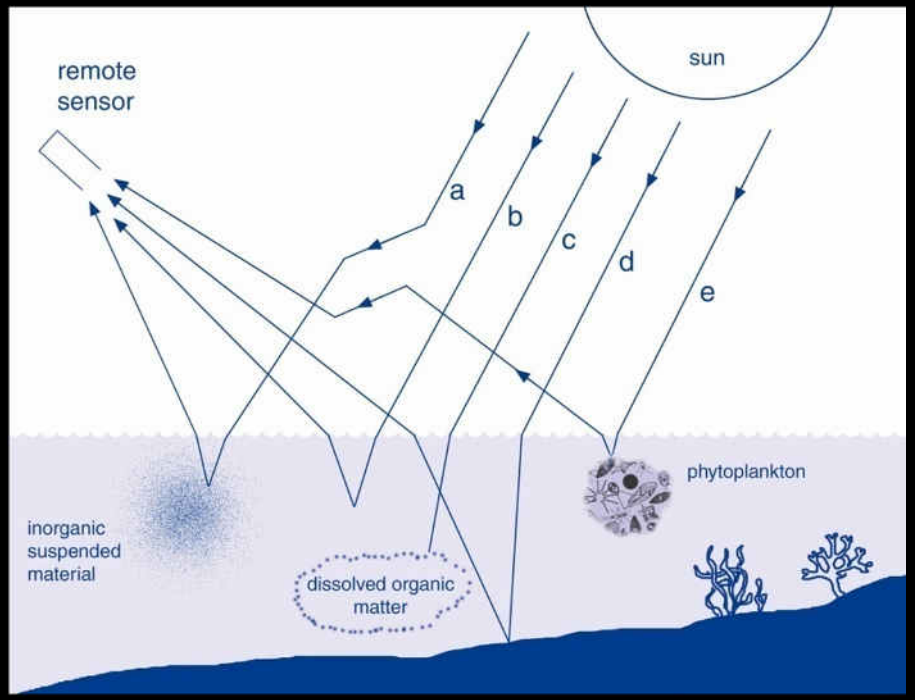


Decoding and exploiting the signal

- What is ocean colour?
- What is its relevance?
  - Physical oceanography
  - Biogeochemistry (carbon cycle, functional types)
  - Ecosystem indicators
  - Marine resources
- Outlook for the future

Factors that influence upwelling light leaving the sea surface





Two optical processes determine the fate of photons that penetrate into the ocean: absorption and scattering. These effects depend on wavelength of the light. Can be described by strict physical theory.

The water-leaving radiance contains information on phytoplankton, suspended sediments, dissolved organic material and bottom type (in shallow waters)

Colour of water varies depending on what is in it. For scientific applications, we need to quantify the effect of marine constituents on water colour.

Green

Turtle pound, Winslow Homer

Blue

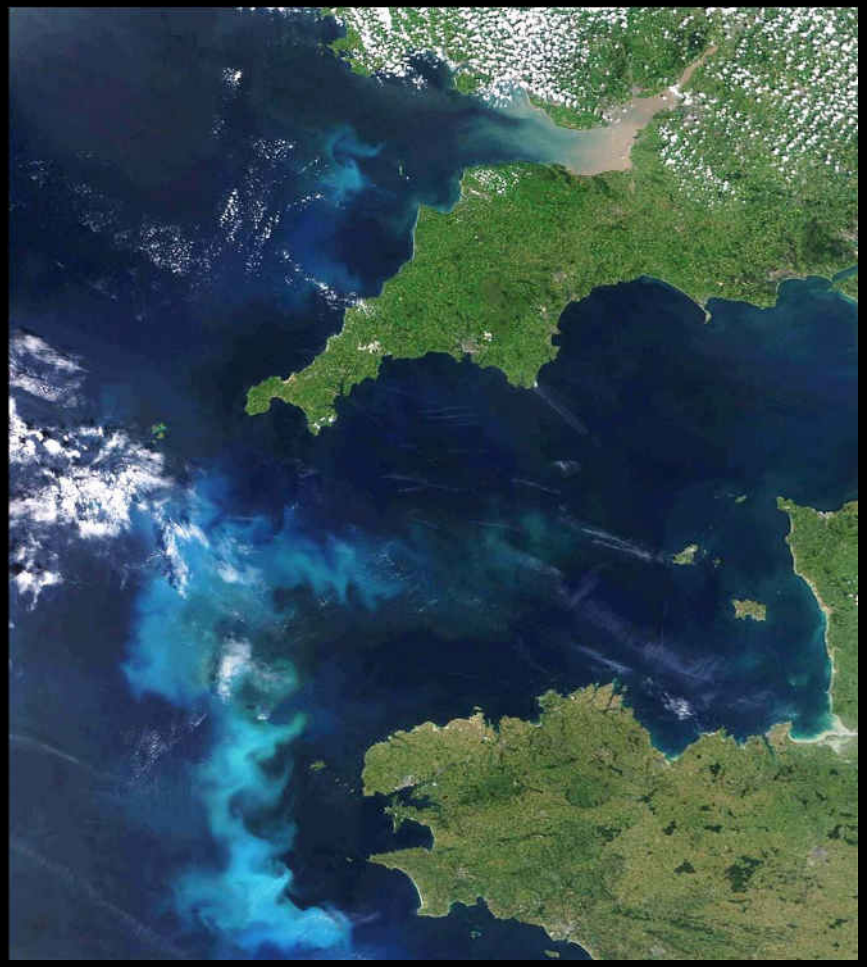
Coral formation, Winslow Homer

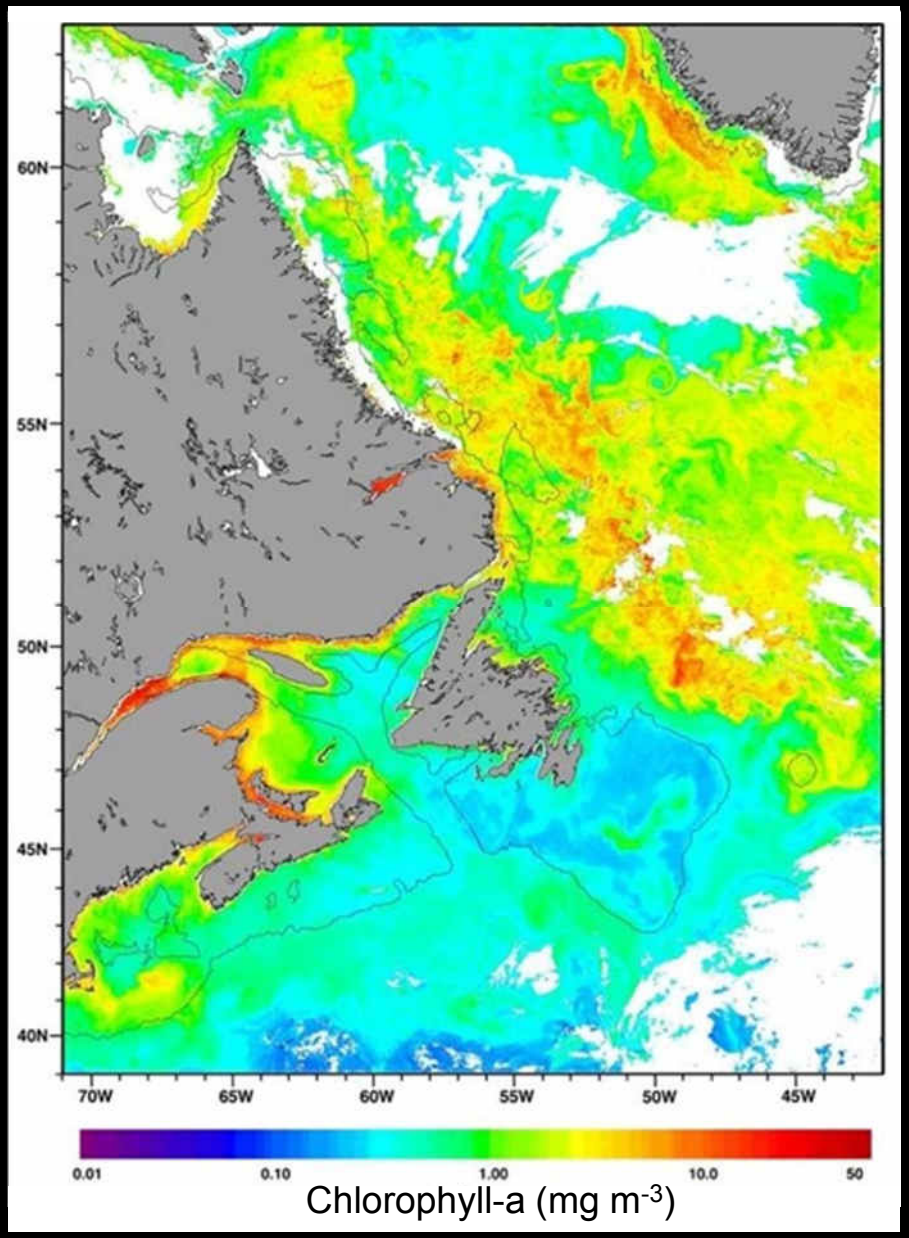
Turquoise

Natural Bridge Bermuda, Winslow Homer

Phytoplankton Bloom June 2005

- Extent of bloom readily shown in this true-colour image
- Sediments colour water flowing out of Bristol Channel





SeaWiFS composite image
1-15 June 1998

A major product of ocean-colour remote sensing is distribution of chlorophyll concentration, the most fundamental property of the ocean ecosystem. It has been designated an Essential Climate Variable (UNFCCC).

