Chemical and biological effects on mesopelagic organisms and communities in a high-CO_2 world

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Carbon sequestration: the "upper ocean"

- Effect of the biological carbon pump on climate is determined by the amount of biogenic carbon that is sequestered (S) in deep waters and sediments, i.e. below the permanent pycnocline

- Carbon above the permanent pycnocline can be exchanged with the atmosphere within decades

- For climate purposes, we must consider the processes that take place between the ocean's surface and the permanent pycnocline: "upper ocean"

Objective of the present study

- Climate related changes in the upper ocean will influence the diversity and functioning of plankton functional types
  ⇒ relevant models must take into account

- the roles of functional biodiversity and pelagic ecosystem functioning
- in determining the biogeochemical fluxes of carbon
- in order to predict the interactions between climate change and the ocean's biology

- First objective of the present study: to develop a framework for modelling the effects of climate change on biologically mediated ocean processes in the upper ocean
  by combining

- plankton functional types (PFTs)
- food-web processes
- biogeochemical fluxes

New class of models

- Usual models of biogeochemical fluxes and marine pelagic ecosystems often consider
- 3-layer water column: euphotic zone, mesopelagic layer and ocean's interior
- variable numbers of plankton functional types
- variable numbers of food-web processes
- wide array of biogeochemical carbon fluxes

- Proposed approach for a new class of models
- 2-layer water column: above and below the permanent pycnocline (average depth ca. 1000 m)
- at least 5 plankton functional types
- at least 3 classes of food-web processes that affect organic matter
- at least 4 biogeochemical carbon fluxes

Plankton functional types (1)

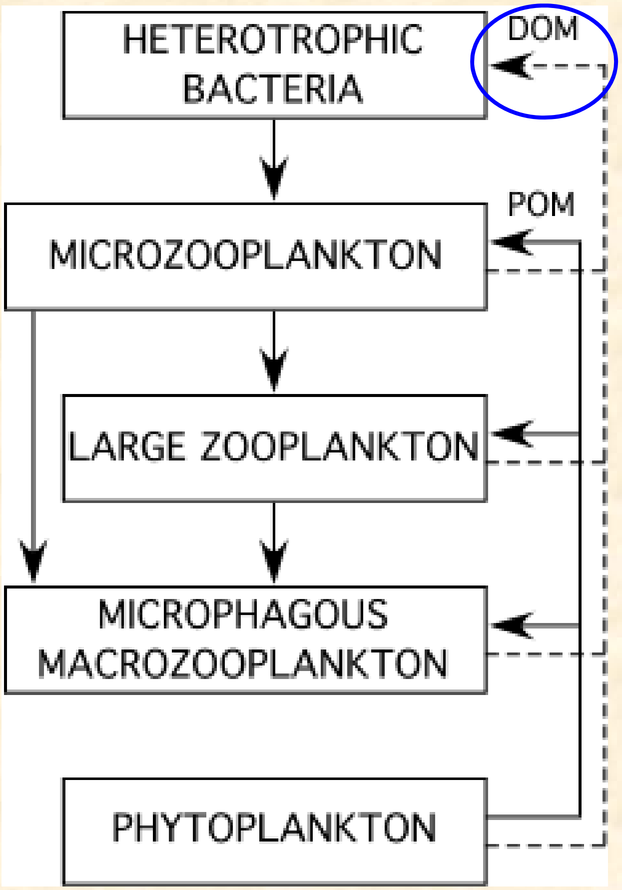
- Models should include at least 5 plankton functional types: based on their roles in the synthesis and transformation of organic matter (OM)

1. phytoplankton (PH): small inorganic molecules —> DOM and POM
2. heterotrophic bacteria (HB): solubilise organic particles, and use DOM
3. microzooplankton (µZ): feed on a narrow size range of particles (commensurate with their own small sizes)
4. large zooplankton (LZ): feed on a narrow size range of particles (commensurate with their own large sizes)
5. microphagous macrozooplankton (MM): e.g. salps, appendicularians, pteropods; feed on a wide size range of particles (from ca. 1 µm to close their own large sizes)

Plankton functional types (2)

- Feeding relationships among the 5 plankton functional types

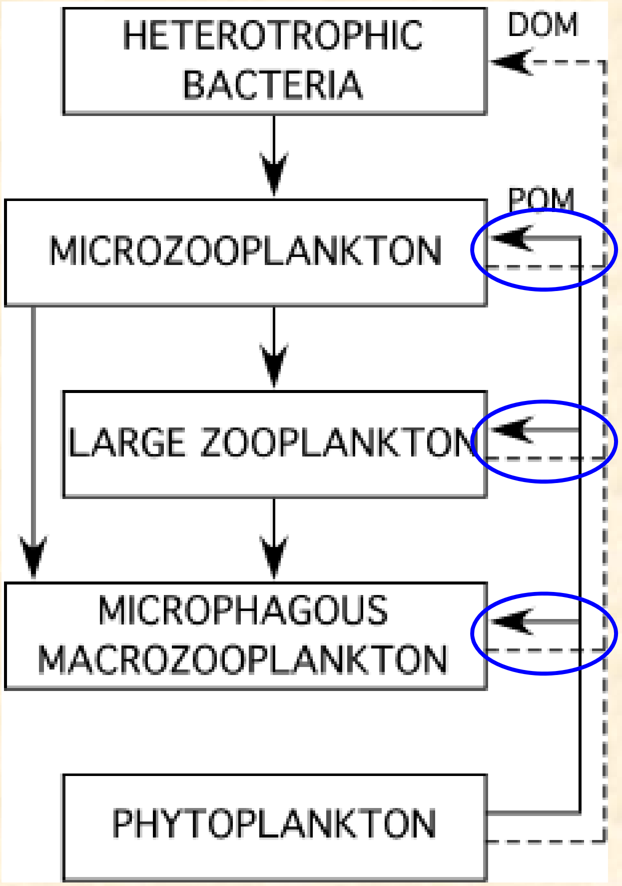
- DOM (phyto. + heterotrophs) —> heterotrophic bacteria



