Arctic Ecosystem Modelling

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Research interests

3D coupled physical and biological modelling from meso- to global scale

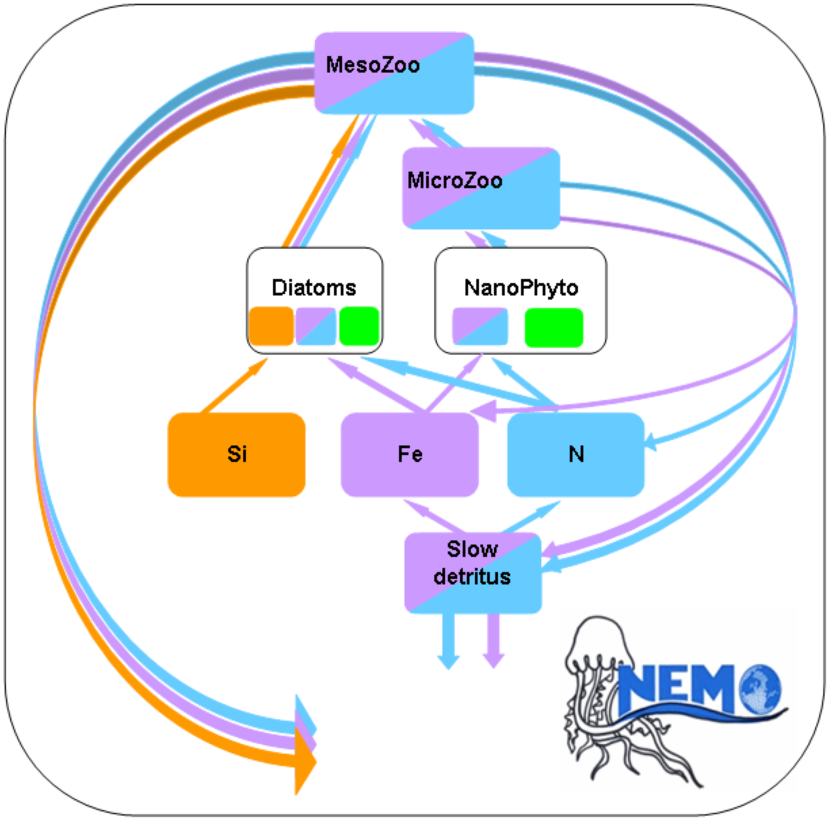
Regional aspects of ecosystem dynamics, biophysical interactions at mesoscale and synthesis of the interdisciplinary surveys

Development of the global high resolution coupled physical and biological model

The model

- Global NEMO (ORCA025) 1/4^{o} resolution
  (providing resolution of 5-10 km in Arctic)
- 50yrs physical run
- LIM2 ice model
- Fully coupled with ecosystem model from year 1996
- Preliminary results from analysis of year 1998

MEDUSA biogeochemistry



- Nitrogen-based plankton ecosystem model, 11 state variables
- Size-structured plankton community (P2-Z2-D2)
- Simplified iron cycle to permit HNLC regions
- Silicon cycle for export-important diatoms
- Slow- / fast-sinking detritus pathways for export

Outline

Introduction (defining scales of interest and aims of modelling, model description, why this review is biased)
Ocean ecosystems: basic facts
Factors controlling ecosystem dynamics and primary production
- Light (short-wave radiation, role of ice)
- Nutrients (mixing, horisontal advection, small-scale processes)

Overview of Arctic ecosystem models
- Conceptual models
- Regional models
- AO in global models

Challenges for ecosystem modelling

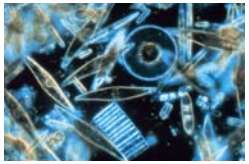
Ocean ecosystems: Basic facts

- Plankton
- Primary production
- Factors limiting production
- Sverdrup's critical depth

Plankton

The name **plankton** is derived from the Greek word πλανκτος ("planktos"), meaning "wanderer" or "drifter".

Plankton are primarily divided into broad functional (or trophic level) groups:



- **Phytoplankton** (from Greek *phyton*, or plant), algae that live near the water surface where there is sufficient light to support photosynthesis (producer)

- **Zooplankton** (from Greek *zoon*, or animal) that feed on other plankton (consumer).

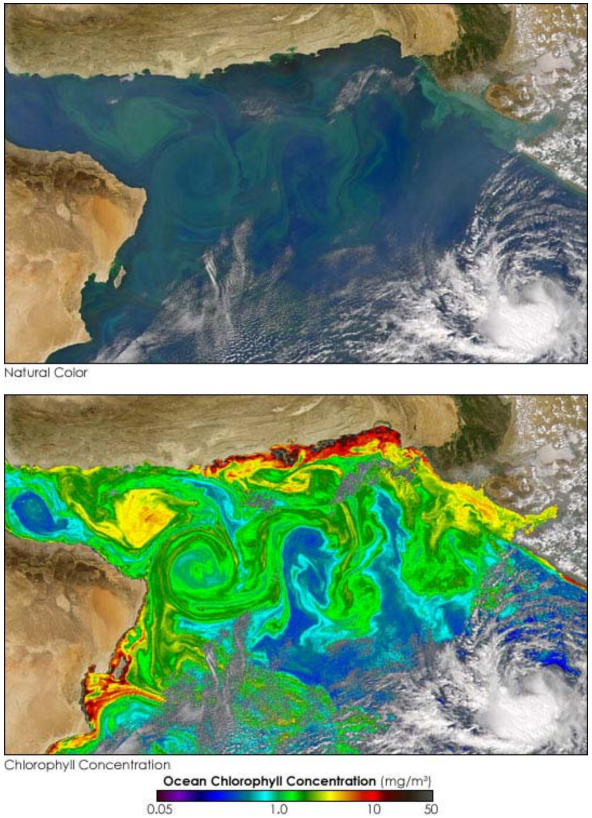
- **Bacterioplankton** which play an important role in remineralising organic material down the water column (recycler).

Primary production is the production of organic compounds from atmospheric or aquatic carbon dioxide, principally through the process of photosynthesis

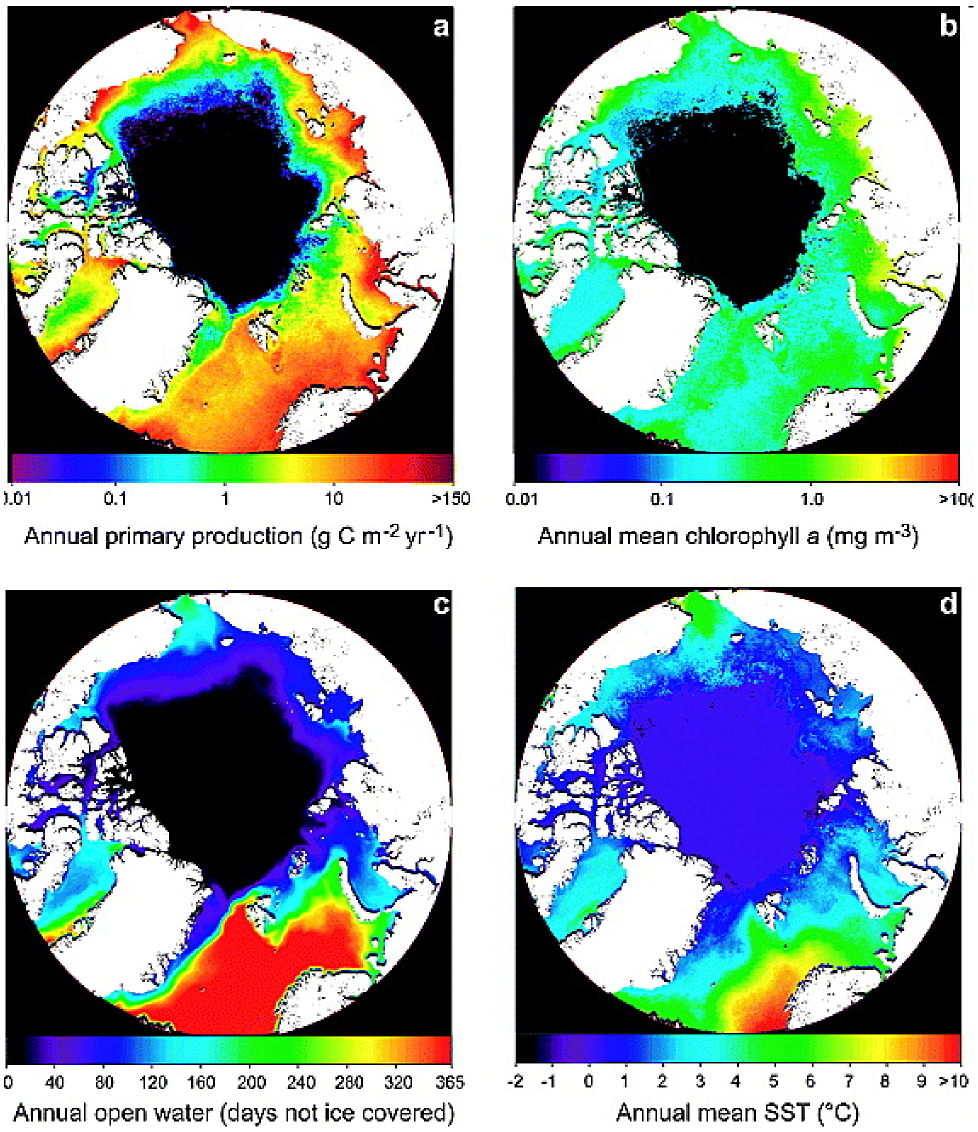
Although accounting for <1% of photosynthetic biomass, ocean phytoplankton are responsible for roughly half of the carbon fixation on Earth.

