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| Title: | Impacts of Marine Ecodynamics on the Dimethyl Sulfide(DMS) Production |
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# Impacts of Marine Ecodynamics on the Dimethyl Sulfide(DMS) Production

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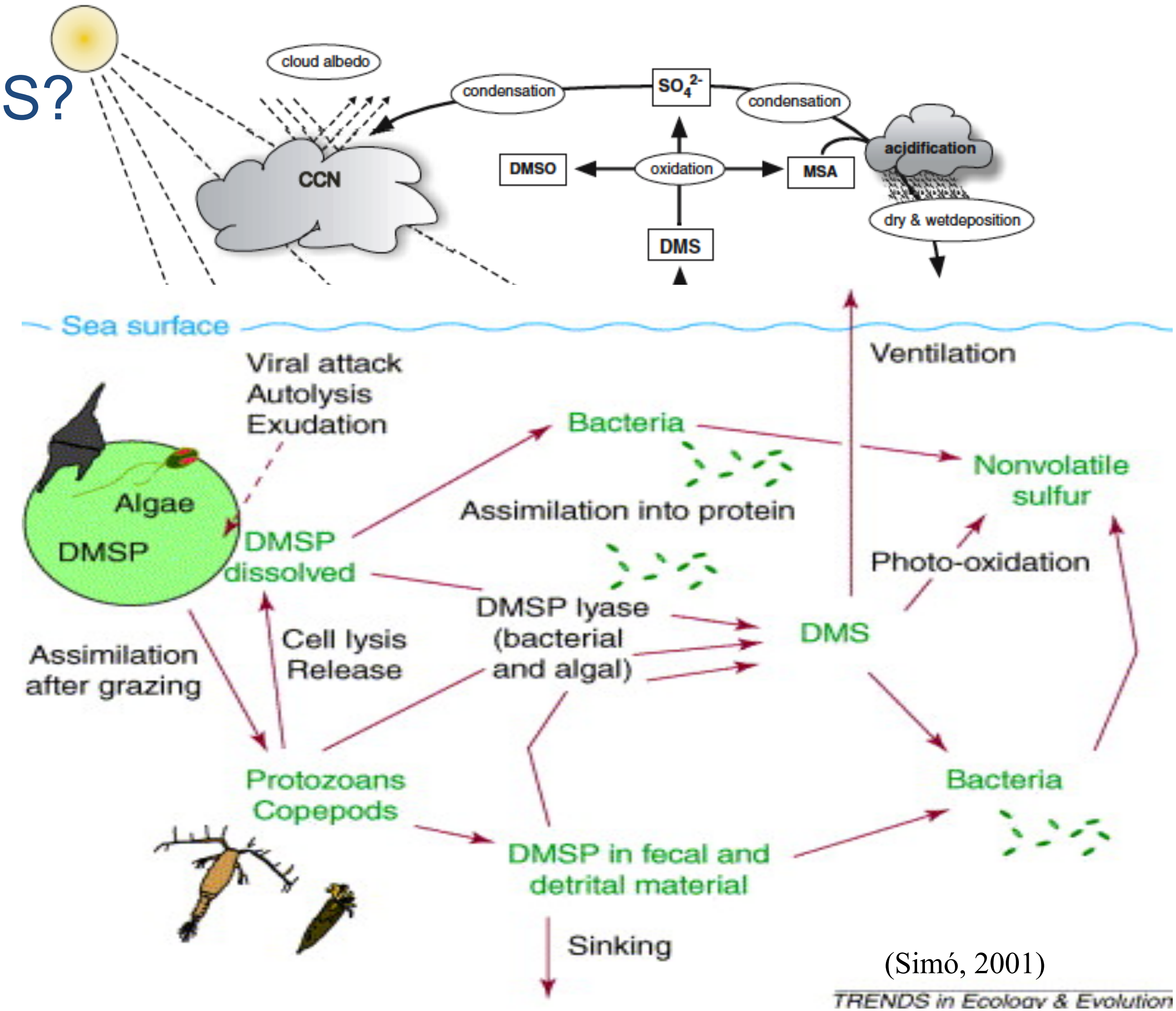
Thanks to Philip Cameron-Smith (LLNL),
Scott Elliott, Mathew Maltrud (LANL)

Mar 4, 2016

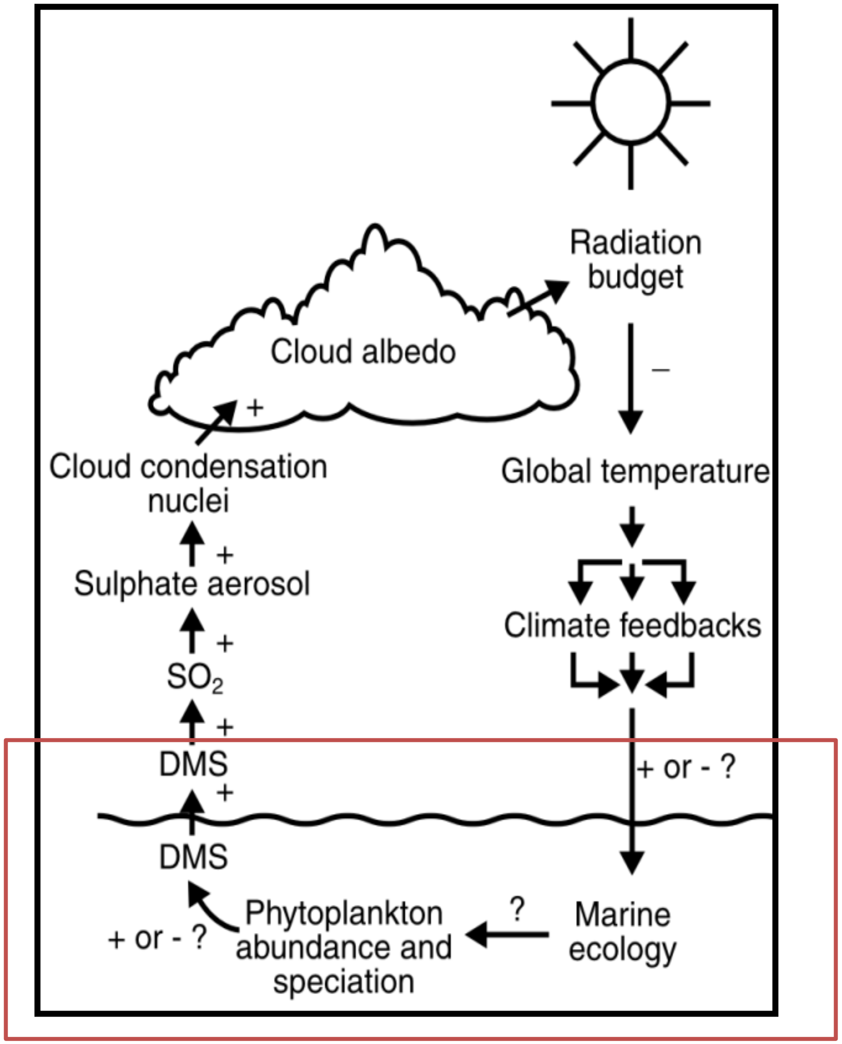
# What is DMS?



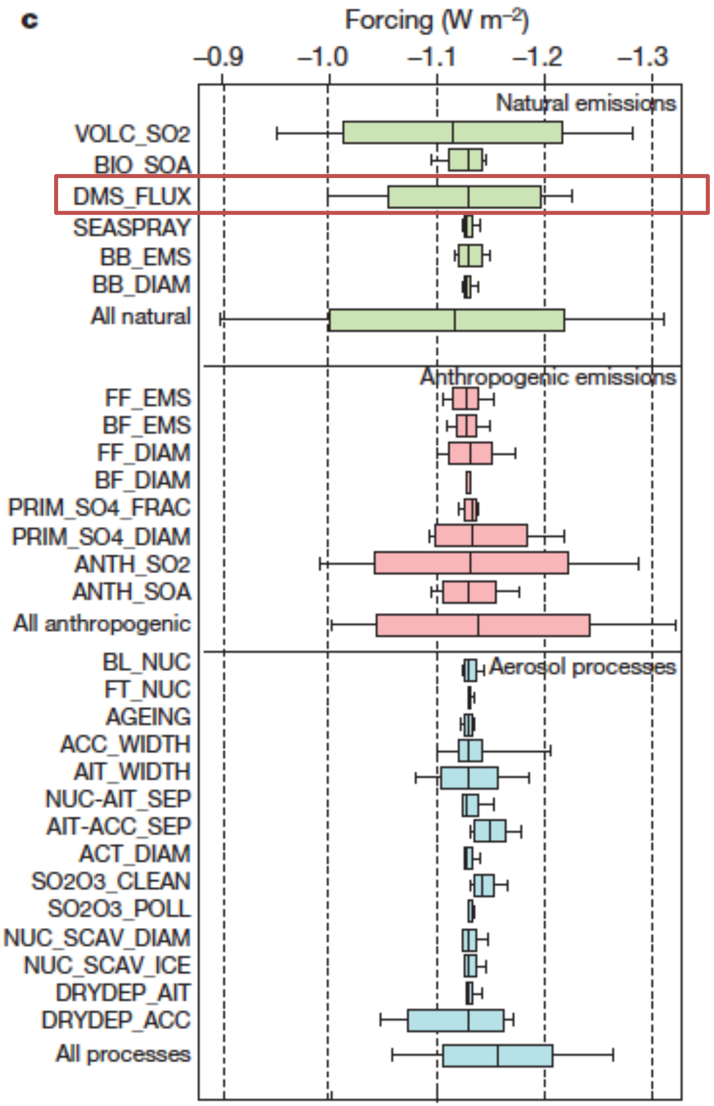

(Simó, 2001)

**Fig. 1** Schematic representation of the processes and pools involved in the marine biogeochemical cycling of DMSP and DMS. Dominant role of functional groups in the different processes is indicated by coloured ellipses: green, phytoplankton; blue, zooplankton; red, bacteria; black, abiotic factors. CCN, cloud-condensation nuclei; DOM, dissolved organic material; DMSO, dimethyl sulphoxide; MeSH, methanethiol; MPA, mercaptopropionate; MMPA, methylmercaptopropionate; MSA, methanesulphonic acid

# Importance of DMS



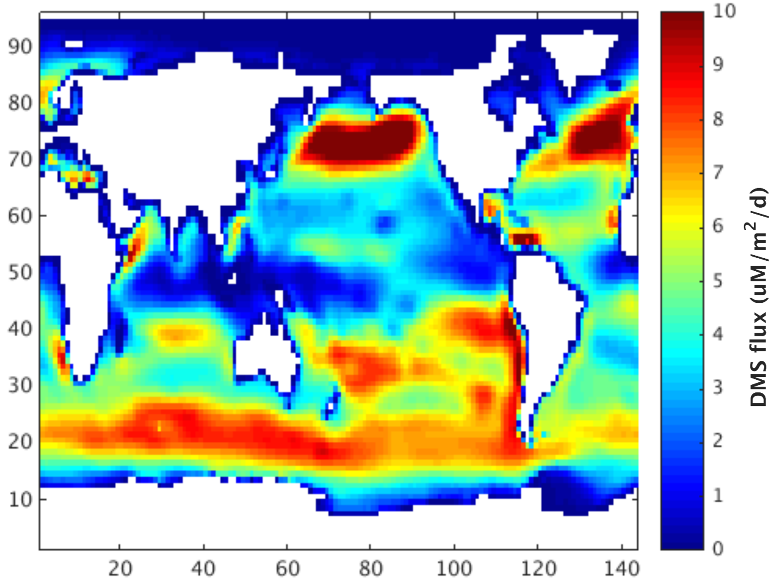

The CLAW Hypothesis
(Charlson et al., 1987)



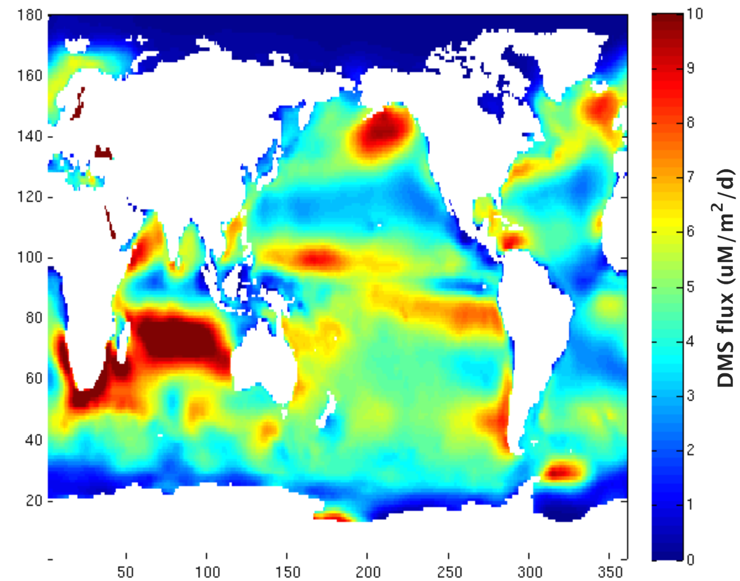

Magnitude and sources of uncertainty in aerosol first indirect forcing (Carslaw et al., 2013)

- These all point out the importance of improving DMS simulations.

# DMS emissions



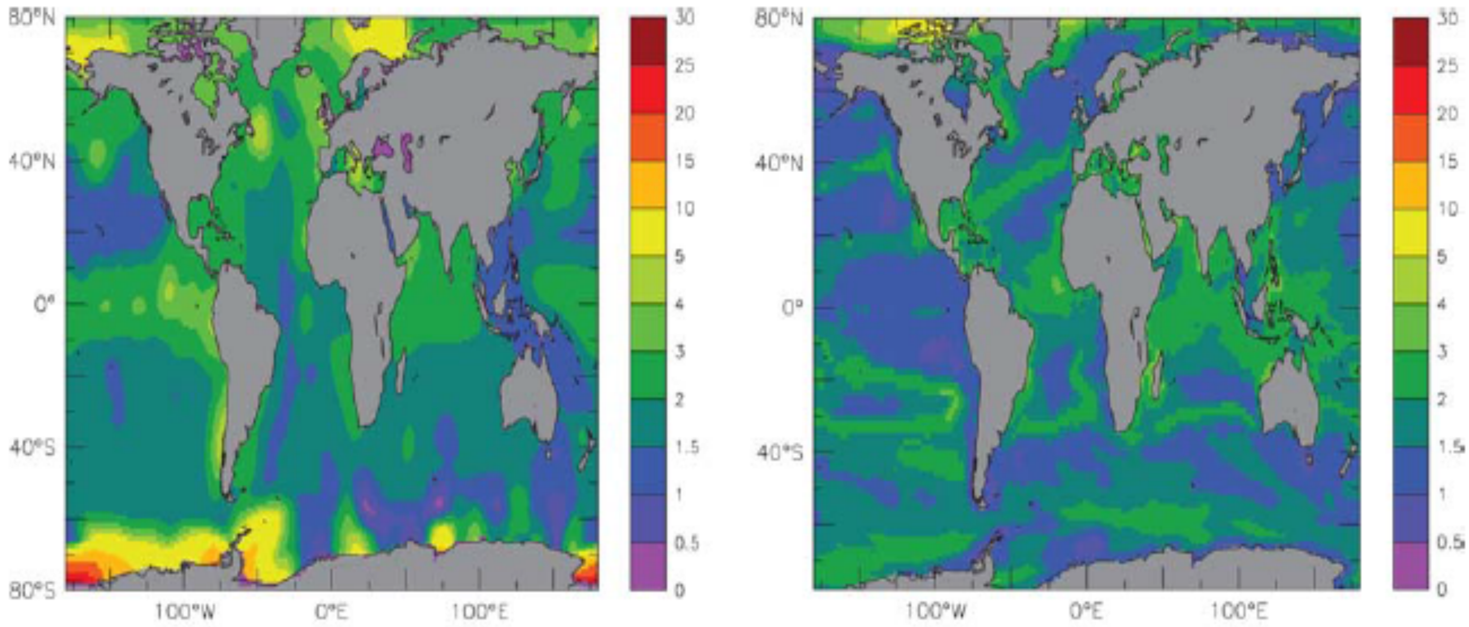

CAM DMS annual emission




Offline data-based emission

- DMS annual emission is 37.1 Tg/yr in data forced simulation
- Previous data-based estimates suggest annual DMS fluxes of 17.6 – 34.4 Tg/yr (Lana et al., 2011) and 15.0 – 29.4 Tg/yr (Kettle and Andreae, 2000)
- There are significant differences between prescribed emission and data based estimates
- The DMS production should be dynamically simulated!

