When Did the Anthropocene Begin? Observations and Climate Model Simulations

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Main Points

- Late interglacial CO_2 and CH_4 trends of previous interglacials differ from the Holocene trends. Why?
- Simulations of 3 climate states with CCSM3 help describe earlier climates and explore possible feedbacks:

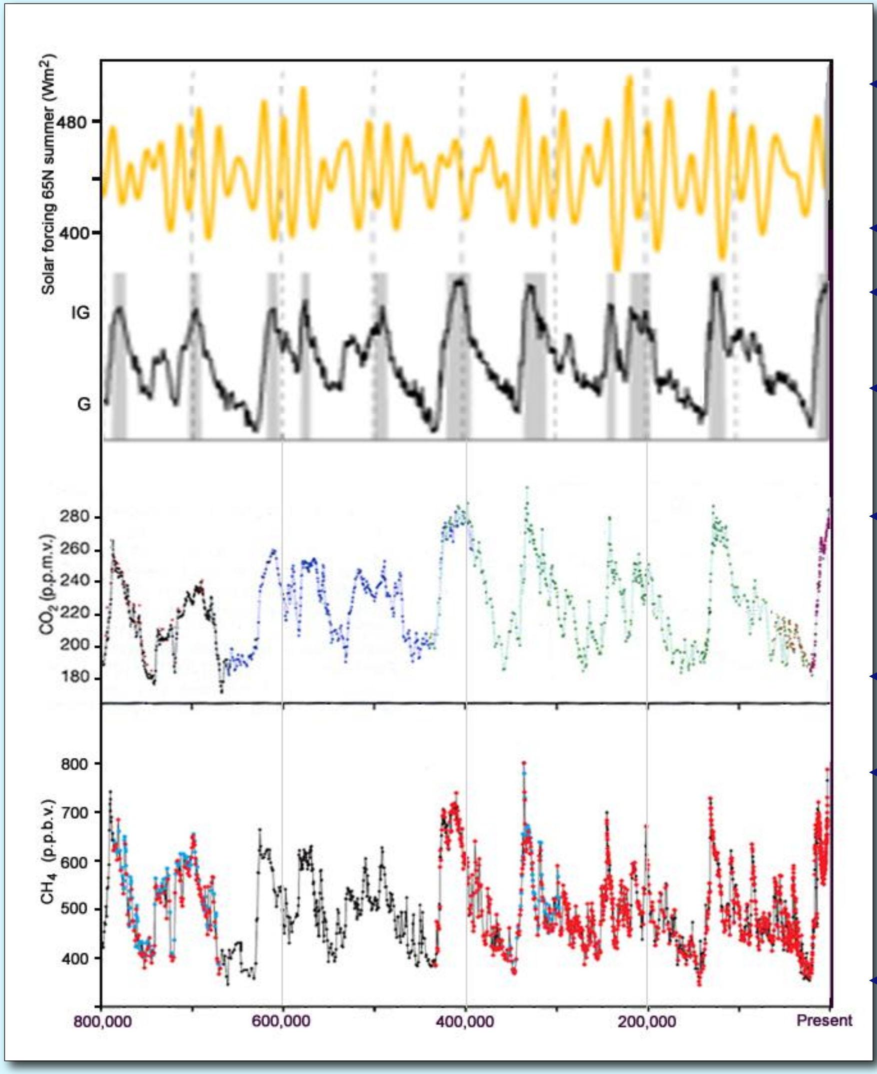
  PD=present day (NCAR control)

  PI =pre-industrial (Otto-Bliesner et al, *J Climate*, 2006)

  NA=no anthropogenic forcing (hypothetical GHG forcing for late interglacial conditions; Kutzbach et al, *Climatic Change,* 2010)

- Partitioning of changes: NA – PD = (NA-PI) + (PI-PD)shows greater sensitivity of climate to increases of greenhouse gases in ‘cold climate states’

New Observations of Glacial, CO_2, and CH_4 Swings from Antarctic Ice Cores: Last 800,000 Years



Strong

Northern hemisphere summer solar radiation, 65° N

Weak

Interglacial

$\delta_{18}O$

Glacial

Warm Earth: more CO_2 in atmosphere, less CO_2 dissolved in ocean.

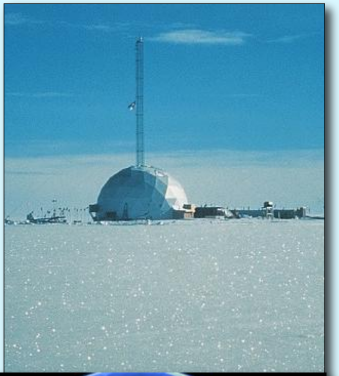
CO_2

Cold Earth

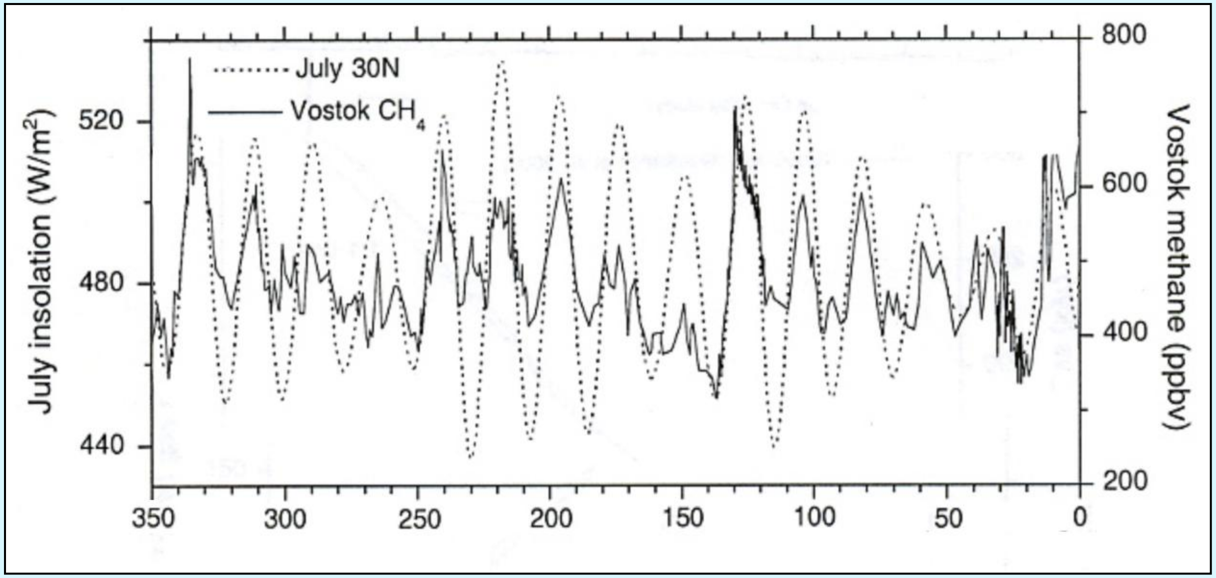
Warm Earth: more wetlands, more methane in atmosphere

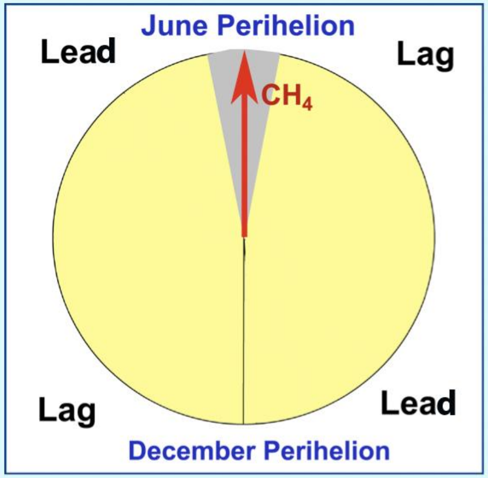
CH_4 (Methane)

Cold Earth



Orbital Forcing causes CH_4 changes: Antarctic ice core records of the last 350,000 Years





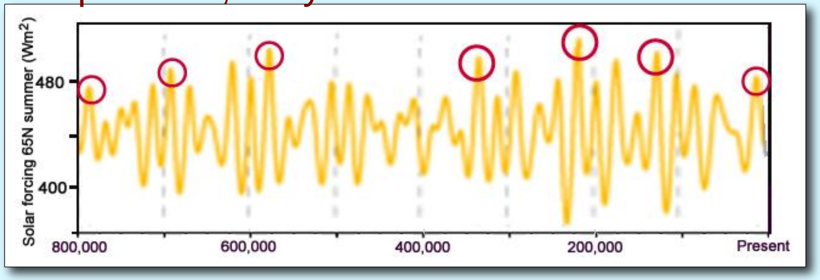
350,000 Year record of methane concentration from Vostock Ice Core and July insolation for 30° N - Methane concentration is index of tropical wetness