Chlorophyll

Like terrestrial plants, phytoplankton contain the pigment chlorophyll, which gives them their greenish colour. Chlorophyll is used by plants for photosynthesis



CZCS (1978-1986),
SeaWiFS (1997-present)
MODIS-Aqua (2002-present)

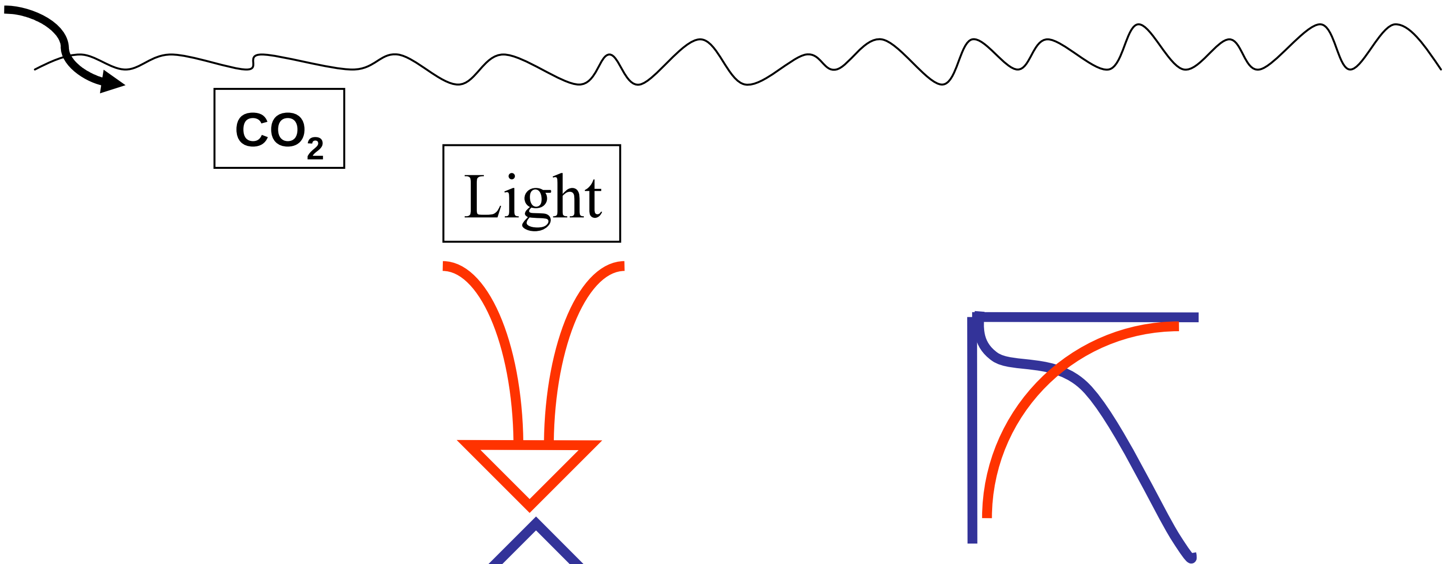


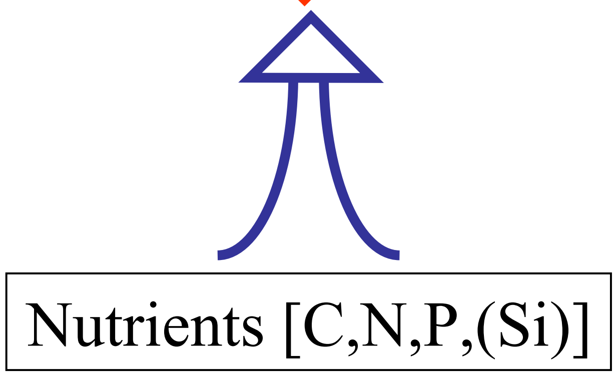
Pabi et al., 2008
Satellite-derived Arctic primary production

Problems:

- 10% Ice concentration
- Arctic fog
- Cloud cover
- Contamination by DOM

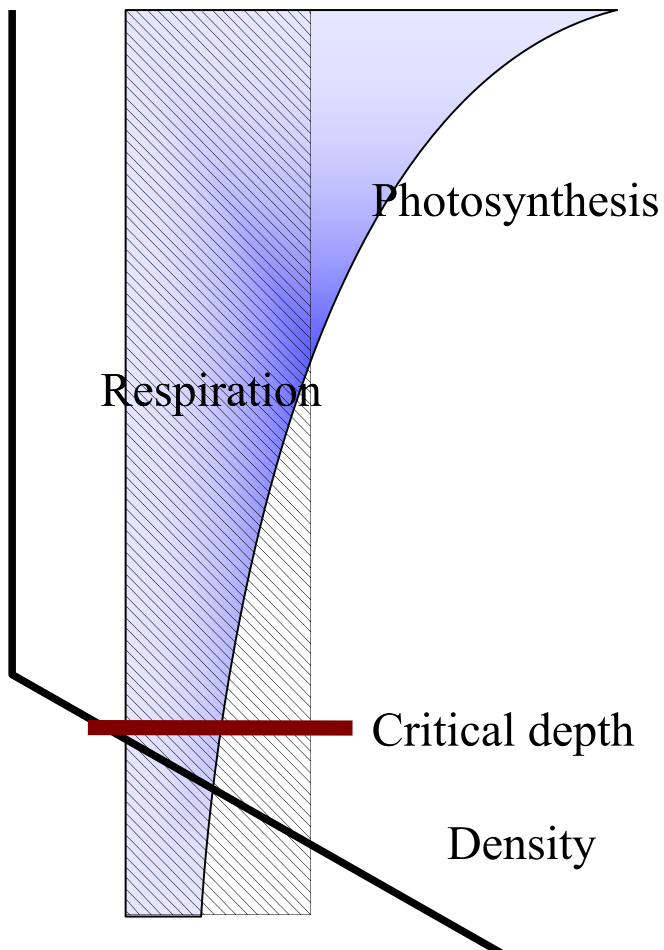
Factors limiting primary production





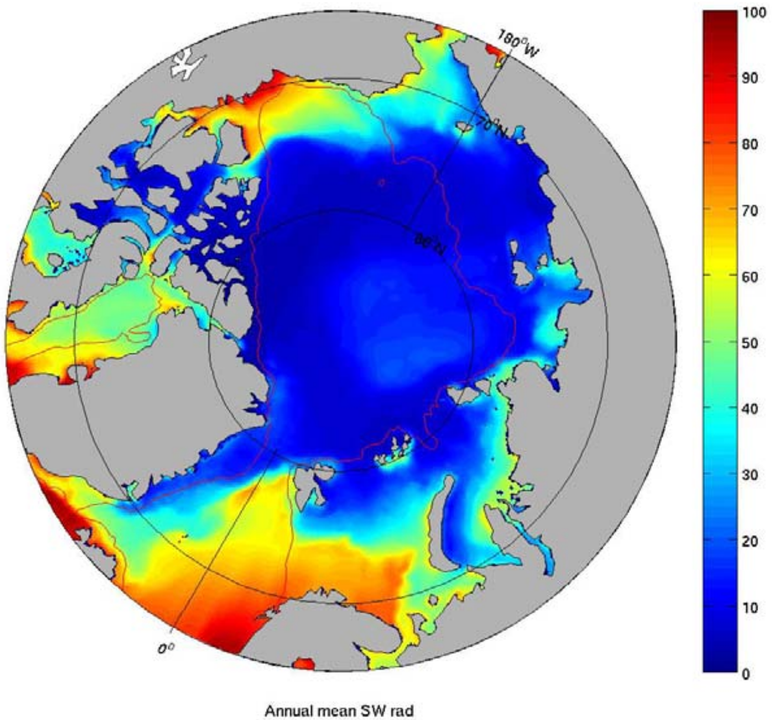
Because of gravitational sinking of particulate material nutrients are constantly lost from the photic zone, and are only replenished by mixing or upwelling.

