Ocean biogeochemistry in the HAMburg Ocean Carbon Cycle Model

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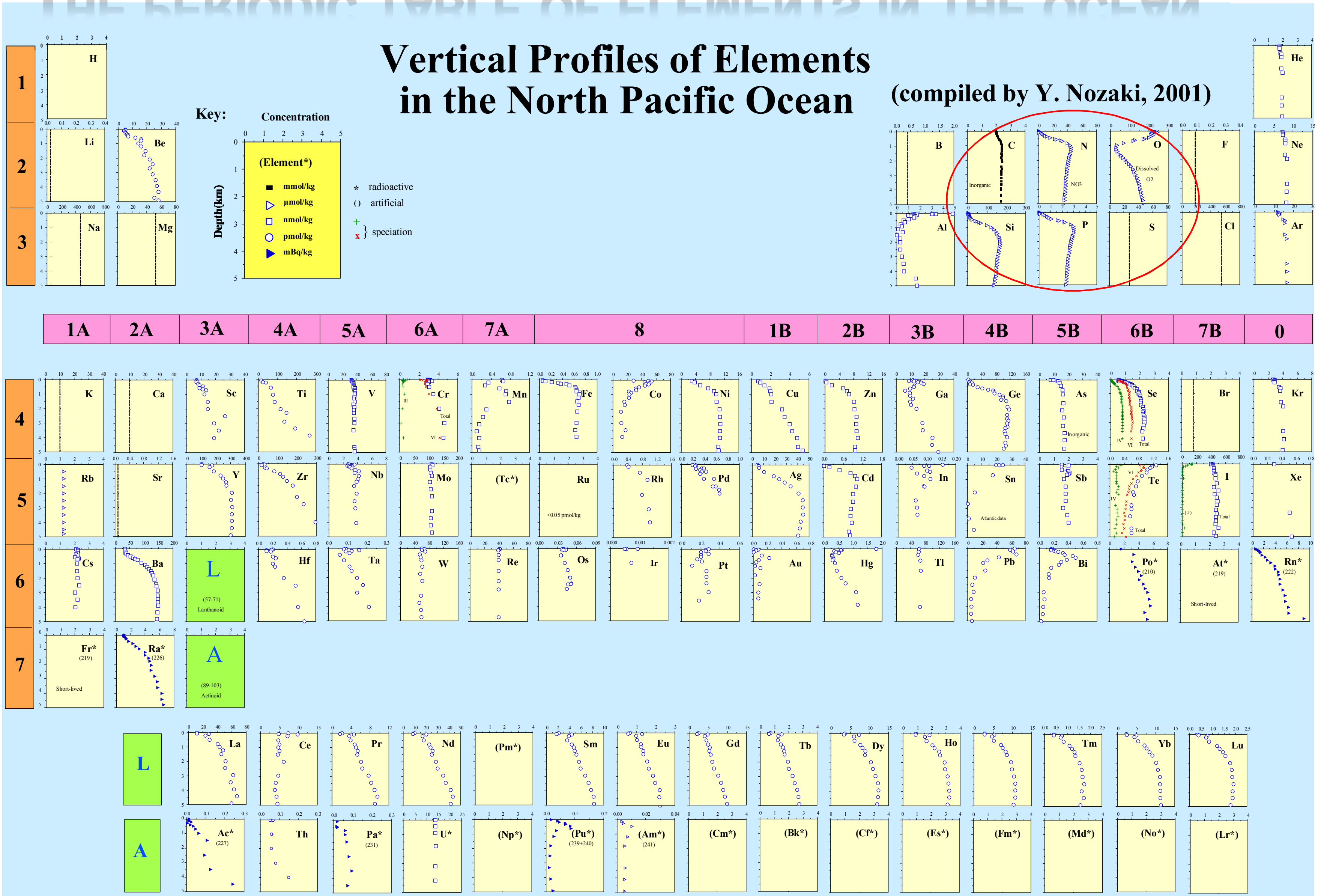
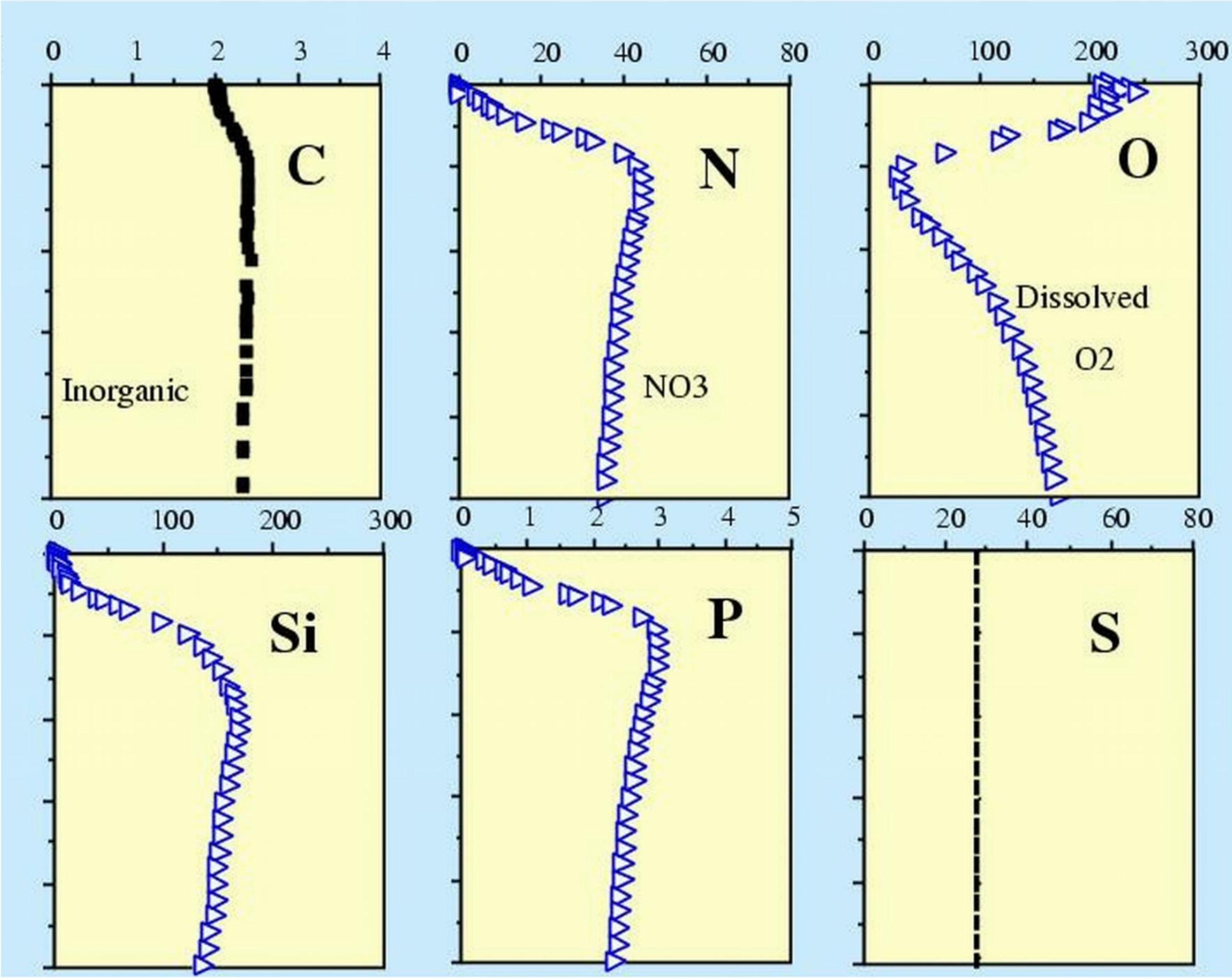
Max Planck Institute for Meteorology

Layout of the presentation

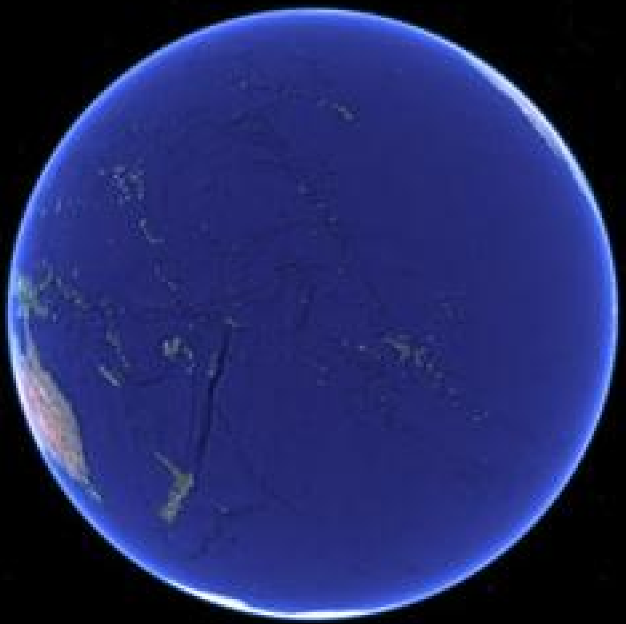
- Main assumptions in setting up an ocean biogeochemistry model
- Overview of the main components of HAMOCC
- Model performance
- Projections of oceanic carbon cycle in CMIP5 experiments

THE PERIODIC TABLE OF ELEMENTS IN THE OCEAN




0 1 2 3 4
C
Inorganic
0 20 40 60 80
N
NO3
0 100 200 300
O
Dissolved
O2
0 100 200 300
Si
0 1 2 3 4 5
P
0 20 40 60 80
S

Ocean



Blue planet
71% covered by Ocean

Ocean is a major reservoir for many chemical elements (i.e. C, P, S)

Biogeochemical cycles in the ocean influence Earth's climate

Changes in climate influence biogeochemical cycles in the ocean

Reservoir masses of C, N, P, S, O

Reservoir	Element (billion metric tons of element)				
	Carbon	**Nitrogen**	**Phosphorus**	**Sulfur**	**Oxygen**
Atmosphere	760	3,950,000	0.00003	0.003	1,216,000
Ocean	38,400[a]	570[b]	80[c]	1,248,000[d]	4100[e]
Marine biota	3	0.5	0.07	0.1	4.2
Land biota	600	10	3	2.5	800
Soil OM	1600	190	5	95	850
Rocks	78,000,000	999,600	4,030,000	12,160,000	1,250,000,000

after: Mackenzie, 2003

[a] Dissolved Inorganic Carbon

[b] NO_3^-

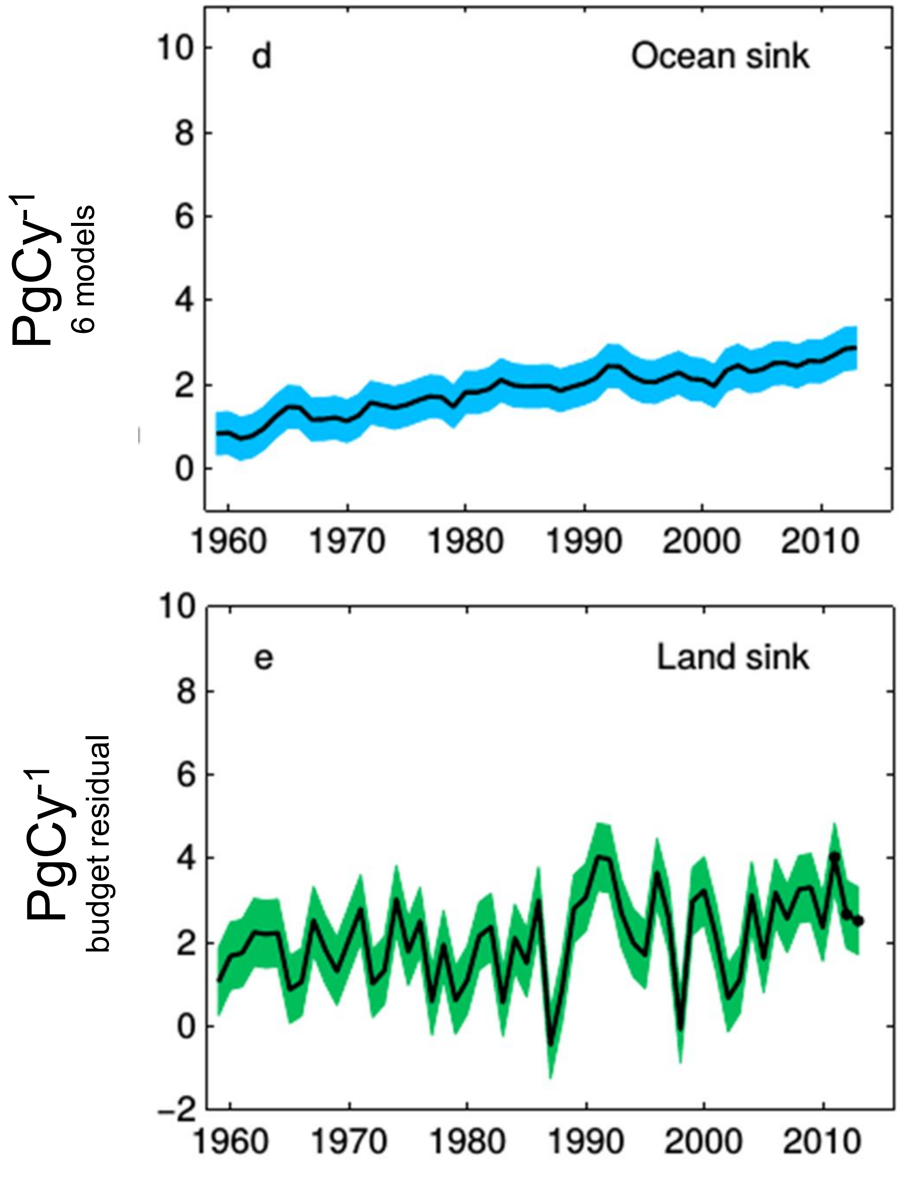
[c] PO_4^{3-}

[d] SO_4^{2-}

[e] Dissolved O_2

SINKS OF ANTHROPOGENIC CARBON DIOXIDE

Le Quéré et al. 2015, Earth Syst. Sci. Data



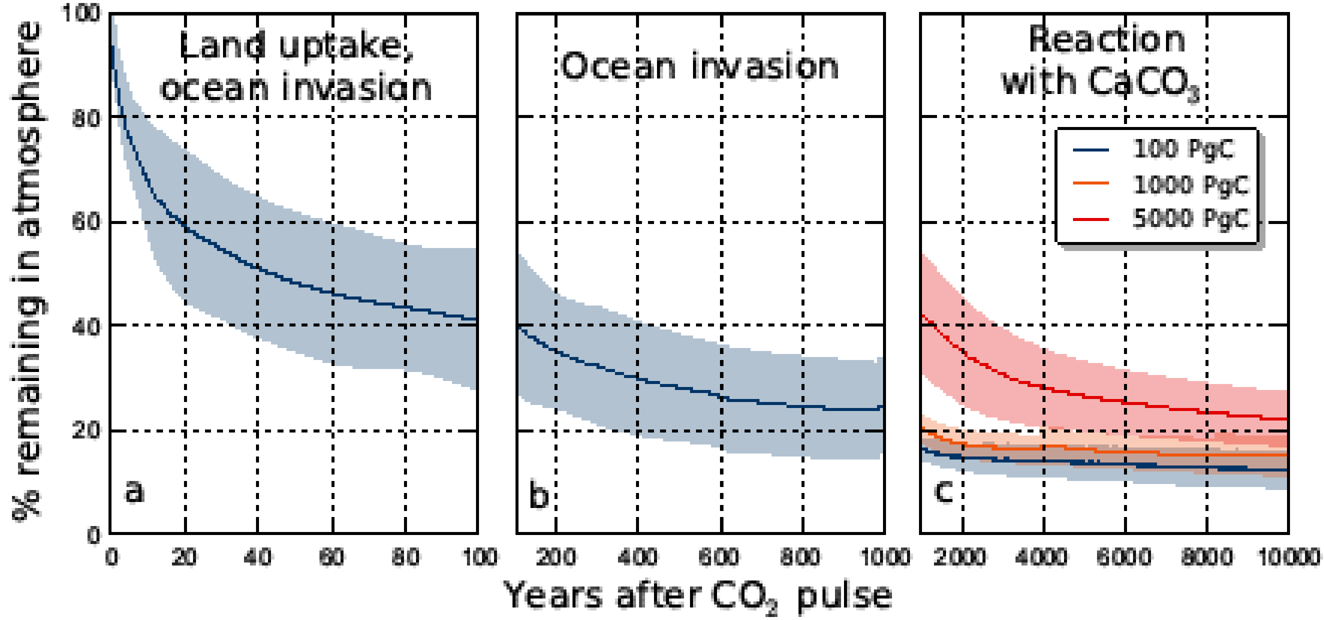
~27% of emissions (2013)