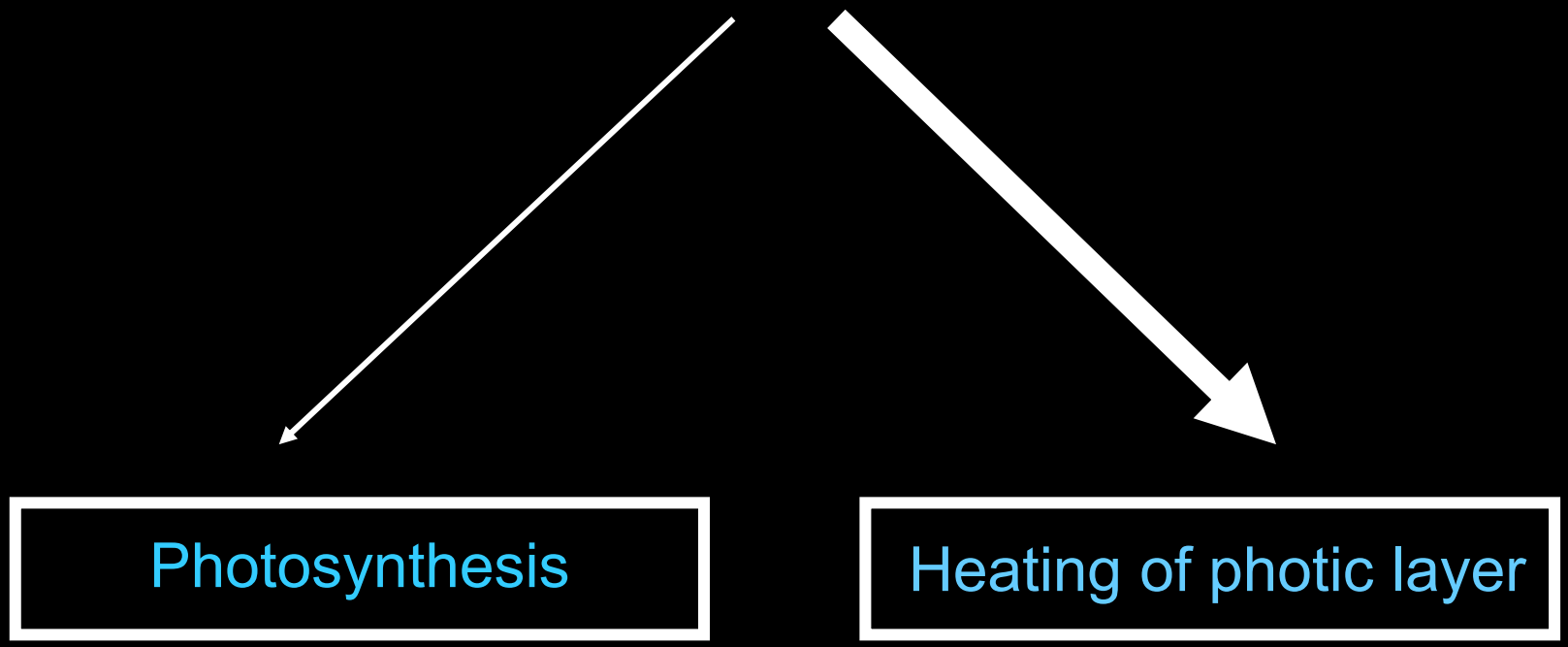
The colour-coded maps are strikingly beautiful. Furthermore, they are based on strict radiative transfer theory, and contain a wealth of information, with many applications.

The technique exploits the absorption of light by the pigment. What happens to the absorbed light? One pathway for the absorbed light is photosynthesis (primary production).

Principal Fate of Light Absorbed by Phytoplankton

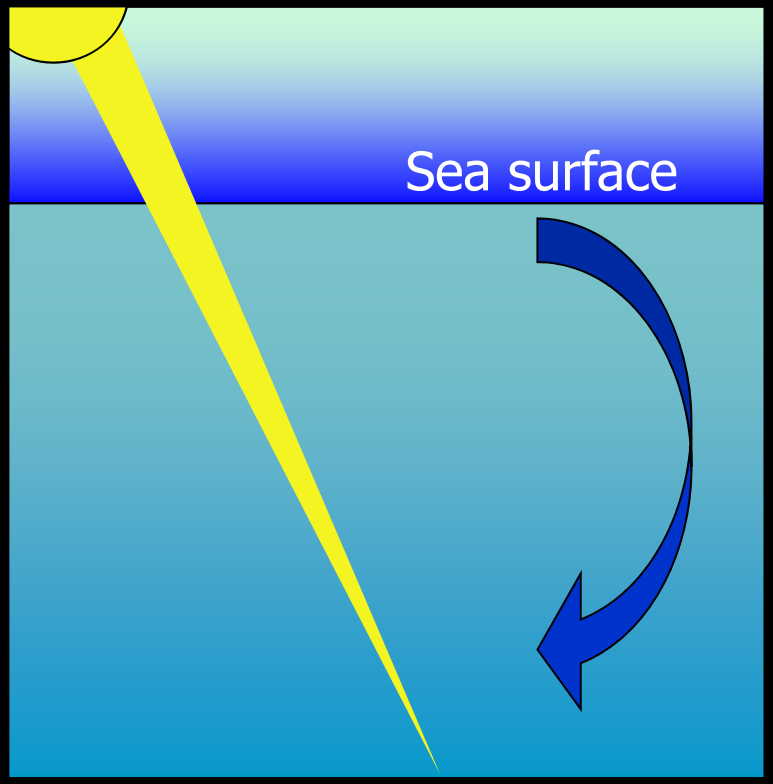
Thermal dissipation is the principal fate of energy absorbed by pigments, with a corresponding effect on the heat budget of ocean's upper layer

Dual Role for Light Absorbed by Phytoplankton



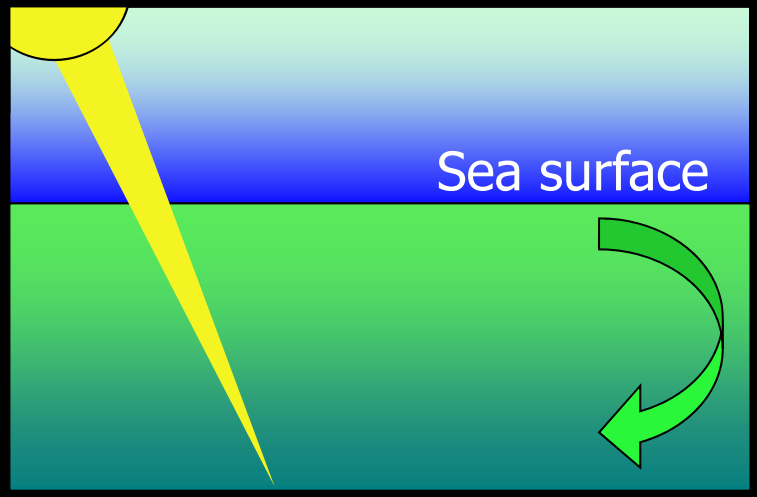
Diffuse attenuation coefficient *K* and mixed-layer depth

