Earth System Models and Uncertainty

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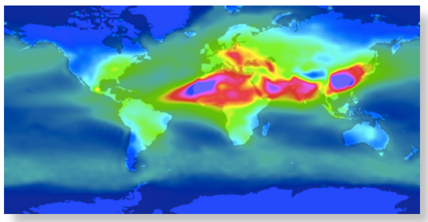
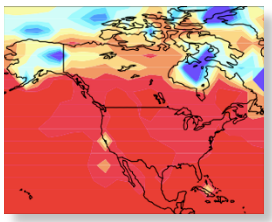
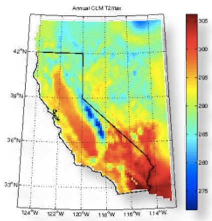
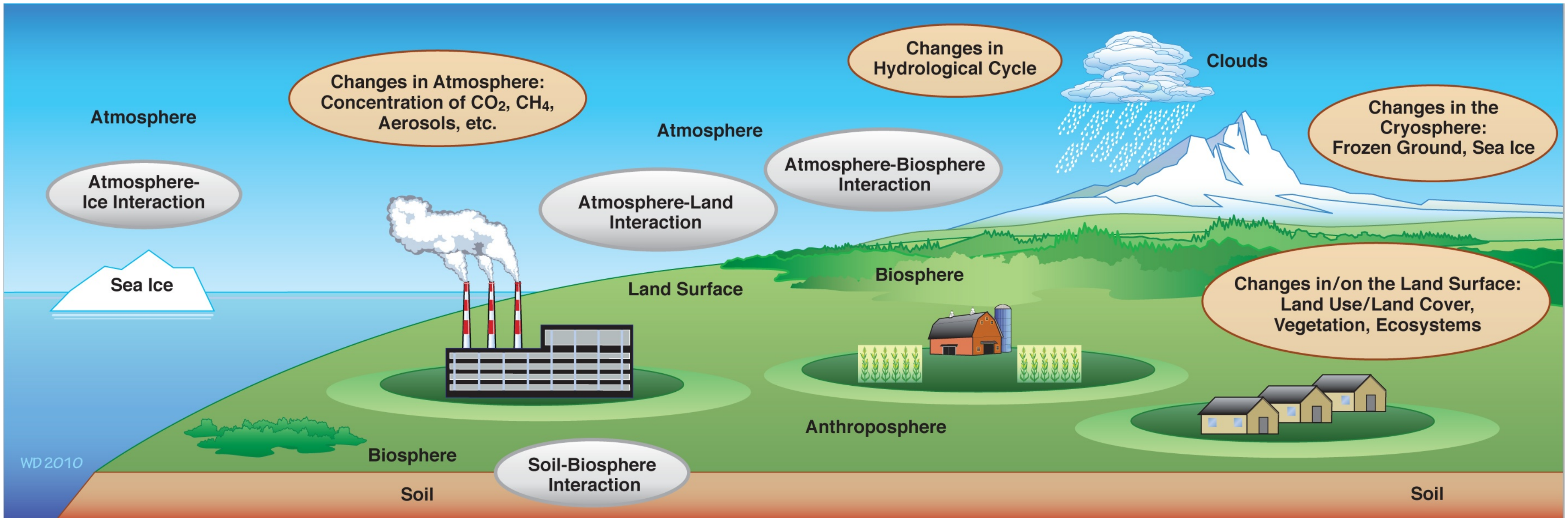






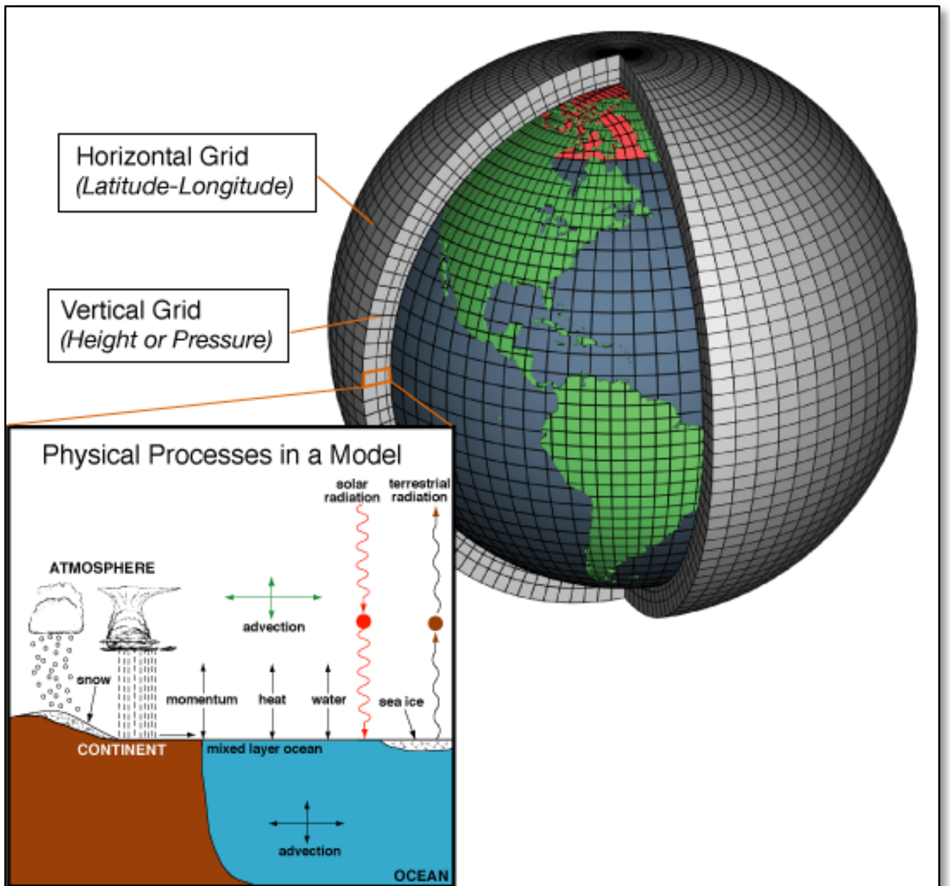
Key questions for our climatic future



Derived from IPCC AR4, 2007

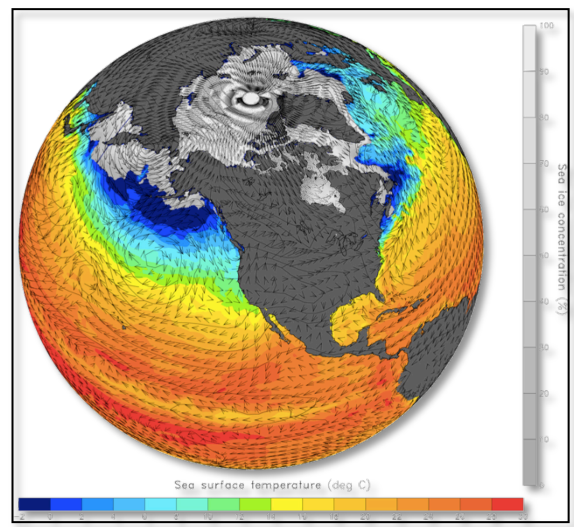
- How are we altering the climate?
- How fast could the climate change?
- How can we shift to a sustainable path?