Sverdrup's critical depth (1953)

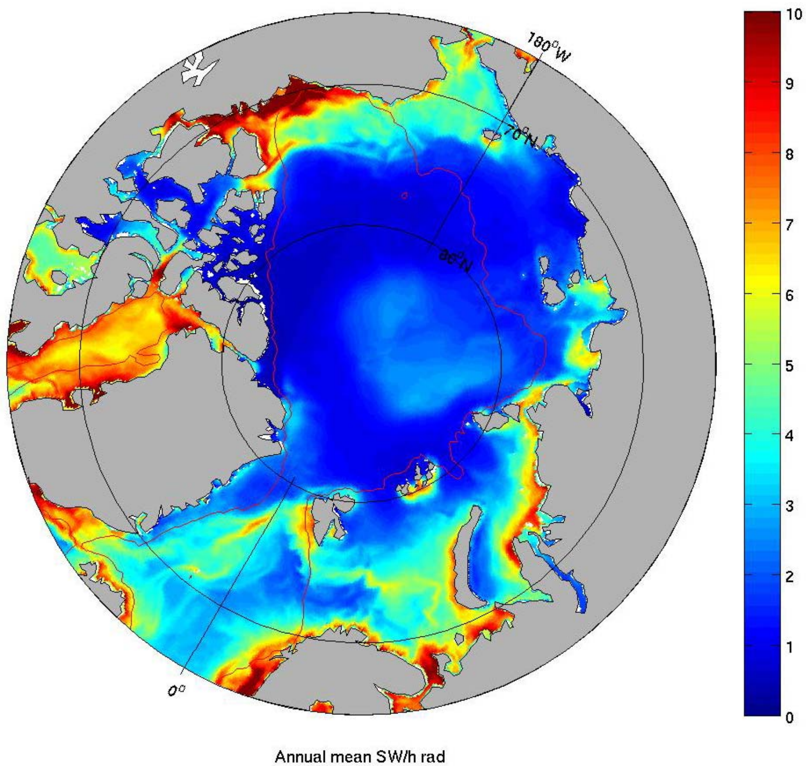


- Photosynthesis decreases exponentially with depth due to decrease in light availability
- Respiration is unaffected by light and remains constant with depth
- Phytoplankton is mixed by turbulence and experiences different light intensities over time, sometimes above and sometimes below compensation point
- Critical depth = depth at which photo-synthesis of the total water column phytoplankton population equals their total respiration

A phytoplankton population can only proliferate if mixing is shallower than the critical depth. Only then is the population net production >0



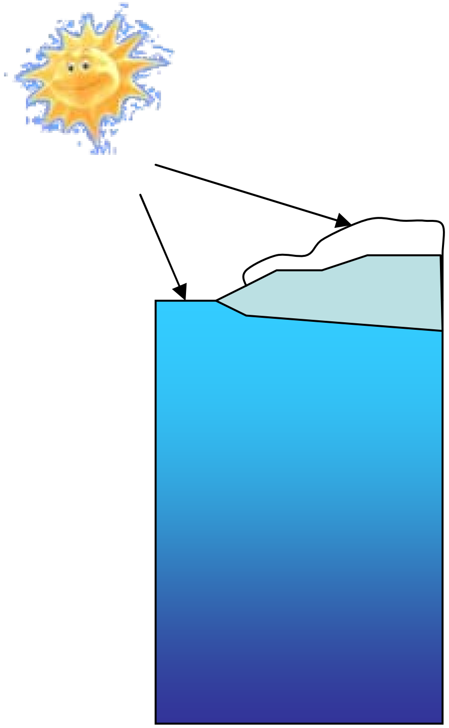
Annual mean sw rad



Annual mean sw rad / h

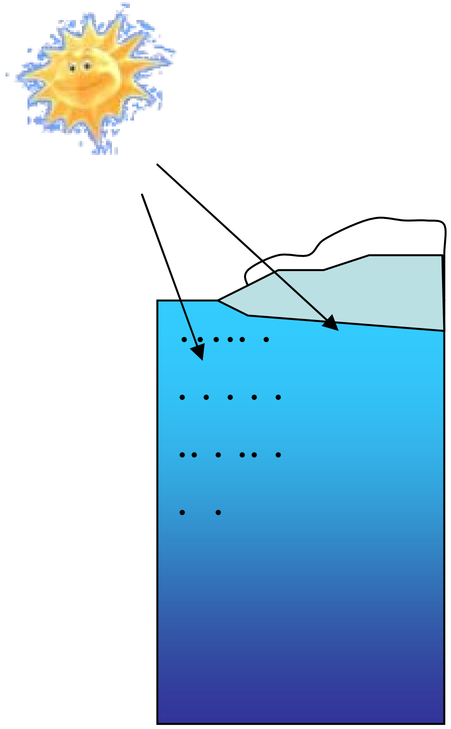
Arctic light regime (1. atmosphere)

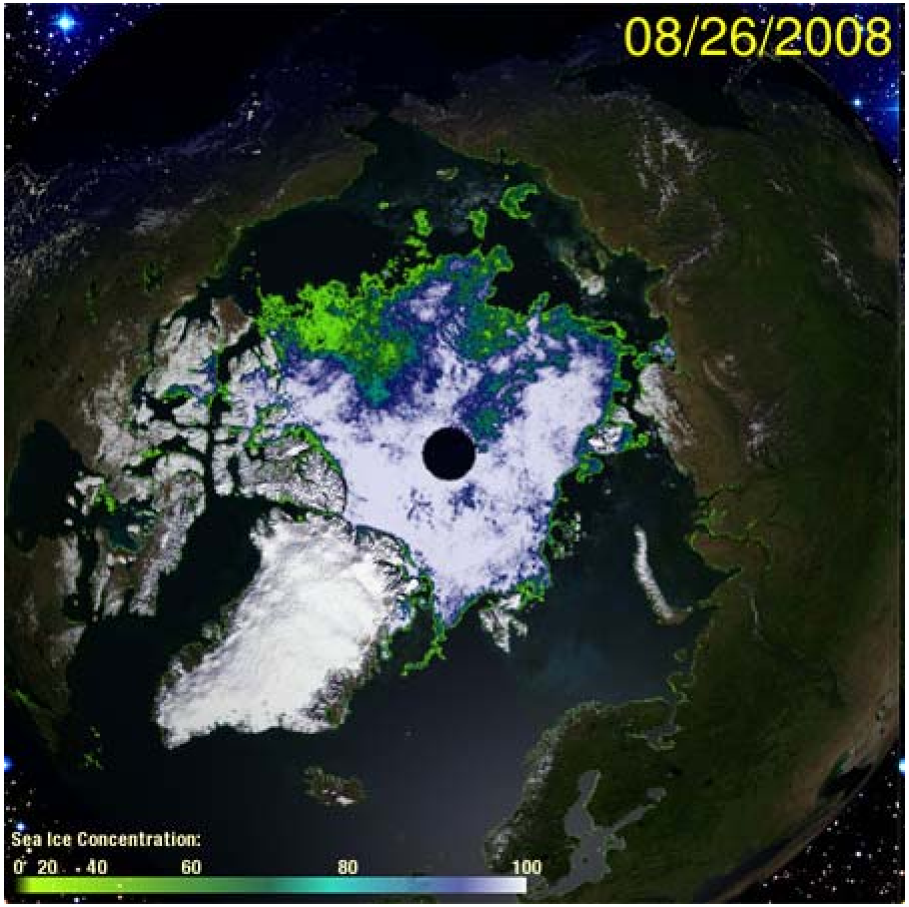
- Extreme variations (from midnight sun to winter darkness)
- Low solar elevation (only 23.45^o on the North pole during summer solstice)
- Polar fog (20-100m layer, typical of summer ice-free areas) can attenuate up to 60%-70% of short-wave irradiance



Arctic light regime (2. Attenuation in water and ice)

- Snow: extremely high attenuation coefficient
  - 15cm of snow on top of the ice can attenuate irradiance to 10% of the surface value
- Ice: high attenuation coefficient
  - 1-2m ice can attenuate irradiance to 0.5-5% of the surface value
- Water (photic zone depth is 1% light level):
  - Clearest pre-bloom water: 66m
  - Typical Chl-a of 0.5-10mg/m^3: 57-15m
  - Extreme Chl-a of >50mg/m^3: <3m
  - Silt (strong scattering, glacier-fed estuary), CDOM (river supply): <1m



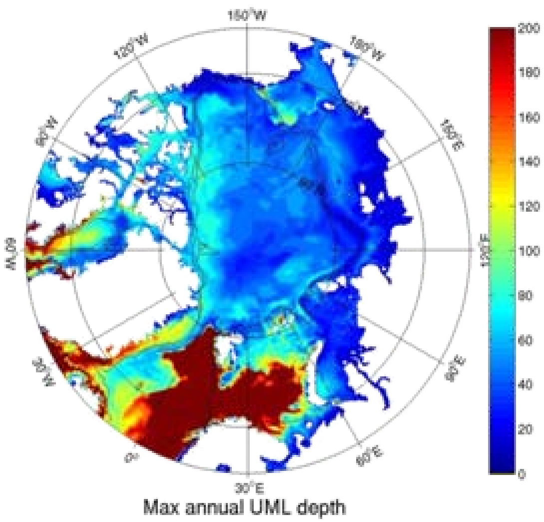


Satellite passive-microvavederived sea ice concentrations in the Alaskan sector on 26 August 2008. Courtesy of Cryosphere Today, University of Illinois

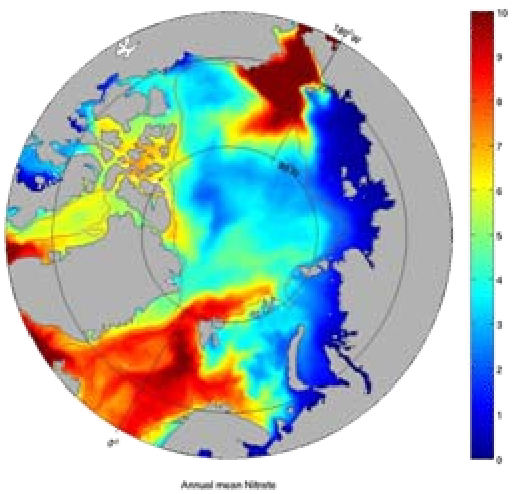
UML animation

Nutrient supply (large-scale)