Ruddiman and Raymo, 2003

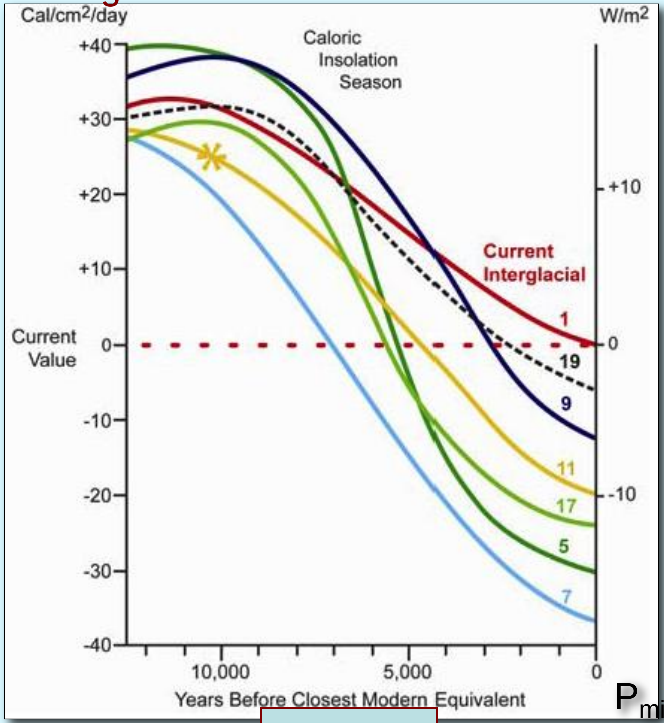
Insolation Trends (orbital forcing) and Greenhouse Gas Trends

Composites of 7 insolation and GHG trends following 7 insolation maxima (circles)

Northern hemisphere summer, solar radiation for past 800,000 years – maxima circled



Composite of 7 solar radiation trends following insolation maxima



P_{min}

12,000 years apart

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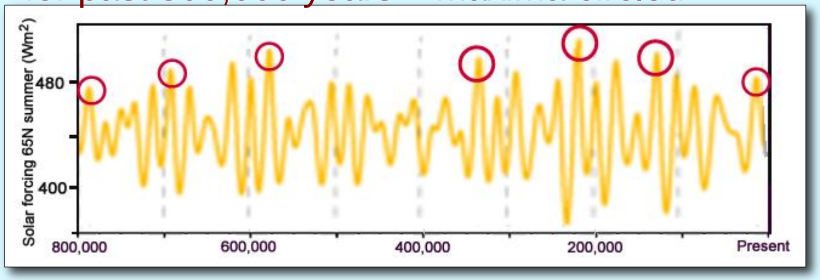
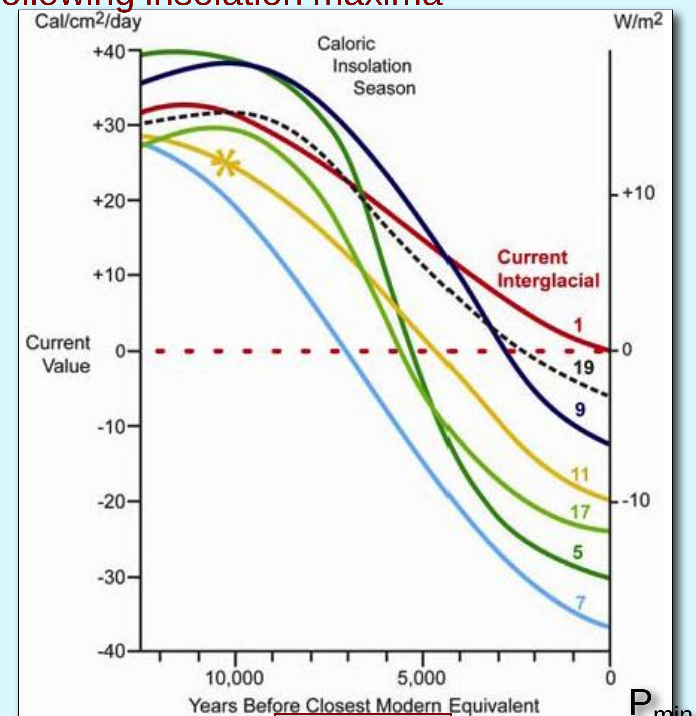
Insolation Trends and Greenhouse Gas Trends

Composites following 7 Insolation maxima (circles)

Northern hemisphere summer, solar radiation for past 800,000 years – maxima circled

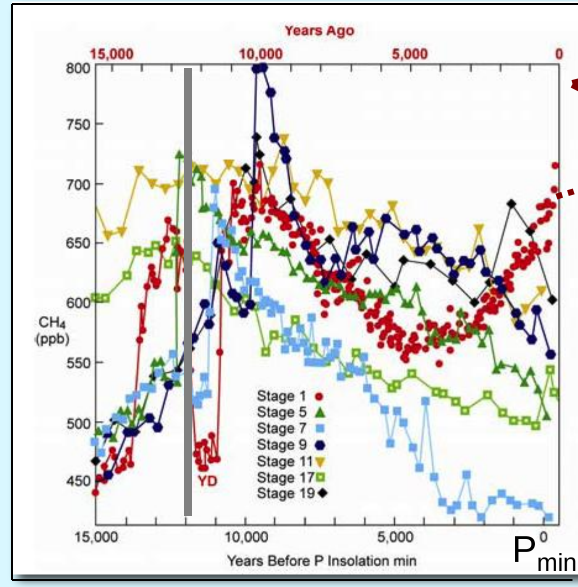


Composite of 7 solar radiation trends following insolation maxima



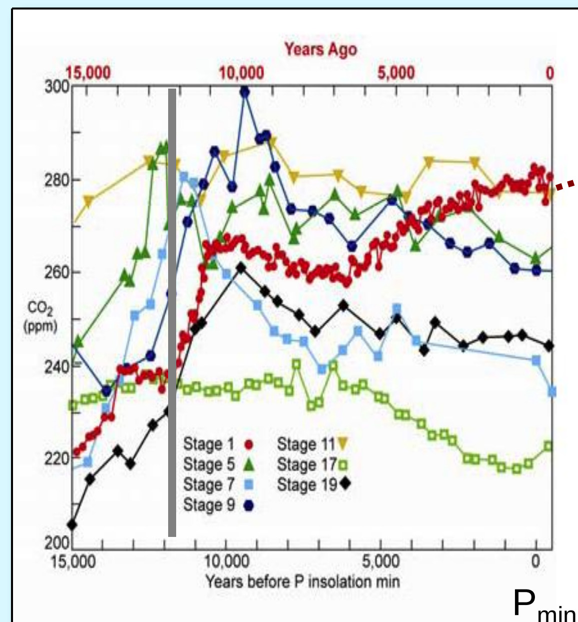
12,000 years apart

1700 ppb



CH_4

360 ppm



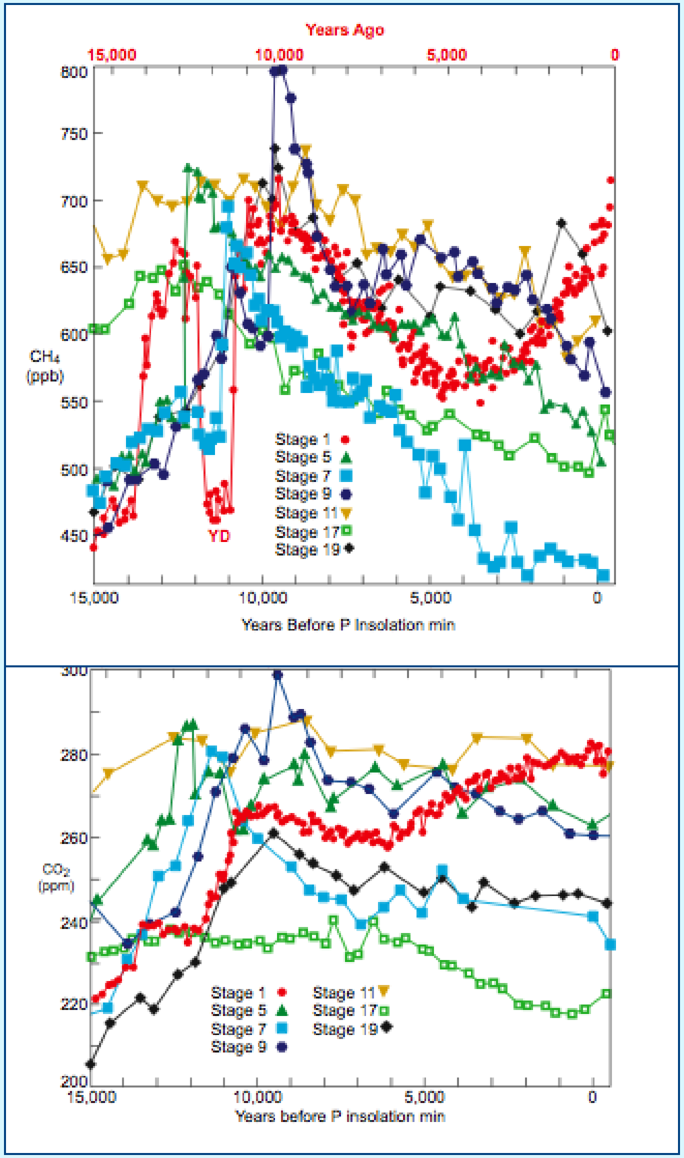
CO_2

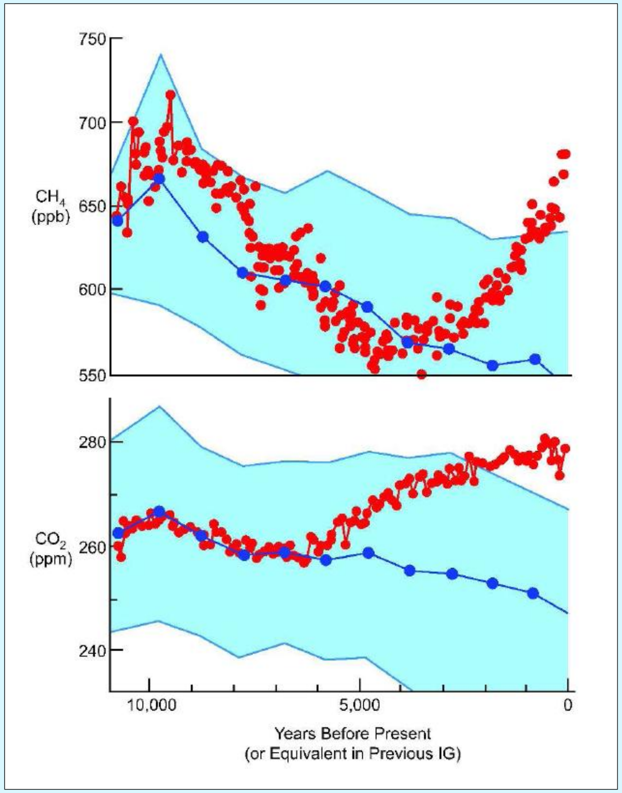
Greenhouse gas trends during 7 interglacials

