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Belastungsfähigkeit des Ozeans: Grenzen der Zumutbarkeit?

Hans O. Pörtner



„Contaminating factors“

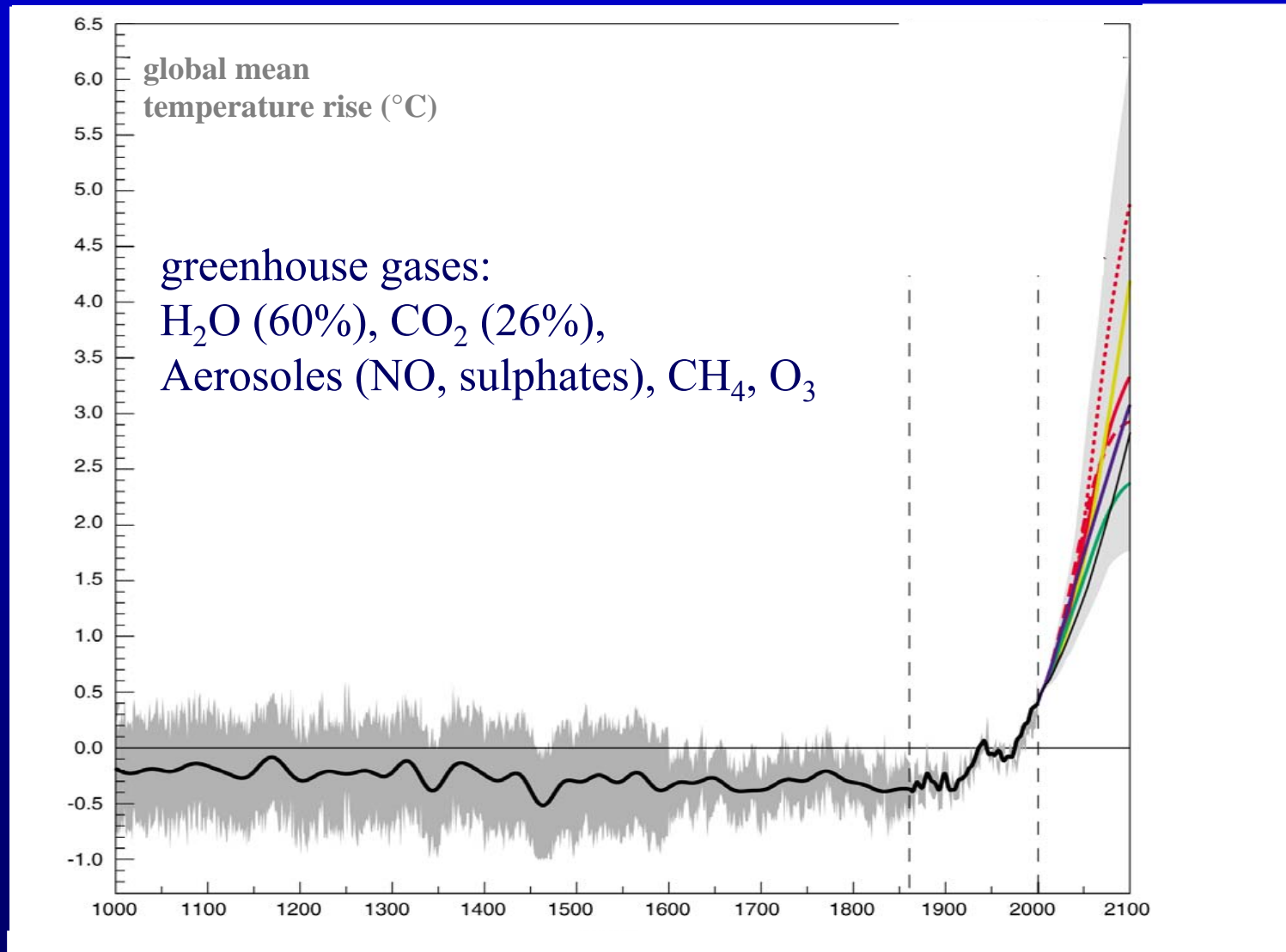
„old, but still persisting“

- Eutrophication
- Hypoxia (!)
- Heavy metals
- Human activities: **Overfishing (!)**

„new“

- Temperature
- CO₂

Interdependence of CO₂ and temperature ...the climate is changing → ocean warming trends



Source: IPCC Third Assessment Report, 2001

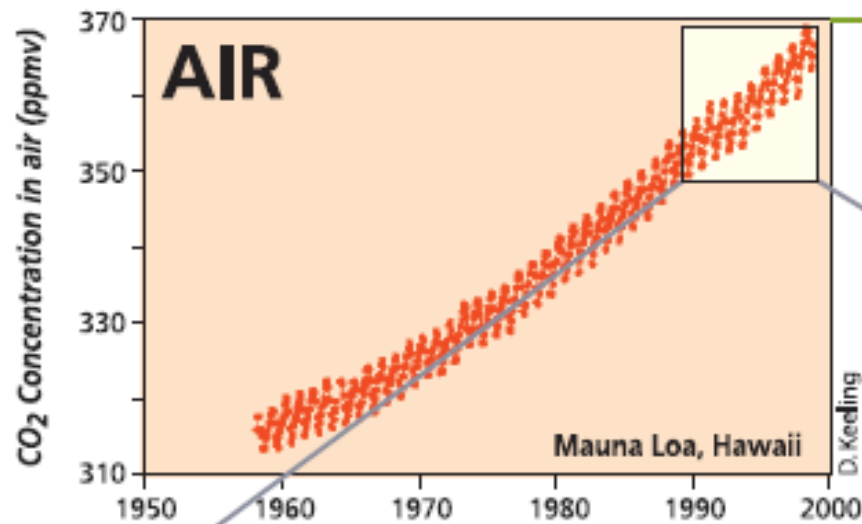
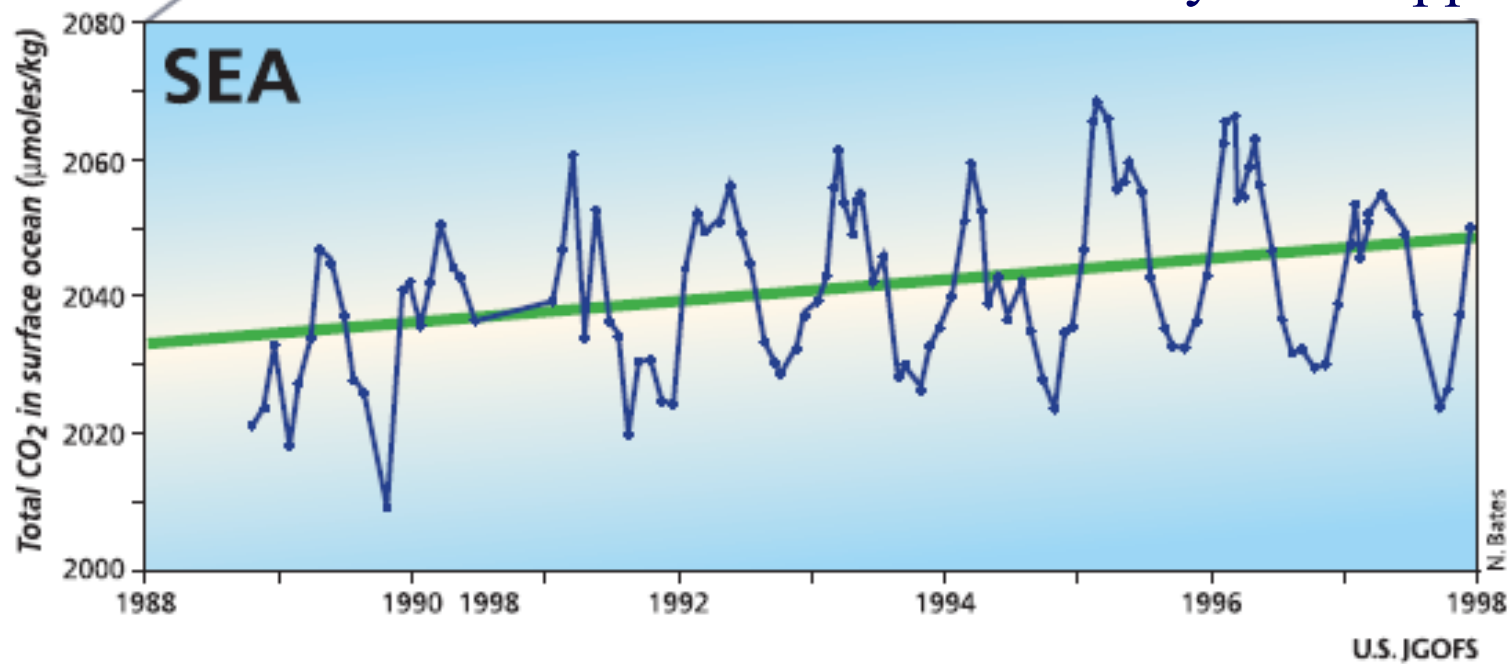
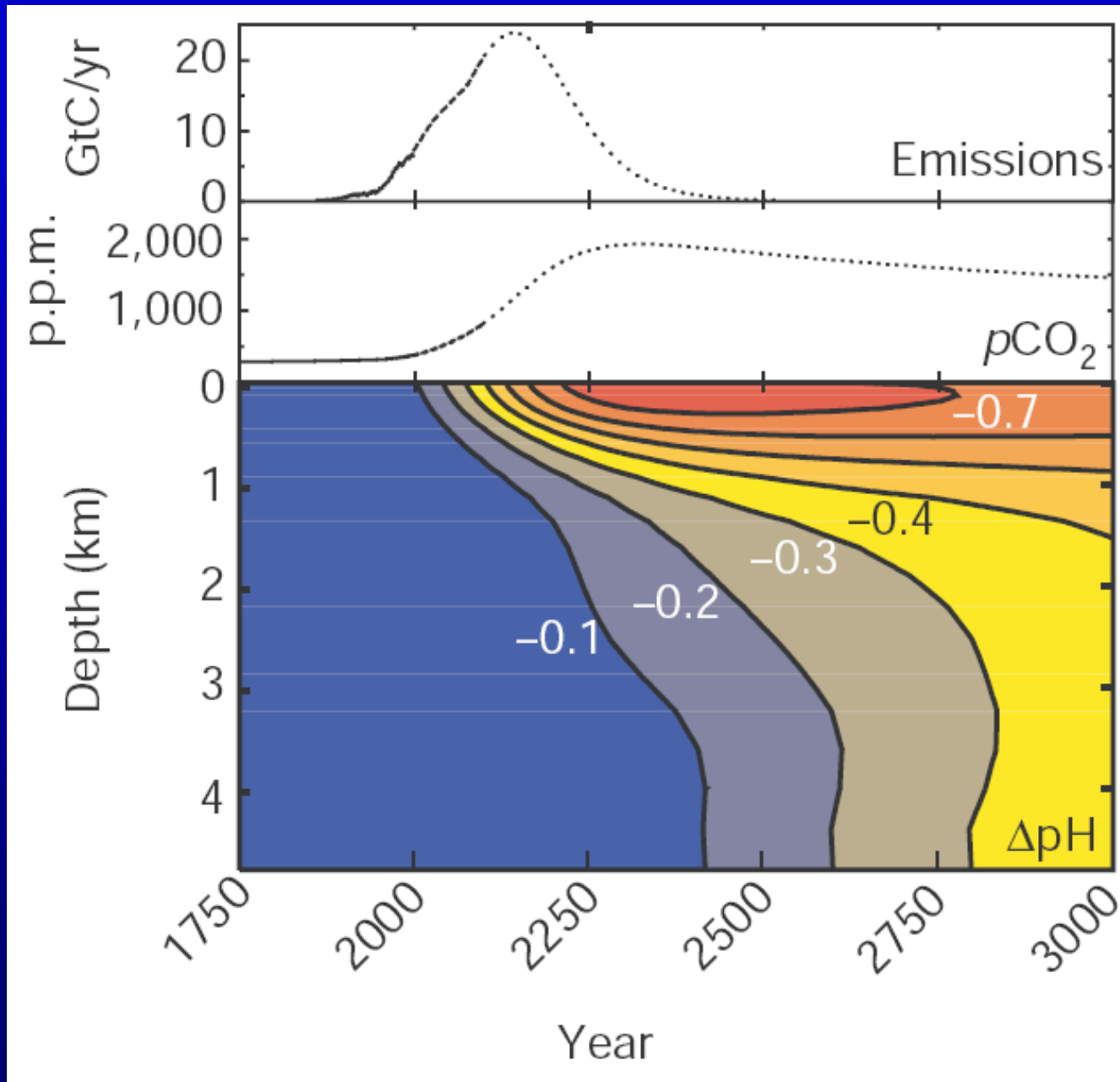


Figure 1. Atmospheric and oceanic CO₂ increases. Courtesy C.D. Keeling and N. Bates; available from U.S. JGOFS web site (www1.whoi.edu/general_info/gallery_modeling/slide7.html).