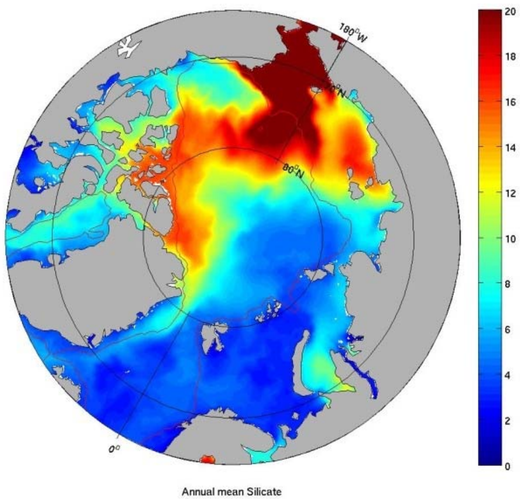
- Deep winter mixing
    - Depth of winter mixing
    - Deep nutrient concentrations
- Horizontal advection



Max UML depth



Mean annual nitrate



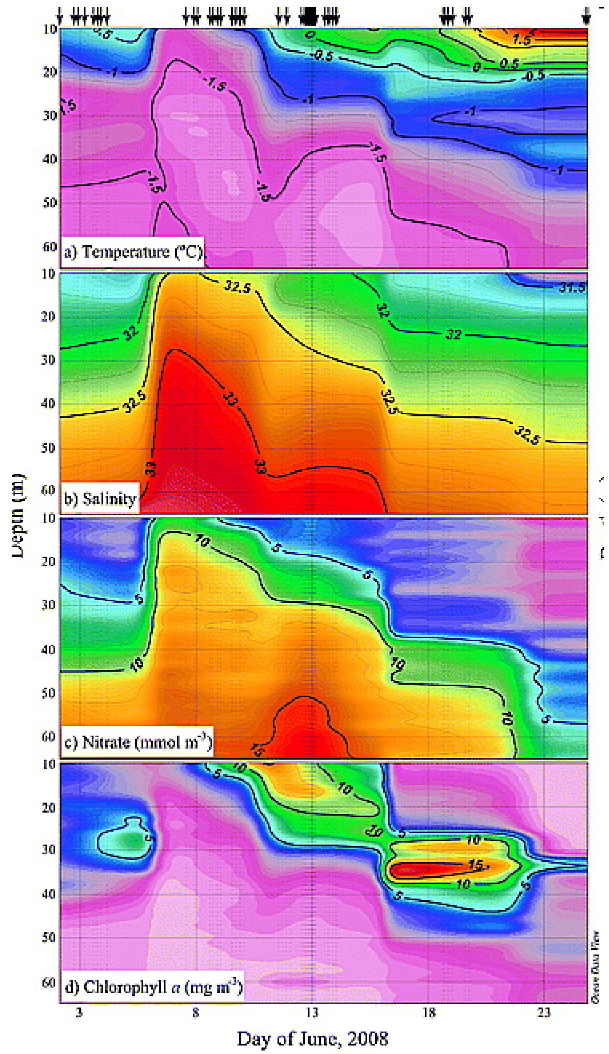
Mean annual silicate

Nutrient supply (local-scale)

- Riverine input (local significance, nutrients get exhausted before plume advances into the sea)

- Localised and/or episodic events:
  - Enhanced tidal mixing on rough topography
  - Shelf-break and ice-edge upwelling
  - Turbulent wake behind banks and islands
  - Severe storms and internal waves eroding the halocline
  - Mesoscale eddies

Ice-edge upwelling

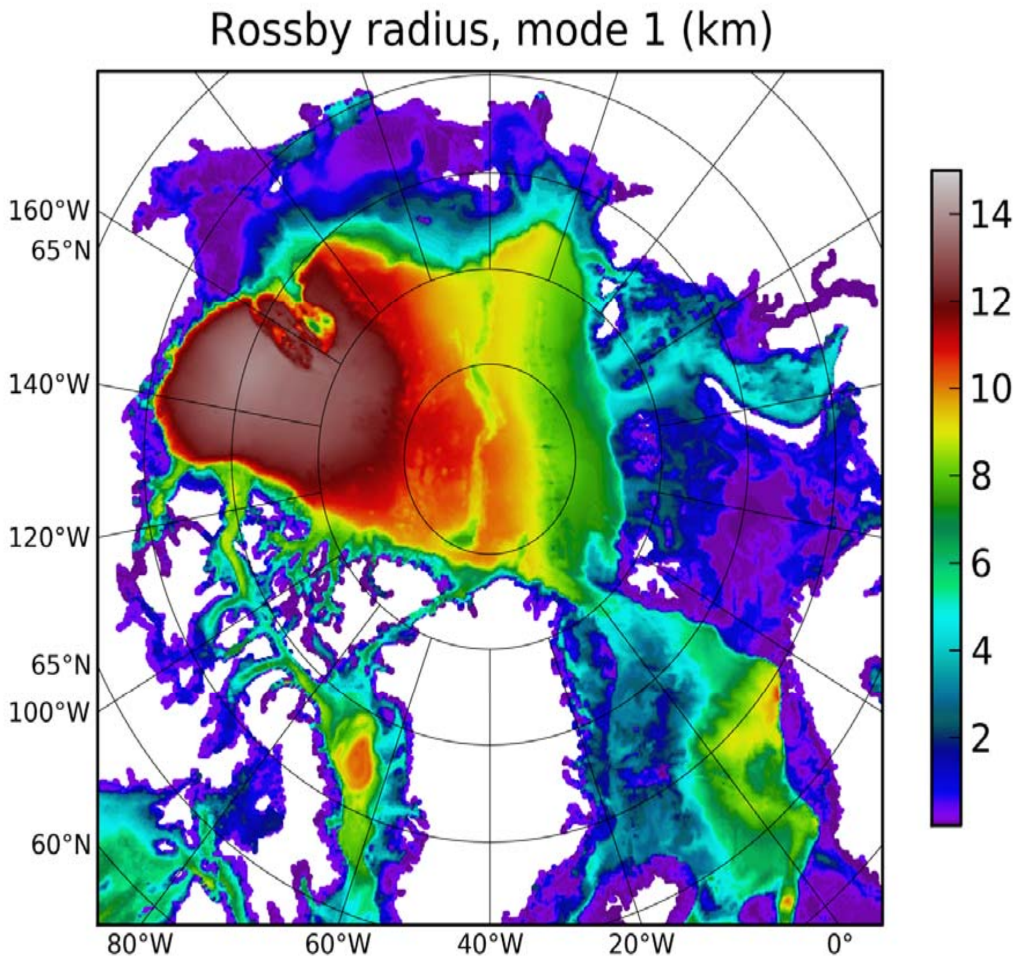


Contribution of under-ice primary production to an ice-edge upwelling phytoplankton bloom in the Canadian Beaufort Sea Mundy et al., 2009

Upwelling event resulted in a 3week long bloom with Primary production twice of previous estimates.

Rossby rad of def ~ 3km, event scale 6km

Figure 2. Interpolated time series of (a) temperature, (b) salinity, (c) nitrate concentration and (d) chl a concentration (via in vivo fluorescence) observed at the Darnley Bay sampling station. Major (labeled) and minor isolines were plotted at regular intervals. Data from 47 hydrocasts (arrows)



Courtesy of George Nurser, NOC, UK

Coupled Ocean-Ecosystem models

1. Conceptual models

2. Process models (aim at understanding basic process by studying simplified and idealised problems)

3. Simulation models (aim at forecasting and simulation of the real complex environment)

- Regional models
    - Pan-Arctic models
    - Smaller-scale models (e.g. Barents Sea)
- Global models

Conceptual models

Arctic ecosystems: α and β type ecosystems (after Carmack, 2006)

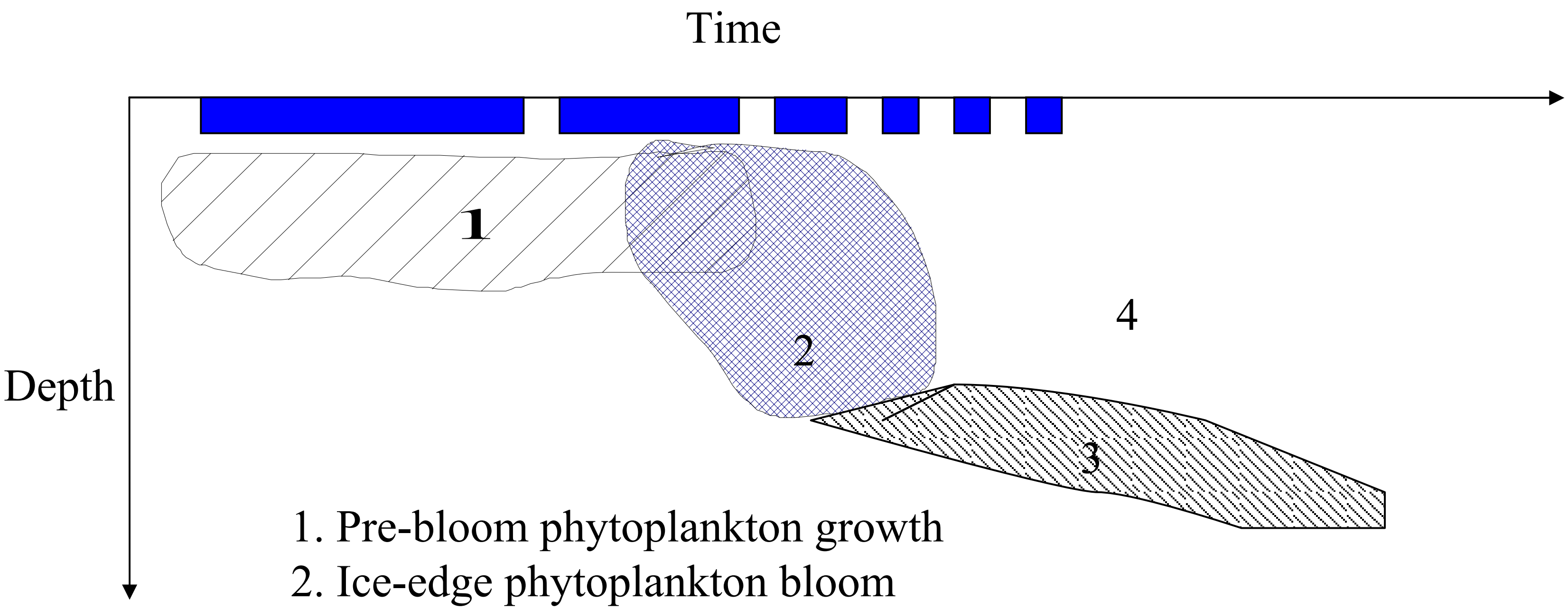
Mid-latitudes are permanently stratified by Temperature ("alpha-oceans" after thermal expansion coefficient)