Summary of GHG Trends:
Holocene trend differs from trends of 6 previous interglacials

CH_4

CO_2





Holocene (red) and composite of 6 previous interglacials (blue)

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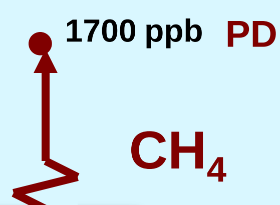
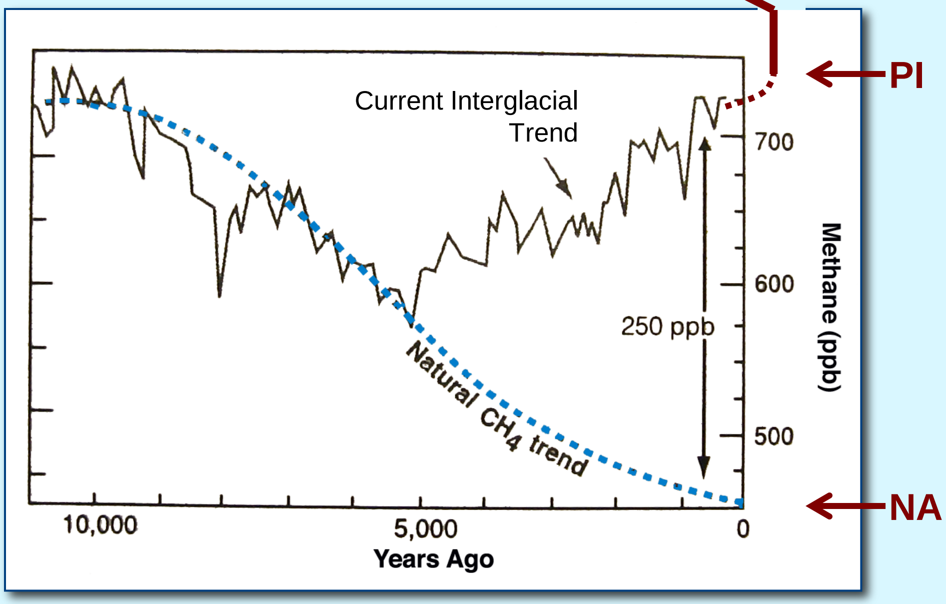
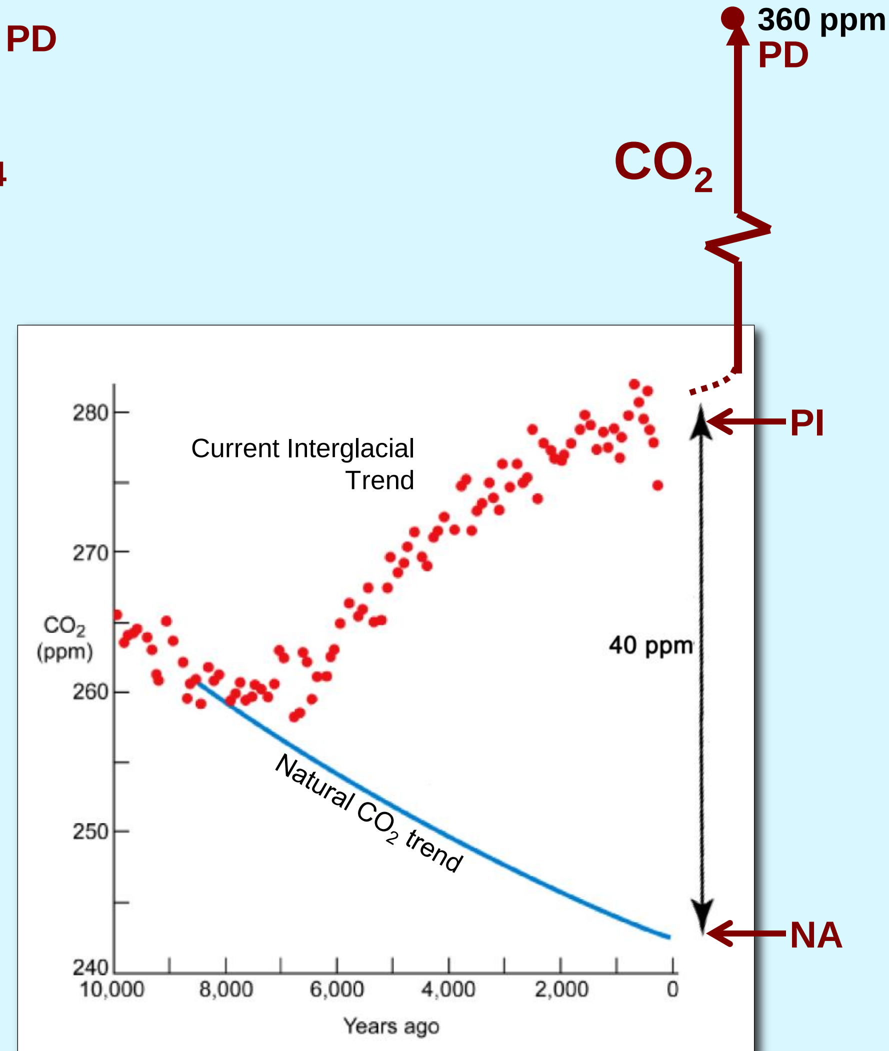
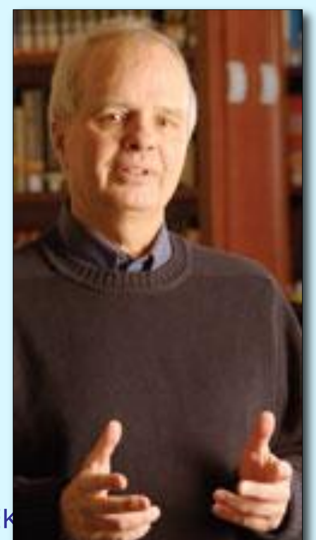
Ruddiman, 2003, 2007, 2011

The Current Trend Differs from the Natural Trend!









Bill Ruddiman

Author of "Early Anthropogenic" hypothesis

Ruddiman, W. F. (2005). Plows, Plagues and Petroleum: How Humans Took Control of Climate. Princeton University Press

Ruddiman WF (2003) The anthropogenic greenhouse era began thousands of years ago. Clim. Change 61: 261-293

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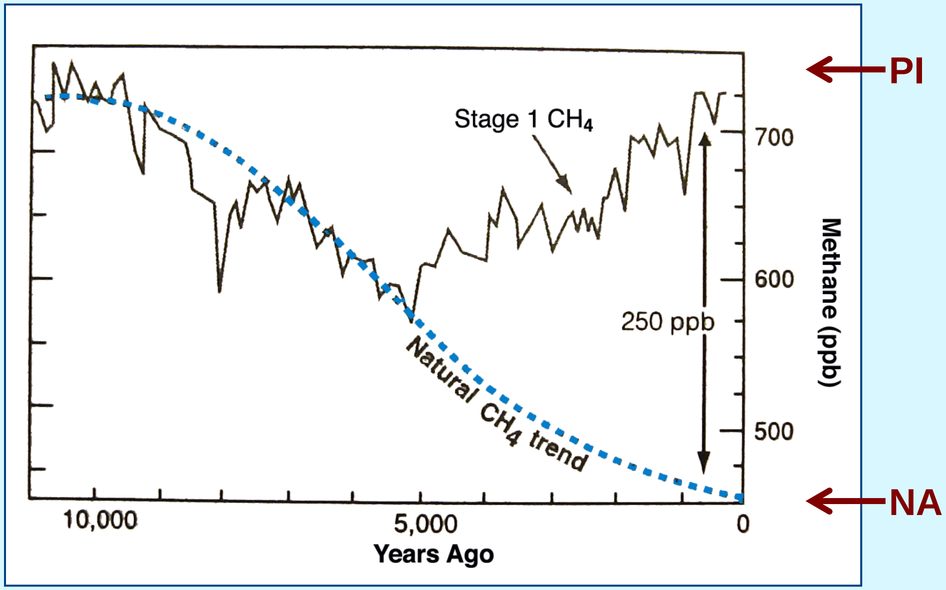
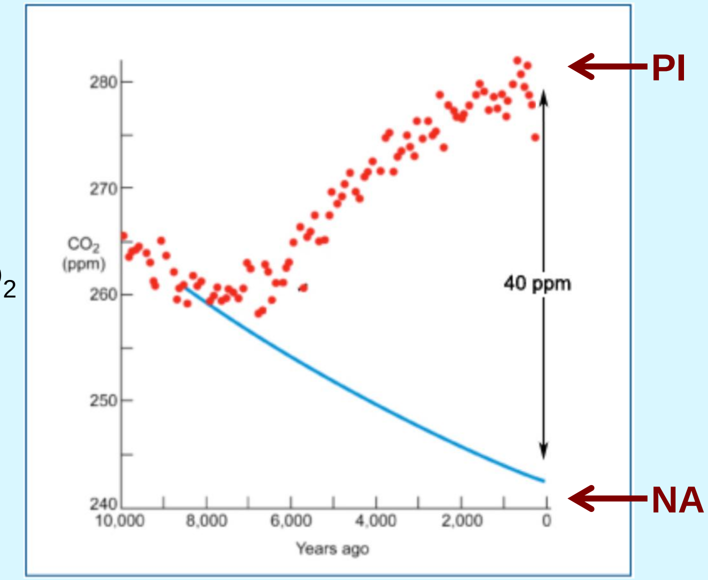
Why does the Current Trend differ from the Natural Trend? – two possibilities

CH_4



CO_2



1) Ruddiman's hypothesis: Holocene trends are different because of early agriculture. (Ruddiman, 2003)

2) Ruddiman's challenge: If trends are NOT due to early agriculture, then what is the natural explanation? (Ruddiman, 2007, 2011; Singarayer et al., 2010, Nature; Stocker et al., 2010, Biogeosci. Dicuss.)

