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Ocean Acidification: Recent Progress in Environmental Sensitivity Studies

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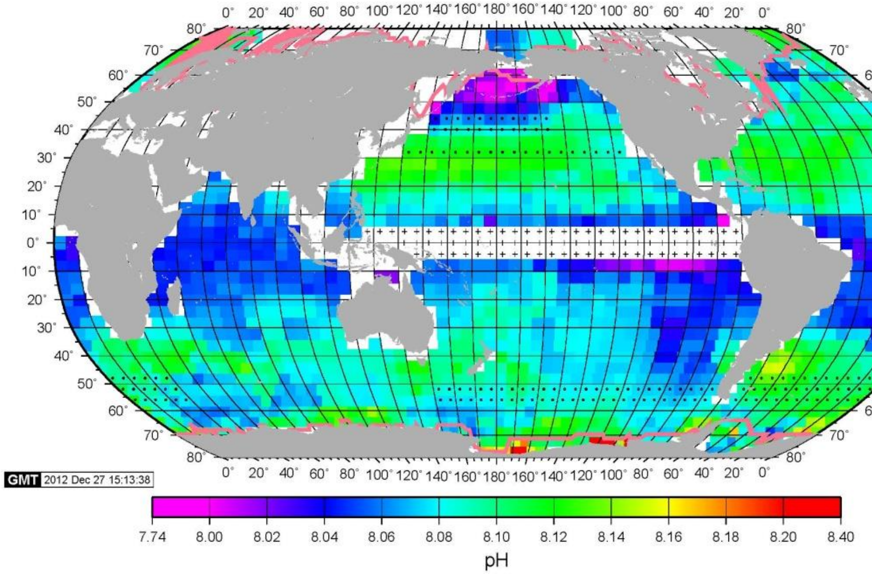
1. Distribution of pH in surface waters of the global ocean:
    a. Present condition of ocean pH
    b. Acidification observed at selected locations

2. Effects of acidification on marine organisms:
    a. Effects on corals
    b. An biological study on Pacific oysters

3. New observations of the Arctic Ocean pH

Climatological mean distribution of pH in global surface ocean water
(Takahashi et al., 2013)

(A)
Calculated pH for
February, 2005

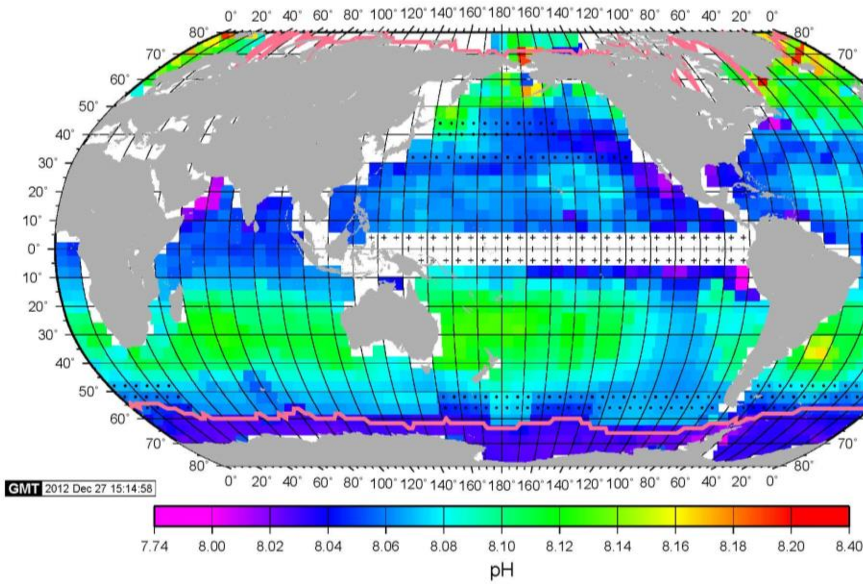


Global range of pH = 7.9 to 8.2
(1.3×10^{-8} to 6.3×10^{-9} mol H^+/liter),
varying by a factor of 2 in the H^+
concentration.)