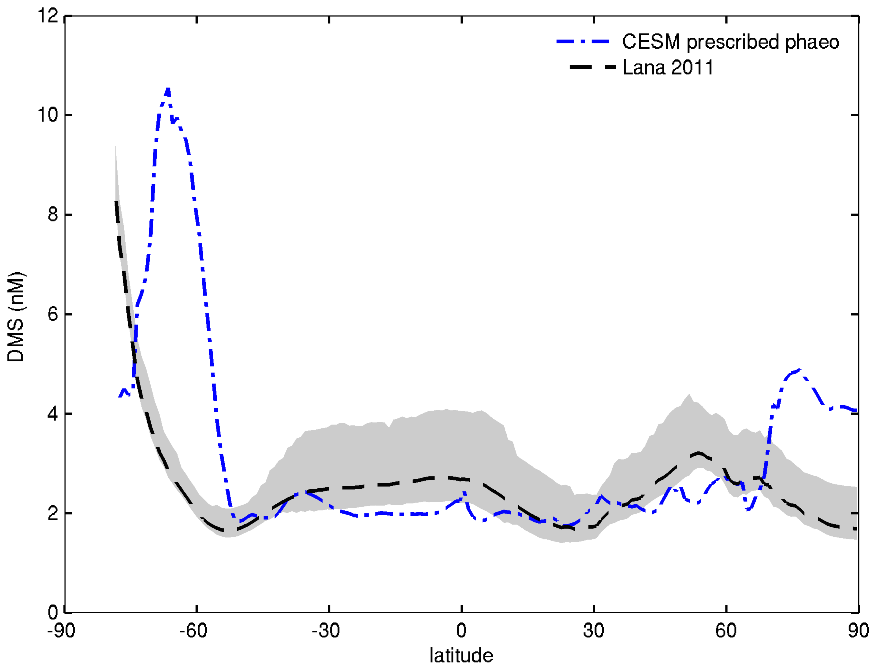
# Importance of marine ecosystems

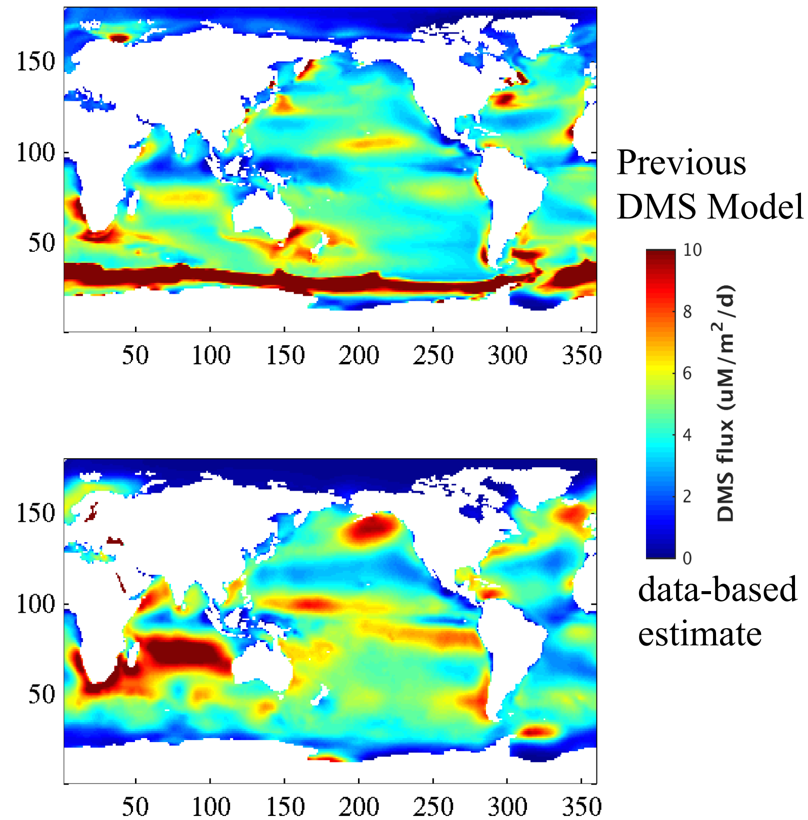



(a) DMS Kettle (nM) (Vogt et al., 2010) (b) DMS PlankTOM5 (nM)

- The underestimated DMS concentrations at high latitudes are potentially due to the absence of *Phaeocystis* group (Vogt et al., 2010)
- *Phaeocystis* is important for high latitude DMS distribution

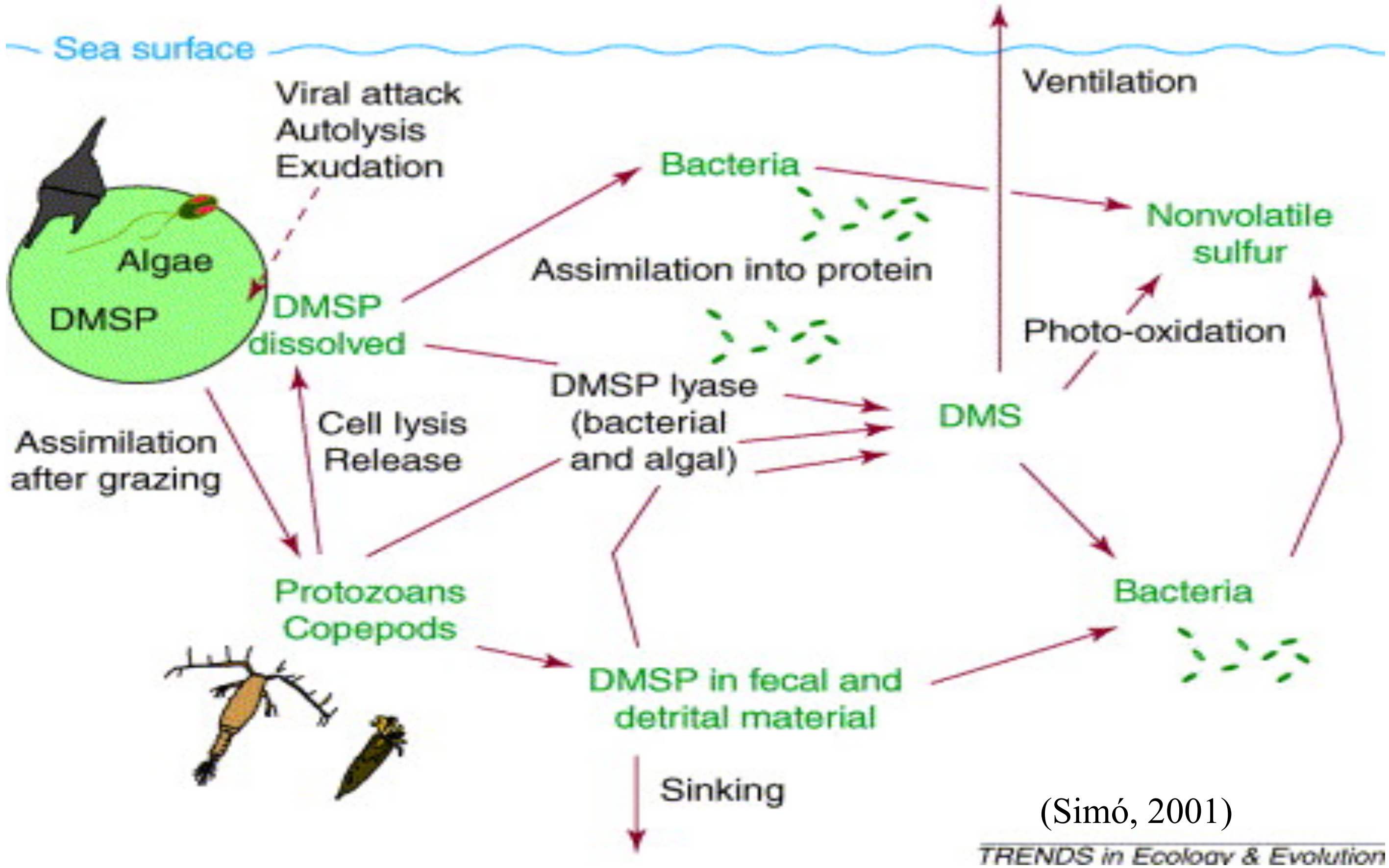
# A previous DMS model




- In the earlier DMS module, *Phaeocystis* was simulated implicitly as a fraction of the global small phytoplankton. The simulated time and location of DMS peaks are biased.
- These results suggest the need of improving the representation of ecosystem structure

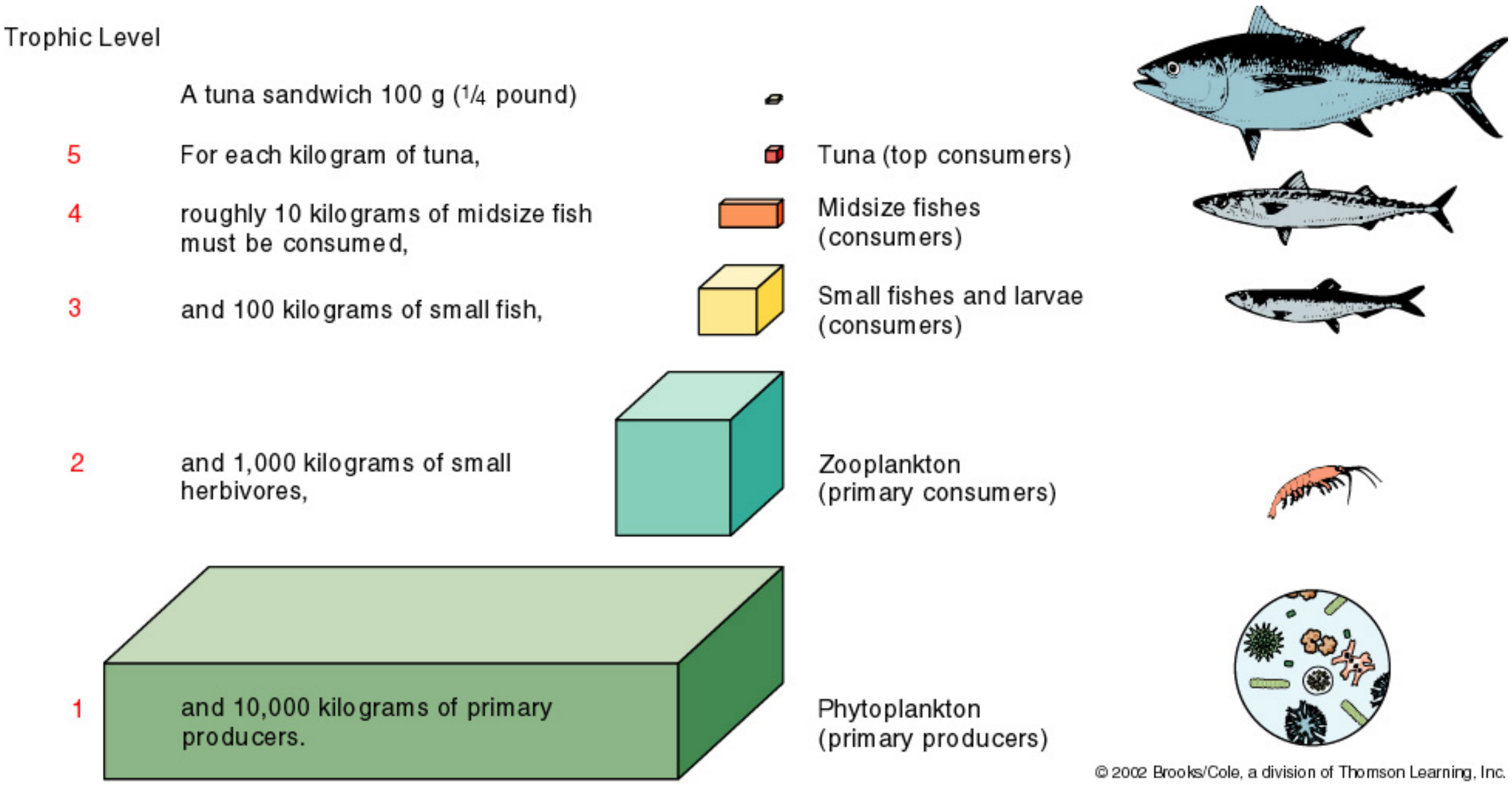
# To simulate DMS…




(Simó, 2001)

- Marine microorganisms are controlling various processes in the sulfur cycle!
- We first need to have the ecological/biogeochemical models

# Ocean Biology

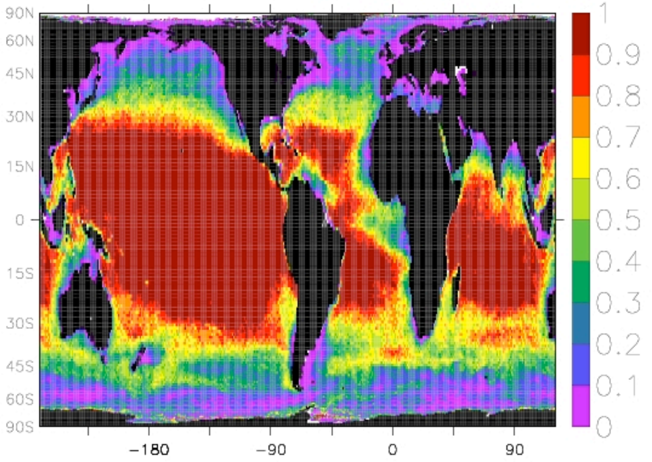


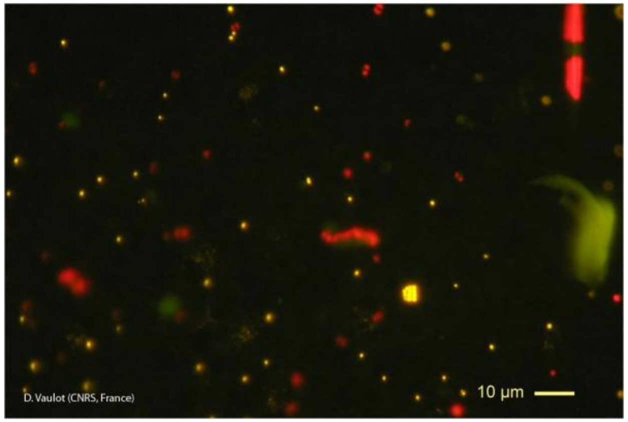

- Higher trophic levels -Important for ecology, marine resources for humans
- Lower trophic levels - Important impact on global biogeochemical cycles
- Many BGC models adapt the concept of "**functional group**". A function group is a collection of organisms that express a similar biogeochemical role.

