Responses of Marine Ecosystems to a Changing Climate

Ken Denman

Fisheries and Oceans Canada

EC Canadian Centre for Climate Modelling and Analysis
c/o University of Victoria, BC, Canada
&
Institute of Ocean Sciences, Sidney, BC

Email: ***ken.denman@ec.gc.ca***

Environment Canada Environnement Canada

Fisheries and Oceans Canada Pêches et Océans Canada

CCCma

U. Victoria

IOS

Contributors

DFO – CCCMA/IOS

- Jim Christian
- Nadja Steiner

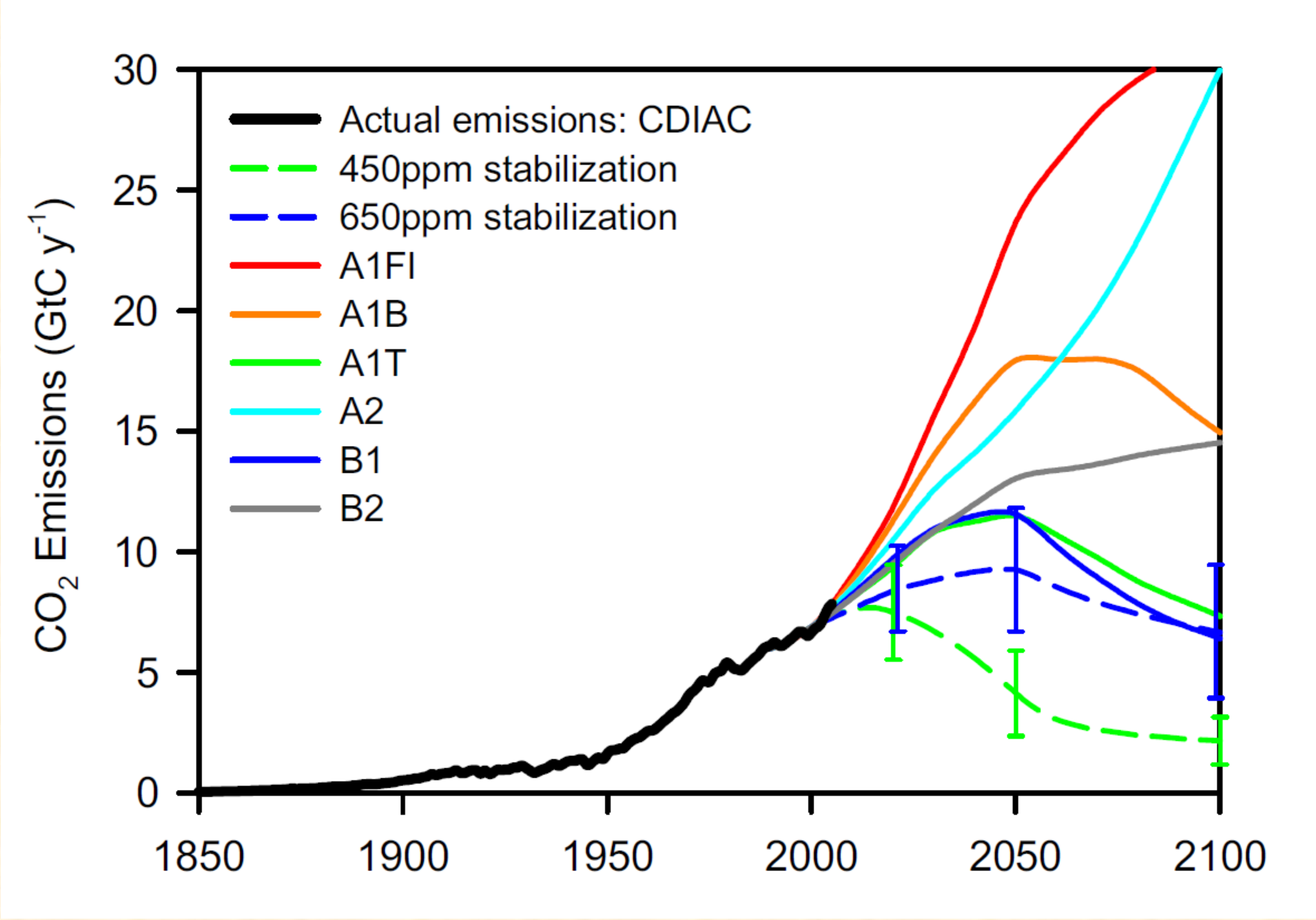
EC – CCCMA

- Bill Merryfield
- John Fyfe

Ocean Ecosystems ⇔ Climate

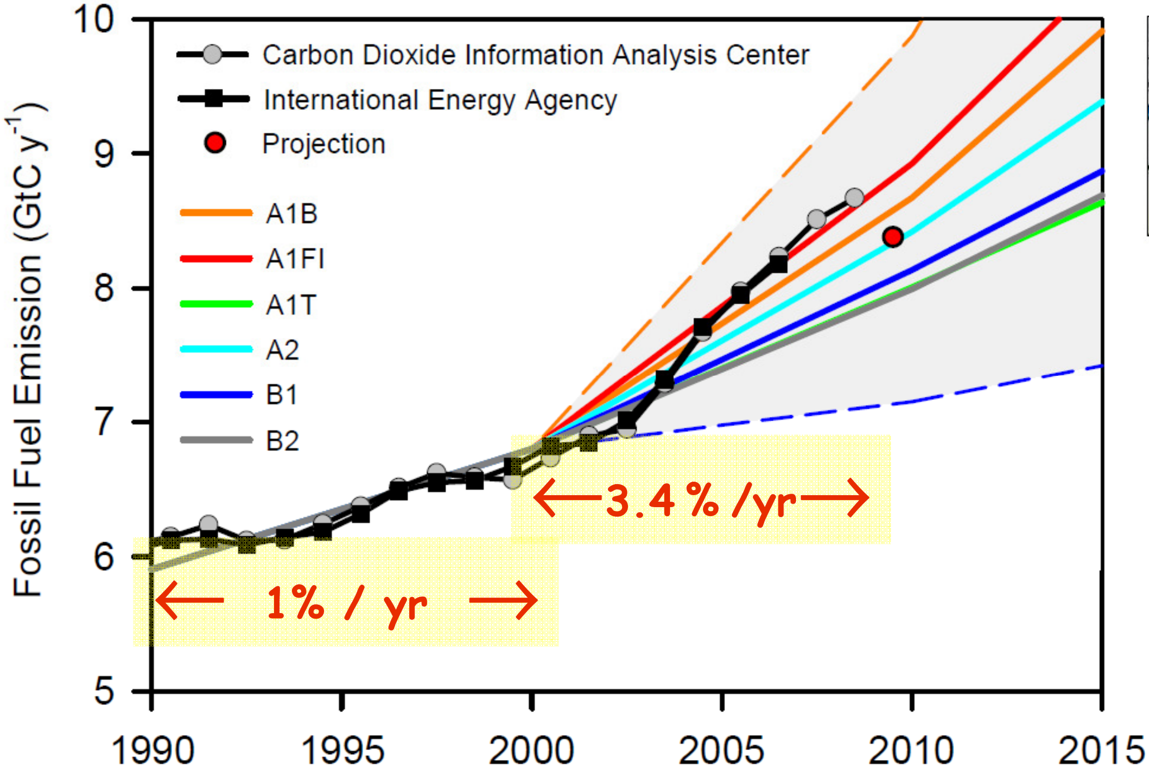
1. Projections of climate change
2. Climate variability in space and time
3. Physical transport and stratification, e.g.
   – currents, controls on mixing, gravitational sinking (& buoyant rising)
4. Direct links between ocean ecosystems and climate, e.g.
   – thermal regulation of physiological rates
5. Indirect links via 'Biogeochemistry', e.g.
   – ocean biota will be affected by the joint effects of increasing temperature, increasing pCO_2, and decreasing O_2

Future 'SRES' CO_2 Emissions Scenarios



[from Raupach et al.,US. Proc. Natl Acad Sci, Vol. 104, 12 June 2007]

Fossil Fuel Emissions: Actual vs. IPCC Scenarios



Projection 2009
Emissions: -2.8%
GDP: -1.1%
C intensity: -1.7%

Raupach et al. 2007, PNAS, updated; Le Quéré et al. 2009, Nature-geoscience; International Monetary Fund 2009

Climate Forecasts vs Weather Forecasts

- Weather forecasts 'know about' the most recent weather
- Climate forecasts are 'initialized' in 1750 or 1800, then 'forced' with ghg emissions or atmos. concentrations
  - objective is to predict climate in 2100 on global and continental scales
  - don't know about recent weather or climate
  - have been 'tuned' to reproduce 20th century climate
- Weather forecasts 'know' little of ocean conditions
  - maybe recent sea surface temperatures or a 'slab' ocean
- New climate forecasts of 1 to 30 years will know about current and recent climate, including ocean conditions
  - regional climate models (RCMs) need to be forced by global climate models, currently RCMs mostly over land

Warming is NOT Spatially Uniform

Global mean warming for A1B scenario is 2.7°C

ΔT (C) highest in northern Polar regions during northern winter

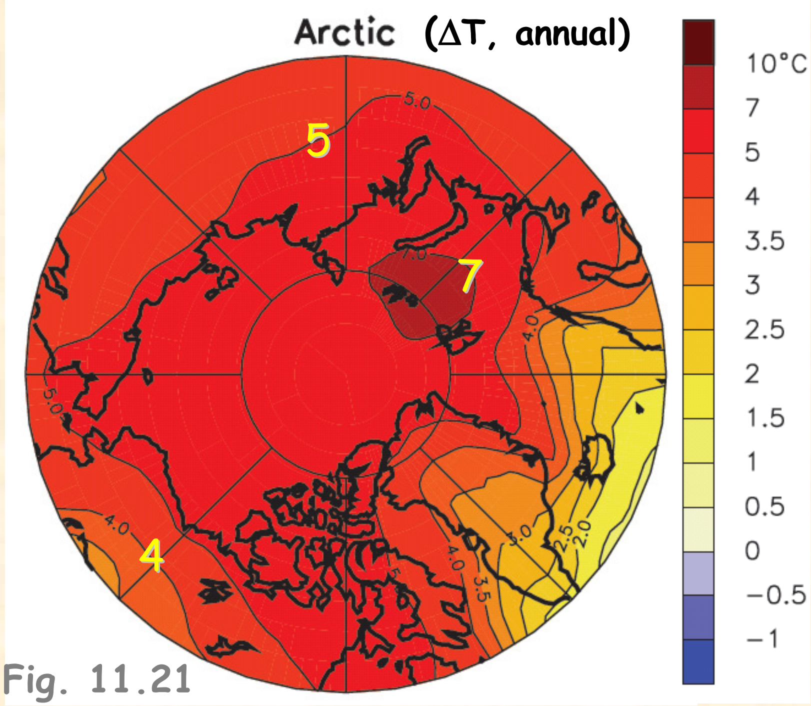
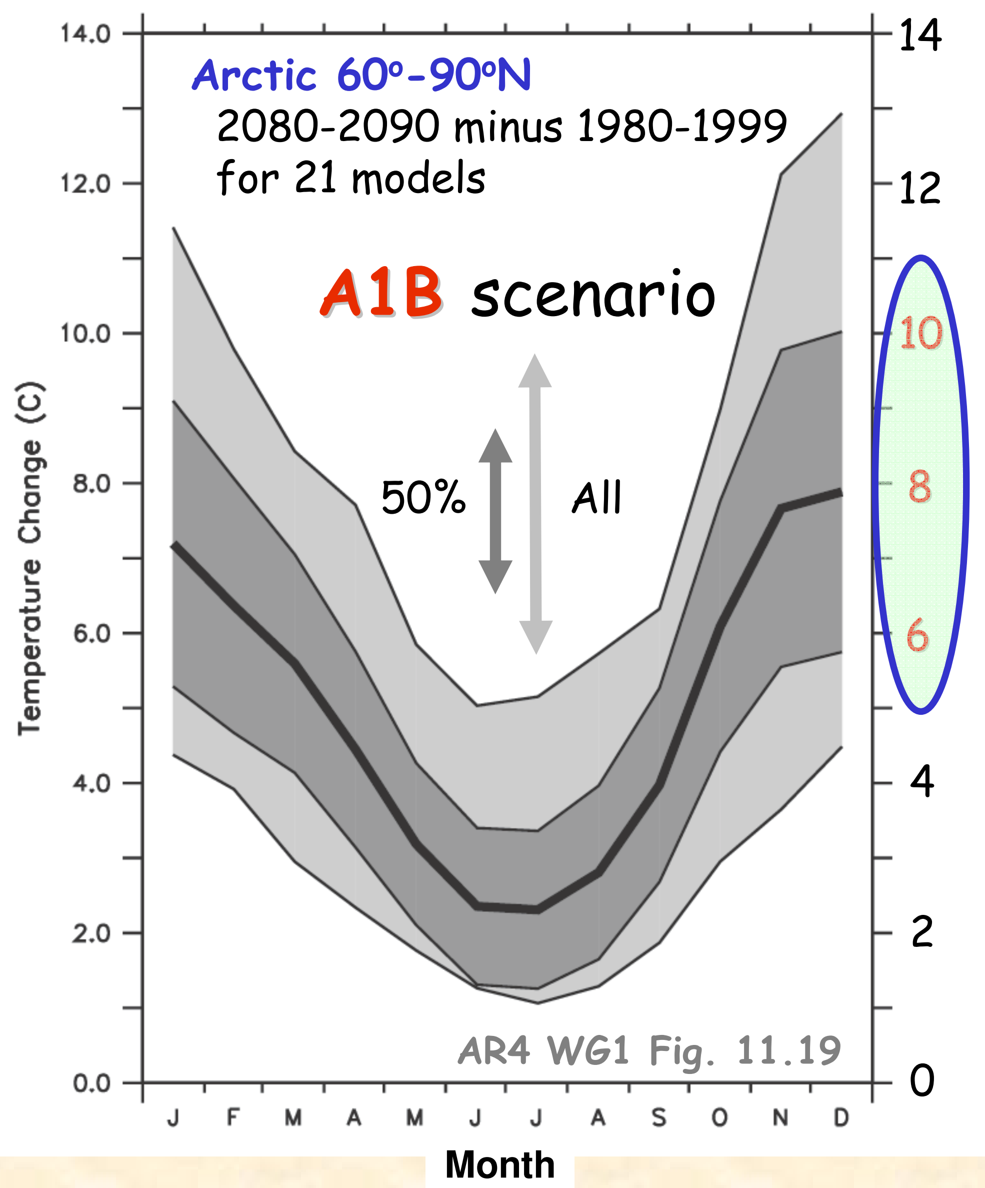