CO₂ in air:
pre-industrial: 280 ppm
today: ~ 380 ppm





Future scenario:
fossil fuel reserve:
5000 Gto C →
18 000 Gto CO₂

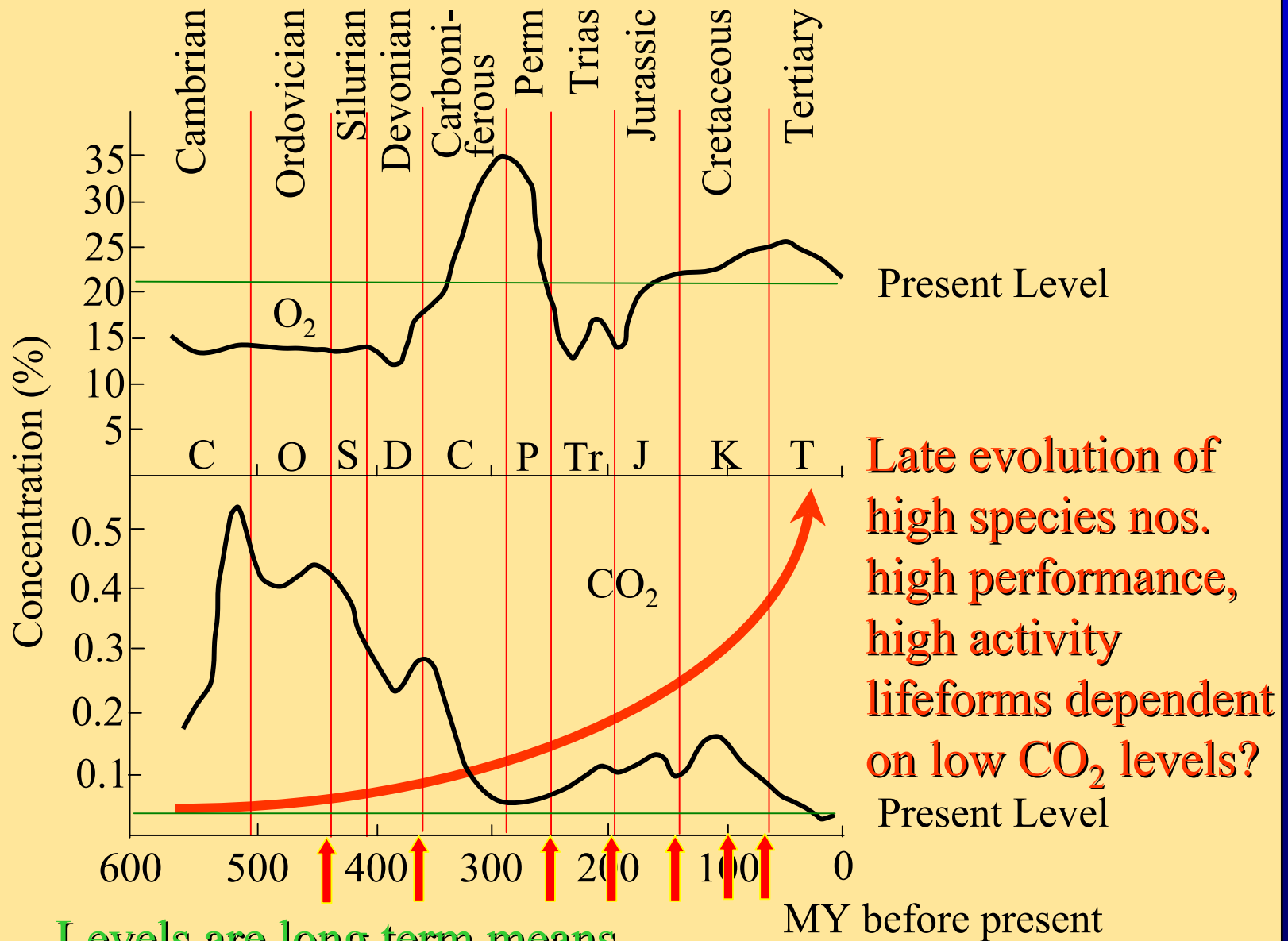
all CO₂ released
into atmosphere:

1900 ppm at 2250

ocean pH:
 $\Delta = -0.77$ units

Role of CO₂ in
ocean biology?
Harmful for
marine life?

Atmospheric O₂ and CO₂ levels in earth history



↑ important mass extinction periods

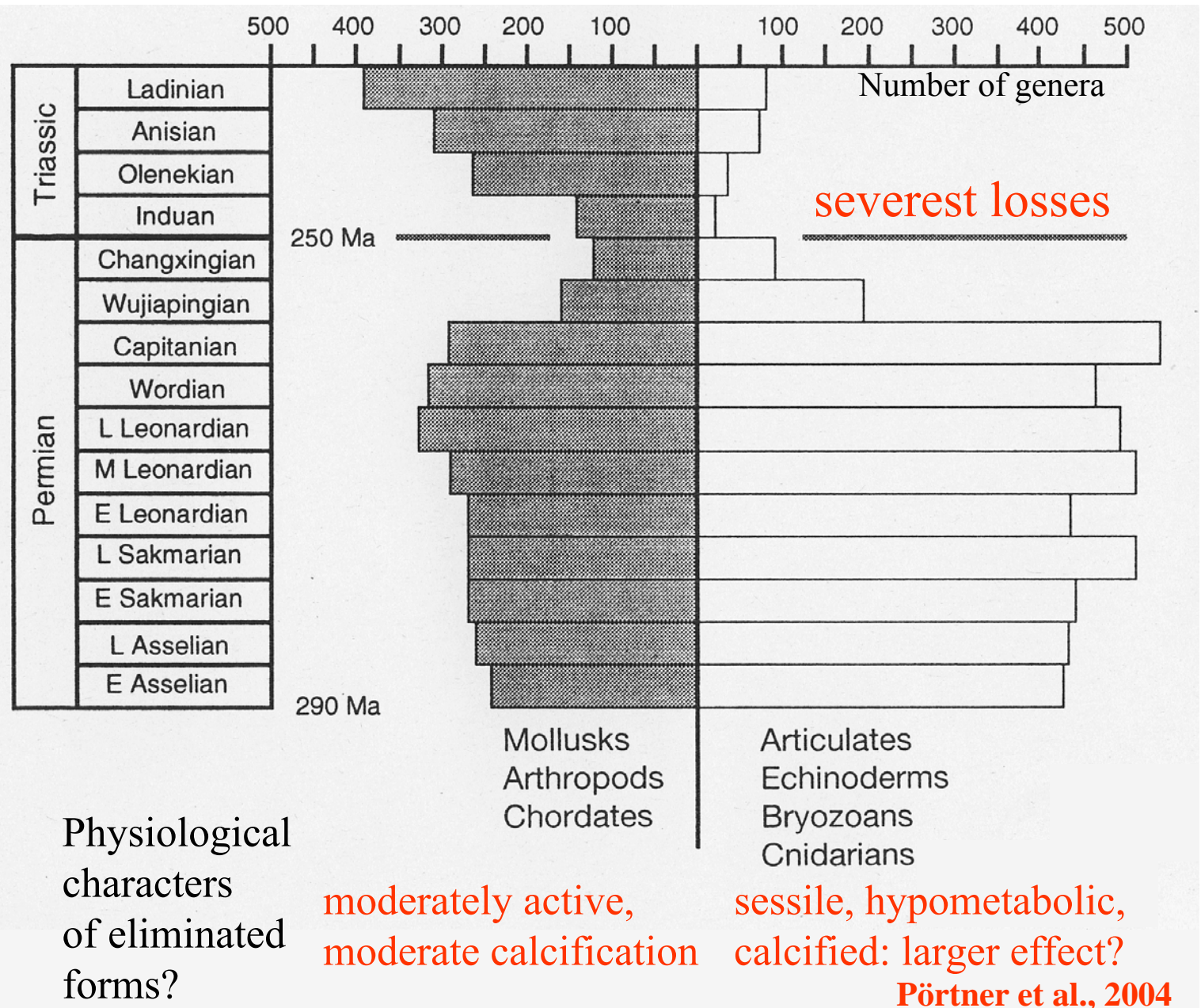
Levels are long term means,
did short term oscillations occur?

Permian-Triassic mass extinctions

Loss of marine invertebrate genera due to CO₂?

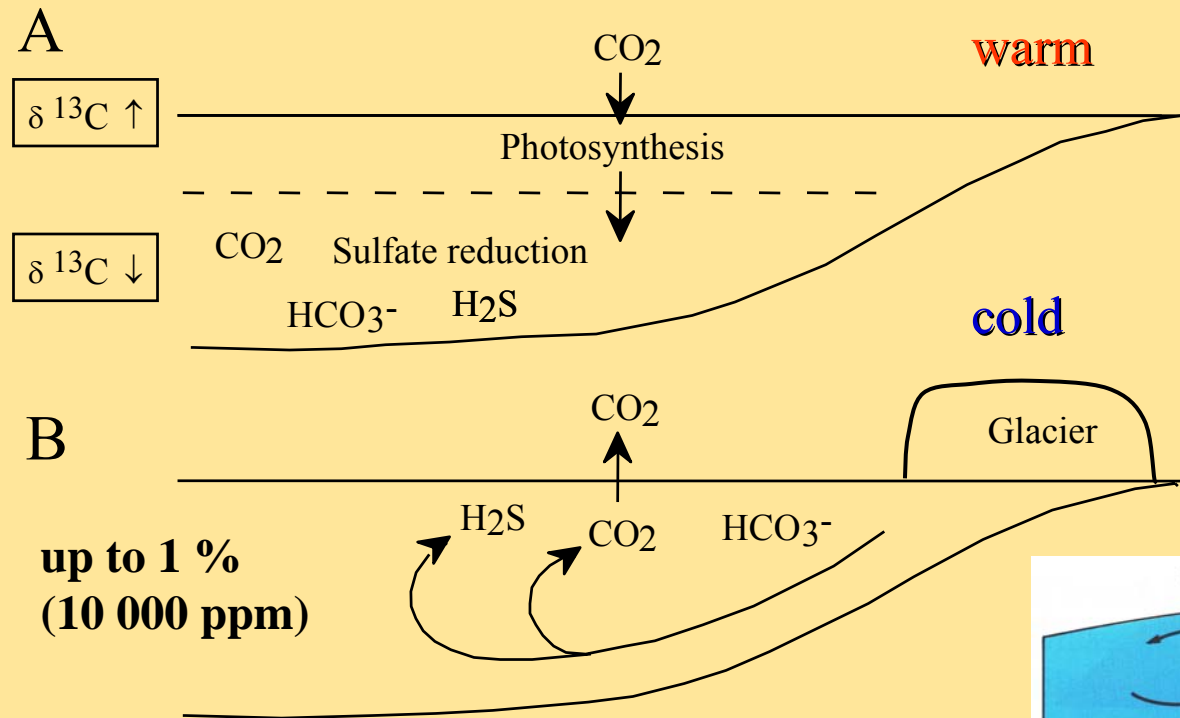
Obs: highest activity forms were not yet existent!!

CO₂ limitations relevant in evolution?



after Knoll *et al.*, 1996

CO₂ „experiments“ in earth history: Water CO₂ oscillations in Perm / Trias mass extinctions

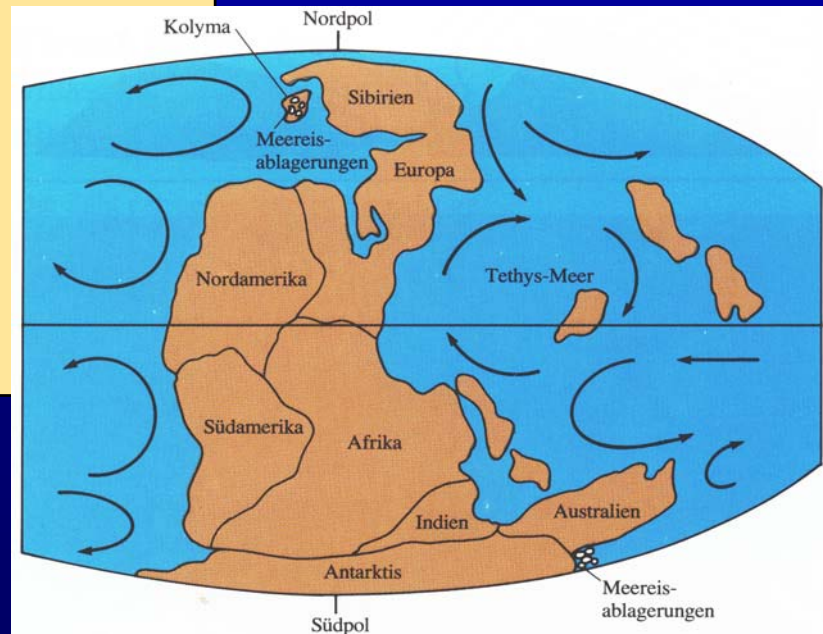


redrawn after Knoll *et al.*, 1996

Preconditions in
Perm/Trias:

No surface to deep
ocean currents

Pangaea as a super-
continent



Parallel oscillations of
temperature and oxygen levels

CO₂ critical in mass extinctions?

CO₂ as a natural factor nowadays, in areas with marine life:

- constantly low in most of the pelagic zones of the sea (Pco₂ < 500 ppm atmospheric pressure).
- fluctuates when
 - volcanic emissions occur in the sea (~ 80 000 ppm).
 - excessive respiration occurs in confined areas
 - hypoxic: rock-pools, sandy sediments, oxygen minimum layers
 - anoxic: marine sediments, stratified bottom waters (up to 16 000 ppm)

What makes organisms susceptible to CO₂?
Sensitivities differ between organisms, why?
Which levels are critical?

Background knowledge to be provided by
ecological and evolutionary physiology

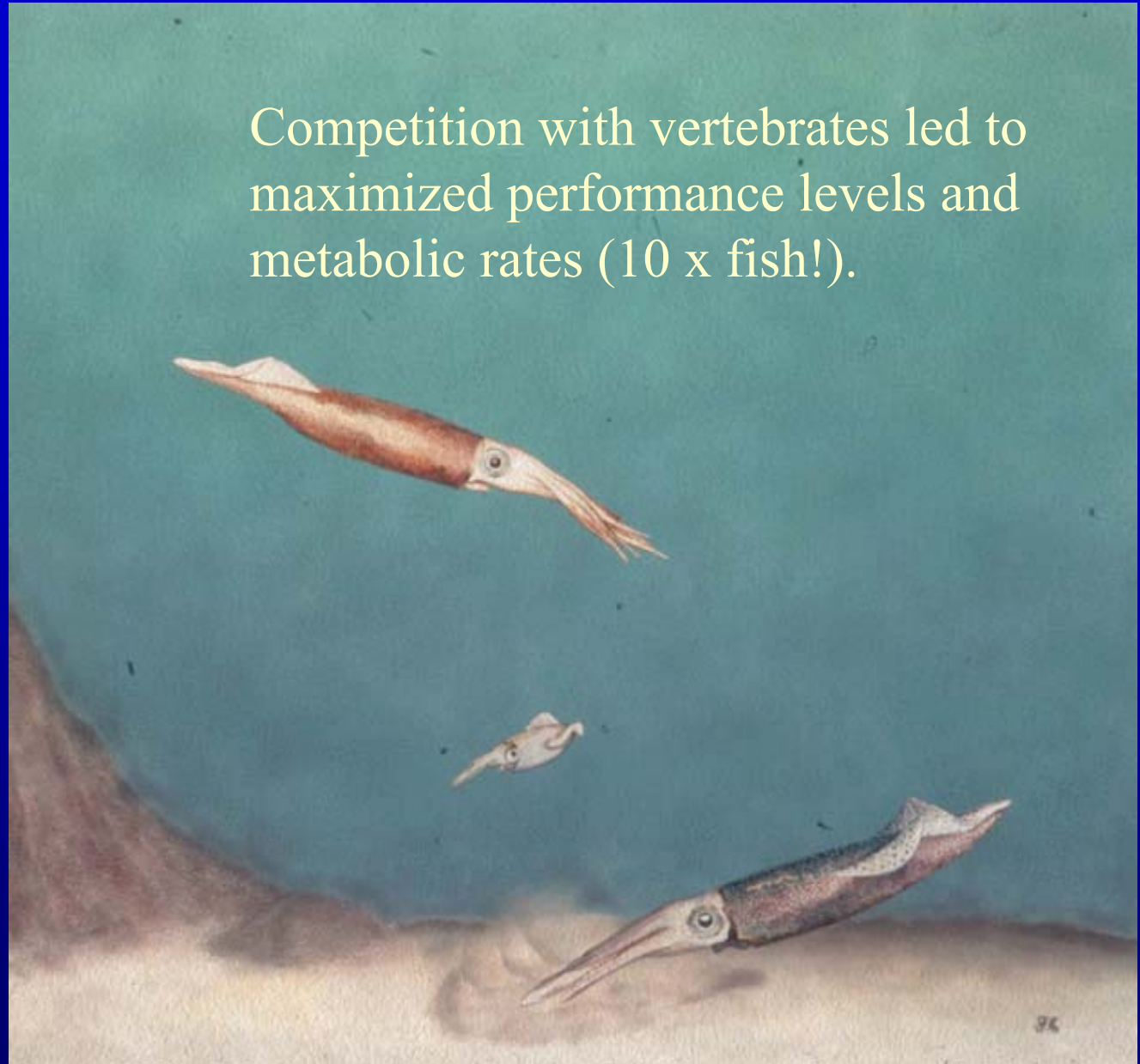
Acute effects of high
CO₂ levels, e.g. on
squid, elite athletes
of the ocean:

Illex illecebrosus

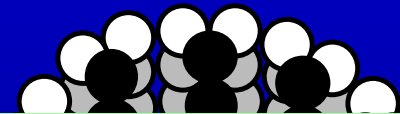
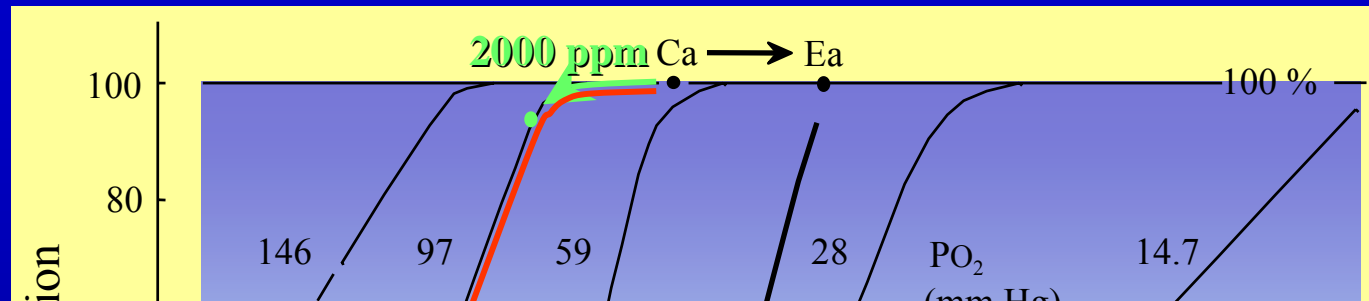
Lolliguncula brevis

Loligo pealei

Competition with vertebrates led to
maximized performance levels and
metabolic rates (10 x fish!).

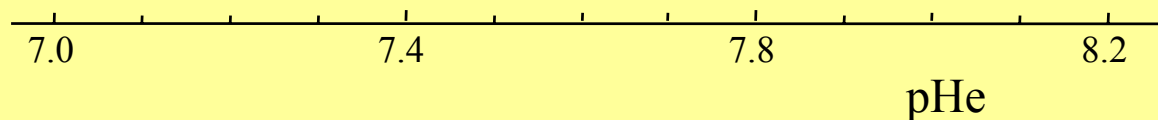


Squid haemocyanin function during exercise, pH / saturation analysis: extreme pH sensitivity



These short term impacts are not important during ocean invasion of anthropogenic CO₂ but may become important during ocean sequestration.

What are the long term effects of CO₂?



- $\Delta \text{blood pH} > 0.15$ ($\Delta P_{\text{CO}_2} > 2\,000 \text{ ppm}$) \rightarrow reduced scope for activity (sublethal).
- $\Delta \text{blood pH} > 0.25$ ($\Delta P_{\text{CO}_2} > 6\,500 \text{ ppm}$) \rightarrow asphyxiation (acutely lethal).

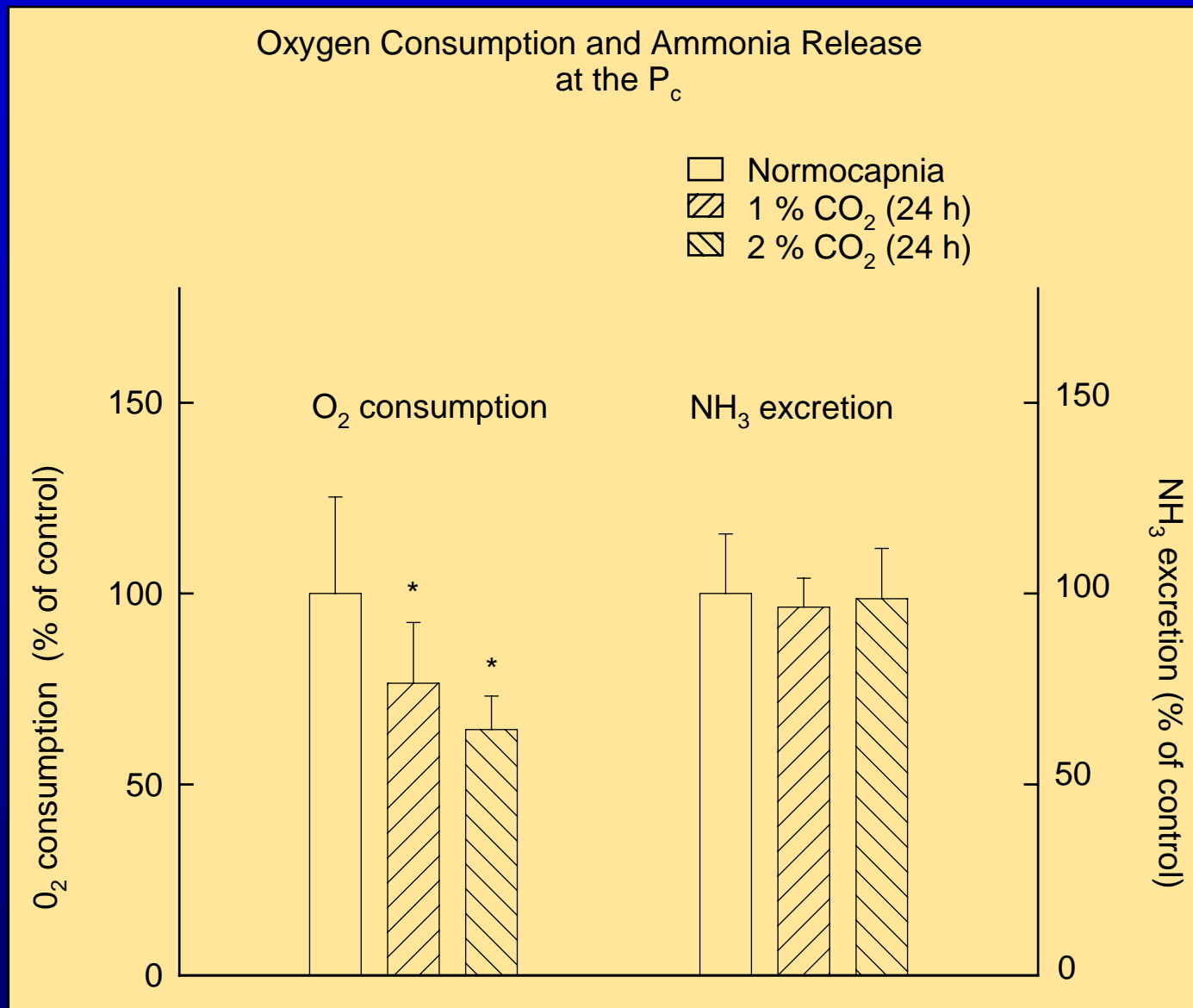
Long term effects
in animal species
tolerant to CO₂
oscillations?
Sipunculus nudus



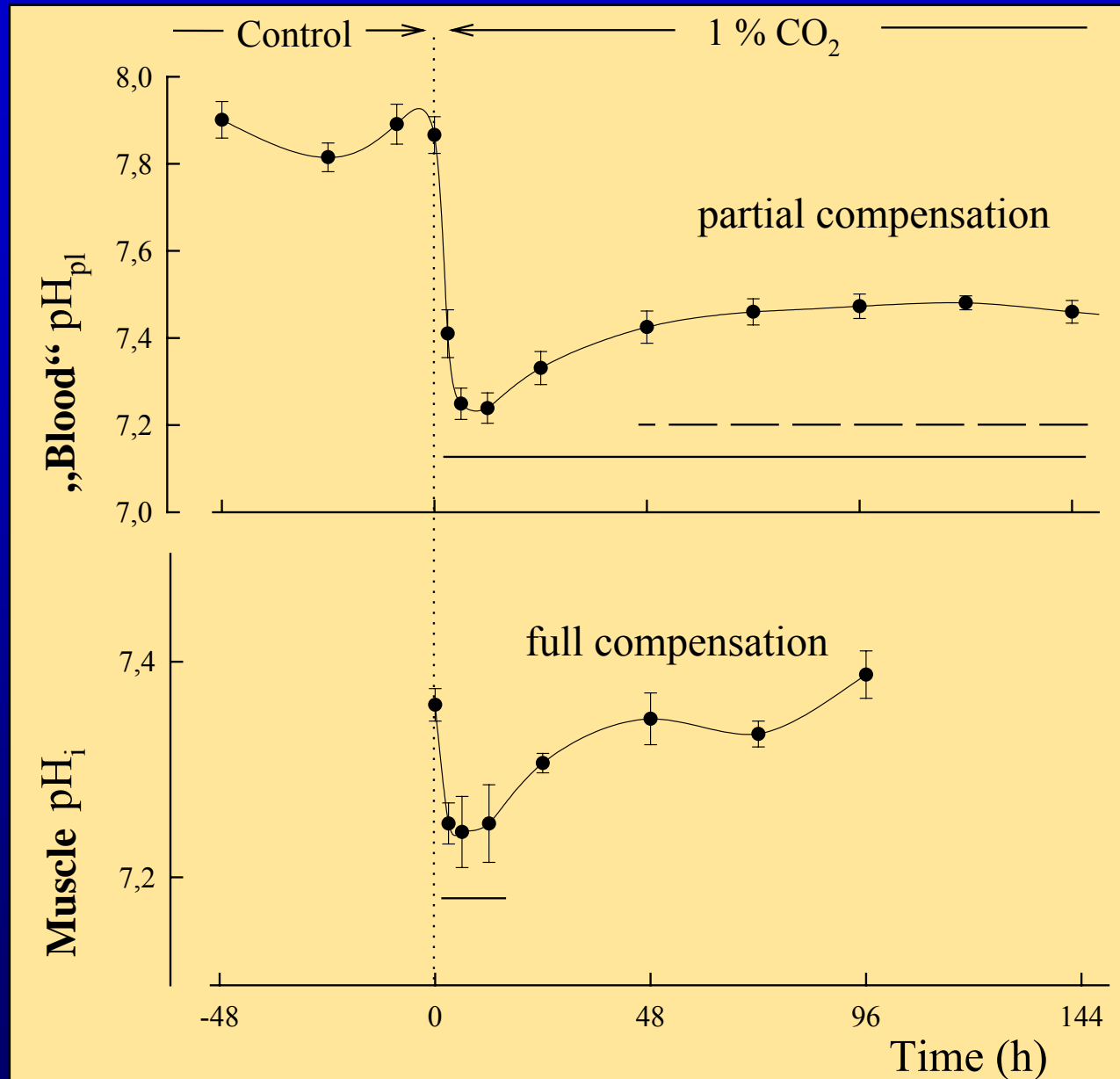
eurybathic:
found between 0 and
2300 m depths

Oxygen
consumption
and ammonia
excretion
in *S. nudus*
under
hypercapnia:

.....saving
energy, but
how?



CO₂ induced metabolic depression: physiological background



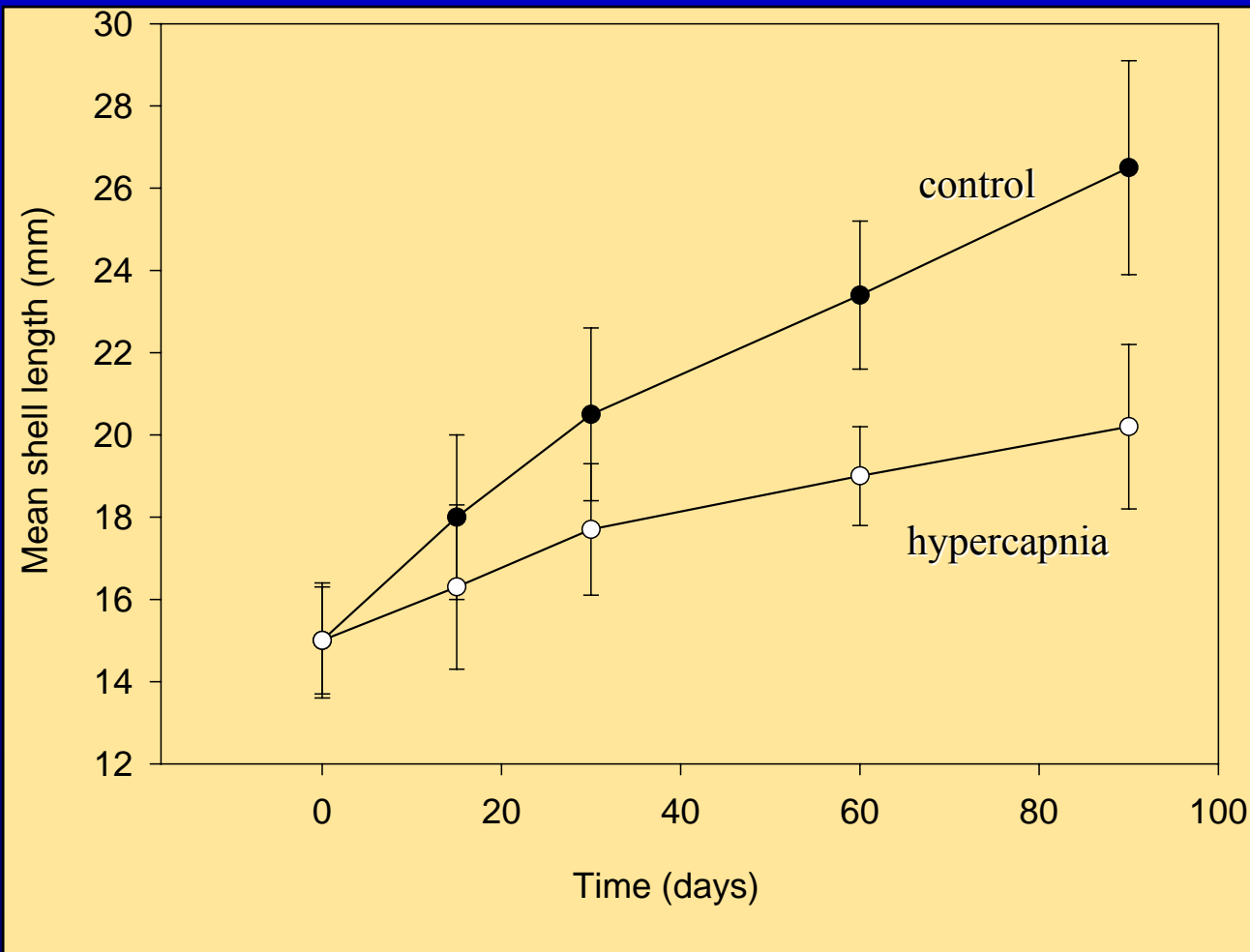
S. nudus:
Extra- and
intracellular
acid-base status

Only partial
compensation of
extracellular
acidosis causing
metabolic
depression:
A typical finding
in invertebrates!

