THE ROYAL SOCIETY
CELEBRATING 350 YEARS

CO_2-CarbonCycle-Climate-Interactions C^4I

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BRIDGE

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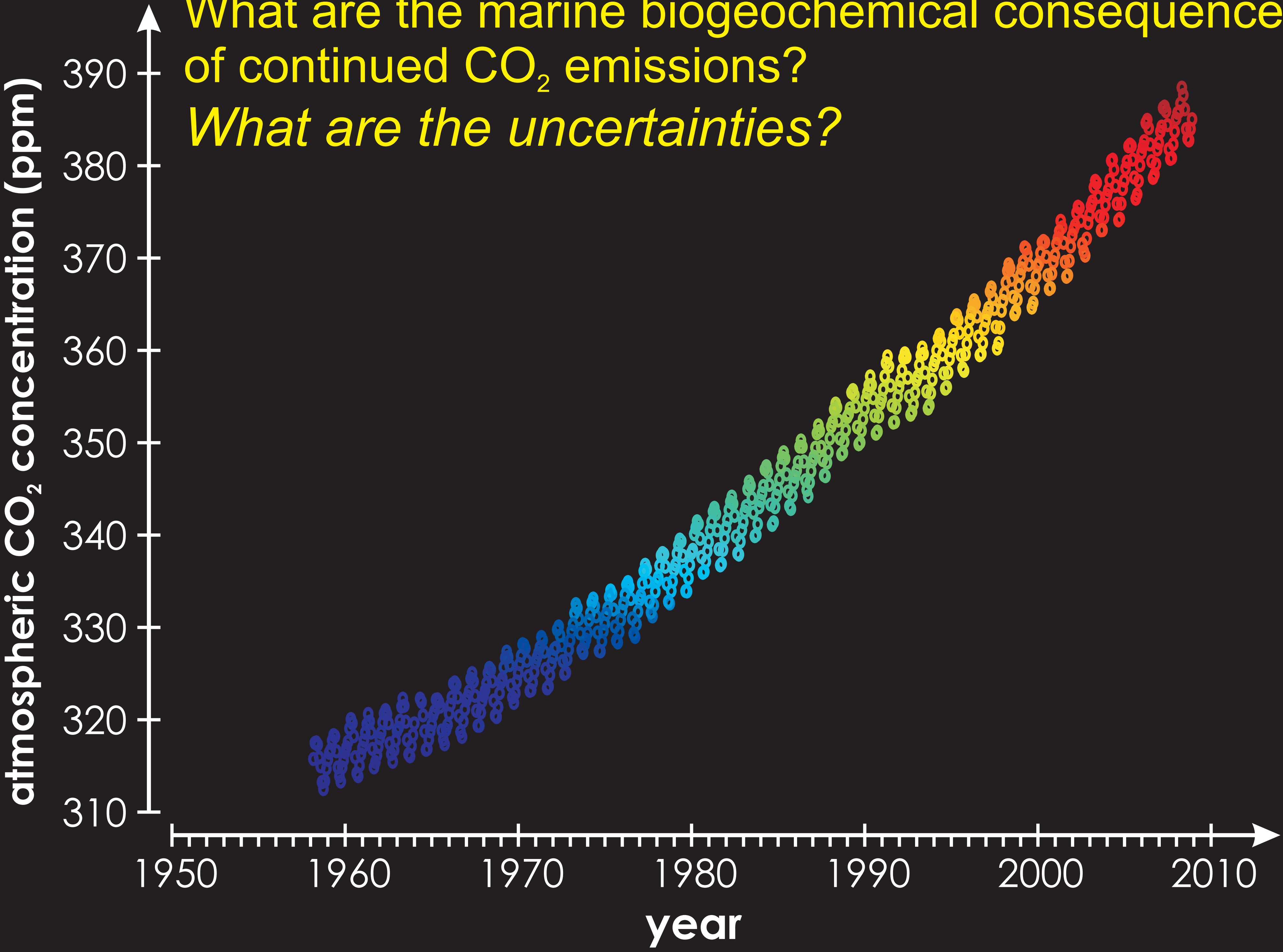
What are the marine biogeochemical consequences of continued CO_2 emissions?

What are the uncertainties?