Climate models: A "Crystal ball" for Earth?

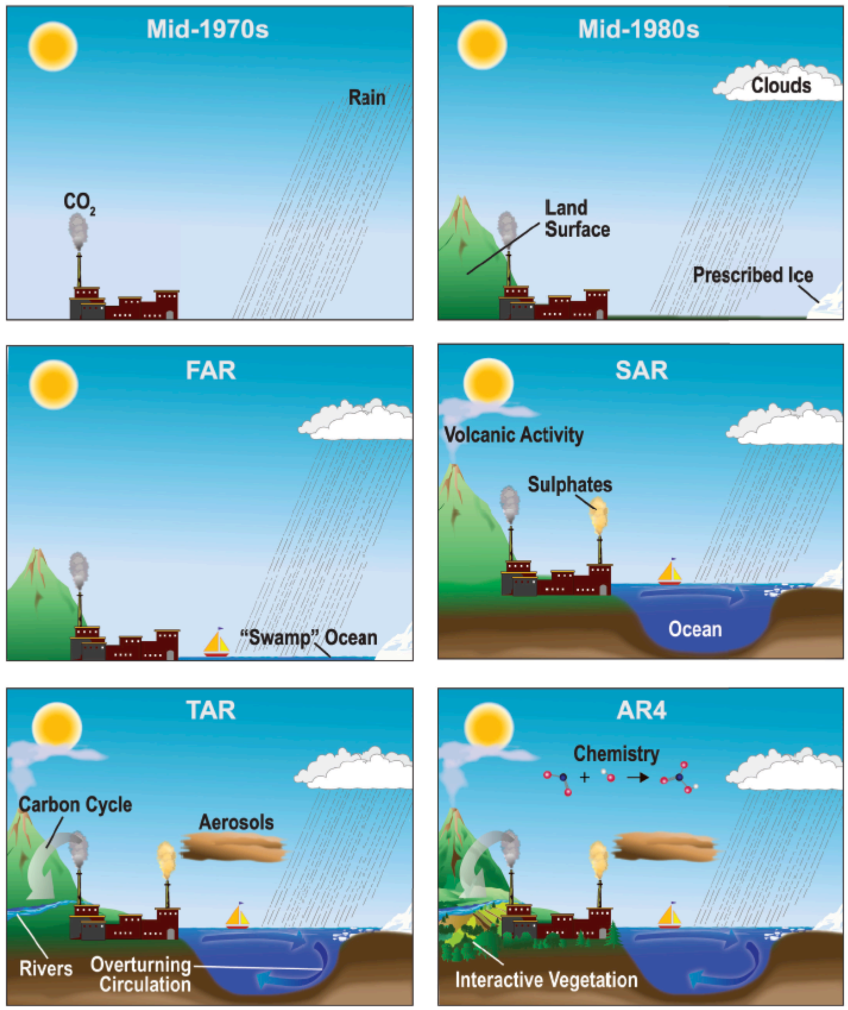


Credit: NOAA

- Tool for predicting the future
- Tool for understanding the past
- Numerical "parallel Earth"



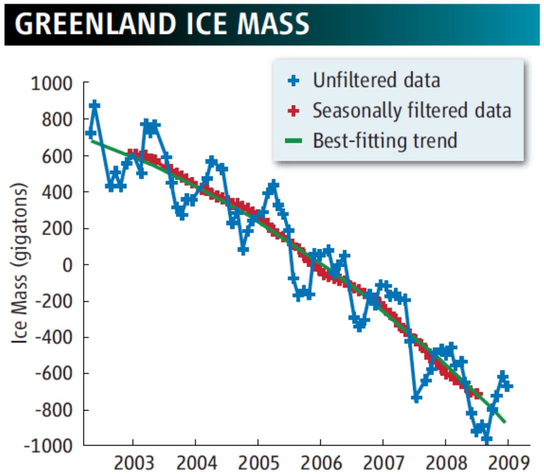
Increasing process realism of climate models: Transition from AOGCMs to ESMs