Metabolic depression and 55 % (!) growth reduction in mussels
(*Mytilus galloprovincialis*) under CO₂
(permanent extracellular acidosis!!)

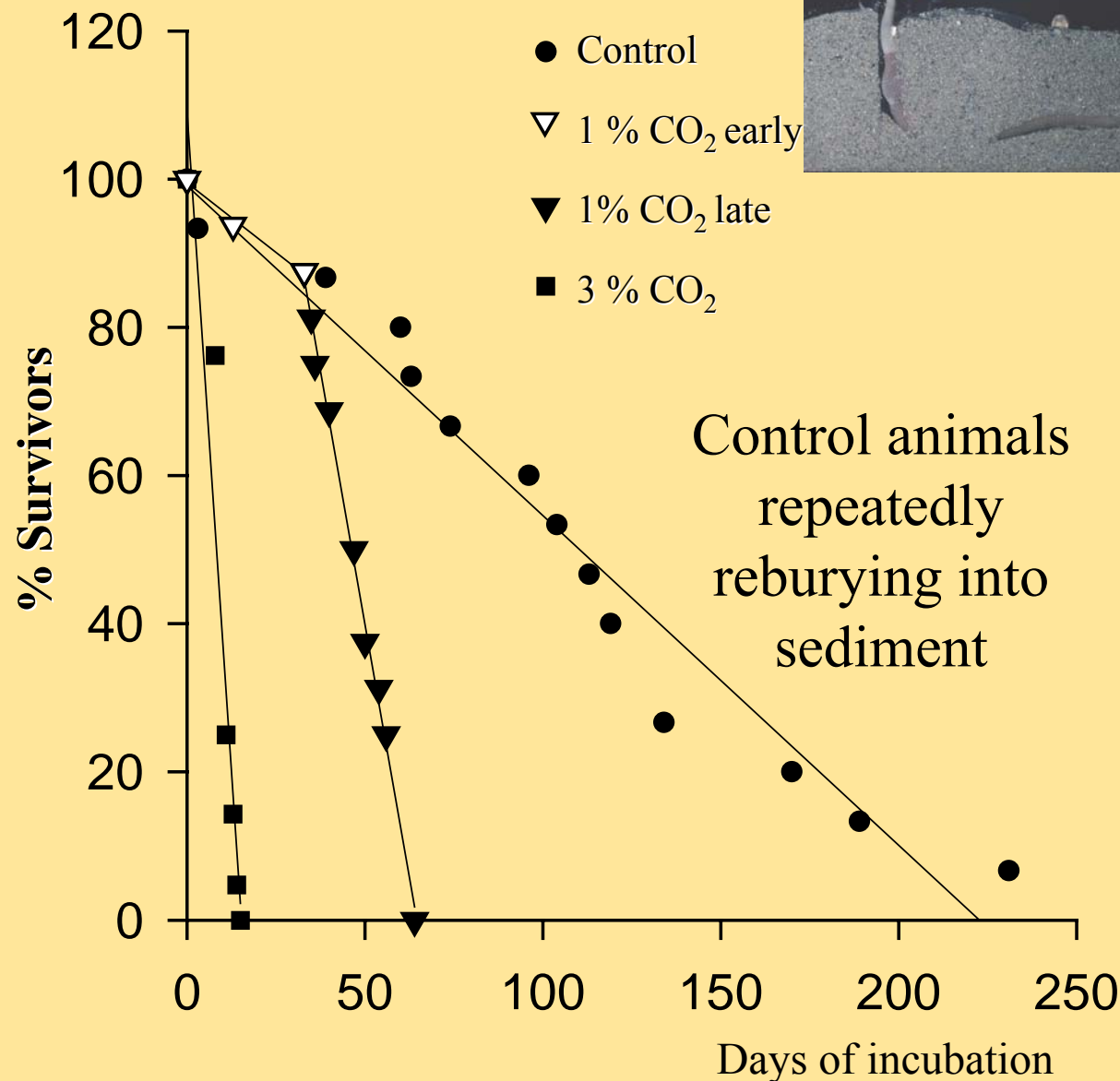


© M.S. Calle



Water pH 7.3:
Maximum pH
drop as expected
from business as
usual scenarios by
2300
(Caldeira and
Wickett, 2003)

Michailidis et al. (2004)



However, tolerance is time limited:
Delayed onset of enhanced mortality during long term „disturbed“ maintenance under 1% CO₂ in *S. nudus*

- no decrease in body energy stores
- behavioral incapacitation involved

Further findings

Shirayama and colleagues:

- long term reduction of growth, survival, and reproduction in Pacific shallow water sea urchins and snails at 550 ppm CO₂,
= IPCC stabilization scenario!!!
- reduced fertilization of sea urchin eggs at CO₂ levels beyond 1000 ppm.

Rates of higher functions are reduced under moderate CO₂ elevations. Effects set in early in invertebrates.

Uncompensated acidosis and metabolic depression in several invertebrates

...contributing to
lower resistance
and enhanced
mortality?

Sepia officinalis



Mytilus

galloprovincialis



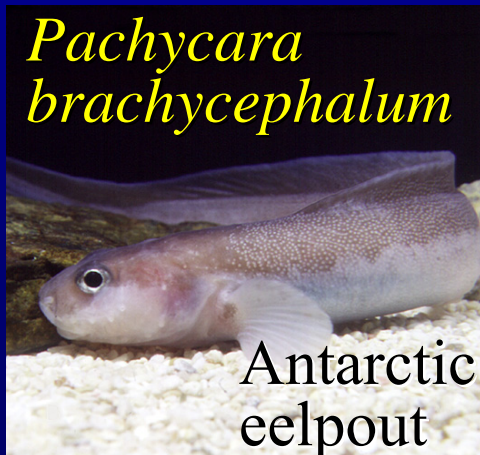
Sipunculus nudus



Compensated acidosis

and, therefore, no metabolic depression in most fish
...a reason for enhanced resistance to high CO₂?

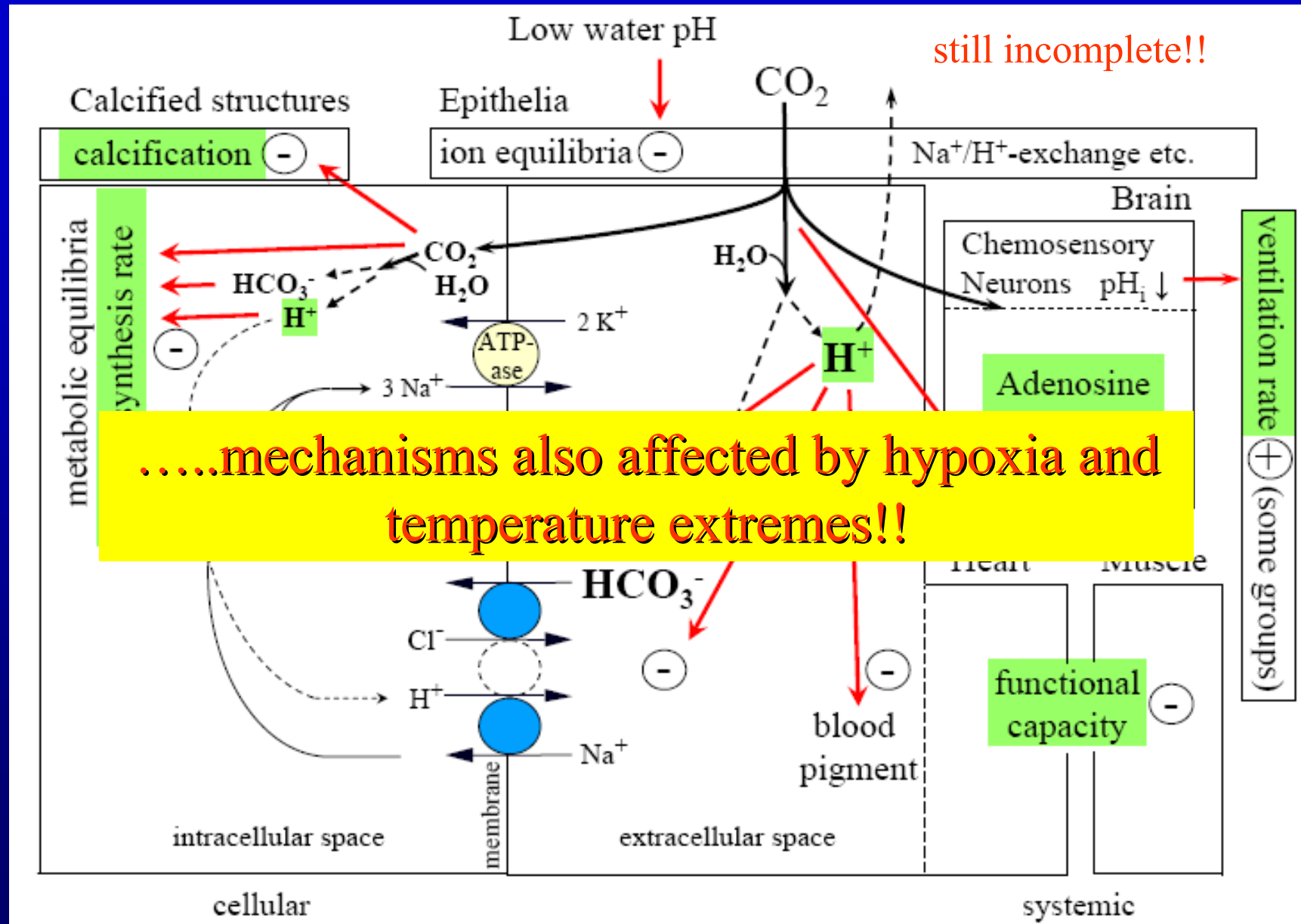
*Pachycara
brachycephalum*



Atlantic
cod

Heisler, 1986, Larsen et al. 1997, Ishimatsu et al., 2004

CO₂ effects: complex physiological background shifting whole animal functioning





Temperature, hypoxia, CO₂ interactions?

A recent hypothesis:

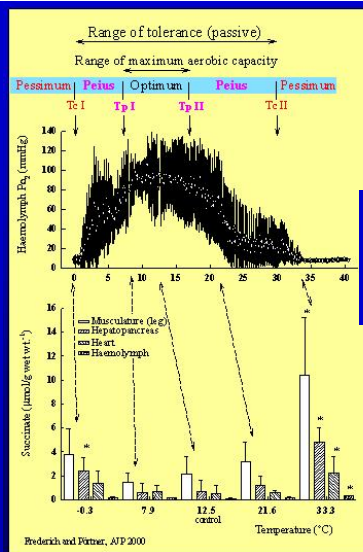
The first level of thermal intolerance at low and high temperature extremes in METAZOA is a loss in whole organism metabolic flexibility (aerobic scope), a unifying principle in ectotherms (!) and endotherms (!?).

Am. J. Physiol 279, R1531-R1538, 2000.

Naturw. 88, 137-146, 2001

Am. J. Physiol. 283, R1254- R1262, 2002

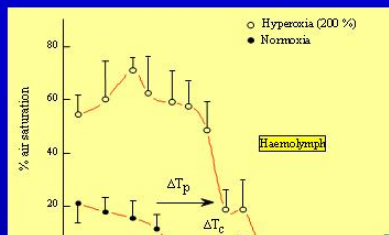
Comp. Biochem. Physiol. 132A, 739-761, 2002



Shelford's law of tolerance
applicable to thermal limitations?



Temperate crustacean,
Maja squinado

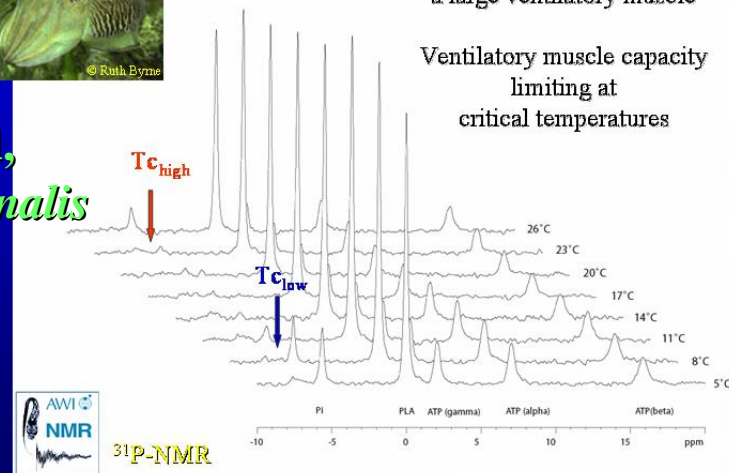


EXAMPLES

Temperate
cephalopod,
Sepia officinalis



Oxygen limitation of
thermal tolerance in the
Antarctic bivalve,
Laternula elliptica
eliminated by hyperoxia?