# Major Phytoplankton Functional Groups

Nano- and Pico-phytoplankton (nano 2-20 μm, pico <2 μm)

- Diverse classes of smaller species
- High surface/volume ratios
- Thrive under low nutrient conditions
- Dominate community in mid-ocean gyres
- Under strong grazing pressure (especially < 5 μM)
- Smaller contribution to sinking C export
- Usually considered as the background community.

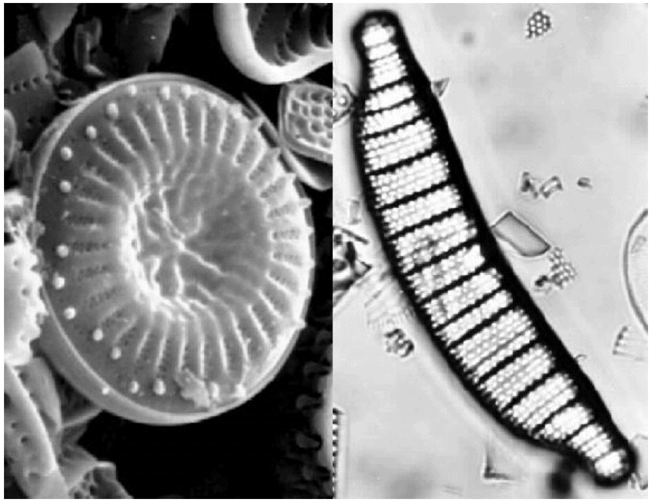


# Major Phytoplankton Functional Groups

Diatoms (20-500 µM)

- Outer frustule composed of biogenic silica
- Large phytoplankton, low grazing losses
- Low surface/volume ratio, thrive under high nutrient concentrations
- Often dominate phytoplankton blooms
- Often dominate sinking C export out of surface waters.
- Weak DMS producers



# Major Phytoplankton Functional Groups

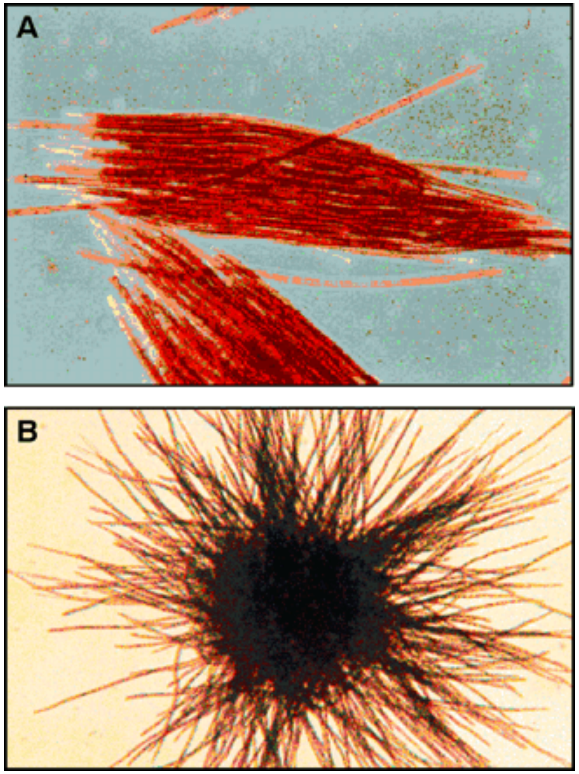
Coccolithophores (10-30 µM)

- Outer platelets, "coccoliths" of $CaCO_3$
- Carbonate requirement alters surface $pCO_2$
- Important component of sinking C export.
- Medium size, moderate grazing losses
- Moderate surface/volume, thrive under medium-high nutrient levels
- Bloom mainly at low to mid-latitudes, typically not found in coldest polar waters.

# Major Phytoplankton Functional Groups

## Diazotrophs (Cells 1 μM, colonies can be mm to cm)

- Capable of fixing dissolved $N_2$ gas into $NH_4^+$.
- Source of new nitrogen to surface waters in tropical/subtropical regions. May influence total ocean nitrate and productivity over long timescales.
- Slow growth rates, low grazing losses.
- High light and Fe requirements.
- Thrive in warm, tropical and subtropical regions, not found at high latitudes.
- Do not produce DMS



# Major Phytoplankton Functional Groups

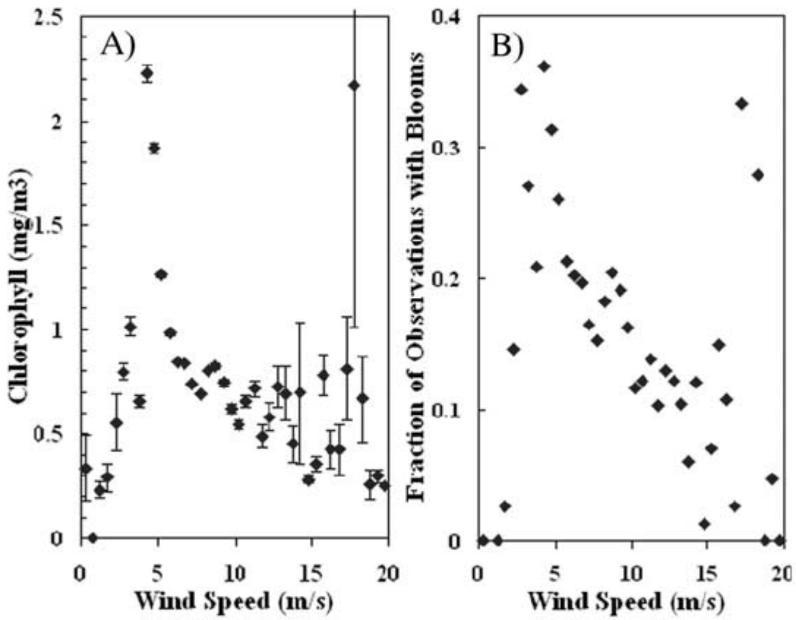
*Phaeocystis* (solitary 3-9 µM, colonies to 3 cm)

- Thrive in colder, polar waters
- Exist in single cell and colonial forms
- Often dominate non-diatom blooms polar waters
- Colonies held together by carbohydrate rich, extra-cellular mucus (~50% of carbon). This can gives colonies higher C/N and C/P ratios, leading to efficient export of carbon.
- Strong producers of DMSP and DMS.

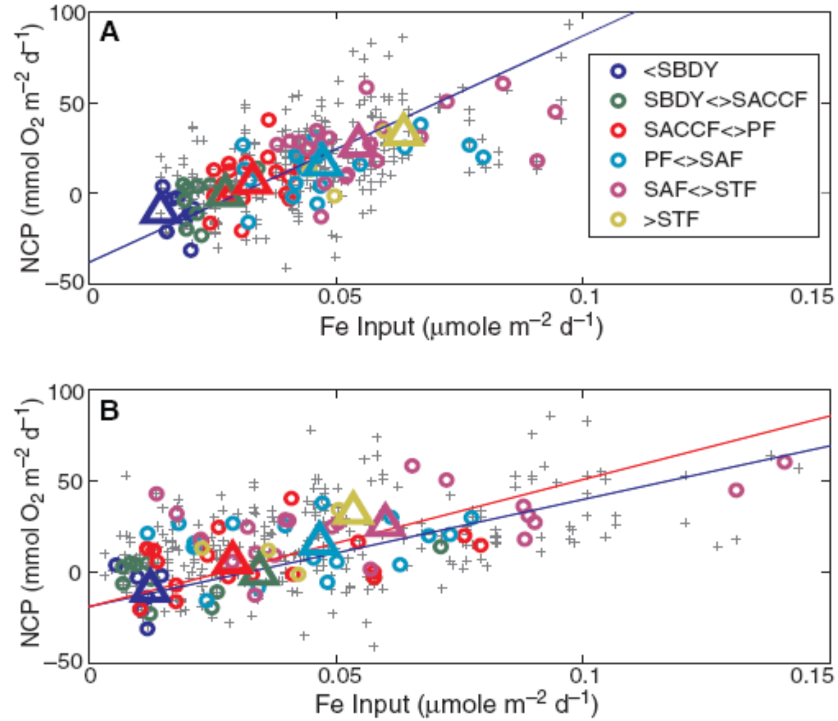

http://www.vims.edu/phae/


(http://hazards.umwblogs.org)

# Controls of phytoplankton growth and competition




Chlorophyll concentrations and wind speed in Marginal Ice Zone (Fitch and Moore, 2007)

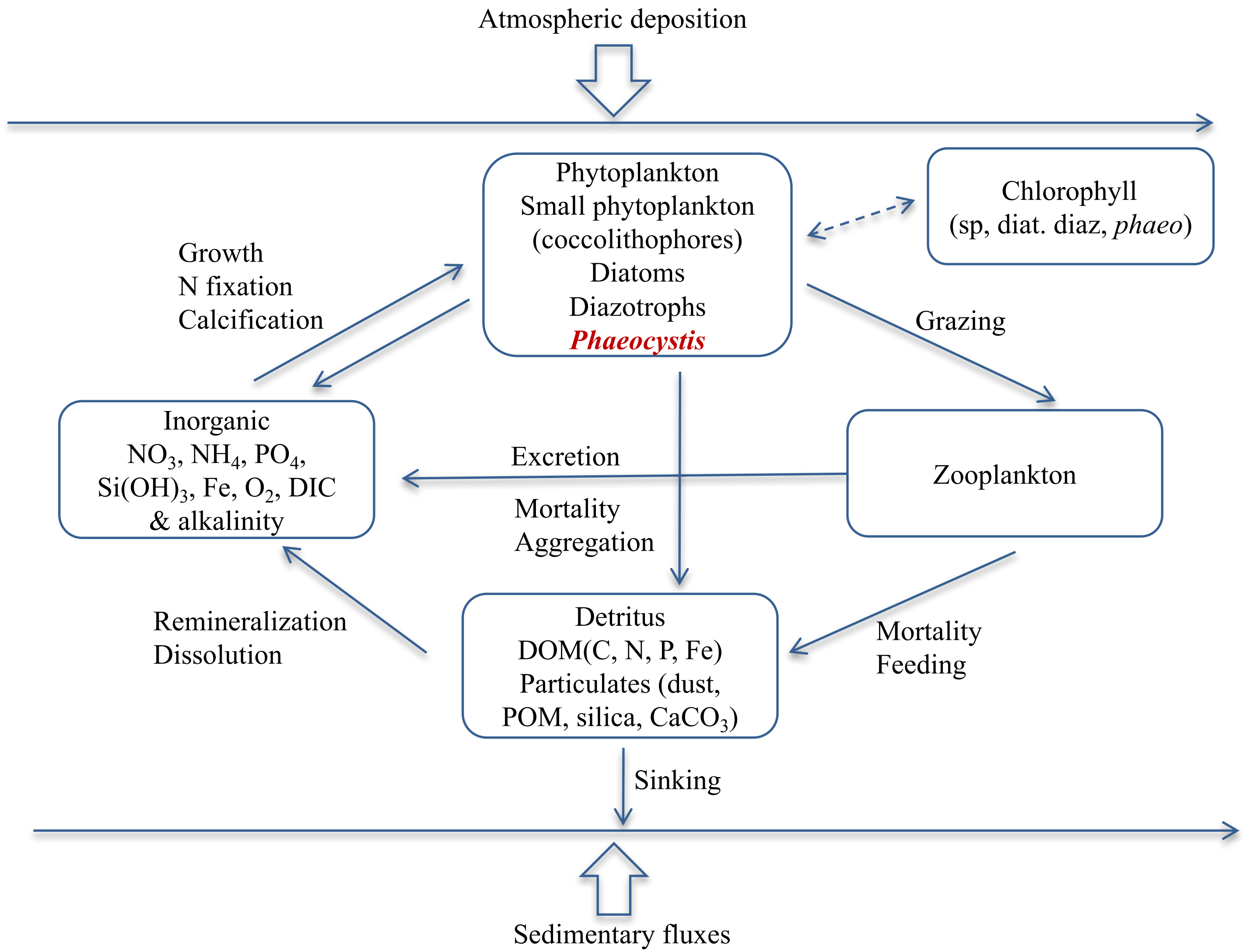



Spring (16%) and summer (84%) NCP measurements versus corresponding modeled annual (A) and 2-week (B) Fe deposition rates. (Cassar et al., 2007)

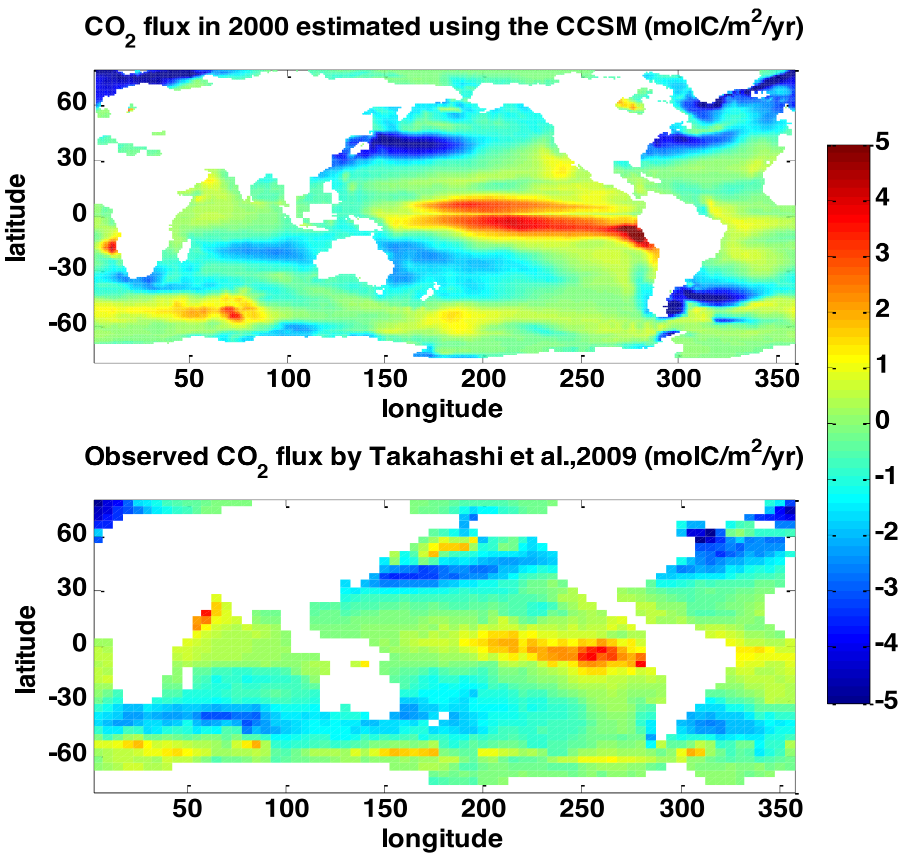
- The distribution of phytoplankton biomass and NPP is determined by the availability of light and nutrients (nitrogen, phosphate, iron, silicate).
- Different phytoplankton groups have different requirements for these factors