(Orbital forcing is somewhat different in each case, perhaps different ice sheet sheet, ocean, and vegetation responses? Lack of detailed observations!)

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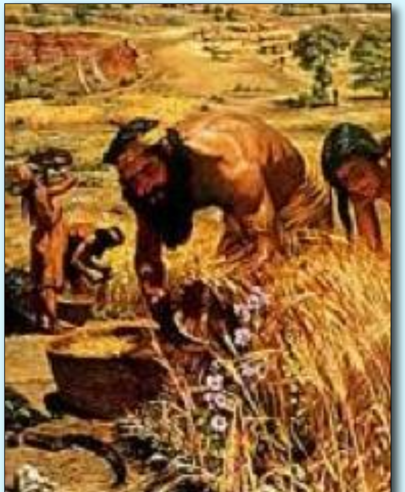
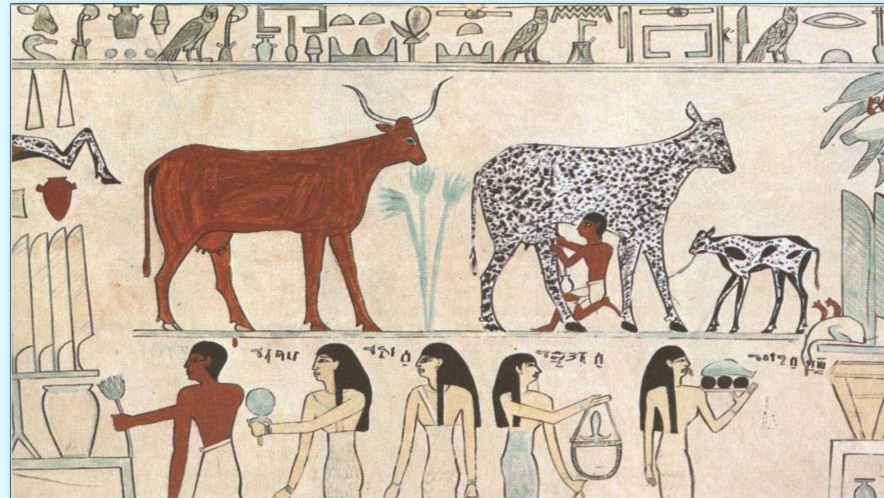
The Case for Early Agriculture



Early farming

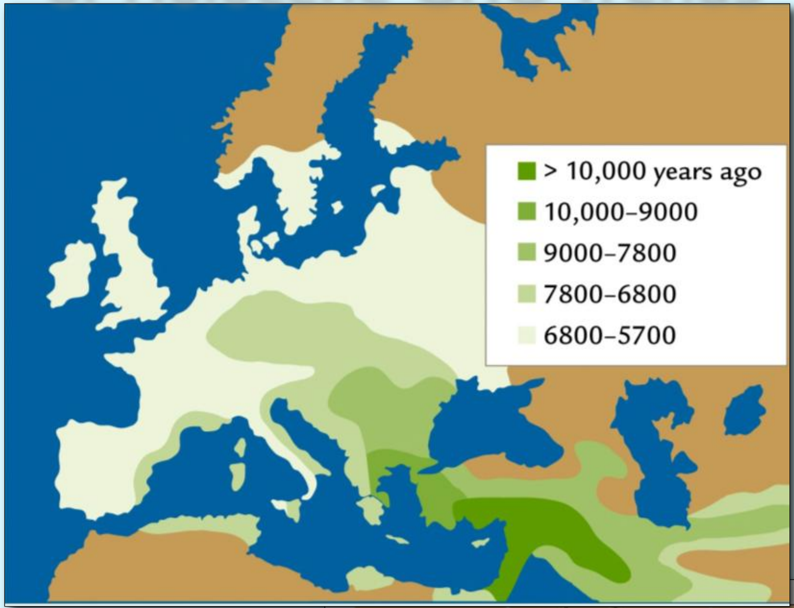


Early domesticated animals

Forest clearance for farming

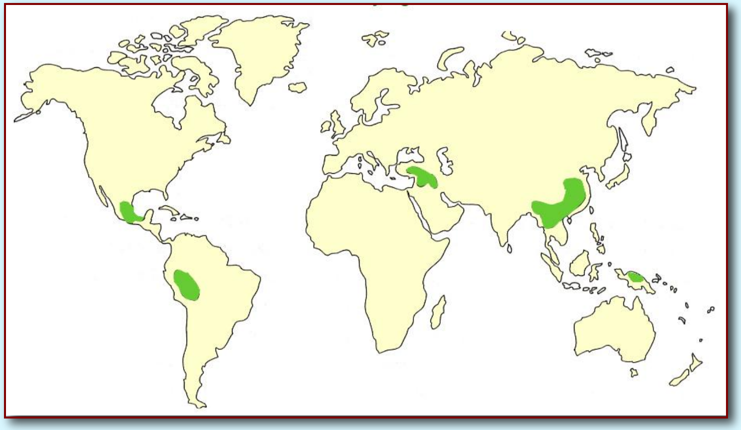
Rice paddies and rice cultivation

Timing of Spread of Early Agriculture agrees with timing of Holocene GHG Trends



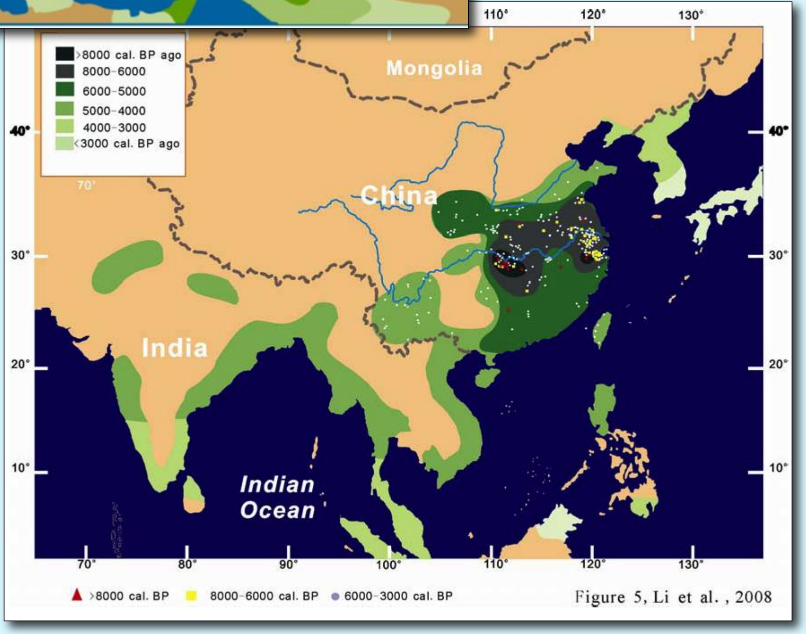
Europe and Middle East

Ruddiman, 2000



Centers of Early Agriculture

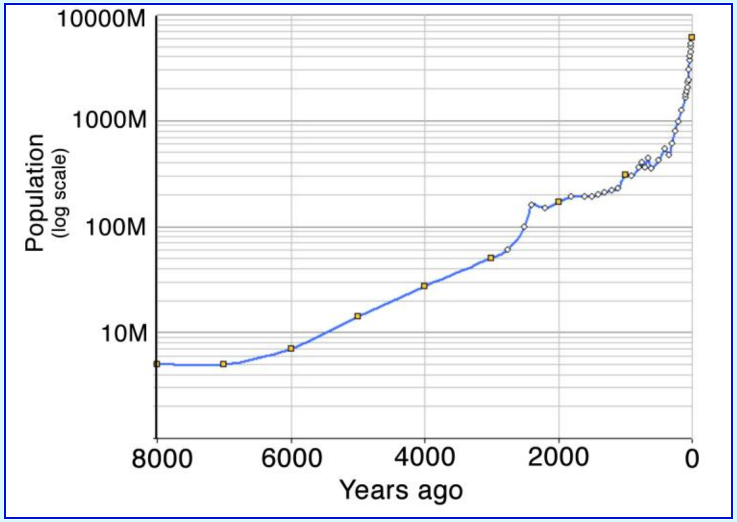
South Asia



Li et al., 2008

Are Land Use Changes Sufficient to Impact the Carbon Budget?