High latitudes are permanently stratified by Salinity ("beta-oceans" after haline contraction coefficient)

Alpha and beta oceans has distinctively different ecosystem regimes

Alpha-oceans	Beta oceans
Deep vertical mixing and convection High nutrient content ss but high water-column integrated prim	Stable shallow stratification Low nutrient availability Major (but short-lived) phytoplankton blooms
Barents sea: South-east Chl: 5mgC/m3 Production: 200hC/m2/yr	Barents sea: North Chl: 20mgC/m3 Production: 30-60 gC/m2/yr (Wassmann et al., 2006)

Ice-edge bloom (From Sakshaug and Skjoldal, 1989)



1. Pre-bloom phytoplankton growth
2. Ice-edge phytoplankton bloom
3. Post-bloom subsurface Chl maximum
4. Oligotrophic post-bloom surface layer

Courtesy of Mahe Perette, NOC

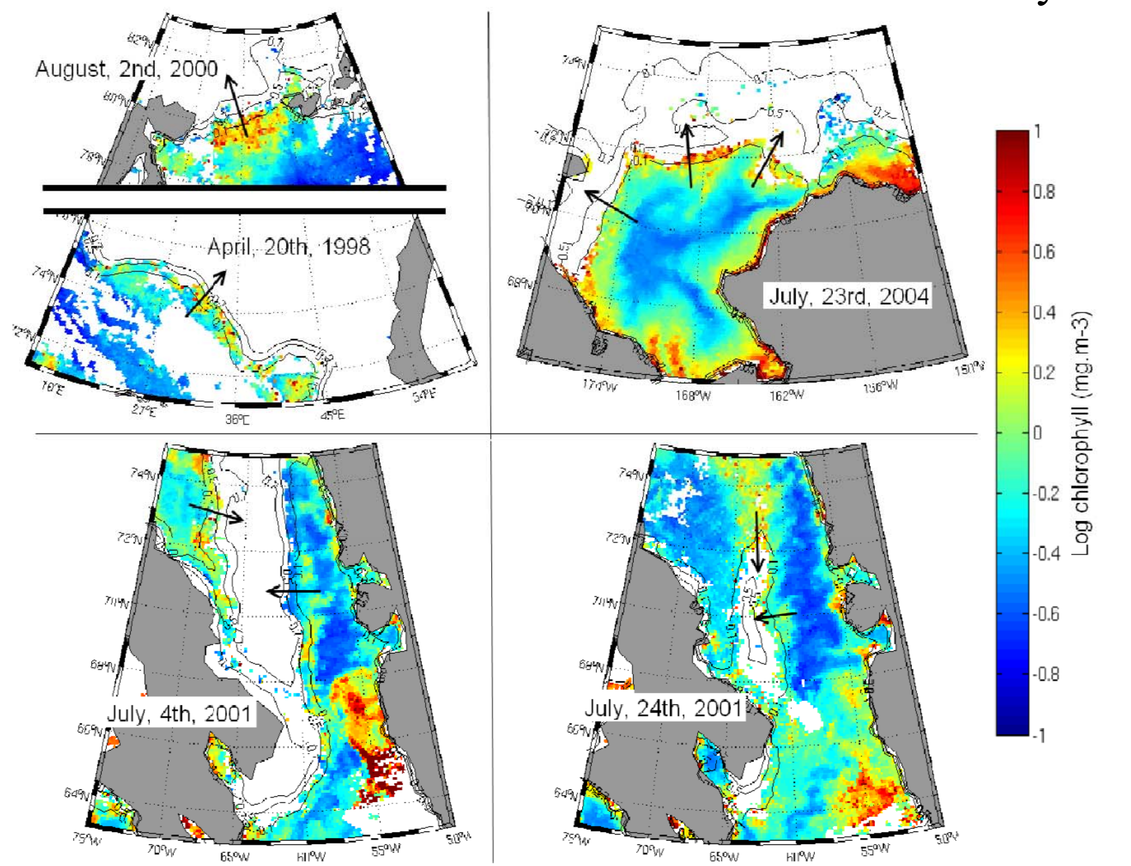


Figure 7. Ice-edge phytoplankton blooms occurring in different Arctic's marginal ice zones. Top left: Barents Sea in April 1998 (71-75°N) and August 2000 (79-81°N) (two thick black lines separate the time periods). Top right: Chukchi Sea in July 2004. Bottom: Davis Strait and Baffin Bay on July 2001, at 20 days interval. Images are 5-day composites of chlorophyll (SEAWIFS) overlaid with sea-ice contours (NSIDC) at 10%, 50% and 70%. White areas are missing data, mainly due to ice cover although it is more likely to be clouds or fog when ice is less than 10%. Arrows indicate the propagation direction of the ice-edge, hence the blooms. Ticks on the Y axis are spaced every 2 degrees latitude.

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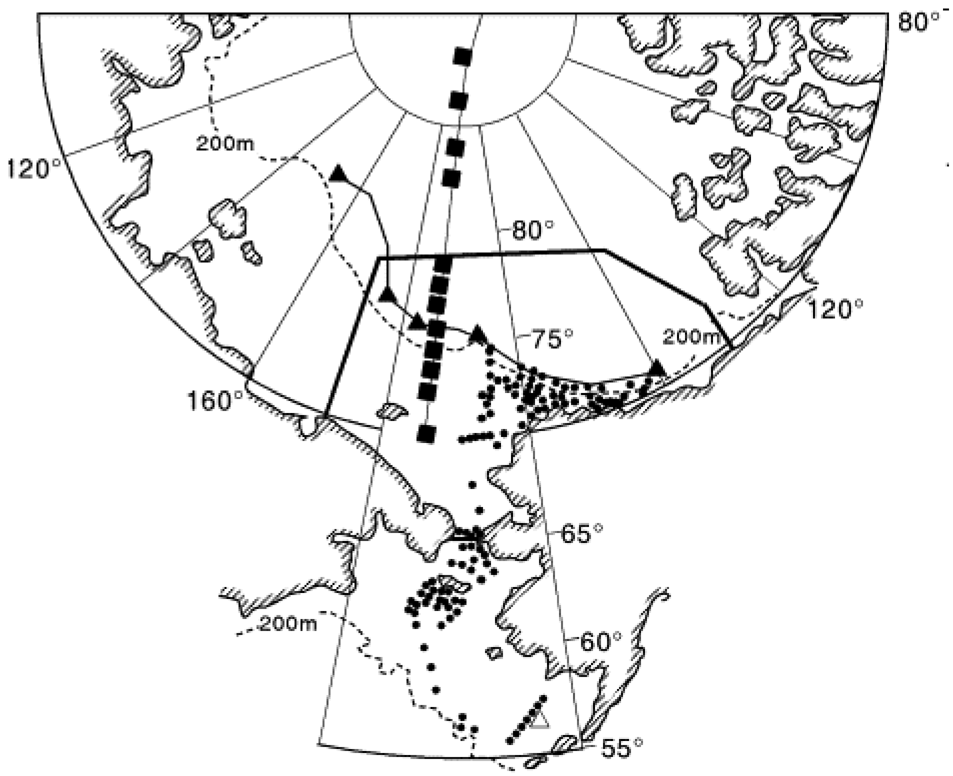
Regional models

Regional Chukchi/Beaufort sea coupled ocean-sea ice ecosytem model

- Resolution: 1/12
- Ocean-ice model (LANL)
- Ecosystem model (18 state vars)
- Decadal shifts in biophysical forcing of Arctic marine food webs: Numerical consequences (Walsh et al., 2004)
- A numerical model of seasonal primary production within the Chukchi/Beaufort Seas (Walsh et al., 2005)



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Chukchi/Beaufort sea Ecosystem model (18 state variables)