Fig. 11.21



AR4 WG1 Fig. 11.19

Recent Projection of Global Warming:

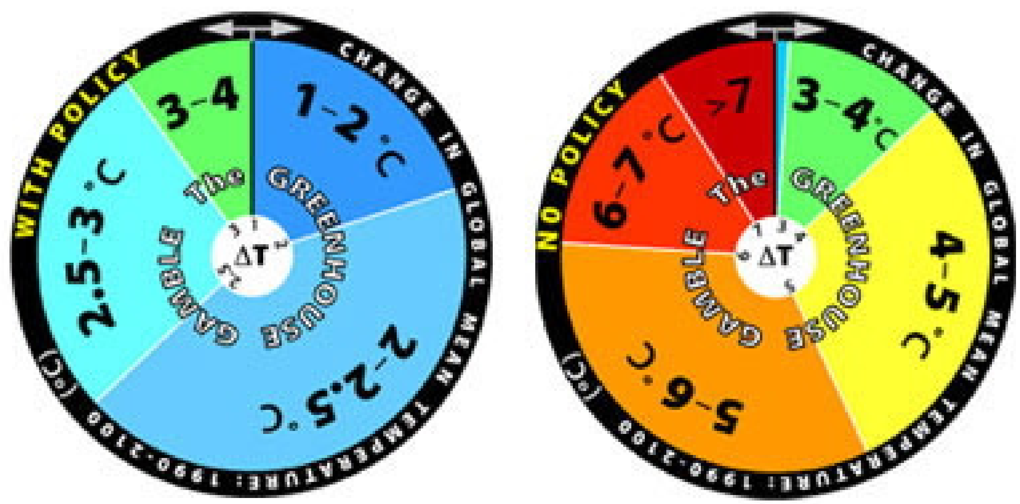
Median Surface Warming 5.2°C (90%: 3.5 – 7.4°C)

(more than 80% probability warming greater than 4°C)

400 simulations with the MIT Integrated Global Systems Model:

- **improved economic analysis & modelling**
- **includes effects of 20th century volcanic activity that was masking warming**
- **terrestrial C & N feedbacks**

Sokolov et al., 2009. J. Climate, 22, 5175-5204.

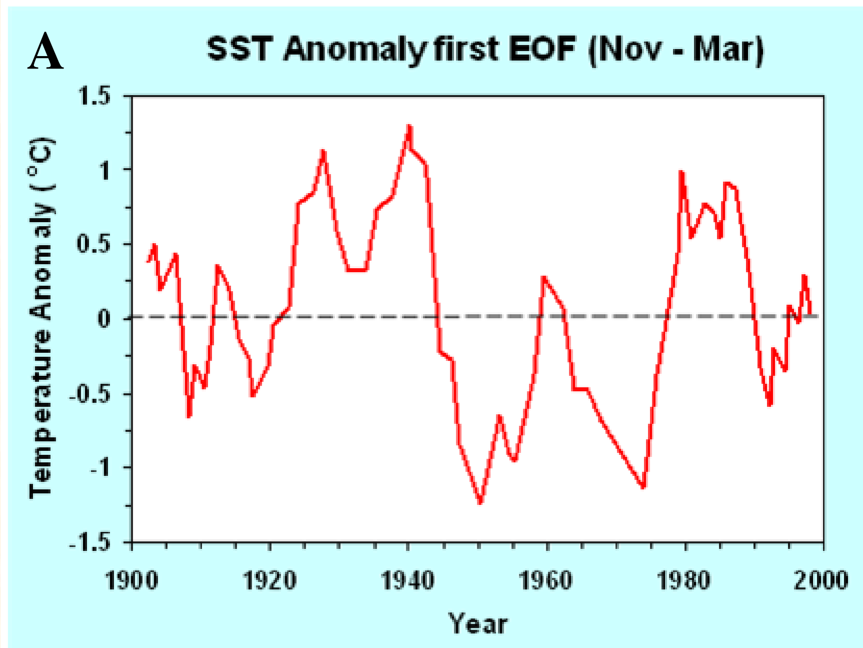


POLICY NO POLICY

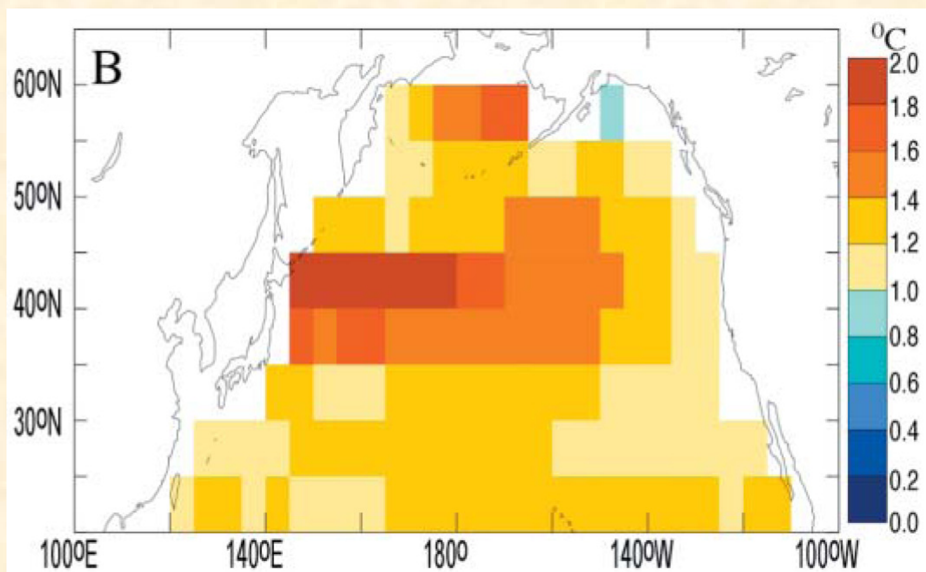
The 'Roulette Wheel'

Climate Variability Is Large

Natural Variability in N. Pacific Sea Surface Temperature (SST)



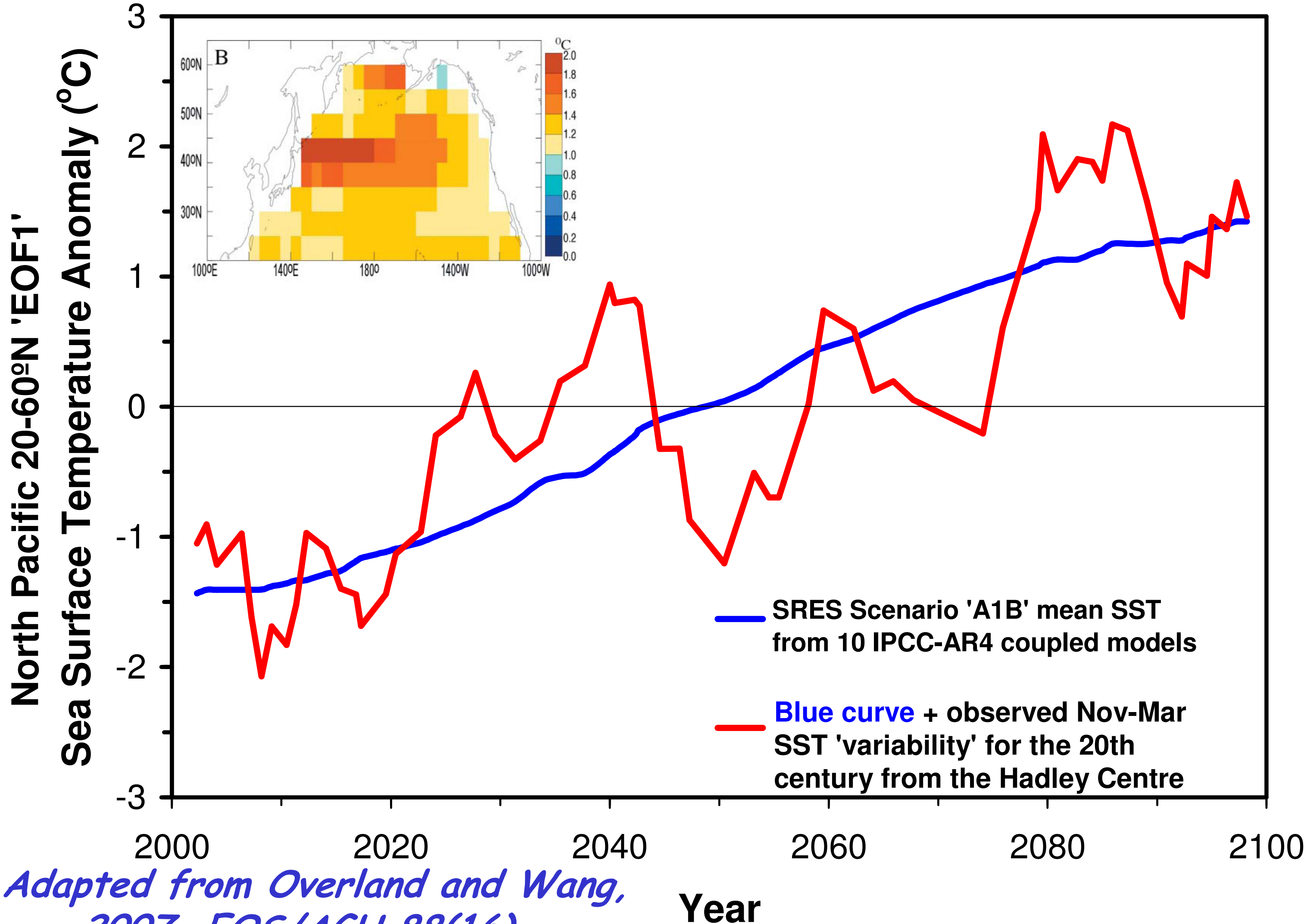
A. *OBSERVED* SST anomaly (Nov – Mar) for 1901-1999 (from UK Hadley Centre SST analysis)



B. Projected 10-model mean decadal winter SST (2040-2049), relative to 1980-1999 pattern from the Hadley Centre data

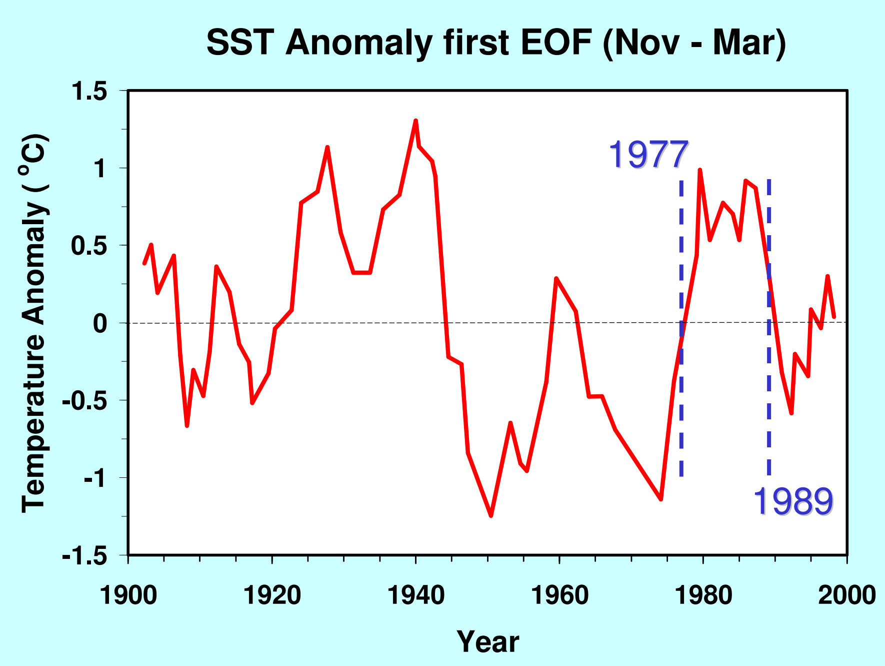
Jim Overland and Muyin Wang 2007, EOS/AGU 88(16)

Warming Is Not Smooth: Natural Variability Can Reverse Warming Trend for a Decade or More



Adapted from Overland and Wang, 2007, EOS/AGU 88(16)

Ecosystem Response:
'Regime shifts' in the N. Pacific ?