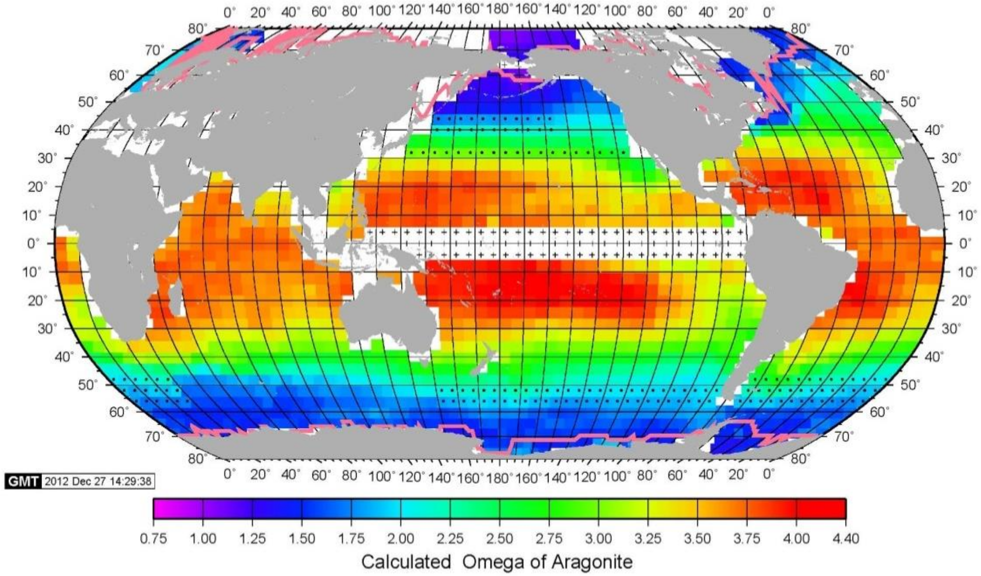
Temperate oceans =
8.05 in warmer months and
8.15 in colder months

Seasonally changes by about 25%
In the H^+ ion concentration.

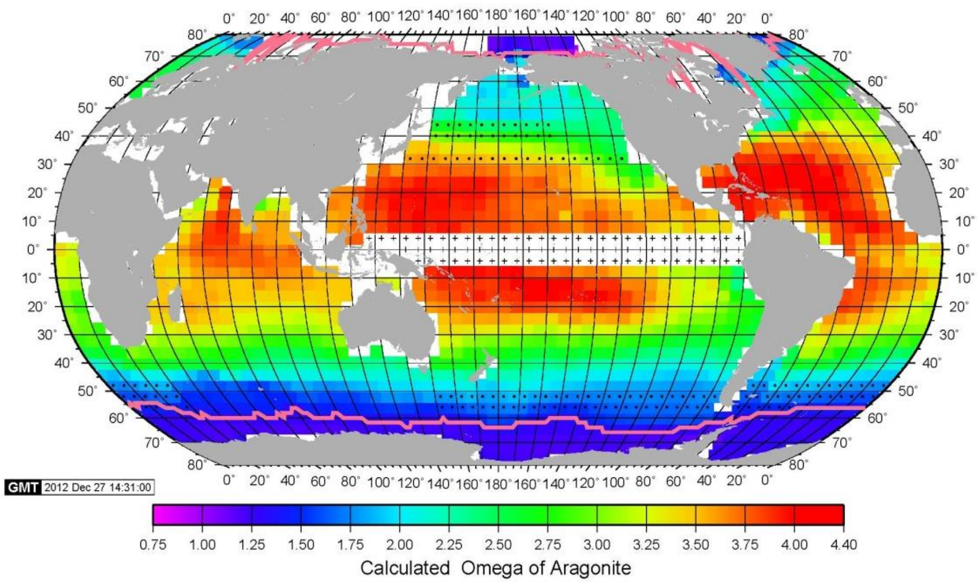
(B)
Calculated pH for
August, 2005



A) February, 2005



B) August, 2005



Climatological Mean Distribution of the Degree of Saturation of CaCO3 (aragonite)
Takahashi et al. (2013)

Many corals are made of mineral aragonite (CaCO3). Surface ocean water is commonly supersaturated with respect to this mineral, and hence provide favorable environment for coral growths.
The degree of saturation is expressed in the OMEGA scale: $\Omega = 1$ is at saturation, $\Omega > 1$ is supersaturation , and $\Omega < 1$ is undersaturation (or dissolution).

Today's surface ocean waters are supersaturated with CaCO3 (aragonite) up to 440 %. Only a small portion of the Arctic Ocean is undersaturated with aragonite.

$\Omega = (Ca^{++})\,(CO3^{=}) / Ksp$
and
Ksp is called Solubility product
$= (Ca^{++})\,(CO3^{=})$ at saturation

Time Trends Observed at the Bermuda Time Series (BATS) and Hawaii Ocean Timeseries (HOT) Stations