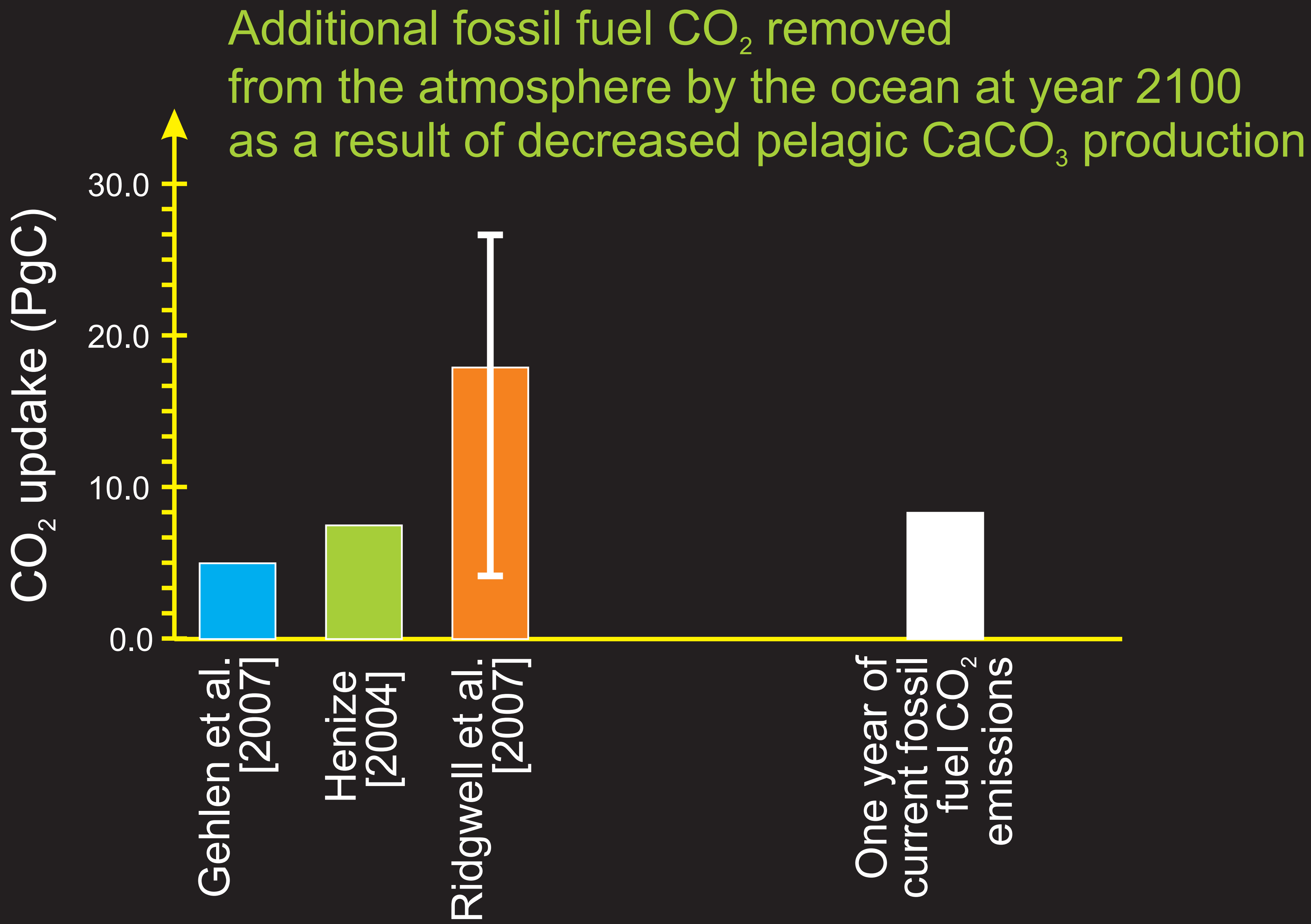


Calcification responses ($CaCO_3$ per cell per day) at elevated (~´2 to ´3) CO_2

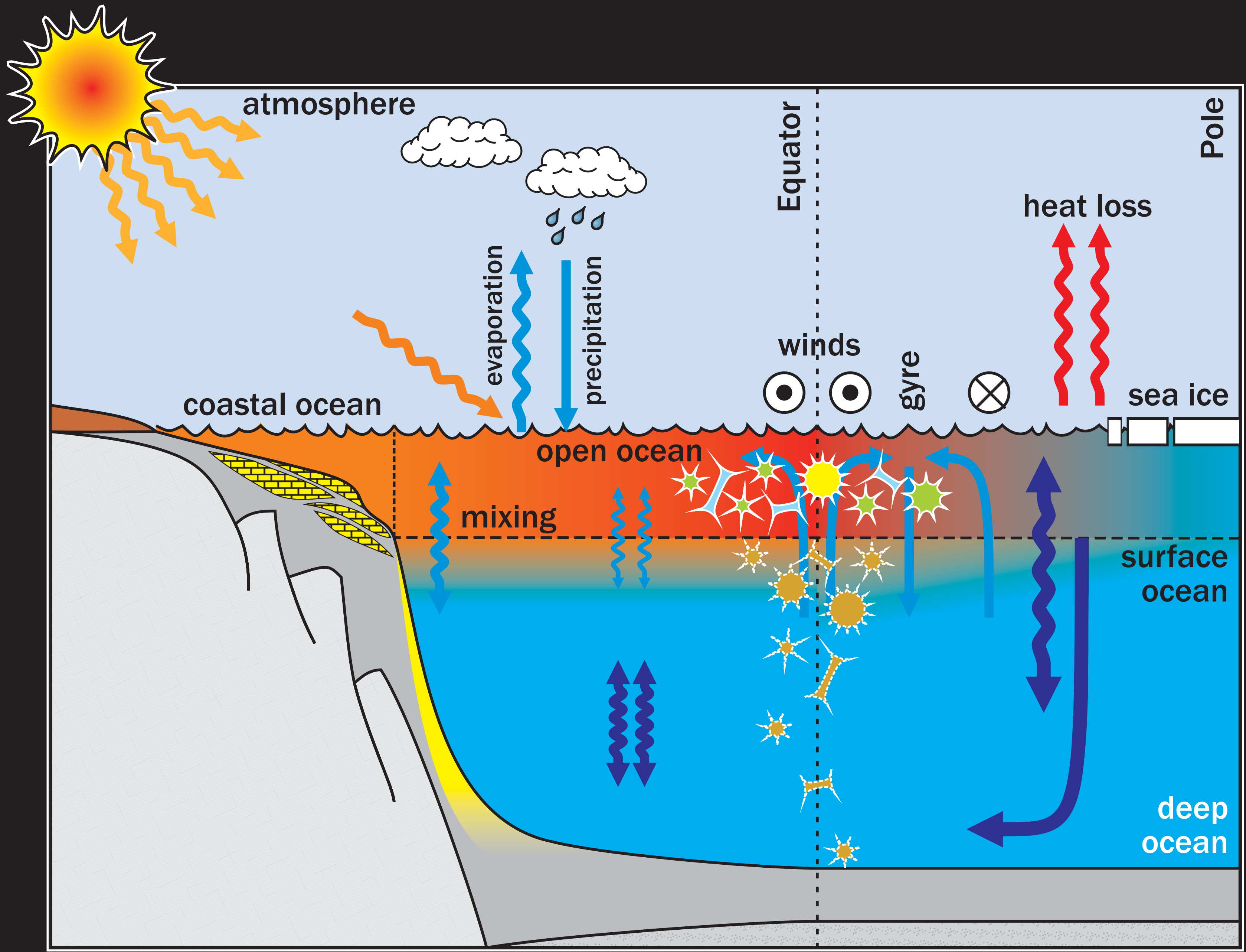
Species	Strain	Year location	Exp. design	Manipulation		Reference
Emiliania huxleyi	PML B92/11A	1992 North Sea	laboratory culture	acid/base	↓ (small)	Riebesell et al. [2000] Zondervan et al. [2001]
Emiliania huxleyi	PML B92/11A	1992 North Sea	laboratory culture	acid/base	↓	Riebesell et al. [2000] Zondervan et al. [2001]
Emiliania huxleyi	CAWPO6	1992 South Pacific	laboratory culture	CO_2 bubbling	↑	Iglesias-Rodriguez et al. [2008]
Emiliania huxleyi	MBA 61/12/4	1991 N. Atlantic	laboratory culture	CO_2 bubbling	↑	Iglesias-Rodriguez et al. [2008] (pers com)
Emiliania huxleyi	CCMP 371	1987 Sargasso Sea	laboratory culture	CO_2 bubbling	↓ (small)	Feng et al. [2008]
Emiliania huxleyi	CCMP 371	1987 Sargasso Sea	laboratory culture	CO_2 bubbling	↓	Feng et al. [2008]
Emiliania huxleyi	TW1	2001 W. Mediterranean	laboratory culture	CO_2 bubbling	↓	Sciandra et al. [2003]
Emiliania huxleyi	Ch 24-90	1991 North Sea	laboratory culture	CO_2 bubbling	↔	Buitenhuis et al. [1999]
Emiliania huxleyi	CAWPO6	1992 South Pacific	laboratory culture	CO_2 bubbling	↑	Shi et al. [2009]
Gephyrocapsa oceanica	PC7/1	1998 Portuguese shelf	laboratory culture	acid/base	↓	Riebesell et al. [2000] Zondervan et al. [2001]
Calcidiscus leptoporus	AC365	2000 S. Atlantic	laboratory culture	acid/base	↓↑	Langer et al. [2006]
Coccolithus pelagicus	AC400	2000 S. Atlantic	laboratory culture	acid/base	↔	Langer et al. [2006]

From: *Ridgwell et al.* [2009] (Biogeosciences)

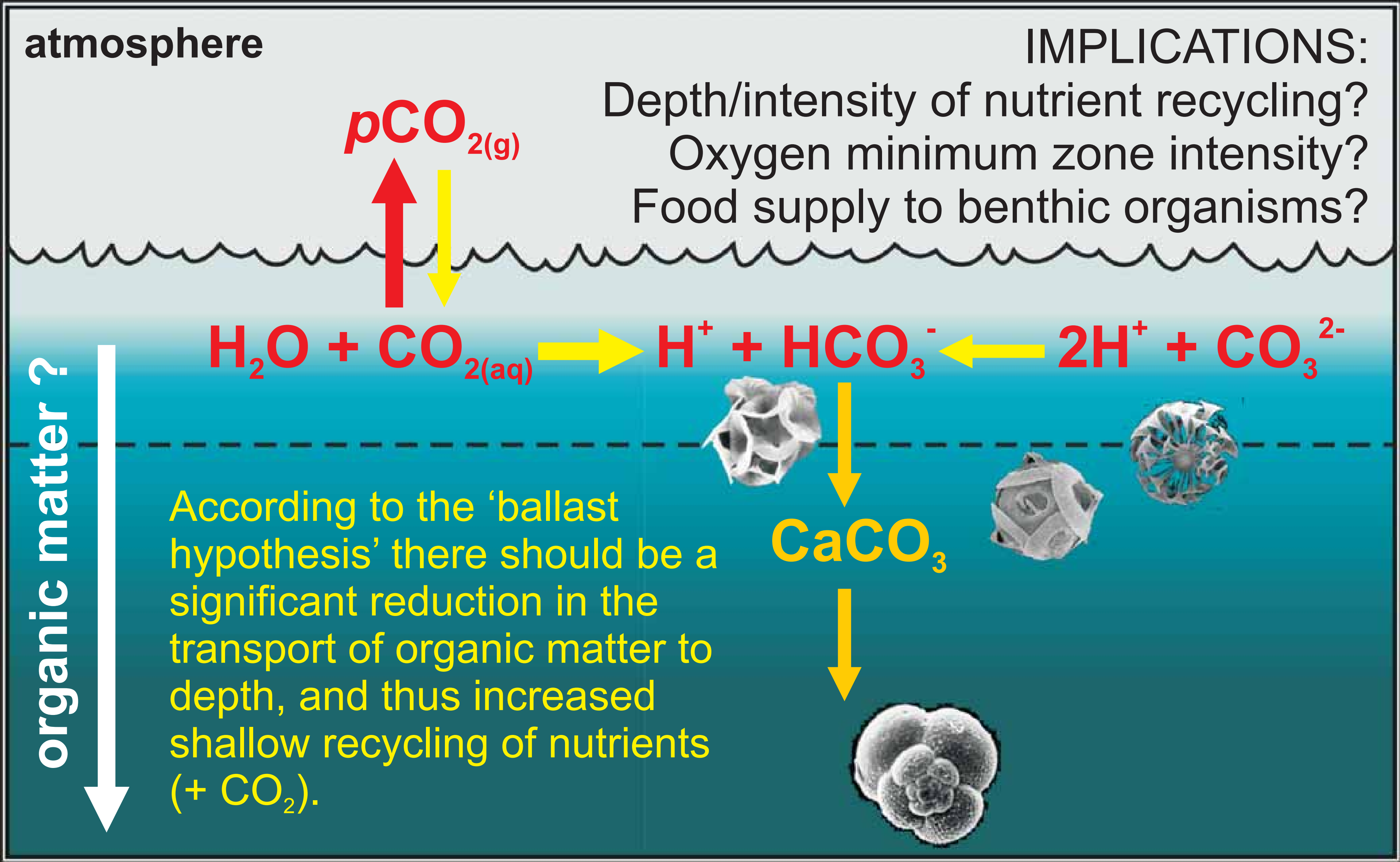
Global carbon cycle impacts



CO_2-CarbonCycle-Climate-Interactions



Global biogeochemical impacts in a High CO_2 World



2 The EnKF

The EnKF is now briefly described with focus on notation and the standard analysis scheme. The notation follows that used in Evensen (2003).

2.1 Ensemble representation for P

As in Evensen (2003), we have defined the matrix holding the ensemble members $\psi_i \in \Re^n$,

$$A = (\psi_1, \psi_2, \ldots, \psi_N) \in \Re^{n\times N}, \quad (1)$$

where N is the number of ensemble members and n is the size of the model state vector.

The ensemble mean is stored in each column of $\overline{A}$ which can be defined as

$$\overline{A} = A\mathbf{1}_N, \quad (2)$$

where $\mathbf{1}_N \in \Re^{N\times N}$ is the matrix where each element is equal to $1/N$. We can then define the ensemble perturbation matrix as

$$A' = A - \overline{A} = A(I - \mathbf{1}_N). \quad (3)$$

The ensemble covariance matrix $P_e \in \Re^{n\times n}$ can be defined as

$$P_e = \frac{A'(A')^T}{N-1}. \quad (4)$$

2.2 Measurement perturbations

Given a vector of measurements $d \in \Re^m$, with m being the number of measurements, we can define the N vectors of perturbed observations as

$$d_j = d + \epsilon_j, \quad j = 1, \ldots, N, \quad (5)$$

which can be stored in the columns of a matrix

$$D = (d_1, d_2, \ldots, d_N) \in \Re^{m\times N}, \quad (6)$$

while the ensemble of perturbations, with ensemble mean equal to zero, can be stored in the matrix

$$E = (\epsilon_1, \epsilon_2, \ldots, \epsilon_N) \in \Re^{m\times N}, \quad (7)$$

from which we can construct the ensemble representation of the measurement error covariance matrix

$$R_e = \frac{EE^T}{N-1}. \quad (8)$$

2.3 Analysis equation

The analysis equation, expressed in terms of the ensemble covariance matrices, is

$$A^a = A + P_e H^T (H P_e H^T + R_e)^{-1}(D - HA). \quad (9)$$

Using the ensemble of innovation vectors defined as

$$D' = D - HA \quad (10)$$

and the definitions of the ensemble error covariance matrices in Eqs. (4) and (8) the analysis can be expressed as

$$A^a = A + A'A'^T H^T \left(HA'A'^T H^T + EE^T\right)^{-1} D'. \quad (11)$$

When the ensemble size, N, is increased by adding random samples, the analysis computed from this equation will converge towards the exact solution of Eq. (9) with P_e and R_e replaced by the exact covariance matrices P and R.