~23% of emissions (2013)

Sinks of anthropogenic CO_2

Source: AR5

Percentage of emitted CO_2 remaining in the atmosphere in a pulse scenario



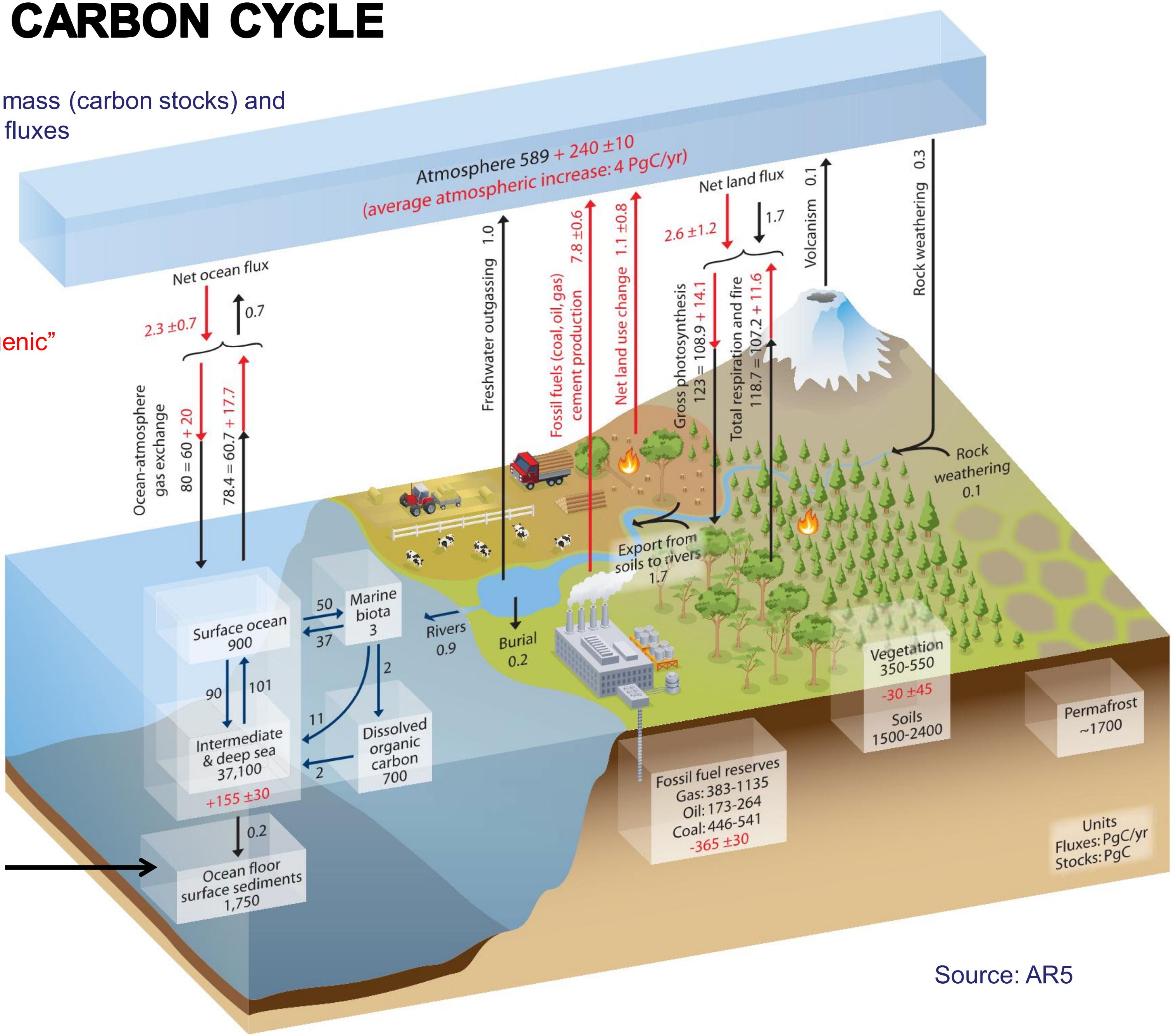
- On the time scale of hundreds of years to millennia, the ocean is the main sink for anthropogenic CO_2
- Oceans and land have taken about a third of anthropogenic CO_2 each.

Global carbon cycle

Numbers show reservoir mass (carbon stocks) and annual carbon exchange fluxes

Units
Fluxes: PgC/yr
Stocks: PgC

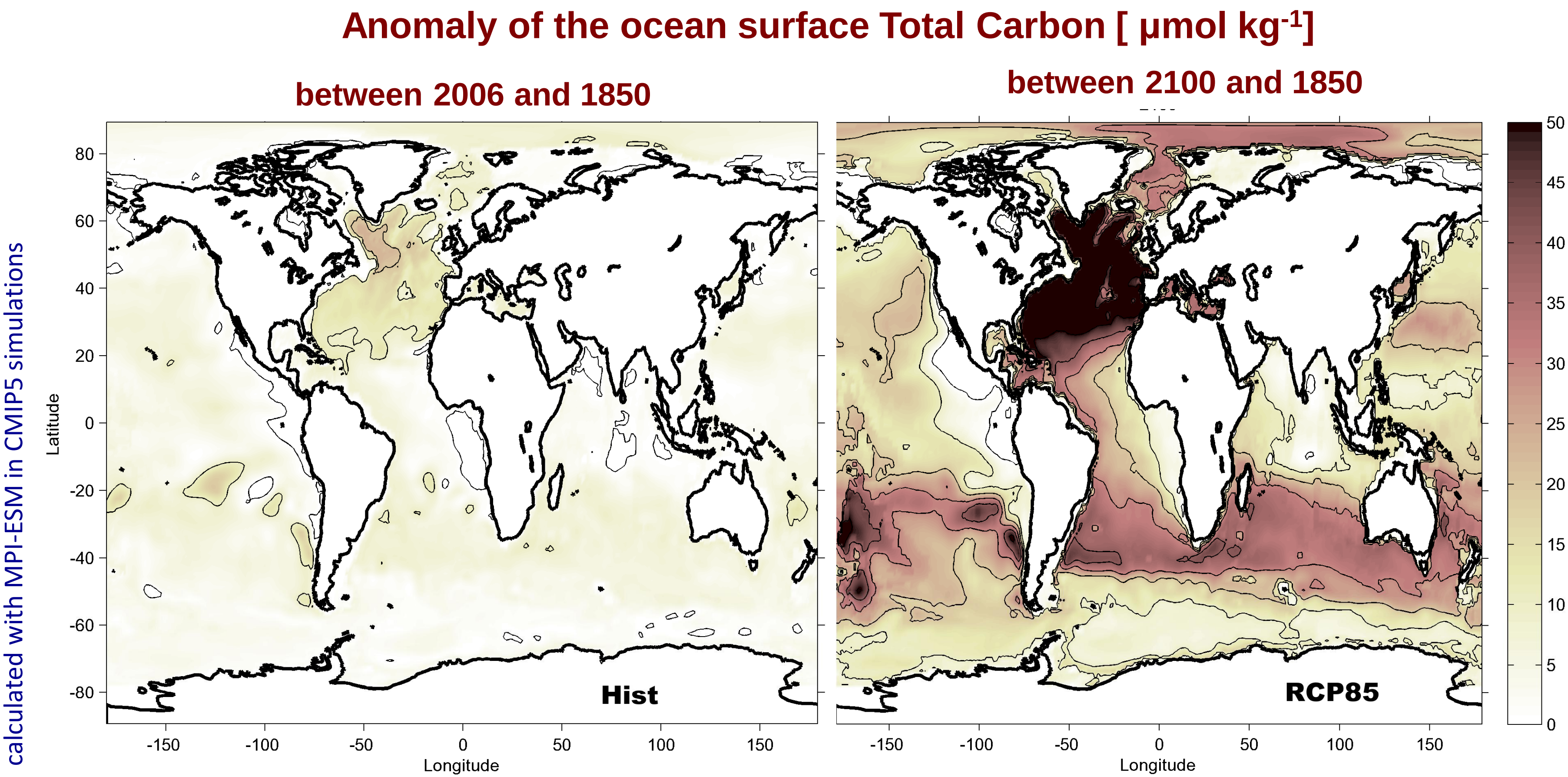
Black - preindustrial
Red – annual "anthropogenic" fluxes



sum of 150 PgC organic carbon in the and 1,600 PgC of the deep-sea CaCO3 sediments available to neutralize fossil fuel CO2

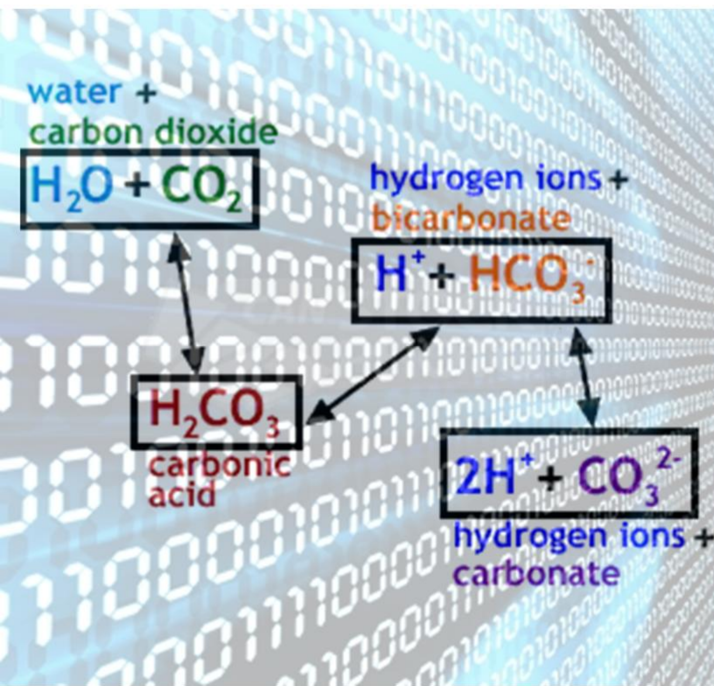
Source: AR5

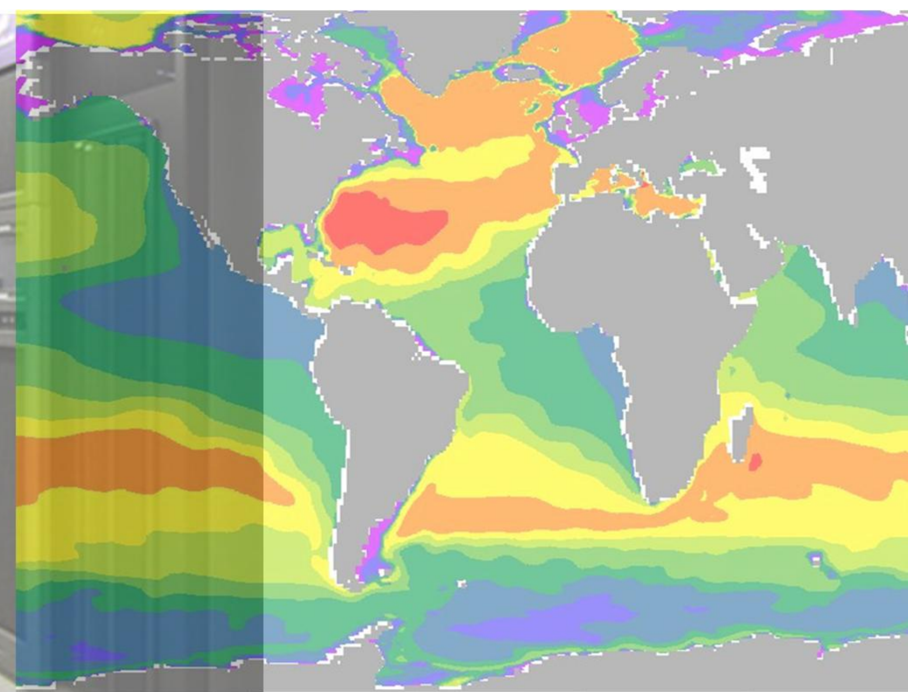
CO_2 Uptake by the Ocean



- The North Atlantic takes up the most anthropogenic CO_2
- Oceanic uptake of CO_2 follows the increase in atmospheric CO_2, but at a different rate

MAIN ASSUMPTIONS



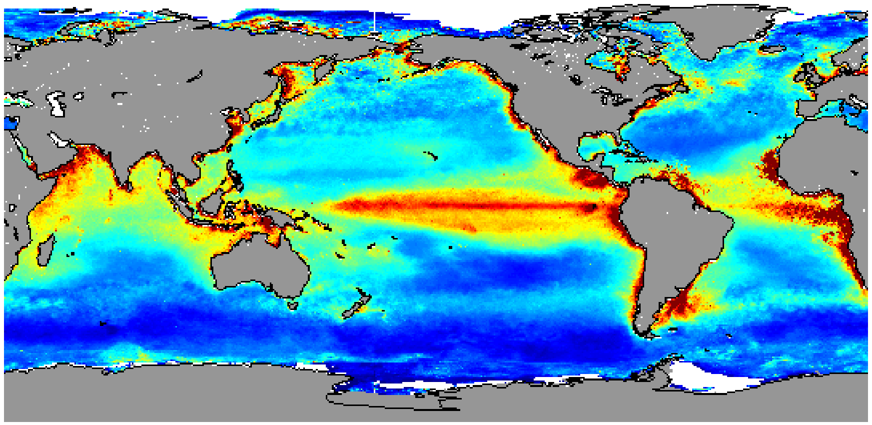


BIOGEOCHEMICAL CYCLES IN THE OCEAN

how the story starts …

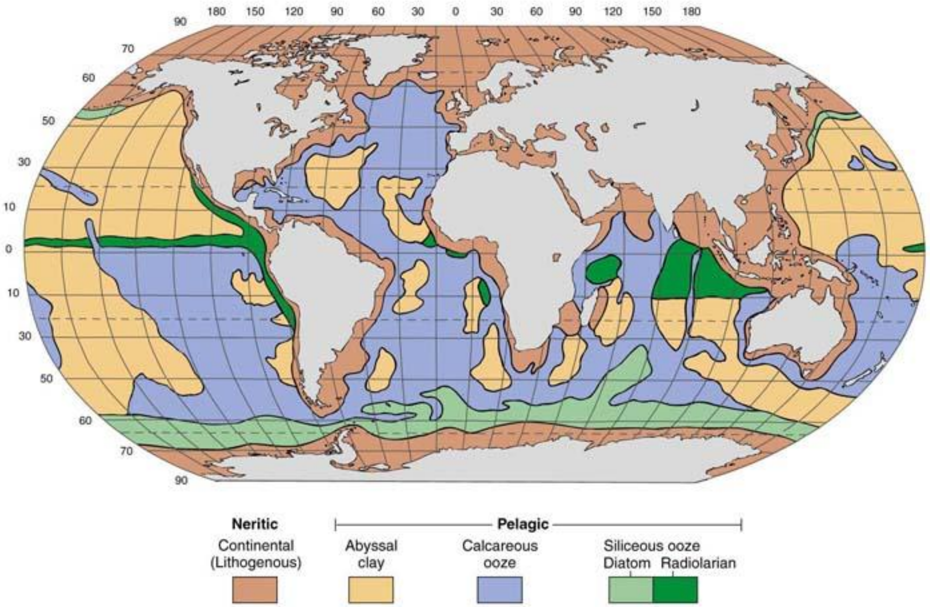
end of story?