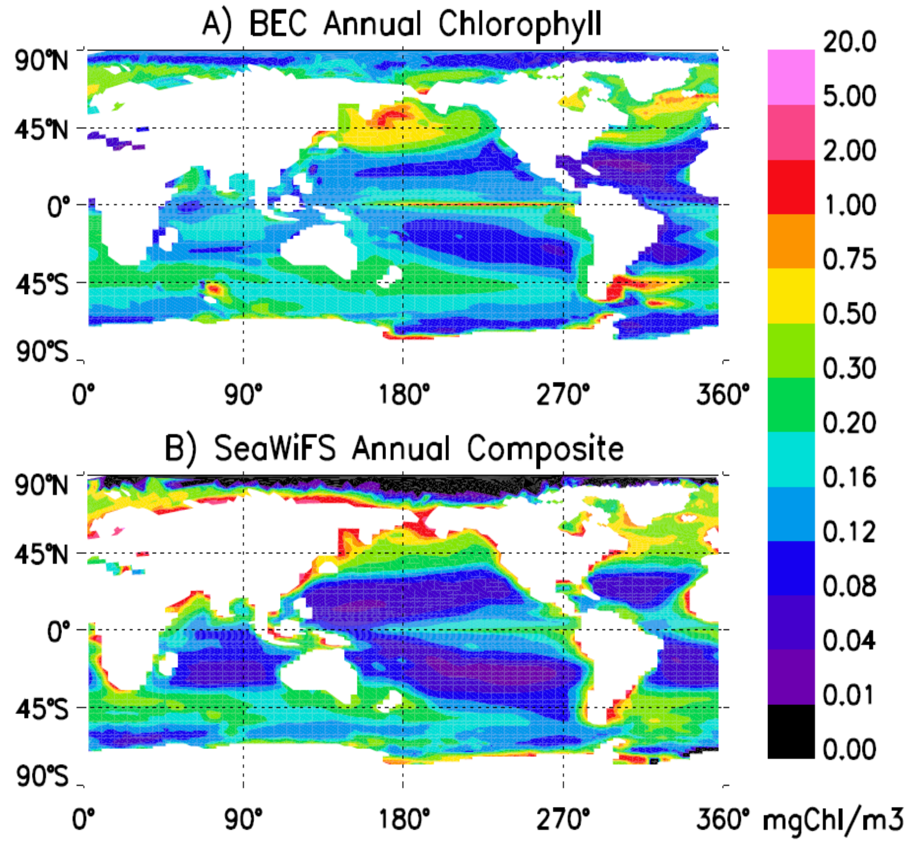
# Model Description

## Biogeochemical Elemental Cycling (BEC) model



# Model performance

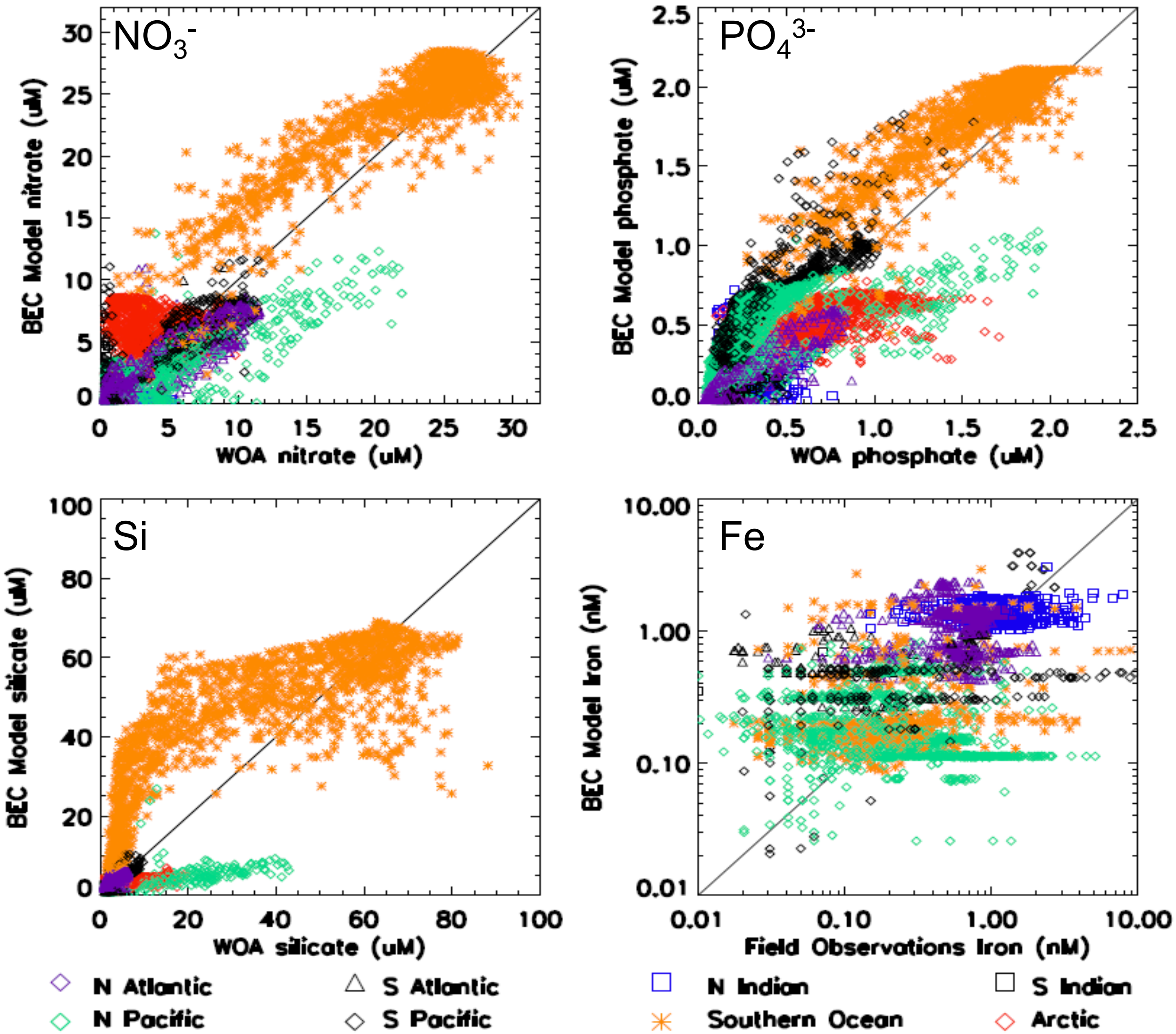



(Wang and Moore, 2012)

- The modeled global sea-air $CO_2$ flux is comparable to the observation-based estimate by Takahashi et al. (2009)
- The BEC model reasonably reproduces the patterns of surface chlorophyll concentrations.

# Model performance




(Wang and Moore, 2012)

- Correlations between modeled and observed major nutrient concentrations are all higher than 0.85
- Regional biases remain

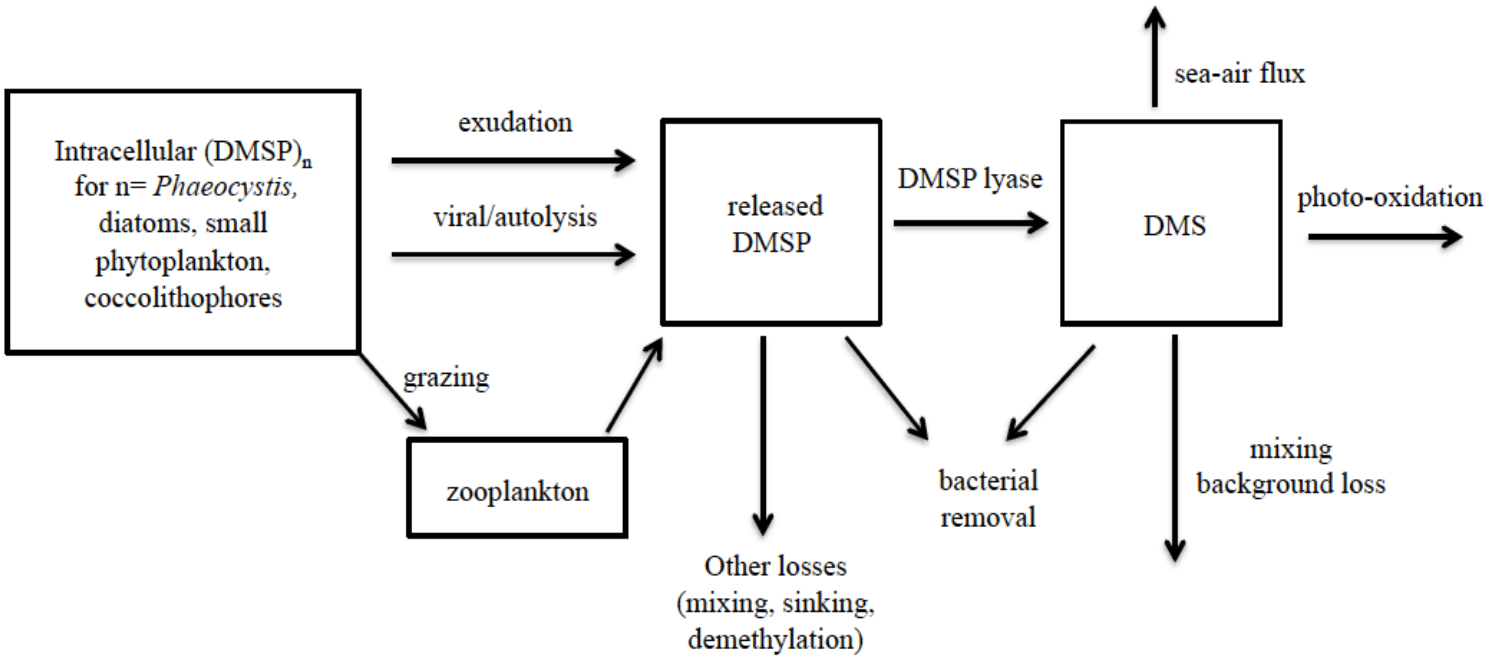
# DMS module

$$Prod^{DMSP} = scale \times \left( \sum_i Prod_i^{DMSP} + Prod_Z^{DMSP} + Prod_{phaeo-dir}^{DMSP} \right)$$

$$Prod^{DMS} = yield \times k \times Prod^{DMSP}$$

$$Loss^{DMS} = Loss_B^{DMS} + Loss_{bkg}^{DMS} + Loss_{photo}^{DMS}$$

$$Loss^{DMSP} = Loss_{DMS}^{DMSP} + Loss_{bkg}^{DMSP}$$



# Model Description

## Biogeochemical elemental cycling (BEC) model

**Ecosystem Module**

5 phytoplankton groups
One zooplankton group
DOM, sinking particulates
Multiple growth limiting nutrients

**DMS module**

Prognostic calculations of the DMS production and removal

Ocean circulation component in Community Climate System Model / Community Earth System Model

# Previous studies

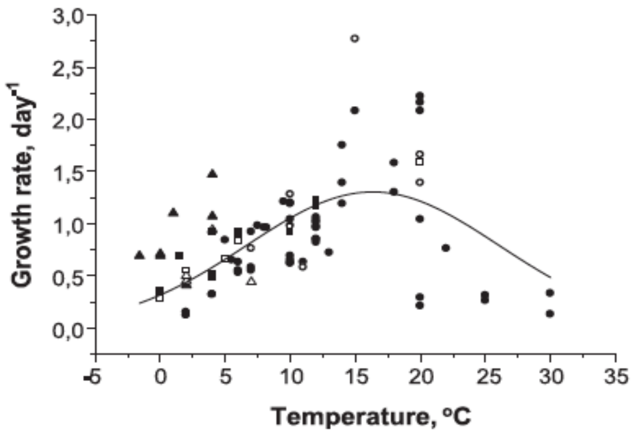
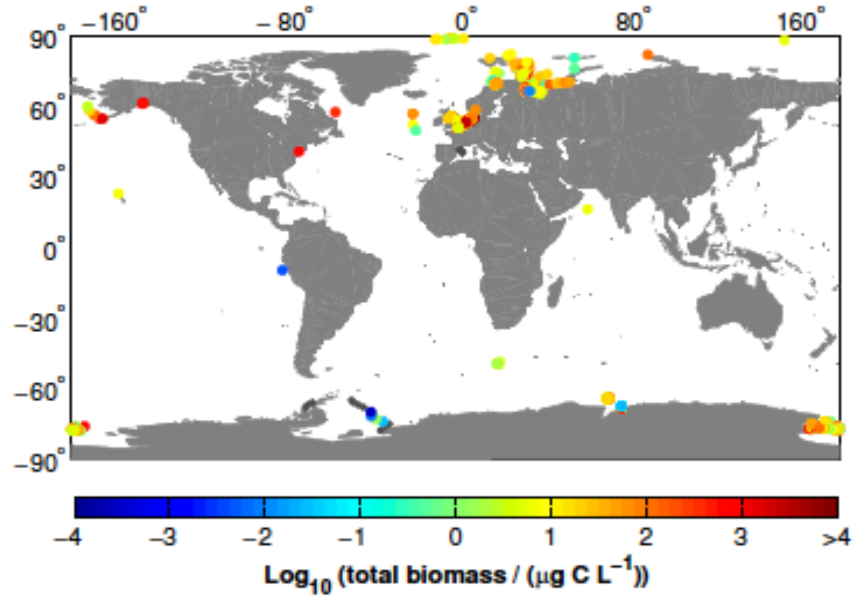
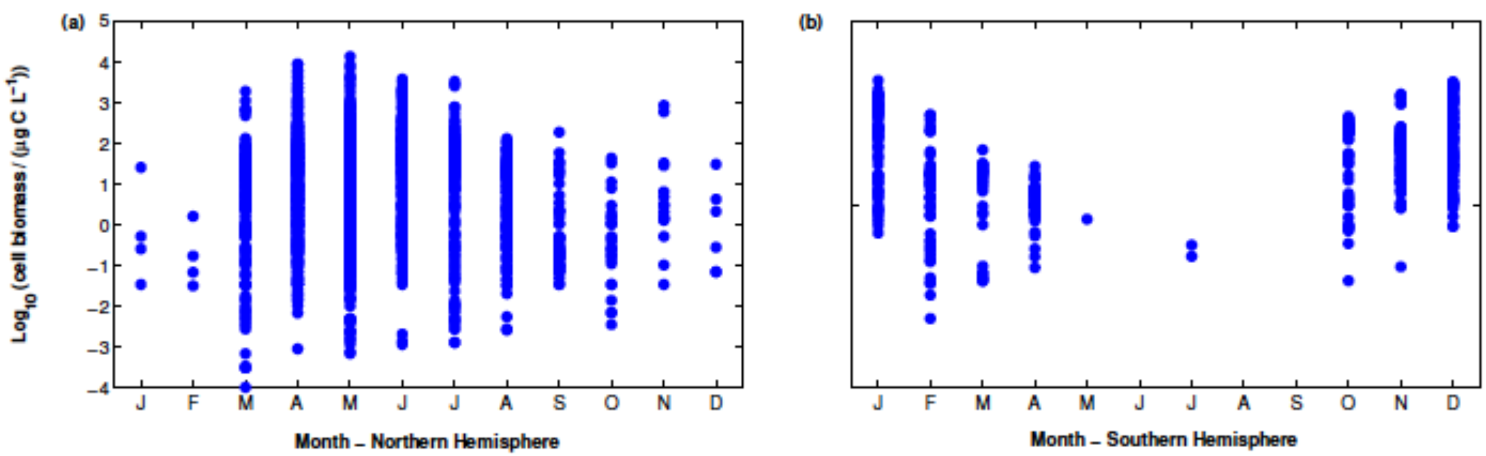



Fig. 3. Relationship between *Phaeocystis* specific growth rate μ and temperature (μ=ln2*υ, with υ=division rate). The closed and the open symbols represent colony cells and solitary cells data, respectively. Squares, circles and triangles represent data for *P. pouchetii*, *P. globosa* and *P. antarctica*, respectively.