Plankton functional types (3)

- Feeding relationships among the 5 plankton functional types

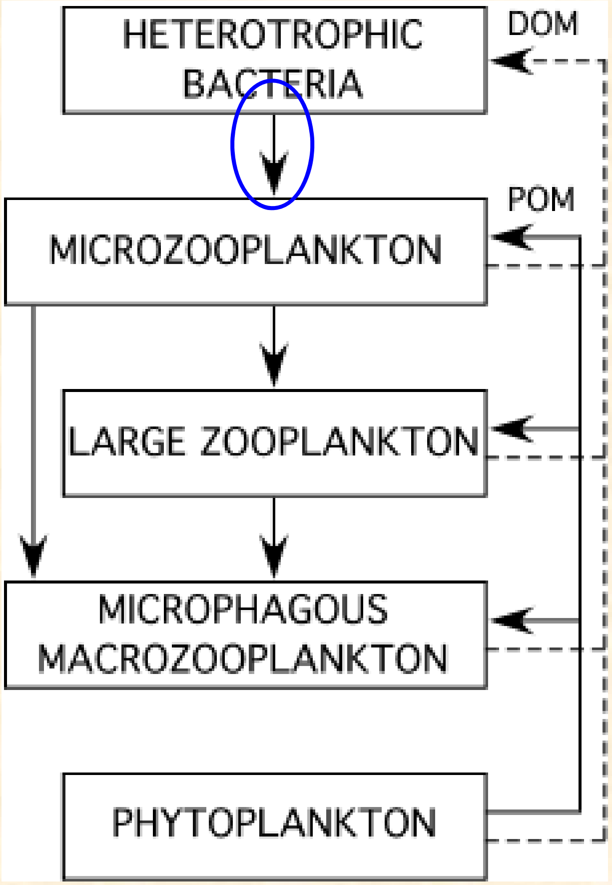
- DOM (phyto. + heterotrophs) —> heterotrophic bacteria
- phytoplankton cells —> all zooplankton



Plankton functional types (4)

- Feeding relationships among the 5 plankton functional types

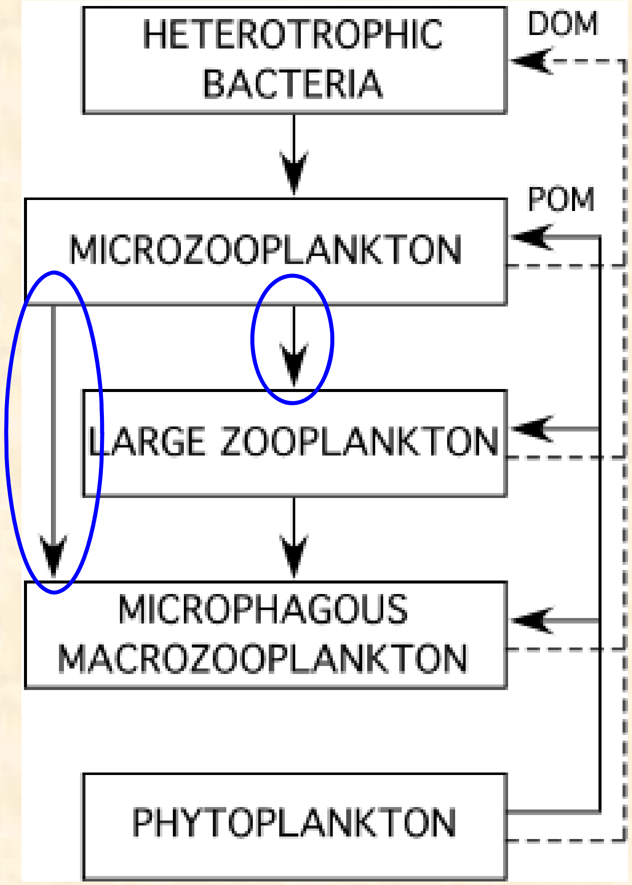
- DOM (phyto. + heterotrophs) —> heterotrophic bacteria
- phytoplankton cells —> all zooplankton
- bacteria —> µ-zooplankton



Plankton functional types (5)