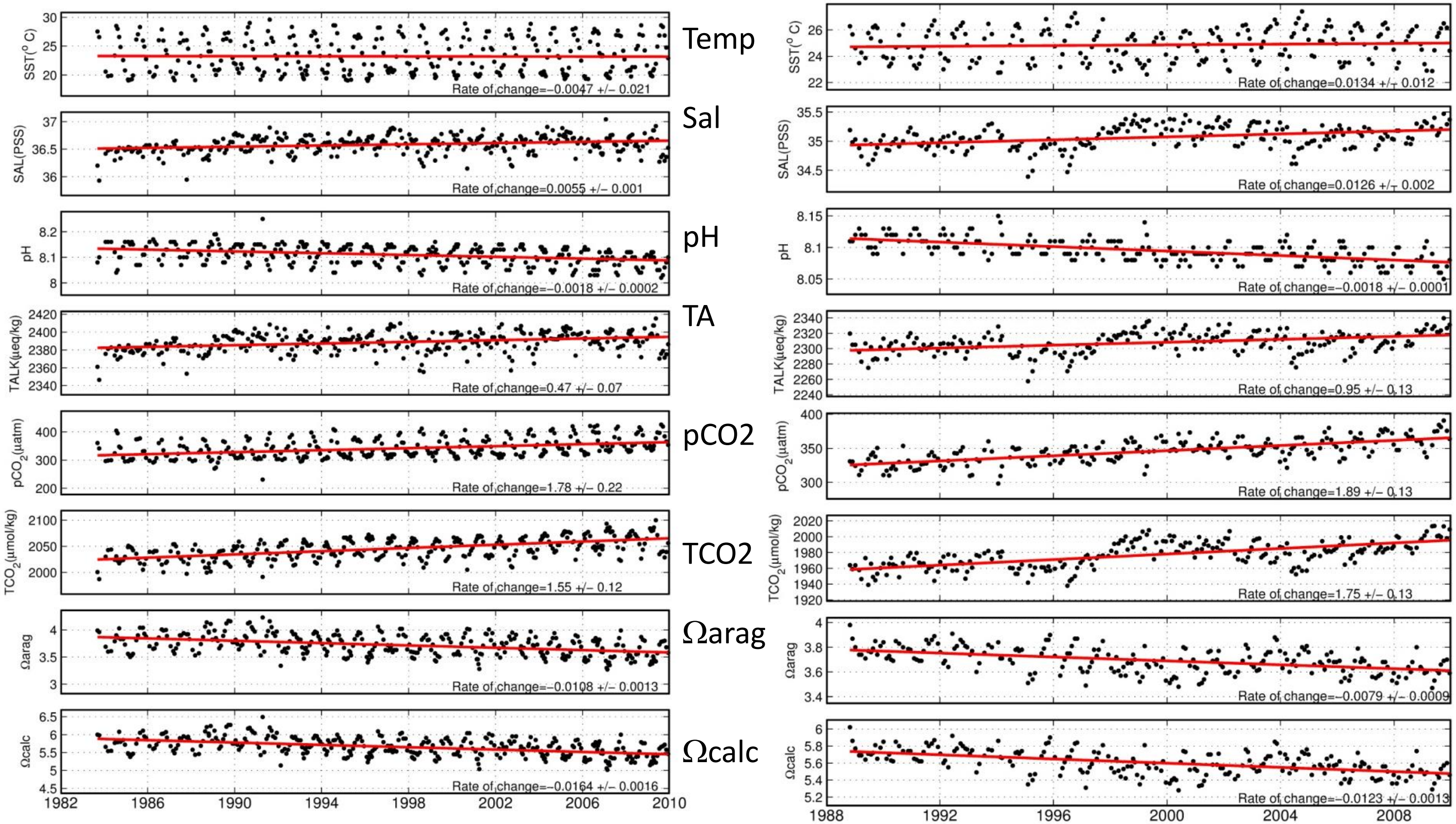
H^+ concentrations in surface ocean increase at a rate of 4.5% per decade or about 50% per century.

BATS

pCO2 = +1.78 uatm/yr, pH = -0.0018 /yr

HOT

pCO2 = +1.89 uatm/yr, pH = -0.0018 /yr



SUMMARY OF THE GLOBAL OCEAN PH AND ACIDIFICATION

1. The pH in surface waters of the global ocean, where most of the marine organisms live, Ranges from 7.9 to 8.2, and varies from 1.3 x 10^{-8} to 6.3 x 10^{-9} mol H^+/liter of seawater, by a factor of 2 in the H^+ concentration.