Ocean Net Primary Productivity [gC $m^{-2}year^{-1}$]



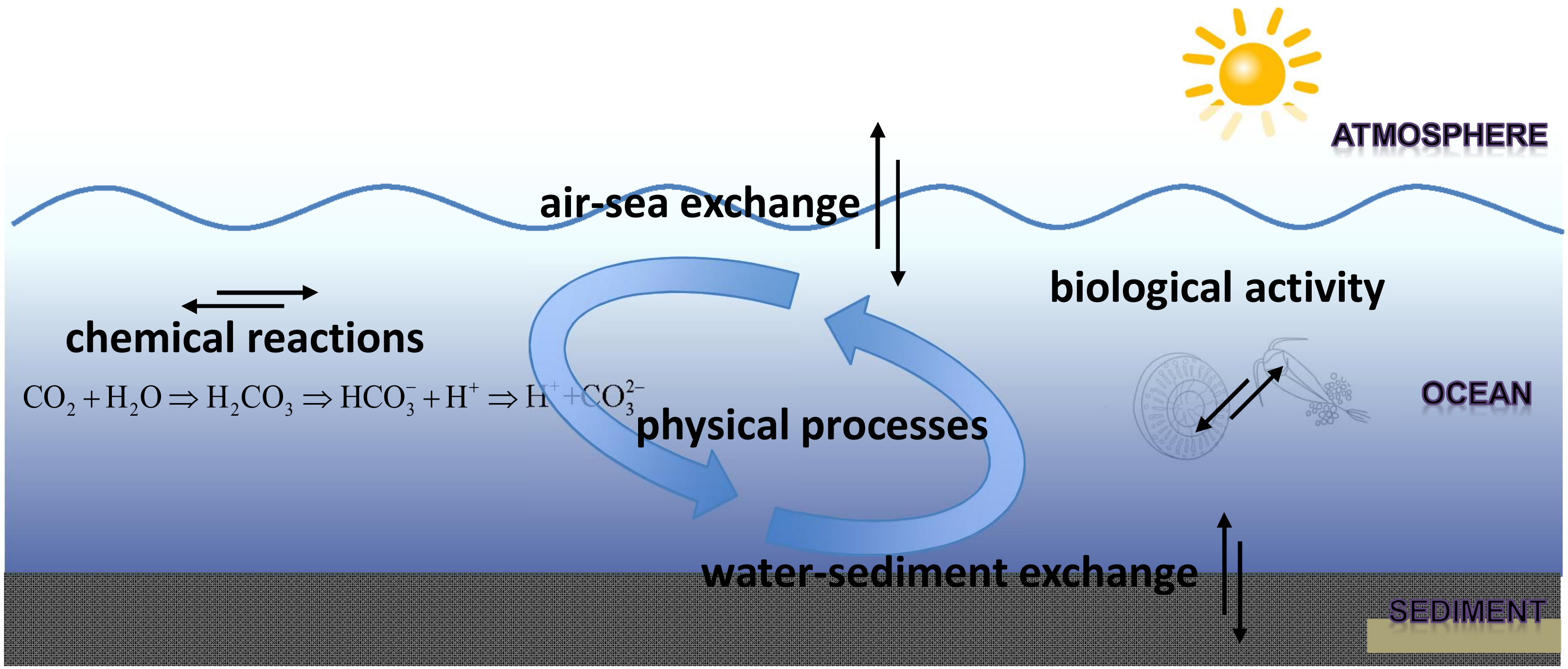
Satellite (MODIS) – based product
Source:
http://www.science.oregonstate.edu/ocean.productivity/index.php

Distribution of deep sea sediments



Biogeochemical cycles in the ocean

the movement (or cycling) of chemical elements or molecules through the biotic (bio) and abiotic (geo) compartments of Earth.



Seawater chemistry processes

Inorganic carbon chemistry

CO_2 *gaseous*

reactions are reversible and fast
interpreted in terms of chemical equilibria

$$CO_2 gaseous \overset{K_0}{\leftrightarrow} CO_2$$

Carbonic acid, Bicarbonate ion, Carbonate ion

$$CO_2 + H_2O \overset{K_1}{\leftrightarrow} H_2CO_3 \leftrightarrow HCO_3^- + H^+ \overset{K_2}{\leftrightarrow} CO_3^{2-} + 2H^+$$

The carbonate system plays a critical role in controlling the CO_2 in the atmosphere:

- controls the acidity of seawater
- acts as a governor of the carbon cycle
- is the primary buffer for the acidity of seawater
- determines the reactivity of most chemical compounds

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$$CO_2 + H_2O \overset{K_1}{\leftrightarrow} H_2CO_3 \leftrightarrow HCO_3^- + H^+ \overset{K_2}{\leftrightarrow} CO_3^{2-} + 2H^+$$

Total Dissolved Inorganic Carbon
(keeps track of the carbon)

$$TCO_2 = \sum CO_2 = [CO_2] + [HCO_3^-] + [CO_3^{2-}]$$

Total Alkalinity
(keeps track of charges)

$$TA = \sum cations - \sum anions$$

TA & TCO_2 are conservative quantities, conserved during mixing

Seawater chemistry processes

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Carbonic acid — Bicarbonate ion — Carbonate ion

$$CO_2 + H_2O \overset{K_1}{\leftrightarrow} H_2CO_3 \leftrightarrow HCO_3^- + H^+ \overset{K_2}{\leftrightarrow} CO_3^{2-} + 2H^+$$

Law of mass action:

$$K_1 = \frac{[HCO_3^-][H^+]}{[CO_2]}$$

$$K_2 = \frac{[CO_3^-][H^+]}{[HCO_3^-]}$$

Total Dissolved Inorganic Carbon
(keeps track of the carbon)

$$TCO_2 = \sum CO_2 = [CO_2] + [HCO_3^-] + [CO_3^{2-}]$$

Total Alkalinity
(keeps track of charges)

$$TA = \sum cations - \sum anions$$

TA & TCO_2 are conservative quantities, conserved during mixing

Knowing TCO_2 and TA, one can calculate all other species diagnostically using the K values that are predetermined.

SEAWATER CHEMISTRY PROCESSES

CO_2 *gaseous*

In equilibrium the next exchange of CO_2 between air and sea is zero

$$CO_2 gaseous \overset{K_0}{\leftrightarrow} CO_2$$

Carbonic acid — Bicarbonate ion — Carbonate ion

$$CO_2 + H_2O \overset{K_1}{\leftrightarrow} H_2CO_3 \leftrightarrow HCO_3^- + H^+ \overset{K_2}{\leftrightarrow} CO_3^{2-} + 2H^+$$

Henry's law:

$$[CO_2] = K_0(T,S) \cdot pCO_2$$

Law of mass action:

$$K_1 = \frac{[HCO_3^-][H^+]}{[CO_2]}$$

$$K_2 = \frac{[CO_3^-][H^+]}{[HCO_3^-]}$$

Total Dissolved Inorganic Carbon $TCO_2 = \sum CO_2 = [CO_2] + [HCO_3^-] + [CO_3^{2-}]$

Total Alkalinity $TA = \sum cations - \sum anions$

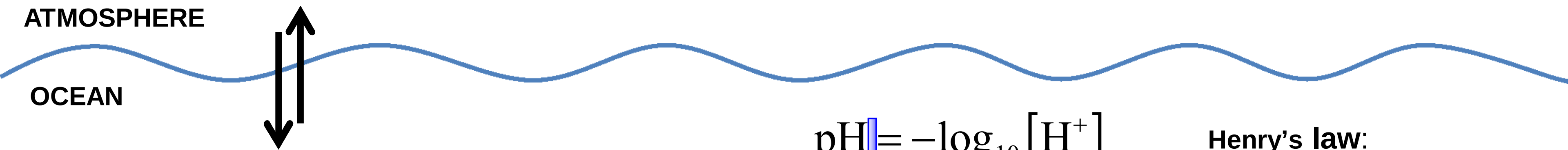
TA & TCO_2 are conservative quantities, conserved during mixing

The amount of gas that dissolves in a given volume of liquid is proportional to the partial pressure of that gas in equilibrium with that liquid

SEAWATER CHEMISTRY PROCESSES

What happens due to uptake of CO_2?

CO_2 *gaseous*



$$\mathrm{pH}\Downarrow = -\log_{10}\left[\mathrm{H}^+\right]$$

$$\mathrm{CO_2}\,gaseous \overset{K_0}{\leftrightarrow} \mathrm{CO_2}$$

Carbonic acid — Bicarbonate ion — Carbonate ion

$$\mathrm{CO_2} + \mathrm{H_2O} \overset{K_1}{\leftrightarrow} \mathrm{H_2CO_3}\Uparrow \leftrightarrow \mathrm{HCO_3^-}\Uparrow + \mathrm{H^+}\Uparrow \overset{K_2}{\leftrightarrow} \mathrm{CO_3^{2-}}\Downarrow + 2\mathrm{H^+}$$

Total Dissolved Inorganic Carbon $$\mathrm{TCO_2}\Uparrow = \sum \mathrm{CO_2} = [\mathrm{CO_2}] + [\mathrm{HCO_3^-}] + [\mathrm{CO_3^{2-}}]$$

Total Alkalinity $$\mathrm{TA} = \sum cations - \sum anions$$

Henry's law:

$$[\mathrm{CO_2}] = K_0\left(T,S\right)\cdot p\mathrm{CO_2}$$

Law of mass action:

$$K_1 = \frac{[\mathrm{HCO_3^-}][\mathrm{H^+}]}{[\mathrm{CO_2}]}$$

$$K_2 = \frac{[\mathrm{CO_3^-}][\mathrm{H^+}]}{[\mathrm{HCO_3^-}]}$$

Seawater chemistry processes

Alkalinity is the master variable of the carbonate system in seawater

according to DOE, 1994 Handbook:

$$TA=[HCO_3^-]+2[CO_3^{2-}]+[B(OH)_4^{-1}]+[OH^{-1}]-[H^+]$$
$$+[HPO_4^{2-}]+2[PO_4^{3-}]+[H_3SiO_4]$$
$$+[NH_3]+[HS^-]-[HSO_4^-]-[HF]-[H_3PO_4]$$

major components

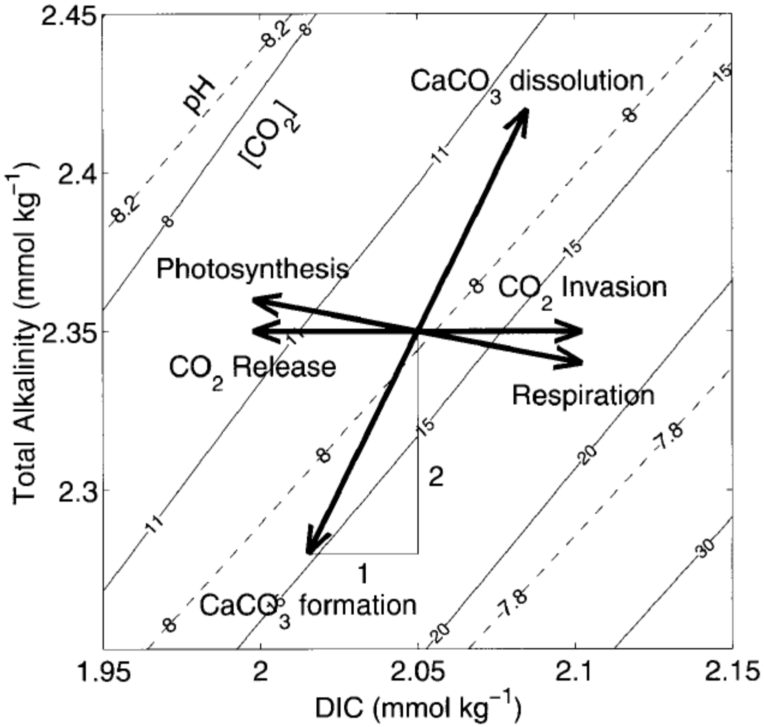
minor components

according to HAMOCC:

TA=Alk(carbonate, borate, water)

SEAWATER CHEMISTRY PROCESSES

Processes that affect Total Alkalinity and Total Dissolved Inorganic Carbon



- TA is a conservative quantity (TA is conserved during mixing)
- TA in seawater varies with salinity
- TA changes during formation and dissolution of calcium carbonate ($CaCO_3$)
- TA changes during nitrogen assimilation and release.