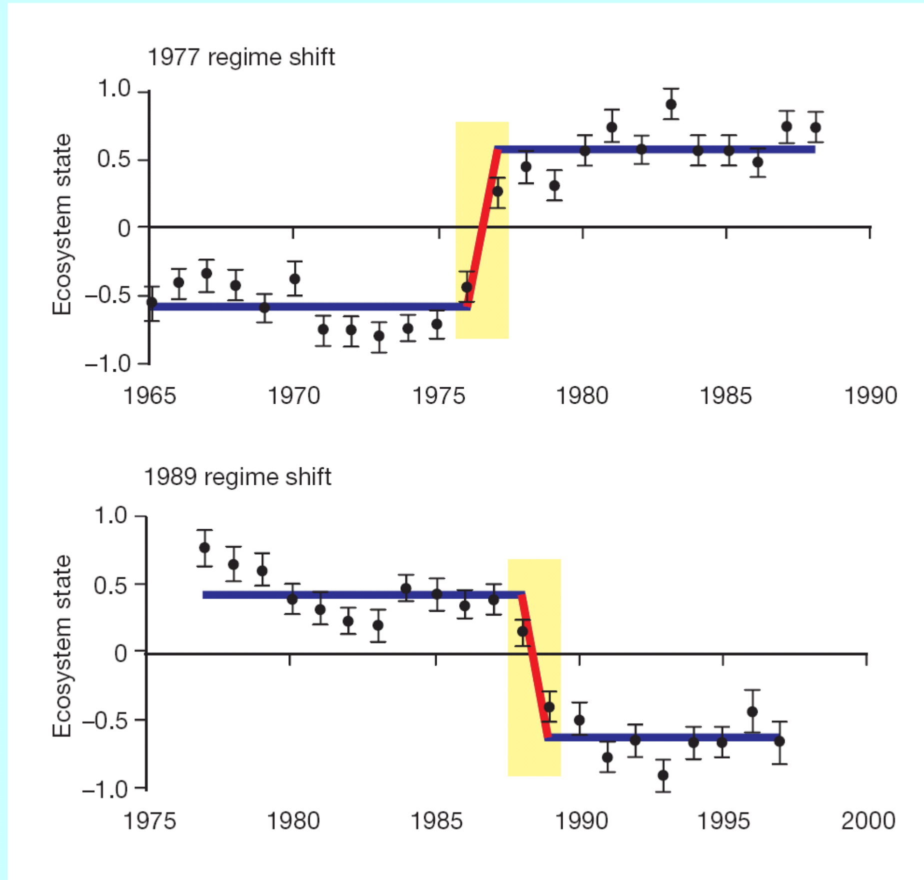


Figure 7 Distinct state shifts occurred in the Pacific Ocean ecosystem around 1977 and 1989. The compound indices of ecosystem state are obtained by averaging 31 climatic and 69 biological normalized time series. Modified from Hare and Mantua.

Scheffer et al., 2001. Catastrophic shifts in ecosystems, Nature, 413, 591-596.

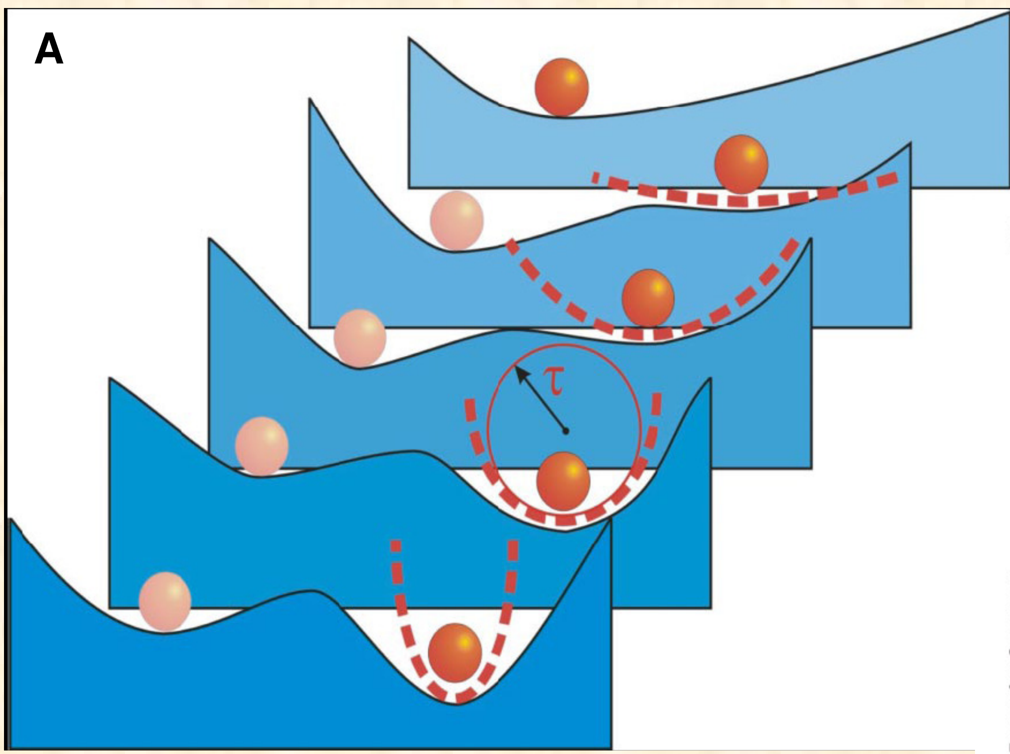
Hare & Mantua, 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Prog. Oceanogr. 47, 103-145.

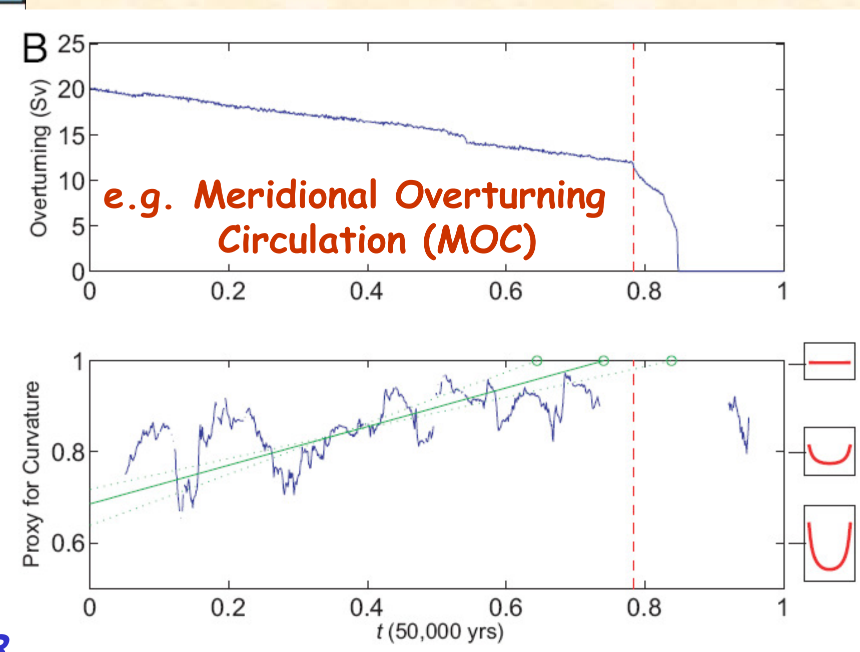
When Might a 'Regime Shift' Occur?

When a "tipping point" is reached:

a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system.

⇒ **introduces the concepts of**
Multiple 'Preferred' States
& Hysteresis

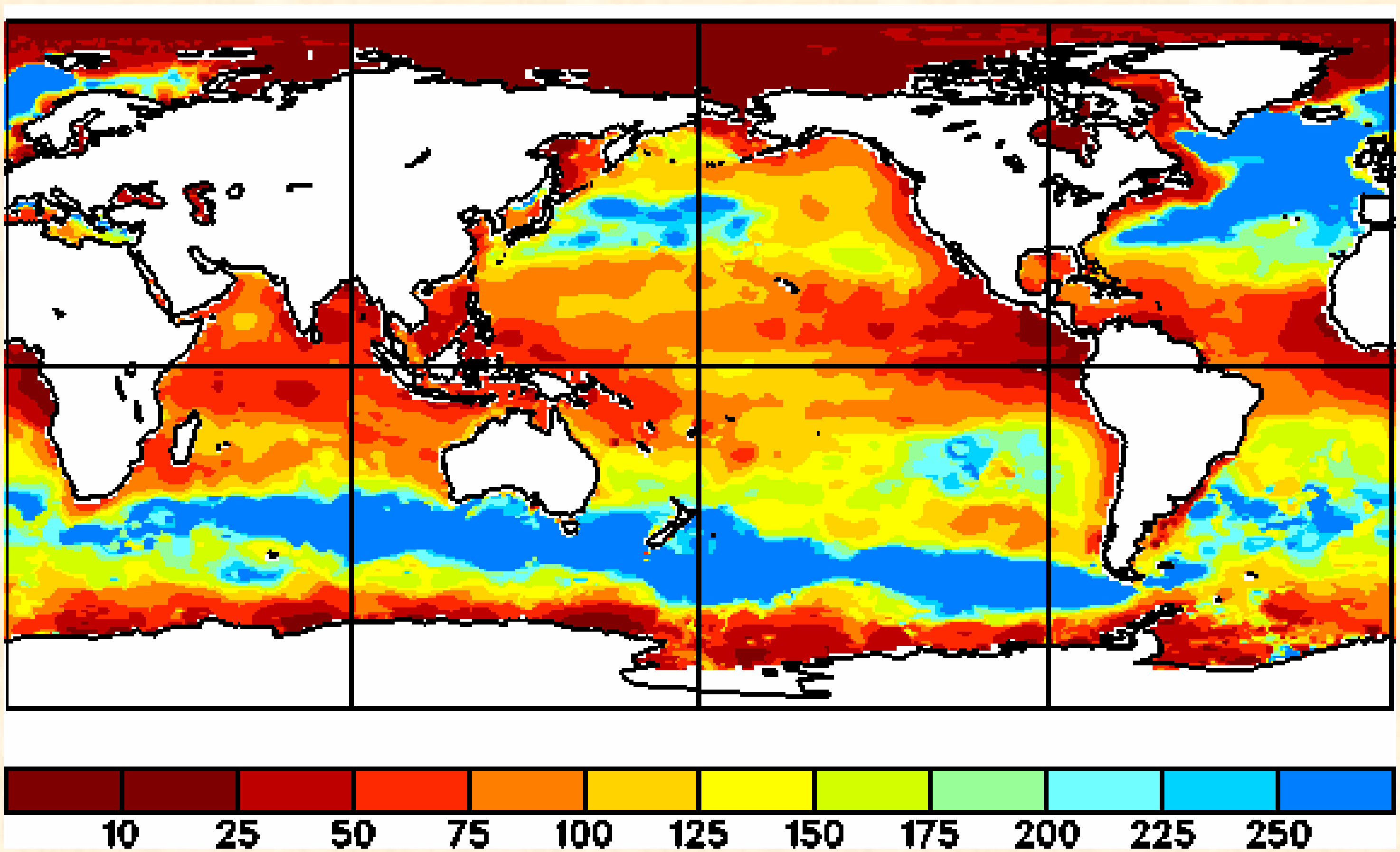




Lenton et al., 2008. Tipping elements in the Earth's climate system, PNAS, 105, 1786-93.

maxMLD: Present-day Climatology

World Ocean Atlas + Polar Hydrographic Climatology



Meters

from Bill Merryfield, CCCMA

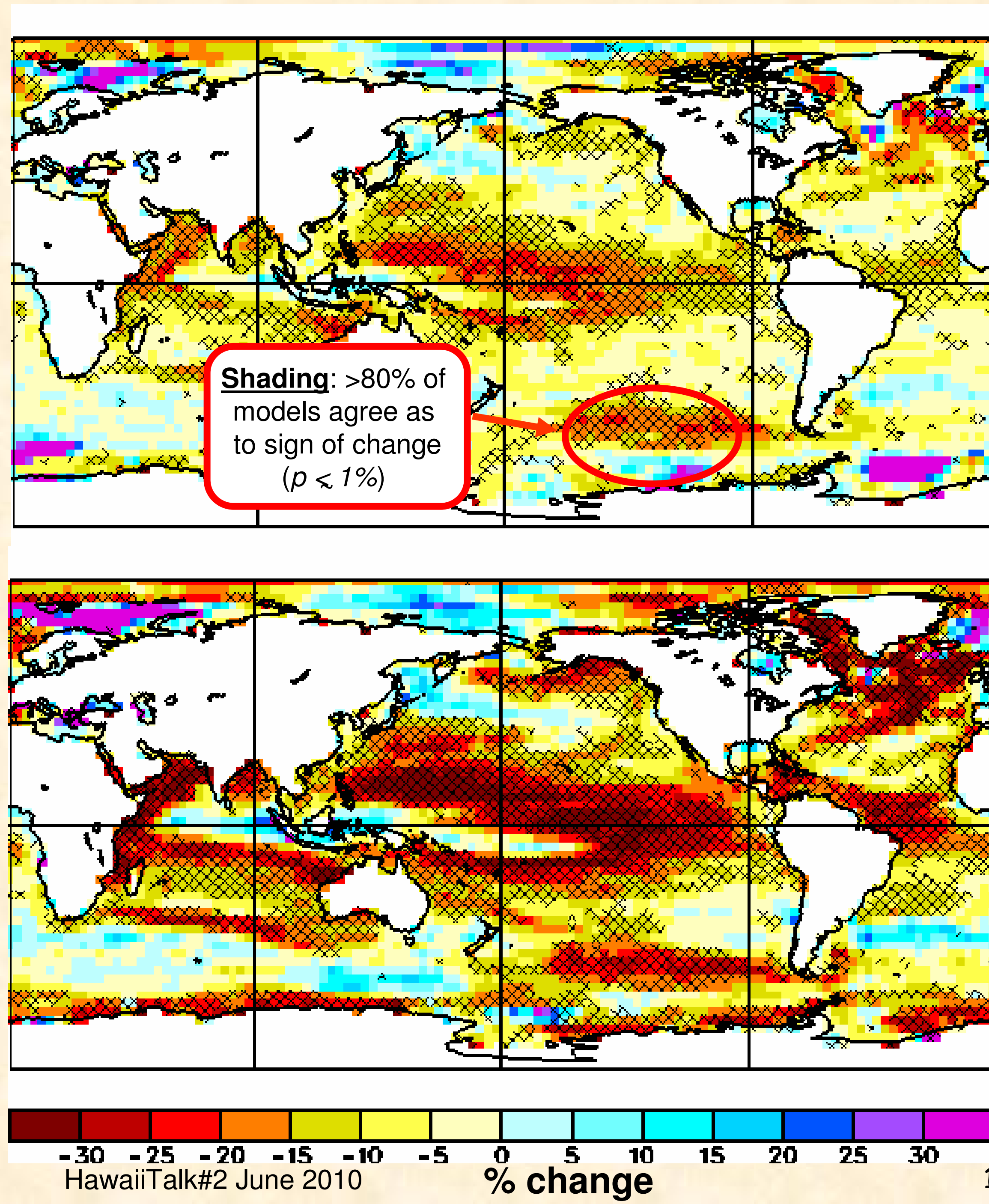
Projected 21st Century Changes

ΔmaxMLD

(2040-49) – (1990-99)