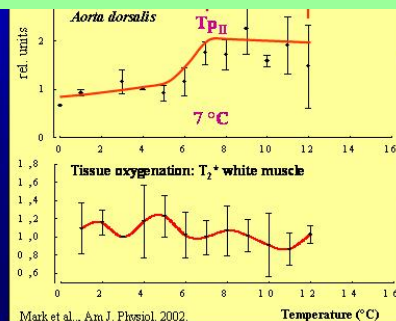


Cephalopod mantle tissue,
a large ventilatory muscle

Ventilatory muscle capacity
limiting at
critical temperatures

O_2 dependent temperature limits verified across phyla:
annelids, sipunculids, molluscs (bivalves, cephalopods),
crustaceans, fish and some air breathers, limited evidence in
endotherms incl. man.

.....interaction with CO_2 effects?



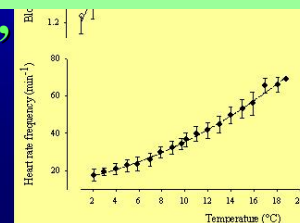
North Sea cephalopod, *Zoarces viviparus*
Do peius temperatures exist in fish?

- ➔ Peius temperatures reflect limited capacity of the circulatory system in fish.
- ➔ Beyond T_{pII} aerobic scope falls at rising oxygen demand



AWI ECOPHYSIOLOGY

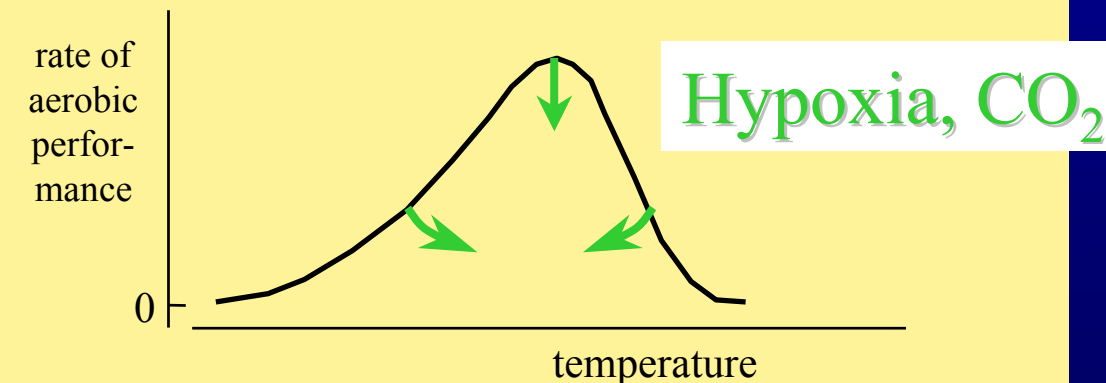
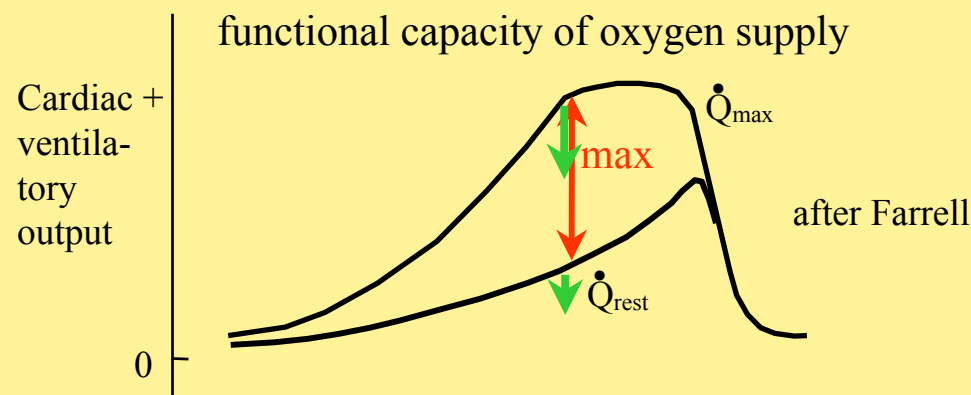
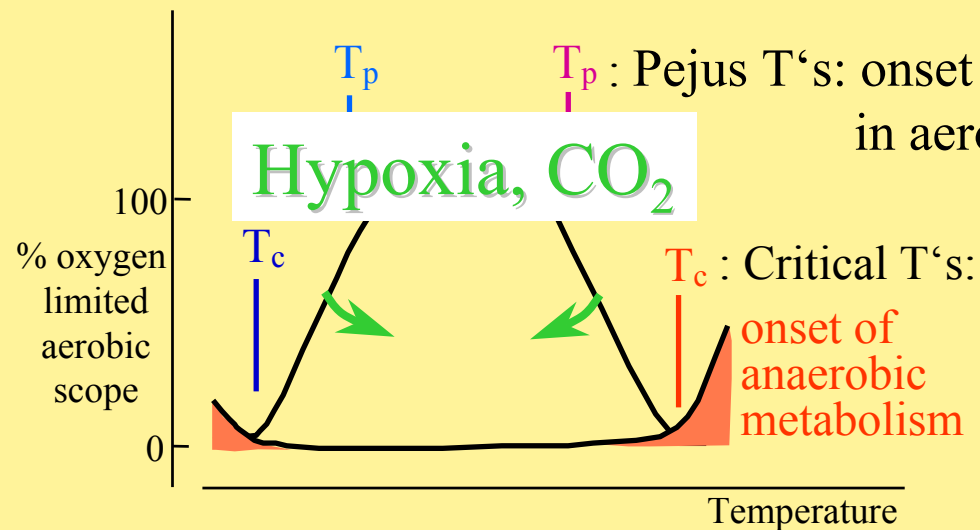
temperate zoarcids,
Pachycara brachycephalum,
Zoarces viviparus



Lannig et al. 2003

AWI ECOPHYSIOLOGY

AWI ECOPHYSIOLOGY



Aerobic scope and performance are maximal at the upper pejus temperature.

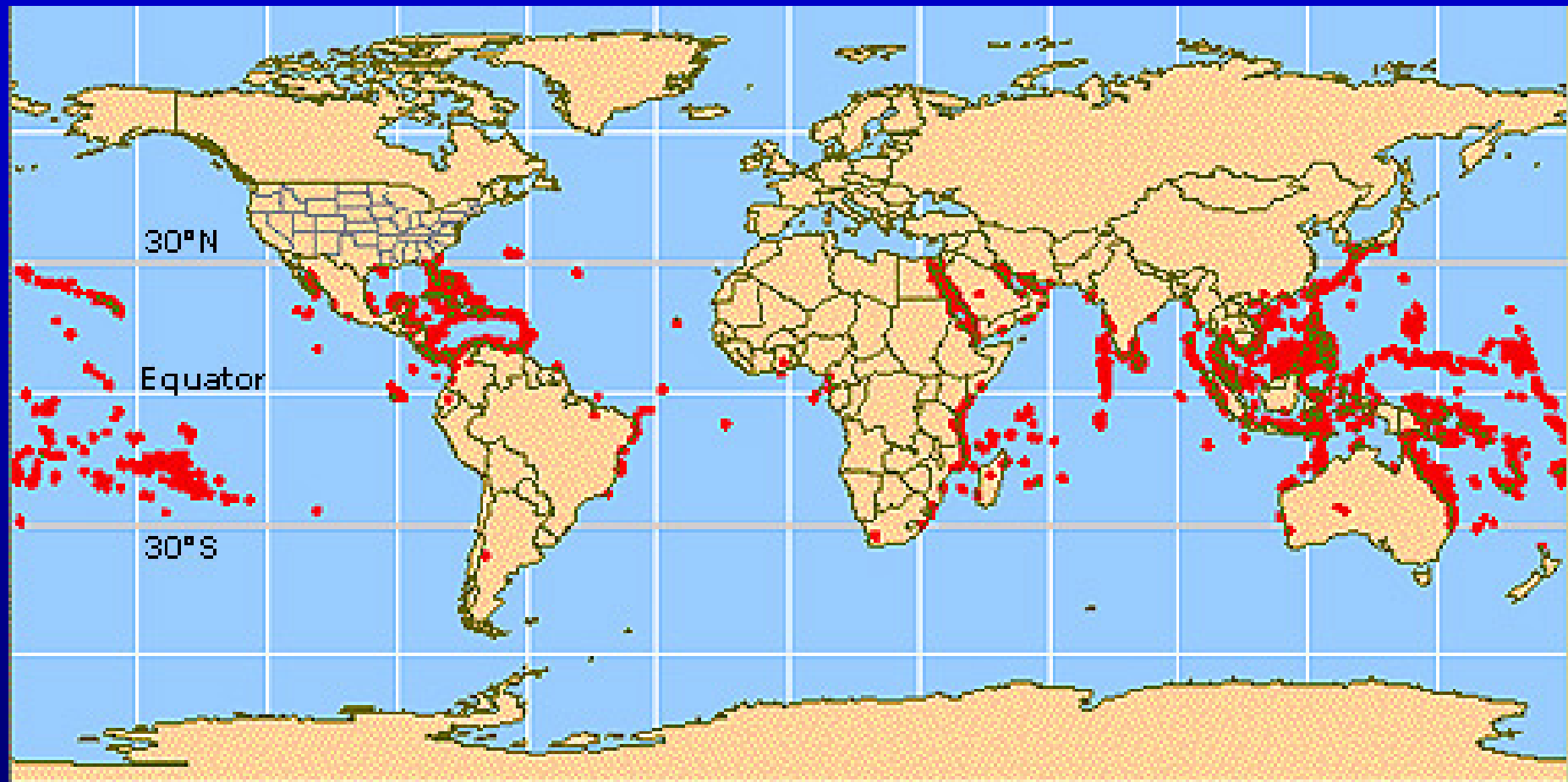
Hypoxia, CO_2 and thermal extremes act synergistically via the same physiological mechanisms!!

after Frederick and Pörtner 2000, Mark et al. 2002
Pörtner et al. 2000, 2004, Pörtner 2001, 2002,

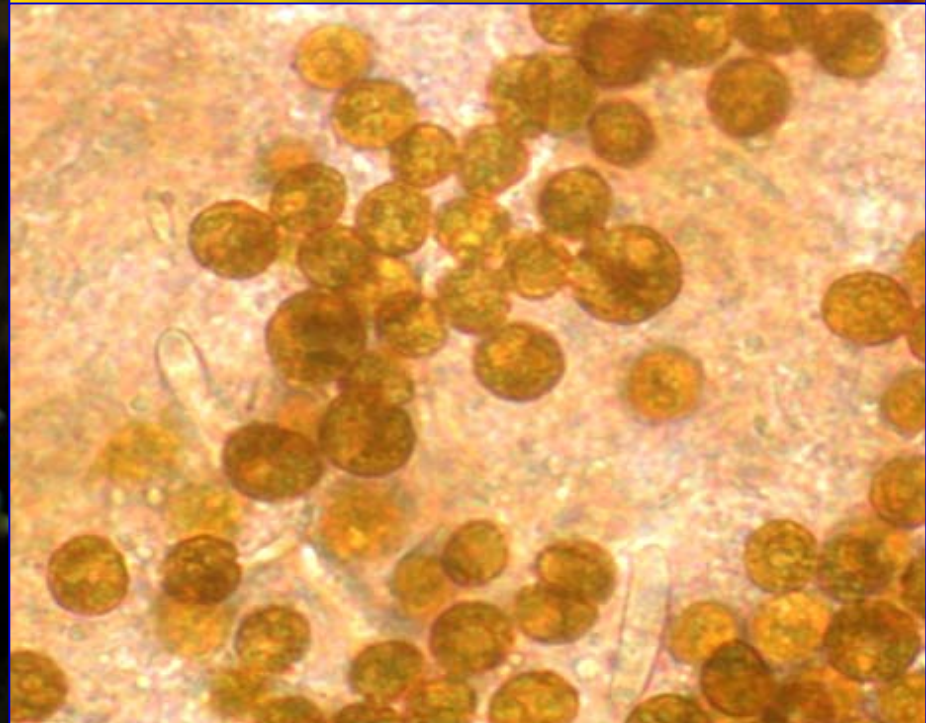
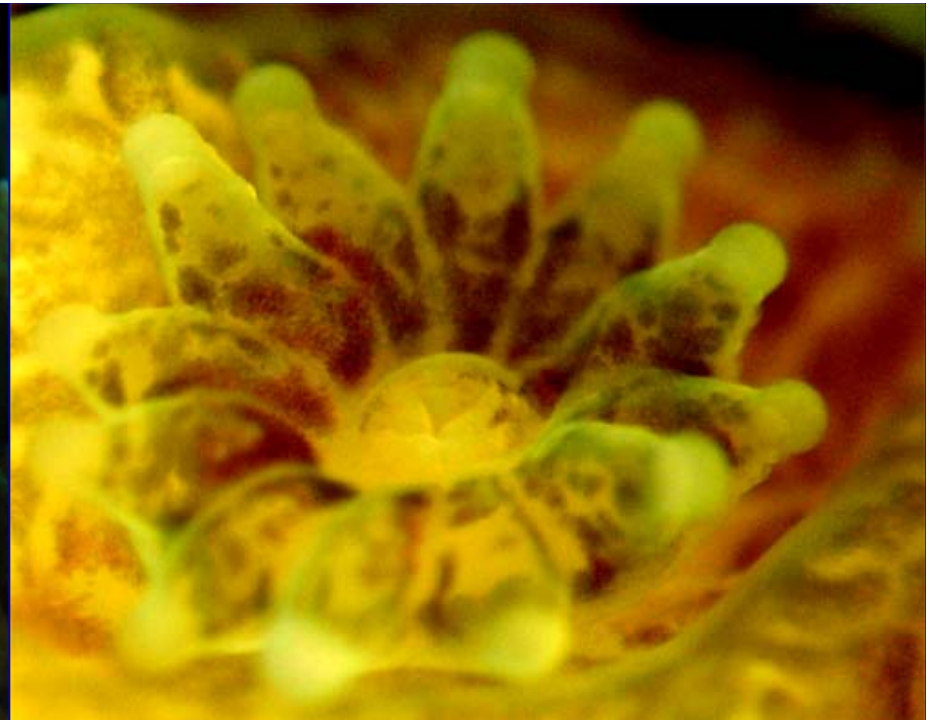
Synergistic effects of CO₂, temperature and hypoxia: perspectives

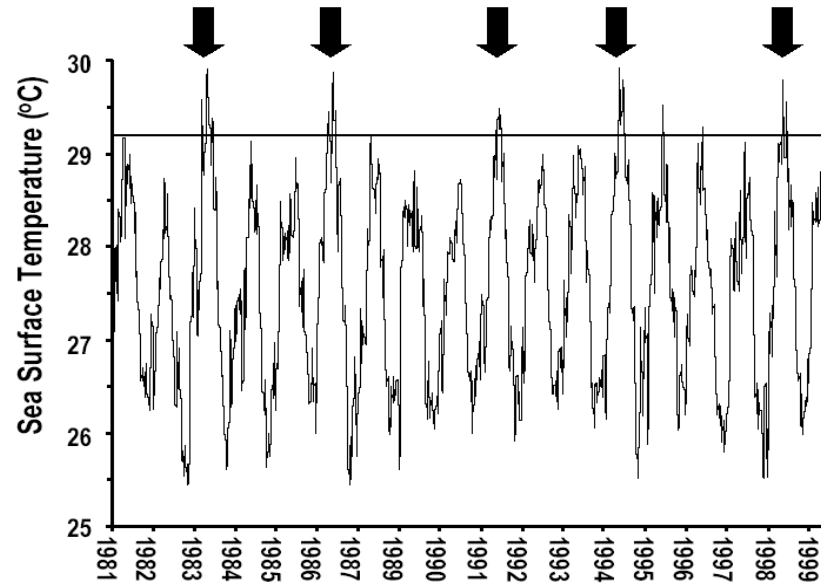
- CO₂ enhances sensitivity to thermal extremes
- CO₂ narrows thermal windows of animals
- CO₂ contributes to temperature dependent shifts in geographical distribution
- CO₂ increases long term hypoxia effects.