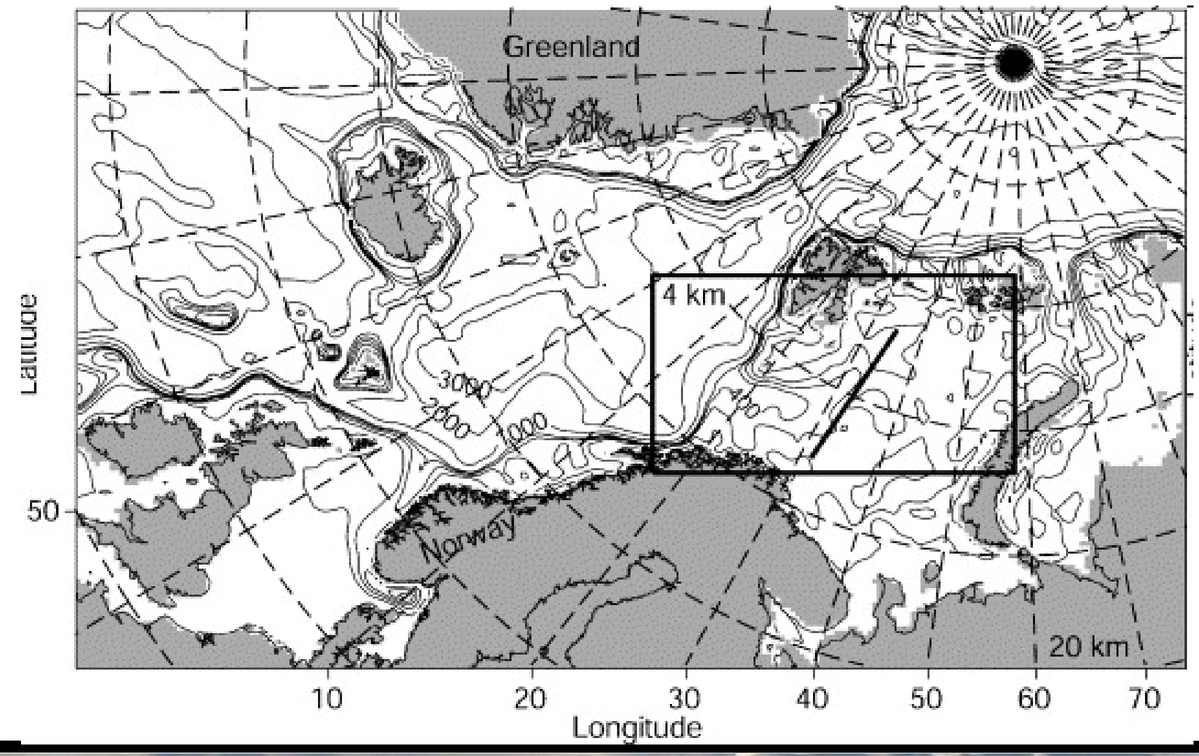
- Phytoplankton (3groups)
- Zooplankton (2 groups)
- Nutrients (4 types, nitrogen and silicate)
- Dissolved organic and inorganic carbon
- Detritus (4 types)

Chukchi/Beaufort Sea Conclusions

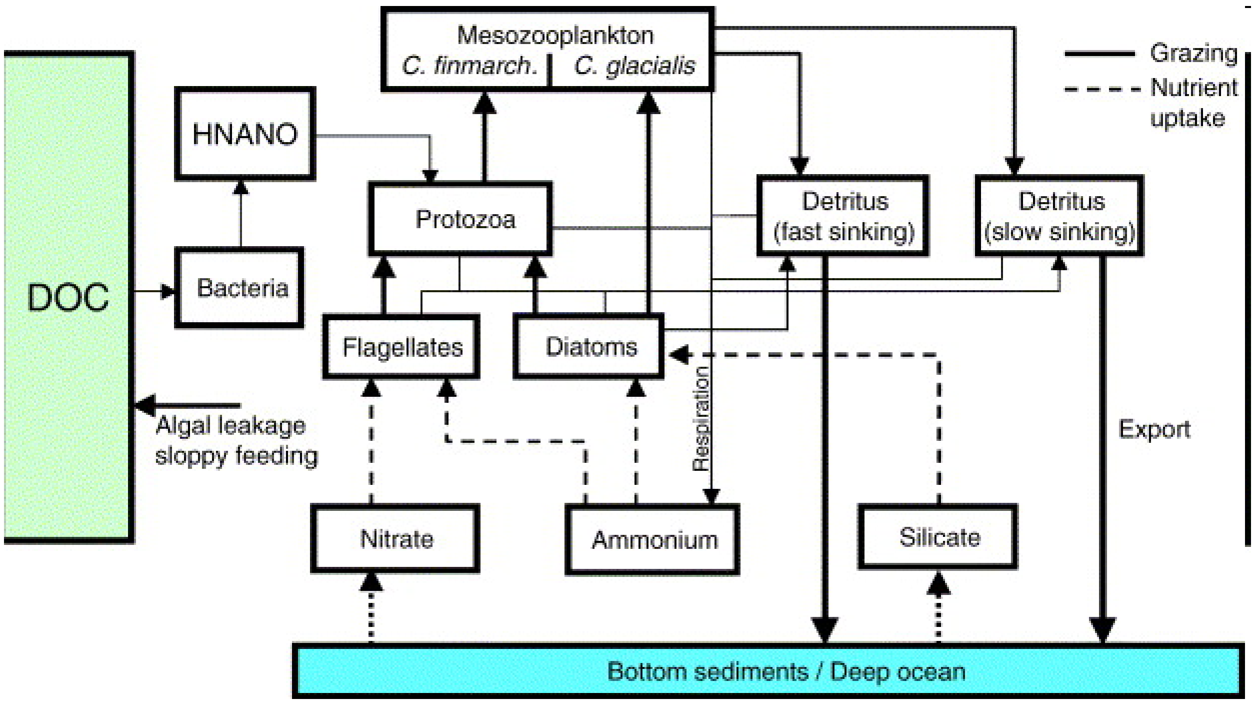
- Substantial limitation by nutrients on the annual scale
- Future ice cover retreat without addition of extra nutrients may have little impact on increased carbon sequestration

Regional Barents sea coupled ocean-sea ice ecosytem model

Modeling the ecosystem dynamics of the Barents sea including the marginal ice zone:
I. Physical and chemical oceanography (Slagstad and McClimans, 2005)
II. Carbon flux and interannual variability (Wassmann et al., 2006)



Barents sea model domain

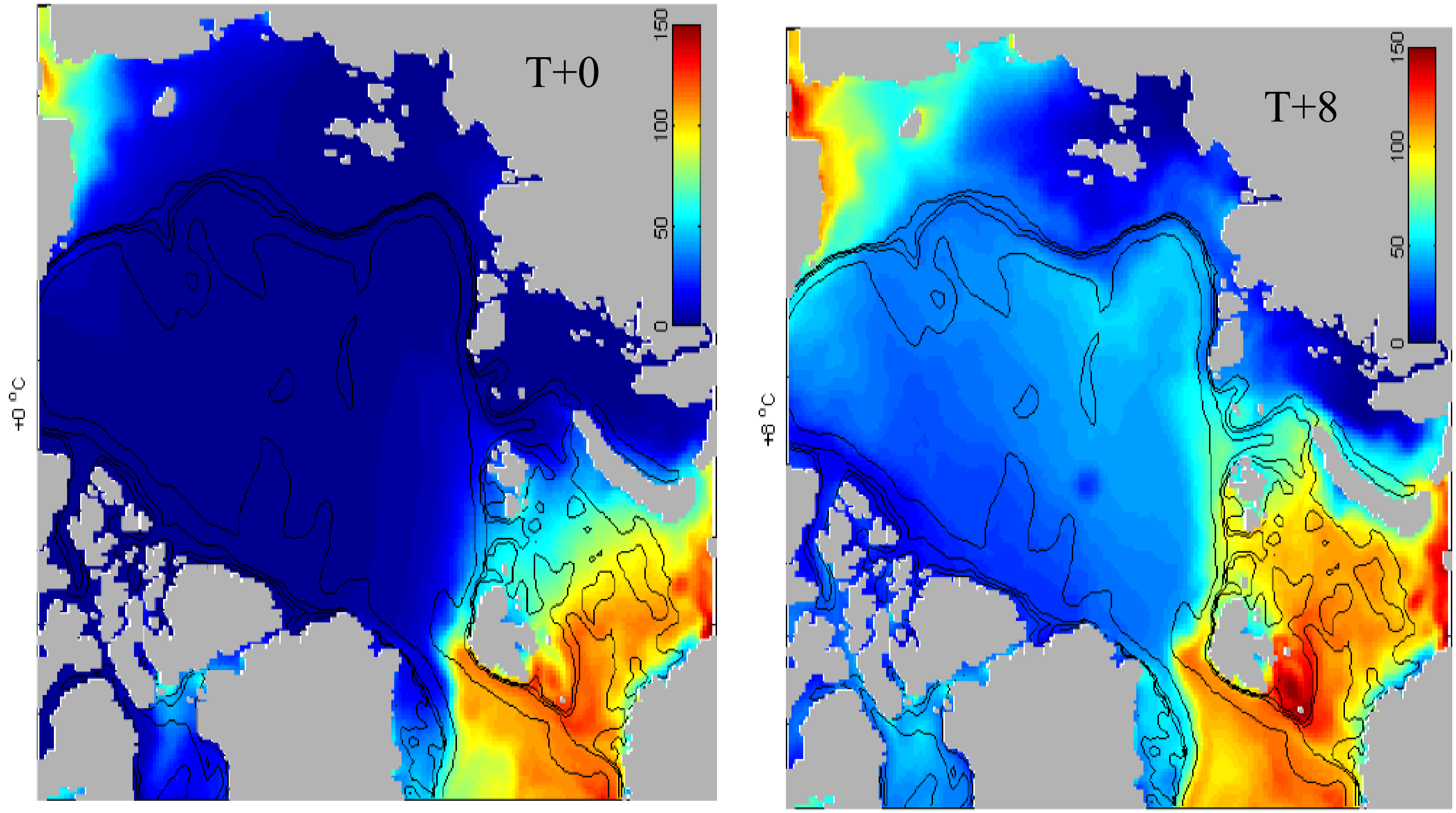


Barents sea regional model: conclusions

Future retreat of the sea ice will give rise to increased “Atlantification” of the area i.e. widening of the weekly stratified region with corresponding increase in primary production