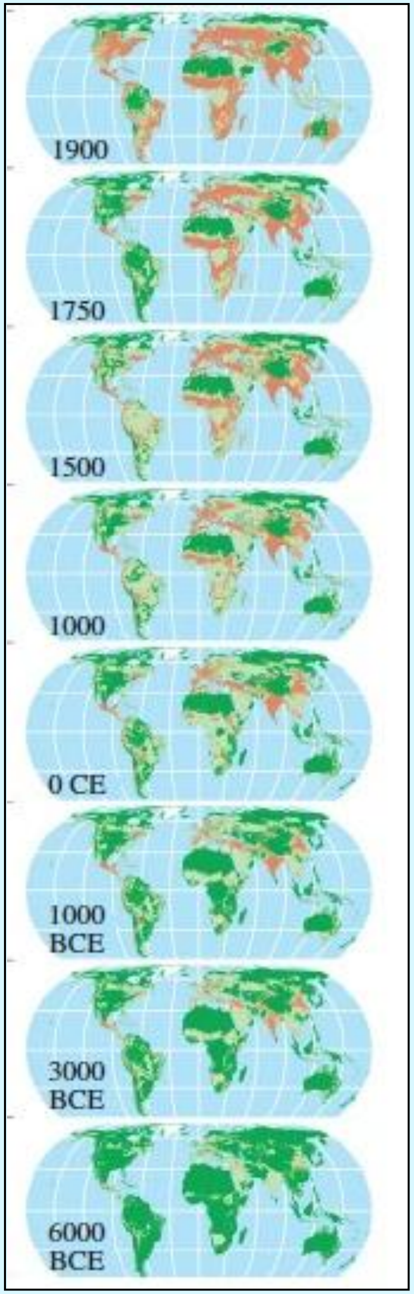
(Land use = Population X Land use/Capita)

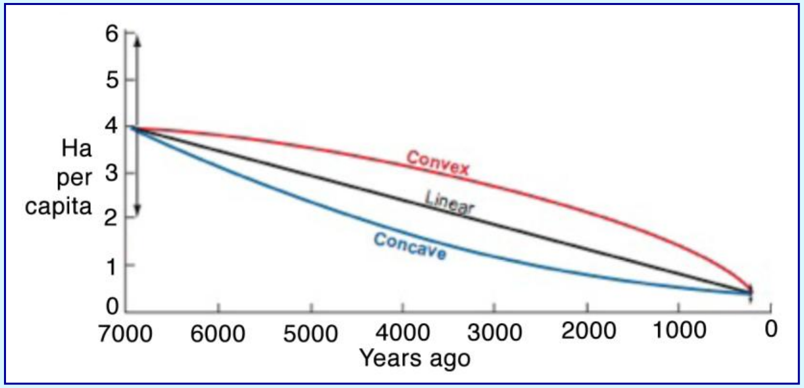


Population estimate

Global land use
Ellis, E, 2011

Used land
Semi natural land
Natural land





Land use/capita
Ruddiman and Ellis, 2009

Early agriculture had a 10X larger "footprint " than at PI

Result so far: Early agriculture could have contributed approximately 20ppm to ΔCO_2 (Kaplan et al, 2011)

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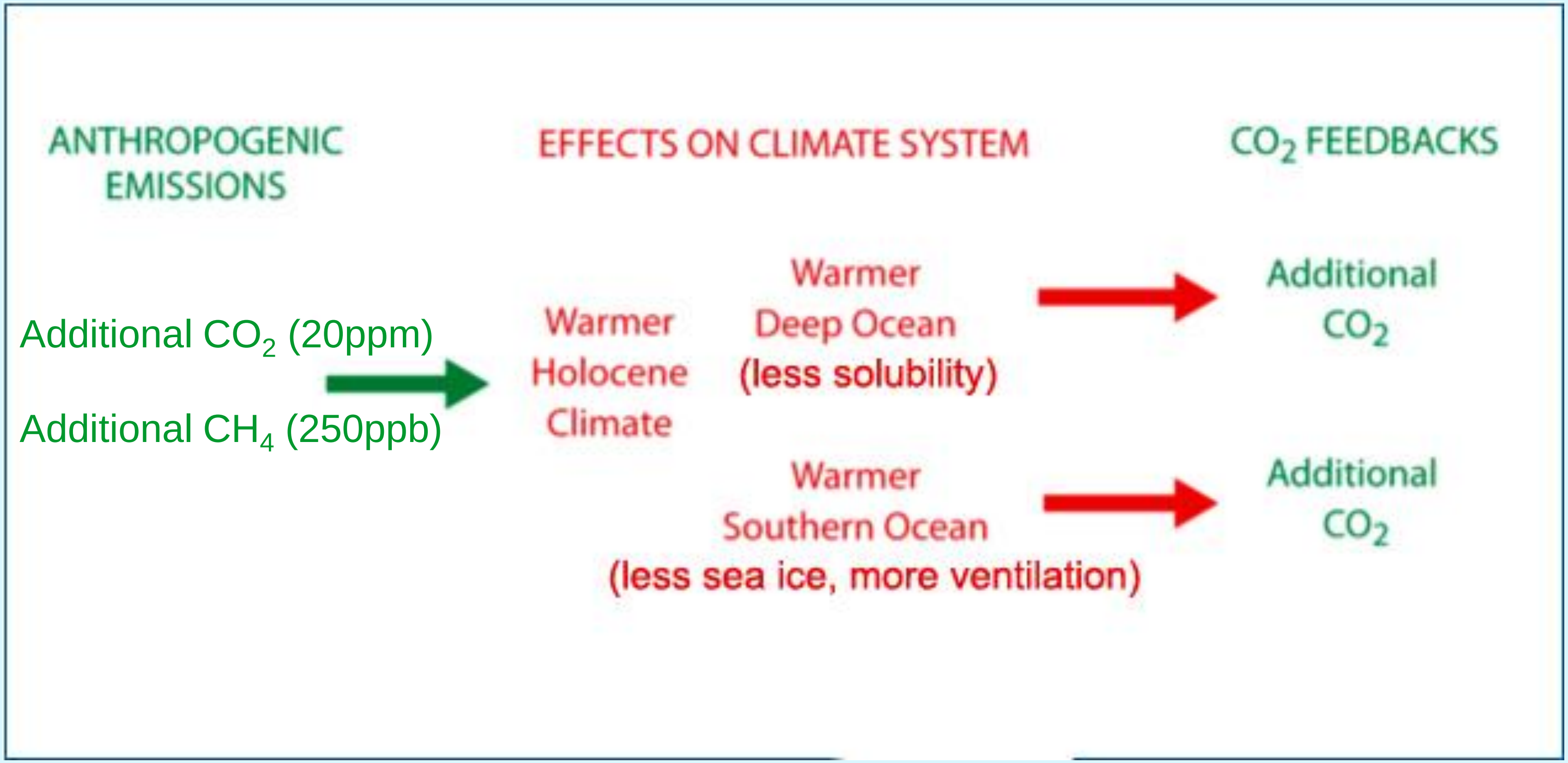
Modified Hypothesis (Ruddiman, 2007, 2011)

The Holocene CO_2 trend may be a combination of direct anthropogenic emissions and internal climate feedbacks



Model Simulations (PD, PI, NA): Question – can models shed light on the kinds of feedbacks that might have amplified the climate response to early agriculture?

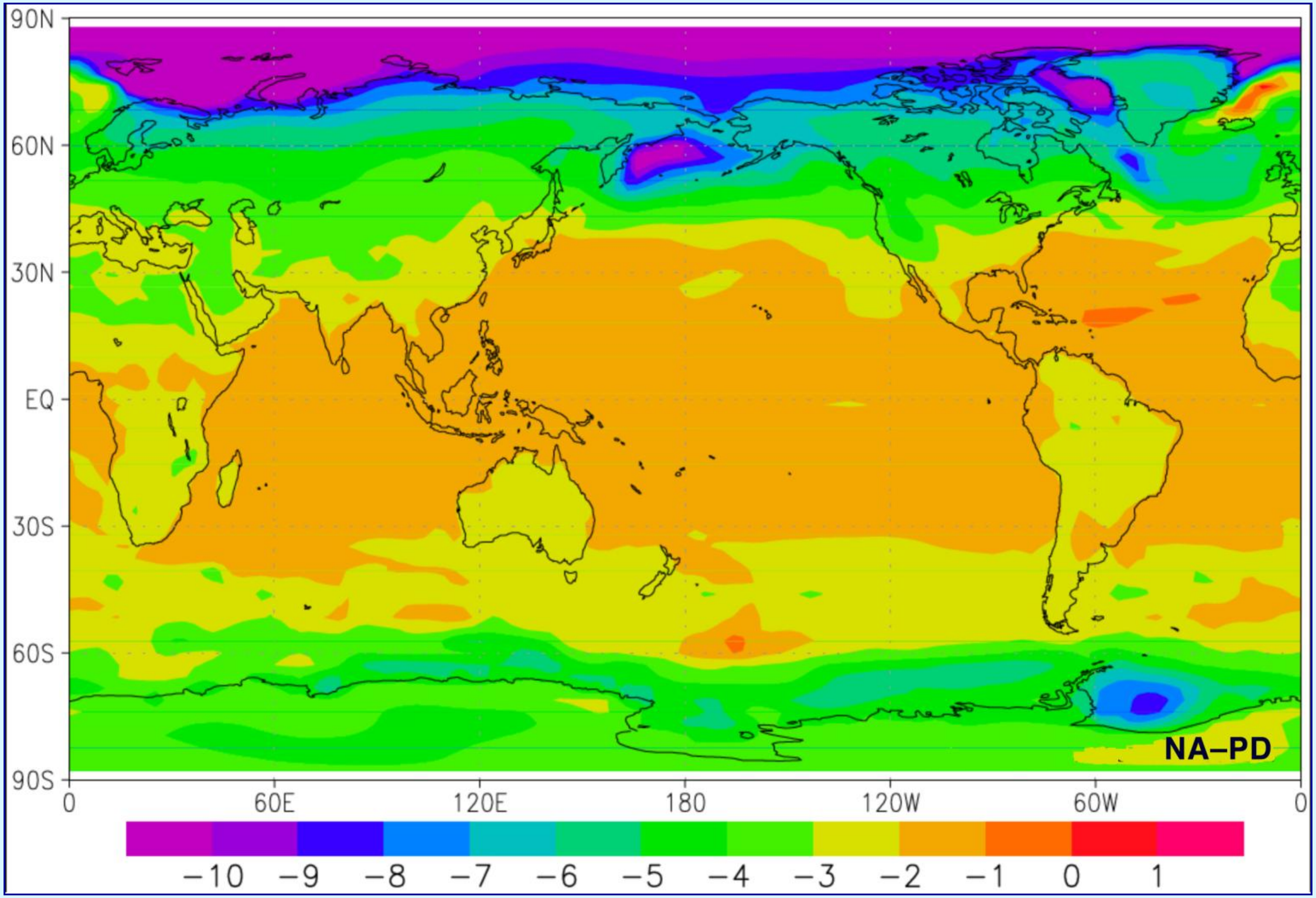
- Use CCSM3 (Kutzbach et al, 2010, 2011)
- Partition results: NA – PD = (NA – PI) + (PI – PD)
- Examine changes and potential ocean feedbacks