Note: **The addition (or removal) of CO_2 does not change the TA!**

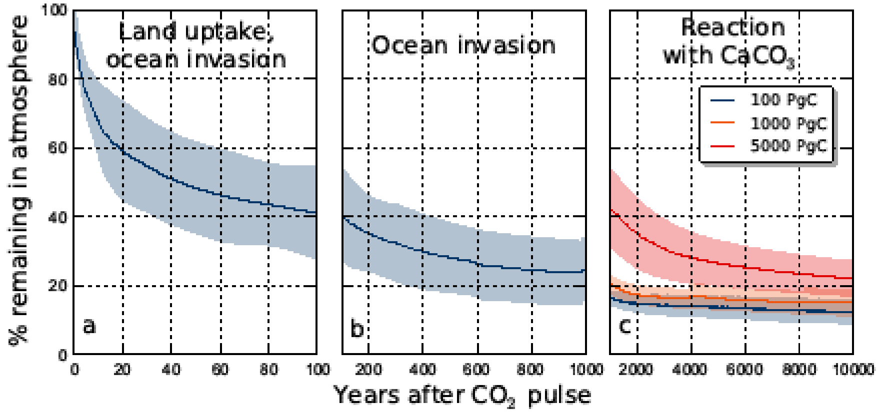
from: Zeebe Wolf-Gladrow, 2001

Seawater chemistry processes

$CaCO_3$ formation/dissolution

Formation and dissolution of $CaCO_3$, only calcite is considered
(formation consumes TCO_2 and Alk (1:2), dissolution releases them)

$$CaCO_3 \leftrightarrow Ca^{2+} + CO_3^{2-}$$



Saturation state of $CaCO_3$ (calcite)

$$\Omega_{calcite} = \frac{\left[Ca^{2+}\right]_{sw} \times \left[CO_3^{2-}\right]_{sw}}{K_{sp}}$$

$$\Omega > 1 \Rightarrow \textit{supersaturation}$$

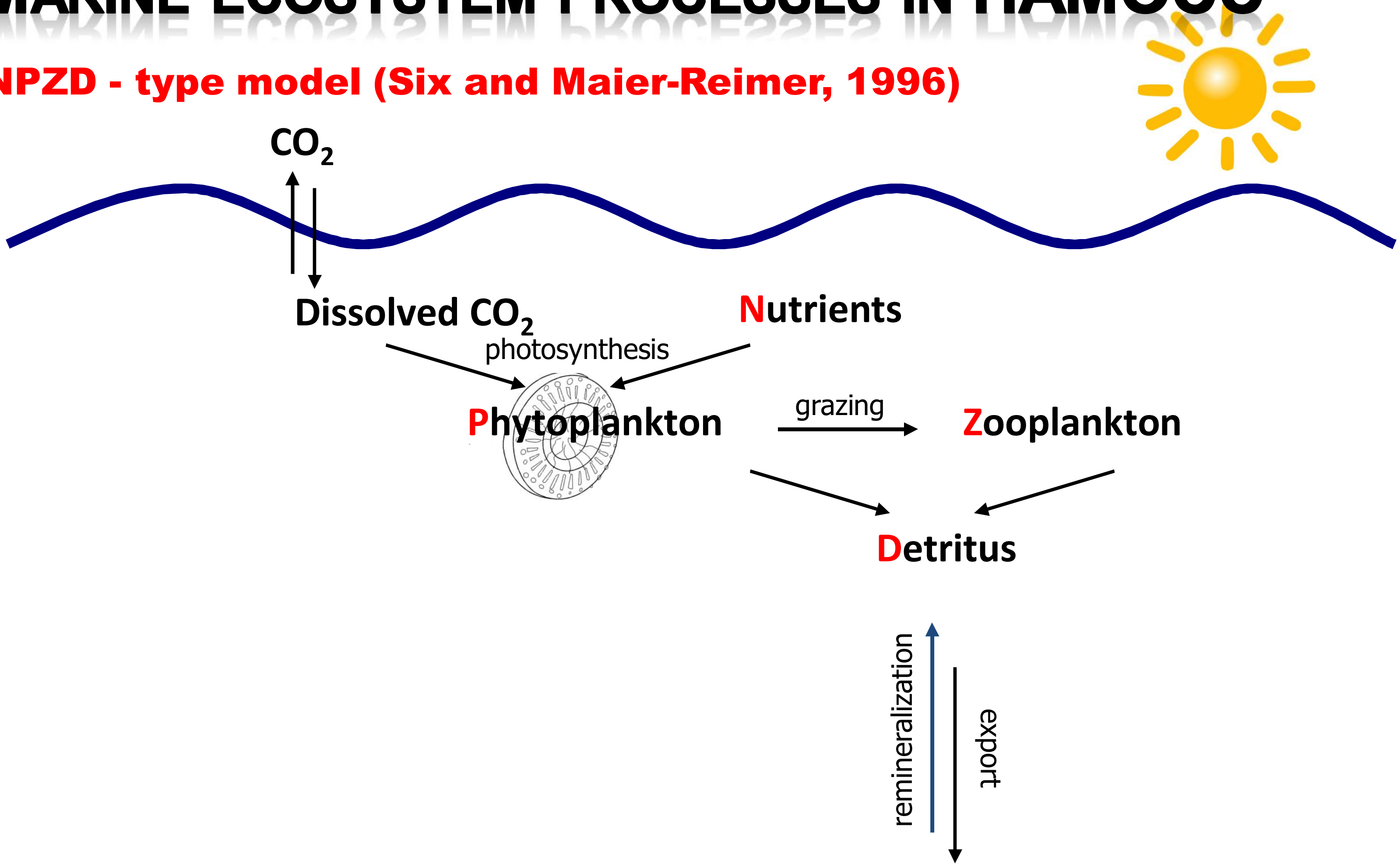
$$\Omega < 1 \Rightarrow \textit{undersaturation}$$

Neutralization of CO_2 by carbonates – efficient long-term sink for atmospheric CO_2

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$$

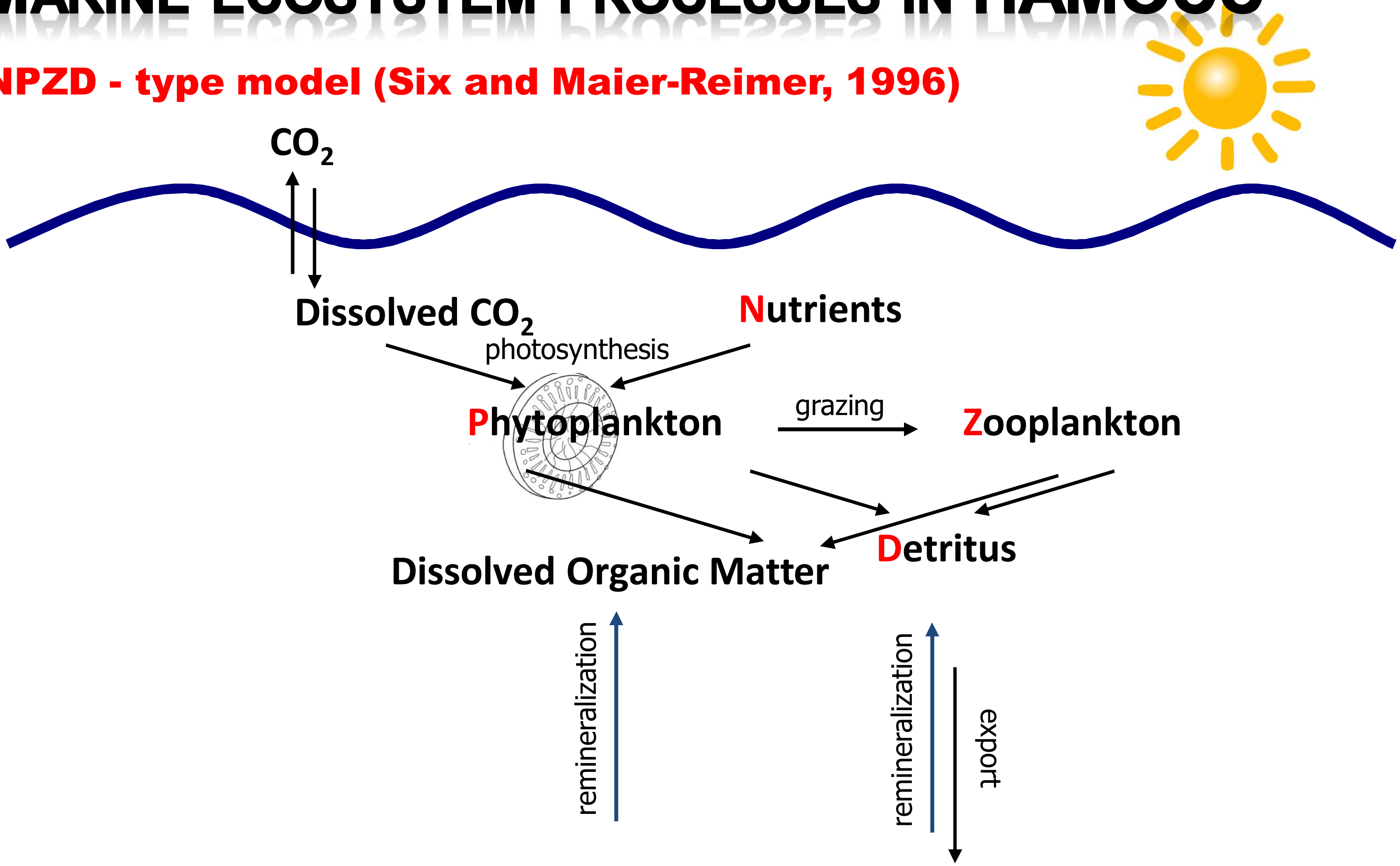
Marine ecosystem processes in HAMOCC

NPZD - type model (Six and Maier-Reimer, 1996)



MARINE ECOSYSTEM PROCESSES IN HAMOCC

NPZD - type model (Six and Maier-Reimer, 1996)



Marine ecosystem processes in HAMOCC

Photosynthesis by phytoplankton as a function of light supply, temperature and **nutrient** supply by co-limitation of *phosphate*, *nitrogen*, and *iron*. Organic matter and oxygen is produced.

Phytoplankton species implicitly treated: competition between opal forming and calcite forming. Diatoms grow first, but they are limited by silicate supply and require iron.

$$\frac{\partial \mathrm{Phy}}{\partial t} = G_{\mathrm{phy}} - F_{\mathrm{pz}} - M_{\mathrm{phy}} - E_{\mathrm{phy}} \, ,$$

Zooplankton: graze phytoplankton to grow. Zooplankton predators are parameterized by a constant mortality rate.

$$\frac{\partial \mathrm{Zoo}}{\partial t} = G_{\mathrm{zoo}} - M_{\mathrm{zoo}} - E_{\mathrm{zoo}} \, ,$$

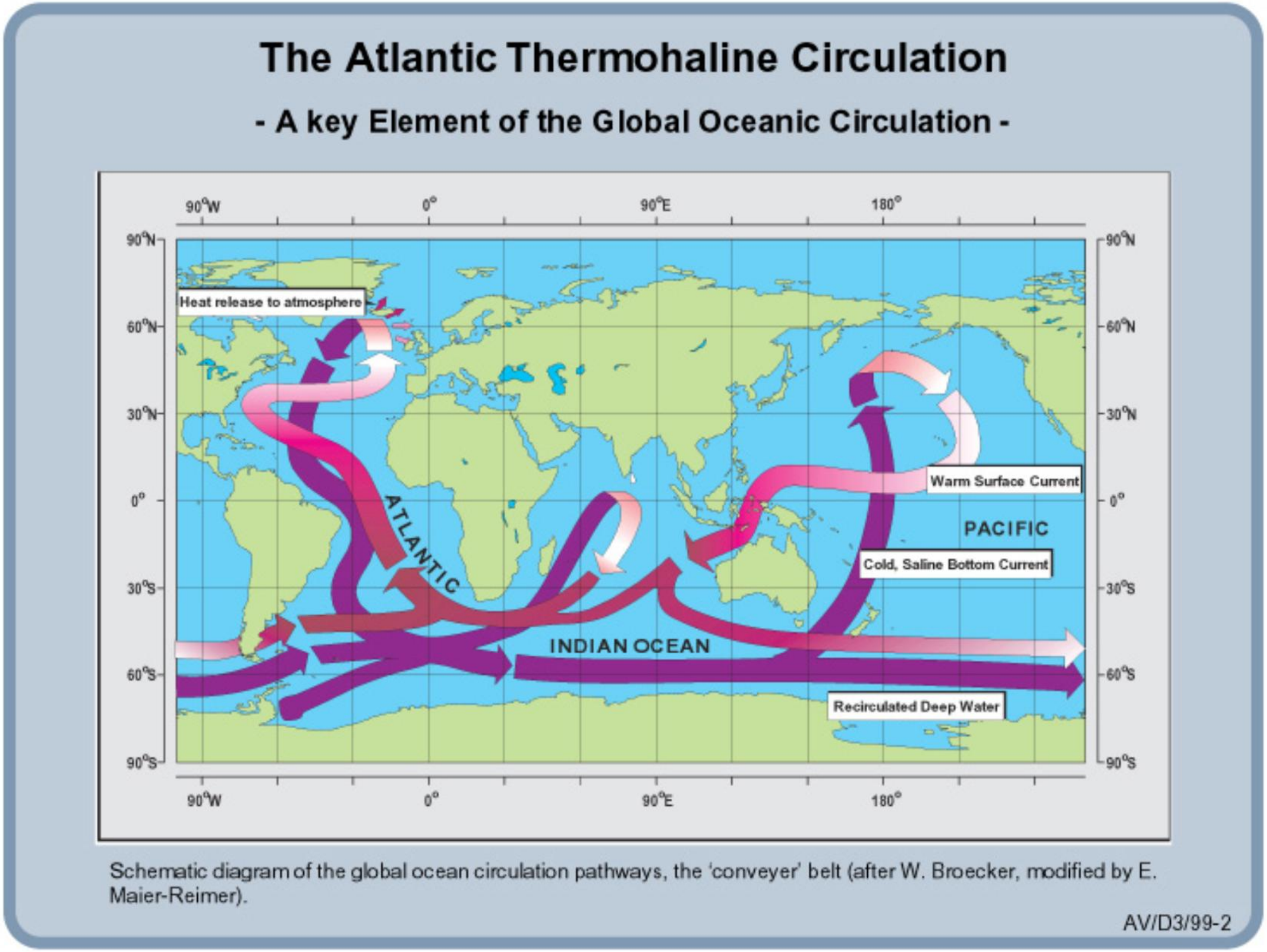
G – growth ***F*** – grazing ***M*** – mortality ***E*** - exudation

Detritus: is formed by dead zooplankton and phytoplankton

DOM: is produced by phyto- and zooplankton

Detritus and DOM are remineralized if O_2 is available

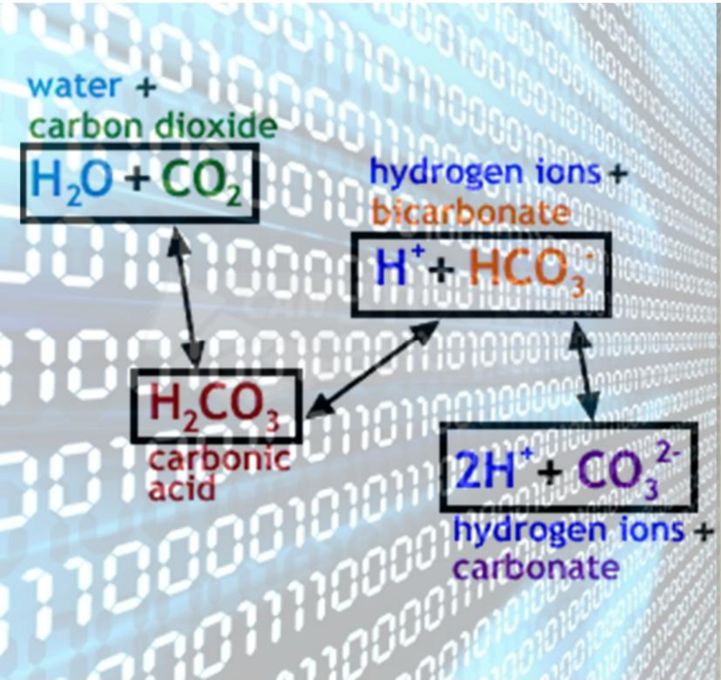
Advection and diffusion of all biogeochemical tracers is computed by an OGCM in the same way as for temperature and salinity.