Mean annual primary production (gC m-2)

Dag Slagstad and Ingrid Ellingsen .SINTEF Fisheries and Aquaculture Trondheim, Norway



Summing up

- We have forced a coupled ocean-ice-biology model with present atmospheric forcing and artificially increased the average air temperature at high latitudes
- We found:
- Summer ice diapered already with 4 °C increase in air-temp.
- Increase in primary production were profound, but was limited by the nutrient supply through a strong pycnocline.
- *C. glacialis* (or possibly *C. hyperboreus*) were able to conquer the Arctic
- *C. finmarchicus* were able to reproduce in the Northern Barents Sea and in the Atlantic water entering the Arctic through the Fram Strait

Global models

Arctic ecosystems in Global biogeochemical models Questions:

- How well do we reproduce Arctic ecosystem dynamics in a framework of a global model?

  - in other words “Does Arctic requires a “special” regional ecosystem model?

- What factors control Arctic primary production at present?

- What are implications for ecosystem in the ice-free Arctic?

Conclusions

•Main features of spatial distribution of AO primary production is disproportionately influenced by physical factors, mainly light availability and vertical mixing;

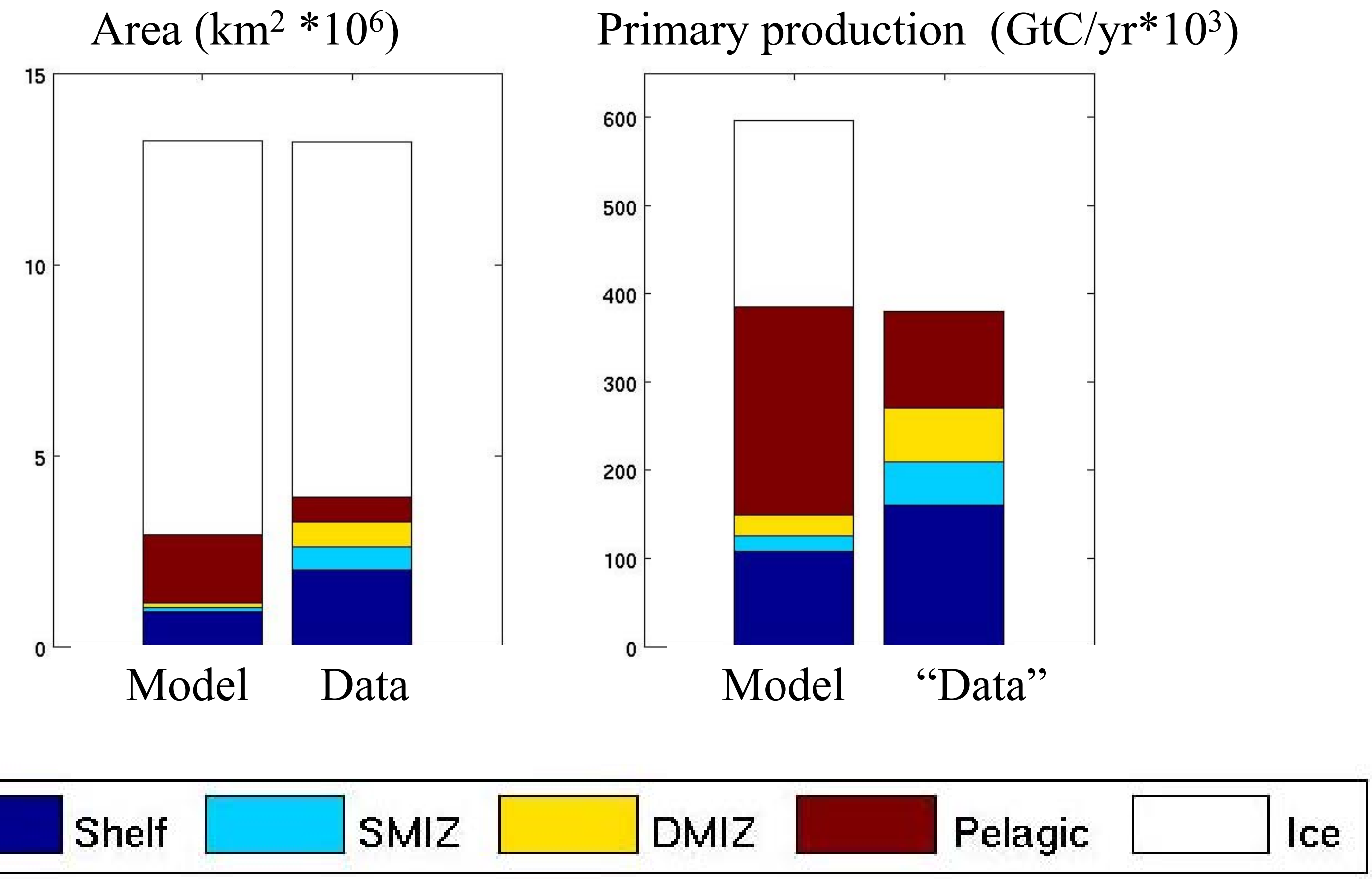
•Both factors are determined by physical properties and not ecosystem dynamics;

•To model large-scale features of the AO primary production no complex biological model is required;

•A simple correlation with the model physical parameters can describe up to 93% of spatial variability in the primary production

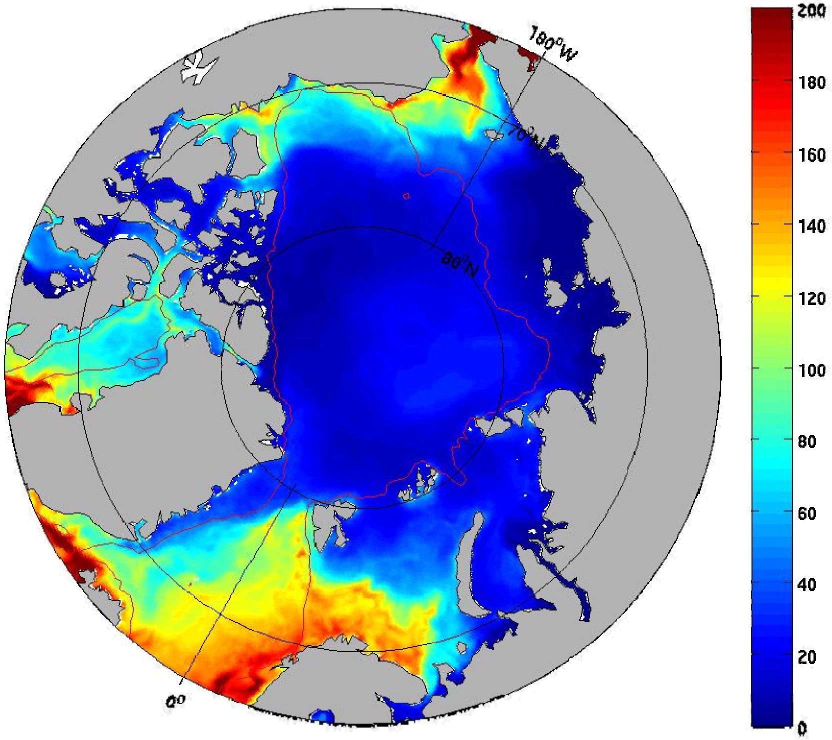
•Thus ecosystem dynamics in Arctic for longer runs might be parameterised rather than explicitly modelled

Comparison with satellite-derived estimates of Pabi et al.
(Primary prod in AO, 1998-2006, JGR, 2008)