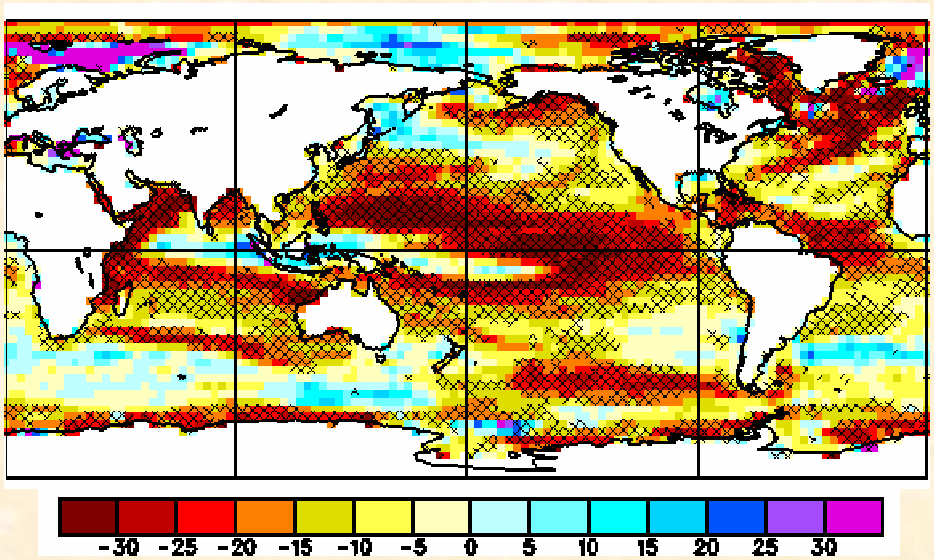
Multi-model ensemble
17 IPCC AR4 models

(2090-99) – (1990-99)

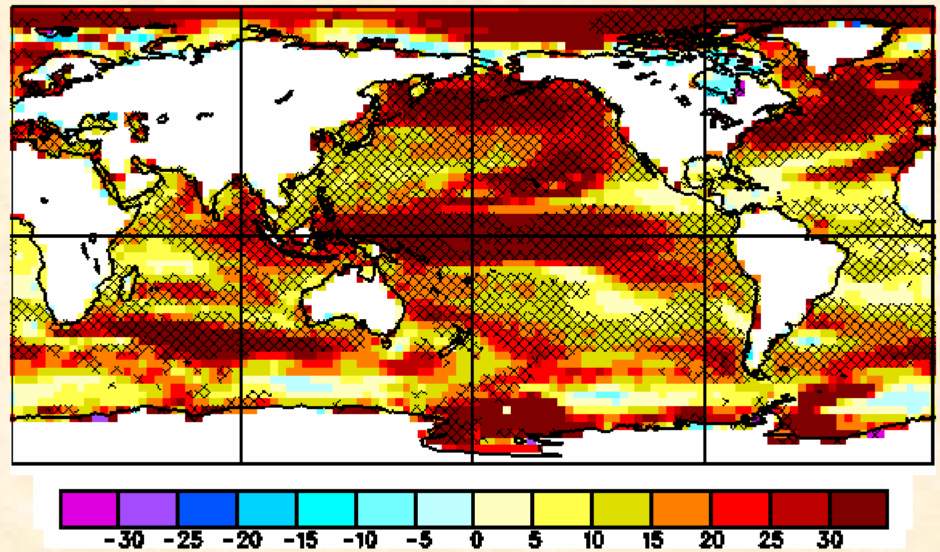


21st Century Changes from Multi-Model Ensemble

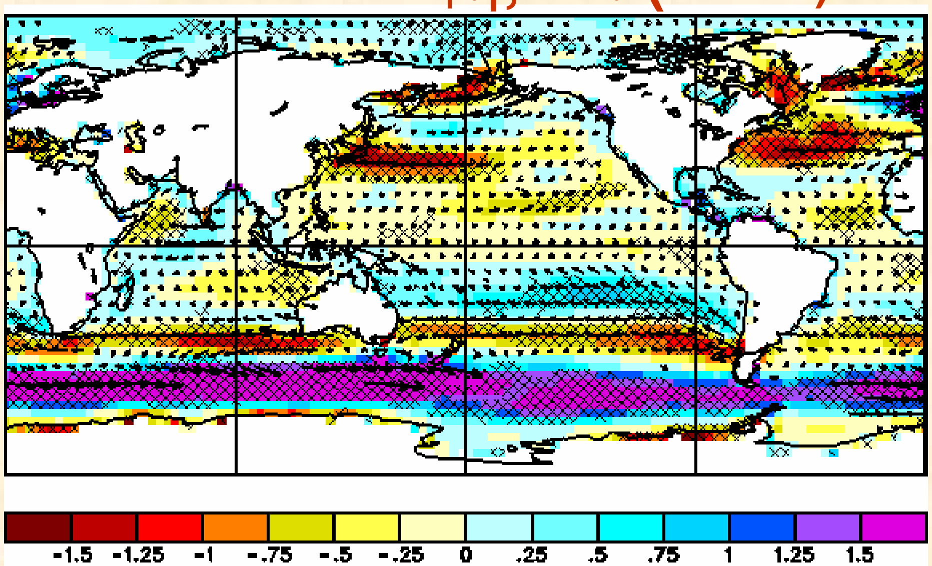
Δ maxMLD %



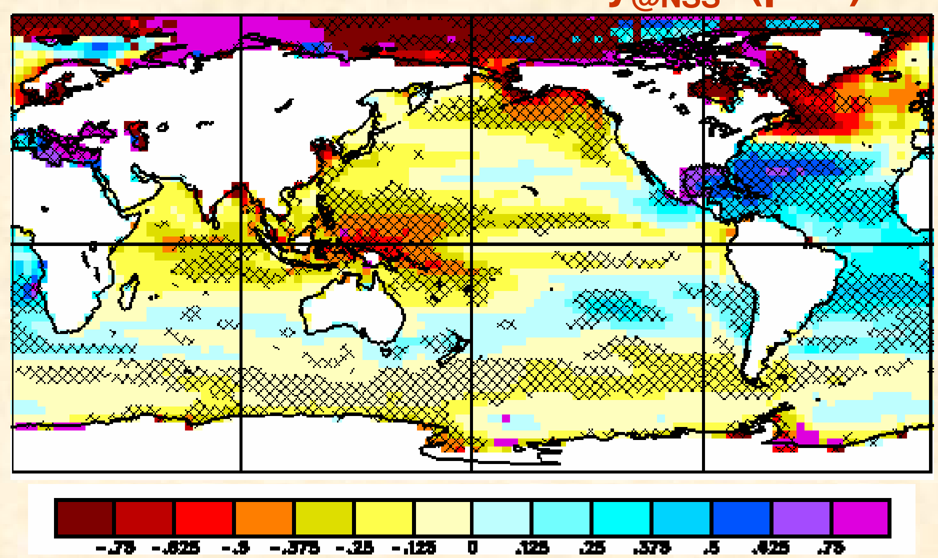
Δ max Near Surface Stratification %

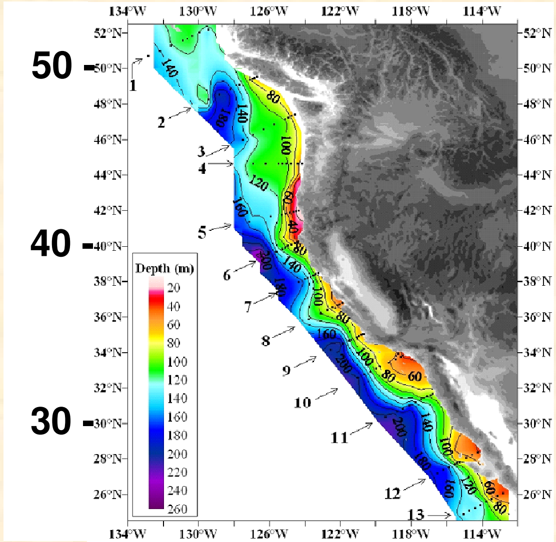


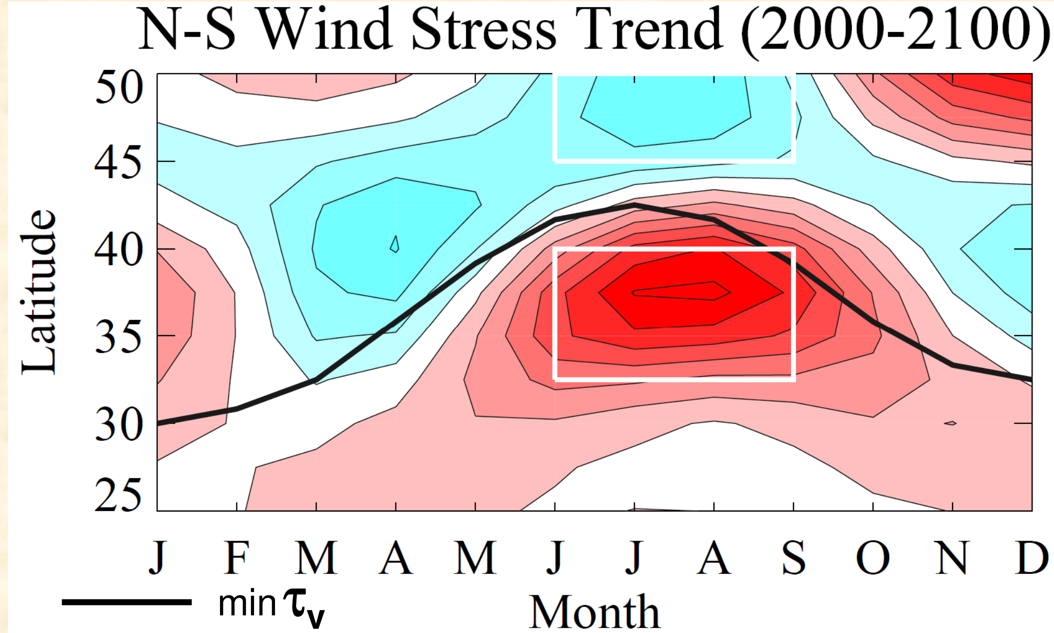
Wind Stress Δ|τ|, Δτ (10^{-2} Pa)



Δ Sea Surface Salinity$_{@NSS}$ (psu)