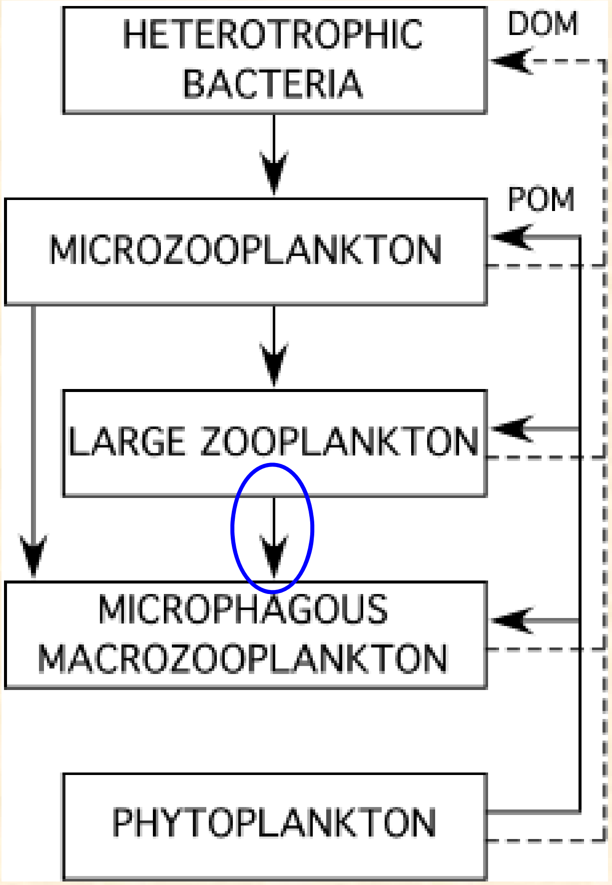
- Feeding relationships among the 5 plankton functional types

- DOM (phyto. + heterotrophs) —> heterotrophic bacteria
- phytoplankton cells —> all zooplankton
- bacteria —> μ-zooplankton
- μ-zooplankton —> large zooplankton + microphagous macrozooplankton



Plankton functional types (6)

- Feeding relationships among the 5 plankton functional types

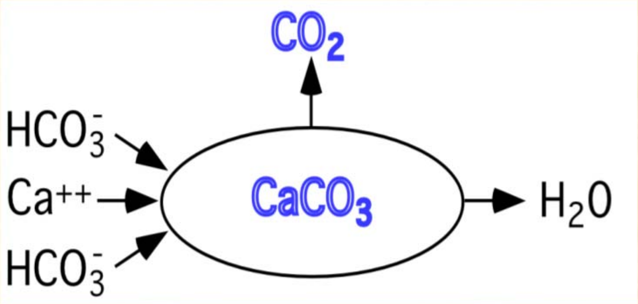


- DOM (phyto. + heterotrophs) —> heterotrophic bacteria
- phytoplankton cells —> all zooplankton
- bacteria —> µ-zooplankton
- µ-zooplankton —> large zooplankton + microphagous macrozooplankton
- some large zooplankton —> microphagous macrozooplankton

Biogeochemical carbon fluxes

- Models should consider 4 biogeochemical carbon fluxes

1. net photosynthesis: DIC —> POC + DOC
2. calcification:
   precipitates
   $CaCO_3$ +
   releases CO_2



3. heterotrophic respiration: (DOC + POC) —> CO_2
4. deep transfer of carbon compounds

- $CaCO_3$
  - » coccoliths (in sinking faecal pellets)
  - » calcareous tests (sinking)
- organic carbon
  - » phytodetritus
  - » fast-sinking faecal pellets (mostly from microphagous macrozooplankton)
  - » deep seasonal vertical migrations (mesozooplankton)

Plankton + biogeochemistry

- Biogeochemical carbon fluxes are controlled by living organisms
- Models of the new class should consider how the 5 plankton functional types control the 4 biogeochemical carbon fluxes

Plankton + biogeochemistry

Flux	**PH**	**HB**	**µZ**	**LZ**	**MM**
Photosynthesis	DIC —> OC				
Calcification	Coccolithoph.		Foraminifera		Pteropods
Hetero. respira-tion		DOC: very high	POC: quite high	POC: high	POC: low
OC deep transfer	Phytodetritus			Seasonal migrations	Faecal pellets
$CaCO_3$ deep trans.	Coccoliths		Foram. tests		Pteropod tests

Food-web processes that affect OM

- Models should address 3 food-web processes that affect organic matter (OM), for the various plankton types

1. OM synthesis: fixation of C and other chemical elements into organic matter (phytoplankton)
2. OM transformations due to the processing by organisms

- decrease in OM size: solubilisation of organic particles (heterotrophic bacteria), excretion of DOM (all heteros.) + fragmentation of particles (zoopl.: sloppy feeding, etc.)
- increase in OM size: incorporation into body mass (heteros.), production of faecal pellets, shedding of clogged houses (appendicularians) [+contribution to TEP, aggregates, etc.]
- change in OM bioavailability: biological transformation