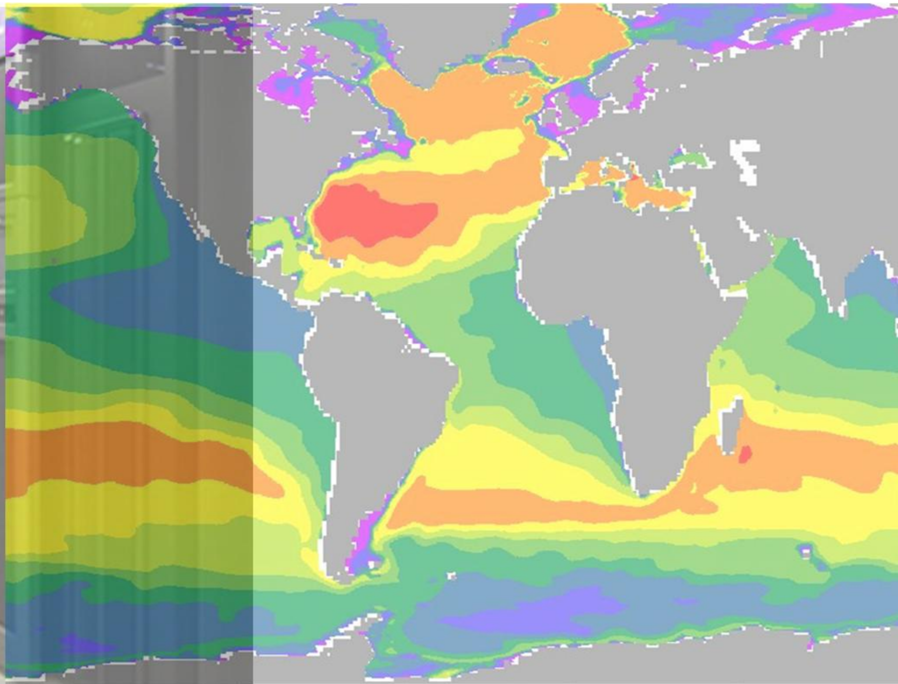


Schematic diagram of the global ocean circulation pathways, the 'conveyer' belt (after W. Broecker, modified by E. Maier-Reimer).

Ocean biogeochemical models are as good or as bad as the underlying OGCMs!

Overview of the main components of HAMOCC





Modeling ocean biogeochemical cycles

1984

Ernst Maier-Reimer
1944-2013

Progress in Biometeorology, 1984, Vol. 3, pp. 295-310.

3.4.4. Towards a Global Ocean Carbon Model*

by

E. Maier-Reimer**

A carbon cycle model of the ocean should elucidate essentially three questions:
(1) how does CO_2 enter the ocean?
(2) how is it transported into the ocean?
(3) what are the effects of biological sources and sinks in the ocean?

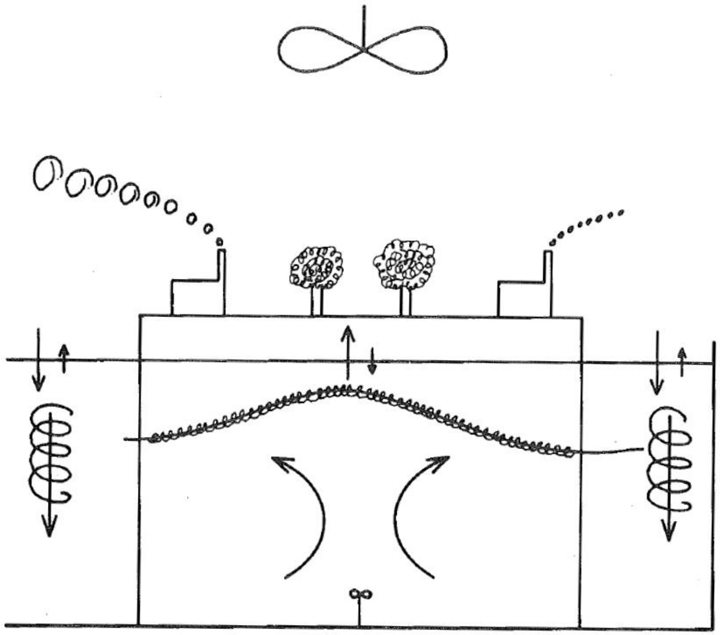
Progress in Biometeorology, 1984, Vol. 3, pp. 295-310.

3.4.4. Towards a Global Ocean Carbon Model*

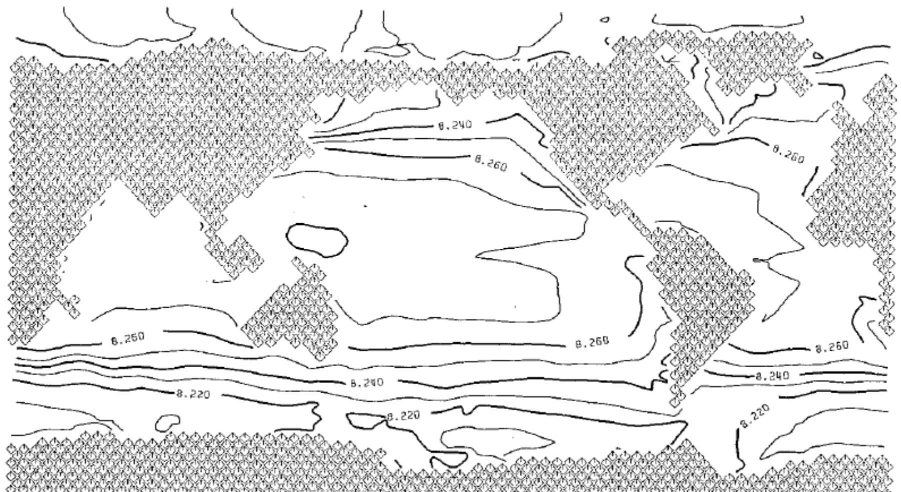
by

E. Maier-Reimer**

1984



Surface pH



1 prognostic tracer (TCO_2), Alk const., no biology

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 7, NO. 3, PAGES 645-677, SEPTEMBER 1993

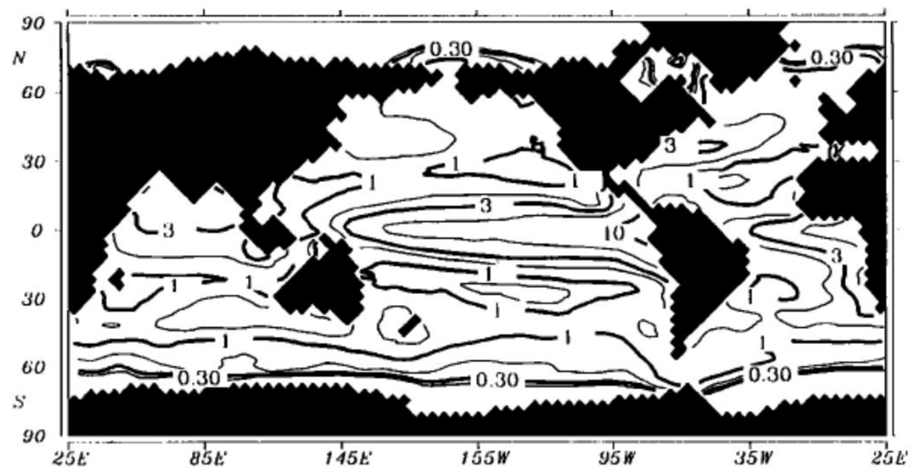
GEOCHEMICAL CYCLES IN AN OCEAN GENERAL CIRCULATION MODEL. PREINDUSTRIAL TRACER DISTRIBUTIONS

1993

Ernst Maier-Reimer
Max Planck-Institut für Meteorologie
Hamburg, Germany

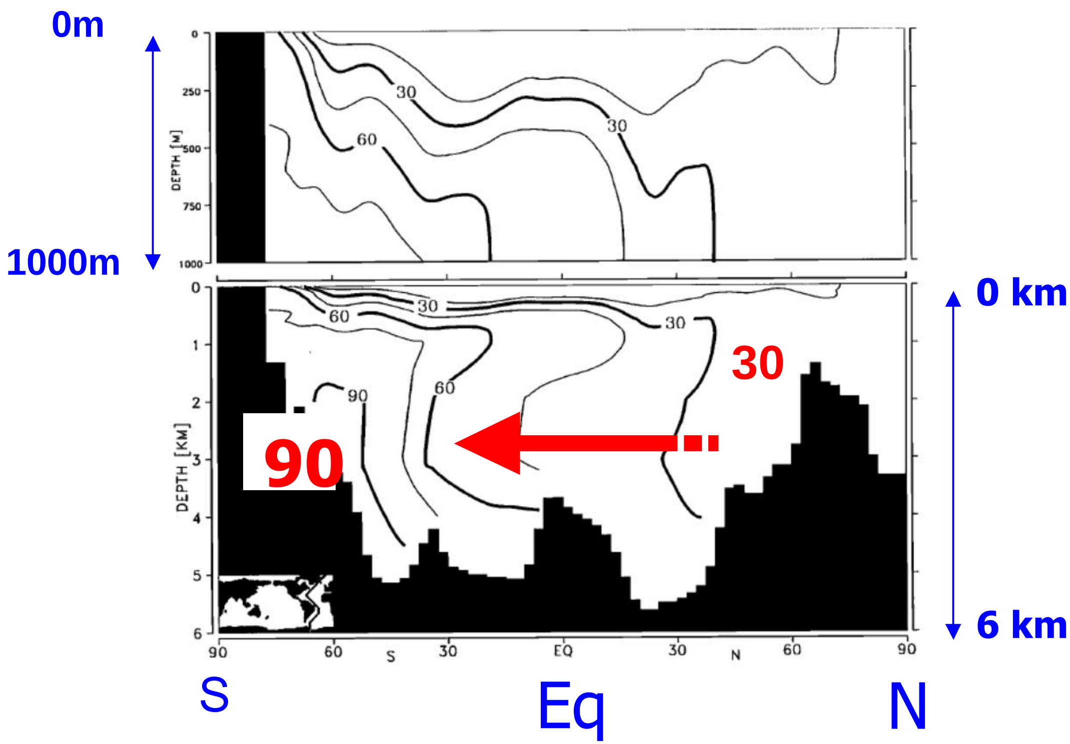
- **15 prognostic tracers**
- **TCO_2, Alk, POC, $CaCO_3$, PO_4, $Si(OH)_4$**
- **simplified biology (org. and shells)**
- **diffusive atmosphere**
- **C- and O- isotops**
- **simplified sediment**

Export production

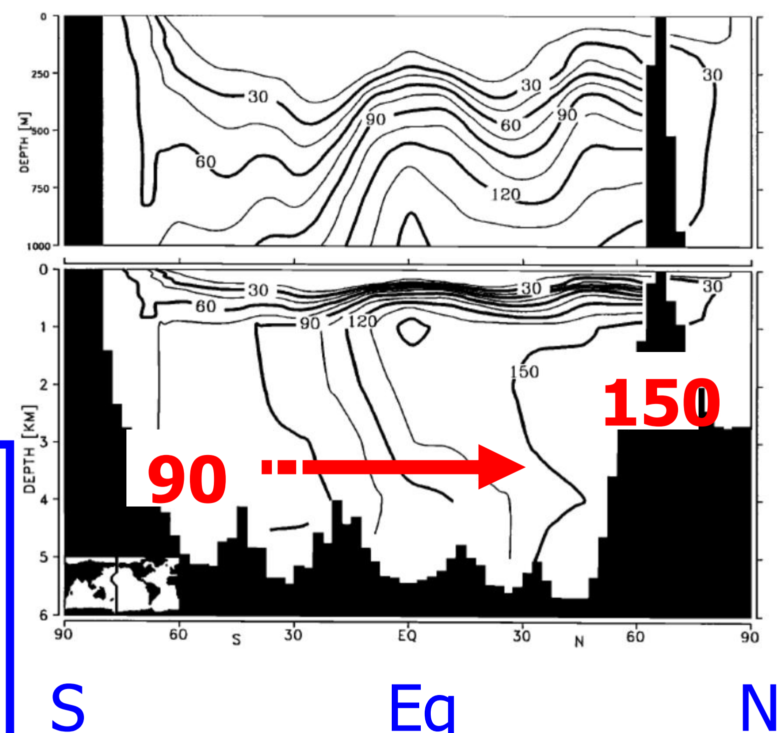


Silicate concentration [mmol/m^3]

Atlantic



Pacific



Selected applications of HAMOCC:

- Glacial times (Heinze et al., 1999)
- ENSO (Winguth et al., 1994)
- Sediment impact of CO2 (Archer et al. 1998)

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 10, NO. 4, PAGES 559–583, DECEMBER 1996

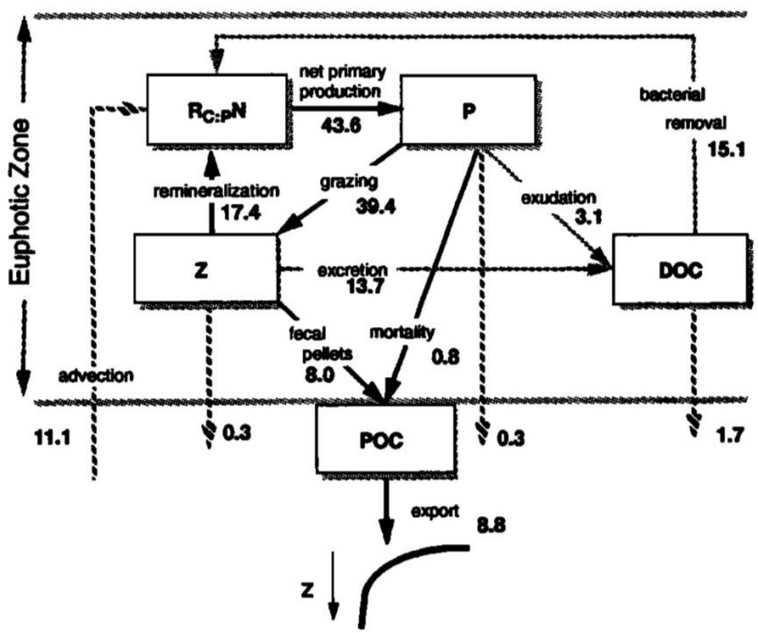
Effects of plankton dynamics on seasonal carbon fluxes in an ocean general circulation model