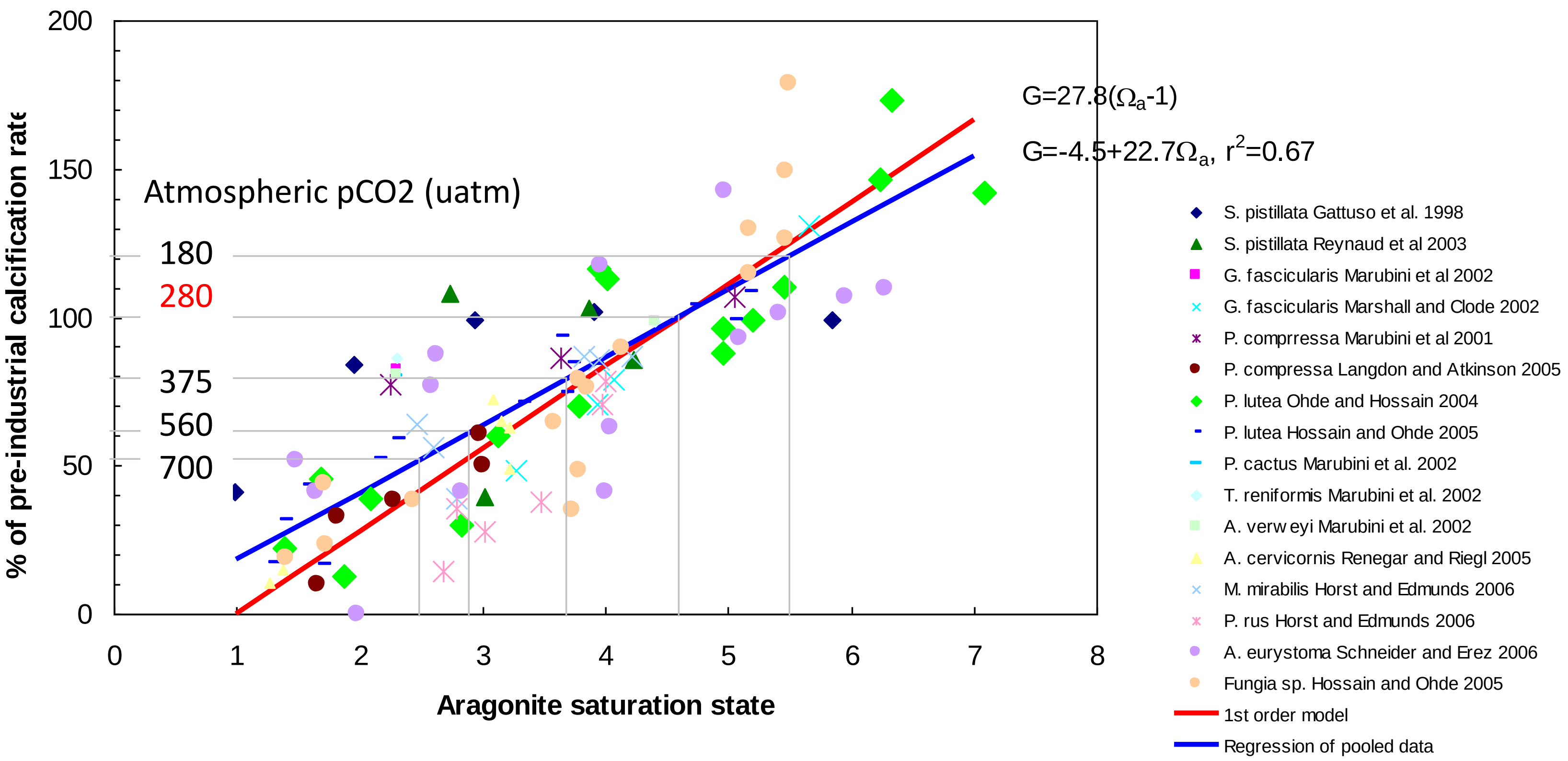
2. In the vast temperate oceans, where many ecosystem thrive, pH changes seasonally from 8.05 in warmer months to 8.15 in colder months. The H^+ ion concentration changes seasonally by 25%. Today's surface ocean waters are supersaturated with CaCO3 up to 4.4 times for aragonite and 6.3 times for calcite, providing favorable environments for calcifiers. Only a small portion of the Arctic Ocean is undersaturated with aragonite.

3. In the temperate oceans, the pH is being lowered at a mean rate of 0.018 pH per decade due to the uptake of CO2 from the atmosphere. At this rate, the magnitude of ocean acidification will exceed the seasonal amplitude of 0.1 pH in about 50 years. The marine ecosystems will encounter a new environment, which they had not been exposed before.