Credit: IPCC

Real climate is changing faster than predicted

First commercial transit across the Arctic Ocean
Science, Oct 2, 2009



Both of the World's Ice Sheets Are Shrinking Faster
Science, Oct 18, 2009

North Pole Summers Will Be Ice Free In A Decade
Huffington Post, Oct 10, 2009

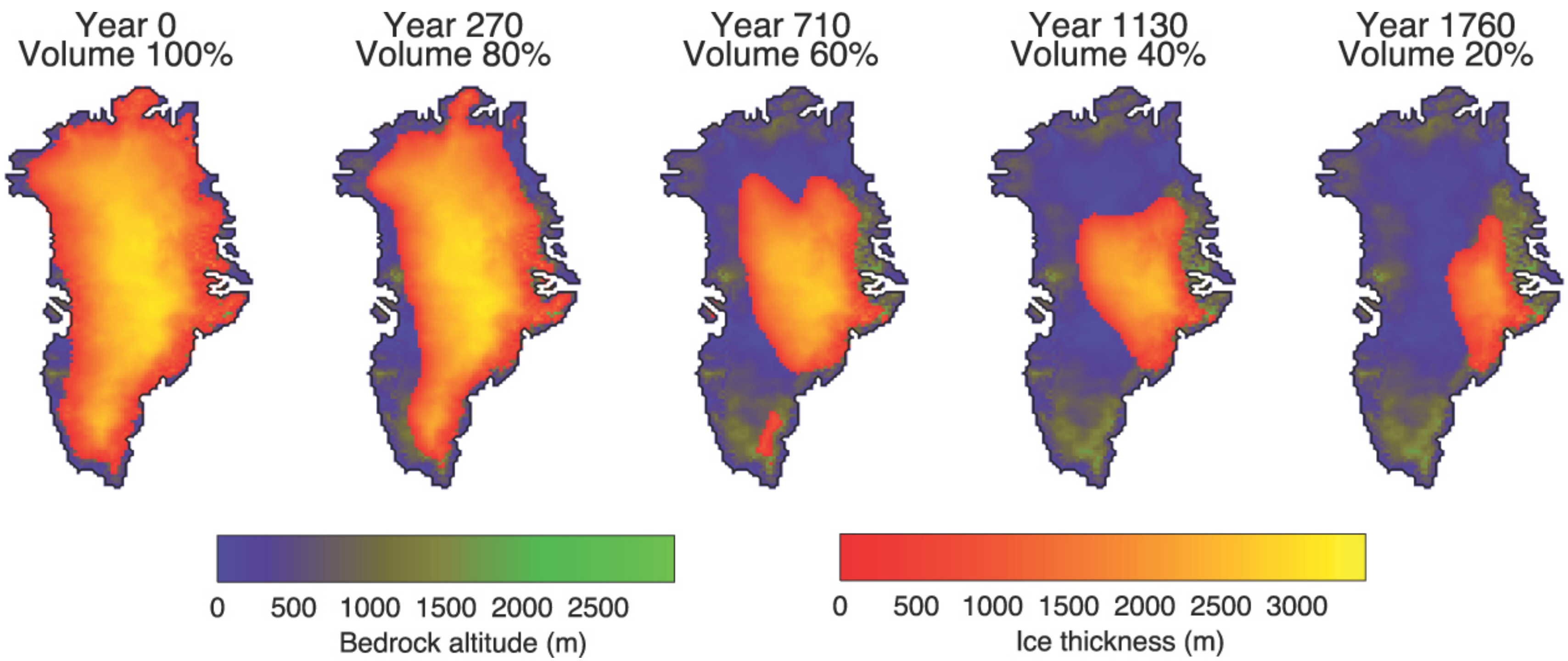
Abrupt and extreme climate change

- **Abrupt climate change** is a fast, large-scale climate shift that **can cause lasting disruptions to society and the environment.**

- **Extreme climate change** increases climatologically unusual events that **can exceed thresholds for adaptation.**

- **Several types of change that would pose a major challenge are:**
  - *Sea level rise from land ice*
  - *Faster warming from oceanic hydrates*
  - *More frequent heat waves and tropical storms*

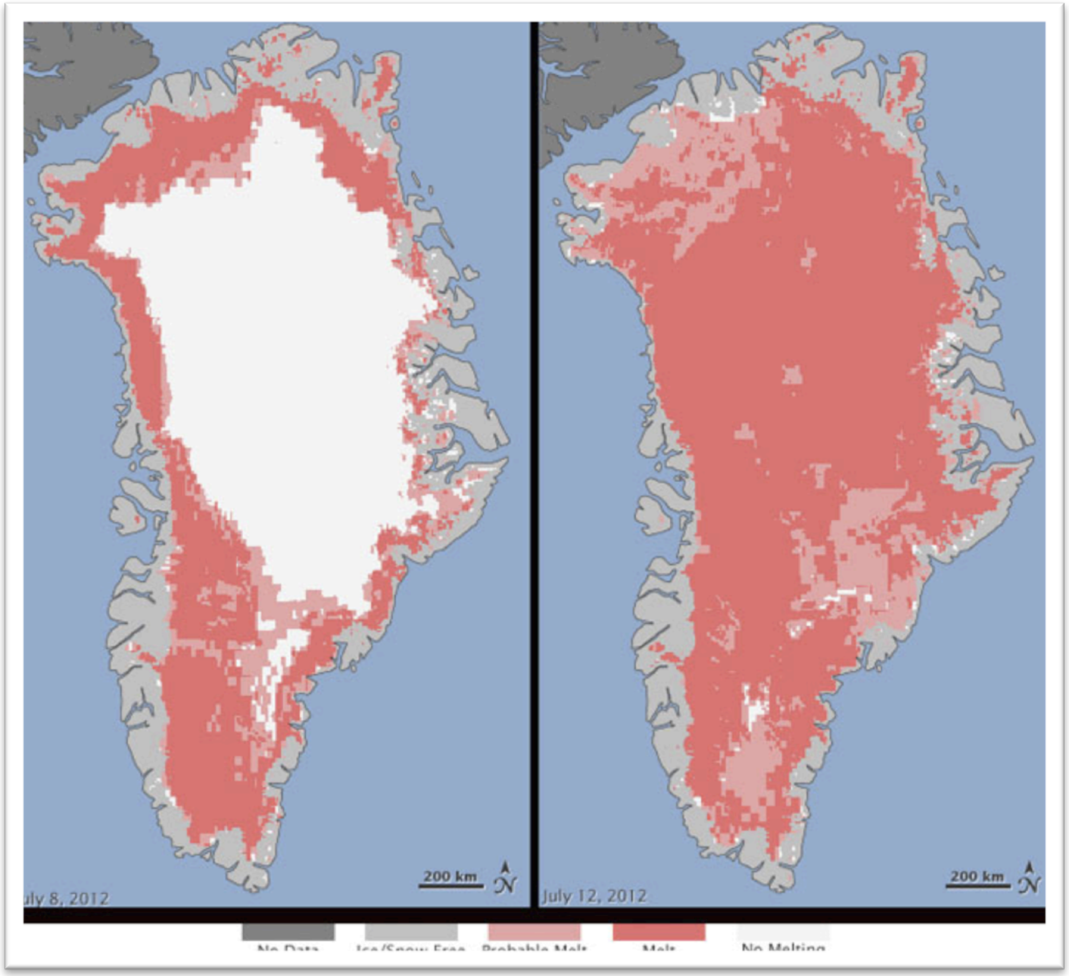
The future of Greenland?



- If all Greenland melts, sea level would rise by 7.2 meters.
- Melt from Greenland adds 0.5 mm/year to sea level now.