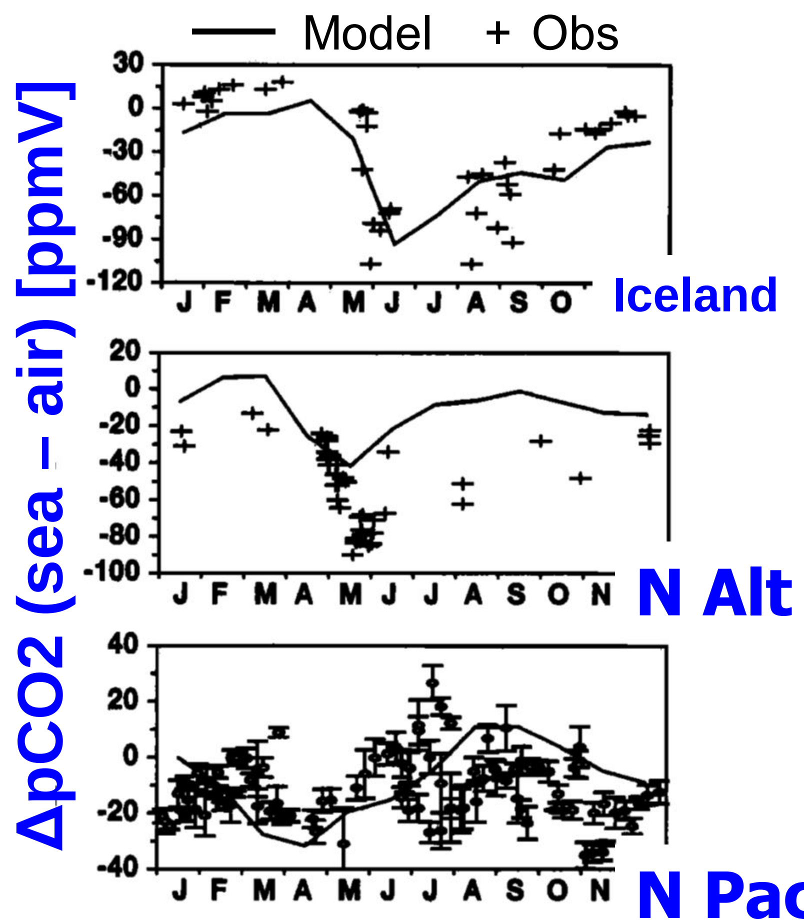
Katharina D. Six and Ernst Maier-Reimer

Max-Planck-Institut für Meteorologie, Hamburg, Germany

1996

+ 3 tracer:
Phytoplankton, Zooplankton, DOC





SEDIMENT PROCESSES

- Sediment with porewater geochemistry and solid constituents (Heinze et al., 1999)
  - bioturbated upper 10 cm of the sediment (12 model layers) and a consolidated (burial layer)
  - equilibrium sediment **accumulation = deposition – dissolution**:

    deposition > dissolution -> accumulation

    deposition < dissolution -> erosion

- **Porewater tracers**: DIC, Alk, Phosphate, Oxygen, N_2, Nitrate, Silicate
- **Solid tracers**: Detritus, Opal, $CaCO_3$, clay (from dust)
- **Processes**: decomposition of detritus, dissolution of opal and CaCO3, carbonate chemistry, vertical diffusion of porewater.

JOURNAL OF ADVANCES IN MODELING EARTH SYSTEMS, VOL. 5, 1–29, doi:10.1029/2012MS000178, 2013

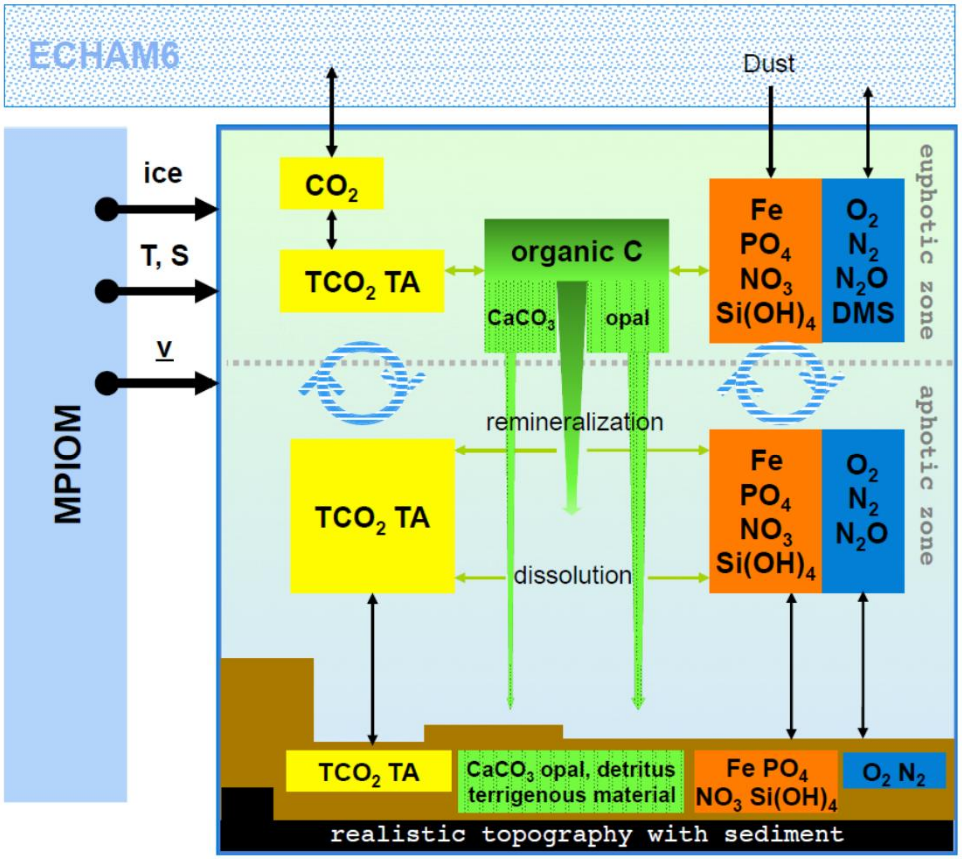
Global ocean biogeochemistry model HAMOCC: Model architecture and performance as component of the MPI-Earth system model in different CMIP5 experimental realizations

Tatiana Ilyina,[1] Katharina D. Six,[1] Joachim Segschneider,[1] Ernst Maier-Reimer,[1] Hongmei Li,[1] and Ismael Núñez-Riboni[1,2]

2015

2013

- **Multi-limiting nutrients: PO_4, NO_3, Fe, $Si(OH)_4$**
- **1 Phytoplankton (implicitly separated into diatoms and calcifiers) 1 Zoo-plankton**
- **N-cycle: denitrification, N-fixation**
- **Explicit treatment of opal and $CaCO_3$ shells**
- **Climate relevant gases: N_2O, DMS**
- **Interactive sediment module**
- **Additional phytoplankton type - cyanobacteria**



HAMOCC

Components of HAMOCC

an interdisciplinary approach

Seawater and pore-water chemistry:
mass balance equations
chemical fields integrated over time/space

Marine ecosystem:
NPZD-type (Nutrients, Phytoplankton, Zooplankton, Detritus)
information based on historical/evolutionary data
dynamics across multiple scales (cells, populations, ecosystems)

Transport of tracers:
governed by set of equations of the underlying OGCM

Prognostic variables – predicted by integration of equations
Diagnostic variables – derived variables

HAMOCC: HAMBURG OCEAN CARBON CYCLE MODEL

tracer models

20+ prognostic variables (tracers) in seawater
Total Dissolved Inorganic Carbon, Total Alkalinity, Phosphate, Oxygen, Dinitrogen, Nitrate, Silicate, Dust, dissolved Fe, Phytoplankton, Cyanobacteria, Zooplankton, Detritus, $CaCO_3$ shells, Opal shells, DOM, total ^{14}C, DMS, N_2O

Optional:
tracers of anthropogenic origin, carbon isotopes

11 prognostic variables in sediment:
pore-water: Total Dissolved Inorganic Carbon, Total Alkalinity, Phosphate, Oxygen, Dinitrogen, Nitrate, Silicate
solid fraction: Detritus, Opal, $CaCO_3$, Clay

Philosophy of HAMOCC

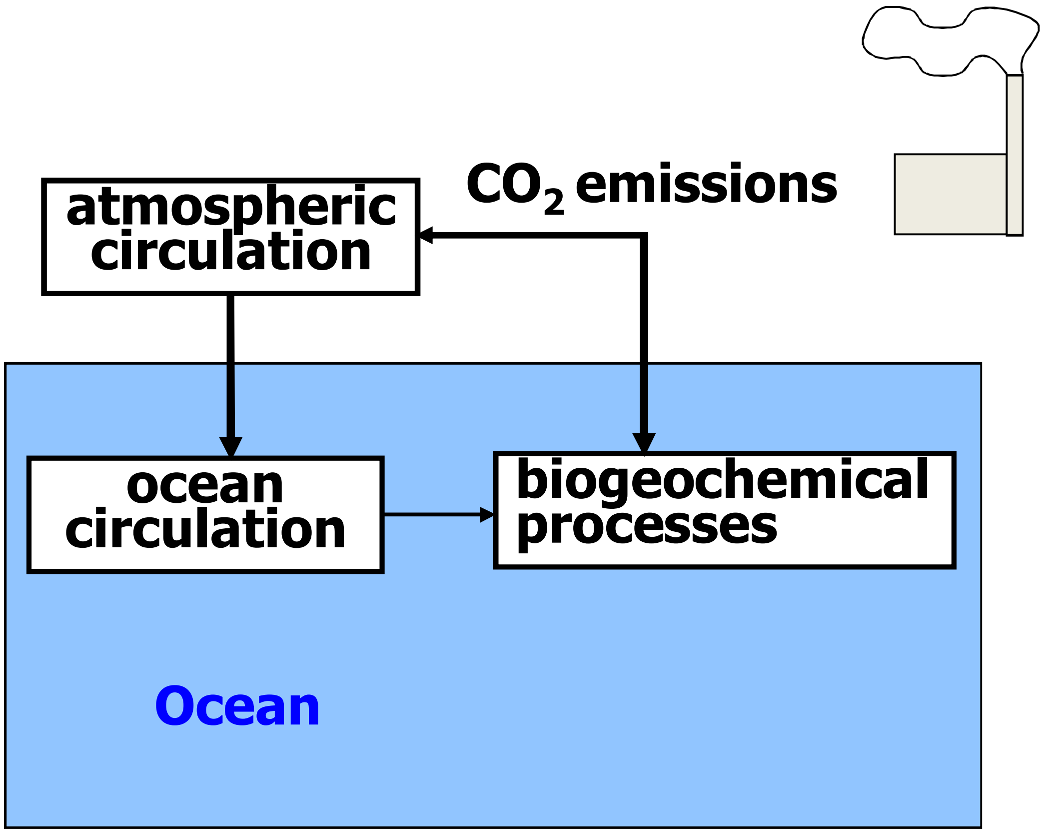
according to Ernst

- The modeler has to look for majority consensus
- But not invent processes biologists are not aware of

MODELING OCEAN BIOGEOCHEMISTRY

OCEAN STAND-ALONE CALCULATIONS

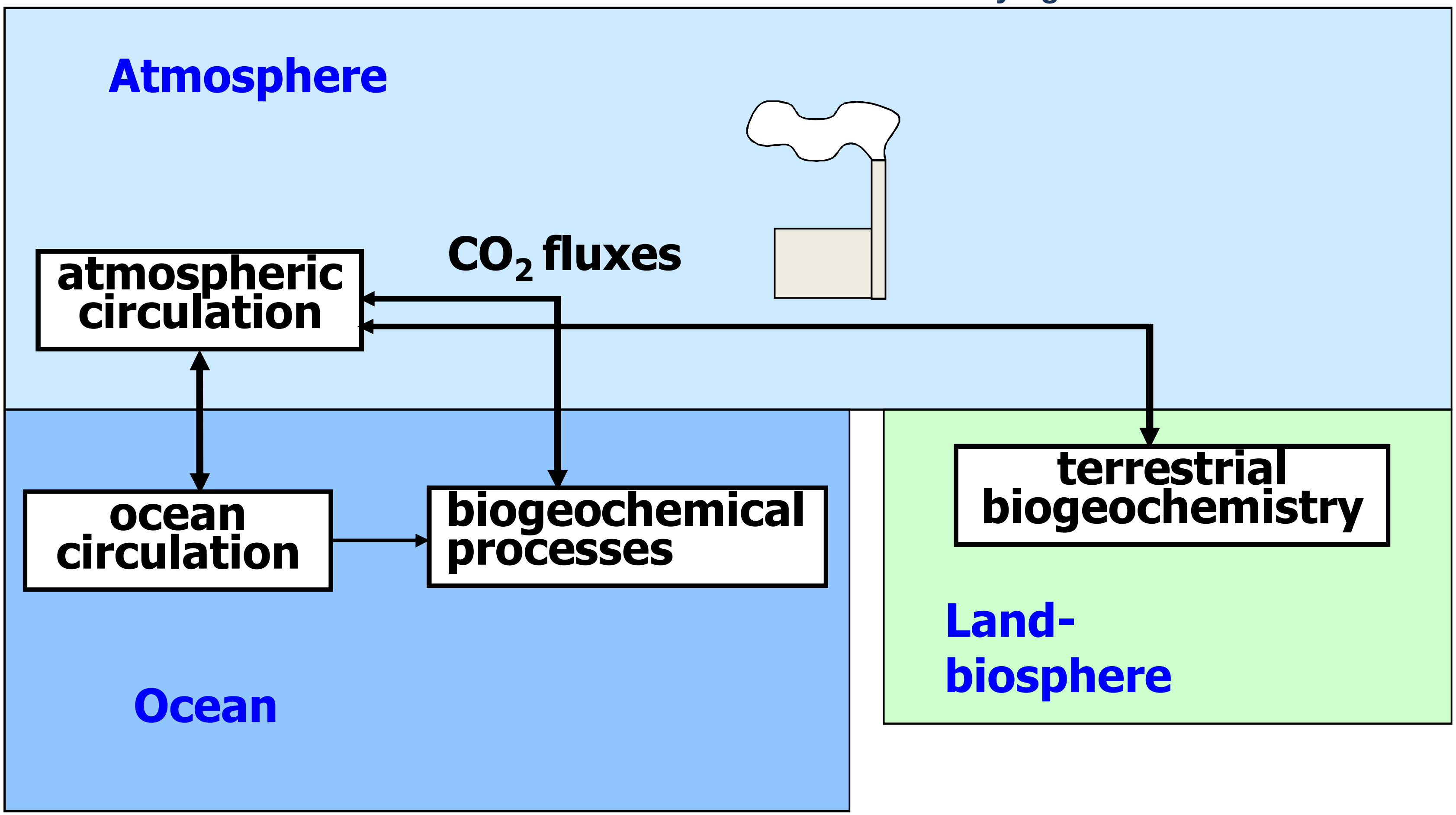
Purpose:
e.g. studying ocean-driven variability