We now introduce the matrix holding the measurements of the ensemble perturbations, $S = HA' \in \Re^{m\times N}$, and we define the matrix $C \in \Re^{m\times m}$ as

$$C = SS^T + (N-1)R, \quad (12)$$

and the ensemble approximation, C_e, of C as

$$C_e = SS^T + (N-1)R_e \quad (13)$$

$$= SS^T + EE^T. \quad (14)$$

Thus, we will consider the use of both a full-rank and exact measurement error covariance matrix R and the low-rank representation defined in Eq. (8).

The analysis equation (11) can then be written

$$A^a = A + A'S^T C^{-1} D' \quad (15)$$

$$= A + A(I - \mathbf{1}_N)S^T C^{-1} D' \quad (16)$$

$$= A(I + (I - \mathbf{1}_N)S^T C^{-1} D') \quad (17)$$

$$= A(I + S^T C^{-1} D') \quad (18)$$

$$= AX, \quad (19)$$

where we have used Eq. (3) and $\mathbf{1}_N S^T \equiv \mathbf{0}$. The matrix $X \in \Re^{N\times N}$ is defined as

$$X = I + S^T C^{-1} D'. \quad (20)$$

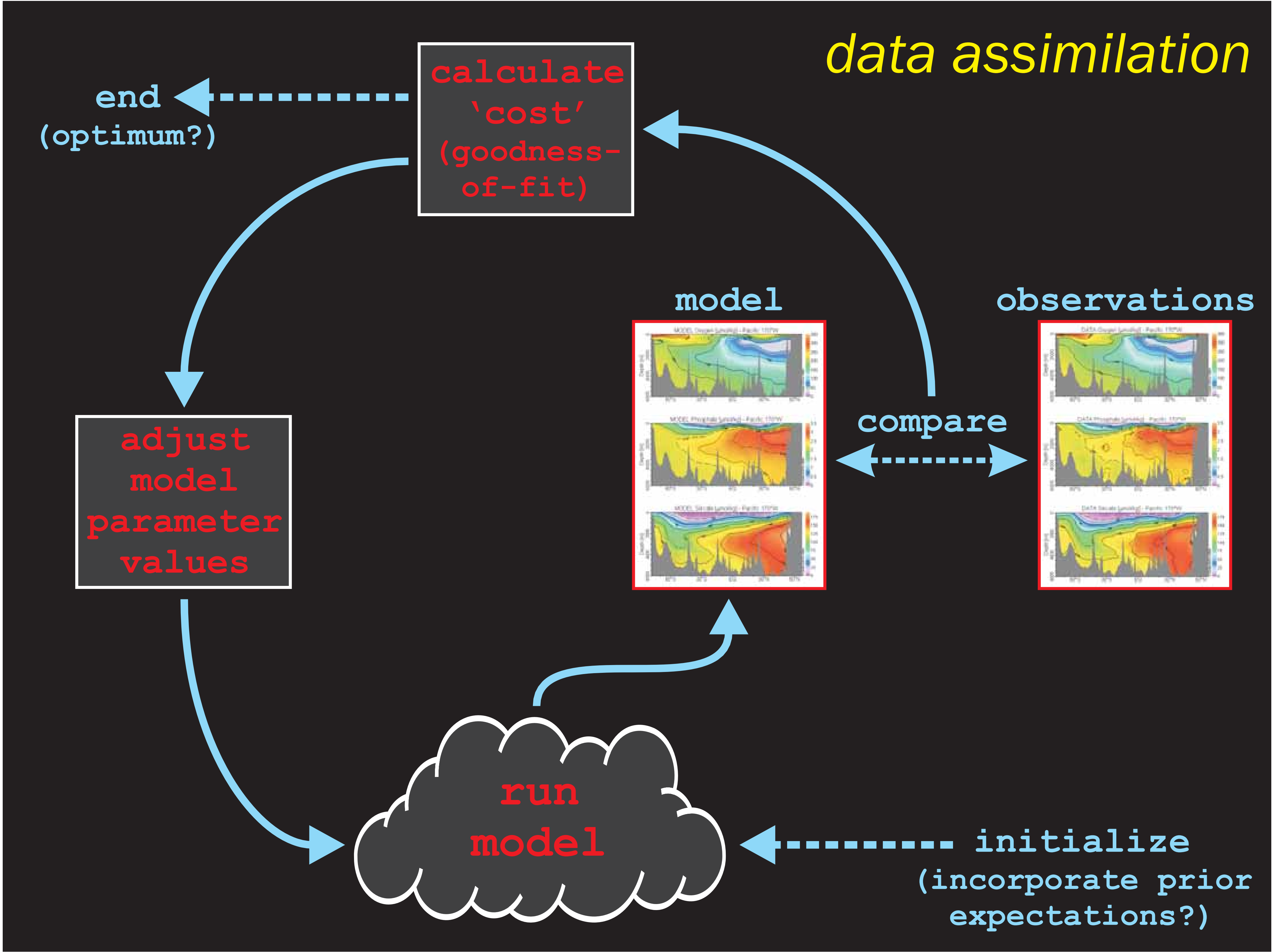
data assimilation

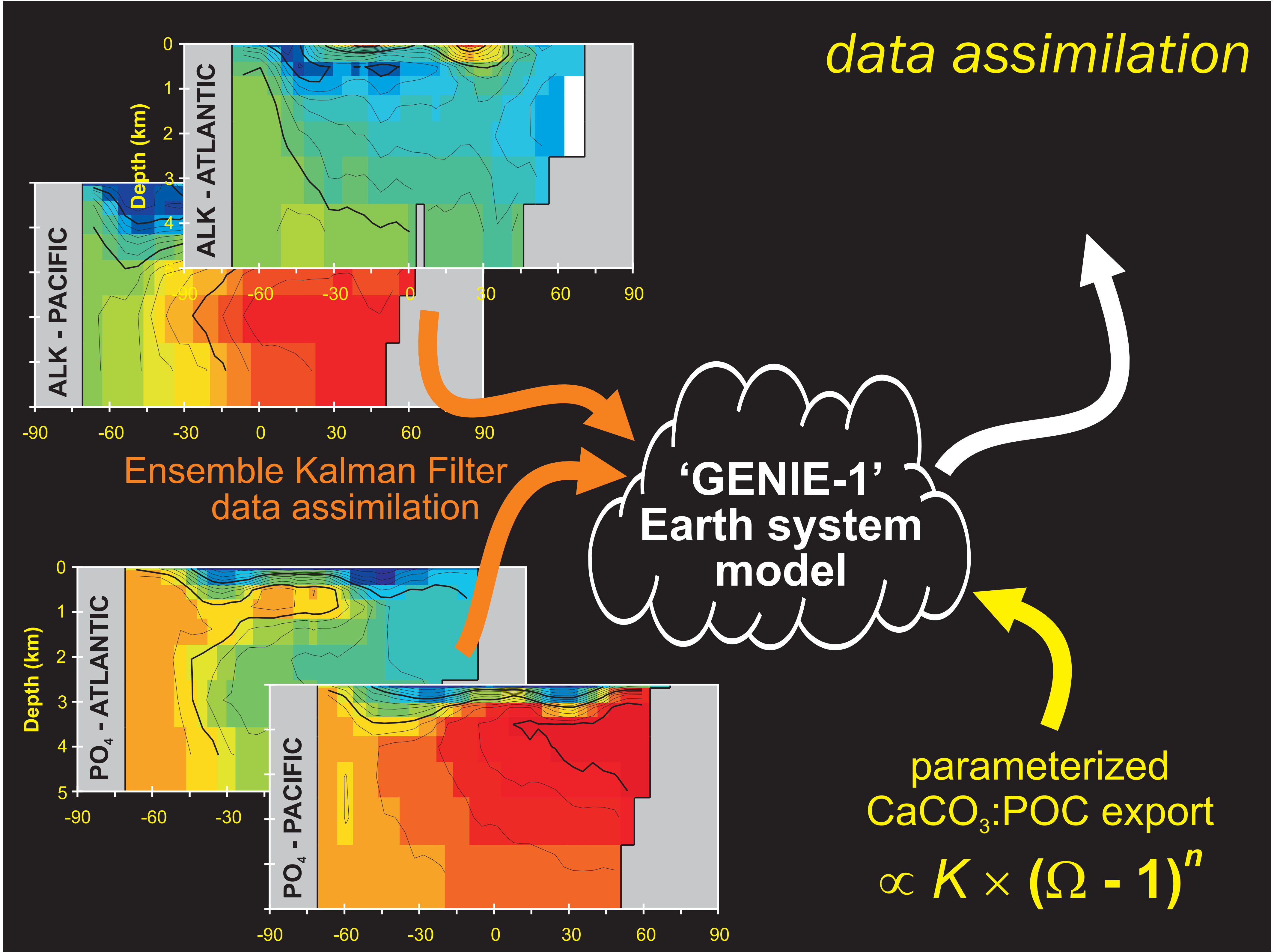
e.g., see:

Evensen [1994] (41 equations)

Evensen [2003] (125 equations)

Evensen [2004] (114 equations)


data assimilation
calculate 'cost' (goodness-of-fit)
end (optimum?)
adjust model parameter values
model
observations
compare
run model
initialize (incorporate prior expectations?)