Low *K*



Implies: deep photic layer
deep mixed layer
lower average growth rates

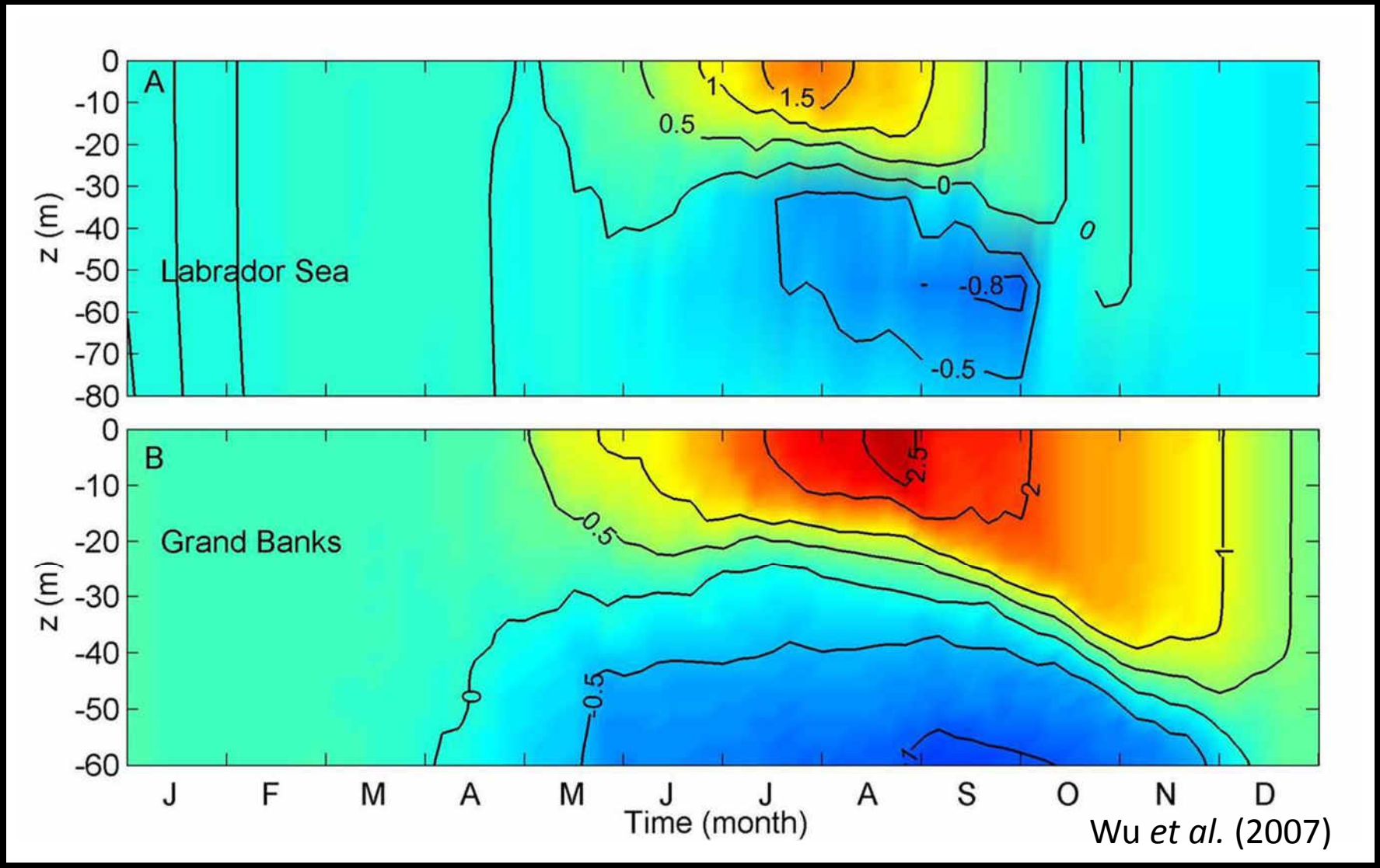
High *K*



Implies: shallow photic layer
shallow mixed layer
higher average growth rates

Sathyendranath & Platt (2007)

Biologically-induced temperature differences in the ocean

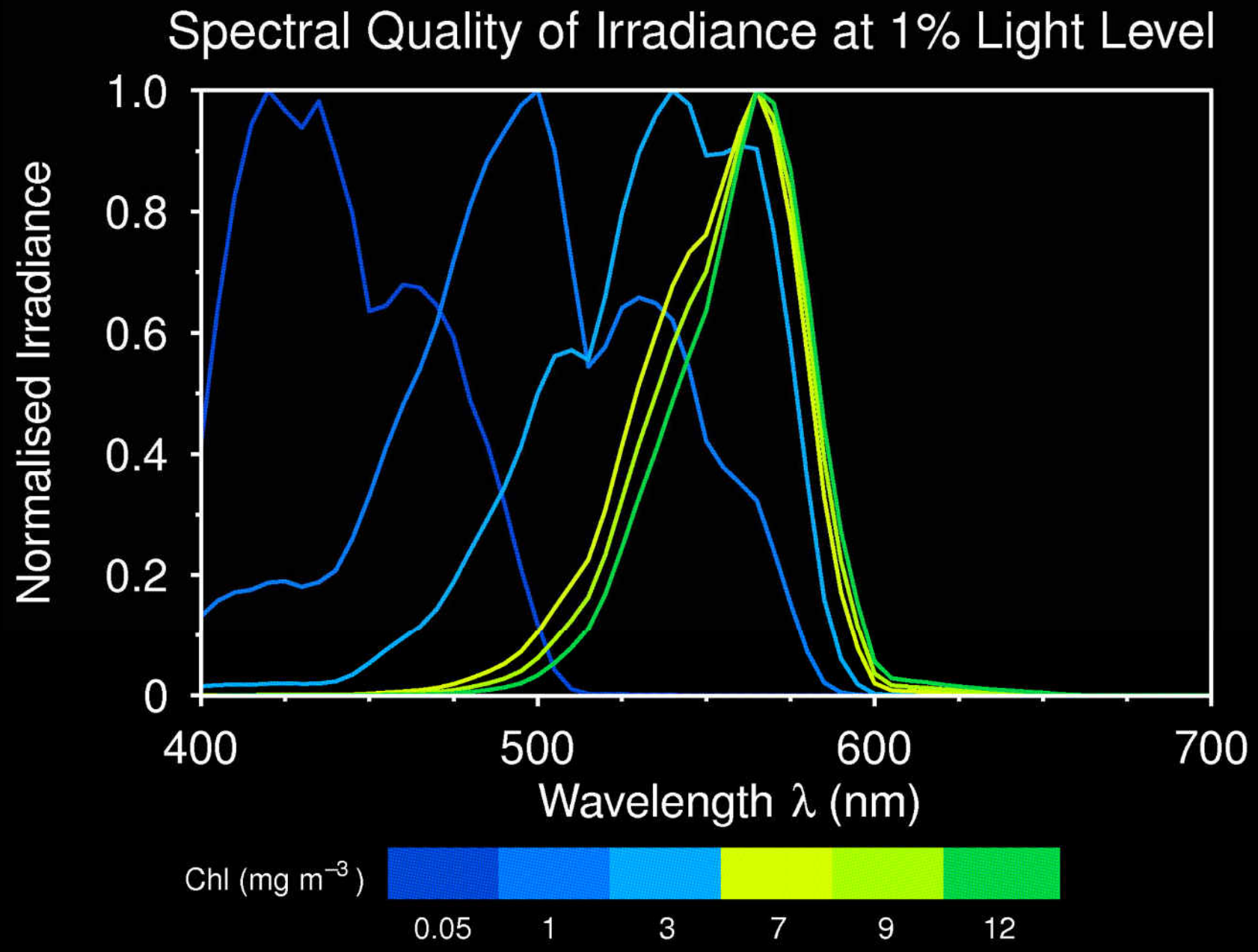


Wu *et al.* (2007)

Coupling between light and chlorophyll and related feedbacks should be an ingredient of Earth System studies in the context of climate change.

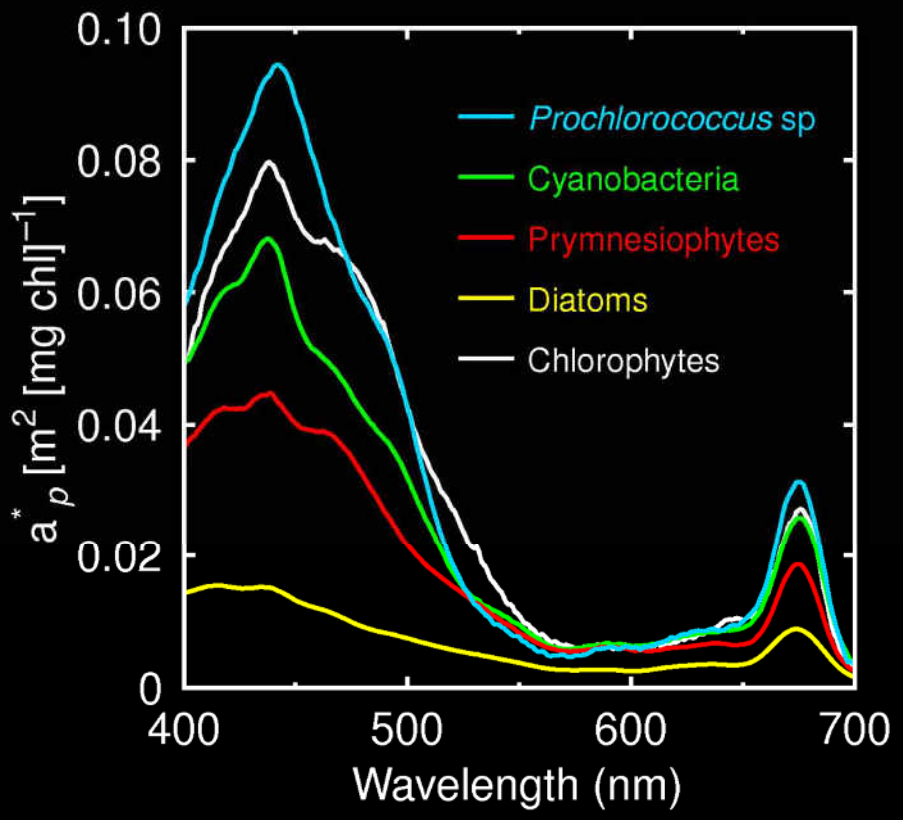
There is more to phytoplankton than just chlorophyll

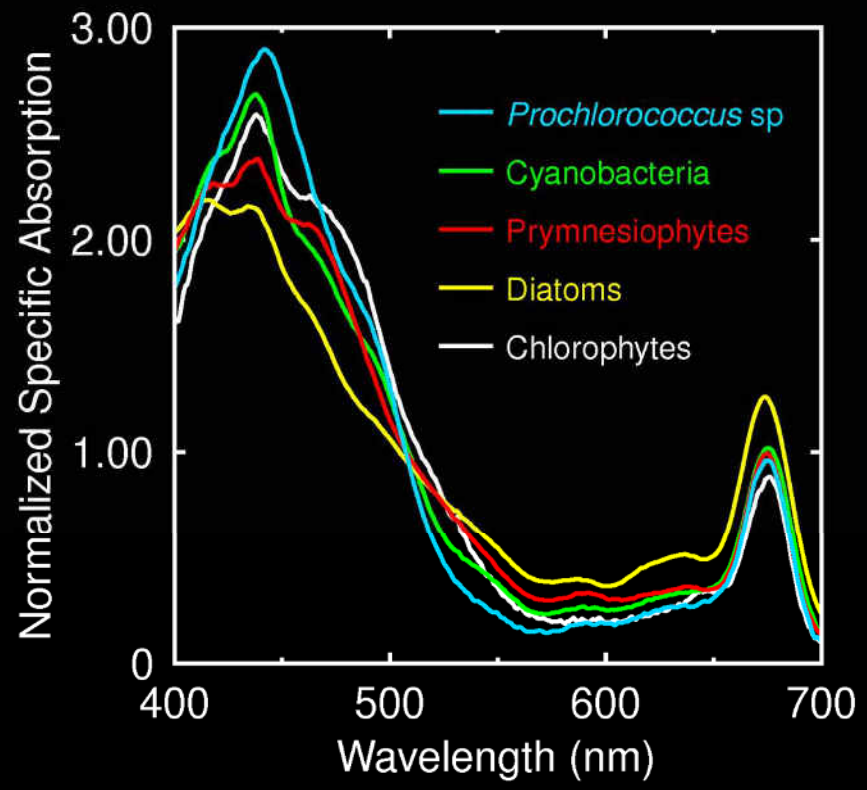
- Phytoplankton contain a suite of auxiliary pigments whose composition varies with taxa and with growth conditions
- Phytoplankton occupy a broad size range
- Both cell size and pigment composition modify optical characteristics of phytoplankton