Credit: IPCC

Land ice is very dynamic

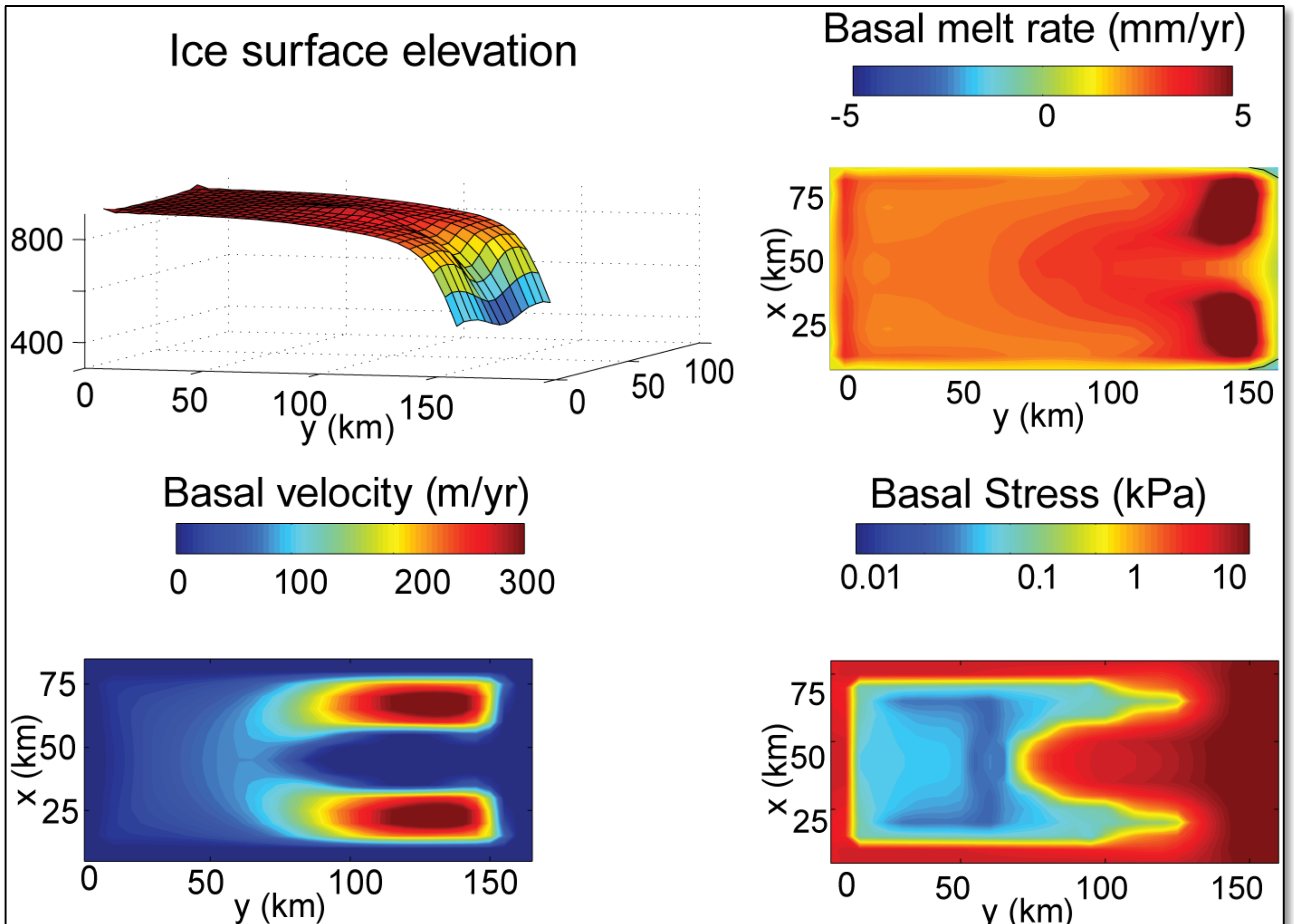


Extent of surface melt over Greenland's ice sheet on July 8 (left) and July 12 (right).
On July 8, about 40 percent of the ice sheet had undergone thawing
On July 12, an estimated 97 percent of the ice sheet surface had thawed.