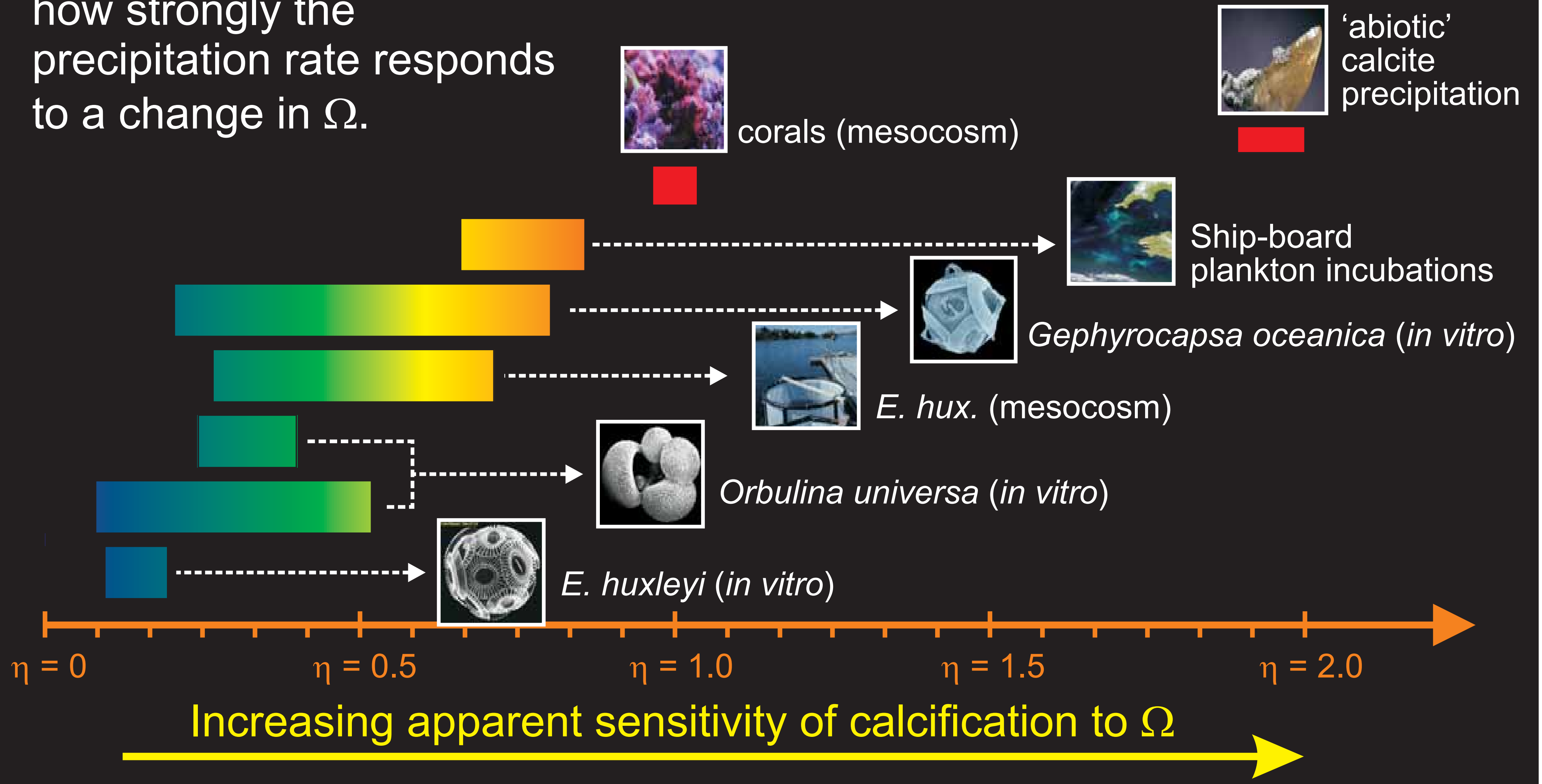

data assimilation
ALK - ATLANTIC
ALK - PACIFIC
Depth (km)
Ensemble Kalman Filter
data assimilation
'GENIE-1'
Earth system
model
PO4 - ATLANTIC
PO4 - PACIFIC
parameterized
CaCO3:POC export
∝ K × (Ω - 1)^n

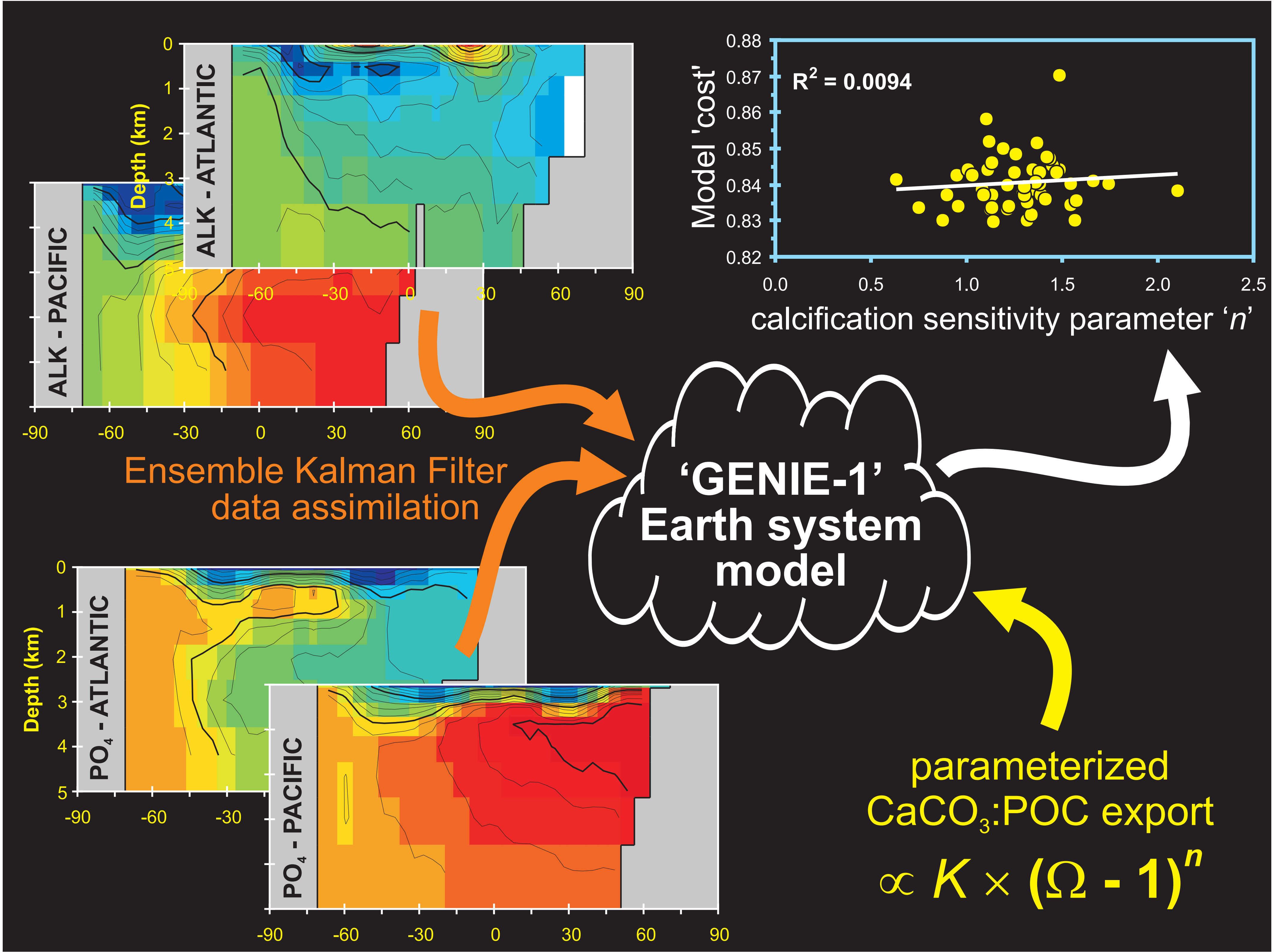
data assimilation

Here, te precipitation of carbonate is described as occurring at a rate;

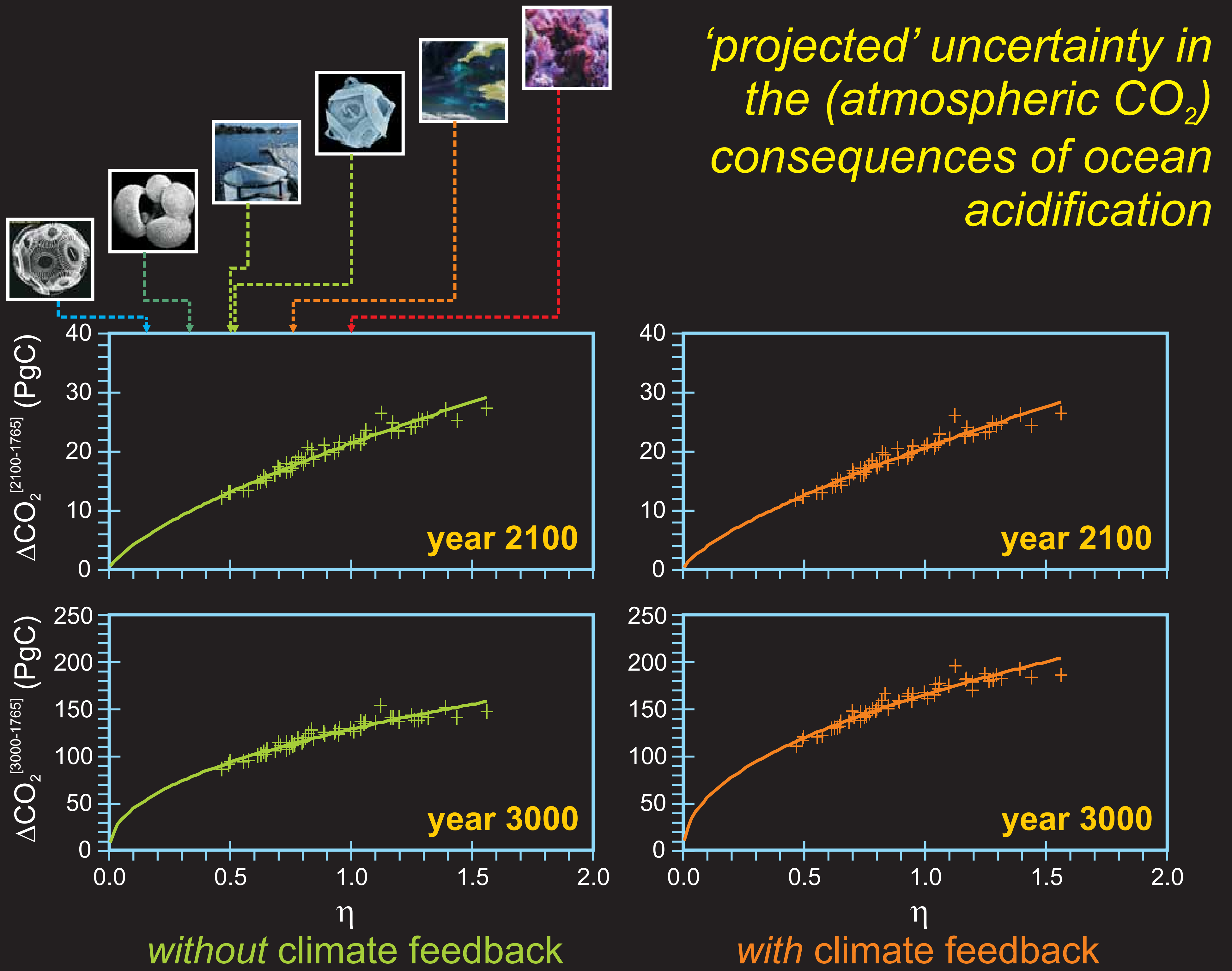
$\propto (\Omega - 1)^{\eta}$

where η is a measure of how strongly the precipitation rate responds to a change in Ω.