(Schoemann et al., 2005)




(Vogt et al., 2012)




(Vogt et al., 2012)

# Incorporating *Phaeocystis*

- Two groups of *Phaeocystis*: One group for northern species, combining *P. globosa* and *P. pouchetii*; One group of *P. antarctica*
- Only the blooming colonial form considered

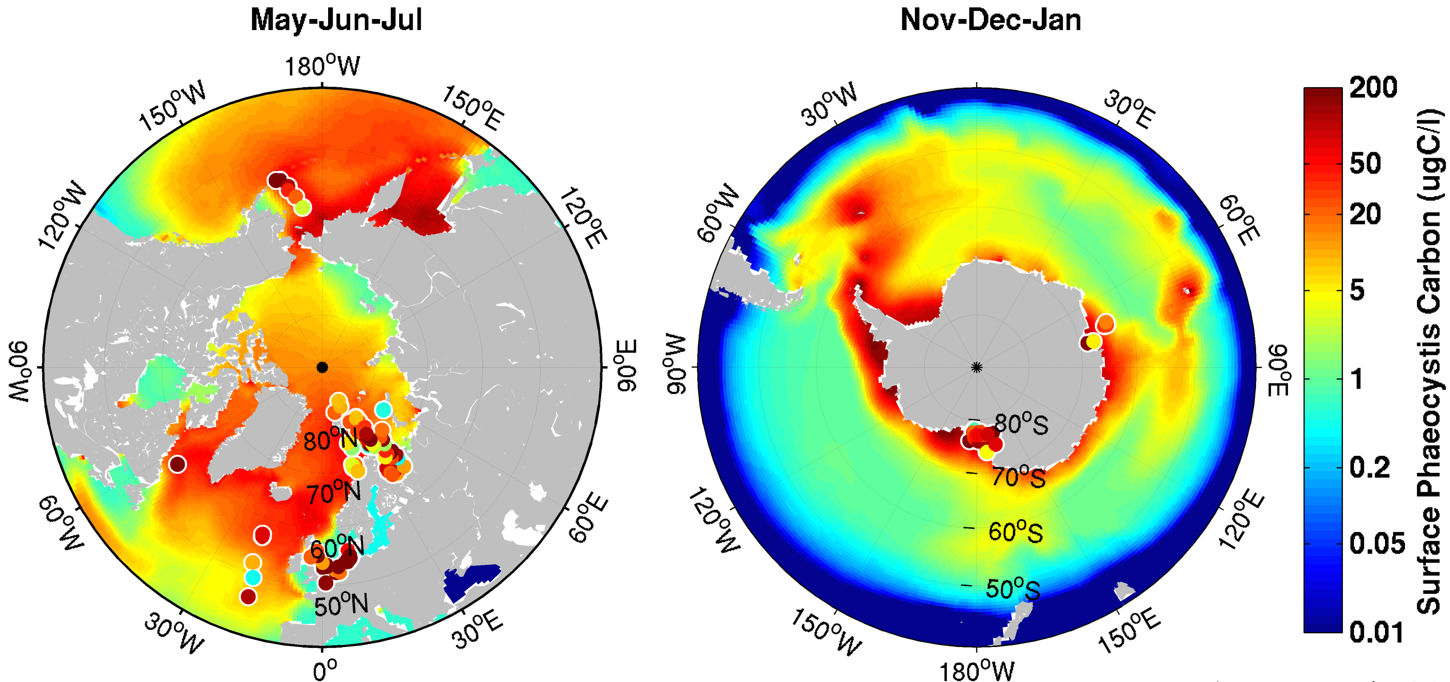
$$PCmax = PCmax \times min(1, \frac{(thres - TEMP)}{(thres - Tpeak)})$$

$$PCmax = max(PCmax, 0)$$

$$graze = Zumax \times zooC \times \frac{phaeoC}{(phaeoC + diatC + Zgrz)}$$

- Key parameters: $k_{NO3}$, $k_{Fe}$, grazing, $T_{opt}$, $T_{thres}$, and alpha
- The values of $T_{peak}$ are 16.3 °C and 5 °C in NH and SH, respectively
- Grazing on *Phaeocystis* or diatoms is influenced by the total biomass of both groups
- In general, our preferred physiological parameters suggest that *Phaeocystis* is well adapted to low-light and nutrient-rich conditions

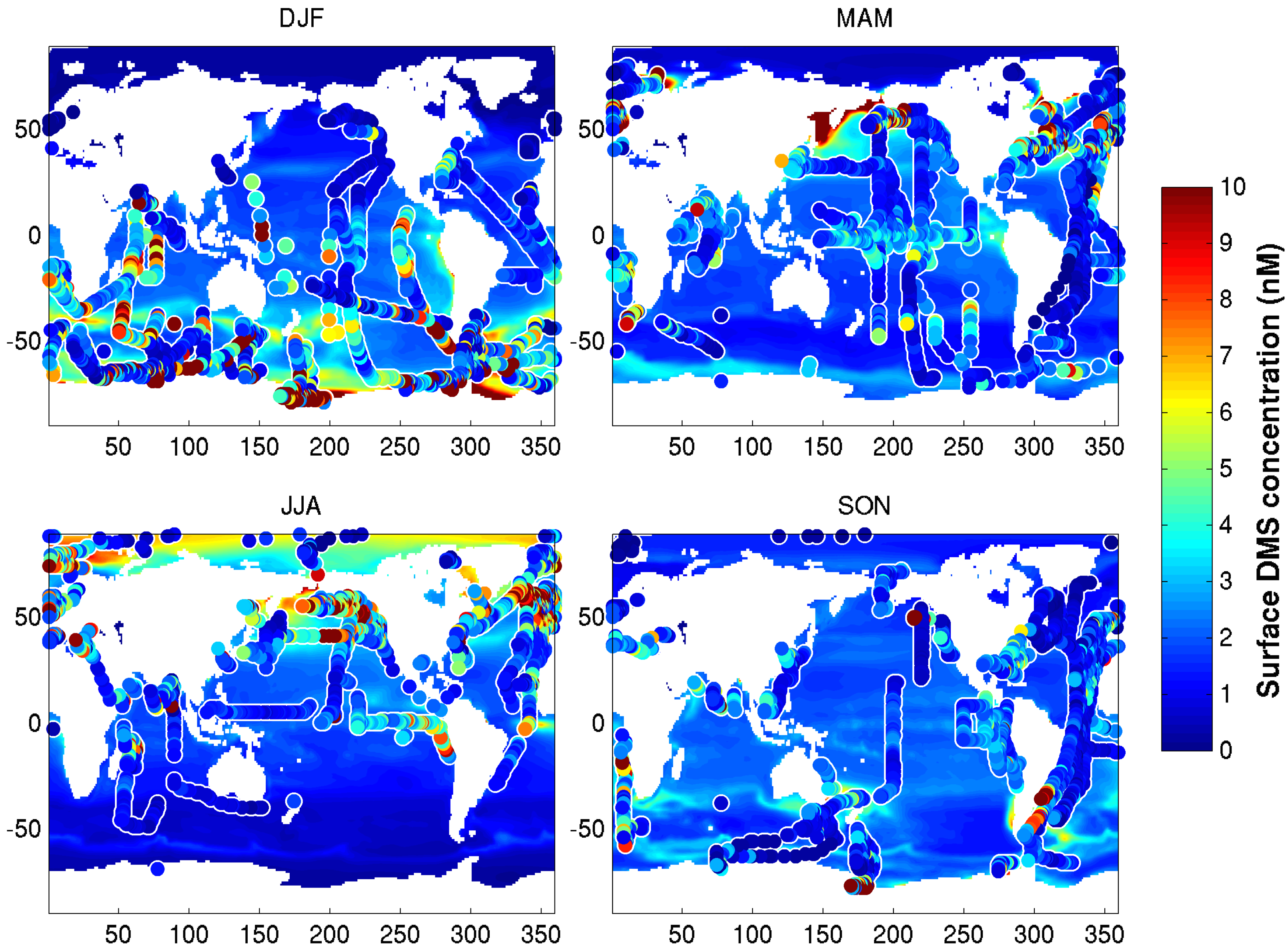
# Simulated *Phaeocystis*




(Wang et al., 2015)

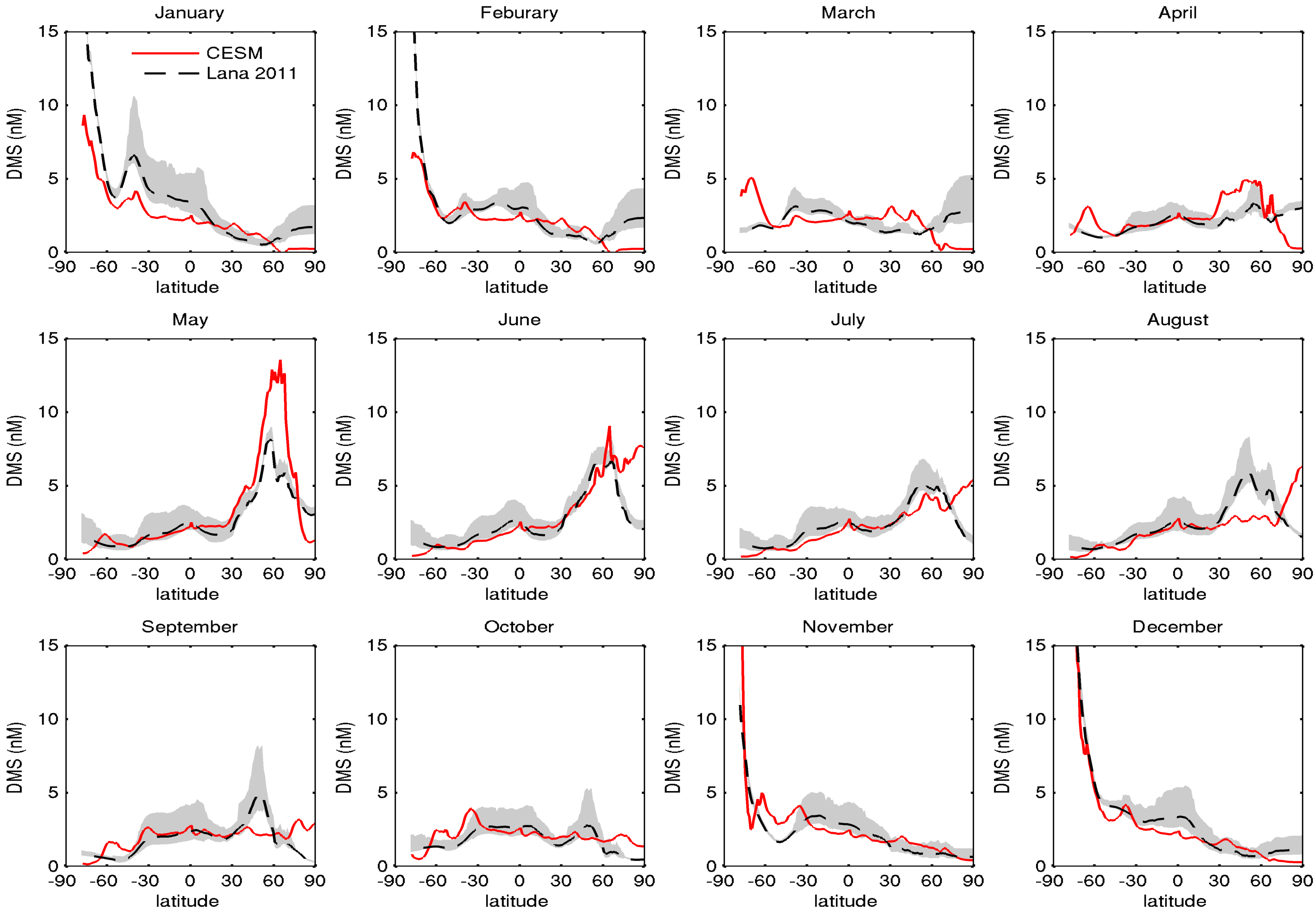
- In general, the model does a reasonable job reproducing the observed seasonality and spatial distributions of *Phaeocystis*
- *Phaeocystis* contributed ~13% of annual primary production and ~19% of sinking carbon export in the Southern Ocean (>40°S).
- Simulated *Phaeocystis* biomass cannot reproduce the extreme high concentrations sometimes reported in field studies due to averaging in large grid and underestimated surface nutrients

# Simulated DMS



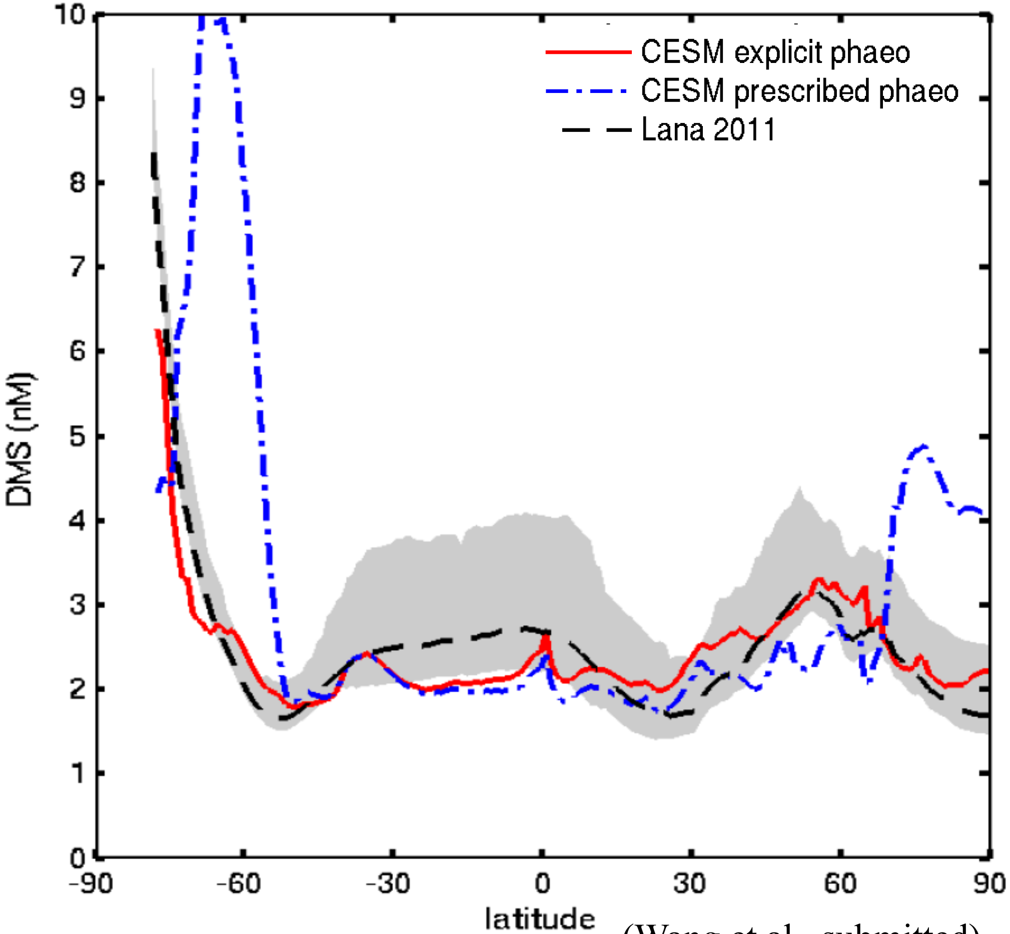

DMS maximum in the North Pacific in May and along the Antarctic coast in December, in agreement with *Lana et al*. (2011)

# Simulated DMS




Simulated DMS shows strong bloom behavior at high latitudes, but weak seasonal cycling at low latitudes. Seasonality and distributions are in good agreement with observations.