3. OM remineralisation: CO_2 and inorganic nutrients

Plankton + food-web processes

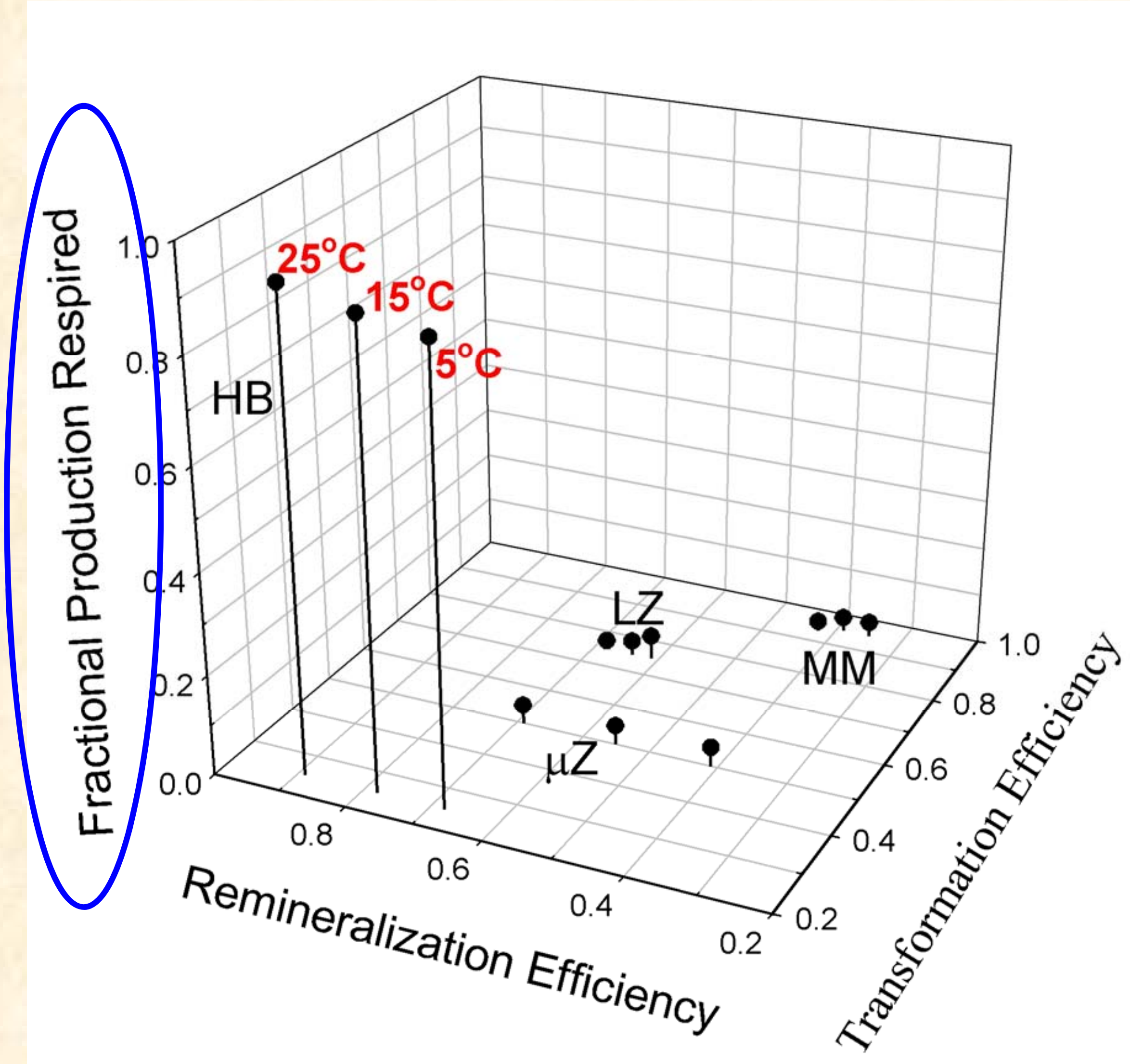
OM	PH	HB	µZ	LZ	MM
Synthesis	Photos. N_2-fix.				
Transform size: decr.		Solubilis. of POM	DOM excretion POM fragment.		DOM excretion
Transform size: incr.		Body mass	+ Faecal pellets		+Clogged houses
Transform bioavail.		Refract. DOM ⇑			
Reminer-alisation	Low	DOM: very high	POM: high	POM: high	POM: low

Plankton + food-web processes + carbon biogeochemistry

- Models of the new class should combine
  the 5 plankton functional types
  and the 3 food-web processes that affect OM
  to predict the 4 biogeochemical carbon fluxes in the upper ocean
- Preliminary *example* of a possible functional relationship to predict one of the four biogeochemical carbon fluxes: *heterotrophic respiration of net phytoplankton production*

PFTs + food web + biogeochem.