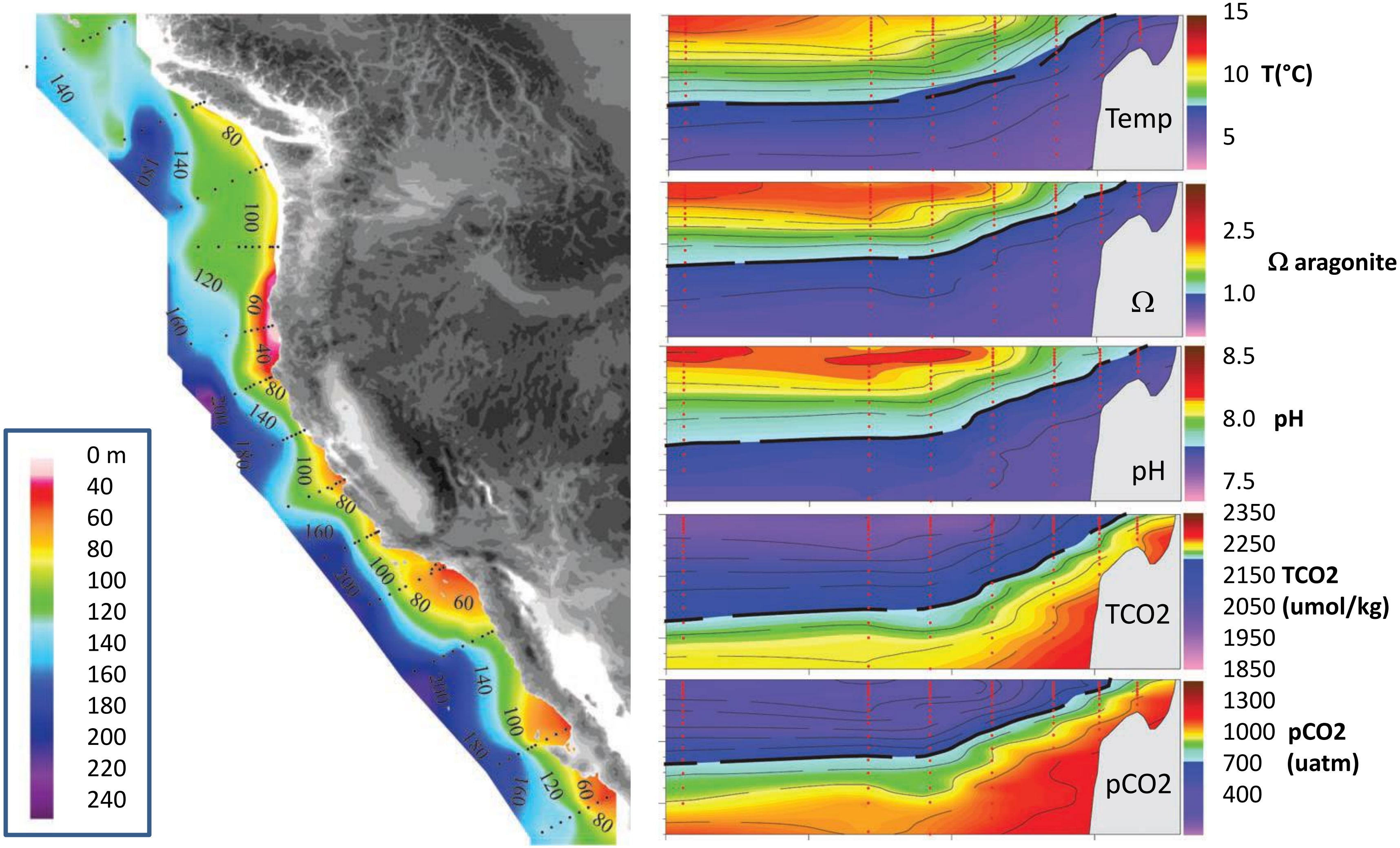
4. H^+ ion is involved in various biochemical processes, and its changes, i.e. ocean acidification, is expected to affect the entire marine ecosystems. Since the degree of saturation of CaCO3 is reduced, we expect that the community of calcifiers (corals, shell fish, coccolithophores, foraminifera, pteropods …) would be most directly affected. The degree of saturation for aragonite will be reduced by 0.1 Ω per decade or 1 Ω per century. How would the small changes in seawater chemistry affect marine life?

Sensitivity of coral calcification to saturation state
(compilation of 12 species)

(After Chris Langdon, 2006)



Oregon-California Coast during Upwelling of Deep Waters
(Feely et al., Science, vol. 320, 2008)



Depth of the waters undersaturated
With aragonite in meters.

Energy Budget of in the Growth Stages of Pacific Oysters

George Waldbusser et al. (2013). A developmental and energetic basis linking larval oyster shell Formation to acidification sensitivity. Geophysical Research Letters, Vol. 40, 2171-2176.

The first shell (periostracum) forms on bare larva in 6~10 hours after the fertilization.

After 24~48 hours, fully formed calcified shell is formed: 160 nano grams CaCO3/larva.
To precipitate CaCO3, H^+ ions must be pumped out at an energy cost of 24 micro Joules/larva.
$Ca^{++} + CO3^{=} \rightarrow CaCO3$; $HCO3^{-} \rightarrow H^+ + CO3^{=}$