Credit: NASA

Land ice can slip and slide

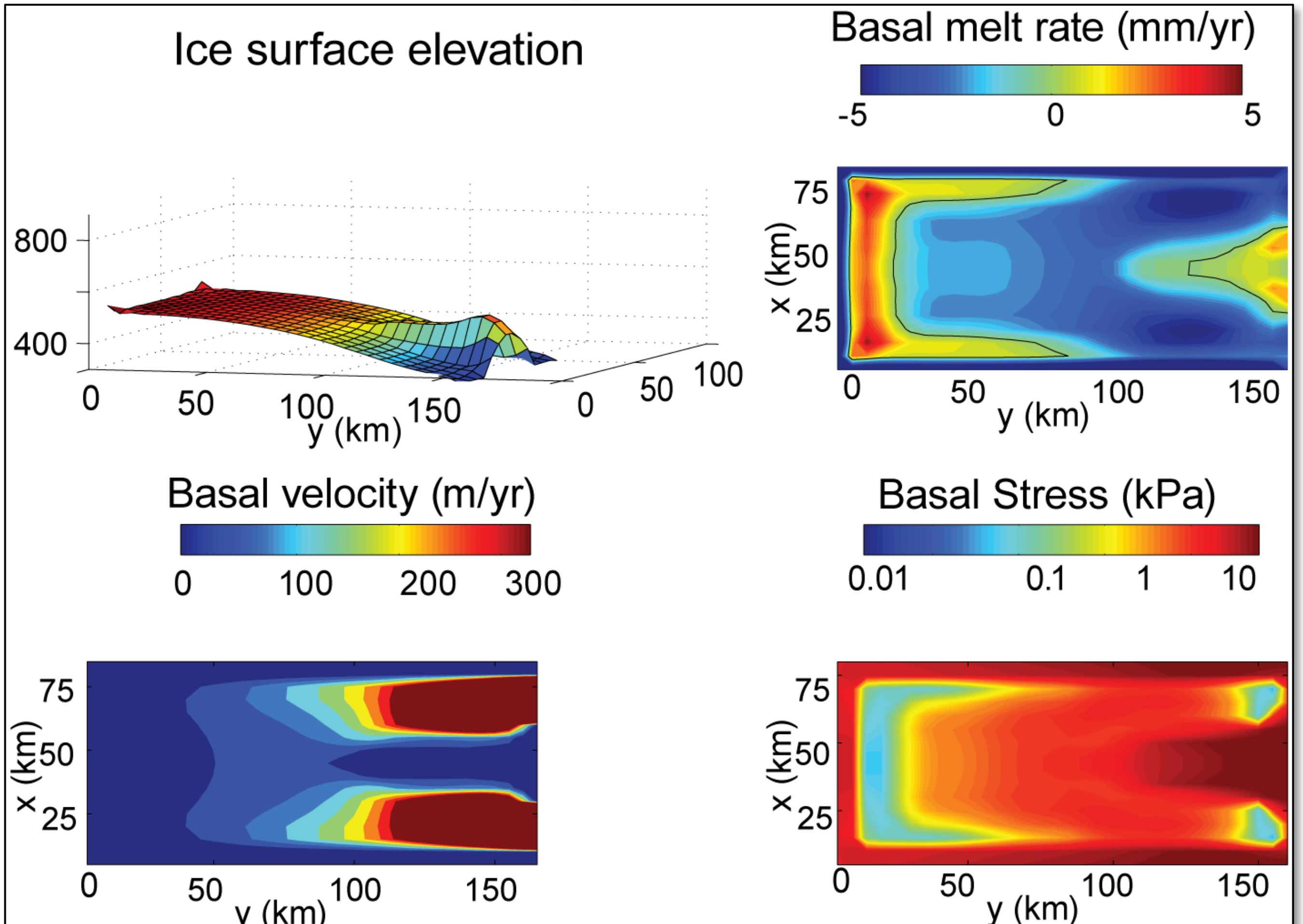
Start



Credit: LANL

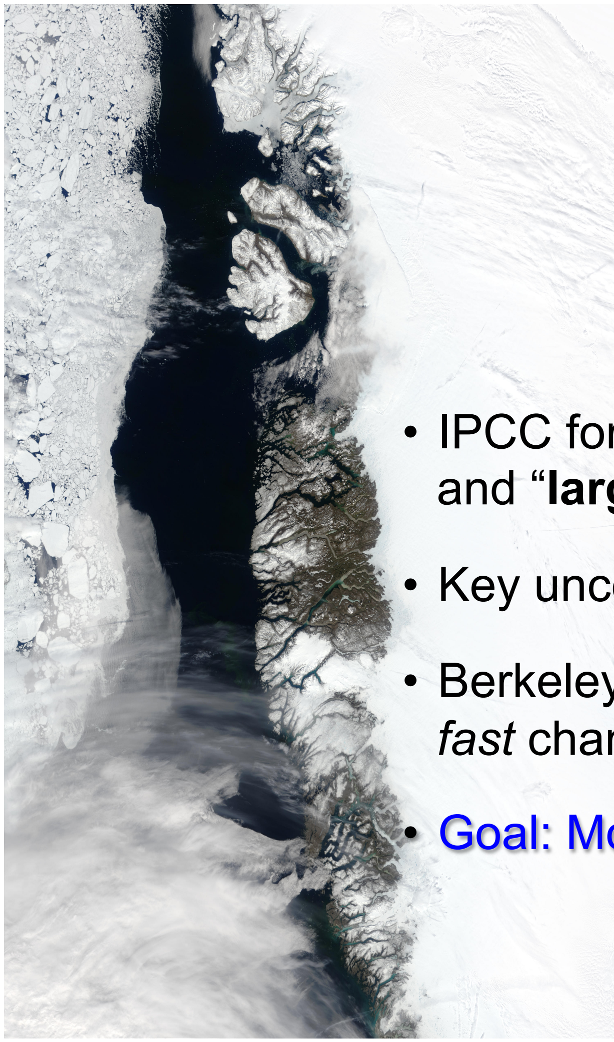
Land ice can slip and slide

100 years later



Credit: LANL

New dynamics for land ice models



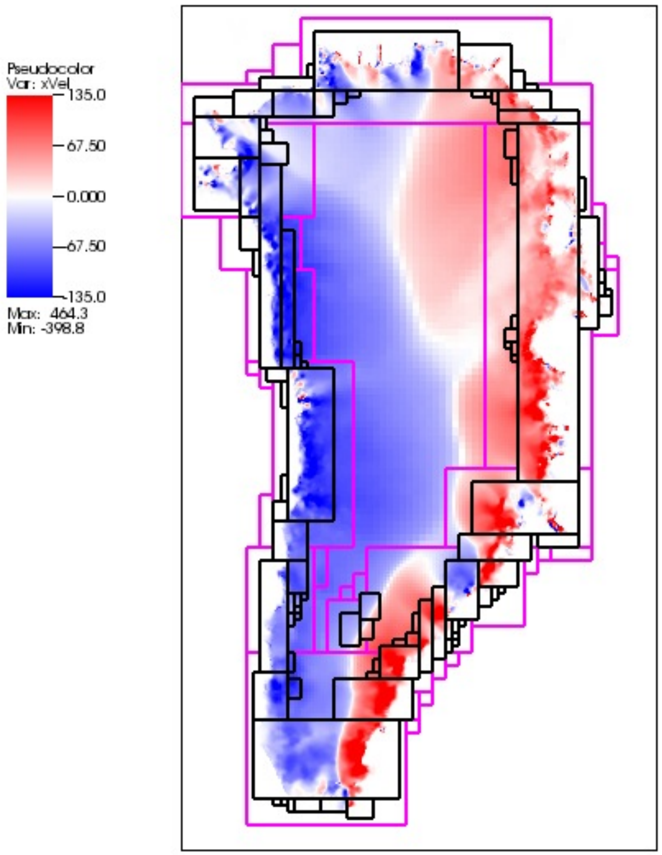
- IPCC forecast sea level rise of 10-50 cm by 2100, and “**larger rises cannot be excluded**”.
- Key uncertainty: “**Future rapid dynamic changes in ice flow**”.
- Berkeley Initiative for Climate at Extreme Scales targets *fast* changes in Greenland and Antarctica.
- Goal: More reliable sea-level projections.