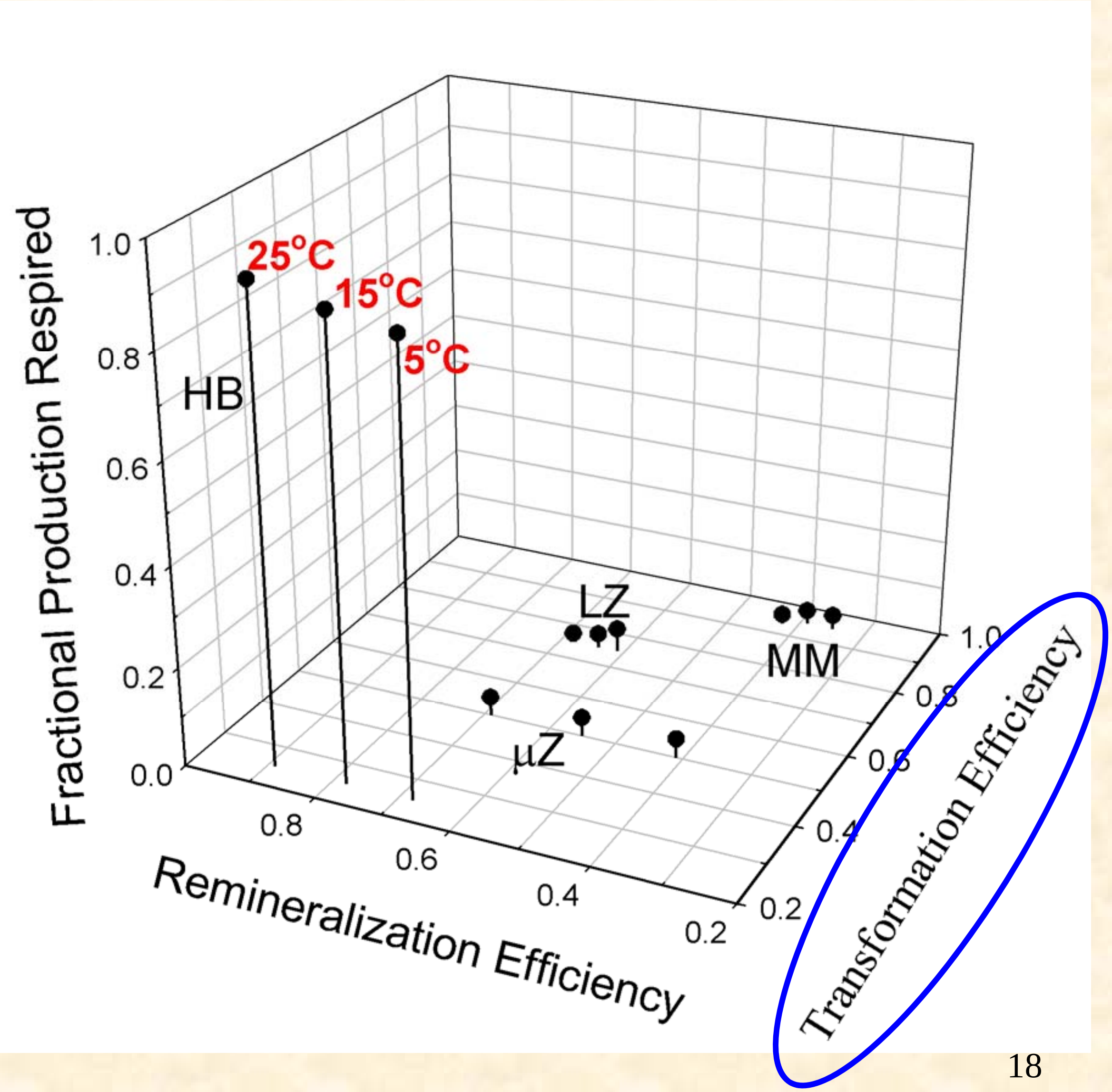
Z: *fraction of net primary production remineralized >1000 m* by each of the 4 heterotrophic plankton types, at 3 temperatures



PFTs + food web + biogeochem.

Z: fraction of net primary production remineralized >1000 m

X: transformation efficiency of food resources by organisms that lead to size increase
= ∑ efficiencies of processes leading to increased OM size