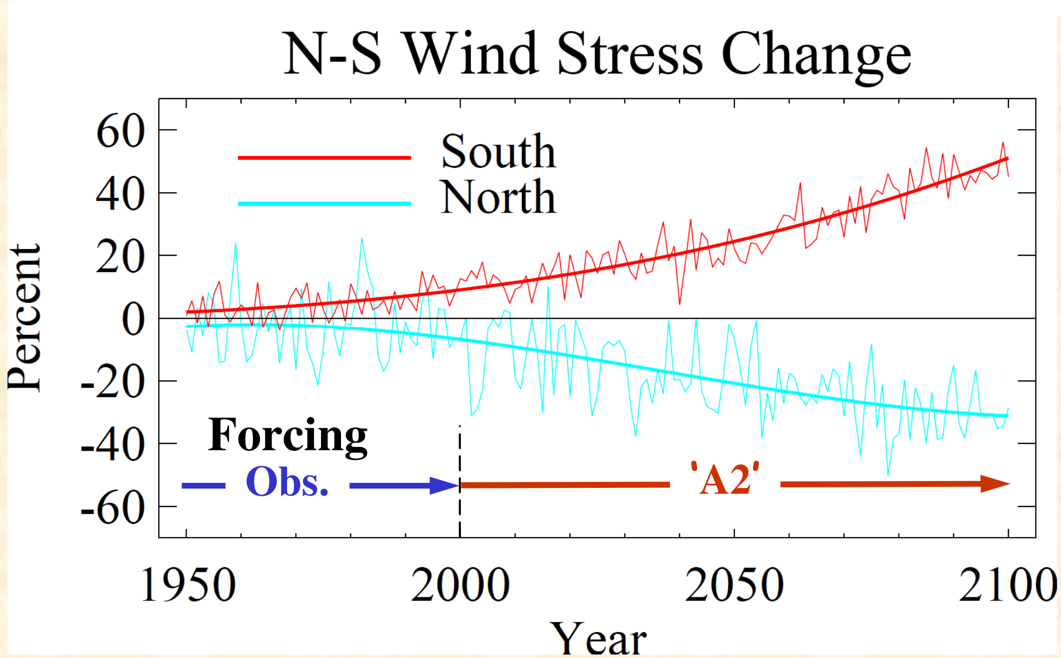






Multi-Model Projection of Upwelling Winds off Western North American Coast

'A2' 15 models



from John Fyfe, CCCMA

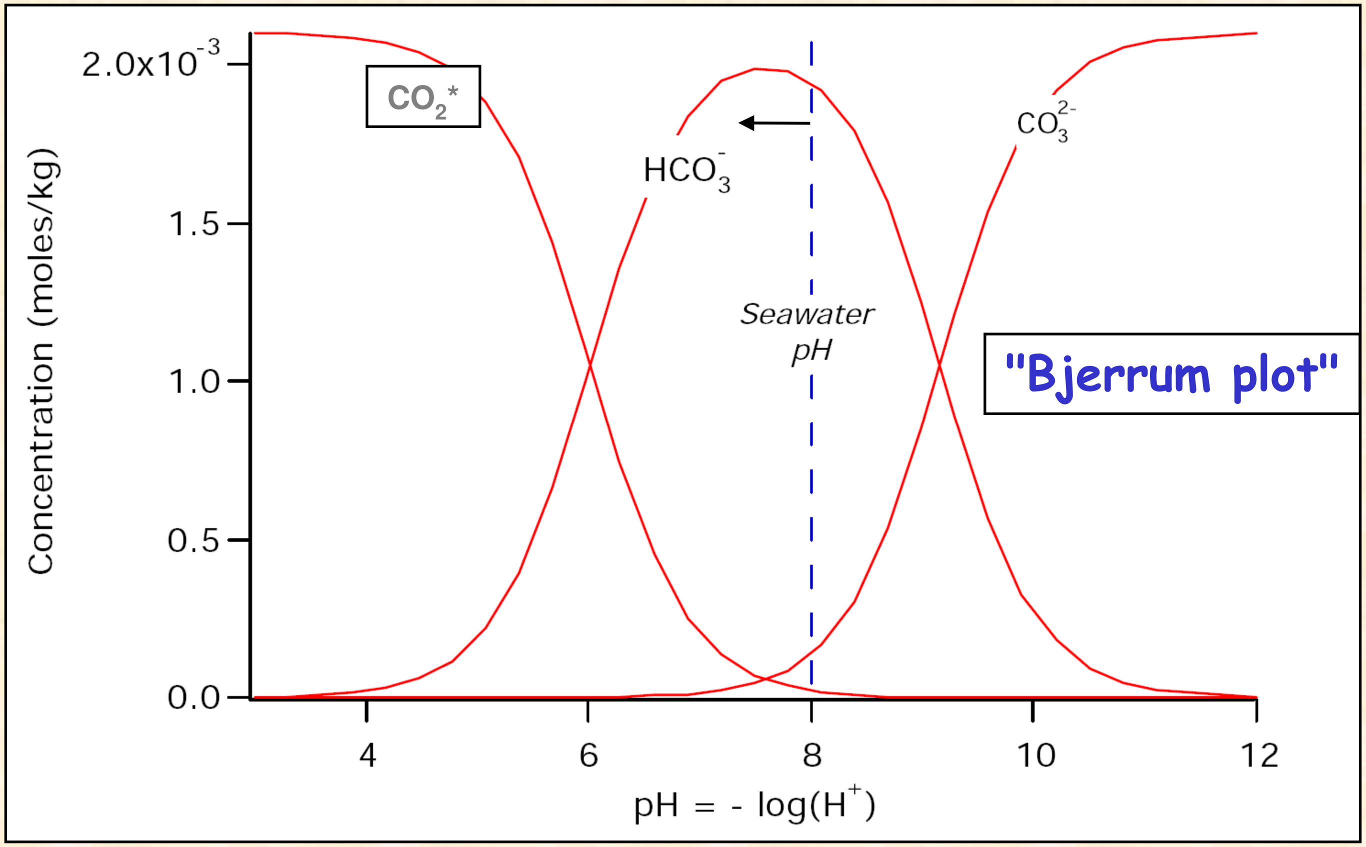
Dominant Physical Changes Expected in the N Pacific

- **Surface layer warming**
- **Surface layer freshening**
- **Shallowing of upper mixed layer**
- **Increased stratification at base of mixed layer**
  - less 'diffusion' of oxygen downwards
  - less 'diffusion' of nutrients upwards
- **Possible changes in wind patterns and/or storm tracks??**

Adding CO_2 Increases Ocean Acidity

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

$$CO_2 + H_2O + CO_3^{2-} \Rightarrow 2HCO_3^-$$



Open Ocean pH Is Decreasing

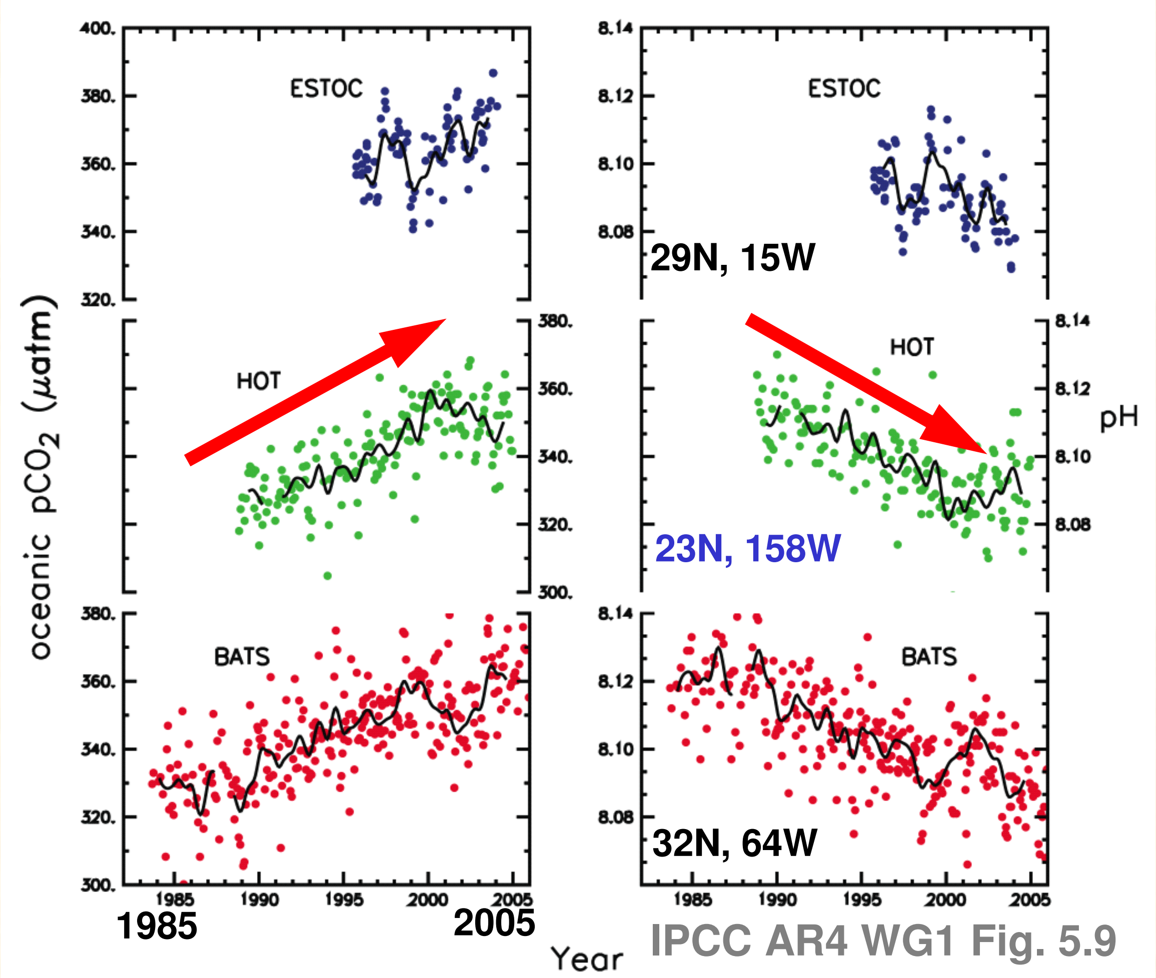
Left

- *Surface pCO_2 increases with time*

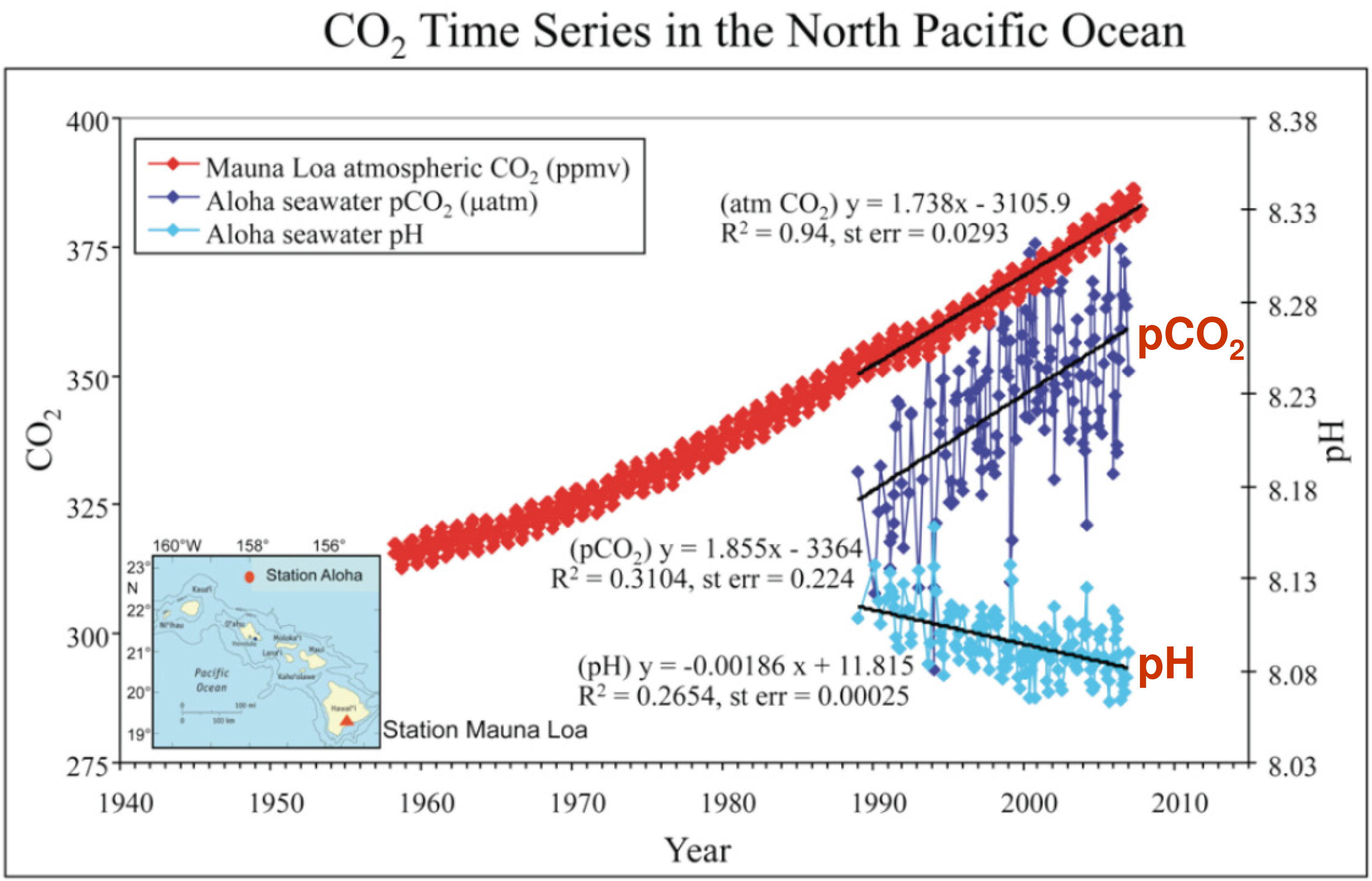
Right

- *Surface pH decreases*

pH = -log [H⁺]

