UNCERTAINTY IN THE CHANGING MARINE CARBON CYCLE IN A FUTURE WARMER WORLD

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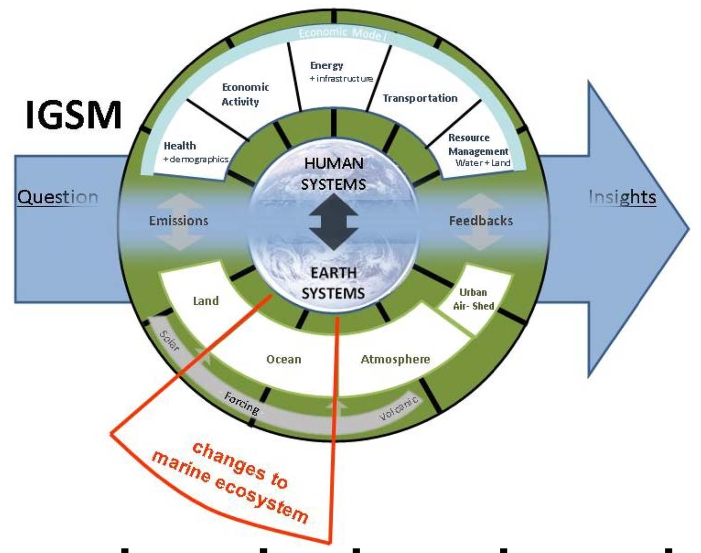
1. INTRODUCTION

An ensemble of simulations, using an earth system model of intermediate complexity, is employed to examine the uncertainties in our ability to represent the ocean carbon cycle in the current and future, warming world.

2. EARTH SYSTEM MODEL DESIGN



Integrated Global System Model Framework, IGSM (Dutkiewicz et al, 2005, Scott et al 2008, Sokolov et al 2009)

- atmosphere, land, sea-ice and economics modules
- 3-D Ocean (MITgcm): 4°x4° horizontal, 15 levels
- marine biogeochemistry
  - cycling of carbon, alkalinity, macro-nutrient
  - simplified biological pump (function of light and nutrients)
  - air-sea exchange of CO_2

3. ENSEMBLE APPROACH

Ensemble consists of 4000 model simulation, each with a different combination of parameters:

1) Background ocean diffusion (K_z)
2) Climate sensitivity (S) – obtained by varying cloud cover
3) Aerosol forcing (A)

Combination of parameters are chosen by model performance over 20[th] century relative to observations using optimal finger-printing diagnostics (Forest et al, 2002).

4. SPINUP AND PROJECTIONS

- 2000 year spinup for pre-industrial conditions: 4 different K_z (0.05, 0.1, 0.2, 0.35 cm²/s)
- 4 initial conditions (IC) from each K_z run: 16 initial states
- 1860-1990 with prescribed atmospheric pCO_2 : 250 combinations of S and A for each of 16 K_z-IC
- 1990-2100 with "business as usual" emissions scenario for each of 4000 combinations of K_z, S, A, IC

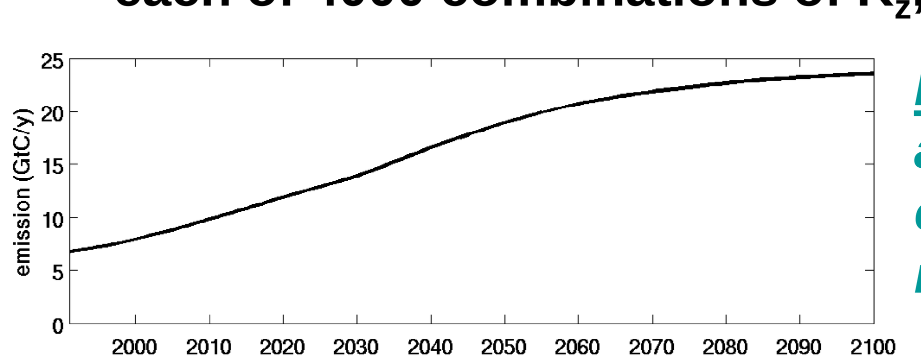


FIGURE 1: Projected anthropogenic carbon emissions (from economics module of IGSM)

Air temperatures increase by between 4° and 9°C by 2100. Ocean circulation and heat uptake differs between ensemble members (see poster C29-W146B). In particular, there is higher meridional overturning circulation for runs with higher K_z.

5. CURRENT DAY OCEAN STATE

- Model captures current day carbon distribution
- There are differences between ensemble members, largely caused by difference in circulation related to K_z values.