Summary of GHG forcing changes

	PD	PI	NA
CO_2(ppm)	355	280	240
CH_4 (ppb)	1714	760	450
Equiv. CO_2 (ppm)	355	243*	199*
Lowered radiative forcing (w/m^2)	0*	-2.05*	-3.06*

*referenced to PD GHG and GHG forcing
(includes reductions in N_2O, CFCs)

Annual Surface Temperature Difference (K), NA-PD
CCSM3



ΔT_S(global) = –2.74K

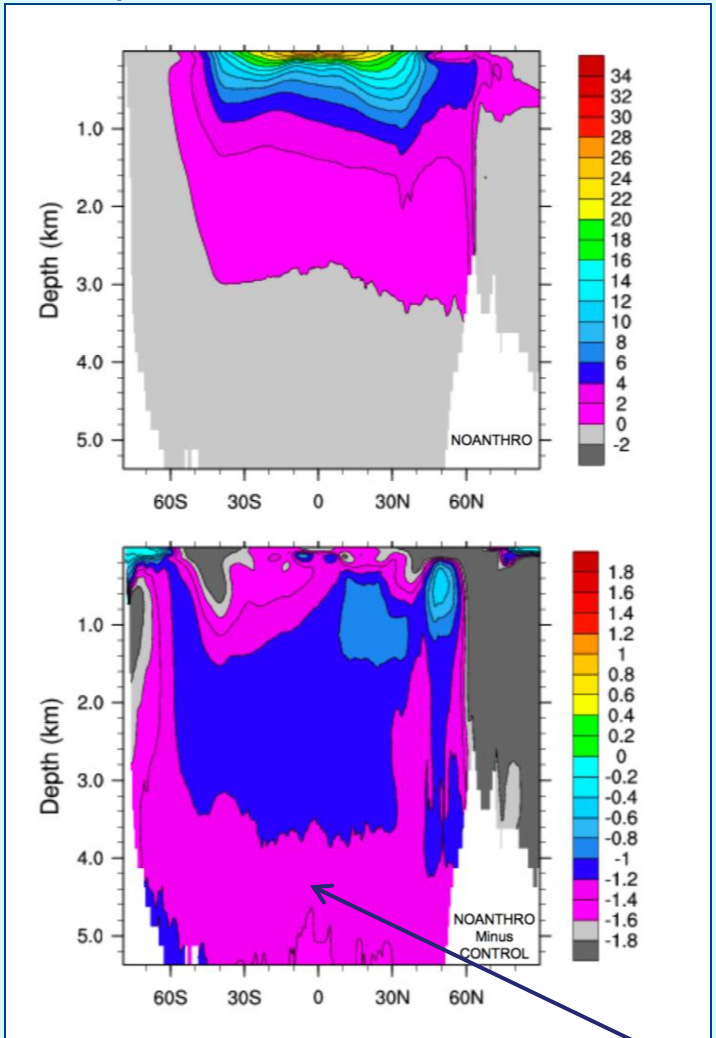
Kutzbach et al, 2010

Zonal Average Ocean (latitude/depth) – CCSM3

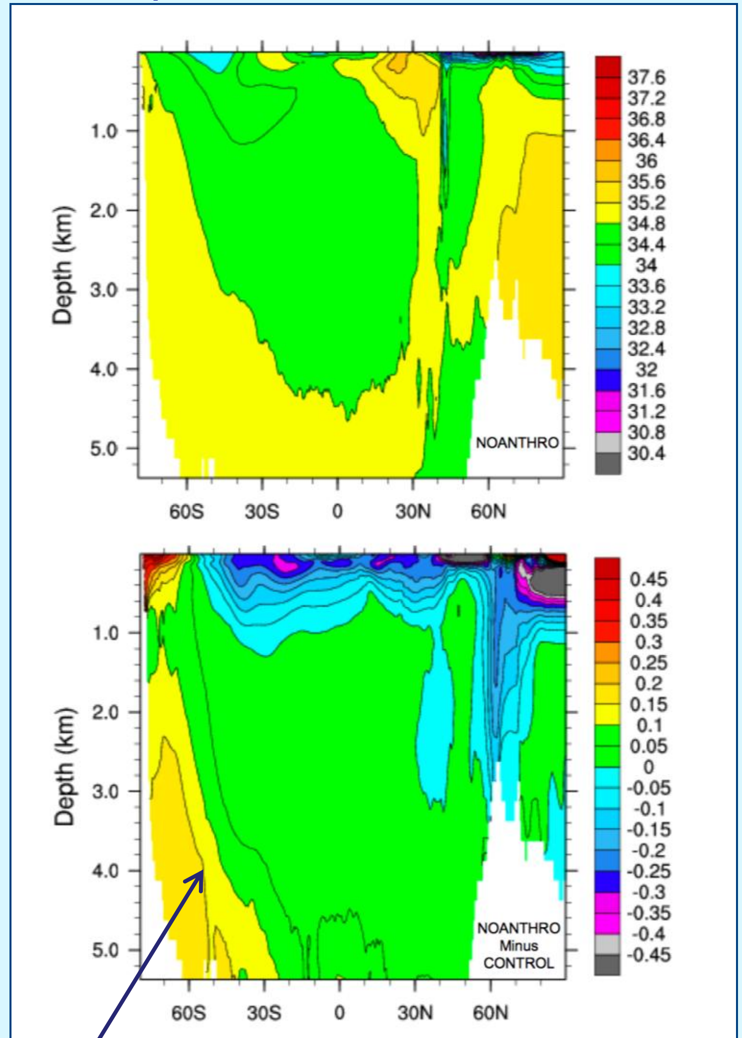
NA

NA – PD

Temperature



Salinity



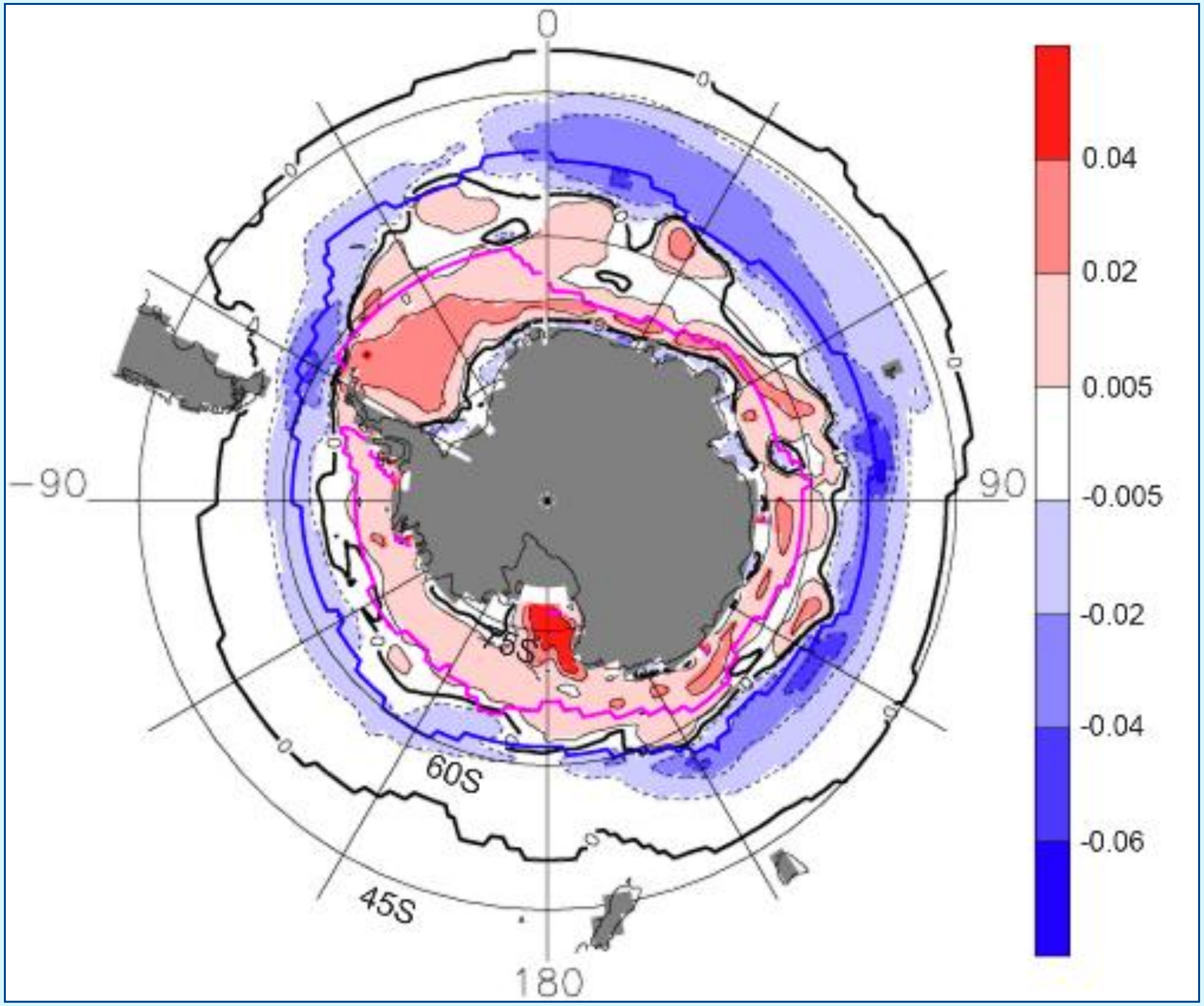
Kutzbach et al, 2010

NA: colder, saltier

Colder – greater CO_2 solubility; Saltier – more deep convection

Increased SH Sea Ice Cover in Simulation NA (less ventilation)

50% Sea Ice Cover in NA; DJF (red line), JJA (blue line)
Salt Flux Changes, NA – PD: increased salt flux to ocean (red), decreased (blue)



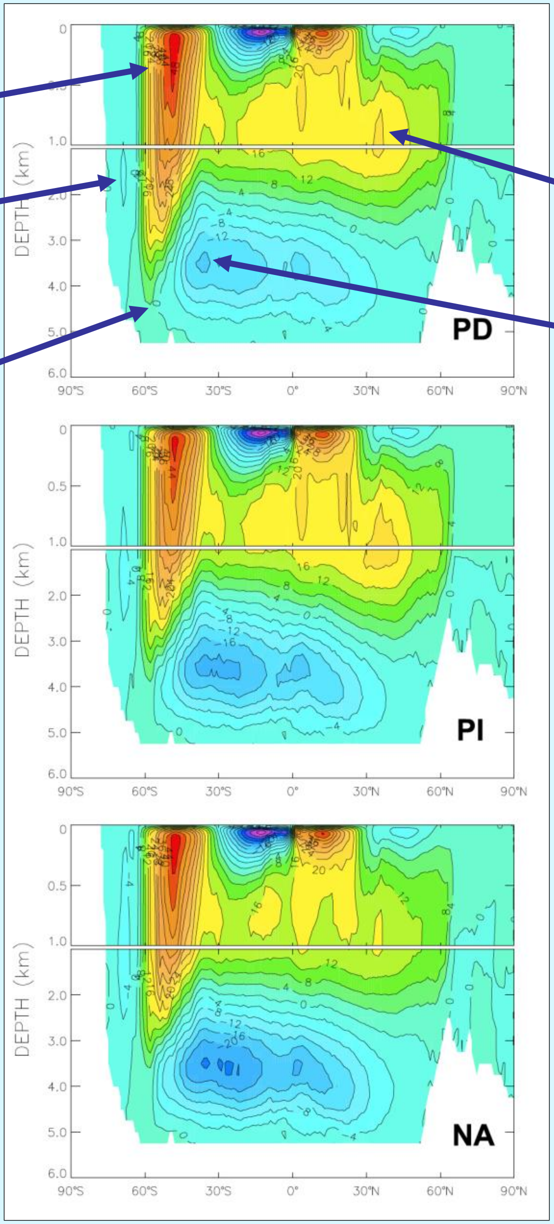
Kutzbach et al, 2010

CCSM3: Zonal Average Overturning Circulation (Sv)

Stronger upwelling (stronger westerlies shifted south)