Sathyendranath & Platt (2007)

Variability in absorption spectra of phytoplankton with community structure

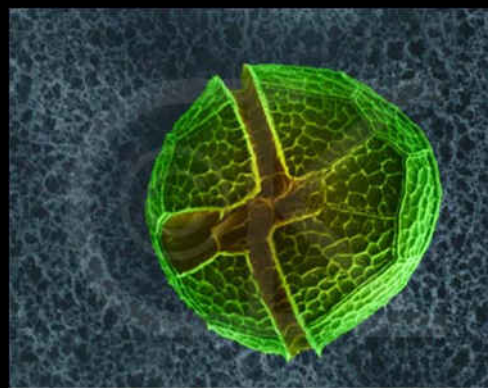




Sathyendranath & Platt (2007)

Community structure of phytoplankton and societal issues

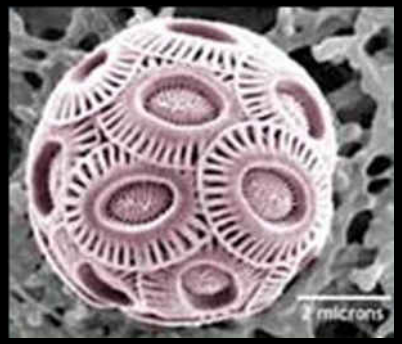
- There is more to phytoplankton than just carbon
- In addition to being major players in the global carbon cycle, phytoplankton also have an important role in the planetary cycles of various other elements, for example
  - Nitrogen
  - Silica
  - Iron
  - Calcium



Some Phytoplankton Functional Groups: Relevance for Climate Change

Silicifiers

Implications for carbon export

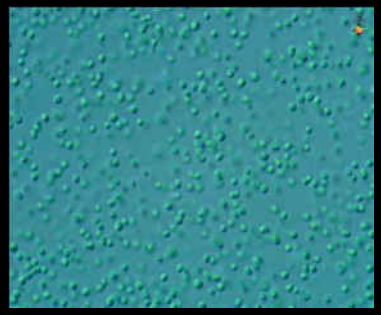


Calcifiers

Ocean acidification
Carbon cycle

DMS Producers

Cloud condensation nuclei



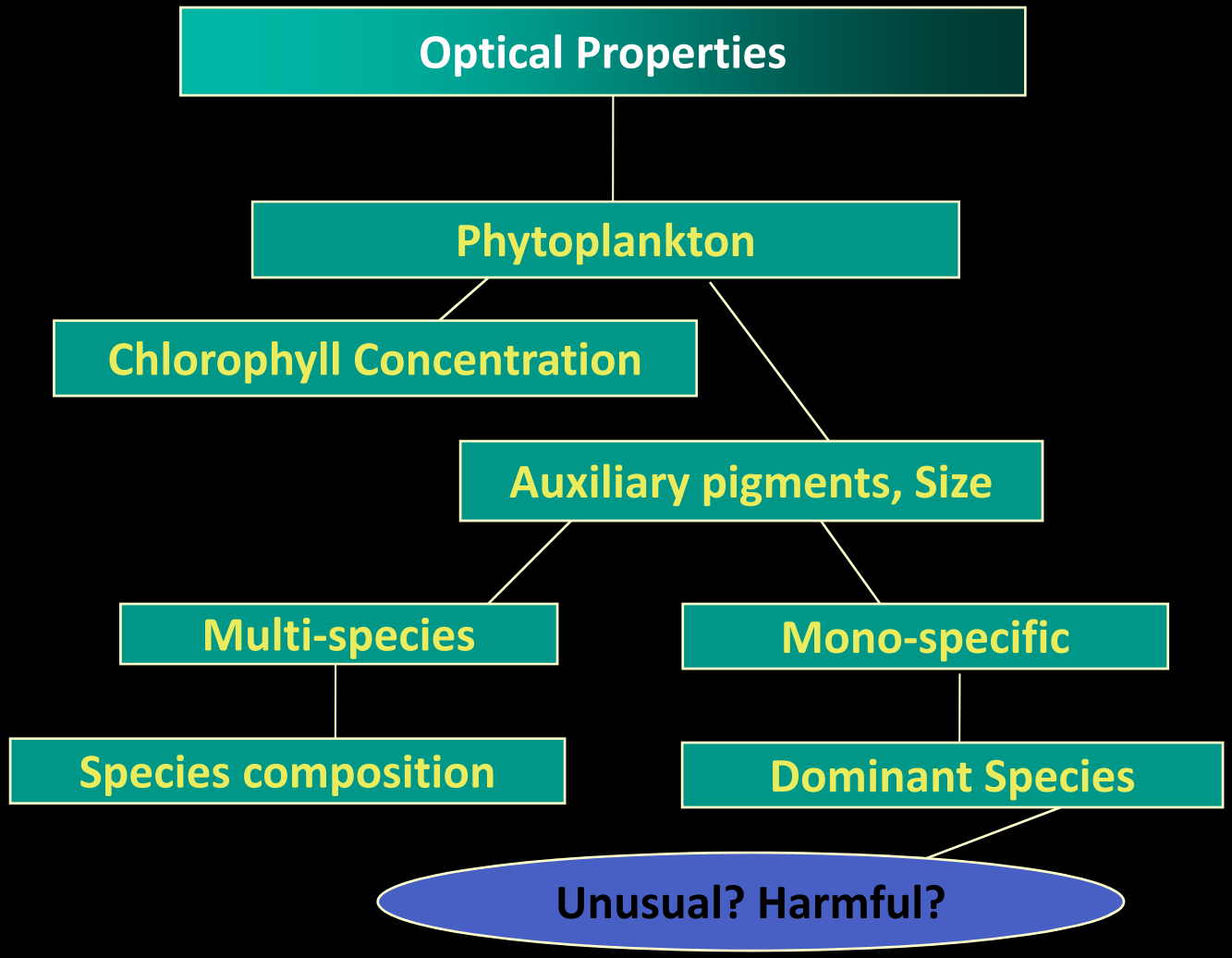
Picophytoplankton

Important in recycled production

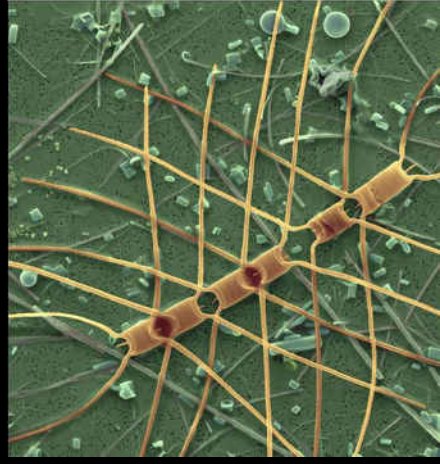
Diazotrophs

Nitrogen cycle

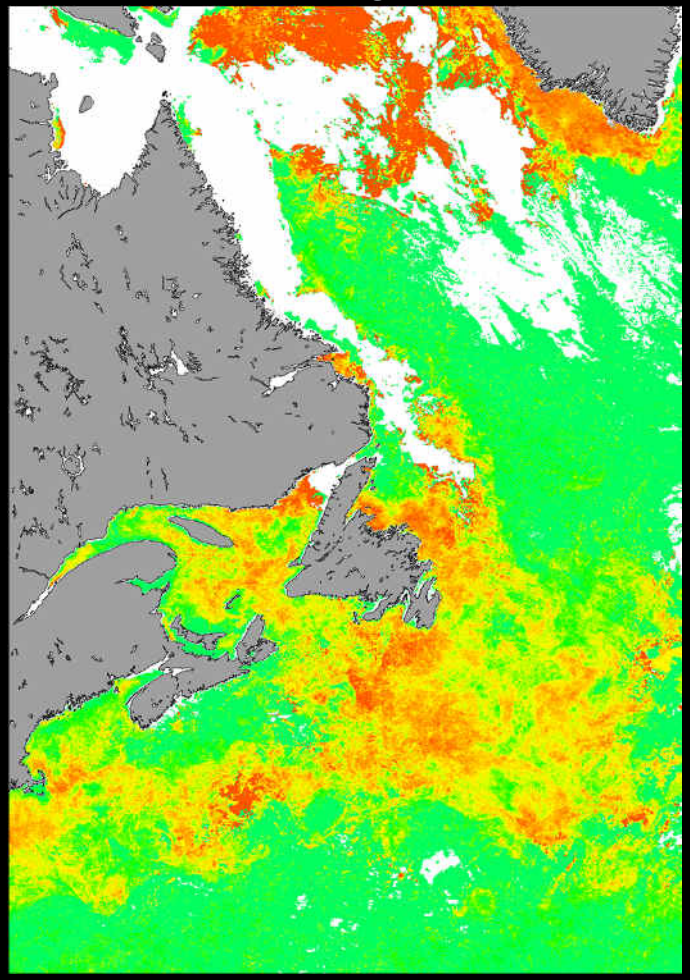
What can Ocean Colour tell us about Phytoplankton Community Structure?