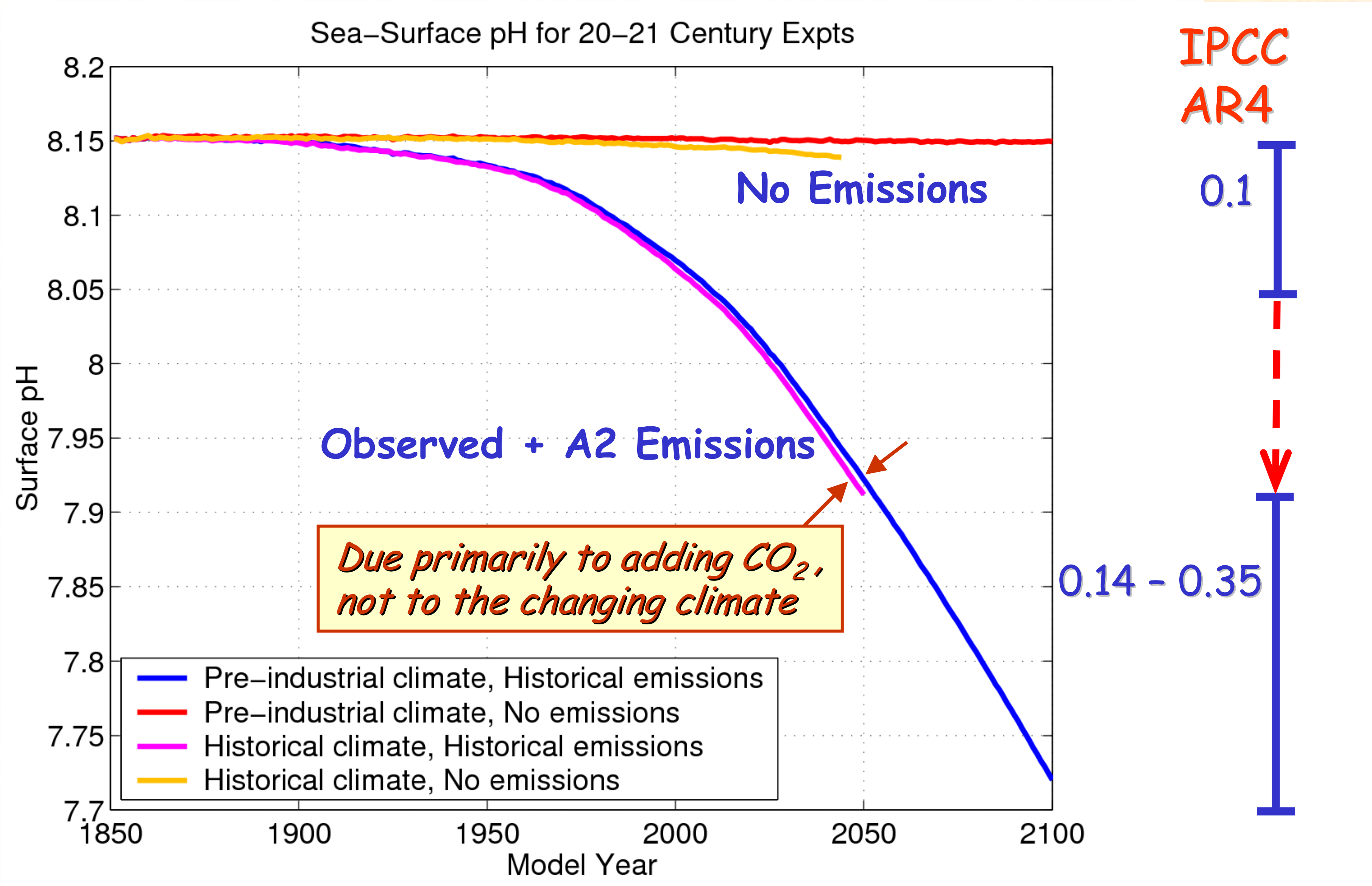


Ocean Surface *p*CO_2 Tracks Atmospheric pCO_2

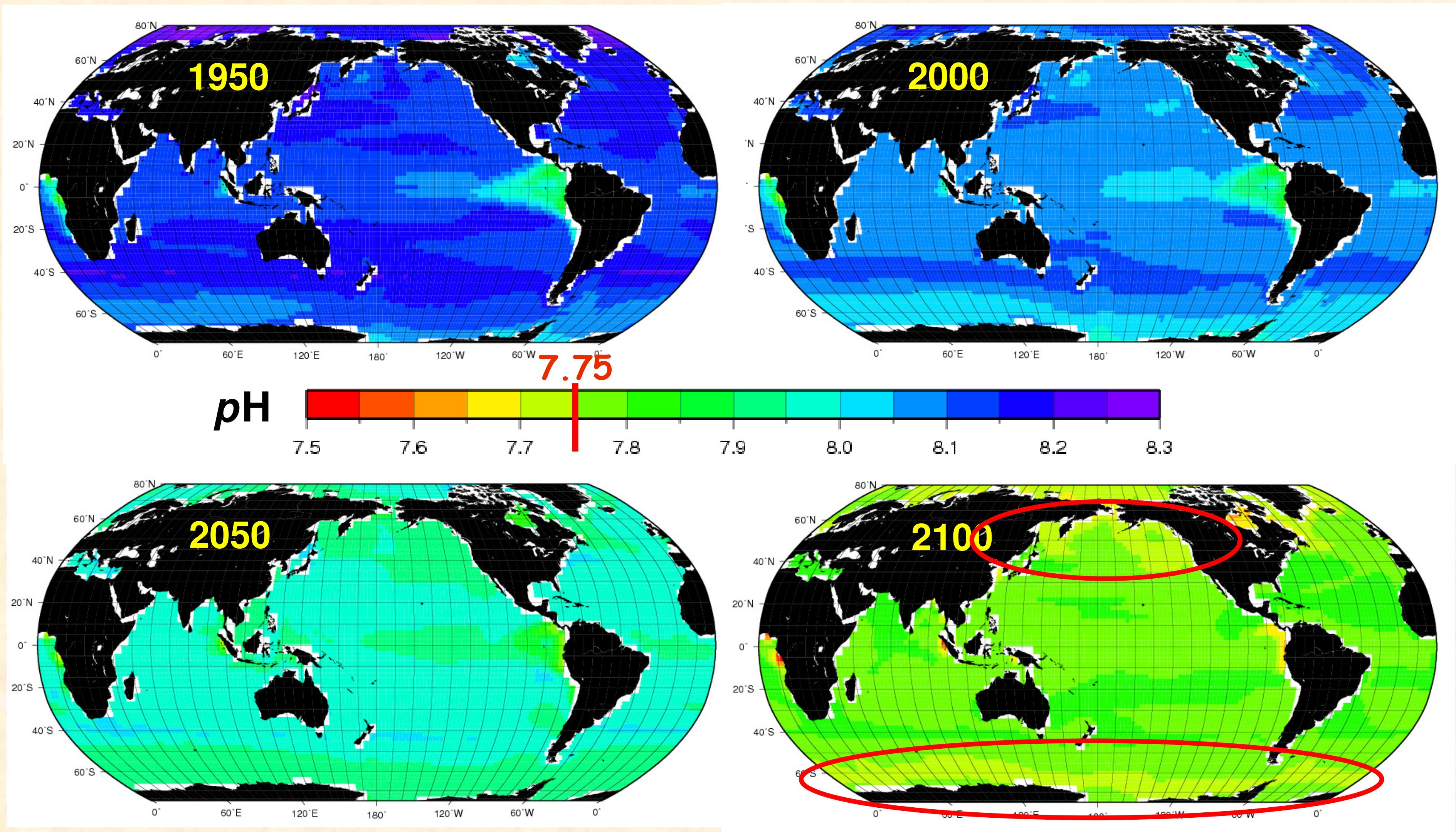


Iglesias-Rodriguez et al., 2010. Plenary Paper, OceanObs09, ESA Publ. WPP-306 (adapted from Dore et al., 2009. PNAS, 106:12235).

CCCma Ocean Model Surface pH Decrease



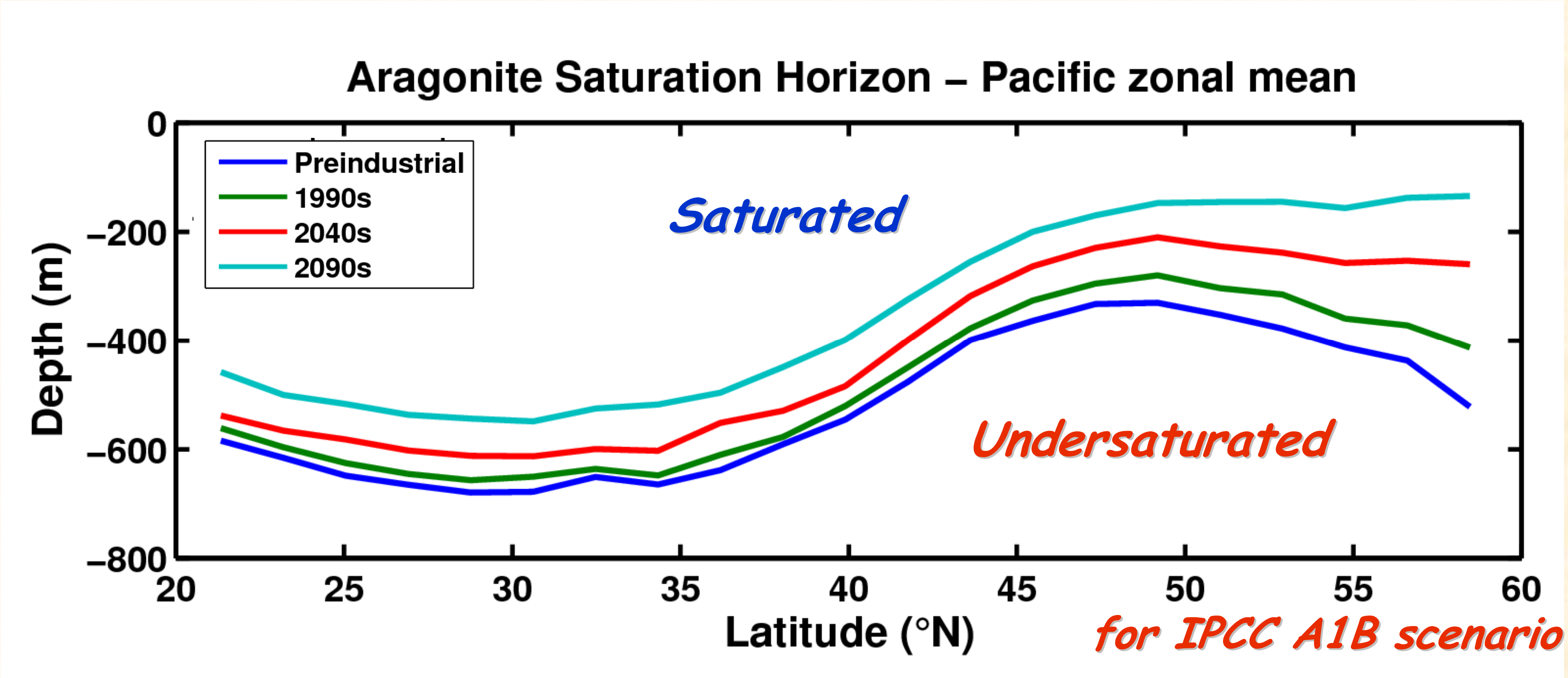
The Acidification of the World Ocean



'A2' Scenario from the Canadian Centre for Climate Modelling and Analysis (CCCMA) Earth System Model CanESM1: ***Zahariev, Christian & Denman, 2008; Arora et al., 2009, J. Climate; Christian et al., 2010, JGR-Biogeosciences***

Increasing Acidity is Reducing $CaCO_3$ Saturation Depths:

N. Pacific Zonal Average



Results from CCCMA coupled carbon climate model CanESM1

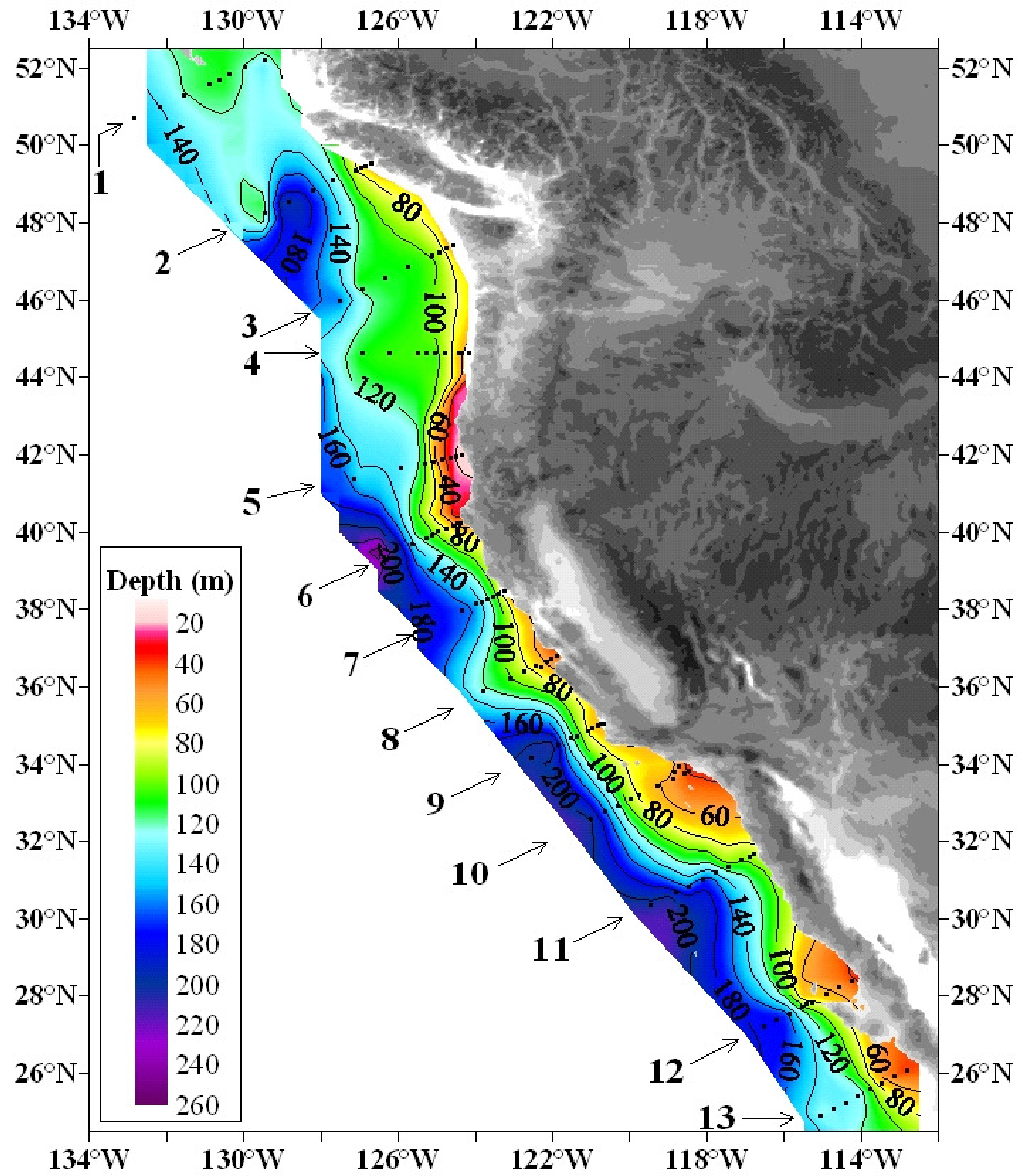
- Calcite levels are about 150 - 200m deeper than aragonite shown
- Rate of shoaling will accelerate this century