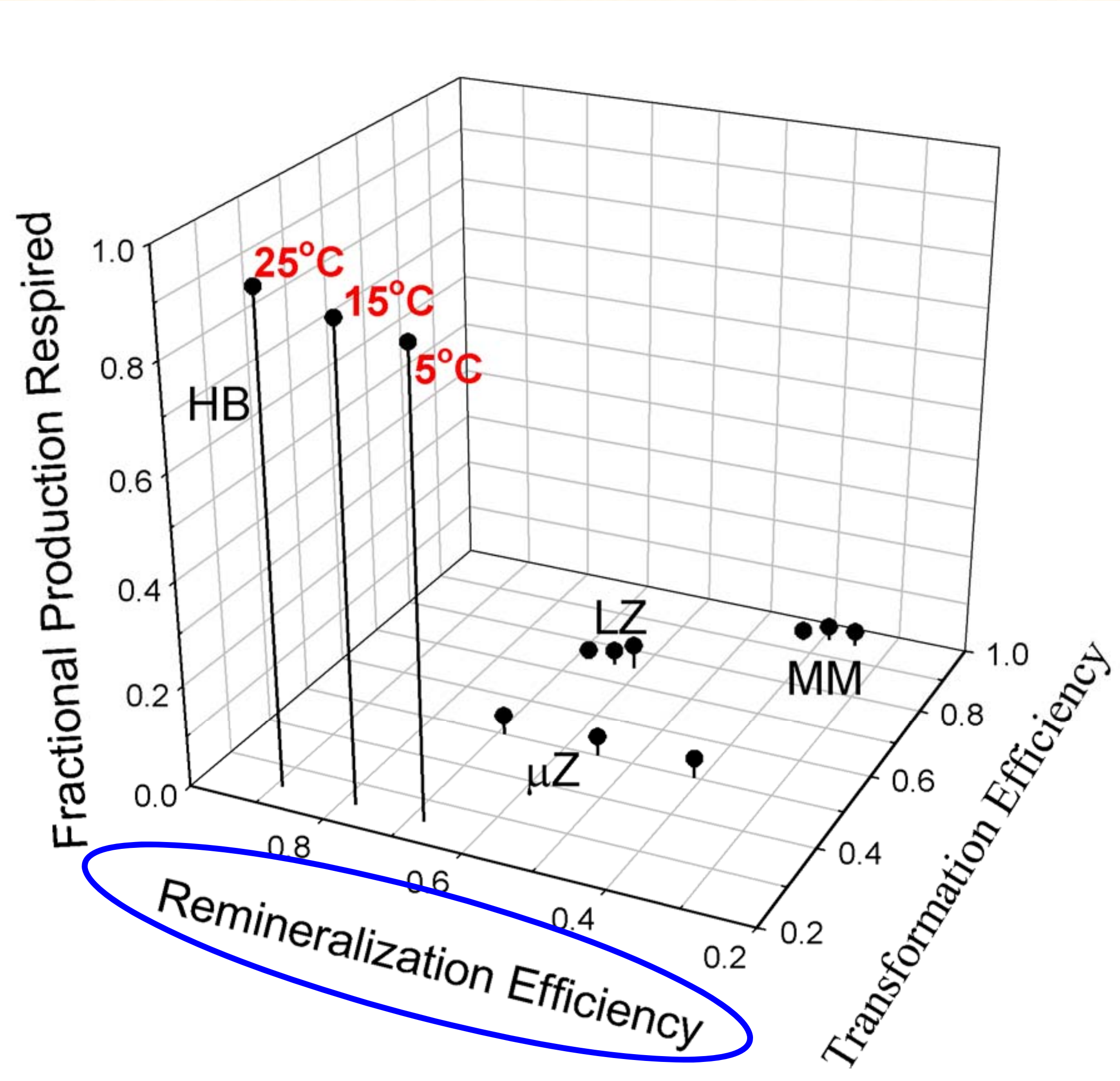


PFTs + food web + biogeochem.

Z: fraction of net primary production remineralized >1000 m

X: transformation efficiency of food resources by organisms leading to size increase

Y: *remineralization efficiency* = 1 - growth efficiency (GE)