Weaker Antarctic water sinking

Deeper extension of Deacon cell
(more ventilation from deep ocean)



PD
higher CO_2, warmer

Stronger NADW

Weaker AABW

PI
intermediate CO_2

NA
lower CO_2, colder

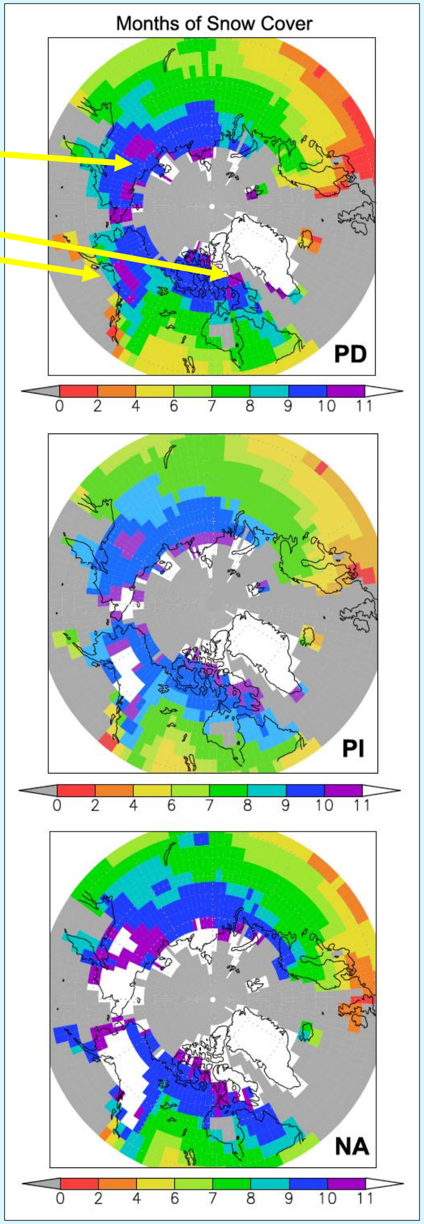
Increasing greenhouse gases

The greater ventilation of the deep ocean as the climate warms might increase the flux of carbon dioxide to the atmosphere.

Kutzbach et al, 2011

CCSM3: Months of Snow Cover (white=12 months)

Less permanent snow cover (white)



PD
higher CO_2, warmer

PI
intermediate CO_2

NA
lower CO_2, colder

Increasing greenhouse gases

More permanent snow cover (white)

Note: white indicates year-round snow cover averaged over a grid cell, but sub-grid-scale topographic features imply non-uniform coverage within each cell

Kutzbach et al, 2011

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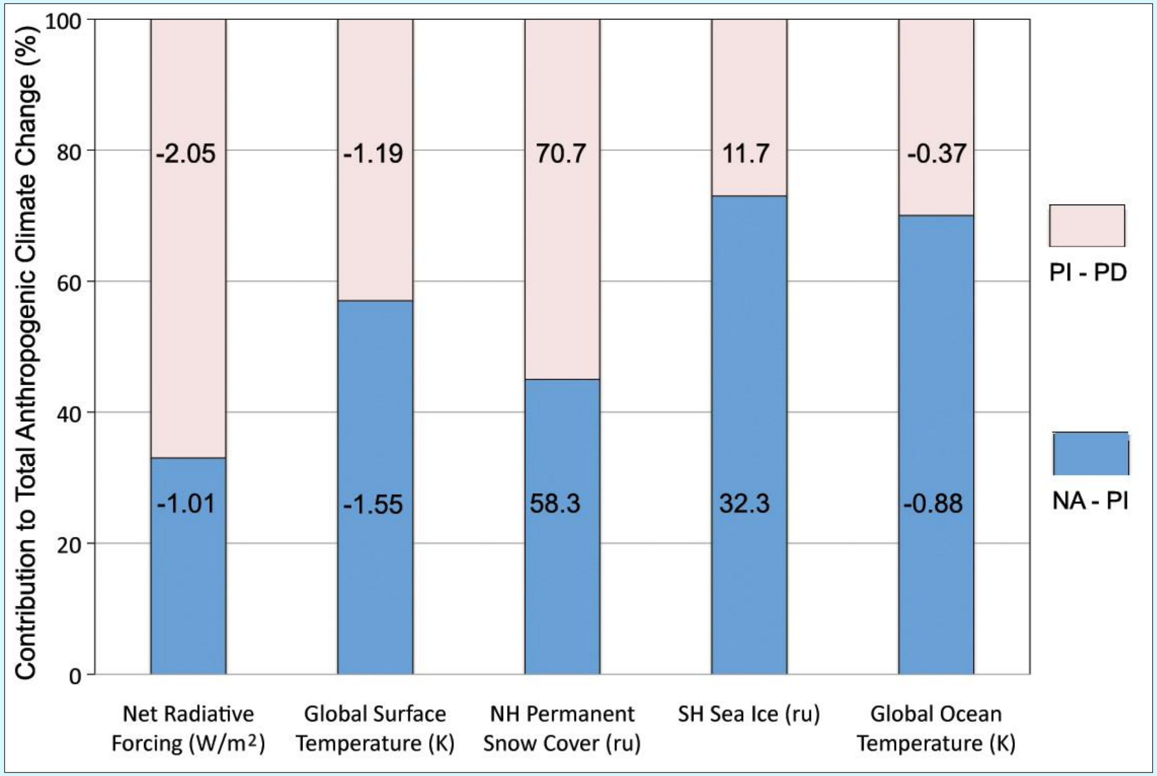
Larger Climate Response to GHG forcing for Colder Climate State: Partitioned results, (NA-PI) compared to (PI-PD)