[prepared by J. Christian]

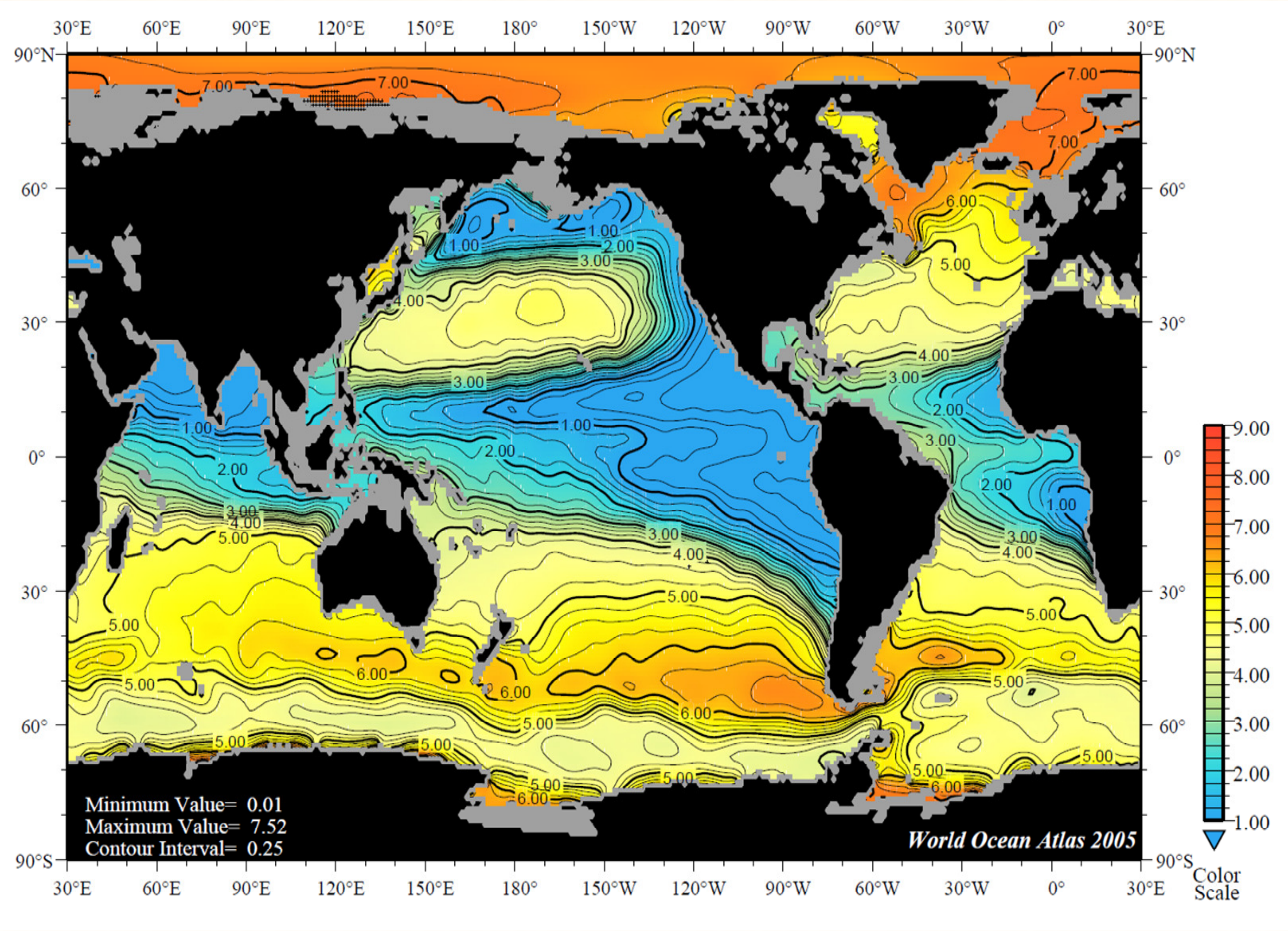
Depth of 'Corrosive' pH < 7.75 Waters on Continental Shelf

Feely et al., 2008, Science

"…without the anthropogenic signal, the equilibrium aragonite saturation level … would be deeper by about 50 m across the shelf, …"



Regions of Low Dissolved Oxygen



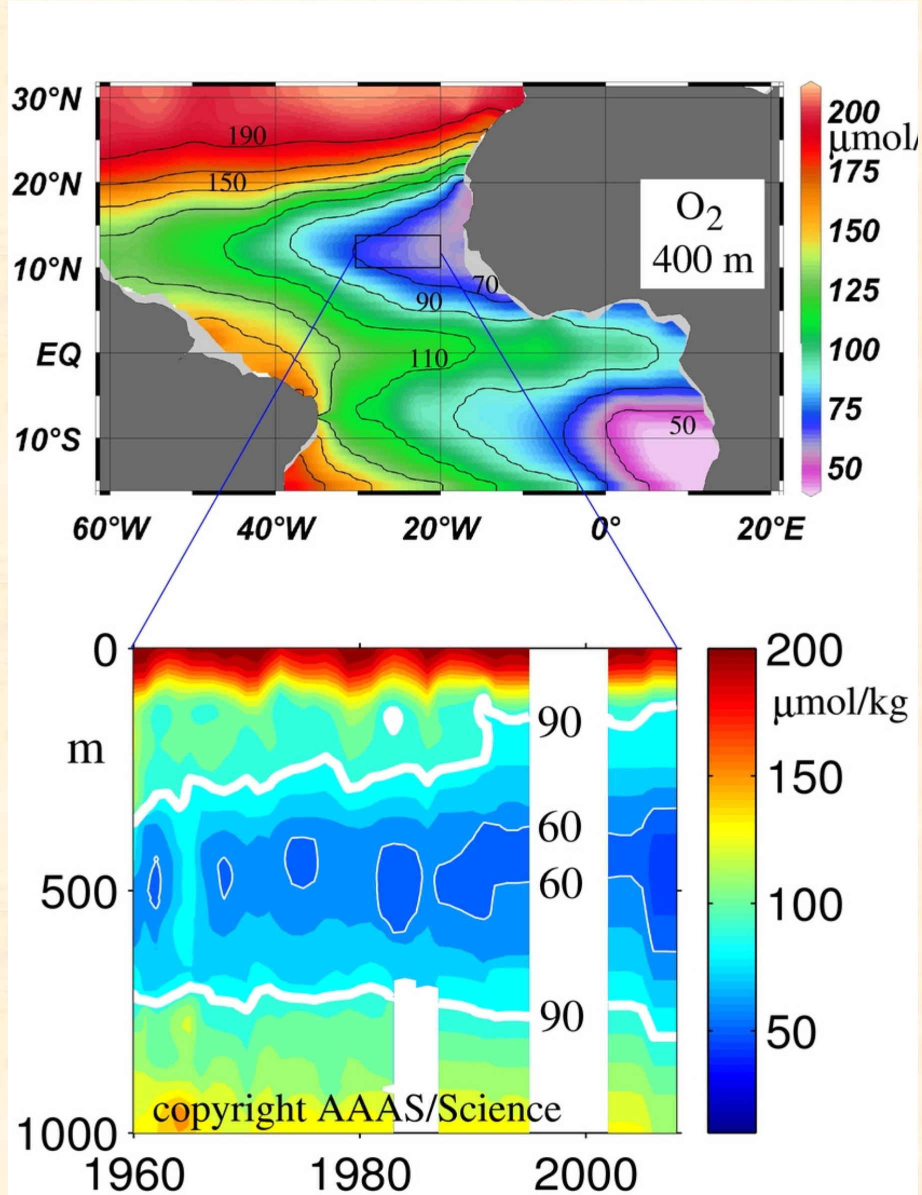
Climatological mean dissolved Oxygen (mL/L) at a depth of 400 m.

1.15 mL / L ≅ 50 μmol / kg

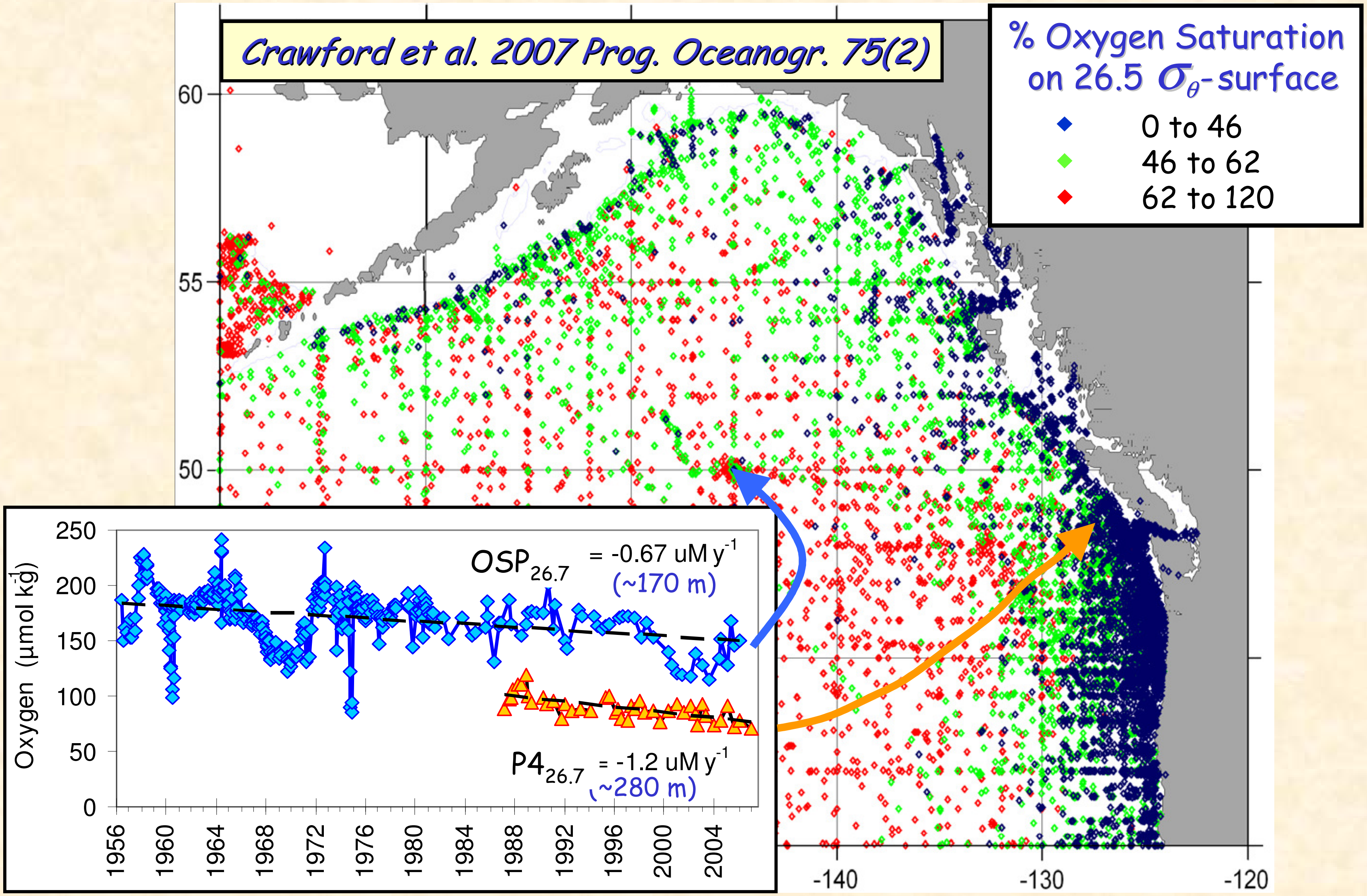
Expanding O_2 Minimum Zones in the Tropical Oceans

Data from Area *'A'*

Stramma et al., 2008, Science, 320.