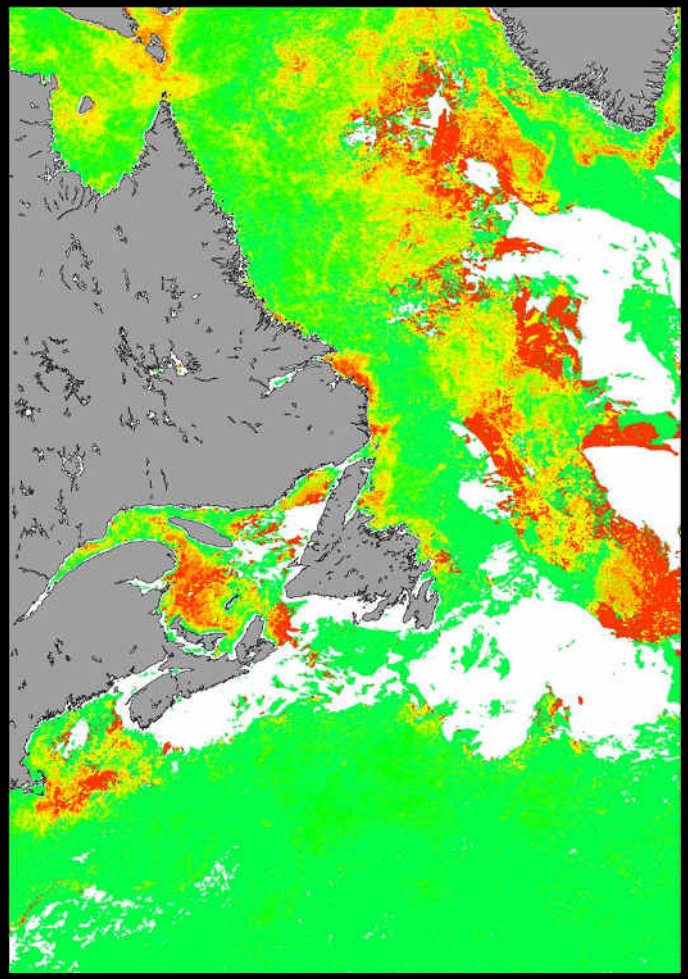
Probability of occurrence of diatoms during 2003 cruises



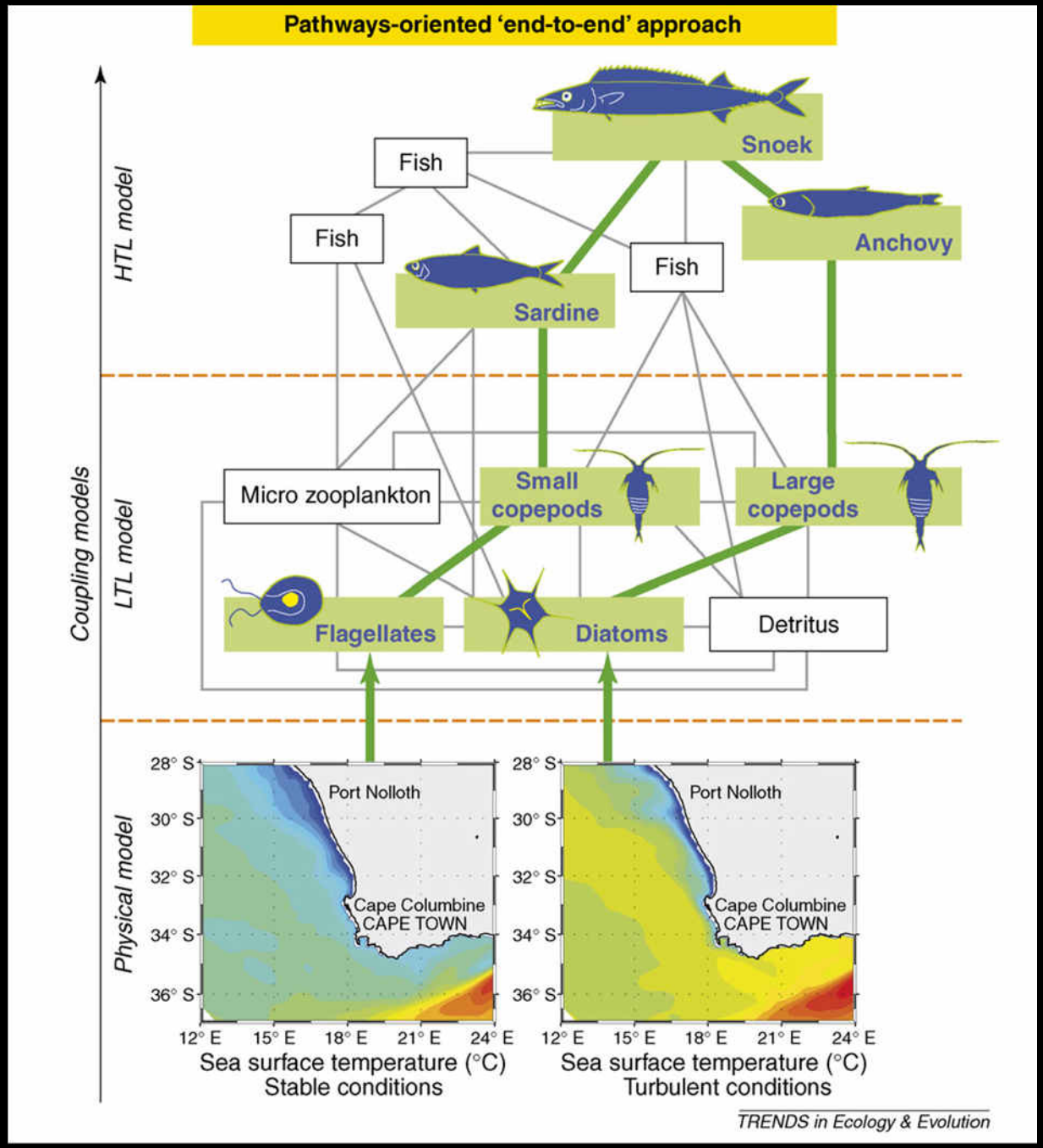
Spring Cruise



Summer Cruise

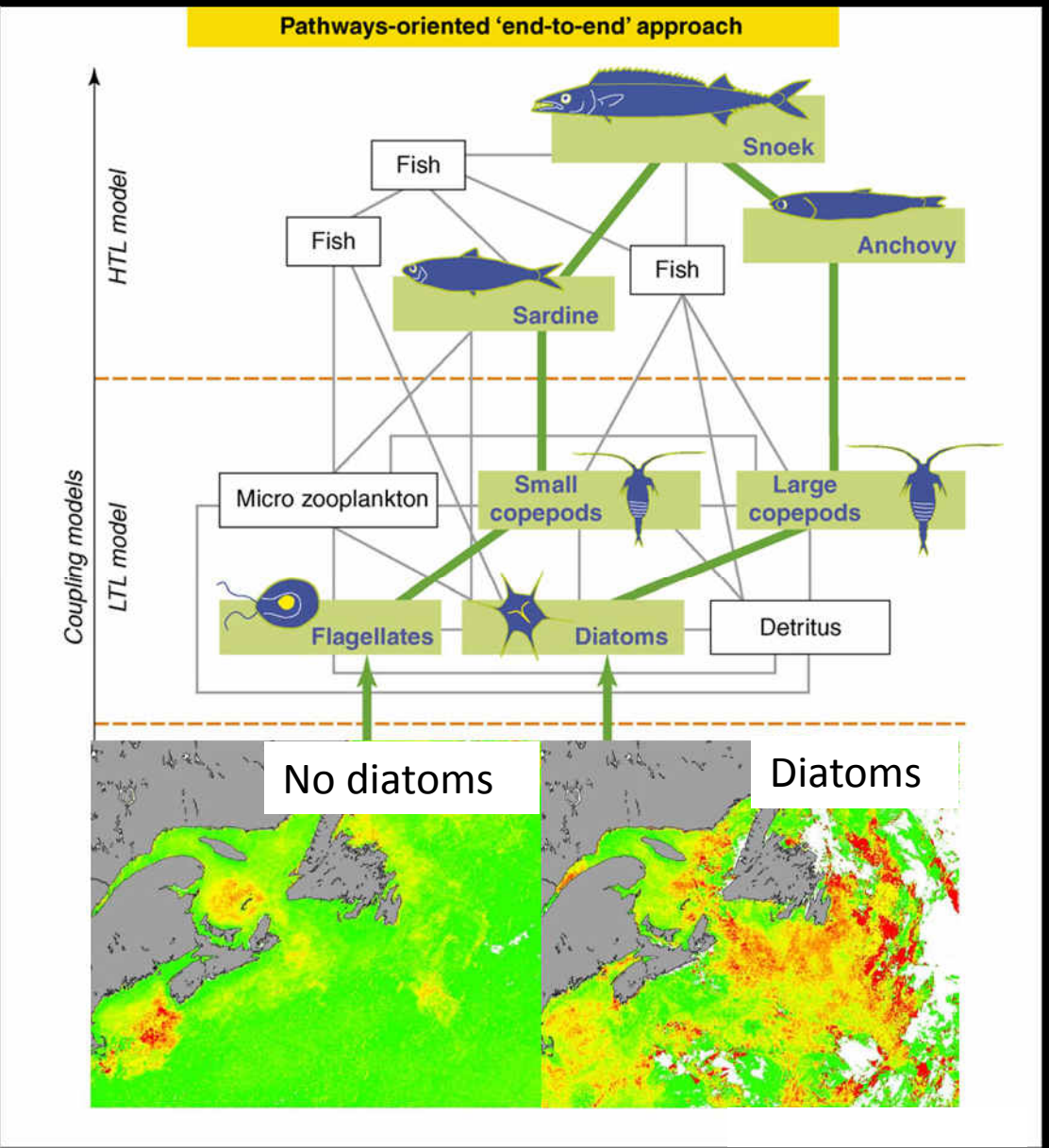


Based on Sathyendranath *et al.* (2004)