Interactions of temperature and CO₂, a special case: tropical coral reefs



Warmest, most sunlit,
highest alkalinity





+2002

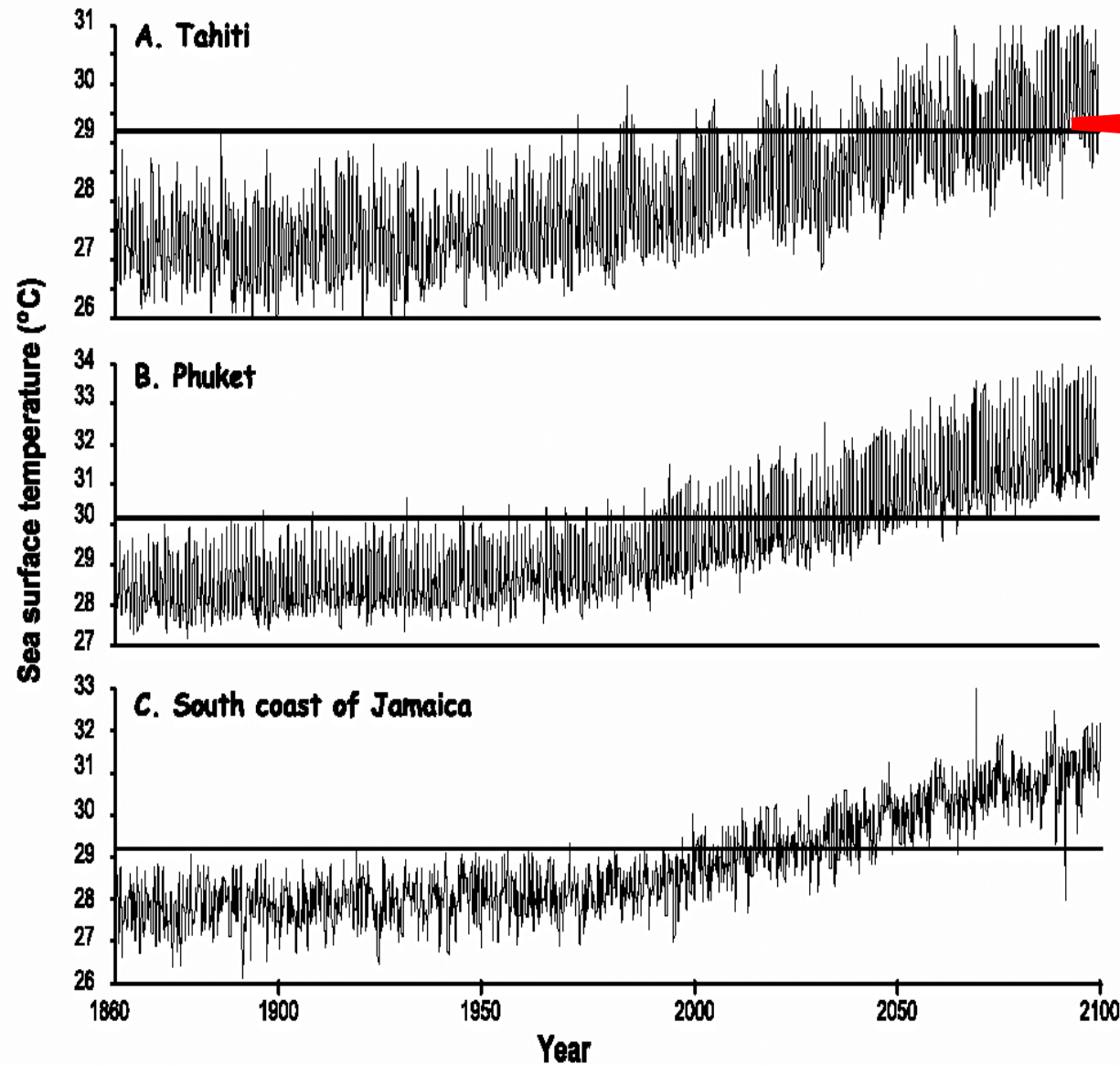
six major events since 1979
none reported formally before
1979

thousands of square miles affected
huge mortalities to be expected
increasing frequency and severity

1998: loss of 20 % of the world's
living coral

Hoegh-Guldberg (2004)

Rising thermal stress

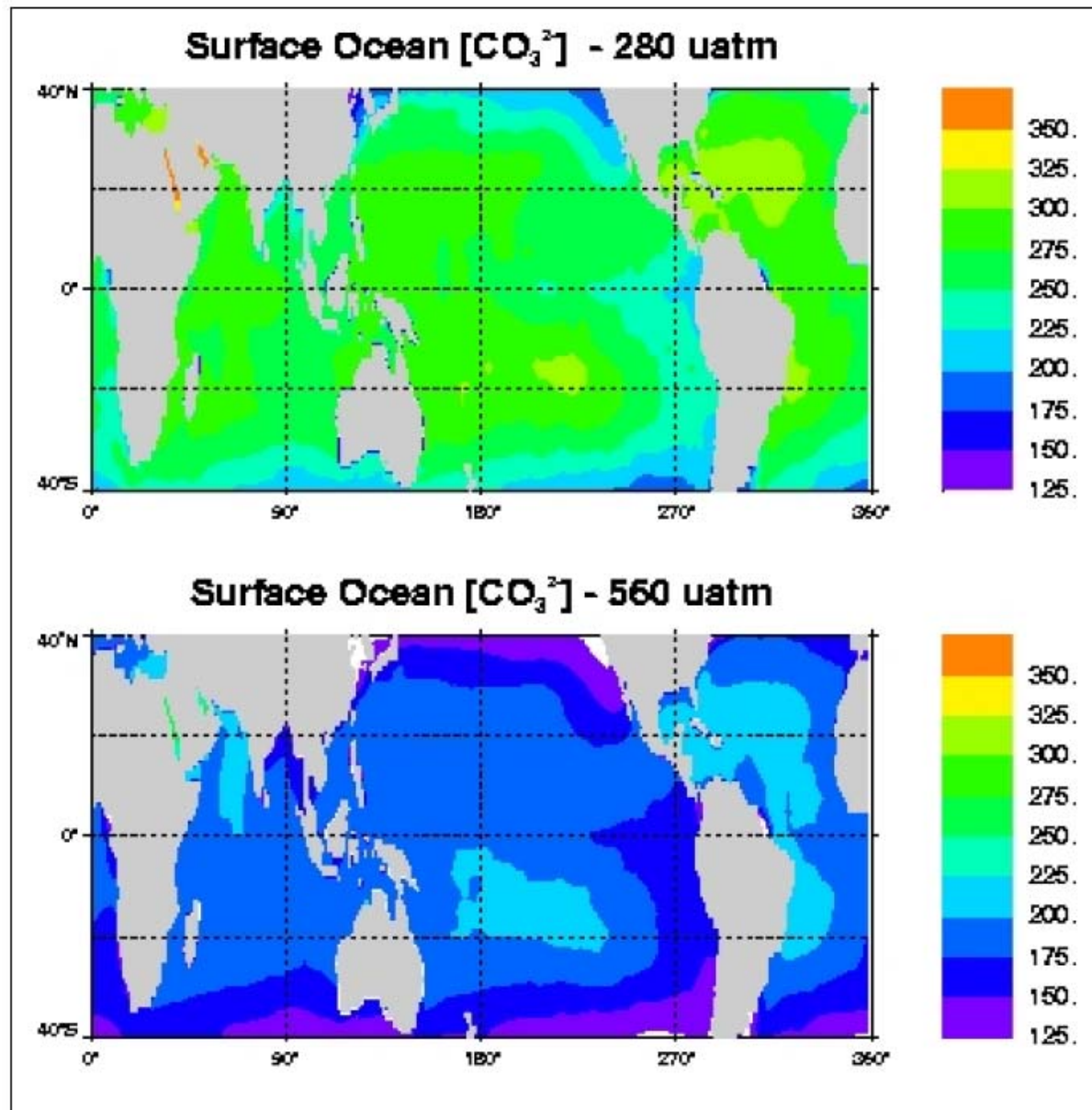


Threshold temperature – above which bleaching manifests itself (1-2°C above the long-term summer maximum temperatures)

WHAT DOES THE FUTURE HOLD?

$[CO_3^{2-}]$ at 280 ppmv and 560 ppmv

CO₂



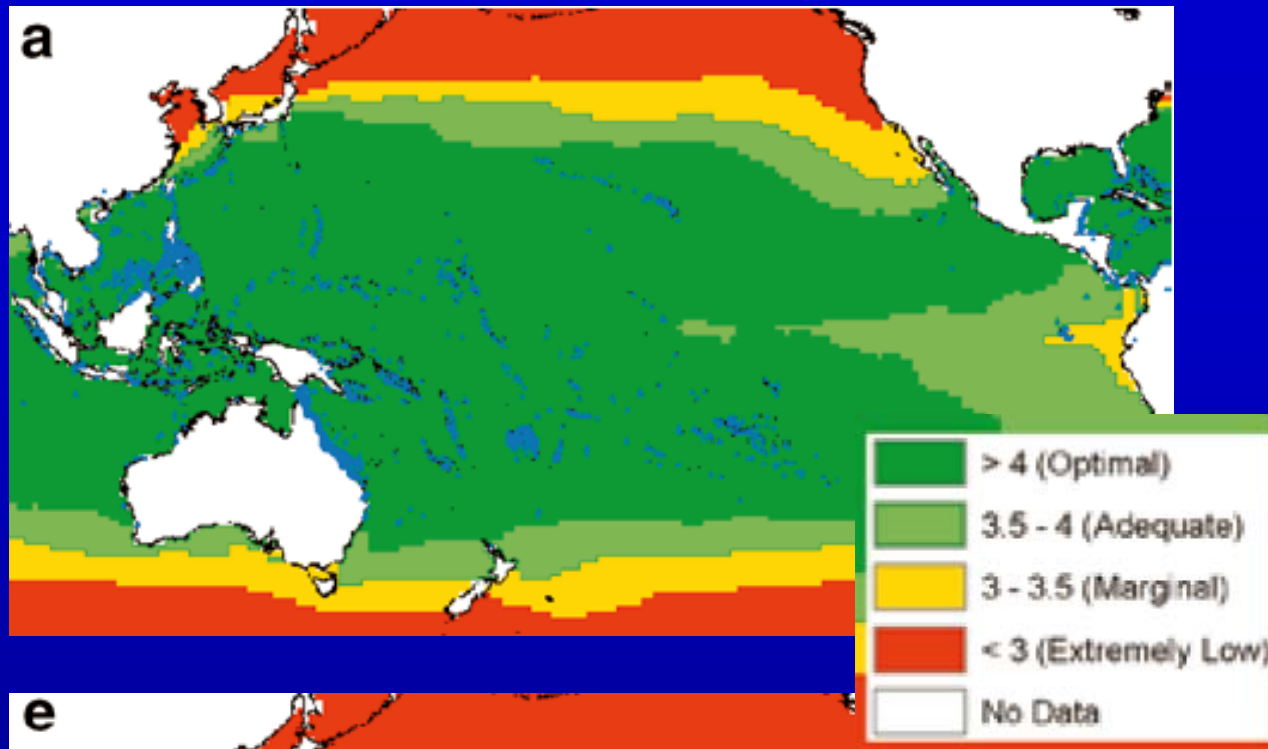
Additional
CO₂ stress at
560 ppm??
IPCC
stabilization
scenario!!

15 to 85 %
reduction in
calcification
rates (plankton
and corals)...

...due to
reduced
carbonate
levels.