# Zonal DMS distributions



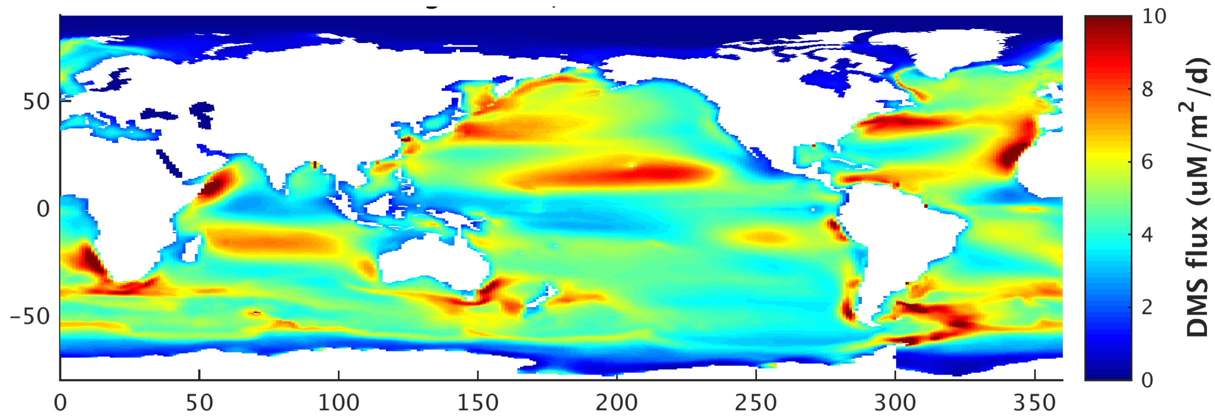

(Wang et al., submitted)

- The simulated average DMS concentration for the surface ocean is 2.26 nM, comparable to data-based estimate of 2.34nM
- Zonal mean DMS is clearly improved, and matches the observation-based estimate closely, with observed DMS peaks between 50° − 60° N and south of 60° S well reproduced

# DMS-climate feedback

DMS flux (pre-industrial)

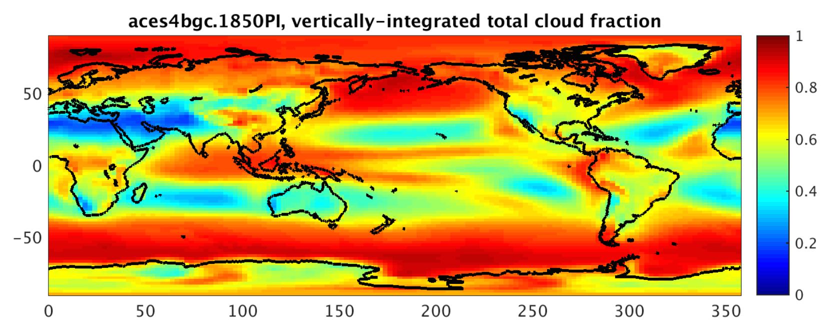
DMS flux off

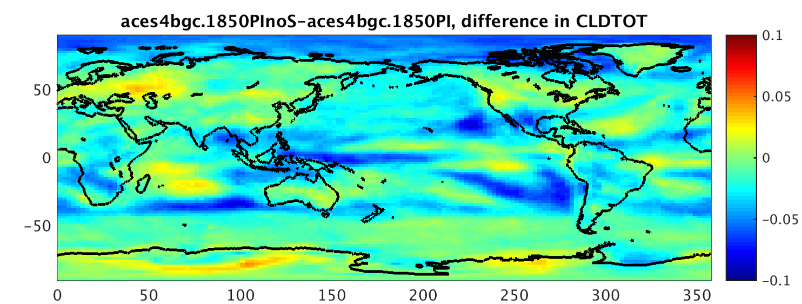



Pre-industrial

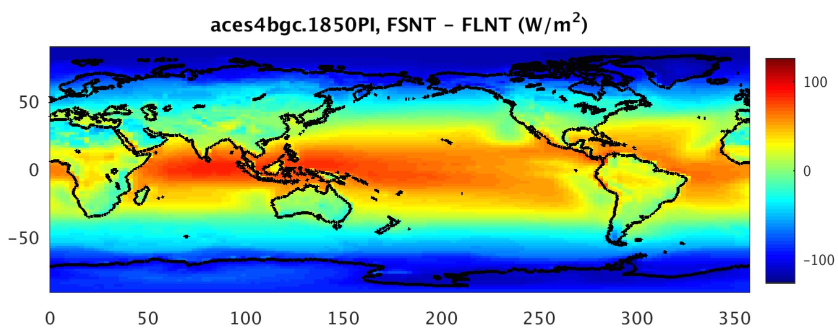
Difference (without DMS – with DMS)

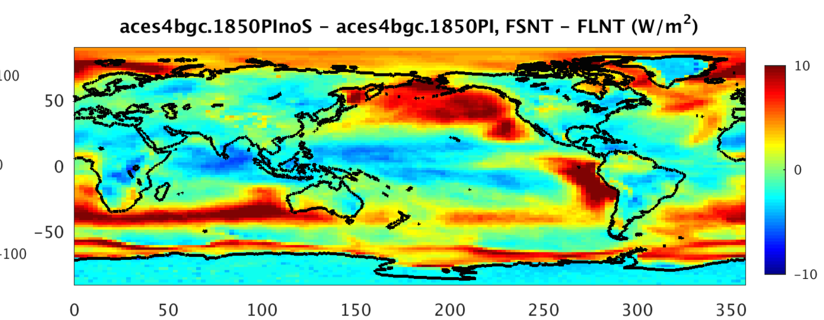
Cloud Frac




TOA rad



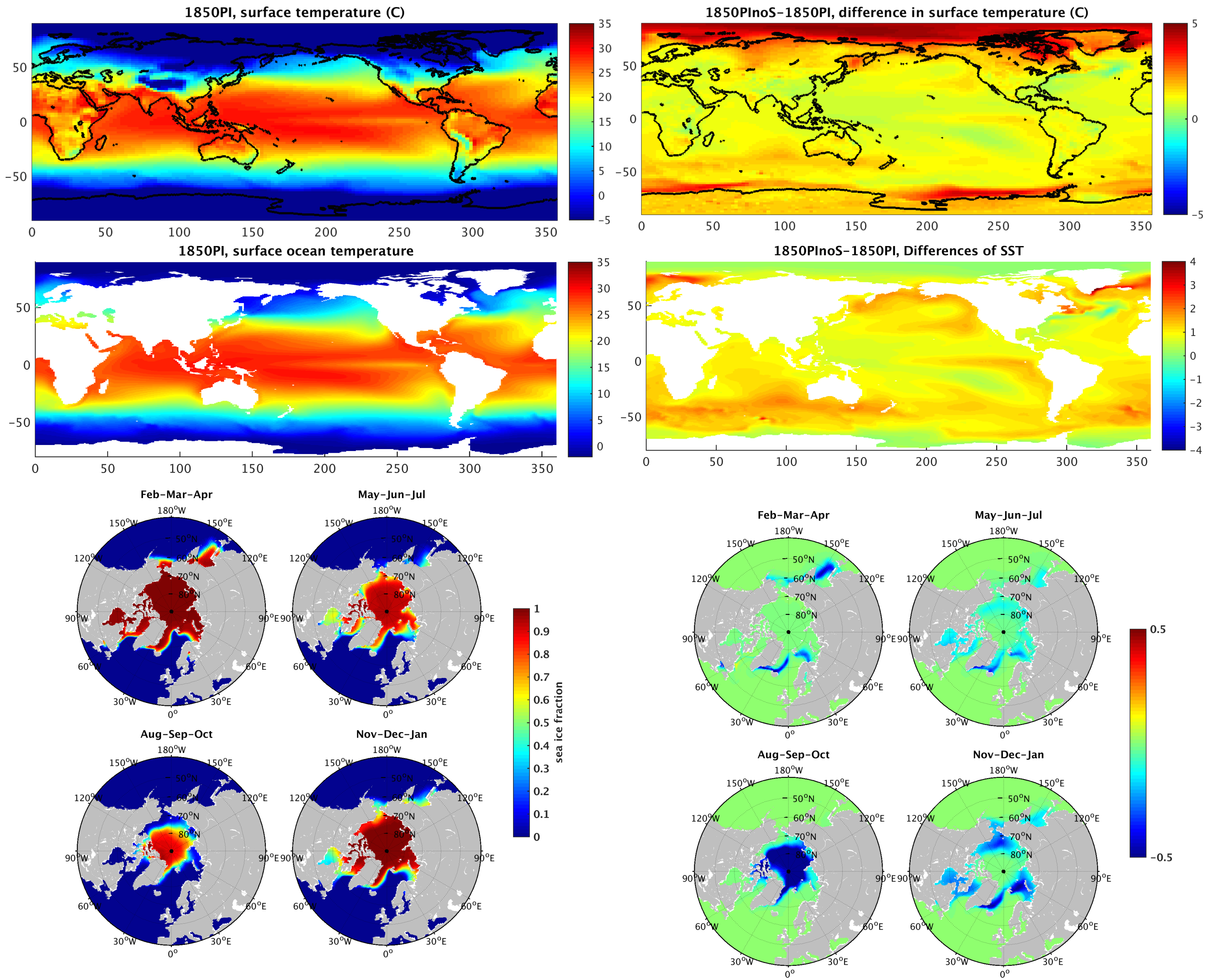
# Pre-industrial

# Difference (without DMS – with DMS)

Surf Temp

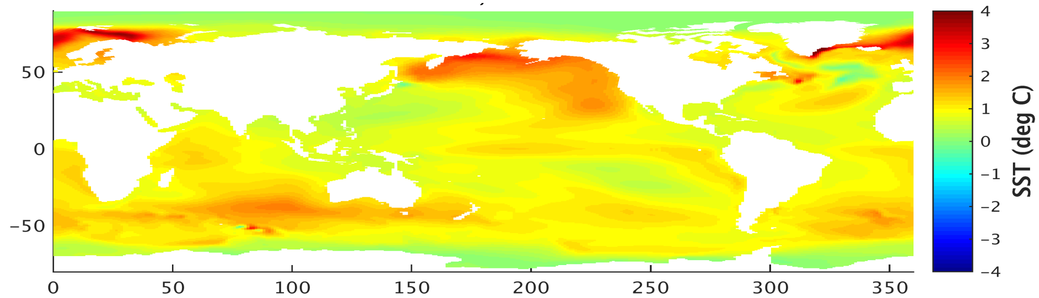
SST

IFRAC



# Surface nutrients

Warming SST in simulation without DMS flux into the atmosphere



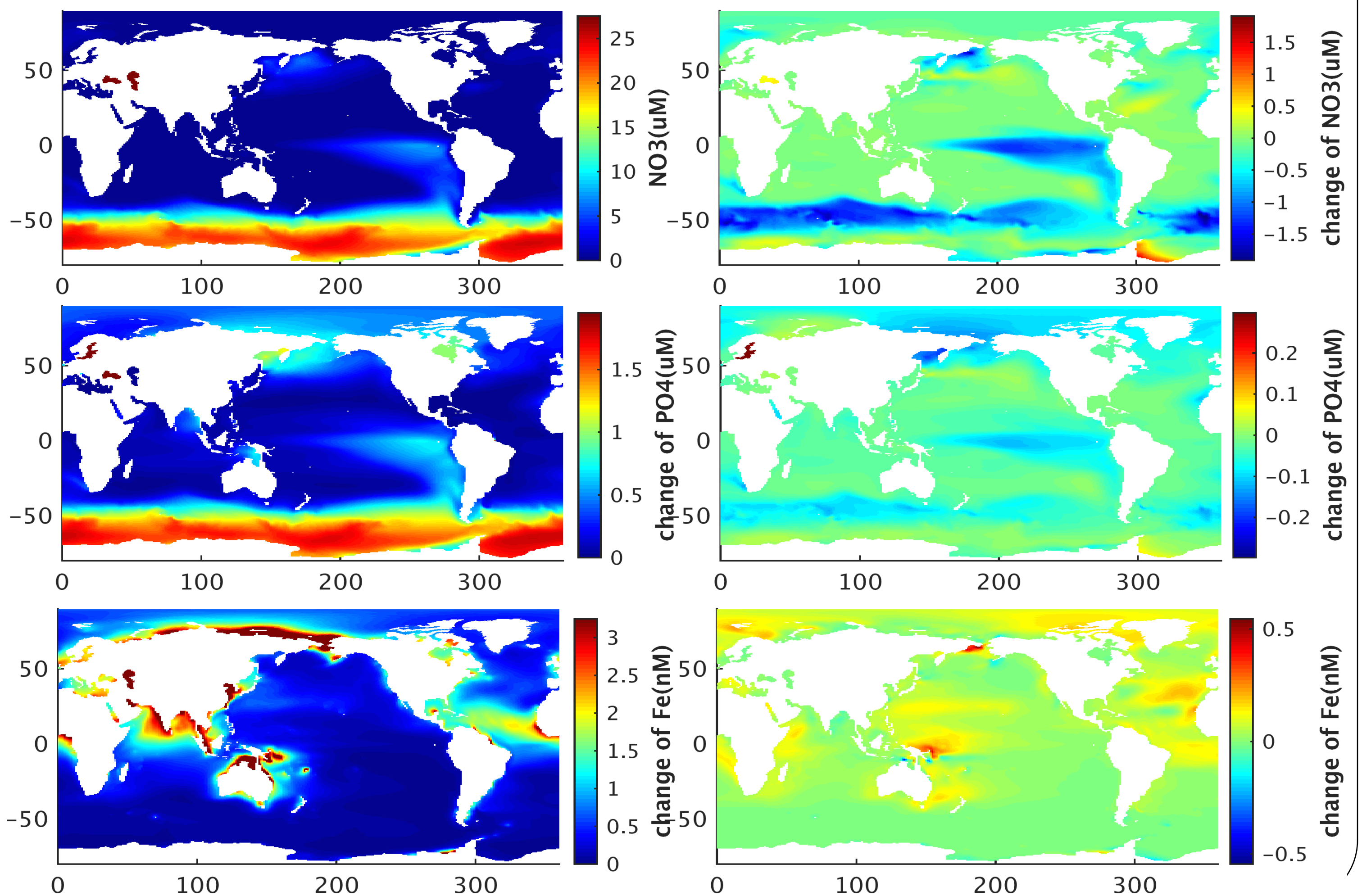

Pre-industrial

Difference (without DMS – with DMS)