Cury *et al.* (2008)

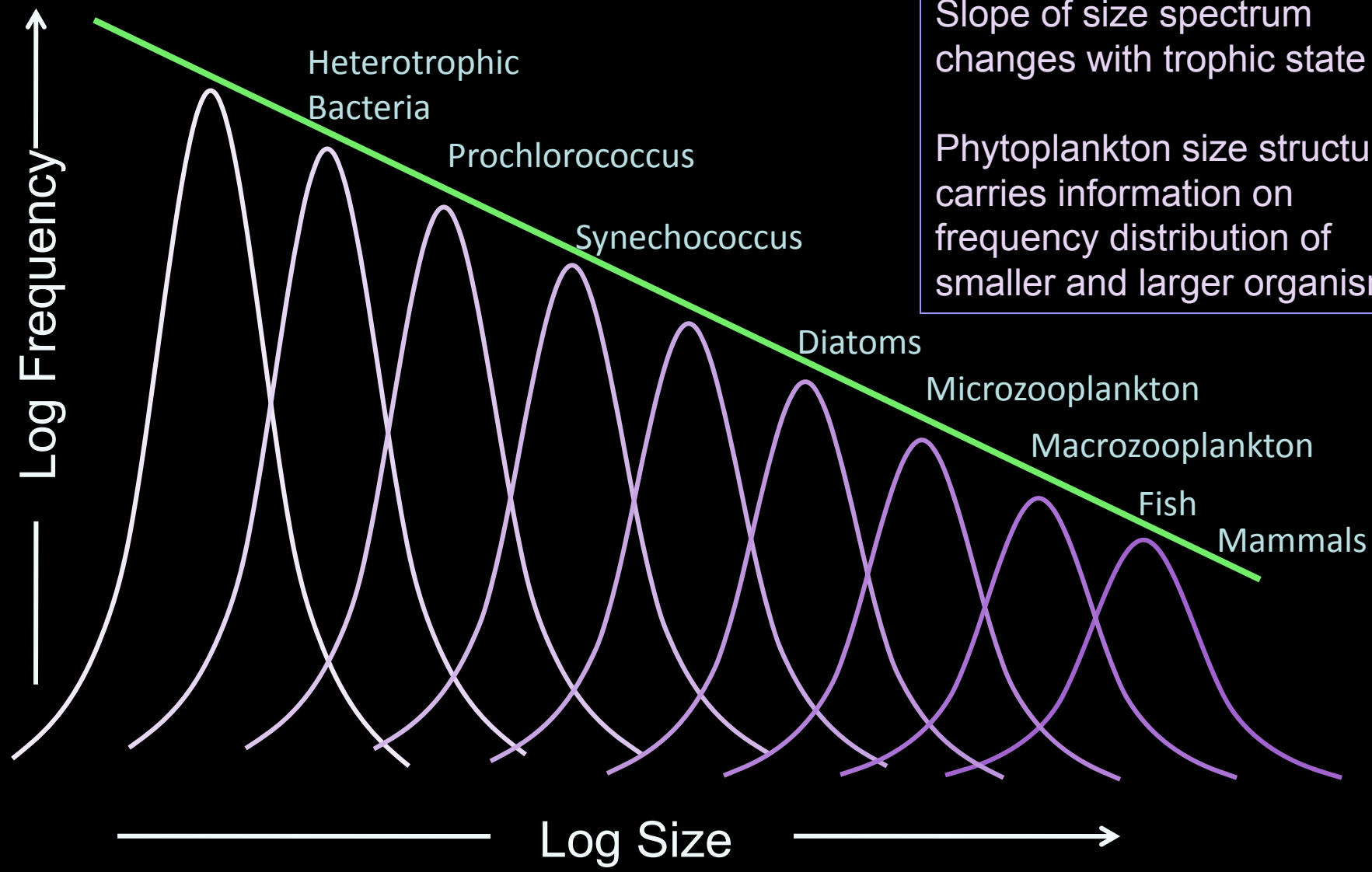
Alternative food chains depending on phytoplankton community structure



Fisheries shift between sardines and anchovies in Benguela system, depending on whether plankton community is dominated by diatoms or flagellates (Cury *et al.* 2008)

Remote sensing of community structure (diatoms) is a key advance (Sathyendranath *et al.* 2004) in this context

Size Spectrum Analysis
(Allometric Models, Metabolic Scaling)

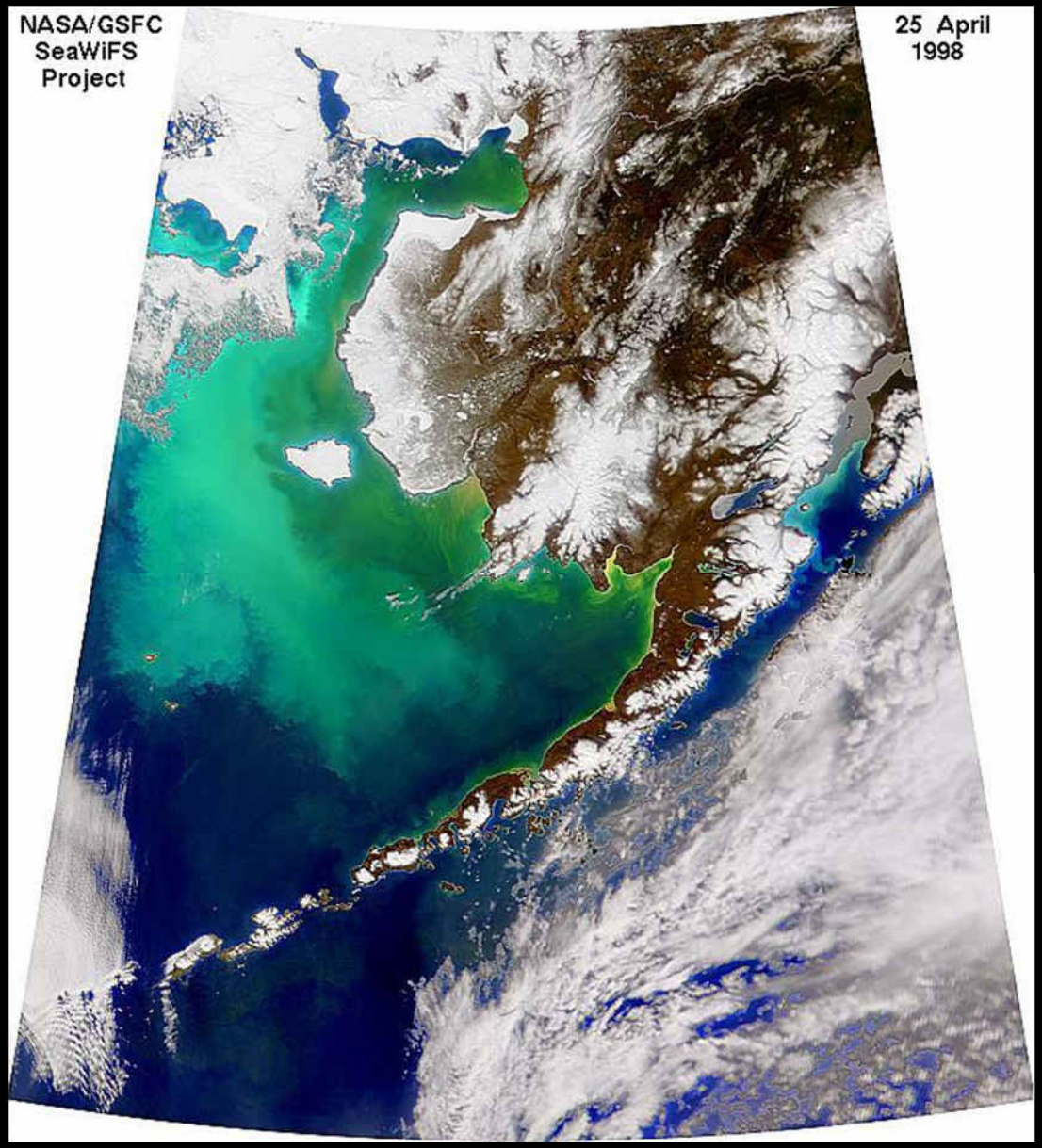


Slope of size spectrum changes with trophic state

Phytoplankton size structure carries information on frequency distribution of smaller and larger organisms

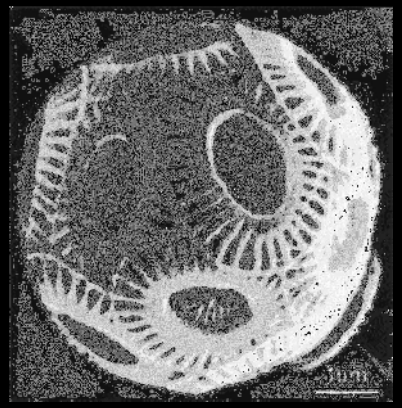
Platt and Denman (1978); Silvert and Platt (1978), Huntley.... Others

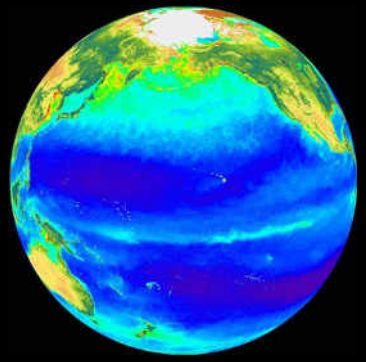
Coccolithophores



- Algorithms exploit the high reflectance of coccoliths
- The images map the distribution of coccoliths
- Successive images can be used to estimate rate of change in abundance of coccoliths

Ocean Acidification: What are the implications for coccolithophore blooms which are known to occur extensively in the North West Atlantic?