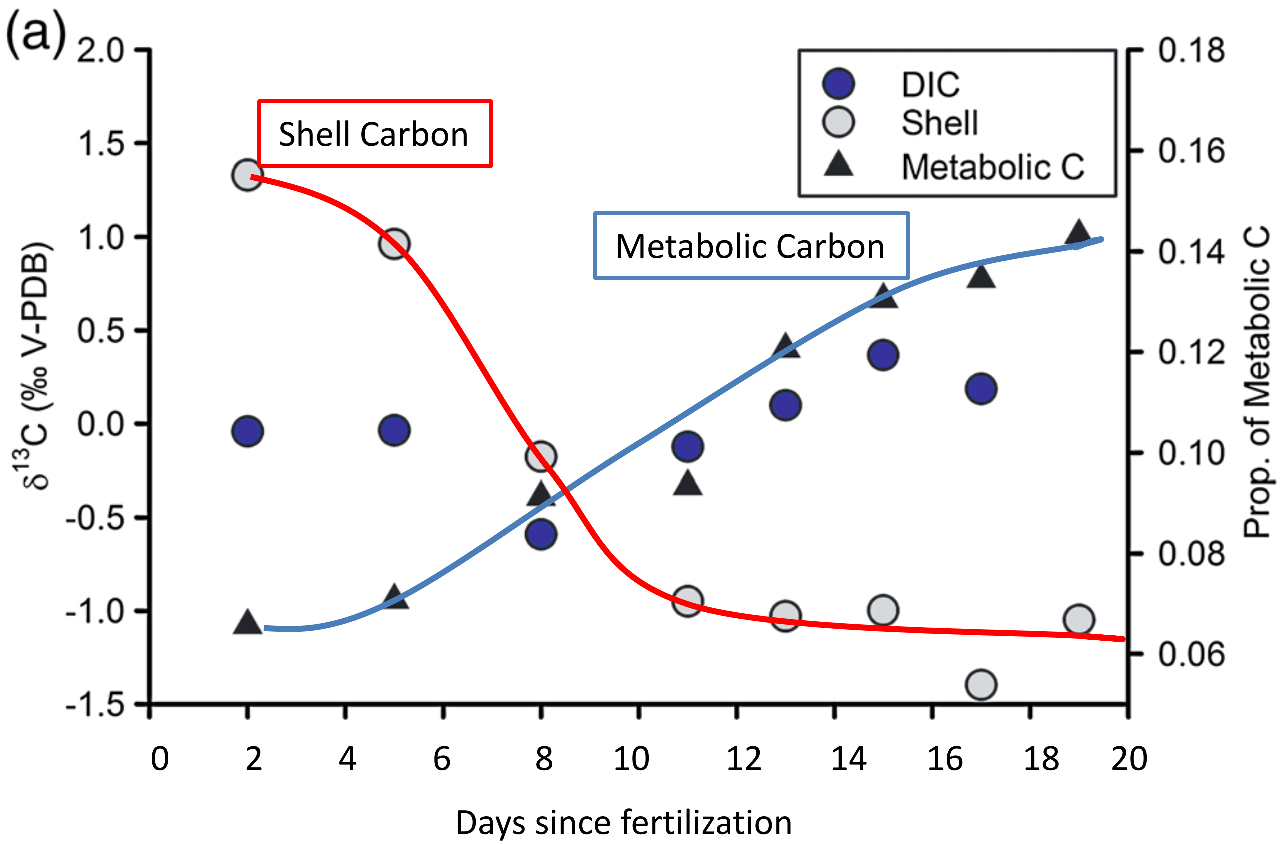
Protein synthesis for the organic matrix for shell structure: 70 micro Joules/larva

Total energy needed for the shell construction for the early larva is 94 micro Joules/larva.

Total energy available in a larva (trochophore) is 316 micro Joules/larva.
30% of the available energy is used for the first shell for protection, and the remaining energy is for the formation (metamorphosis) of mature shell (prodissoconch II) and body. Slow transition of energy source from endogenous (egg) to exogenous food sources occurs.

The degree of saturation of CaCO3 in seawater is reduced by acidification. This will cause an increase in the energy cost for calcification, and hence lowers energy available for the metamorphosis and results in greater failure of larva. Food supply is another important factor.

Pacific Oyster Study -- Waldbusser et al. (GRL, 2013)



Carbon isotope ratio ($^{13}C/^{12}C$) in the larval shell (red curve) and in the seawater in the growth tank. Proportion of metabolic carbon (blue curve) is estimated using the isotope data. During the first five days, about 6% of carbon in CaCO3 was derived from metabolism of larva and the rest from the maternal sources. After the 12th day, the larva's metabolism contributed 10~14% of the carbon in the shell.