BISICLES

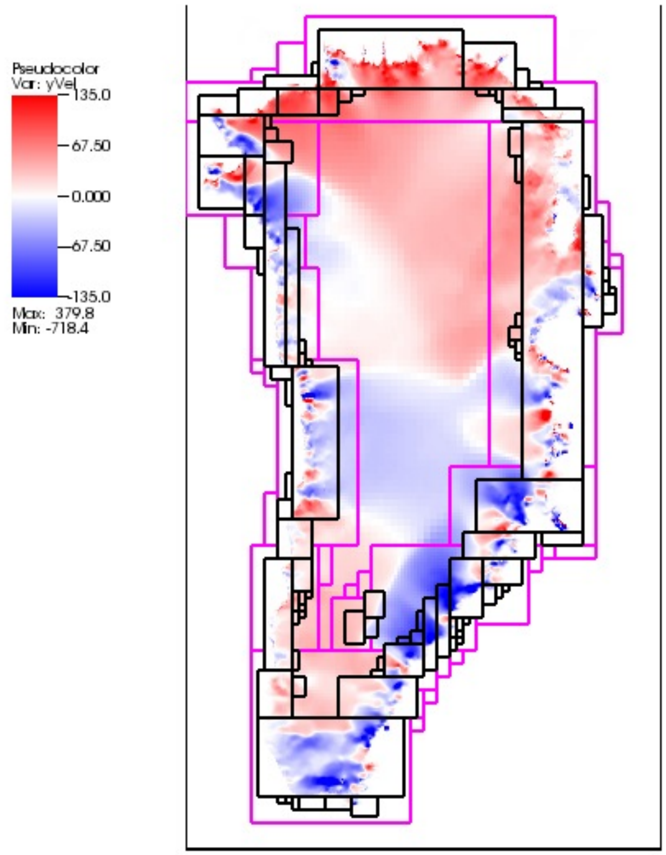
BISICLES: Dynamics of Greenland

Introduction of Adaptive Dynamics: Near-term developments

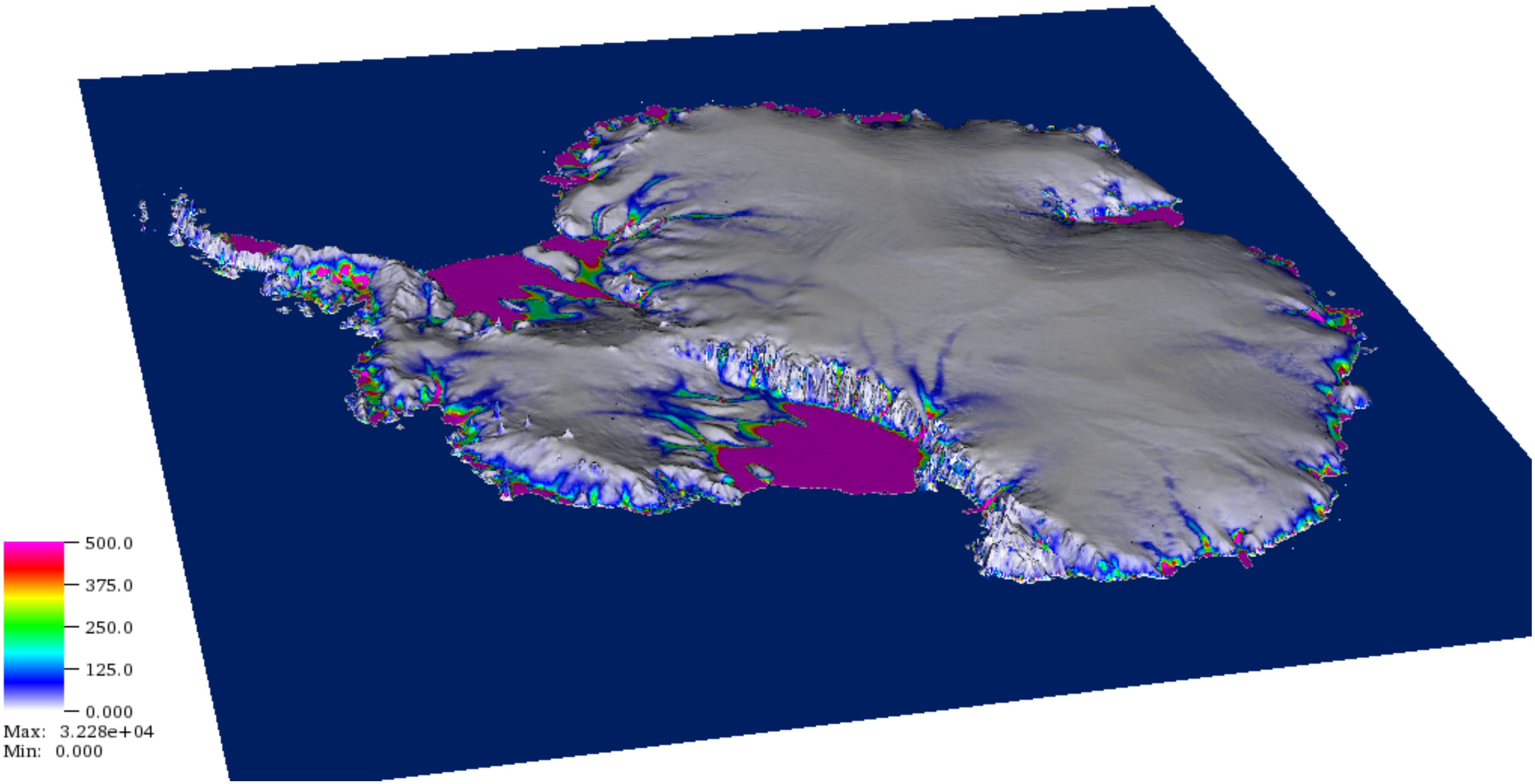
E-W Velocity



N-S Velocity

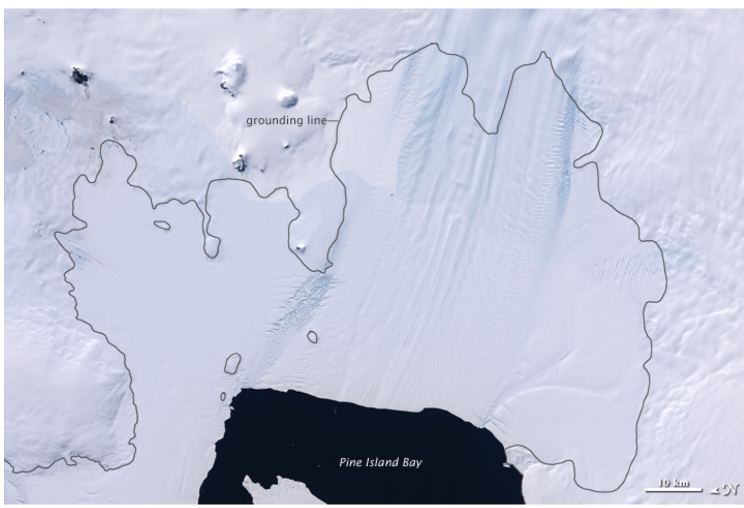