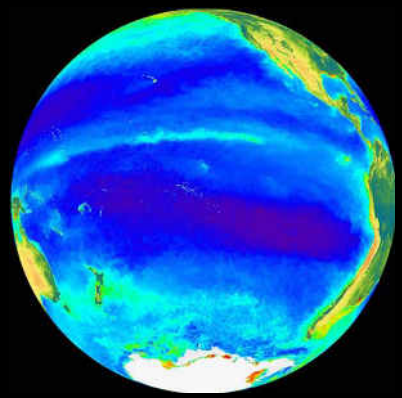
Context: Stewardship of the Ocean

Global consensus: Management should have ecosystem basis, integrity of ecosystem should not be compromised. Concepts such as the health, vigour and resilience of the ecosystem are subjective and difficult to quantify.

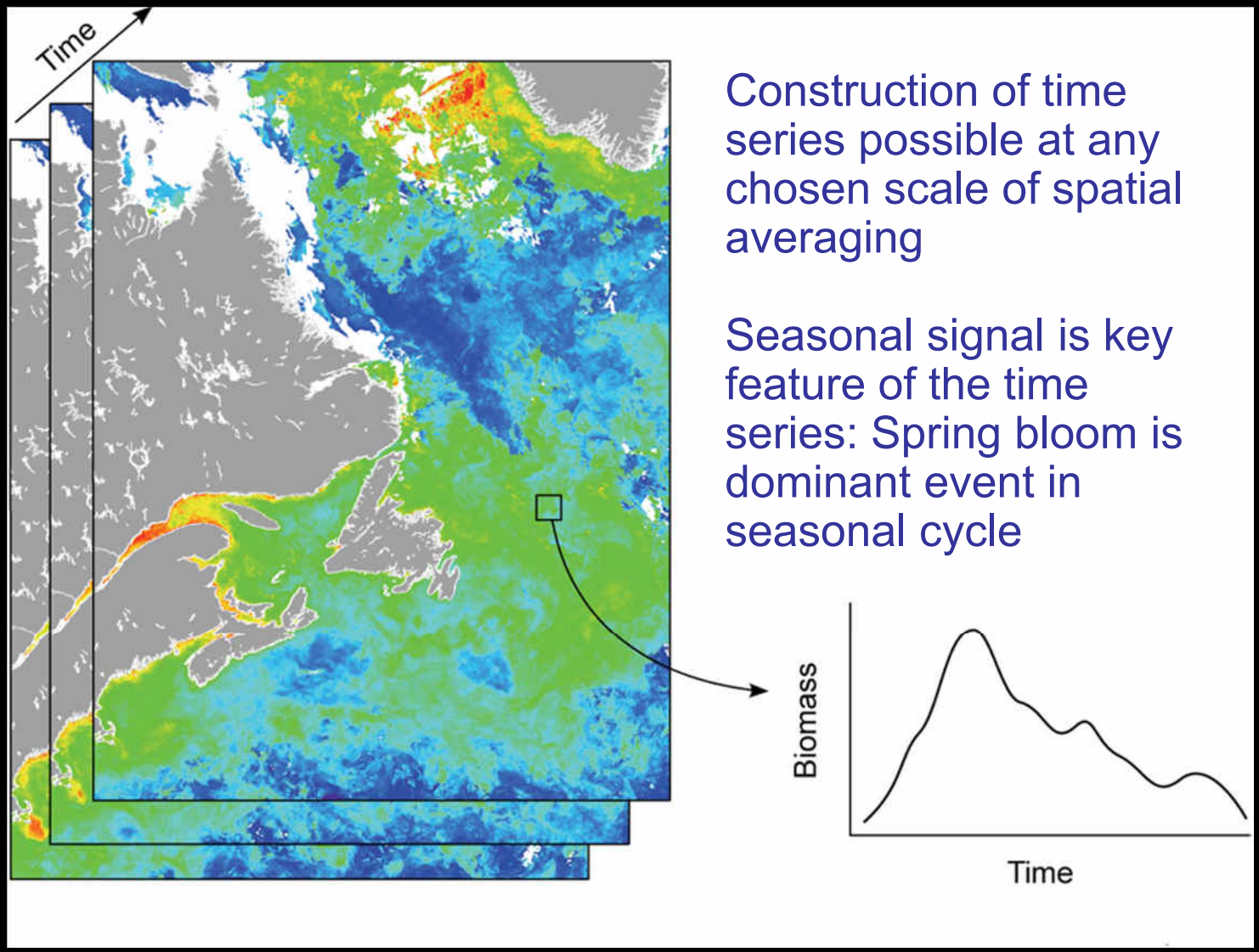
Instead, develop suite of Ecological Indicators as an aid to ecosystem-based management.

They are objective metrics for the pelagic ecosystem that can be applied serially, in operational mode, to detect changes that may occur in response to environmental perturbation.

Remote sensing meets many of the requirements of an ideal set of ecological indicators (repeatability, low-cost, applicable at a variety of scales, rapid measurement, long time series, standardised).