Lower surface $NO_3$

Lower surface $PO_4$

Higher surface Fe



# Phytoplankton and DMS

Pre-industrial

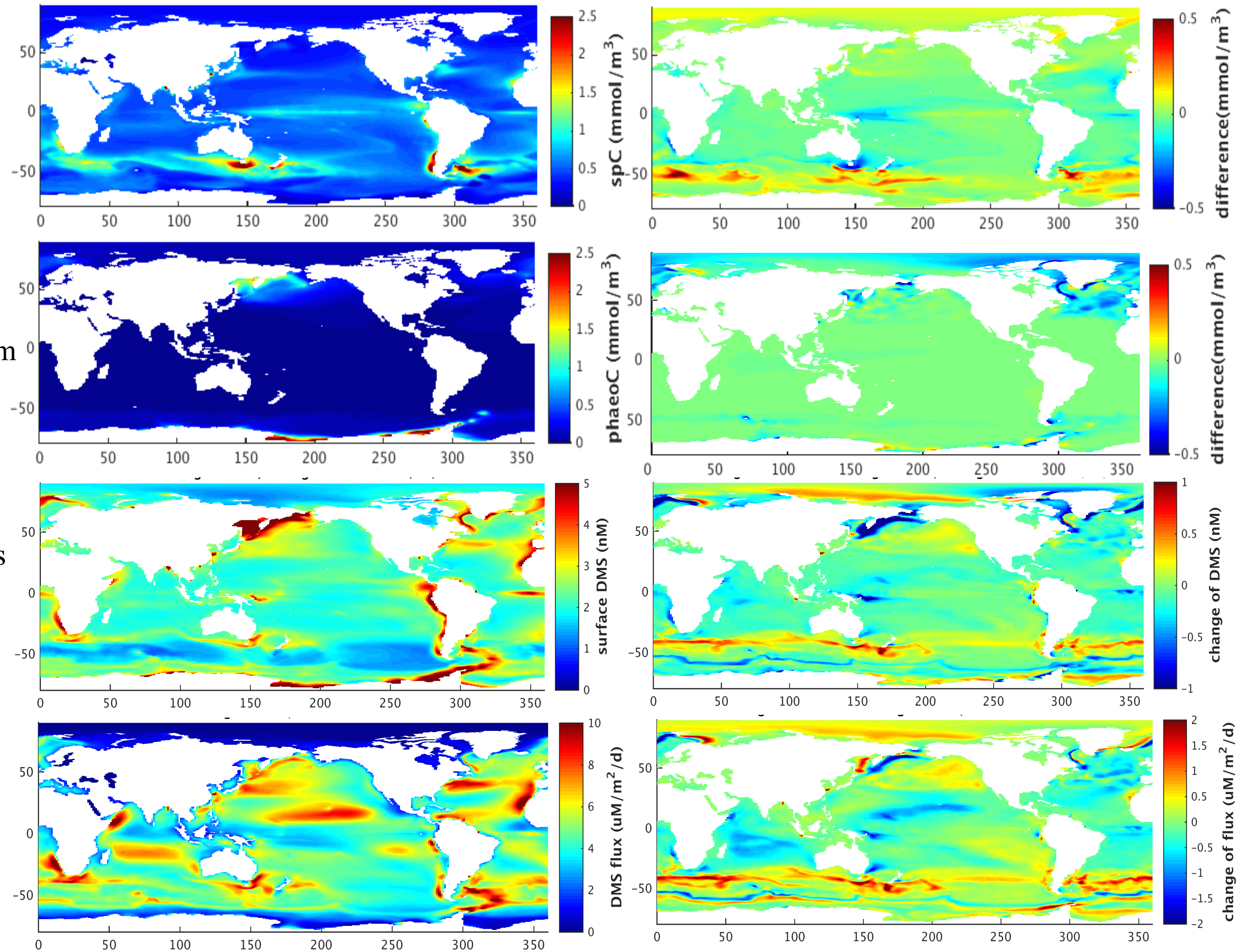
Difference (without DMS – with DMS)

Small phytoplankton
Increase 40 - 60 °S

*Phaeocystis* decrease
Similar change to diatom

DMS difference follows
marine ecosystems

DMS flux also affected
by wind and sea ice

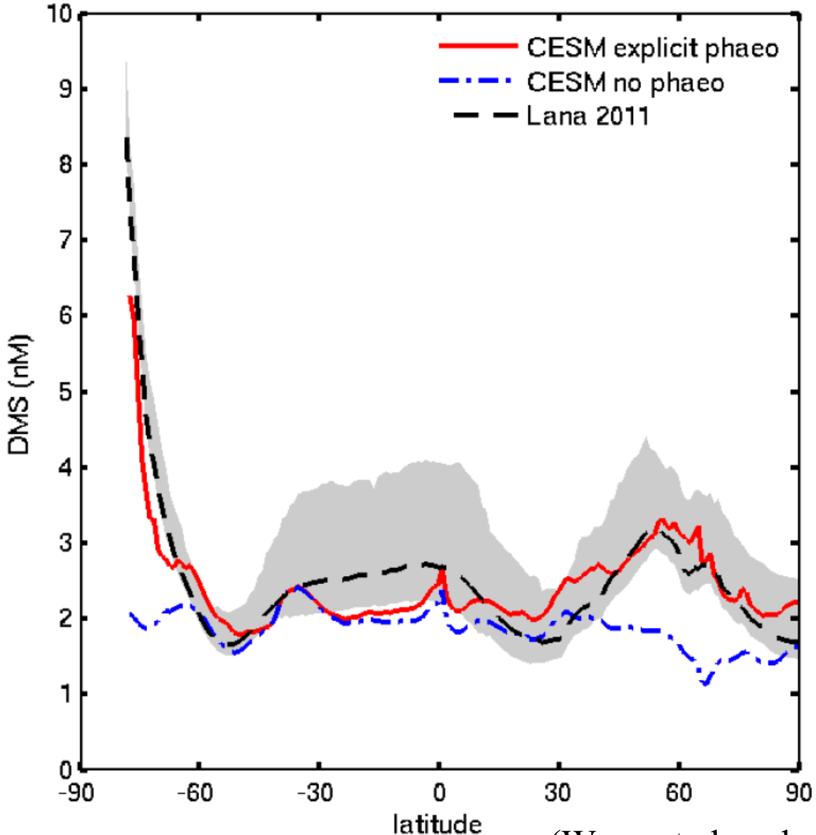



*There is no uniform feedback patterns.*

| Simulation | PI | PInoS | PD | PDnoS | FUT | FUTnoS |
| --- | --- | --- | --- | --- | --- | --- |
| Model top radiation ($W/m^2$) | 0.44 | 1.06 | 0.61 | 0.93 | 2.6 | 3.18 |
| Sea ice area (September, millions of $km^2$) | | | | | | 6.34 |
| Sea ice area (February, millions of $km^2$) | | | | | | 1.95 |
| SST (°C) | | | | | | 23.34 |
| Primary Production | | | | | | 52.36 |
| Sinking POC at 100m | 7.63 | 7.51 | 7.62 | 7.5 | 6.65 | 6.37 |
| Surface DMS (nM) | 2.30 | 2.23 | 2.30 | 2.23 | 1.96 | 1.89 |
| DMS flux (Tg/yr) | 19.74 | 19.61 | 19.62 | 19.39 | 18.14 | 17.81 |

The feedback seems weak, then is phytoplankton important?

# Phytoplankton cannot be ignored -*Phaeocystis*

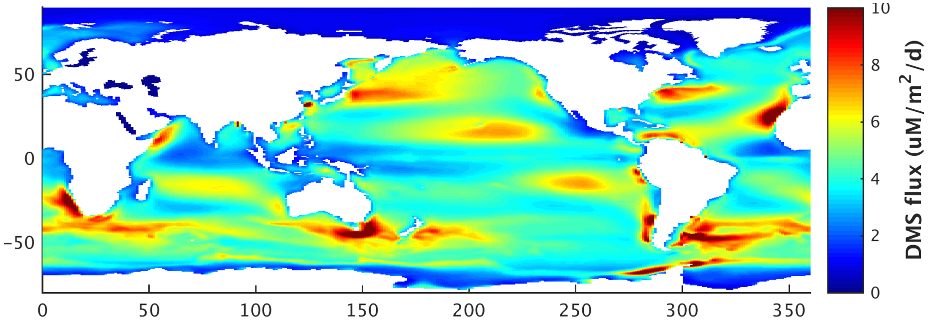



(Wang et al., submitted)

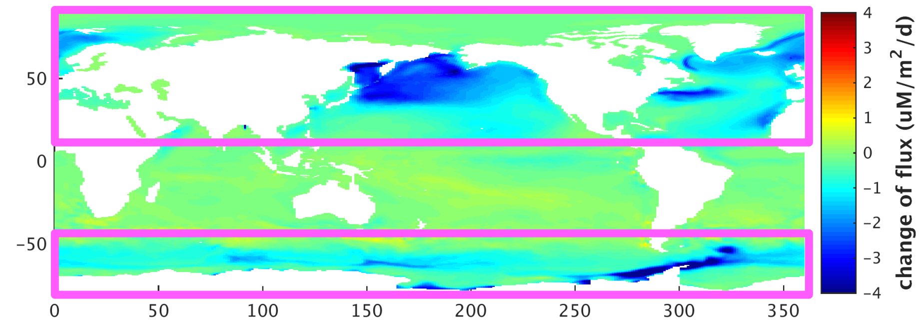
- *Phaeocystis* contributes up to 23% of upper ocean DMS during the growing seasons, and 8.6% of the annual DMS flux.
- *Phaeocystis* dominates DMS distribution at middle to high latitudes.
- None previous global DMS simulations included dynamically simulated *Phaeocystis*.

# Without *Phaeocystis*

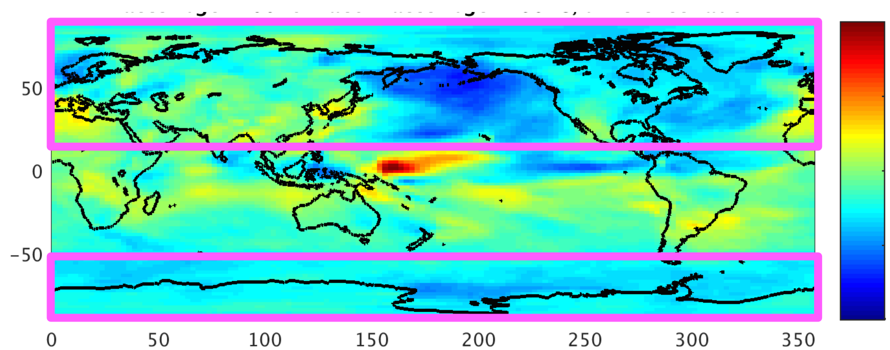
Sea-air DMS flux (2100)



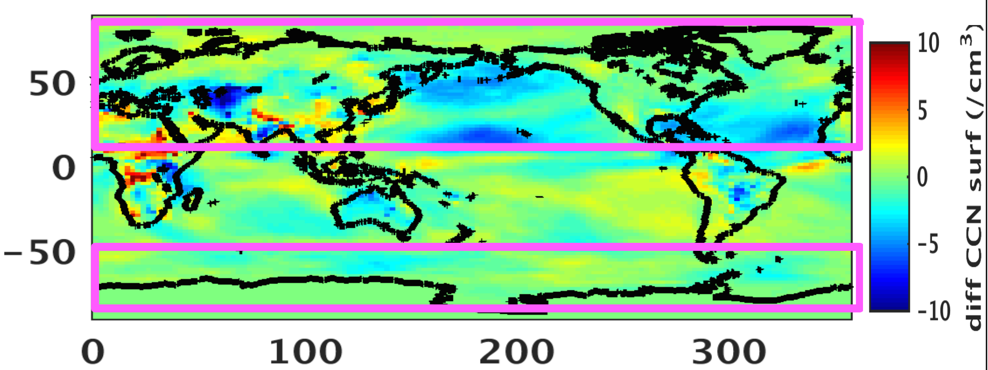

Change in DMS flux




Change in sulfate aerosol burden (ratio)



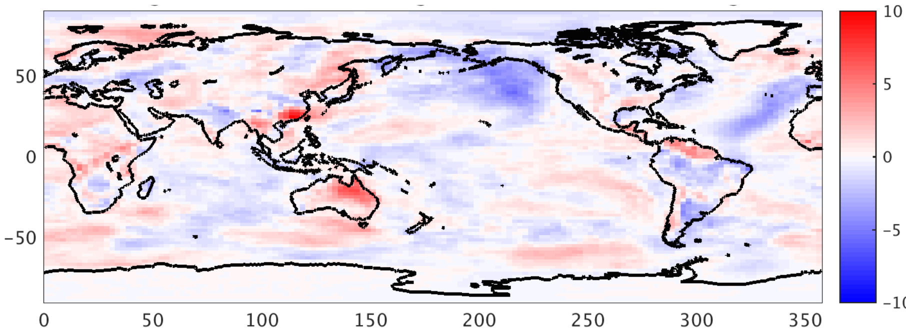
Change in surface CCN



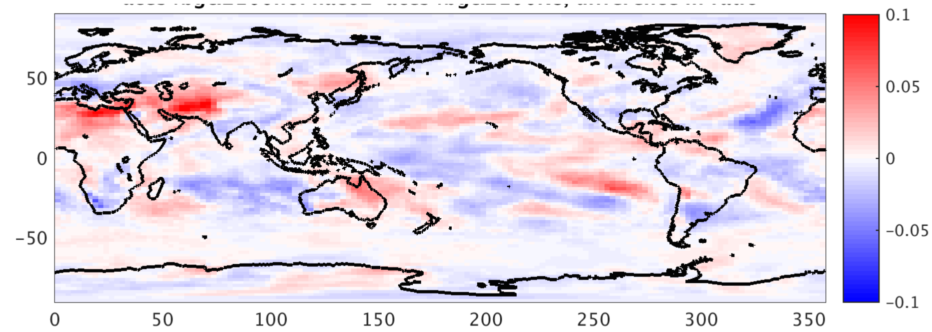

➢ *Phaeocystis* contributes 8.6% of the DMS flux

# Without *Phaeocystis*

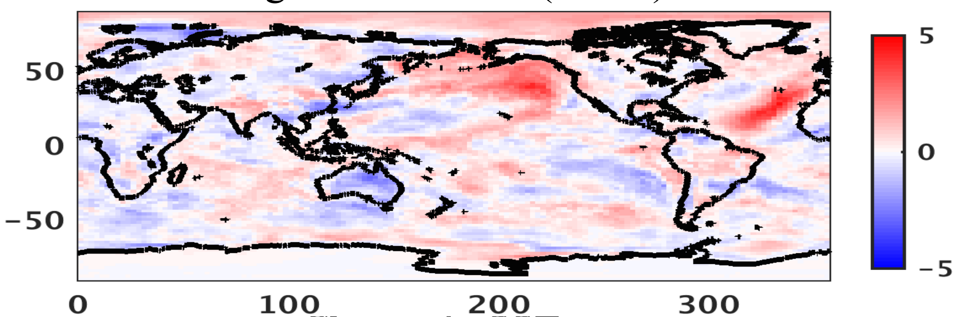
Change in LWP ($g/m^2$)