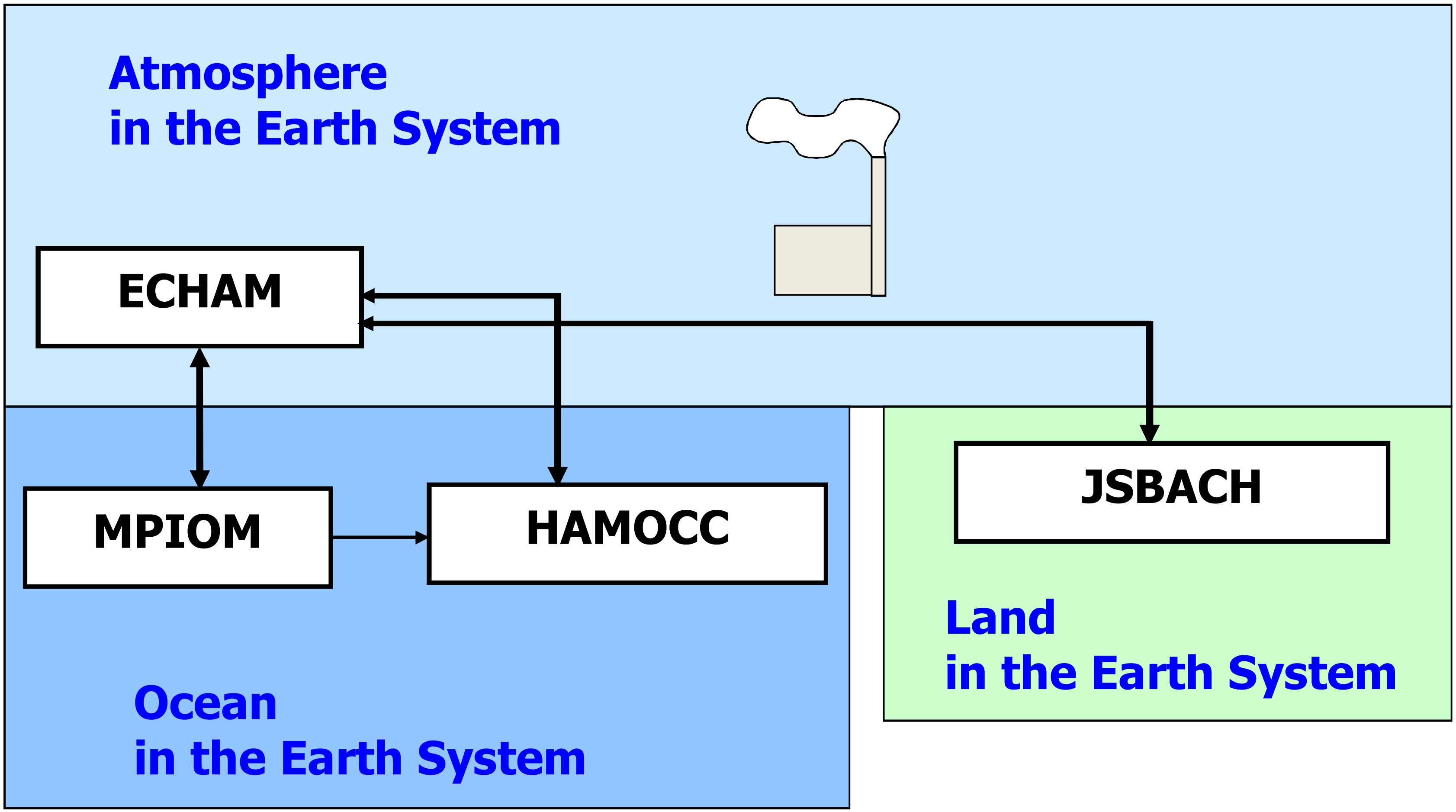
Modeling ocean biogeochemistry

Calculations with the interactive carbon cycle

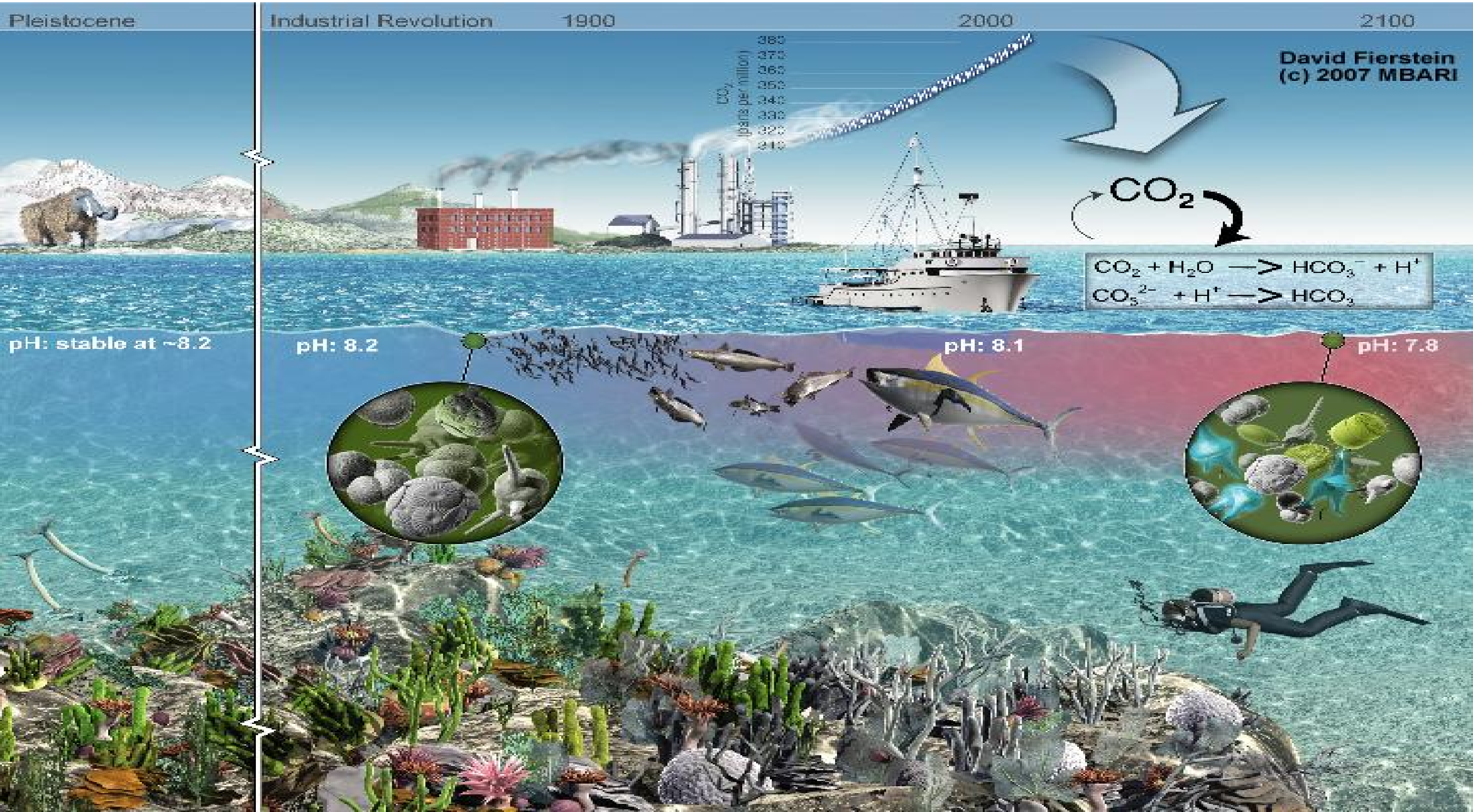
Purpose:
studying climate feedbacks



Earth System Modeling
MPI-ESM



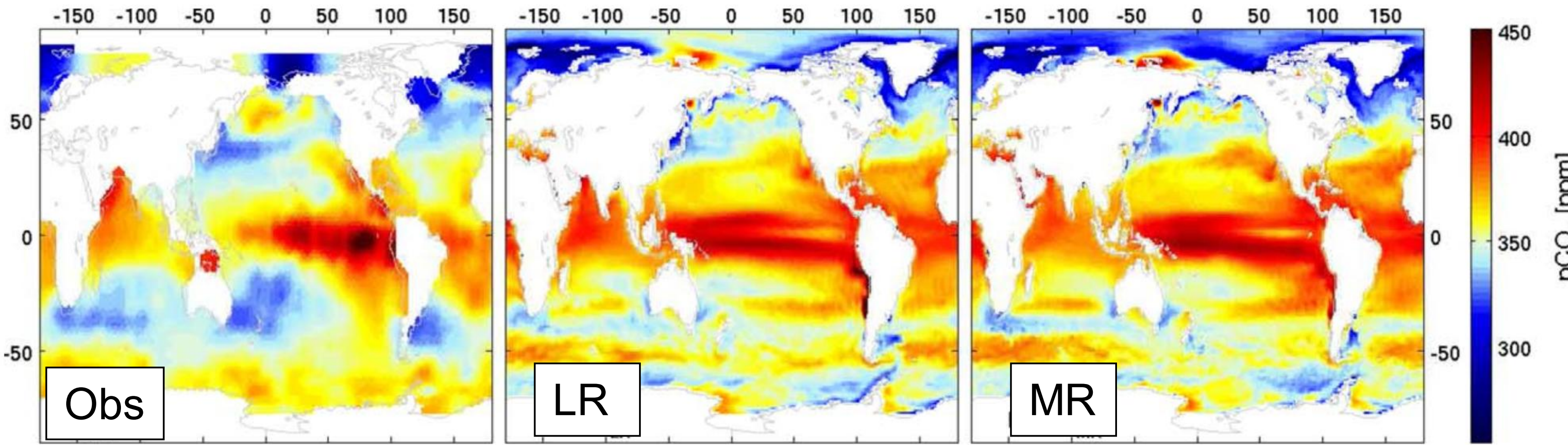
Model performance and projections



CO_2 IN HAMOCC

Coupled Model Intercomparison Project, 5th Phase

sea surface

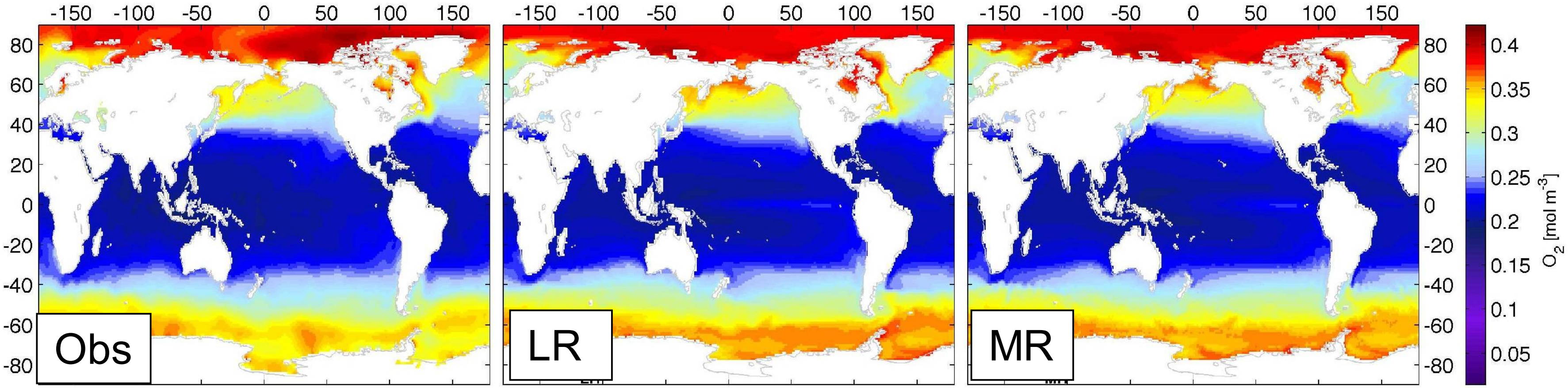


Ilyina et al., JAMES, 2013

Oxygen in HAMOCC

Coupled Model Intercomparison Project, 5th Phase

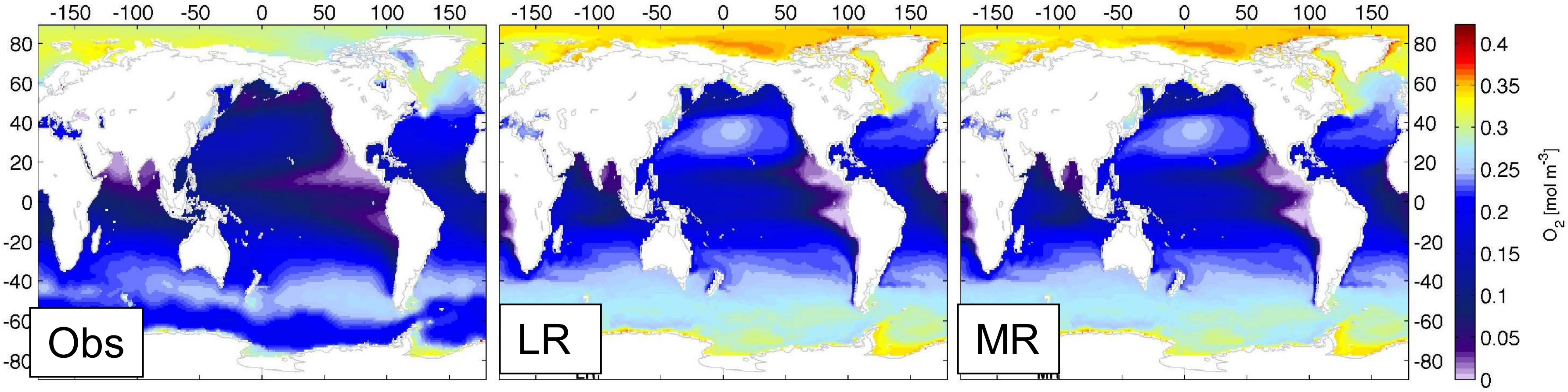
sea surface



Ilyina et al., JAMES, 2013

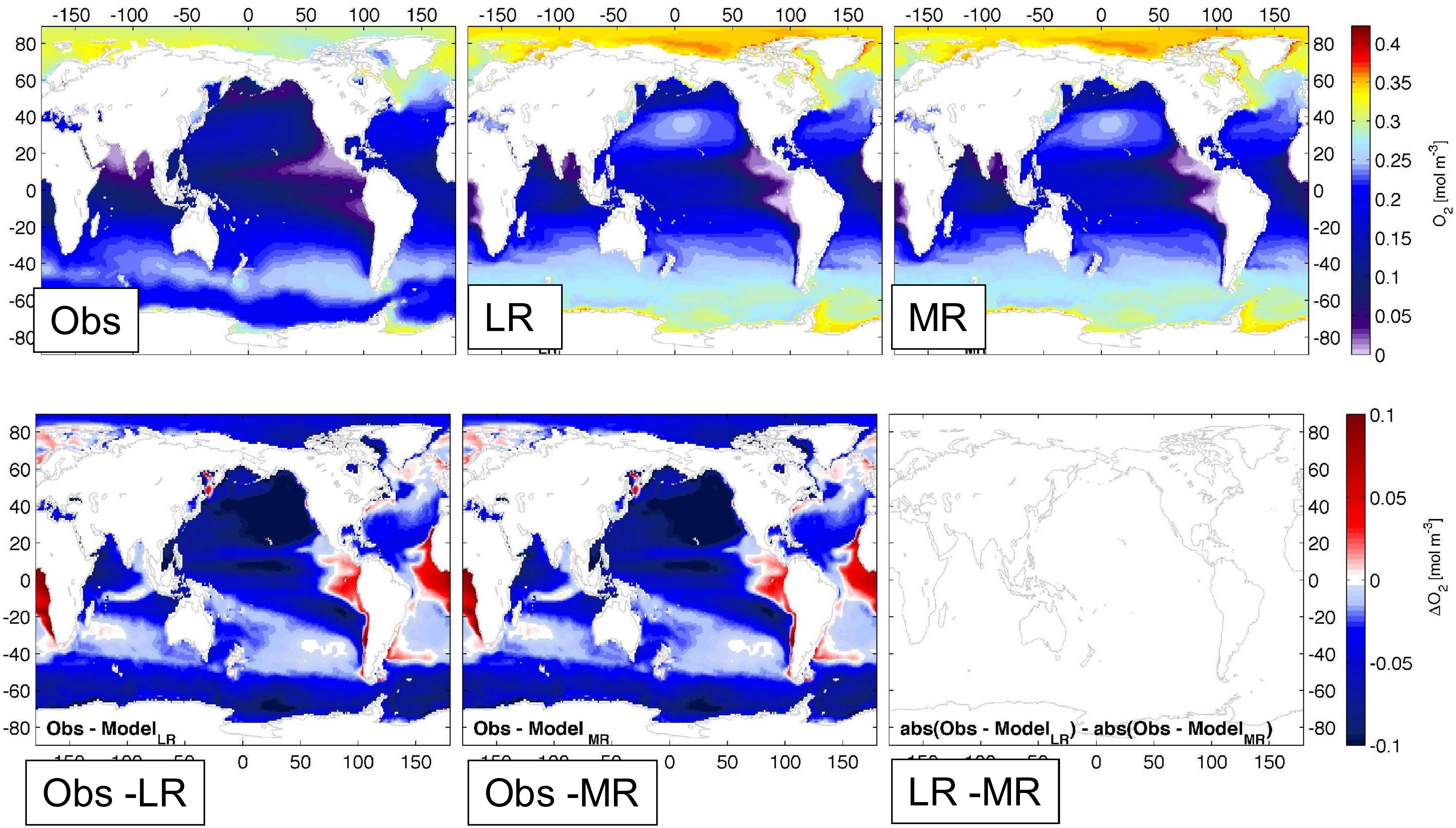
Oxygen in CMIP5 experiments

averaged over the upper 100-600 m



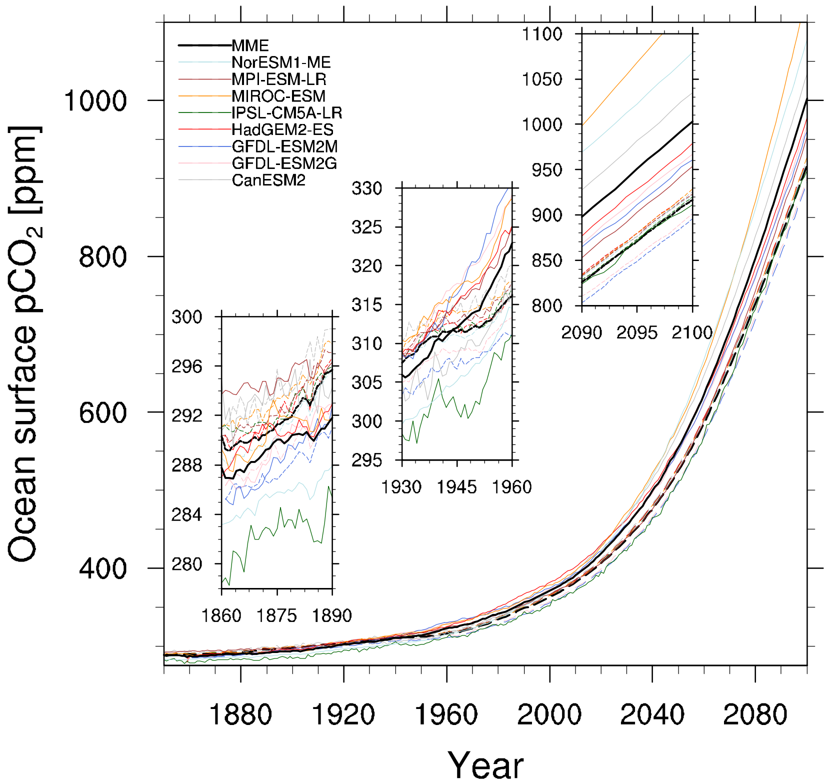
OXYGEN IN CMIP5 EXPERIMENTS

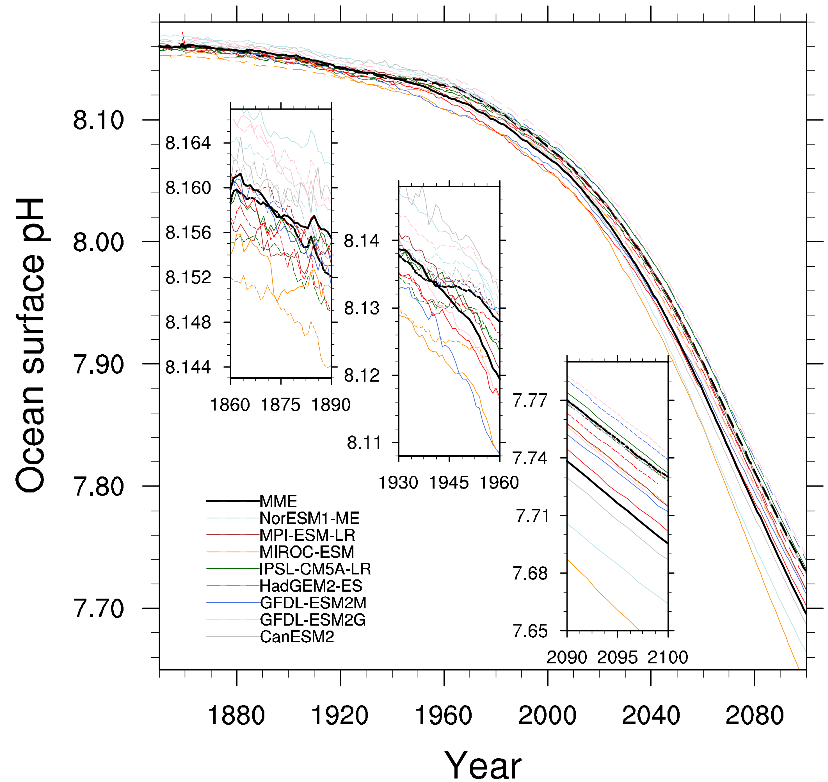
averaged over the upper 100-600 m



Projections of seawater chemistry

Coupled Model Intercomparison Project, 5th Phase





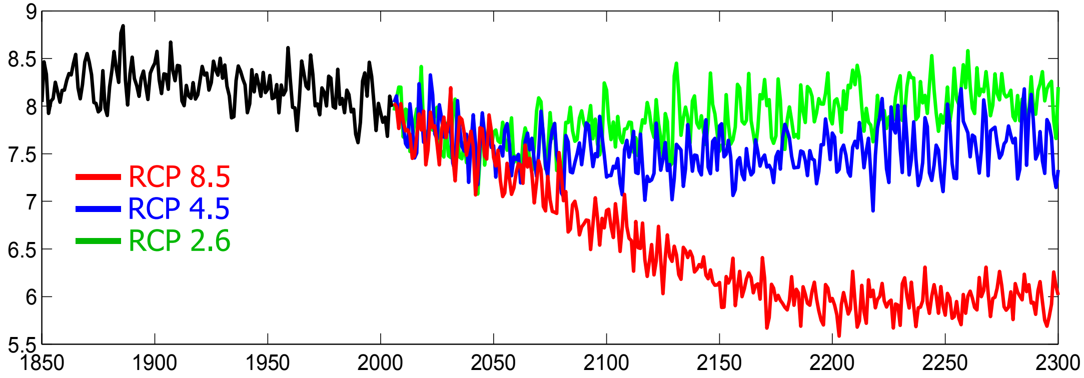
Hongmei Li

Ocean carbon chemistry is well constrained

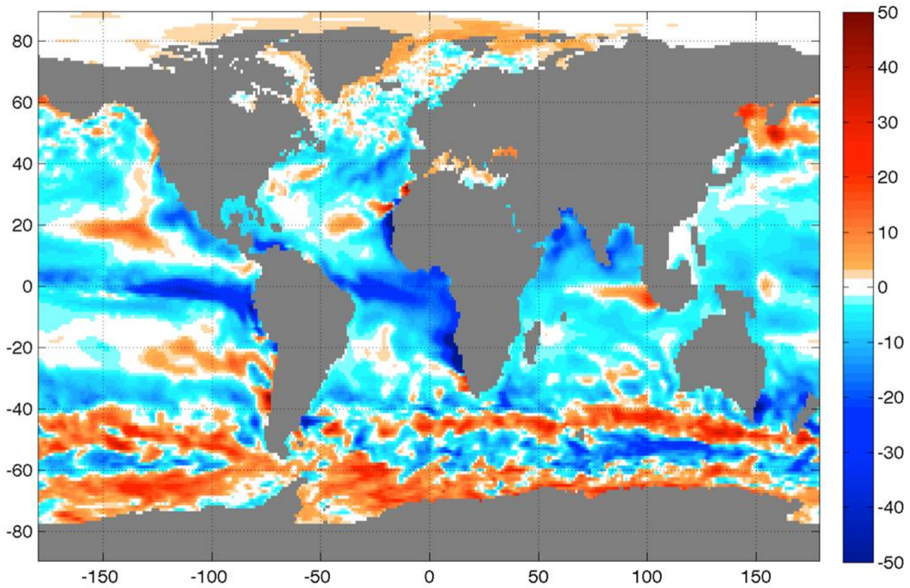
Models a relatively robust in their predictions of the response of marine carbon cycle to fossil fuel CO_2 perturbation.

Changes in biological production

Organic material flux at 90 m [Pg C year^{-1}]



Anomaly of organic material flux [mg C m^2 day^{-1}] between the year 2100 and 1850 under RCP 8.5

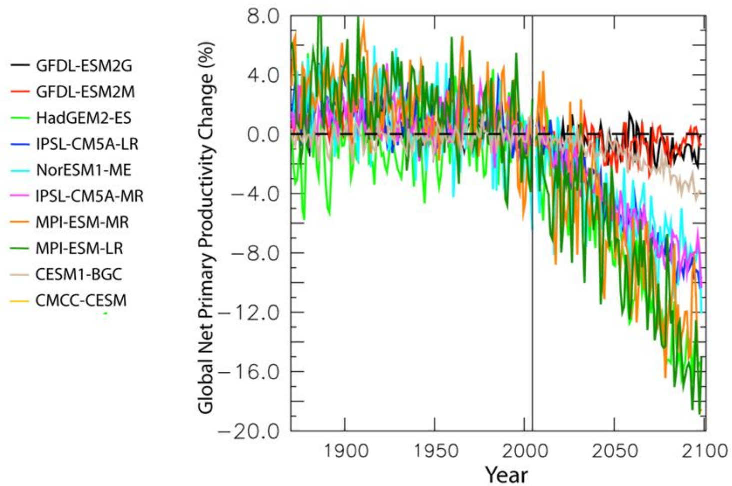


calculated with MPI-ESM in CMIP5 simulations

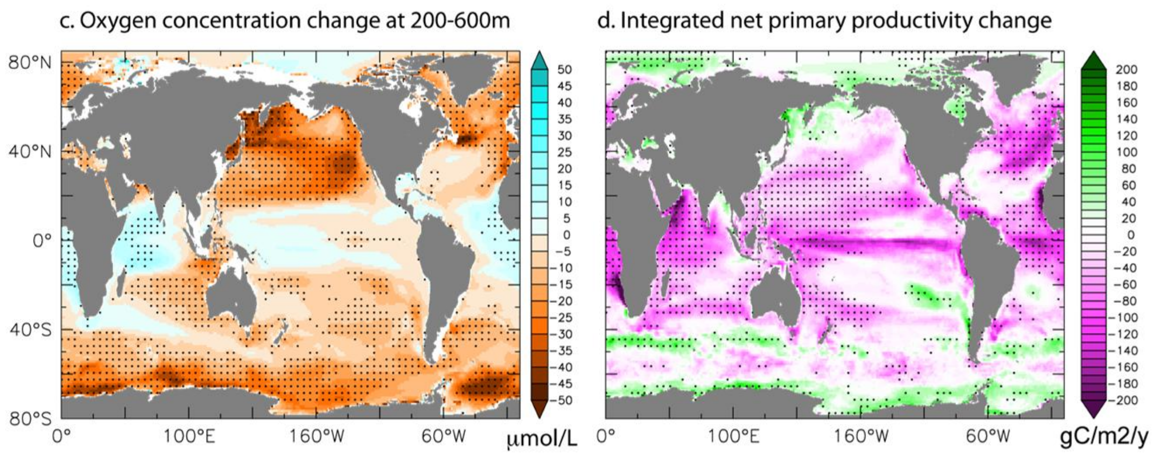