Forcing —— Response ——



- Larger climate response to GHG forcing for cold climate state
- Enhanced response greater for CCSM3 than for CAM3 + SO
- Agreement with limited number of observations:

ΔT_s, PI – PD , -.7 to -1.2K, Jones and Mann, 2004

ΔT_0, NA –PI , -0.85K, Lisieki and Rayno, 2005

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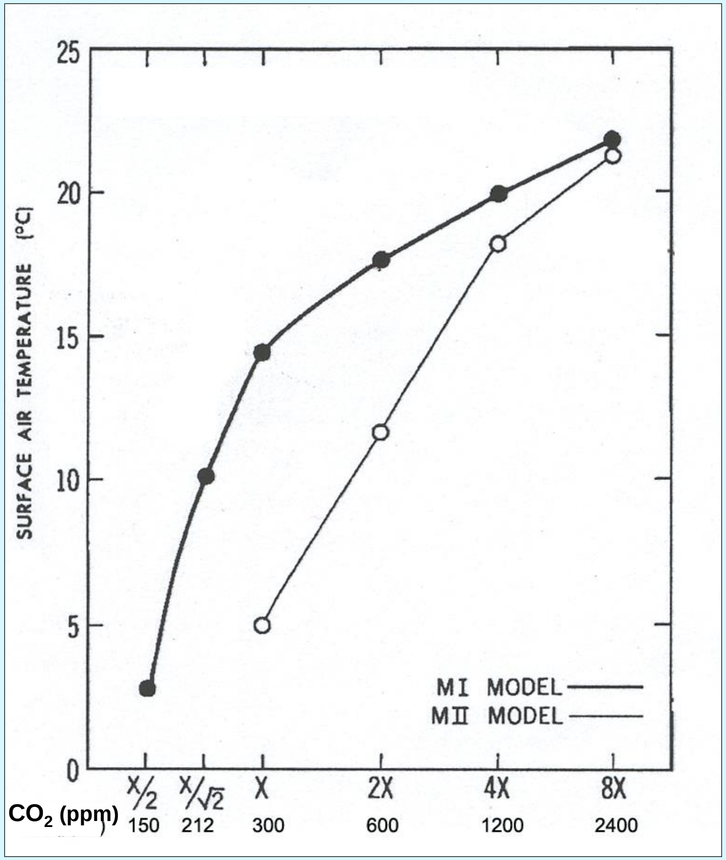
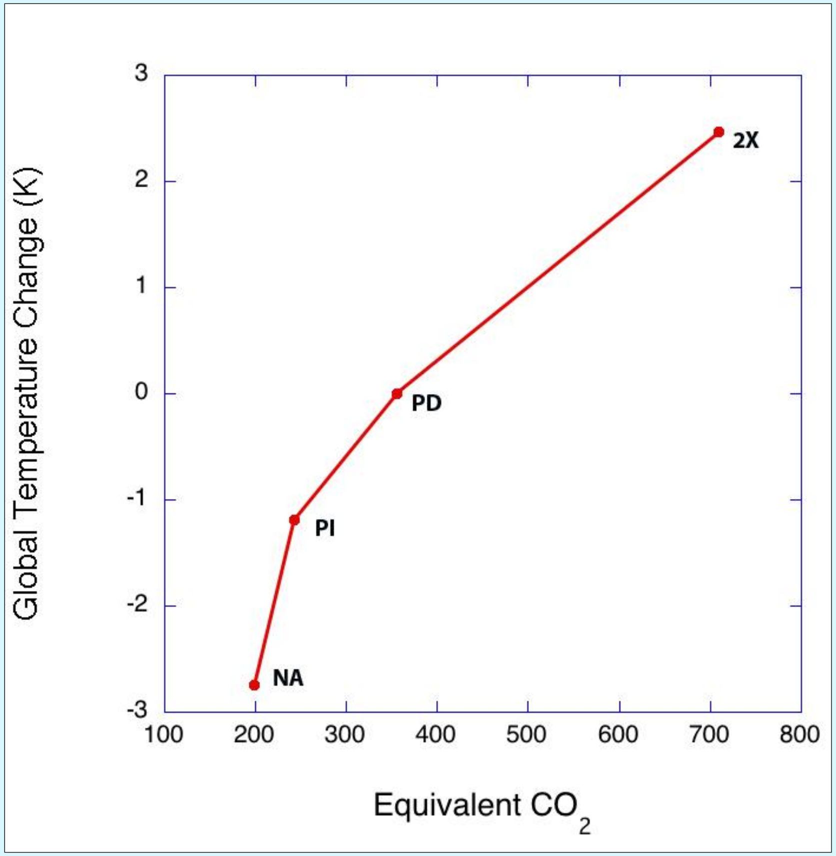
Kutzbach et al, 2011, Holocene

Larger Climate Response to GHG Forcing for Cold Climate States (results from two models, early GFDL model and CCSM3)





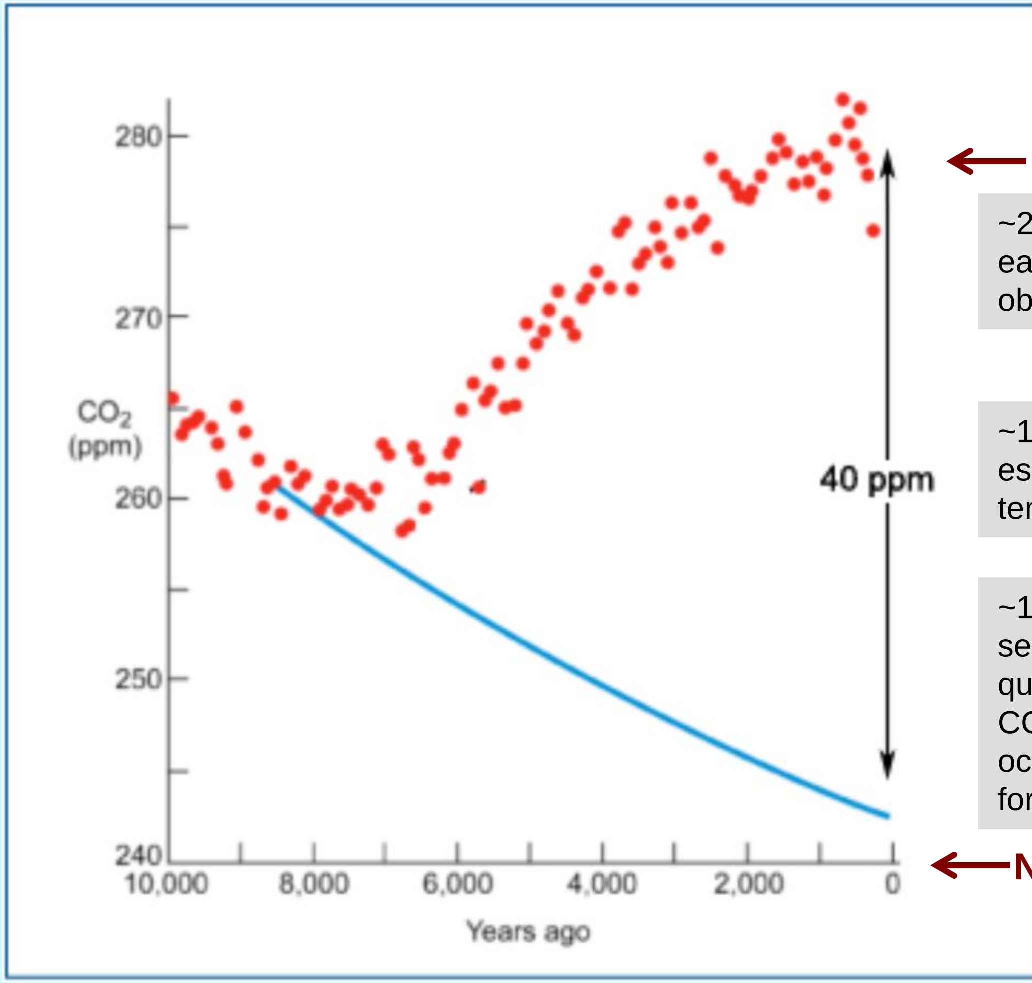
Idealized land/ocean planet
M1: atmosphere – ocean model
M2: atmosphere – slab ocean model

CCSM3

Kutzbach et al, 2011, Holocene

Manabe and Bryan, 1985, JGR 90:11689-11707

Explaining the Difference Between Holocene CO_2 Trend and Trend of Six Previous Interglacials: Current Status!



PI

NA

~20 ppm, direct anthropogenic effect of early agriculture – estimate based on observations (Kaplan et al, 2011)

~10 ppm, reduced ocean solubility – estimate based on CCSM3 ocean temperature increase, NA to PI, ~0.9K

~10 ppm, other ocean feedbacks (less sea ice, increased ventilation)??? – qualitative changes inferred from CCSM3 results; new experiments with ocean biogeochemistry will be needed for quantification

Kutzbach et al., 2011
Ruddiman et al., 2011

Main points

- Late interglacial CO_2 and CH_4 trends differ from Holocene trends
- Early agriculture may explain the difference (and if not early ag, what?)
- CCSM3 simulations (PD, PI, NA) explored climate trends/feedbacks
- The partitioned changes, NA – PD = (NA-PI) + (PI-PD), show greater sensitivity of climate to greenhouse gas increases in ‘cold climate states’
- There are potential ocean feedbacks from changes in solubility, sea ice, and deep ocean ventilation
- The partitioned CCSM3 results are in general agreement with an earlier GFDL model study and with limited observations
- Next steps: repeat experiments with CCSM4 with bio feedbacks and land use changes included; refine estimates of early agriculture impacts