Hoegh-Guldberg, 2004, Source: J. Kleypas

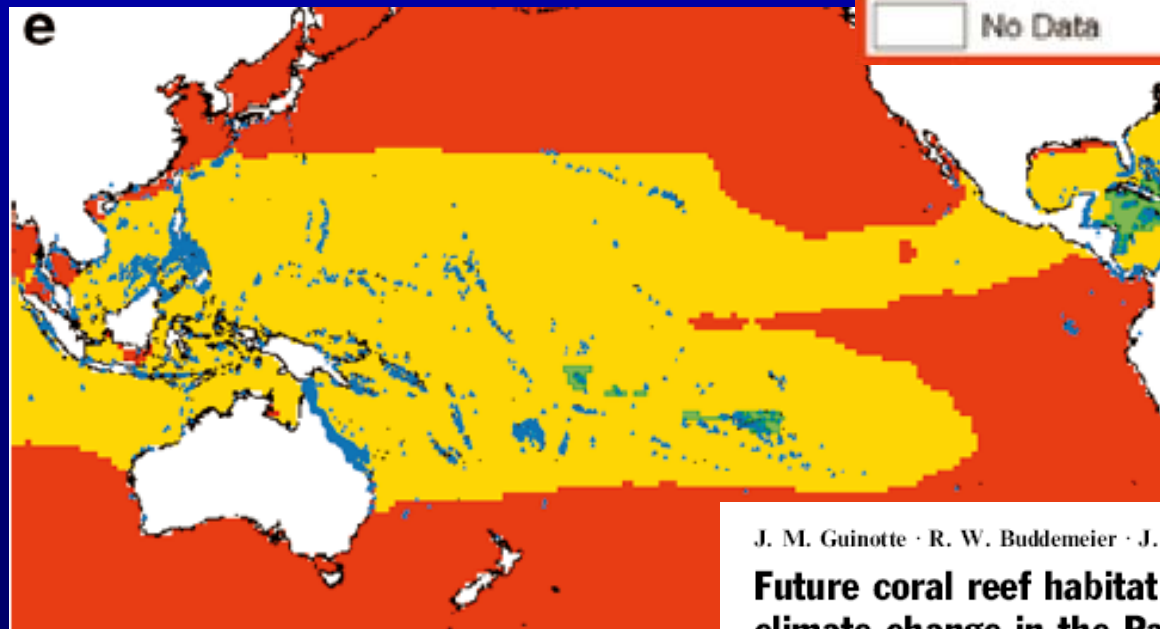
PHYSIOLOGY



Combined effects of
CO₂ accumulation
and global warming:
Marginalization of
coral reef cover

Pre-industrial
PCO₂ : 280 ppm

carbonate saturation state (Ω_{arag})



2060-69;
PCO₂ : 517 ppm
warmer temperatures

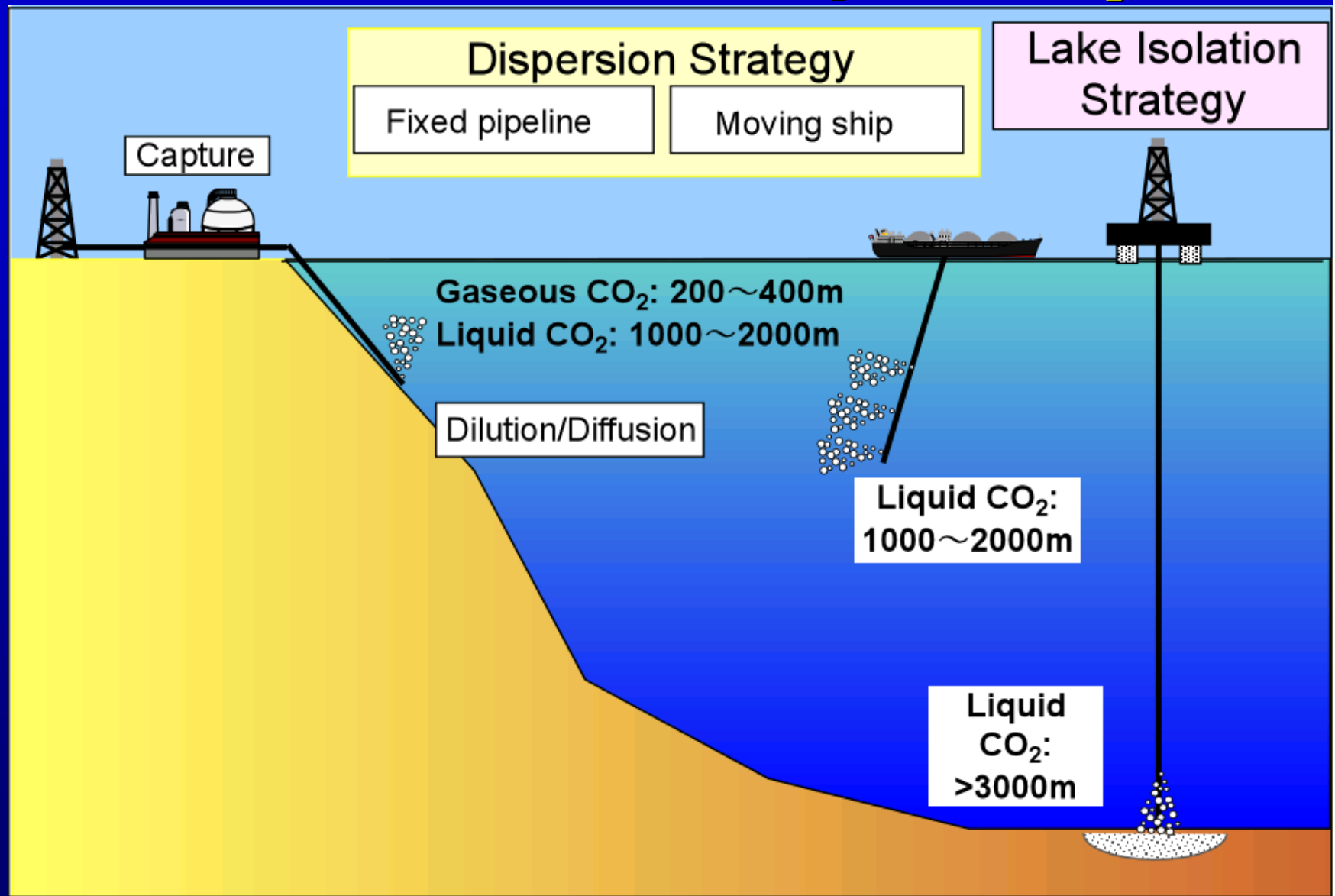
J. M. Guinotte · R. W. Buddemeier · J. A. Kleypas

**Future coral reef habitat marginality: temporal and spatial effects of
climate change in the Pacific basin**

Coral Reefs (2003) 22: 551–558
DOI 10.1007/s00338-003-0331-4

Hoegh-Guldberg (2004)

What can we do? Ocean disposal of CO₂?

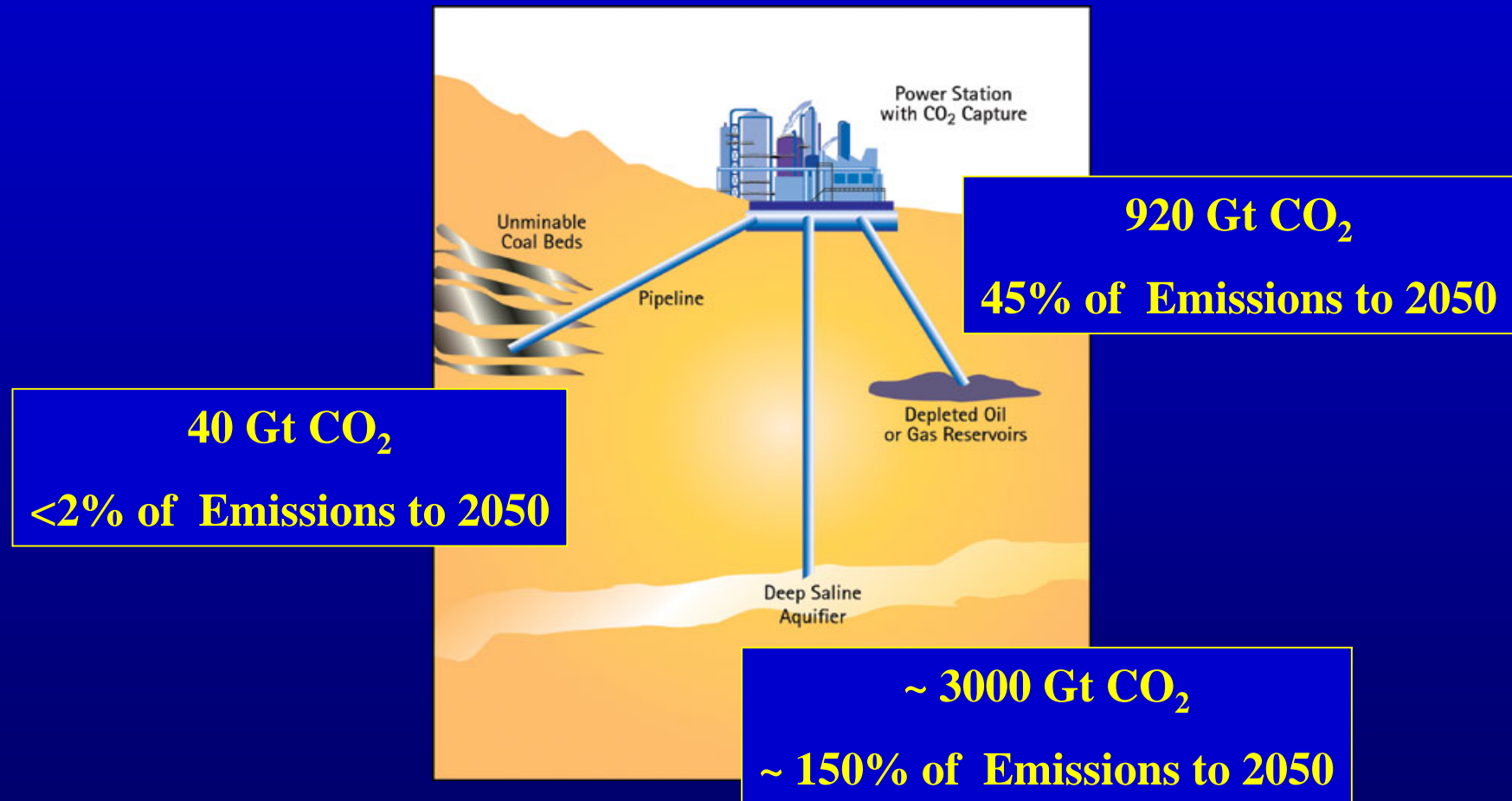


Ohsumi
2003

Capacity defined by acceptable
environmental impact!

Geological Storage Capacity

Global Storage Potential limited



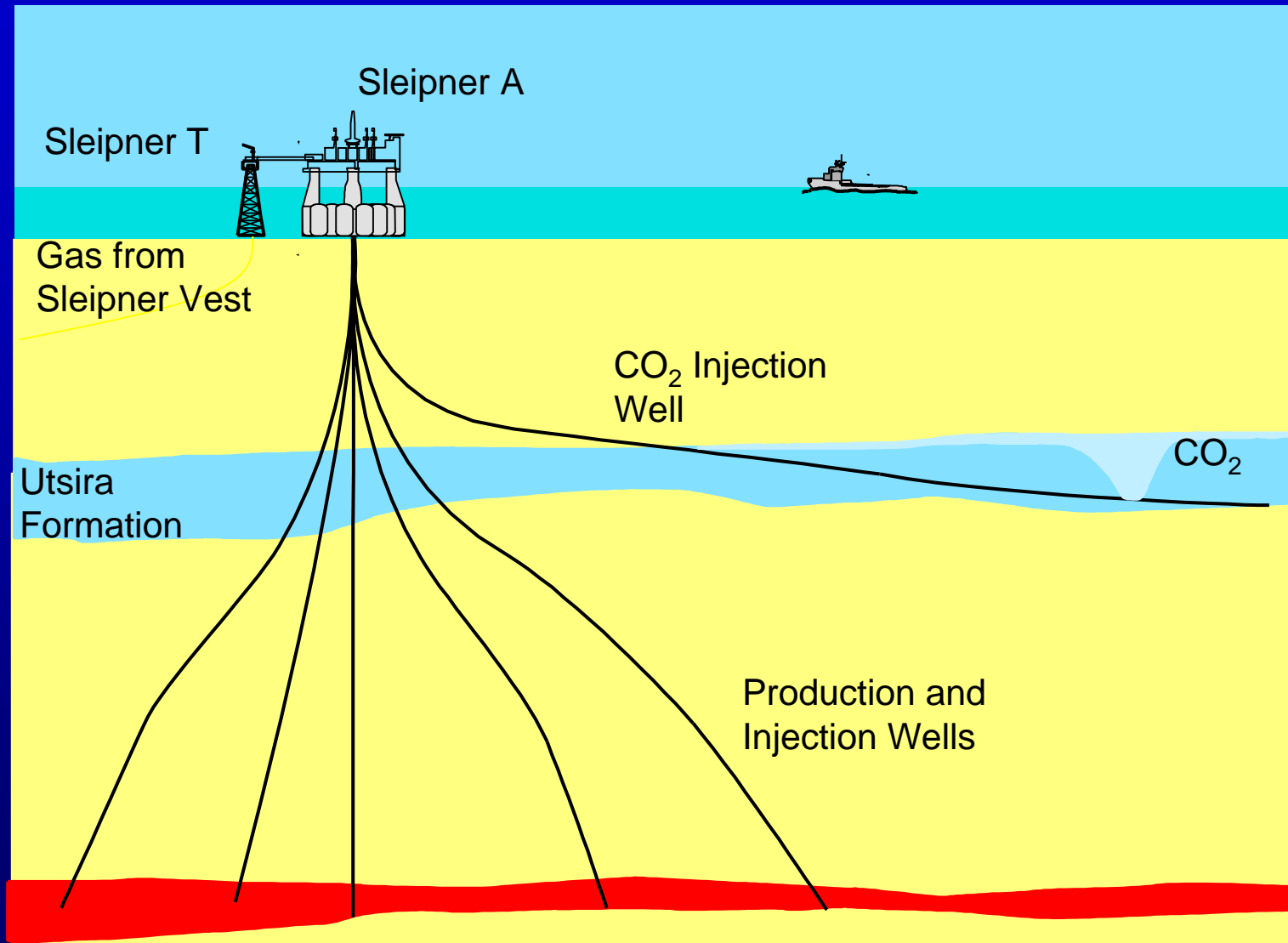
Comparative potentials at storage costs of up to \$20/t CO₂