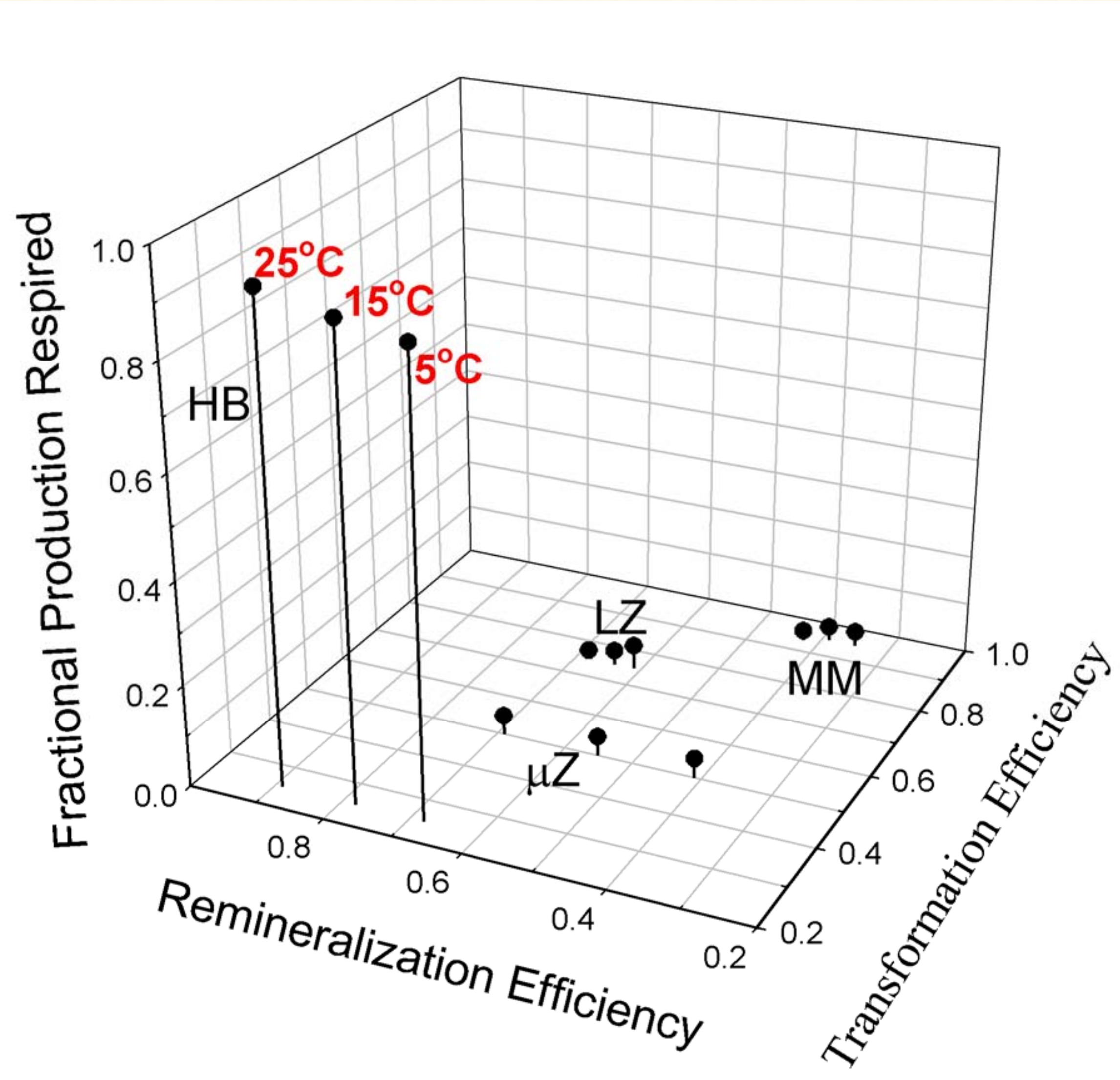


PFTs + food web + biogeochem.

Fraction of net primary prod. remineralized >1000 m by the 4 heterotrophic plankton types

- inverse function of temperature

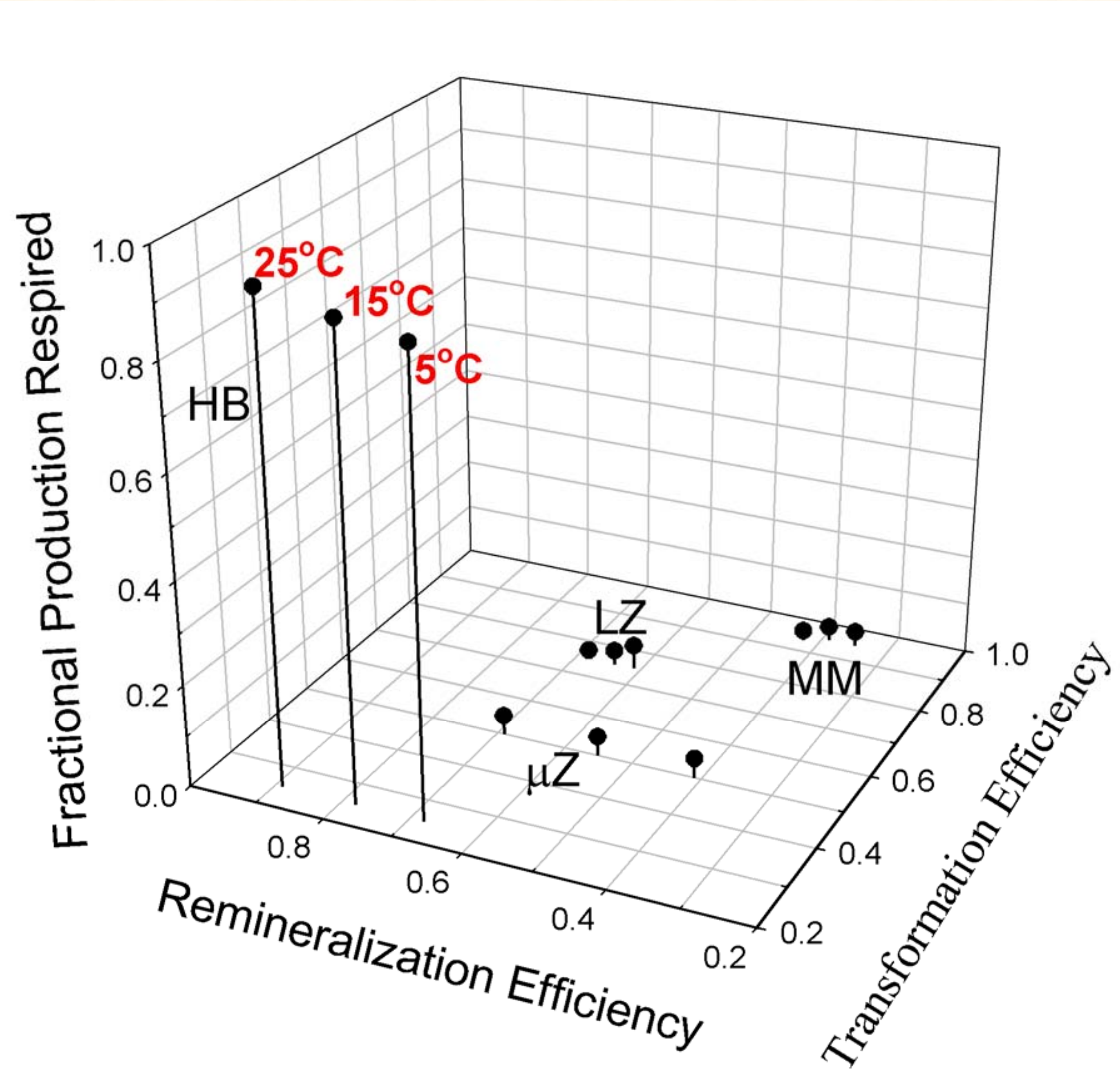
- varies coherently with the transformation and remineralization efficiencies of the plankton types



PFTs + food web + biogeochem.