Summary of Effects of Ocean Acidification on Biology

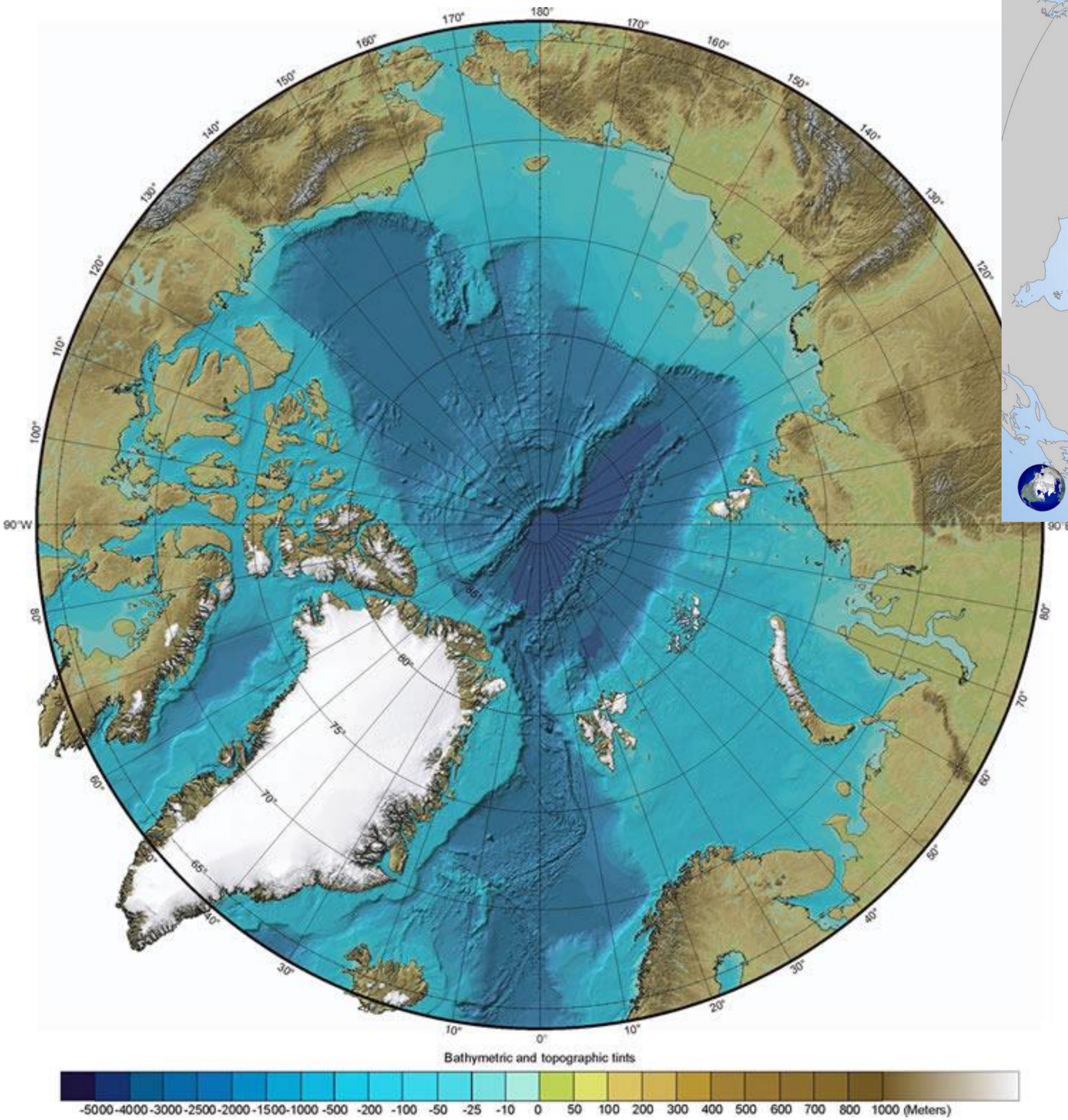
1. As a result of ocean acidification, the CaCO3 saturation levels in seawater is reduced, and many calcifier ecosystems appear to be negatively impacted.

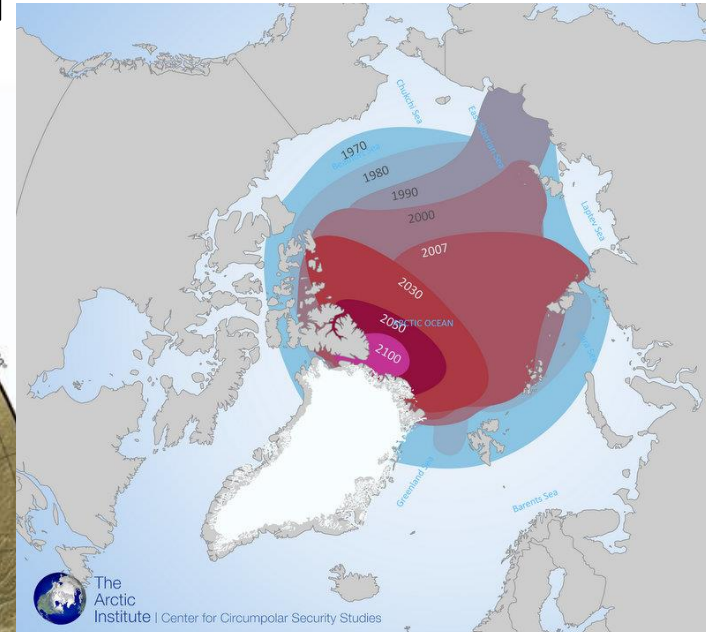
2. In the nature, organisms and ecosystems are subjected to combination of multiple environmental stressors including the changes in temperature, pH, degree of saturation of CaCO3, and others (e. g. trace elements and man-made pollutants). It is difficult to indentify a single stressor for particular ecosystem or organism.