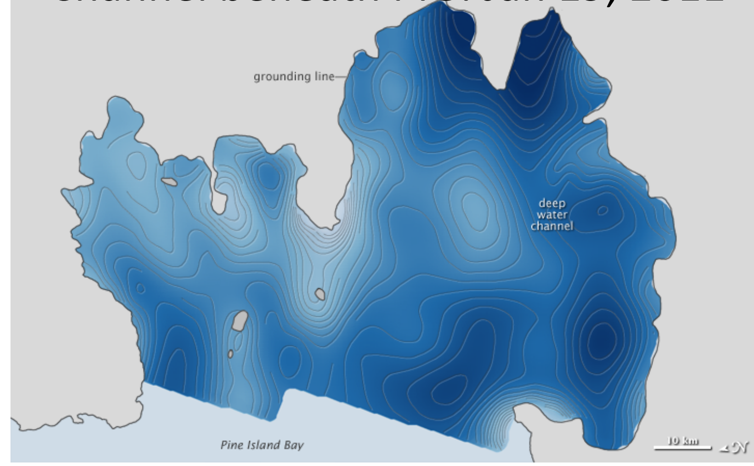
BISICLES: Dynamics of Antarctica



Recent Changes in Pine Island Glacier


300 $mile^2$ portion of PIG to break off: Nov. 4, 2011

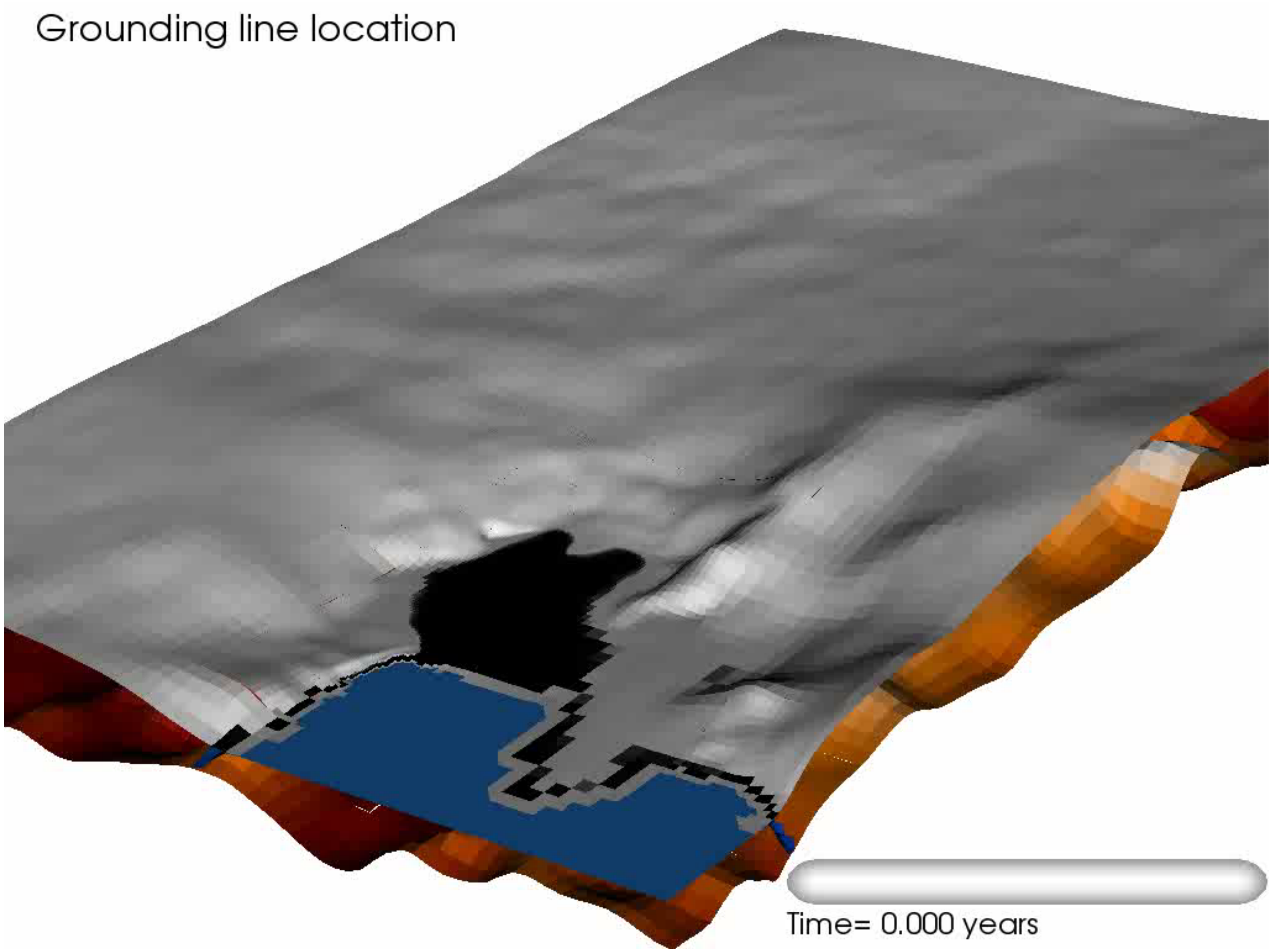




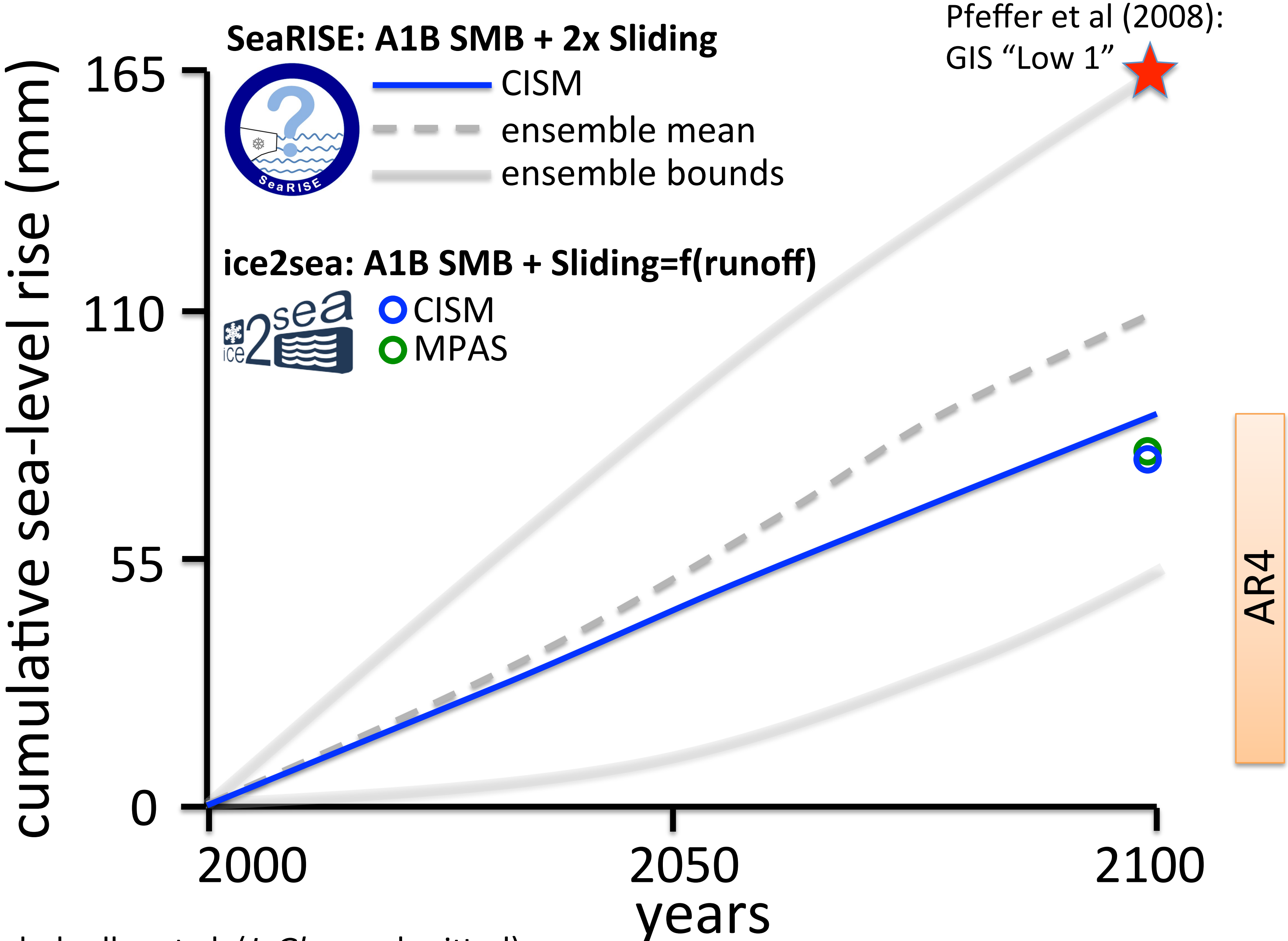