Sleipner project



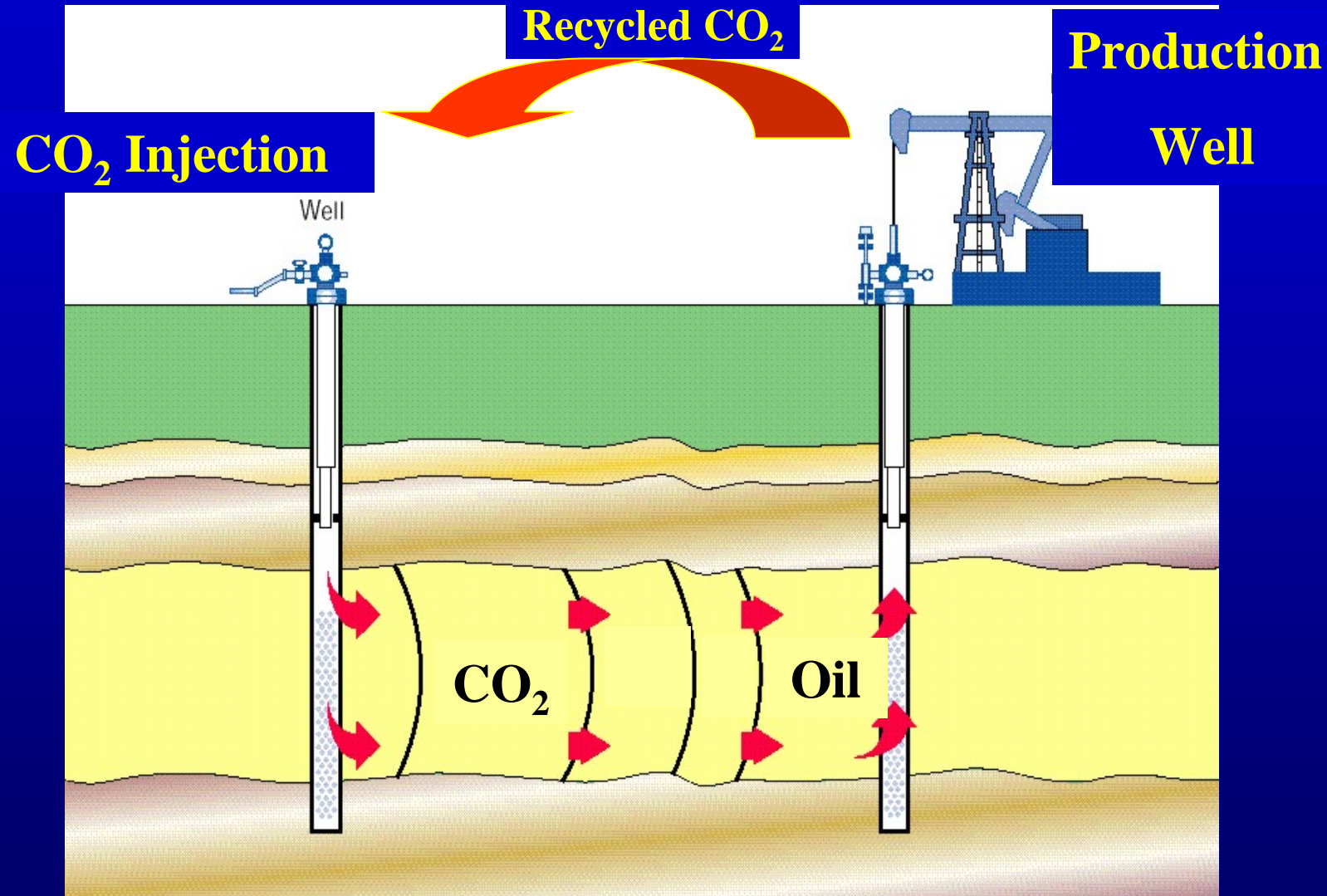
Courtesy of Statoil

Sleipner CO₂ Injection

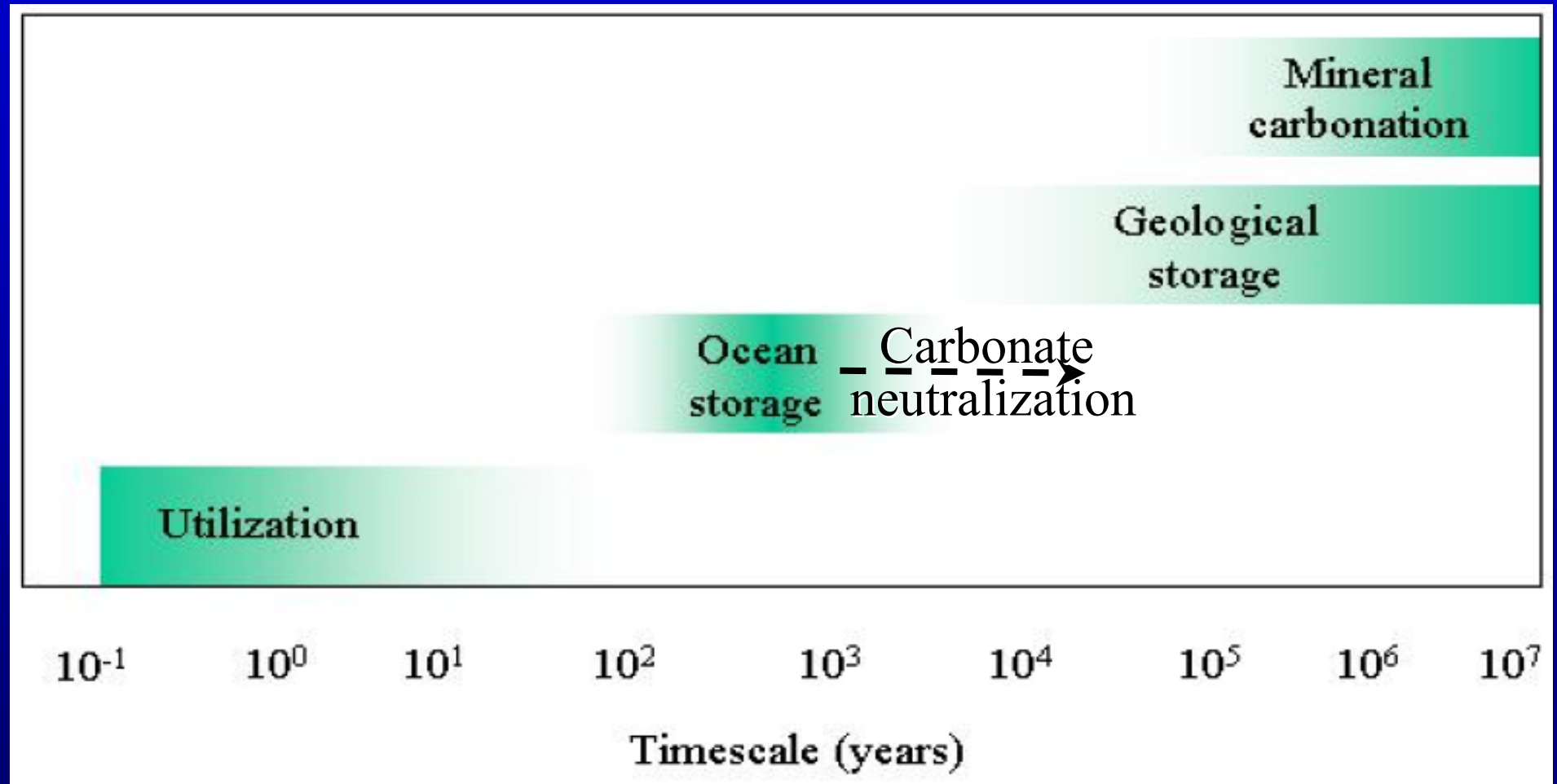


Courtesy of Statoil

CO₂ Enhanced Oil Recovery (e.g. Texas, Canada)



Storage timescale for different storage options



Ethical dilemma

Contaminating factor
„new or incrementing“

Viability

Public perception if it exists (?)

ongoing events

- | | | |
|--|---|--------------------------------|
| - Temperature, | - |passive /rising attention |
| - CO ₂ , „business as usual“, | - |passive |
| - CO ₂ , „IPCC stabilization
at 550 ppm“ | - |passive |

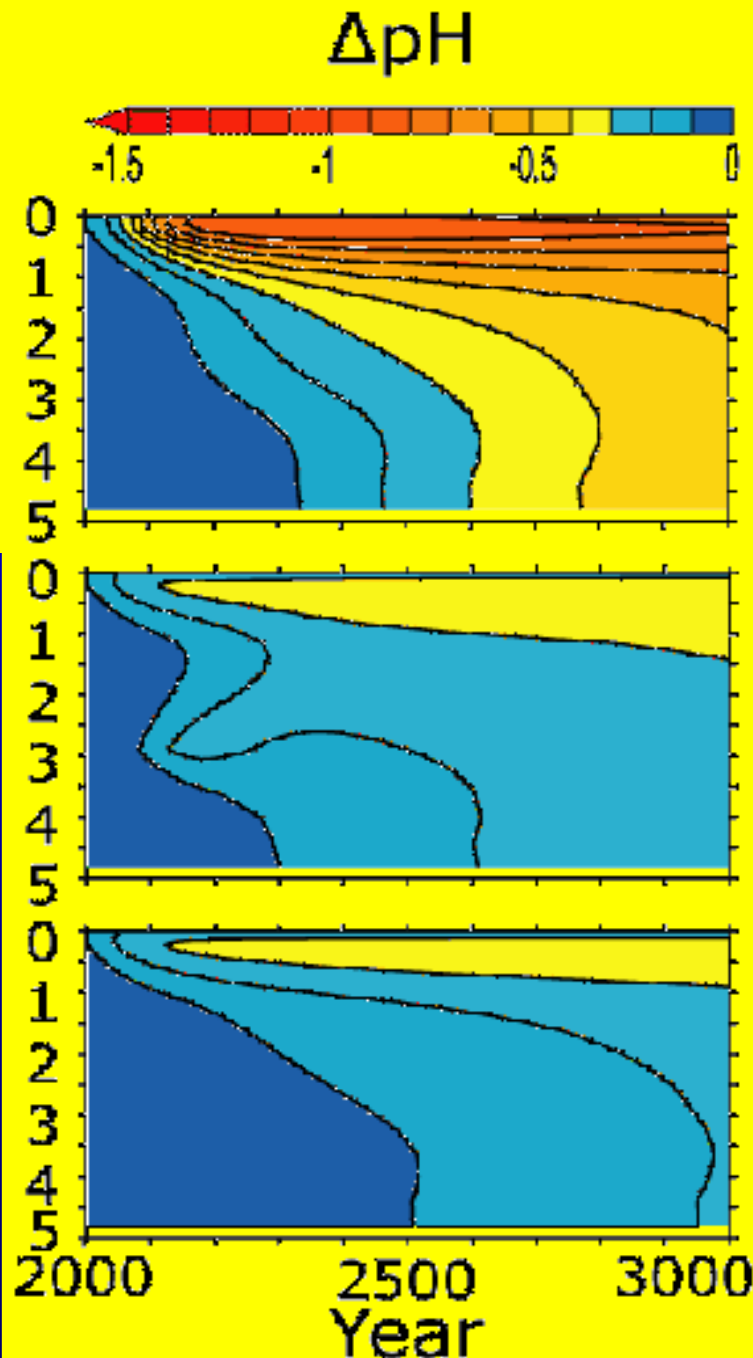
active measures for mitigation

- | | | |
|--|-----|----------------------------|
| - CO ₂ , „geological storage,
leakage“ | +/- |sceptical, |
| - CO ₂ , „ocean disposal“ | - |sceptical, negative.. |

Decisions needed

Whatever we do: Anthropogenic CO₂ rises in the world's ocean over time.

Depth (km)



5000 GtC
released,
no intentional
storage

surface waters:
up to - 0.77 pH,
1900 ppm CO₂

5000 GtC
550 ppm stabilized
<90 % in geol. stor.,
10 % leakage

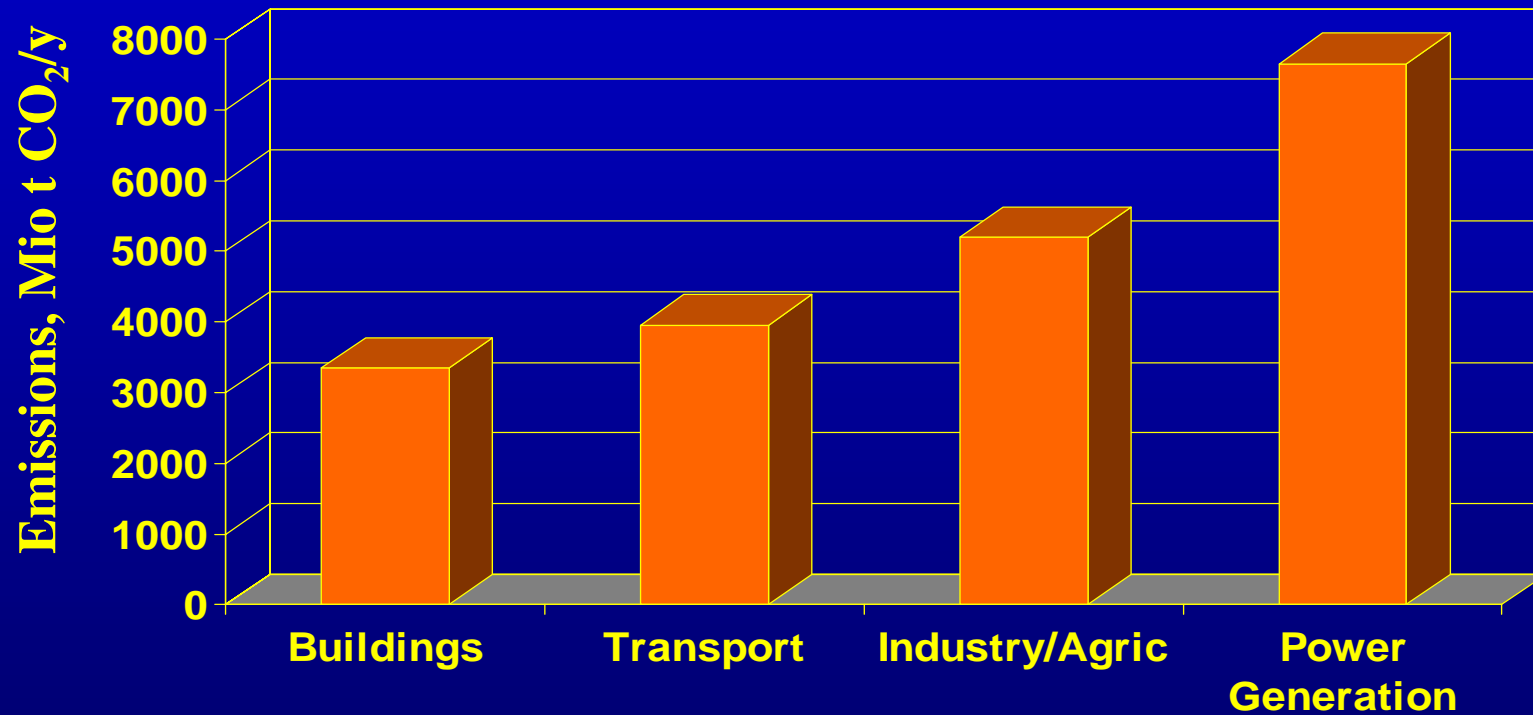
variable
bodies of
water with
- 0.2 to 0.4
pH units
550 ppm CO₂

5000 GtC
550 ppm stabilized
<100% stored
no leakage

Effects are unavoidable!

Global sources of CO₂

The final solution: Emission reduction!!



CLIMATE CHANGE, CO₂ effects, ENERGY BUDGETS

Dr. Christian Bock
Carsten Burkhard
Dr. Martina Langenbuch
Dr. Vasilis Michailidis
Dr. Anke Reipschläger
Susann Schmidt
Rolf-M. Wittig



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