3. The Oregon State University group investigated the energy sources needed for the first formation of CaCO3 shell on a naked larva for the California oyster. They show that the energy demands for shell formation during the transition period of the maternal endogenic energy source to exogenic source may be increased due to the reduced degree of saturation of CaCO3 in seawater. This would reduce the energy available for the growth and hence increase the fatality of larva.

4. We need to understand the biological and biochemical steps which are sensitively affected by the ocean acidification and increase in the amount of CO2 dissolved in seawater. For example, corals are a symbiotic system of calcifier and photosynthetic organisms, and the acidification should negatively affect the calcifier, whereas an increase in CO2 could affect the photosynthetic organisms positively. The completing effects need to be understood.

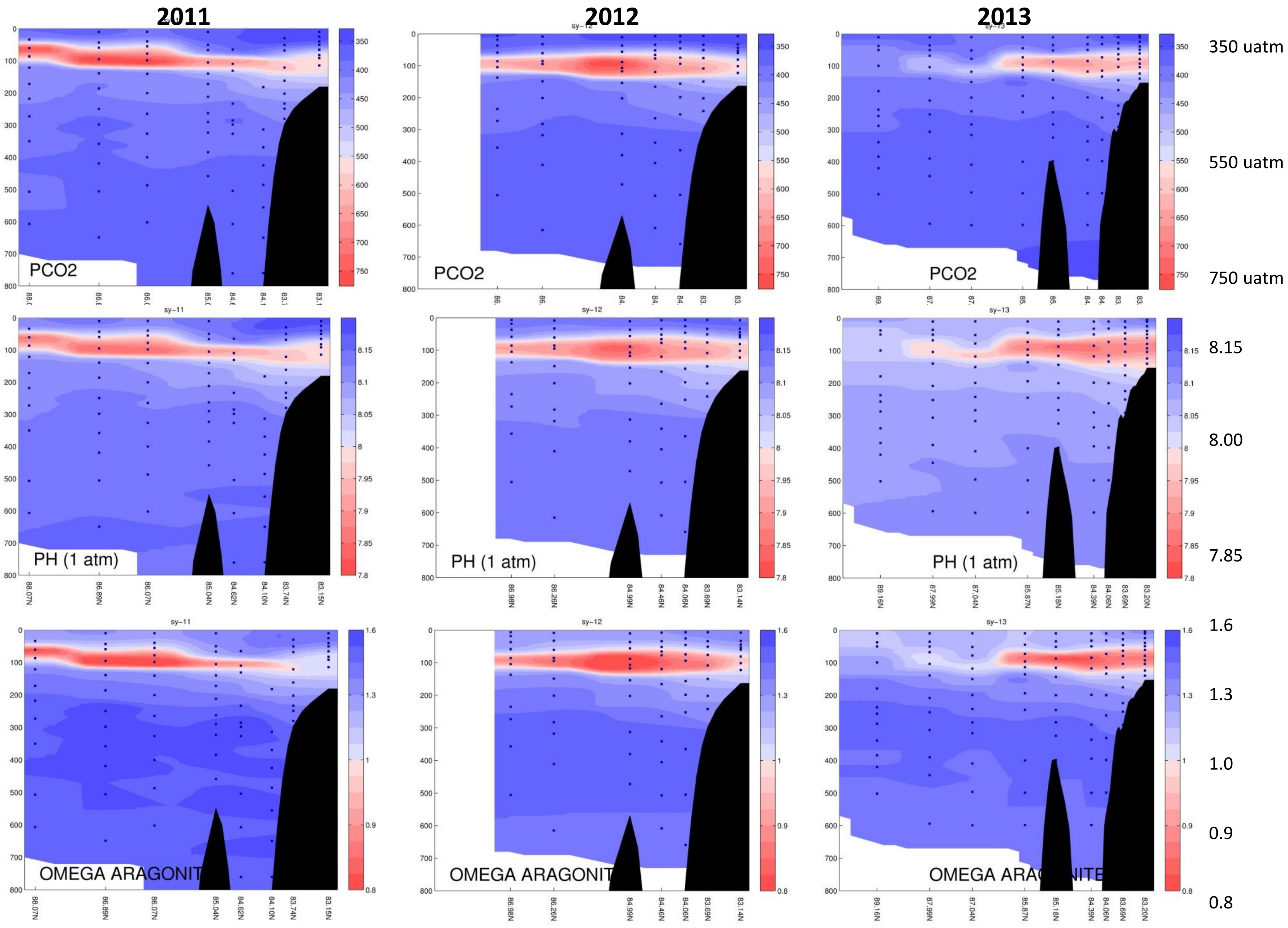
MAP OF THE ARCTIC OCEAN





Arctic Inflow and Outflow

The North Pole-Alert (Canada) Transect (Takahashi et al, in preparation)



ARCTIC REGION