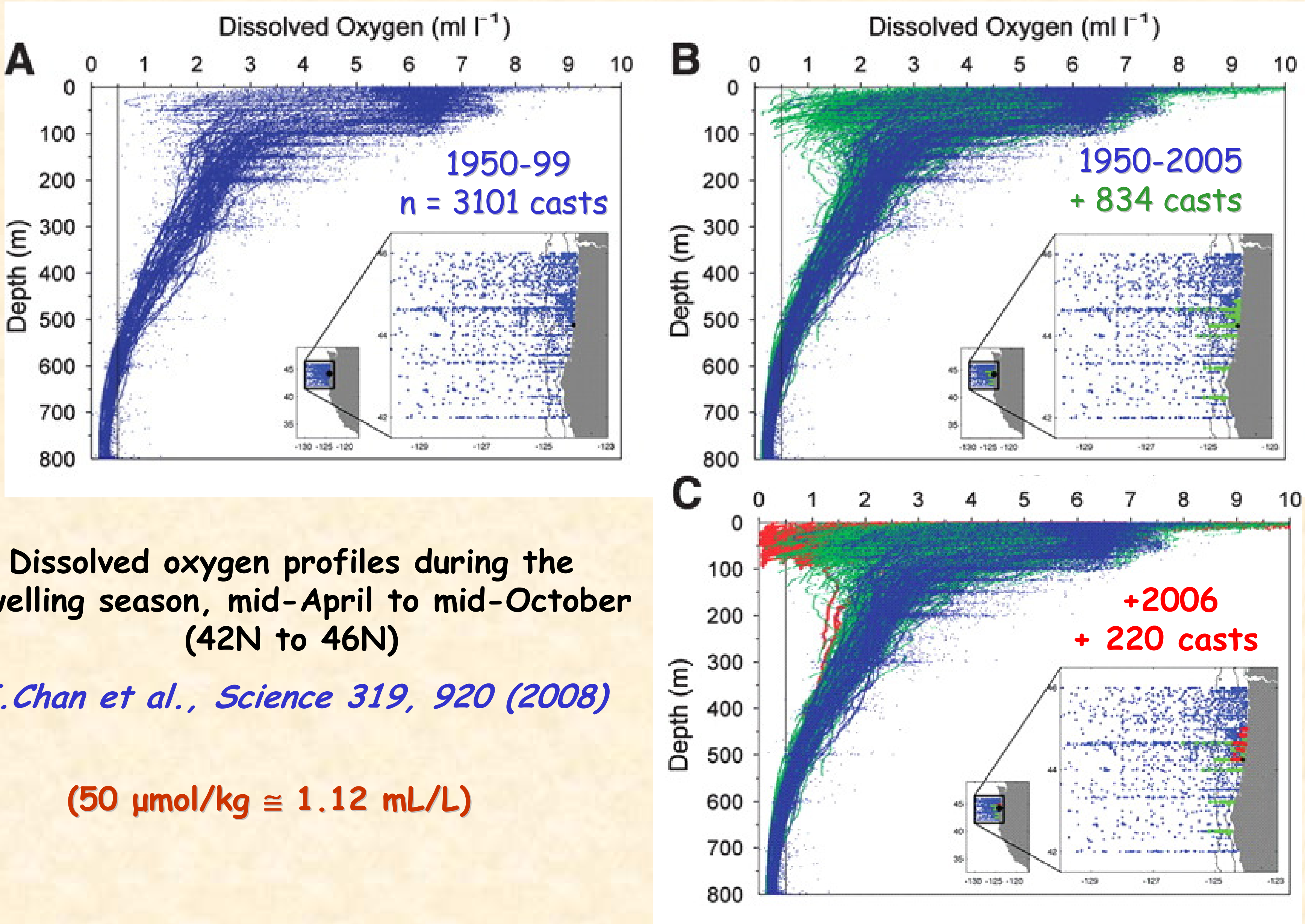


Dissolved O_2 in NE Pacific



F. Whitney, in: DFO Ocean Status Report 2006, W. Crawford (ed.)

Recent O_2 Changes off Oregon



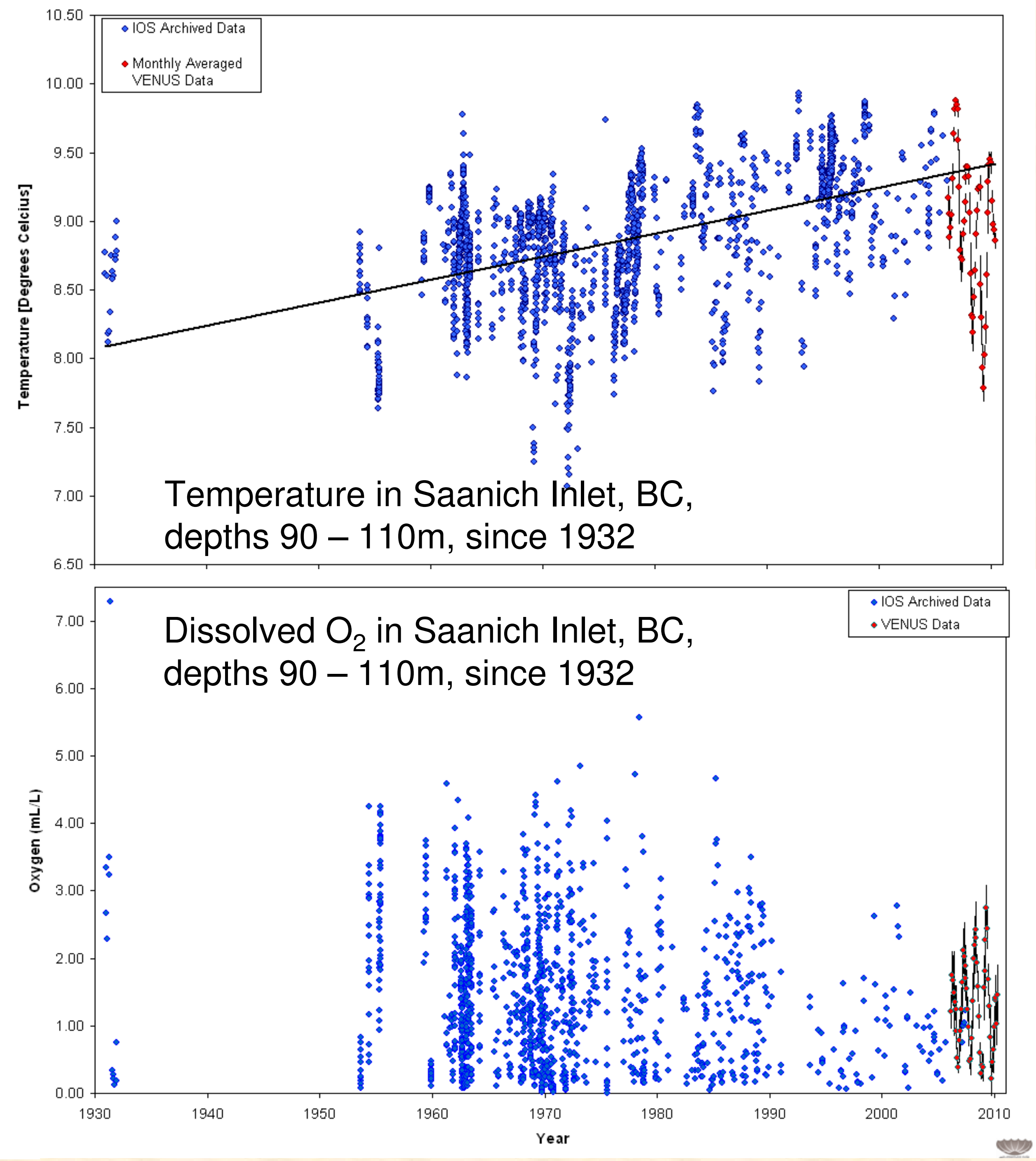
Dissolved oxygen profiles during the upwelling season, mid-April to mid-October (42N to 46N)

F.Chan et al., Science 319, 920 (2008)

(50 µmol/kg ≅ 1.12 mL/L)

Declining O_2 in an Inshore Coastal Fjord in BC, Canada

Red circles ● are from the VENUS ocean observatory



Remineralization Uses O_2 & Produces CO_2

Subsurface areas of low O_2 may also be areas of high CO_2 / low pH due to cumulative effect of *respiration / remineralization* of organic particulates by bacteria

In *aerobic* conditions:

Organic Matter 'OM' — *Loss*

$$C_{106}H_{175}O_{42}N_{16}P + 150\,O_2$$

$$\Rightarrow 106\,CO_2 + 16\,HNO_3 + H_3PO_4 + 78\,H_2O$$

Source — *Dissolved nutrients*

Equation from Sarmiento and Gruber, 2007. Ocean Biogeochemical Dynamics

New Energy-Based Respiration Index 'RI'

[P. Brewer & E. Pelzer, Science 324, p327,2009]

Simple oxic respiration: $C_{org} + O_2 \rightarrow CO_2$

The free energy relation is:

$$\Delta G = \Delta G^o - RT \ln\{[fCO_2] / [C_{org}][f\,O_2]$$

Rearranging, simplifying and replacing fugacity f with partial pressure p they write:

$$RI = \log_{10}(pO_2 / pCO_2)$$

The basic idea is that the lower the ambient O_2, the more energy it takes to transfer O_2 across the cell wall into the organism for respiration, and the higher the ambient CO_2, the more energy required to transfer CO_2 from respiration out of the cell into the surrounding water.

How Fast Can Organisms Adapt & Evolve?

1. Our foodweb models need parameters that 'adapt/change' in response to changing ocean conditions:
   - What is the species diversity within a functional group?
   - What is the phenotypic diversity (plasticity) within a species?
   - Is a century a long enough time for evolution via genetic mutations?
     - *Probably for bacteria and phytoplankton, maybe for zooplankton*
2. Which species will be threatened with extinction?
3. Need to develop relationships/models linking phenotypic diversity and current environmental variability, with ability to adapt to future conditions: *'Ecosystem evolution'* via *'adaptive dynamics'*

Potential impacts of ocean acidification on marine ecosystems and fisheries

Workshop at Conference on *'Climate change and its effects on fish and fisheries'*, Sendai Japan, April 2010

Co-Convenors:

Kenneth Denman, Yukihiro Nojiri, Hans Pörtner

The Key Question:

What are the responses and adaptive capacities of individual species and whole ecosystems to a multidecadal decrease in pH of 0.1 – 0.5 units?

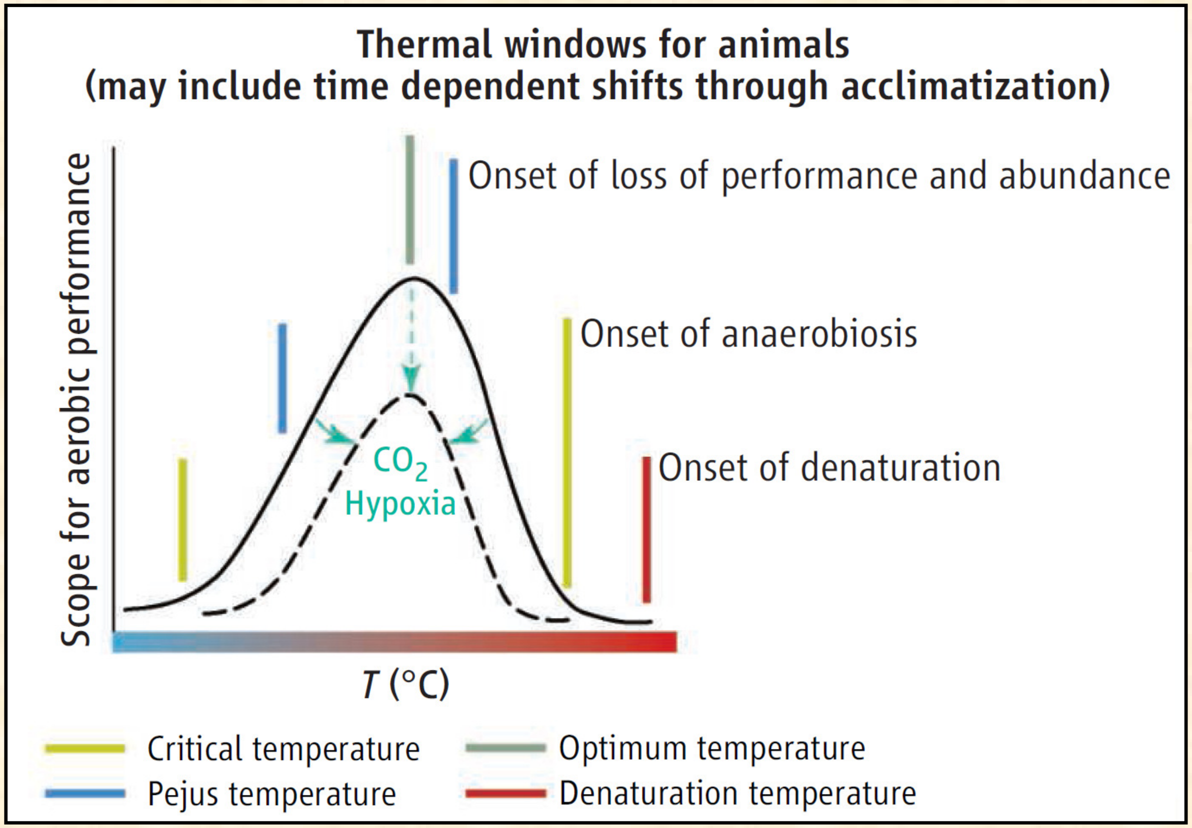
pH = - log ([H⁺])

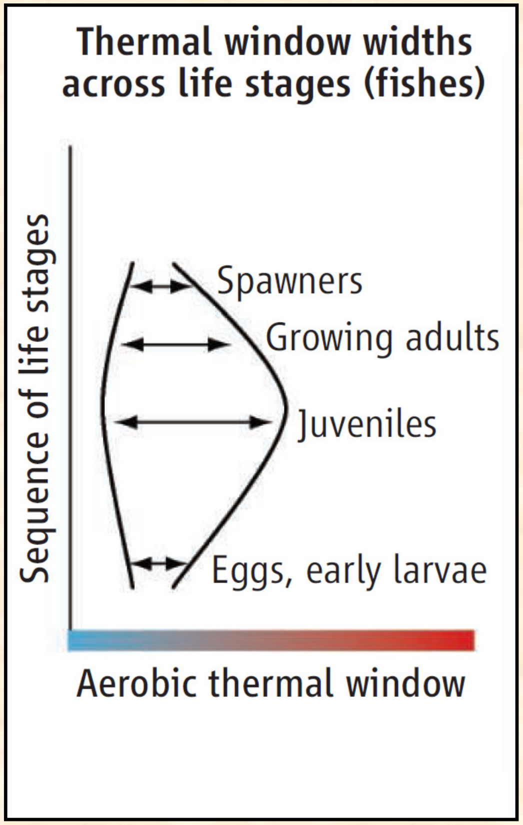
Animal Physiology and Climate Change

Basic respiration reaction:

$$C_{org} + O_2 \rightarrow CO_2$$

Rate is function of (Temperature, O_2, CO_2)





H. Pörtner & A. Farrell, 2008. Science 322, 690-692.

Thanks

ken.denman@ec.gc.ca