Supports our idea that the new class of models should consider the interactions among:

- functional bio-diversity (PFTs)
- ecosystem functioning (X, Y)
- fluxes of elements and associated feedbacks (Z)



High CO_2 World

Upper ocean in future climate

- What about the upper ocean with higher atmospheric CO_2?
- Model predictions for the future ocean, forced with an increase in atmospheric concentrations of CO_2 until 2100 (Bopp et al. 2001, Bopp 2002)

- environment: increases in sea surface temperatures and stratification, decrease in nutrient supply to the surface and increased available light

- global decline: chlorophyll, primary production and export from the euphotic zone

- food-web structure
  - » decrease in phytoplankton cell numbers
  - » shift in phytoplankton taxa: decrease in diatoms relative to smaller phytoplankton cells

Ecosystem structure

- Consequences of model predictions (1)
- Ecosystem structure (PFTs)

- predicted reduction in primary production: decreased heterotrophic biomass in the upper ocean ⇒ favour microphagous macrozooplankton (e.g. salps), which can outcompete large zooplankton at low food concentration
- predicted shift toward smaller phytoplankton: select against large herbivorous zooplankton (consistent with predicted lower zooplankton biomass), and could select for microzooplankton
- overall result: decrease in the relative abundance of large zooplankton, and increase in the relative abundances of microzooplankton, and perhaps microphagous macrozooplankton

Food-web processes

- Consequences of model predictions (2)
- Food-web processes

- predicted generally higher water temperature: enhanced remineralization of POM and DOM
- predicted lower abundances of large zooplankton: reduced fragmentation of food into smaller particles, transfer of OM into the body masses of large organisms and production of relatively large faecal pellets
  ⇒ combined effect: contribute to reduce particle size in the upper ocean

Biogeochemical carbon fluxes

- Consequences of model predictions (3)
- Biogeochemical carbon fluxes

- predicted generally higher water temperature:
  - » reduced CO_2 solubility in seawater
  - » increased carbon respiration

$\Rightarrow$ enhanced CO_2 evasion from ocean to atmosphere

- combined with the predicted lower primary production and export from the euphotic zone and the general shift toward smaller particles in the upper ocean: lower carbon sequestration

High CO_2 World
+ Fe fertilisation

Fe fertilisation in future ocean

- Effect of Fe fertilisation of an ocean with higher atmospheric CO_2
- overall: system would shift toward larger PFTs
- rapid response of diatoms: magnitude determined by the rate of supply of silicic acid to the euphotic zone
- Fe-enhanced growth of diatoms would rapidly slow down or stop, depending on the supply of silicic acid, and be followed by the growth of non-siliceous phytoplankton

- Blooms dominated by diatoms can vertically export carbon from the euphotic zone, whereas communities dominated by other types of plankton tend to recycle and retain carbon in the upper ocean

Initial Fe fertilization

- Net result of the initial Fe fertilization: shift toward larger PFTs and more generally larger particles, and storage of some atmospheric carbon in the upper ocean (not sequestration, except under specific physical conditions, e.g. deep subduction, eddies)
- Upon termination of fertilization, the upper ocean would likely revert back, within decades, to the condition described in previous slides for ocean with higher atmospheric CO_2 but without Fe fertilization
- In order to keep in the upper ocean the carbon initially stored there, Fe fertilization must be continued indefinitely without gaining additional storage above the value resulting from the initial fertilization

Carbon sequestration

- Effect of continued Fe fertilization on C sequestration?

- present results of short Fe fertilizations do not provide evidence that the growth of diatoms caused by Fe addition is accompanied or followed by much C export from the euphotic zone, and consequently sequestration

- even if the pelagic food web shifted toward larger PFTs
  - » increased temperature would enhance carbon remineralization in the upper ocean
  - » increased stratification could impede the replenishment of silicic acid in the euphotic zone

- Combined factors could constrain carbon sequestration in Fe-fertilized regions, except in areas of the World Ocean were deep subduction could carry biogenic carbon downwards to sequestration depths

Studies needed to resolve present uncertainties

Studies needed: first step

- First step in approaching the upper ocean as a whole

- to assemble and synthesize the existing information, with special attention to the mesopelagic layer
- international programs have usually focused on either the euphotic zone or the deep ocean, with little attention to the mesopelagic layer

- Simultaneously and as part of the first step

- development of models that integrate functional biodiversity, ecosystem functioning, and the fluxes of elements and associated feedbacks in the upper ocean
- ongoing efforts in that direction show that developing models of the new class will require well-organized interactions between modelers and data synthesizers

Studies needed: second step

- Second step

- to use the available models to identify gaps in knowledge about the upper ocean, and use the new observations to improve the models, in a continuing interactive mode
- as the models reduce uncertainties and improve our predictive capabilities: used to provide more robust predictions on the effects of higher CO_2 concentrations and sequestration strategies in the upper ocean

- Success of this second step is crucially dependent on the existence of an international program dedicated to the upper ocean as a whole: within the context of the Earth System Science Partnership (which includes IGBP II), e.g. IMBER

Studies needed: conclusion

- On-going development of models to assess the role of climate feedback on ocean ecosystems and biogeochemistry

- necessitates the reconsideration of the distinction between the euphotic zone and the underlying waters (above the permanent pycnocline)
- in an Earth-System integration, where feedbacks and indirect effects are important and are often the dominant drivers, disciplinary distinctions between functional biodiversity, ecosystem functioning and the fluxes of elements and associated feedbacks are no longer appropriate
- programs, field studies and models must integrate these components over the whole upper ocean

Thank you for your attention