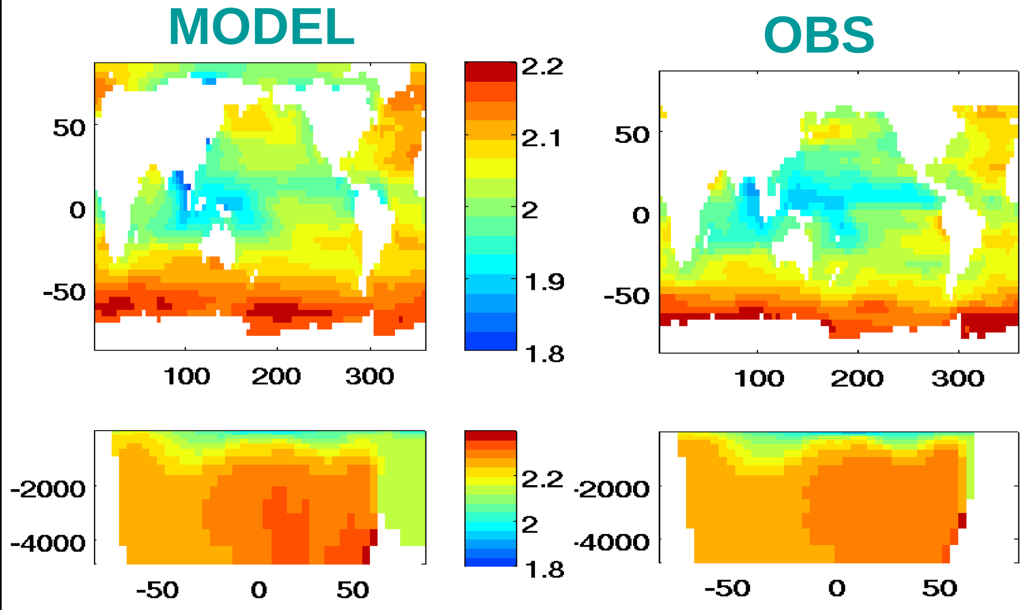


FIGURE 2: Current day dissolved inorganic carbon (DIC, mol/m³). Top: surface, Bottom: zonal mean transect. Left, model ensemble mean; Right, GLODAP climatology (Key et al 2004)

- Current ocean CO2 uptake is within, but on low side, of estimates from the literature; higher uptake with higher K_z.

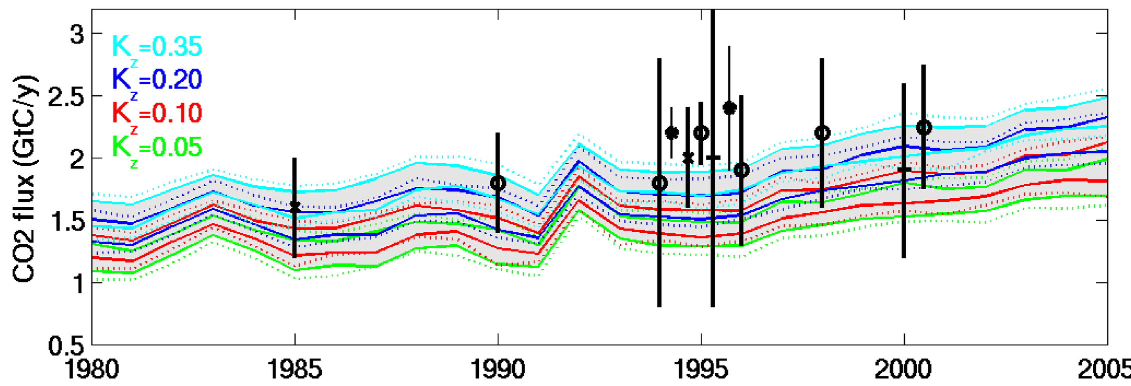


*FIGURE 3: Air-sea flux of CO_2 (GtC/y).Symbols indicate estimates with error bars: + shipboard pCO_2 measurements (Takahashi et al 2002, 2009); o inversion studies (Gloor et al, 2003; Gurney et al 2004; Manning and Keeling, 2004; Mikaloff-Fletcher et al 2006; Khatiwala et al 2009); x deduced from CFC's (McNeil et al 2003); * other model studies (Watson and Orr, 2003; Matsumoto et al 2004). (Colored lines indicate 95% confidence interval for each K_z, dotted lines indicate outliers.)*

6. PROJECTED OCEAN CARBON UPTAKE

- Ocean uptake projection uncertainty span 2 GtC/y by 2100
- By 2100, uncertainty in land and ocean uptake leads to atmospheric pCO_2 ranging 899-971ppmv (95% confidence level).