- A warmer future ocean will be accompanied by a more sluggish ocean circulation and an increased density stratification.
- This will reduce nutrients supply from the deep ocean.
- As a result global, biological production is projected to decrease.
- It increases in high latitudes due to decrease in ice cover and changes in upwelling regime

CHANGES IN BIOLOGICAL PRODUCTION

source: Bopp et al., *Biogeosciences*, 2013



RCP8.5 scenario



Marked area represent areas of high robustness.

Currently models do not fully agree about changes in spatial and temporal dynamics of biomass.

SUMMARY

- HAMOCC simulates biogeochemical tracers in the ocean (i.e. C, N, P, O, Fe …).

- Given the system complexity and model assumptions, it addresses first order process in ocean biogeochemistry and tackles different spatial and temporal scales.
- Good representation of large scale gradients
- Applicable for long simulations periods (future and past)
- But only limited use for questions on the ecosystem (with 1 or 2 tracers for phyto- and zoo-plankton functional types)

- Advection and diffusion of all biogeochemical tracers is computed by an OGCM in the same manner as for temperature and salinity.

KEY REFERENCES

- HAMOCC: Maier-Reimer, Hasselmann (1987), Maier-Reimer (1993)
- NPZD system: K. Six and E. Maier-Reimer (1996)
- Sediment: Heinze et al. (1999)
- Technical Report on HAMOCC 5.1: Maier-Reimer et al. (2005)
  http://www.mpimet.mpg.de/fileadmin/publikationen/erdsystem_14.pdf
- HAMOCC in CMIP5: Ilyina et al. (2013)