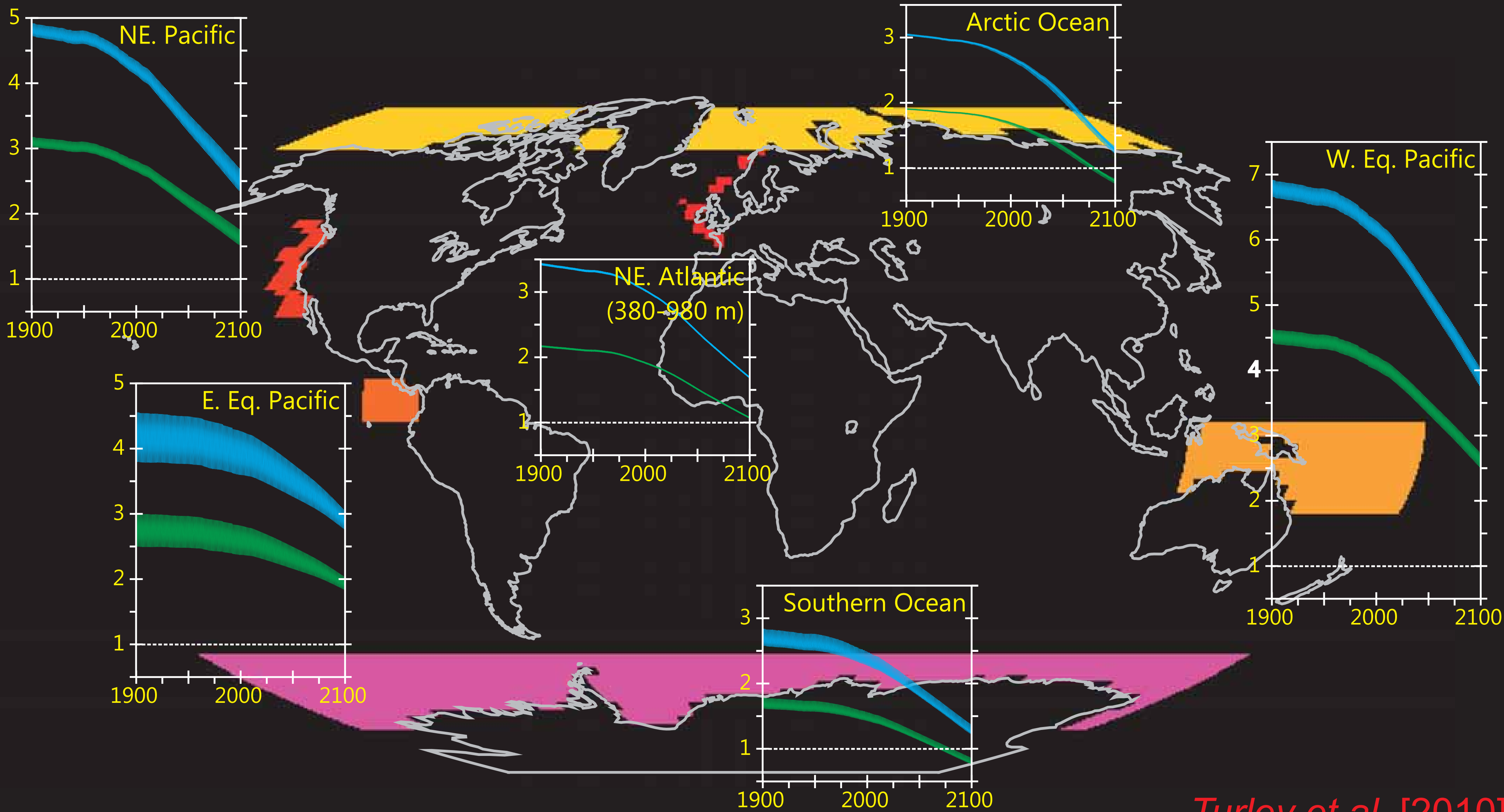



ALK - ATLANTIC
ALK - PACIFIC
Depth (km)
PO$_4$ - ATLANTIC
PO$_4$ - PACIFIC
Model 'cost'
R^2 = 0.0094
calcification sensitivity parameter 'n'
Ensemble Kalman Filter
data assimilation
'GENIE-1'
Earth system
model
parameterized
$CaCO_3$:POC export
$\propto K \times (\Omega - 1)^n$

‘projected’ uncertainty in the (atmospheric CO_2) consequences of ocean acidification

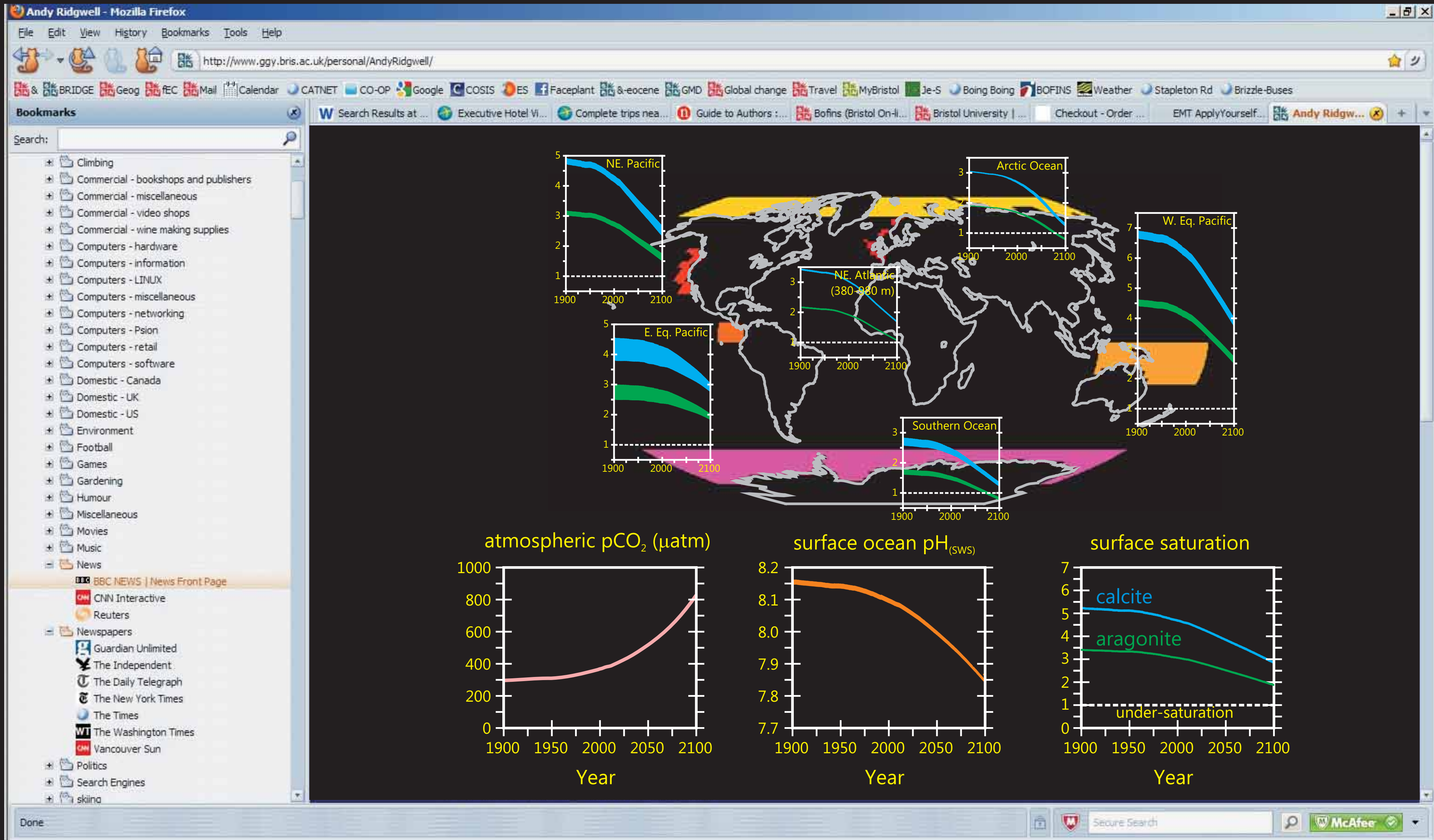


Projected (single CO_2 emissions scenario) Seasonal/Regional ocean acidification in the UVic Earth System Model