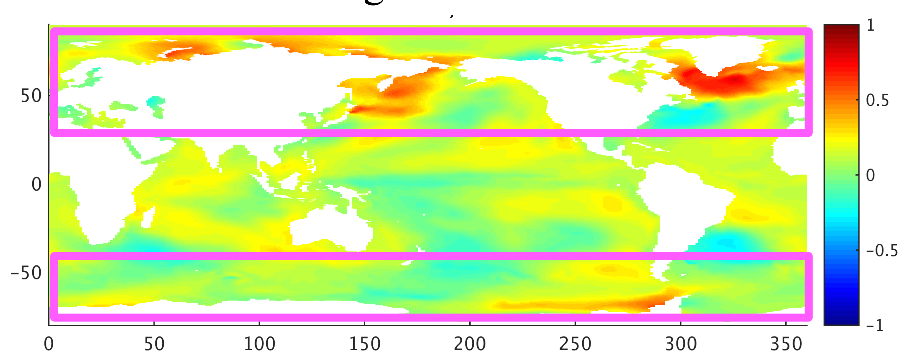

Change in cloud fraction (ratio)



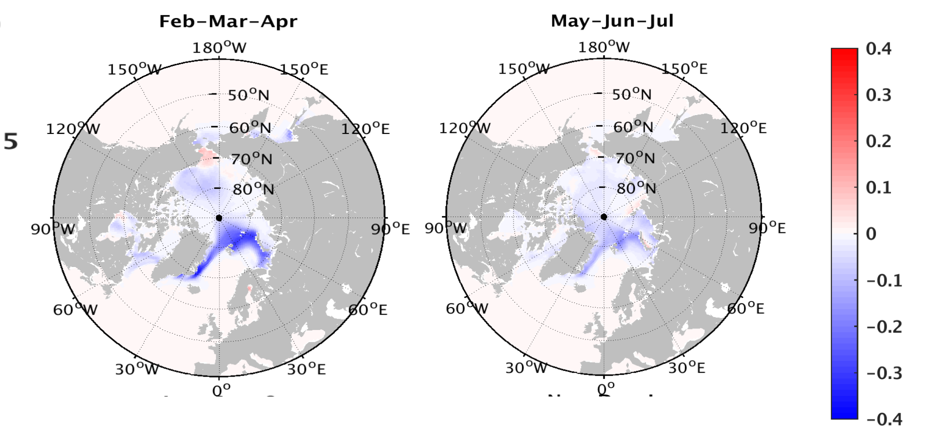

Change in total CRF ($W/m^2$)




Change in SST

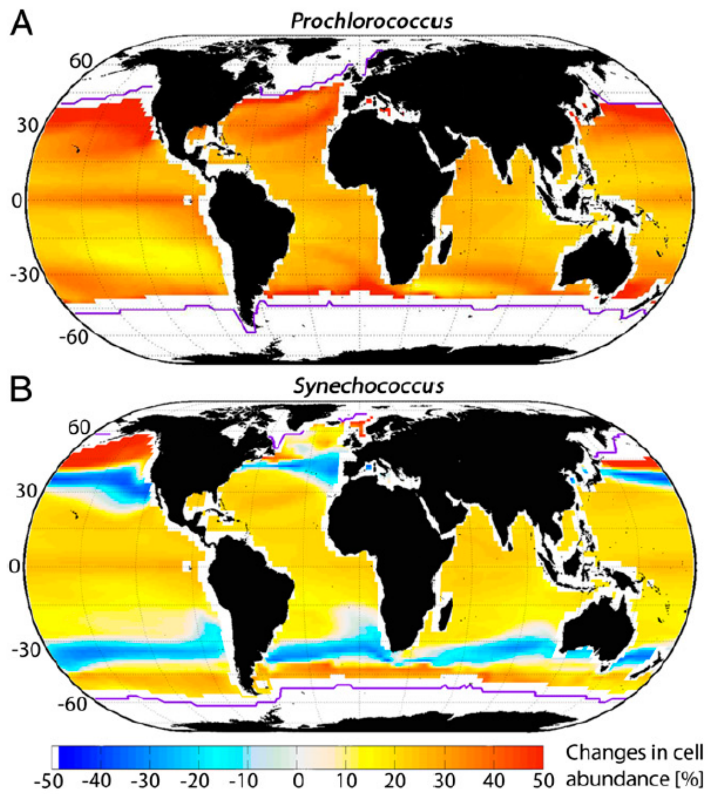



Change in IFRAC




- Without DMS produced by *Phaeocystis,* there are significant changes in the shortwave cloud radiative forcing and warms the surface ocean at high latitudes

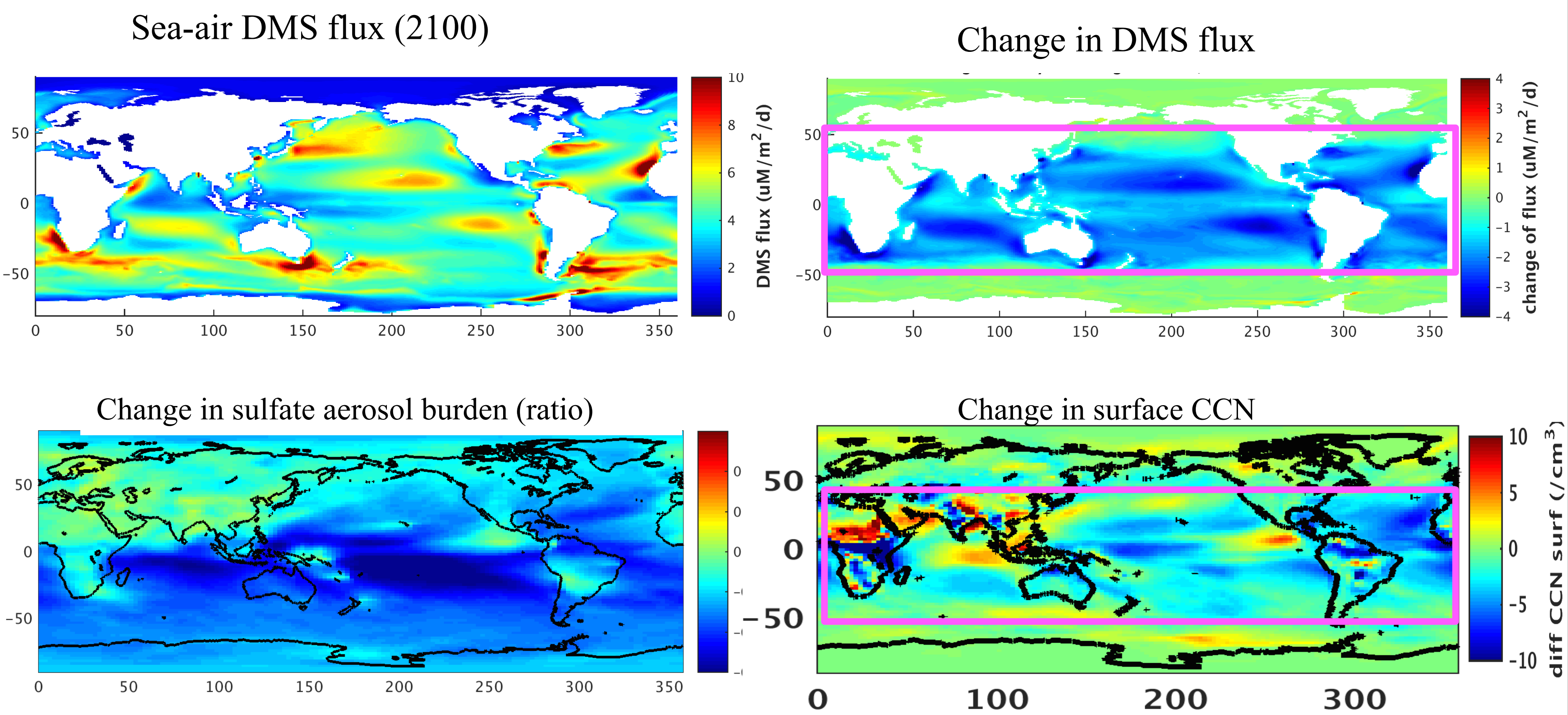
# Phytoplankton cannot be ignored - Cyanobacteria




(Flombaum et al., 2013)

- Cyanobacteria group does not produce DMS.
- Fraction and total biomass of this group will increase in a warmer climate

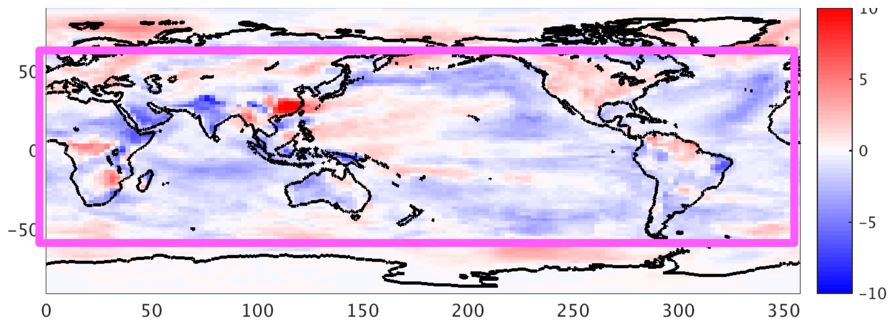
# Phytoplankton cannot be ignored



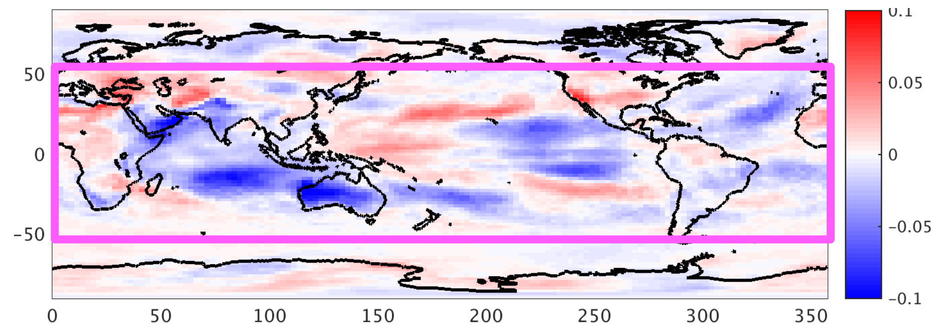

- Increasing cyanobacteria fraction leads to declines in DMS production at low-middle latitudes.
- If the maximum fraction of this group increases by 50%, DMS flux decreases ~39% at middle – low latitudes

# Phytoplankton cannot be ignored

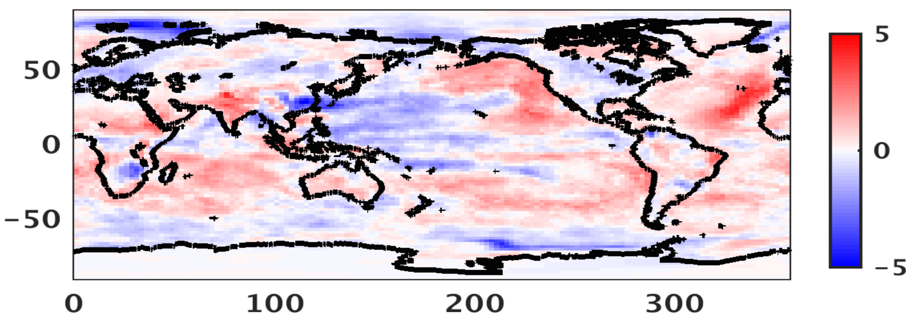
Change in LWP (g/m²)



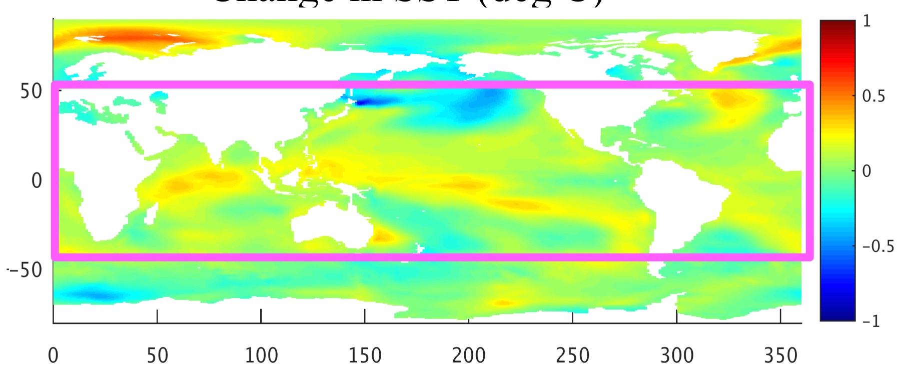
Change in cloud fraction (ratio)



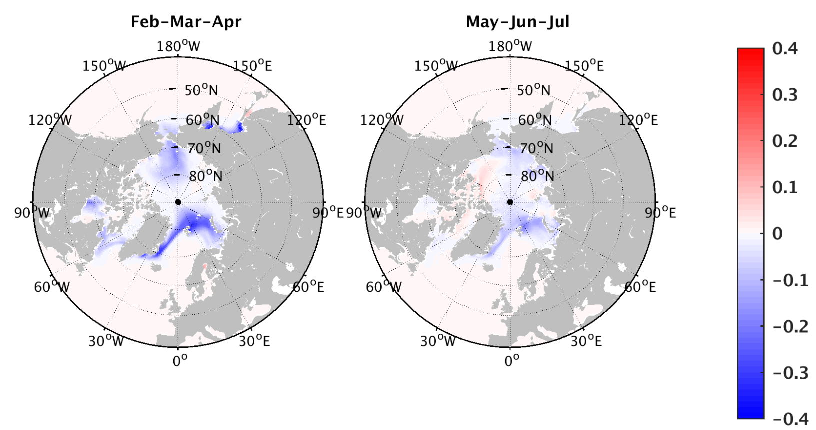
Change in total CRF (W/m²)

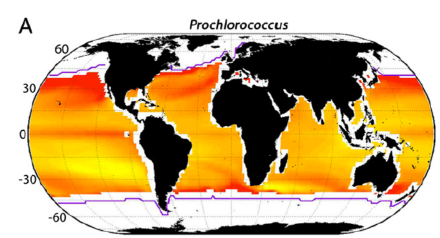


Change in SST (deg C)



Change in IFRAC




- Significant change in sw cloud radiative forcing at low to middle latitudes, > 4 W/m² in some regions.

# Summary

- Given the new explicit *Phaeocystis* representation, the DMS distribution shows significant improvements, especially regarding the amplitude and location of high latitude peaks
- The simulated mean surface DMS value is 2.26 nM. The total oceanic DMS source to the atmosphere is 20.3 Tg S/yr. Both are comparable to data-based estimates.
- Different phytoplankton groups play various roles in the DMS production. Shifts in phytoplankton community composition will feedback to climate
- DMS plays an important role in regulating climate
- Production of DMS varies with climate. It is therefore necessary to couple the dynamic DMS module in climate projections.

# Thanks!