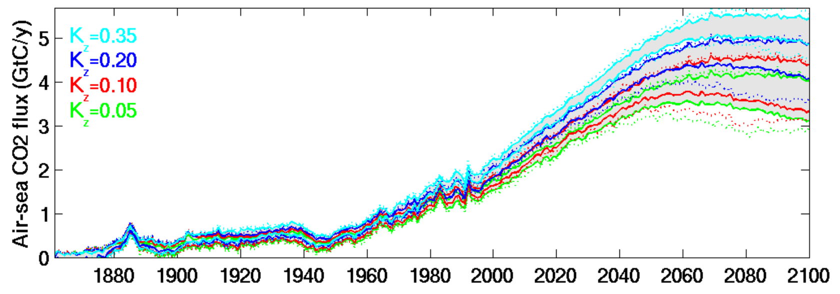


FIGURE 4: Ocean uptake of carbon. (Colored lines indicate 95% confidence interval for each K_z, dotted lines indicate outliers.)

- Uptake most uncertain in Arctic (related to uncertainty in SST) and in Southern Ocean (related to uncertainty in circulation)

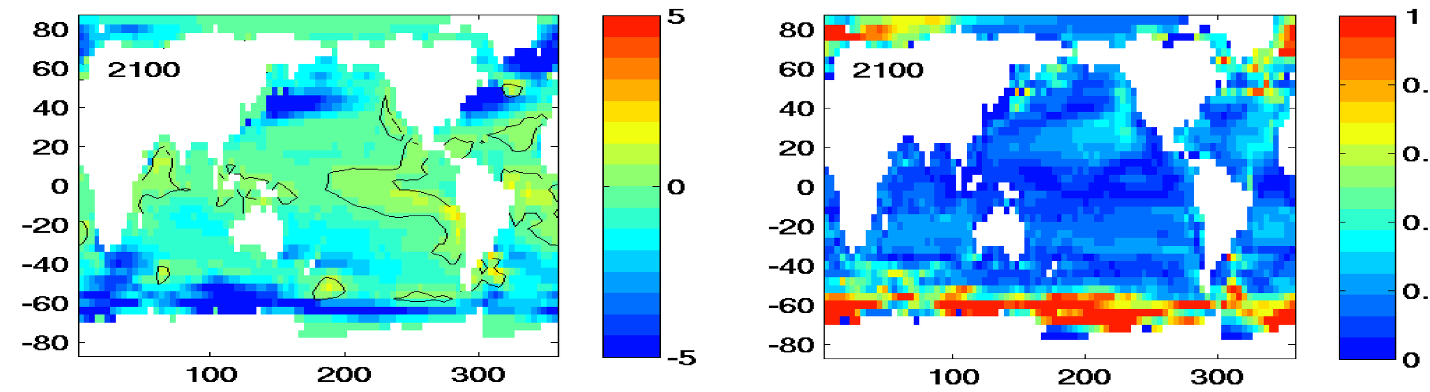


FIGURE 5: Air-sea flux of CO_2 (mol C/m²/y) in 2100. Left: mean of ensemble members; Right: standard deviation from ensemble. (+'ve out of ocean)

We are grateful for funding from DOE

7. PROJECTED CARBON STORAGE

- Anthropogenic carbon is most efficiently stored in the mid-latitudes
- Uncertainty at surface dictated by S, A; uncertainty at depth related to circulation differences related to K_z