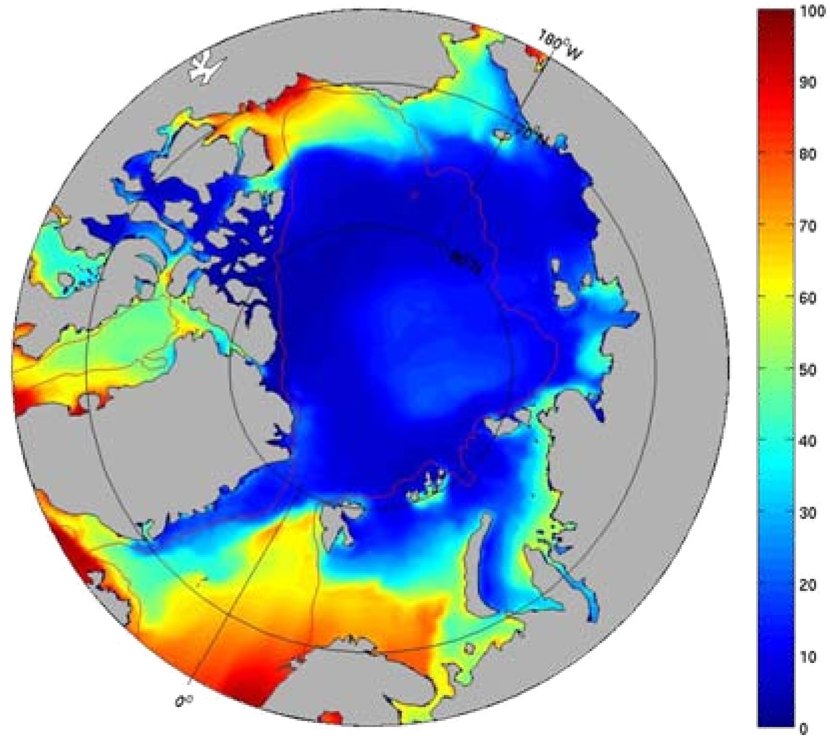


Pan-Arctic primary production

Factors controlling AO primary production
1. Light



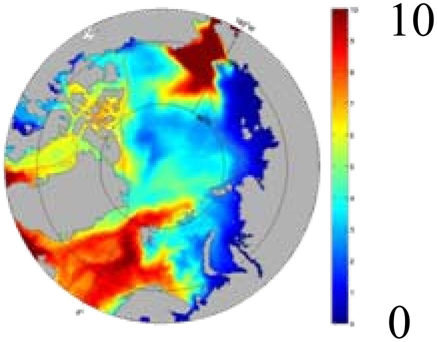
Pr.Production (gC/m2/yr)



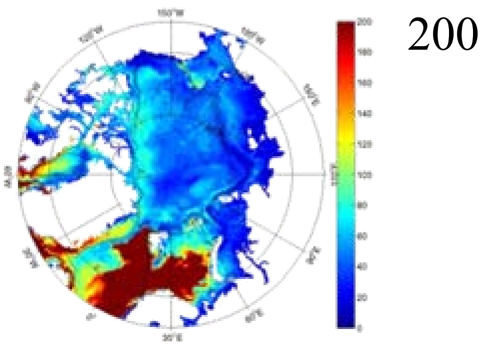
Annual mean short-wave radiation

Corr.=0.85

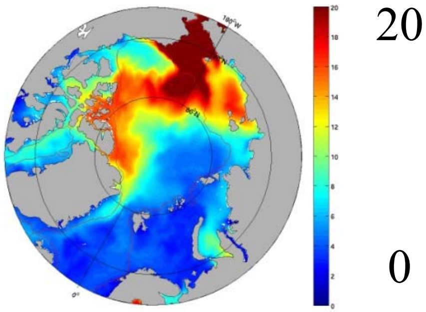
Factors controlling AO primary production
2. Nutrients



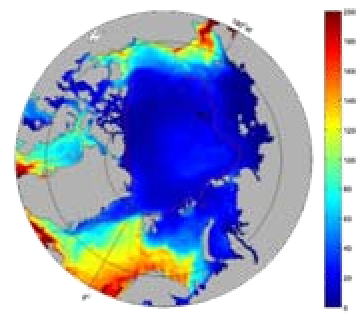
Annual mean Nitrate



Max UML depth

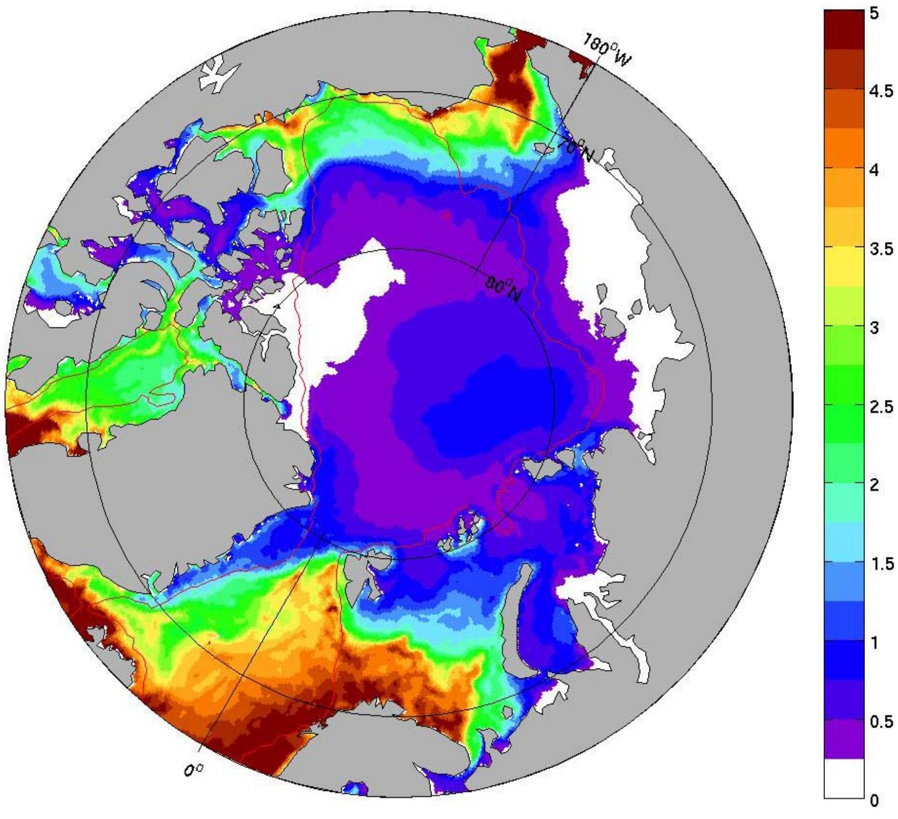


Annual mean Silicate

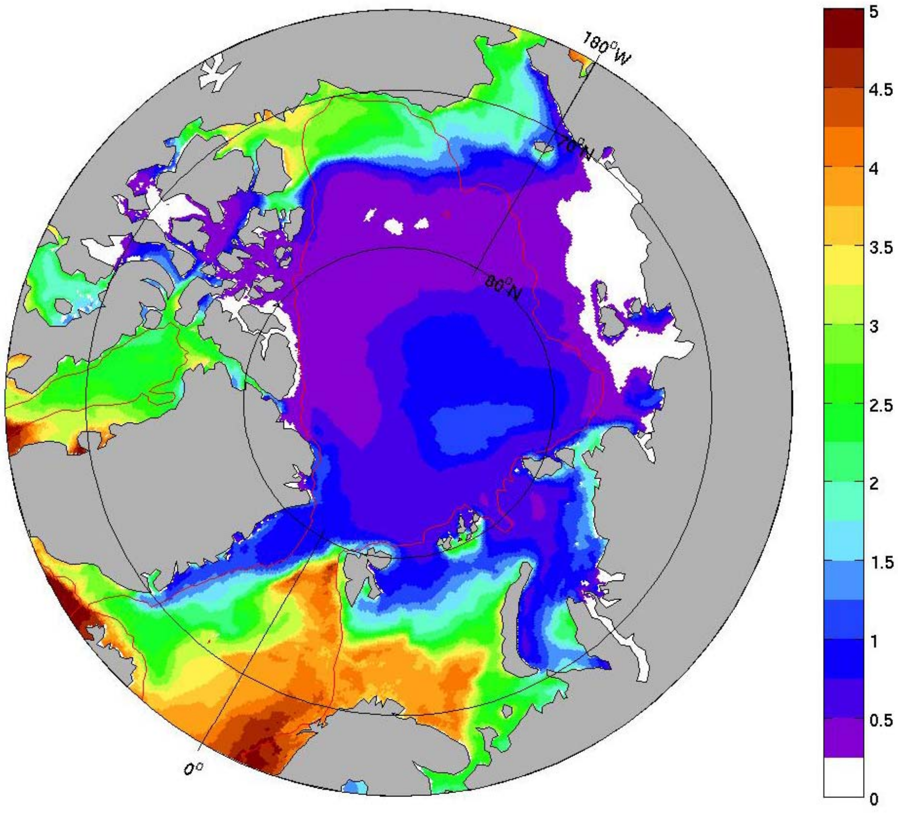


Pr.Production (gC/m2/yr)

Mean annual primary production



Pr.prod (Full model)



Pr.prod (corr withSW, hmax, S)

What are implications for the ice-free Arctic ecosystem?

Future ice-free Arctic productivity will be determined not by changing short-wave radiation (direct impact of the ice retreat) but by changes to the vertical mixing such a retreat would initiate:

•Longer exposure of the surface waters to wind and negative buoyancy forcing in the late autumn will increase the depth of winter mixing

•Retreat of the ice cover beyond the shelf break will set up shelf-break upwelling of nutrient-rich waters

Challenges in Arctic ecosystem modelling

1. Lack of pan-arctic observational information for model validation: good observational data sets exist for a number of contrasting regions, but not for compilation of pan-Arctic synthesis

2. Ice-related and weather-related problems make satellite Chl-a observations very limited in Arctic

3. Rossby deformation radius is smaller than in the rest of the WO, so global models performance is problematic

4. Ecosystem dynamics is extremely sensitive to the physical characteristics, more so than physical models themselves. Ecosystem dynamics would heavily rely on the quality of the ice model

5. Arctic (and Arctic future) is becoming an area of major political and economic interest. Models are being pushed into the predictive modes without sufficient work devoted to their validation and verification.