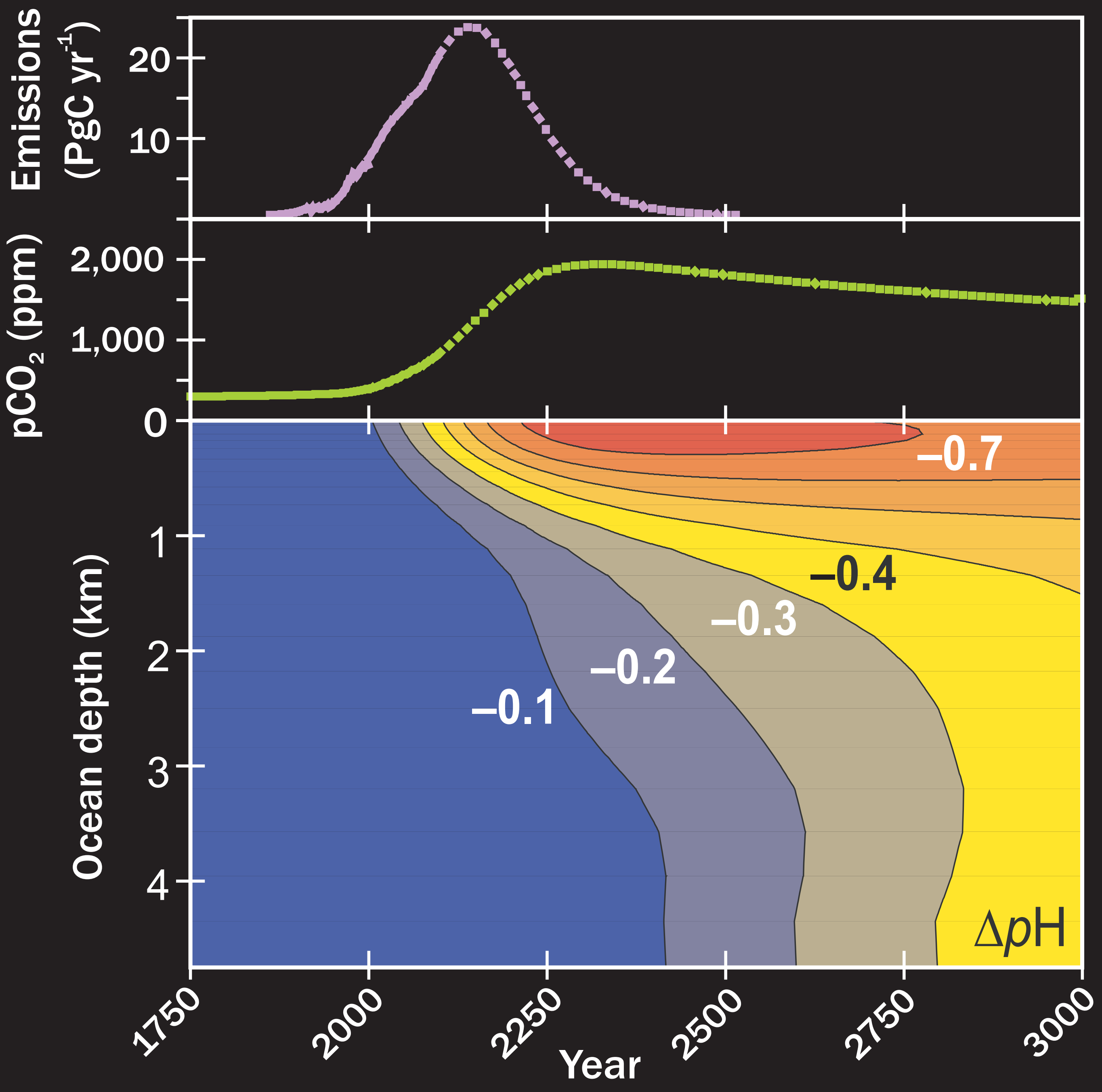


Turley et al. [2010]

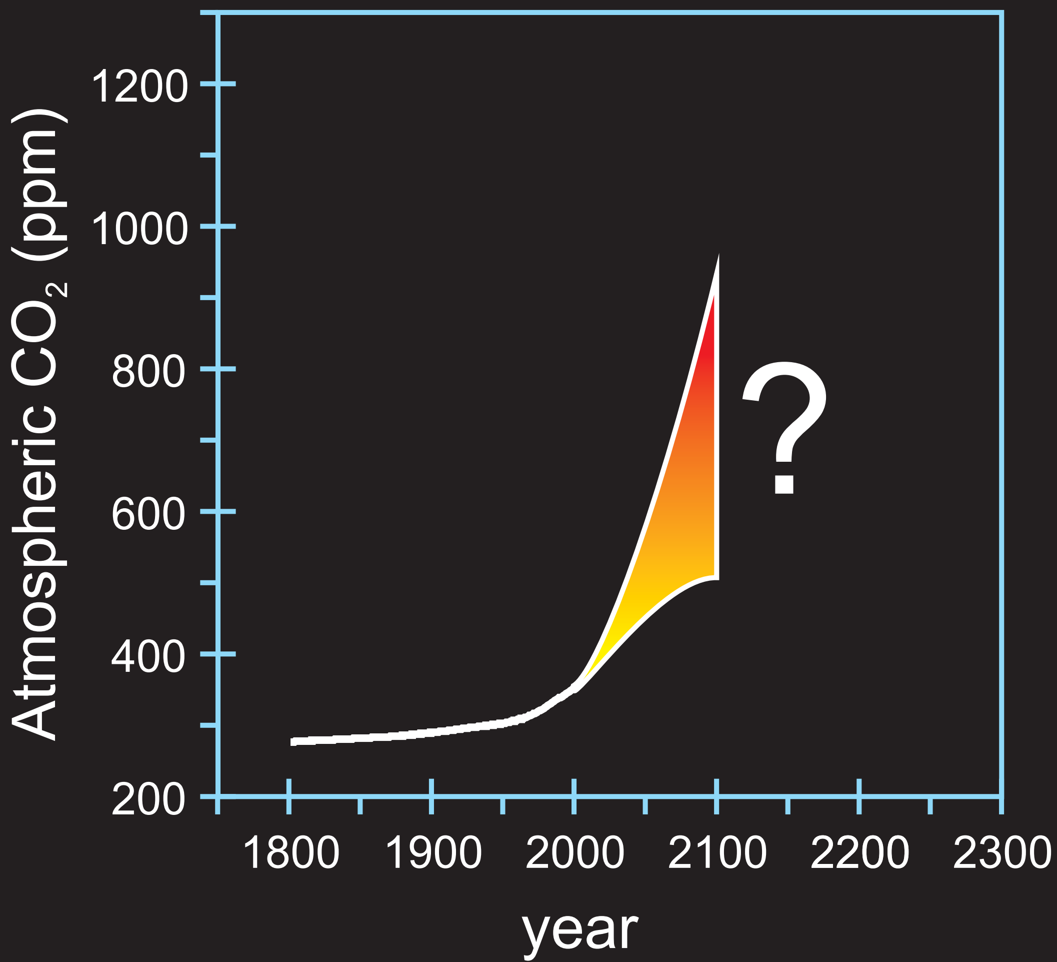
the 'ocean acidification viewer'



Future trajectories of ocean pH

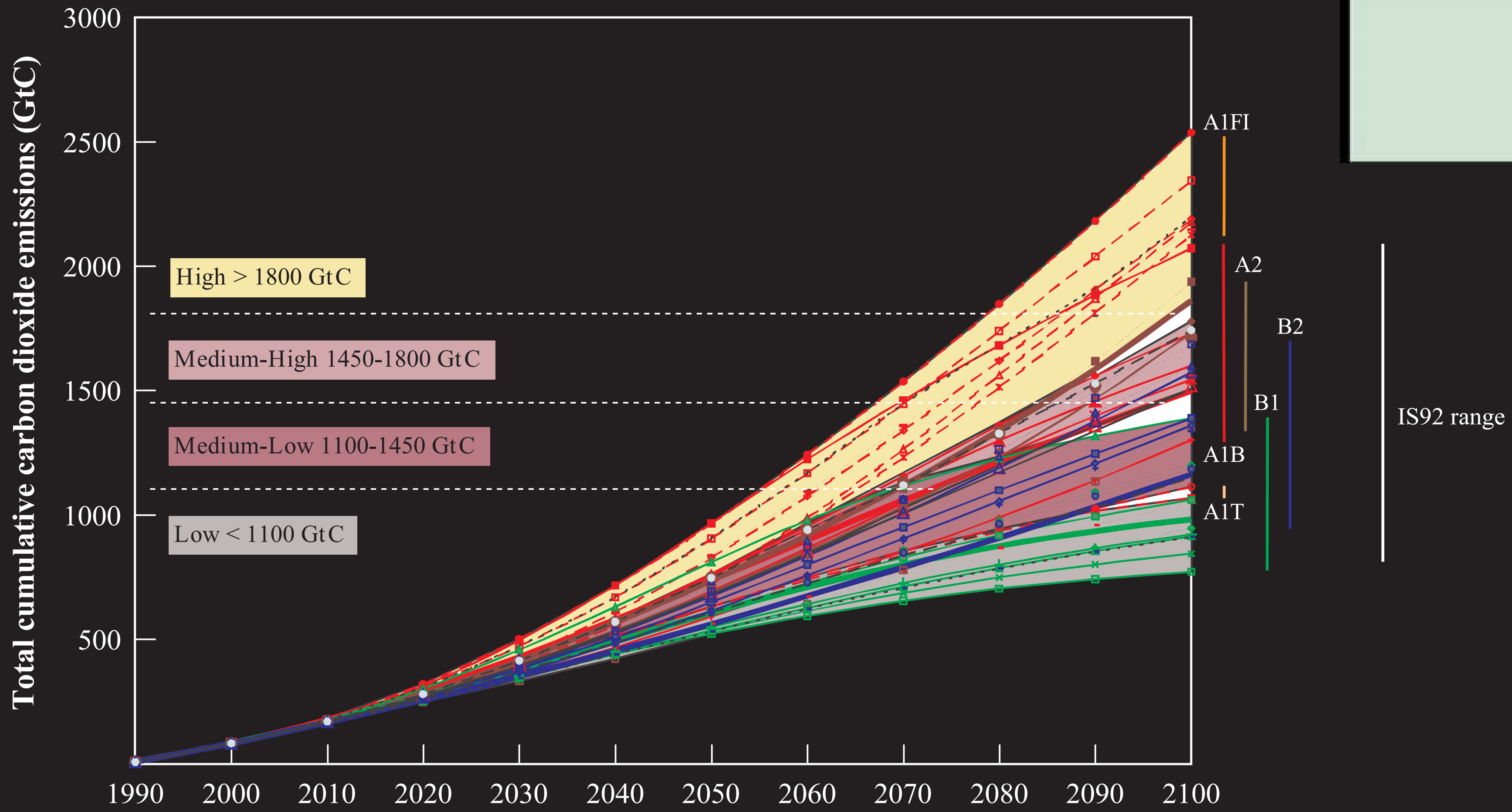


Caldeira and Wickett [2003]