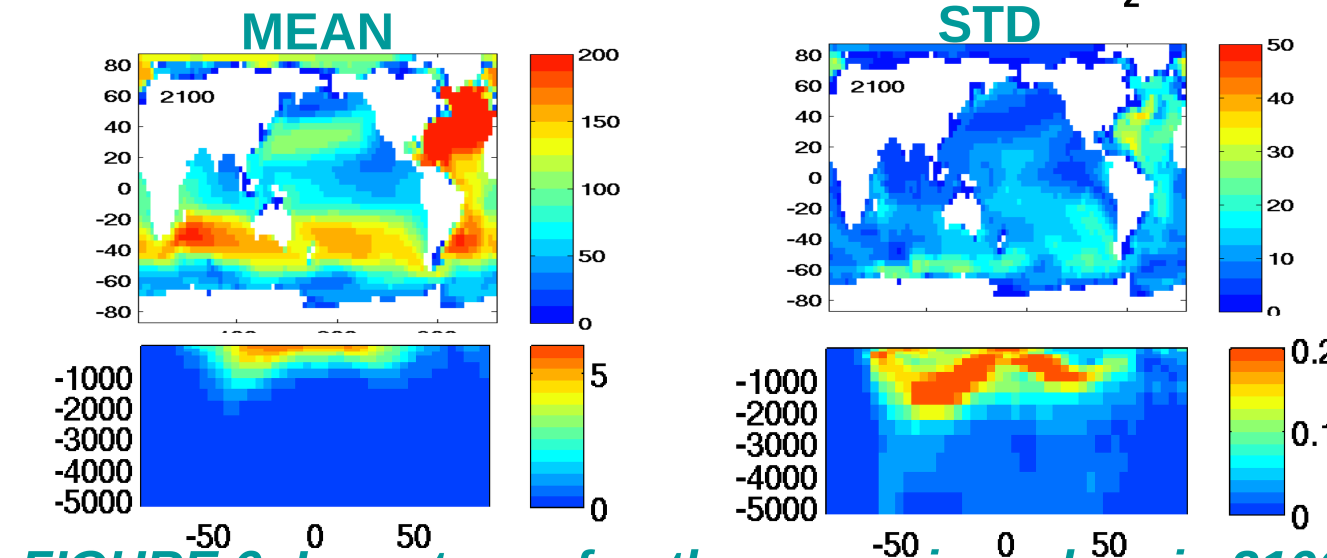


FIGURE 6: Inventory of anthropogenic carbon in 2100. Top, Column (mol/m²); Bottom, zonal (Pmol/m²). Left, mean of ensemble members; Right, standard deviation from ensemble.

8. PROJECTED ACIDIFICATION

- Ocean pH drops by 0.425 (±0.02) units by 2100
- The ensemble exhibits large uncertainty on when and how much of the surface waters become under-saturated with respect to aragonite and calcite (corrosive to some organisms)

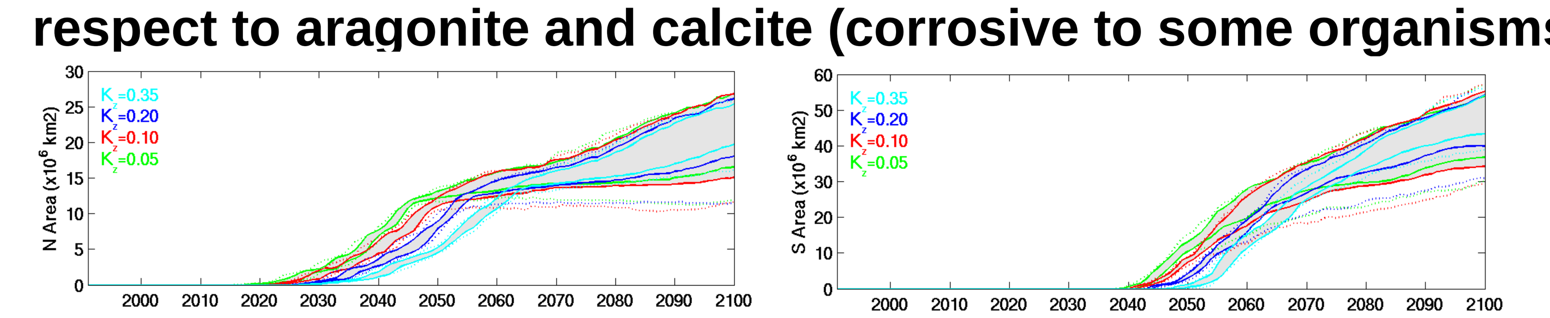


FIGURE 7: Area (10⁶km²) of surface water under-saturated with respect to aragonite. North (left) and South (right) hemispheres. (Colored lines indicate 95% confidence interval for each K_z, dotted lines indicate outliers.)

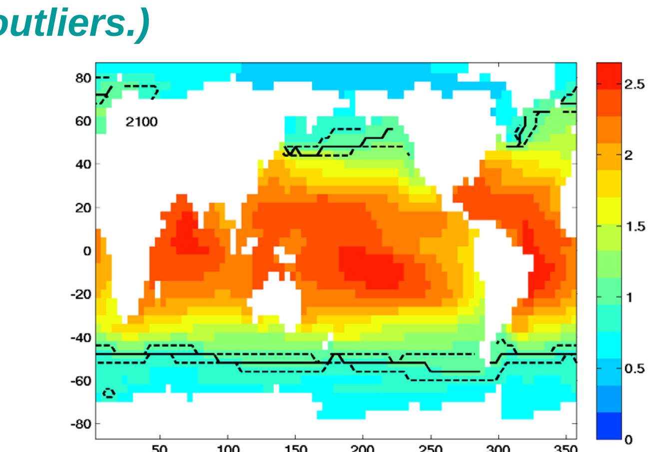


FIGURE 8: Ensemble mean aragonite saturation state, Ω, in 2100. Values less than 1 indicate under-saturated water. (Solid line indicates ensemble mean 1 contour, dashed lines indicate range of under-saturated water within 95% confidence level from the ensemble.)

9. SUMMARY

- We use an ensemble approach to examine the uncertainty in our model projections of ocean carbon cycle in a future world.
- We start with a viable range of possible "current" ocean states and explore a range of climate responses (sensitivity and aerosol feedback) under a no-policy emissions scenario.
- Uncertainty in projections of:
  - ocean carbon uptake is linked to regional uncertainty in SST and circulation changes, but also initial state.
  - carbon storage, especially with depth, is largely influenced by differences in initial state of ocean.
  - timing and areal extent of under-saturated water with respect to aragonite and calcite are related to changing state of ocean.