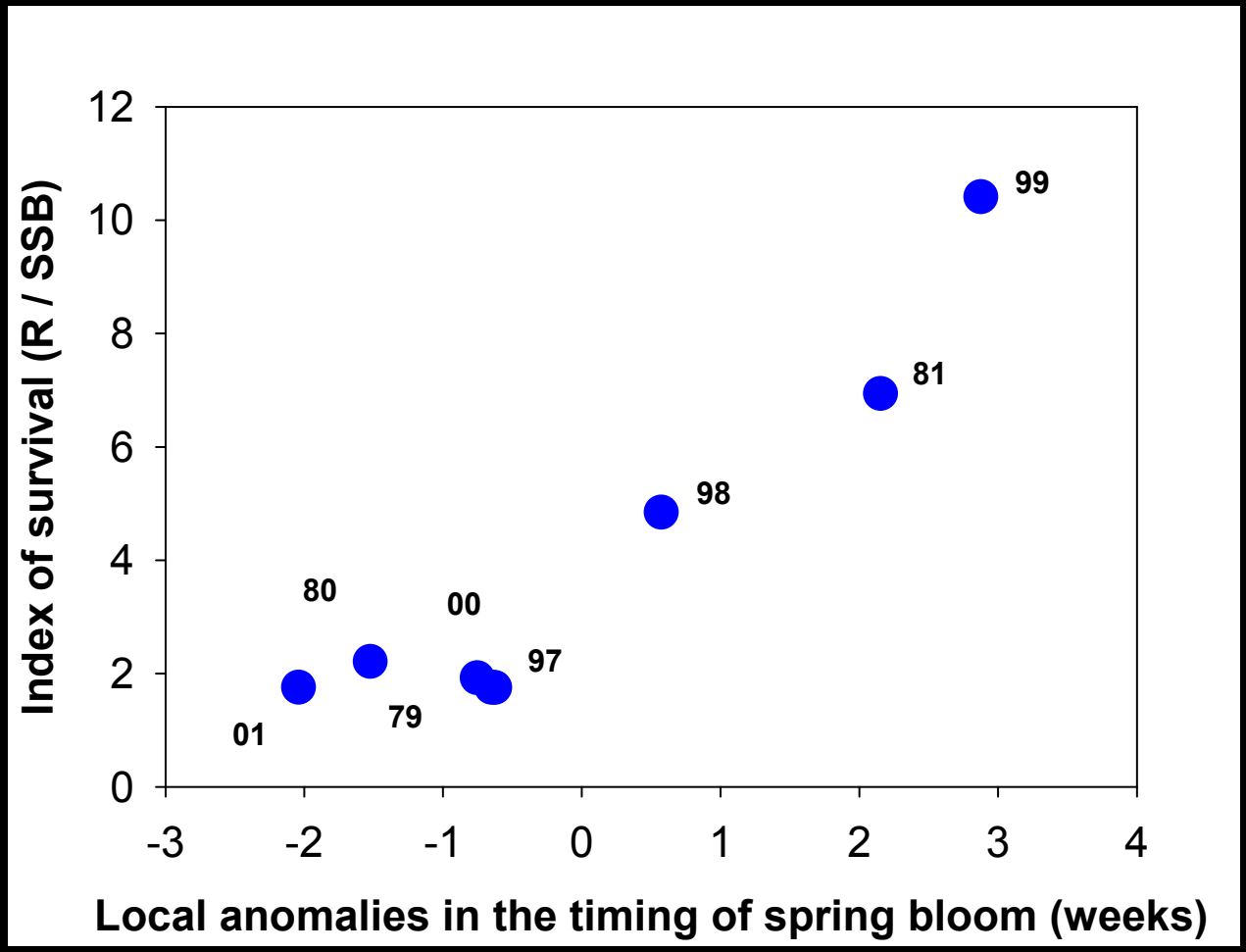
Time Series and Seasonality



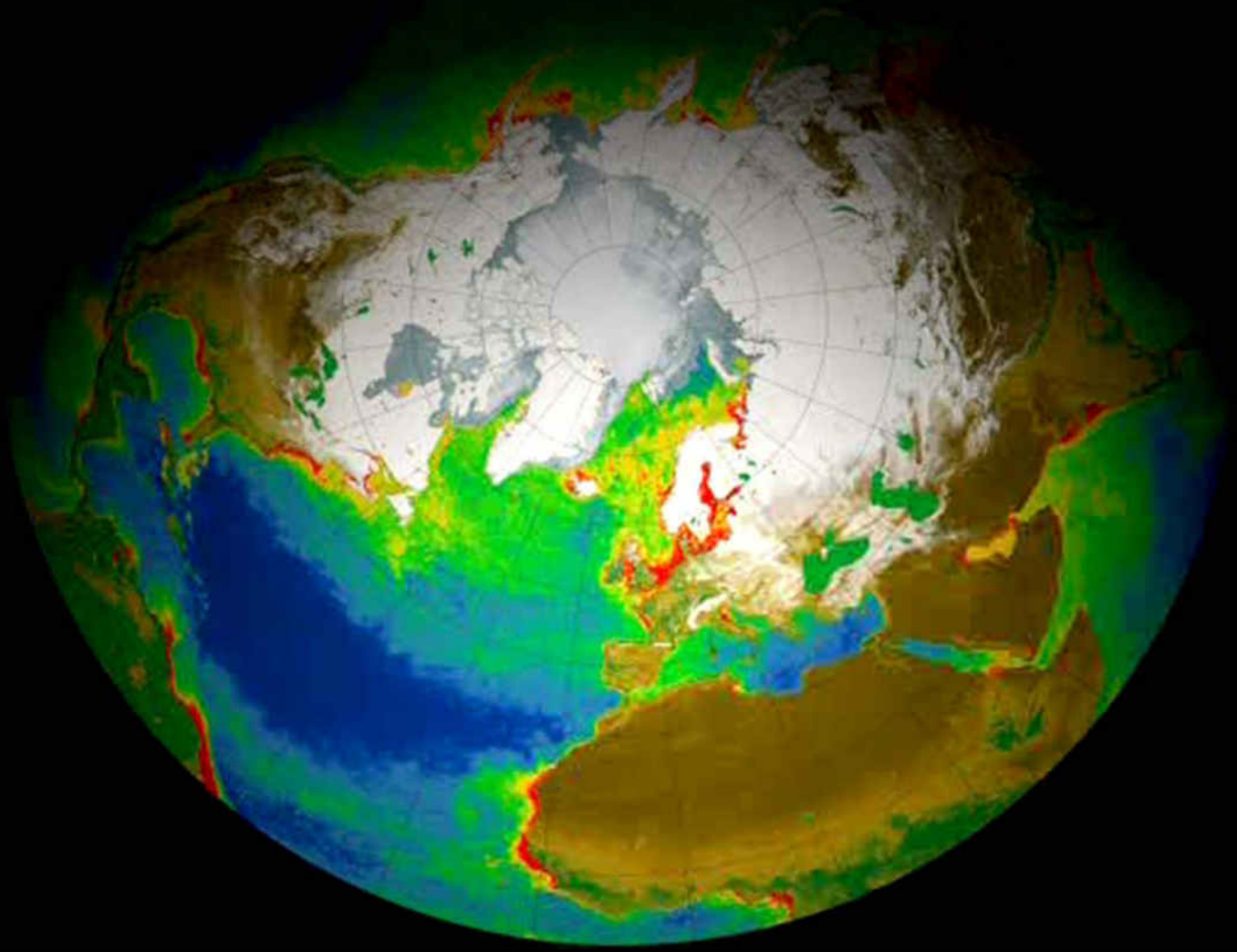
Construction of time series possible at any chosen scale of spatial averaging

Seasonal signal is key feature of the time series: Spring bloom is dominant event in seasonal cycle

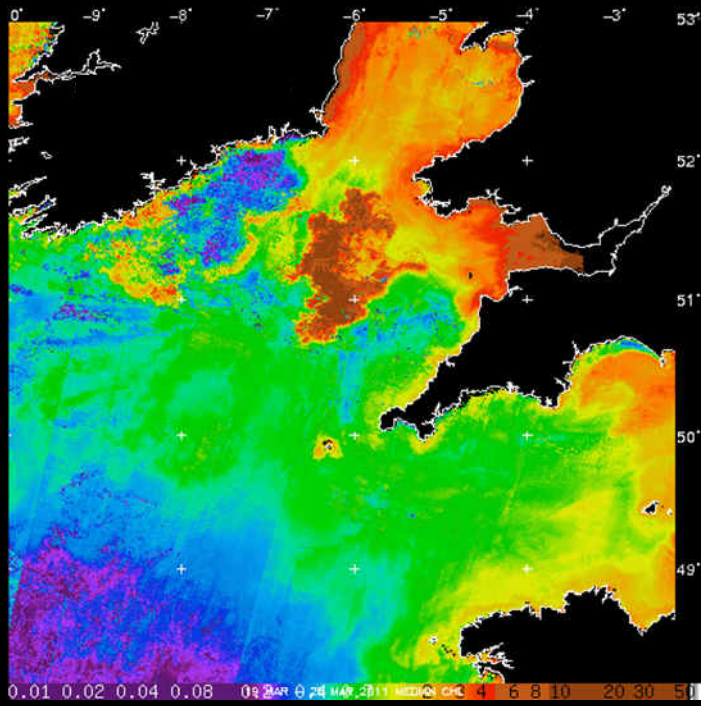
Normalised Survival as Function of Timing of Spring Bloom



Platt et al. 2003

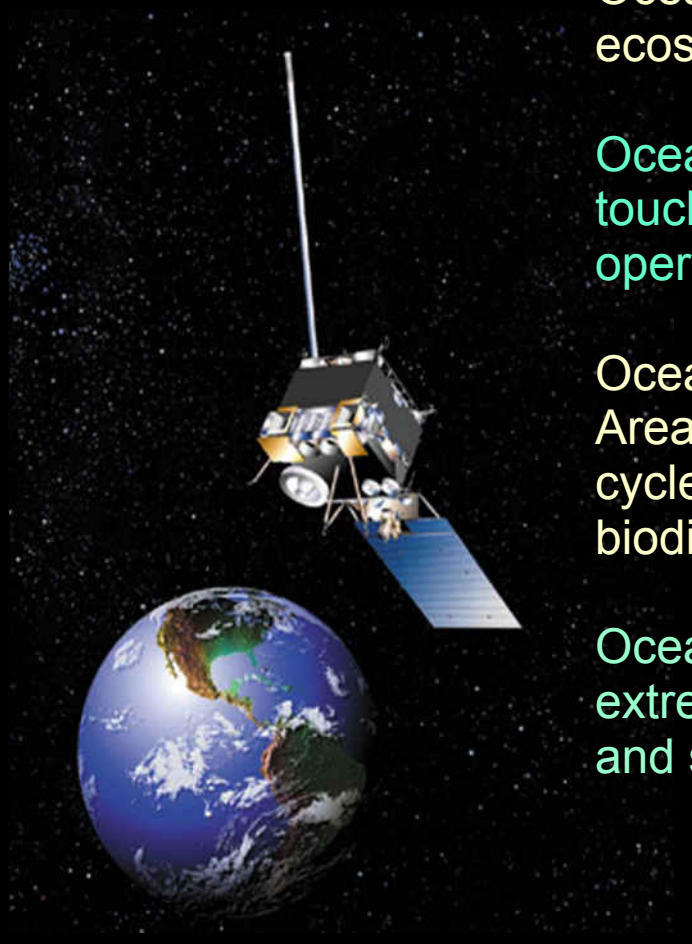


Applications are many:



- Harvest Fisheries
  - economies of fuel and time
- Fisheries Management
  - intelligence on ecosystem fluctuations and effect on future states of exploited stocks
- Aquaculture Industry
  - carrying capacity, harmful algal blooms
- Protection of Species at Risk
  - exclusion zones and reduction of by-catch
- Marine Protected Areas & Vulnerable Marine Ecosystems
  - delineation of these
- Ecosystem Health and Ecosystem Services
  - monitoring health, evaluating services, biodiversity, ecosystem indicators
- High Seas Governance
  - international governance strategy, ecosystem delineation, straddling stocks

Ocean Colour as an Integrating Discipline: Science in the Service of Man



Ocean colour provides our only window into the pelagic ecosystem on synoptic scales.

Ocean colour is an integrating discipline because it touches all aspects of marine science, research and operational.

Ocean colour is relevant to important Societal Benefit Areas (GEO/GEOSS) such as climate change (carbon cycle); fisheries (ecosystem indicators); marine biodiversity.

Ocean colour is not a universal panacea, but it is extremely versatile and cost-effective. Many important and stimulating problems remain to be solved.

Future Directions

Ocean colour is at its best when combined with other aspects of oceanography (in-water observations, modelling). Much more remains to be done to bring these diverse techniques together, to improve our understanding and predictions of the state of the ocean.

Ocean colour technology is still improving: with corresponding progress in radiative transfer theory, as well as in relevant statistical techniques, we can exploit the full potential of ocean colour.

Ocean colour as a tool in ecosystem-based management deserves further development.

The fascination of ocean colour can be used to draw in new disciples to the field: new recruits are necessary to fill the world-scale shortage of relevant expertise.

Thank you

Alister Hardy National Maritime Museum, UK