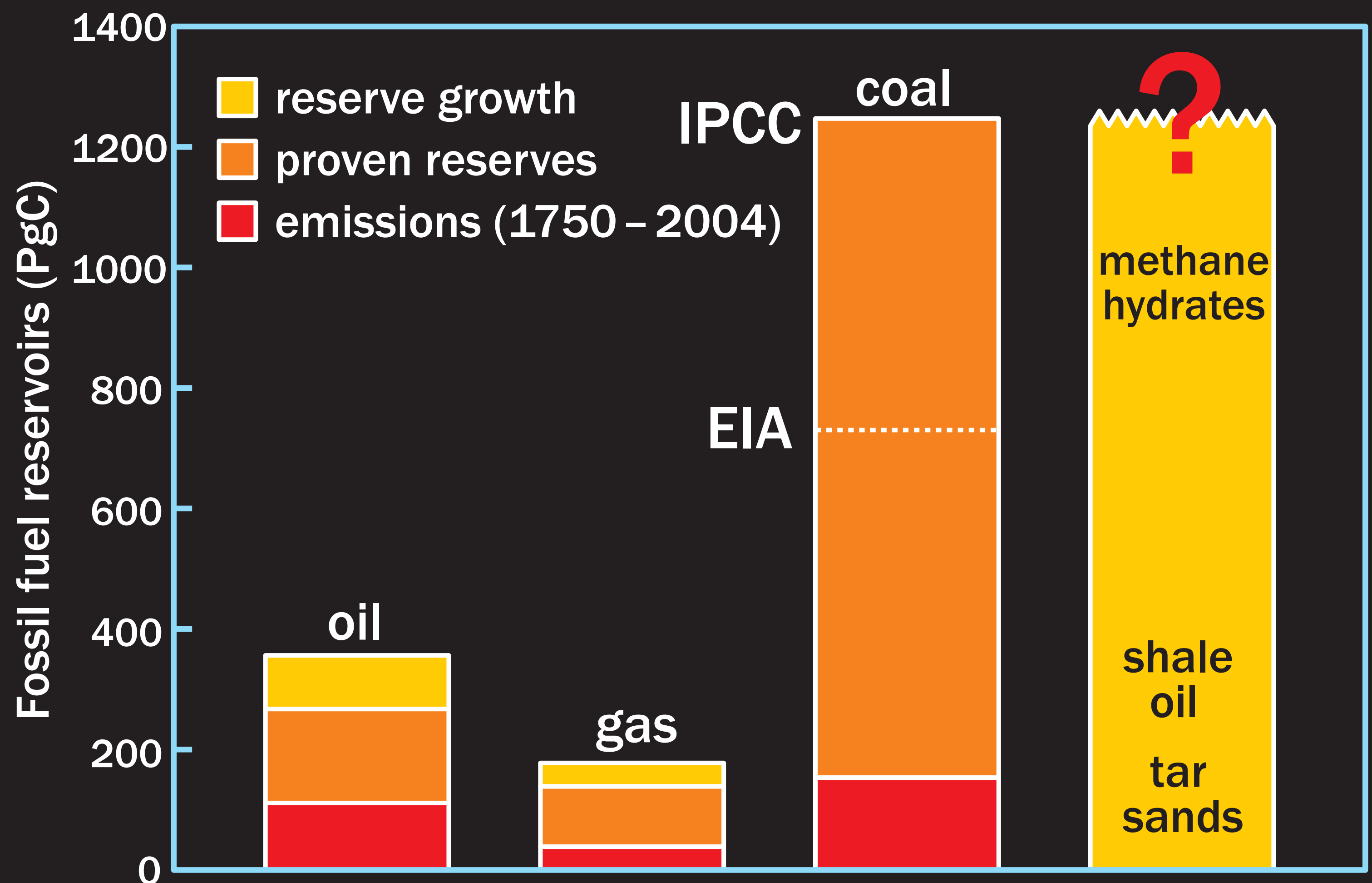
How will fossil fuel CO_2 emissions change in the future?

What are the uncertainties regarding the (fossil fuel CO_2 emissions) driver of future climate change?



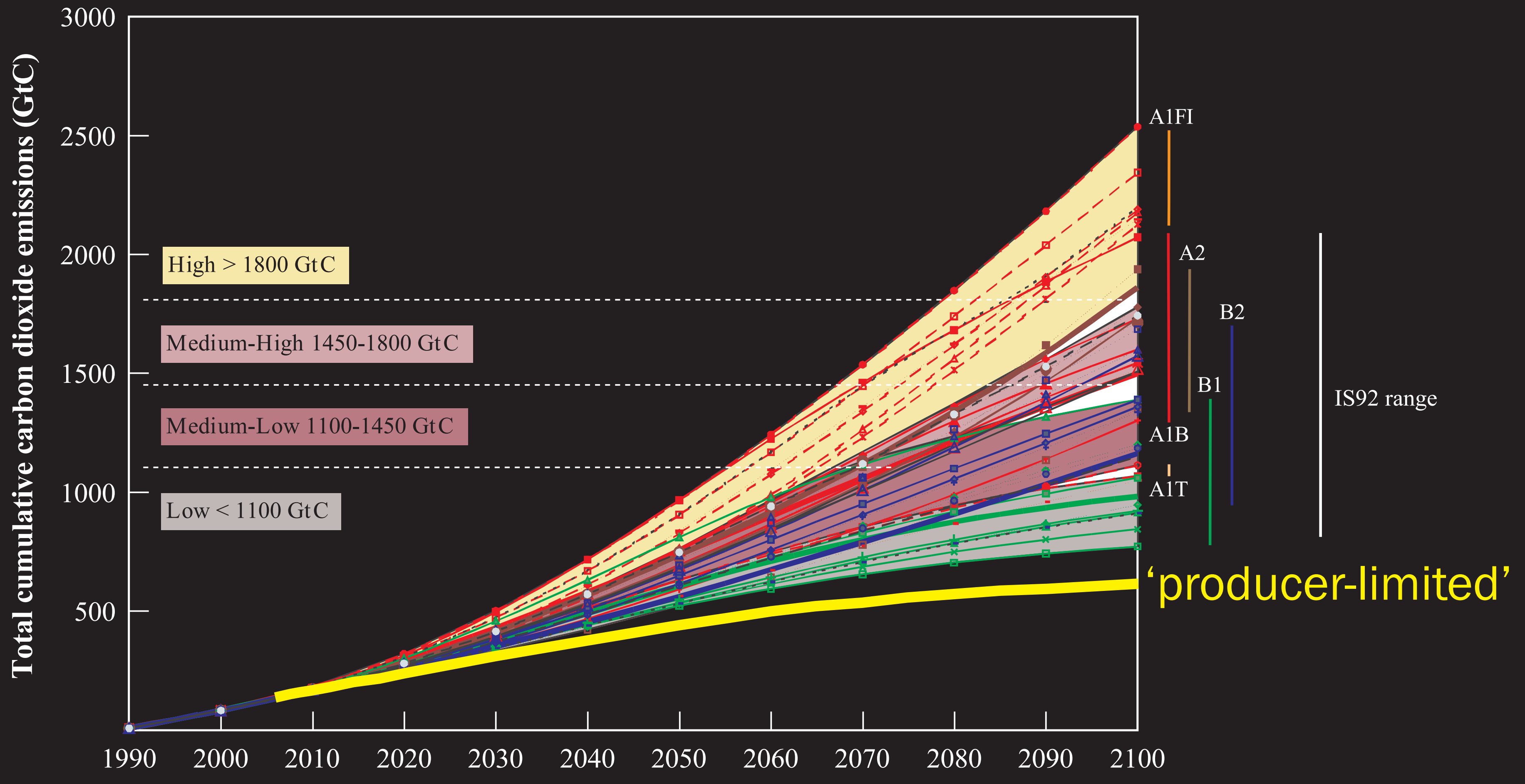
How much carbon <u>can</u> (or will) we burn?

cf.:
~5,000 PgC [Caldeira and Wickett, 2003]
up to 15,000 PgC [Lenton et al., 2006]



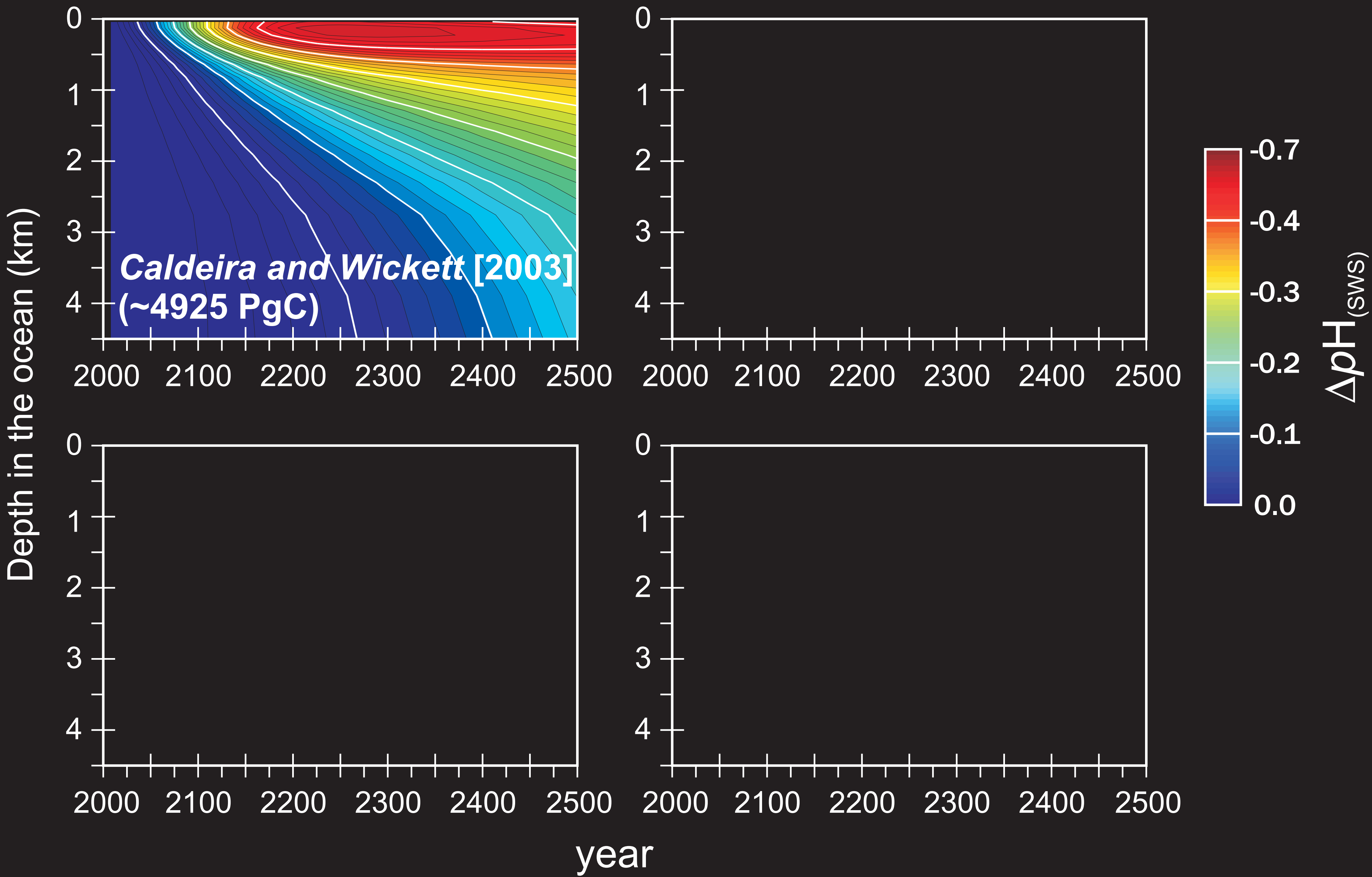
Hansen et al. [2006]

Hubbert's Peak, The Question of Coal, and Climate Change (Dave Rutledge, Caltech)



GENIE
Grid ENabled Integrated Earth system model
www.genie.ac.uk

Future ocean pH projections



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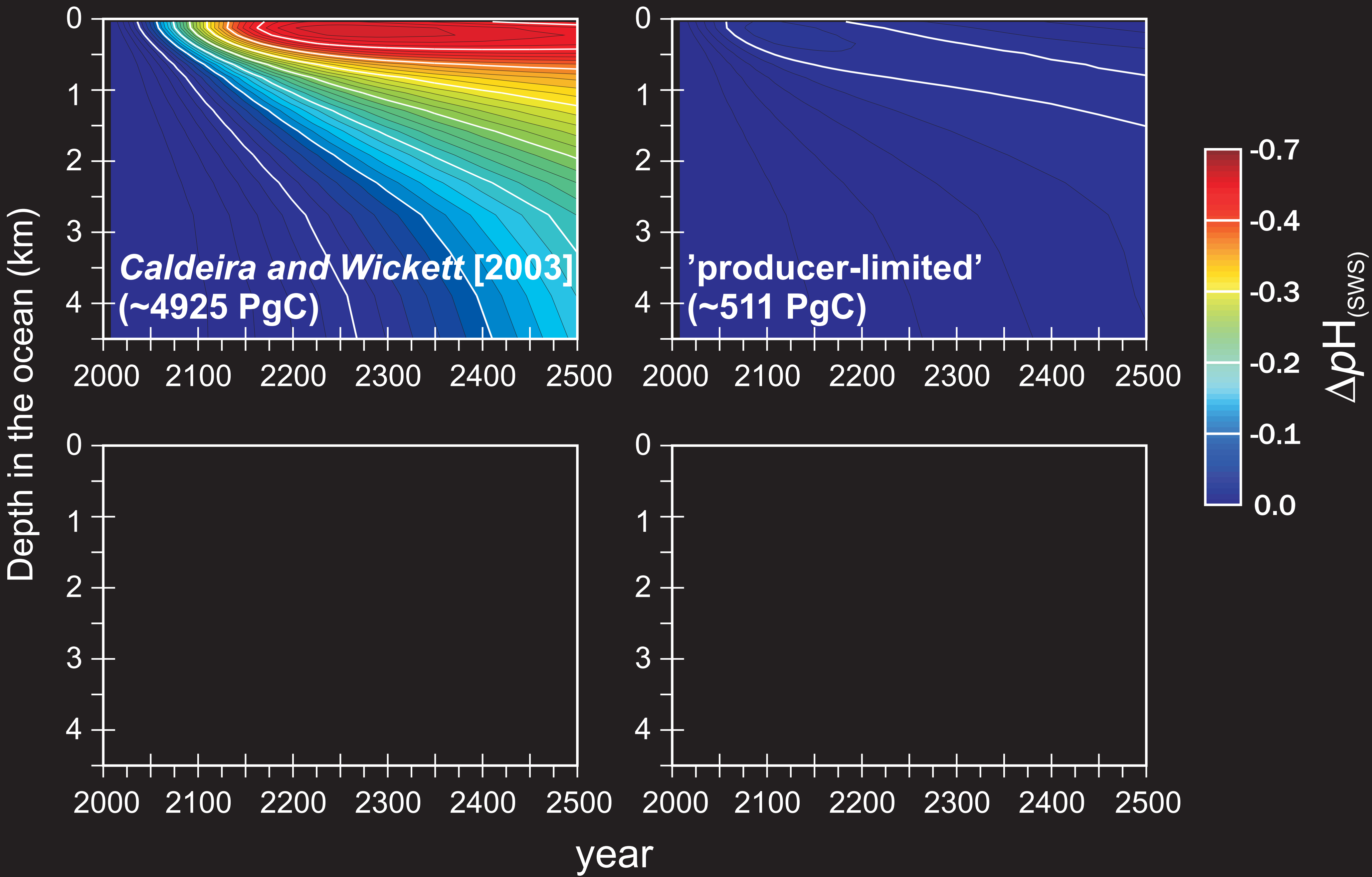
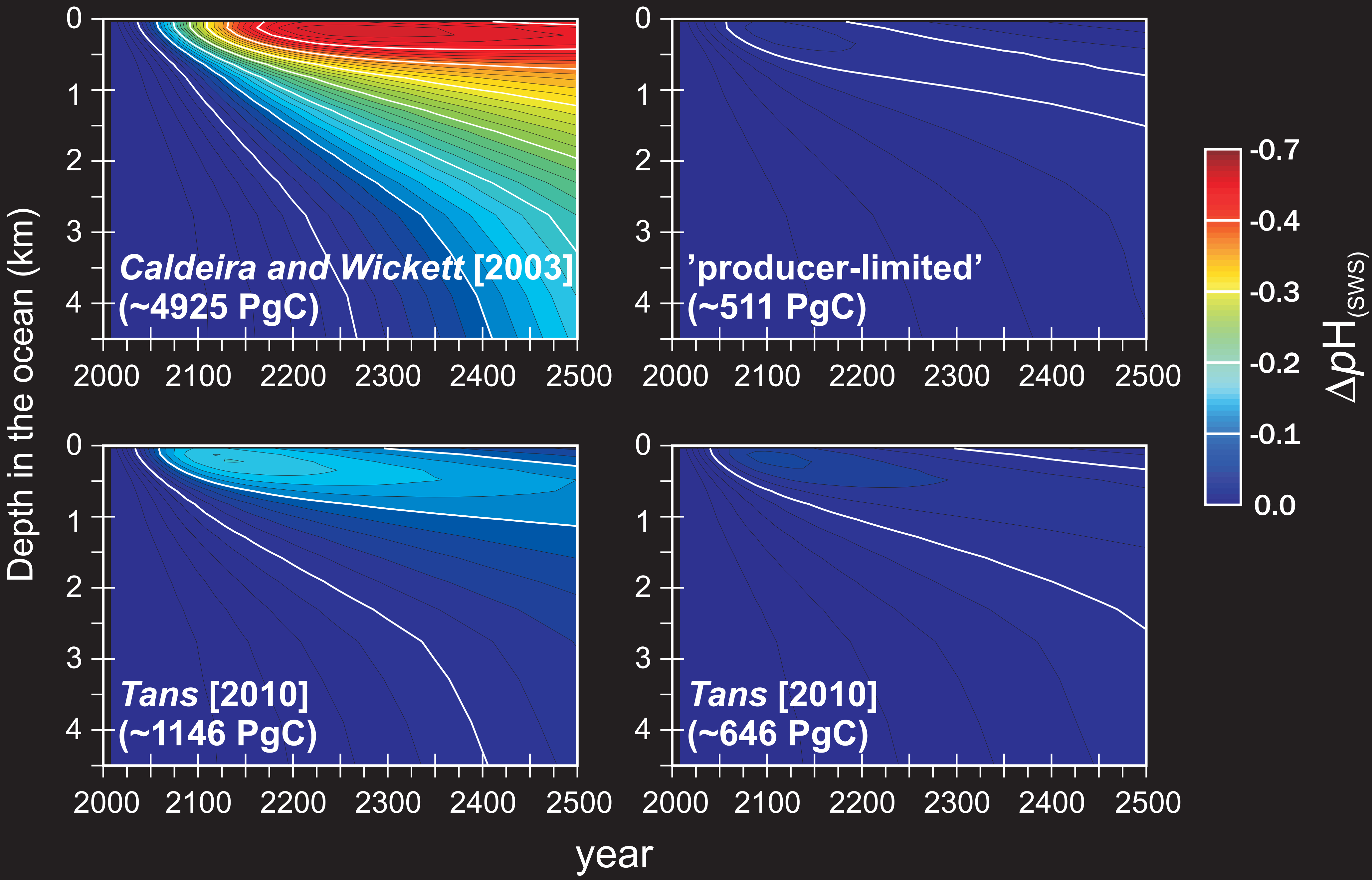


Future ocean pH projections



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