Channel beneath PIG: Jan 19, 2011

Images: NASA

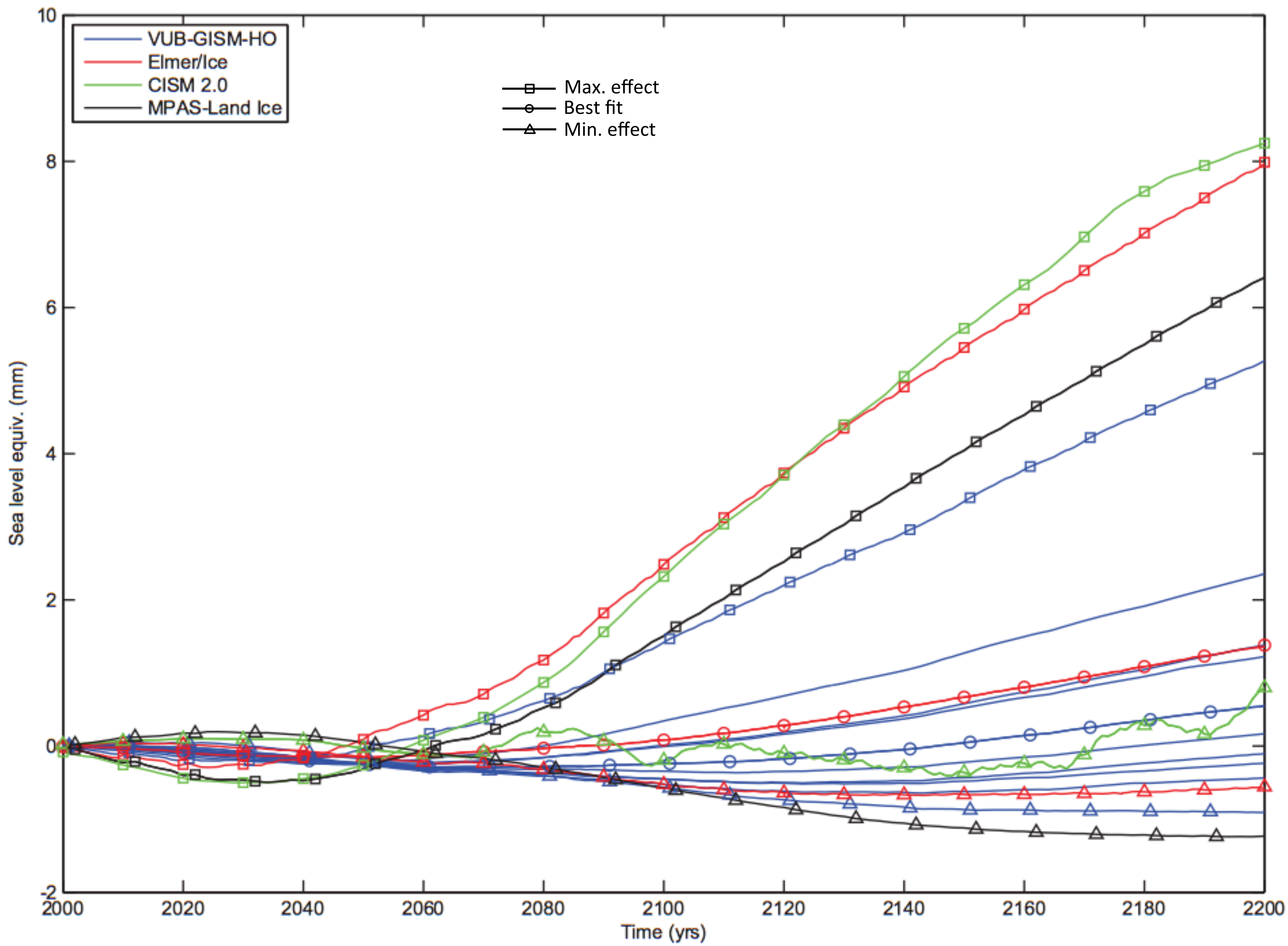
BISICLES Simulations of Pine Island Glacier



Greenland Model Results

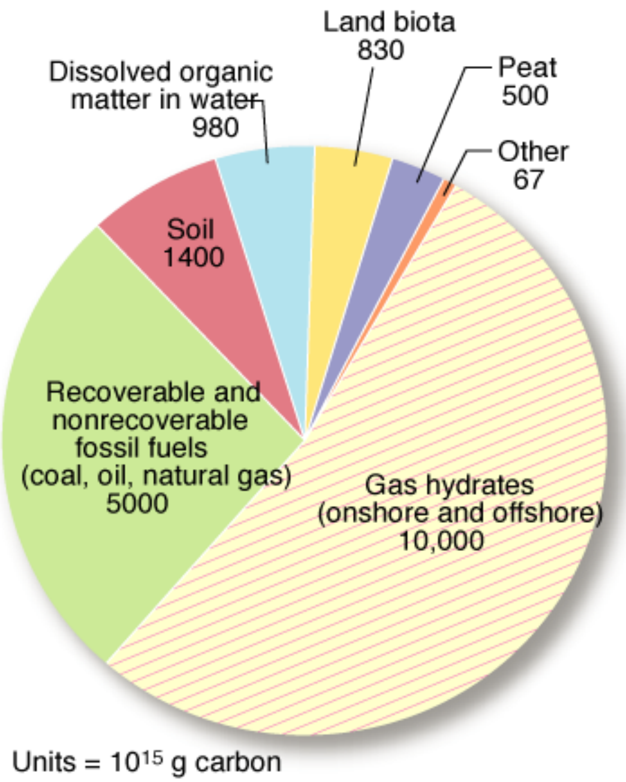


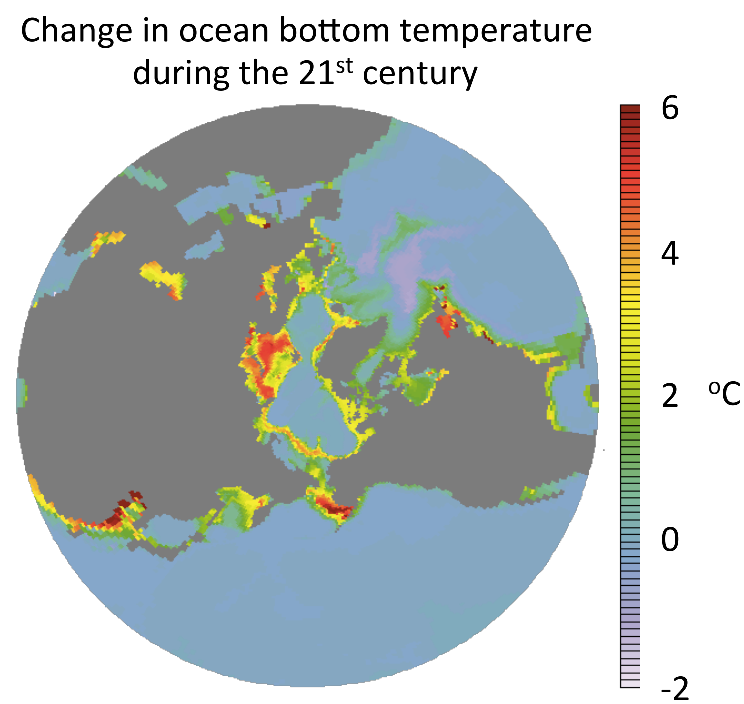
Bindschadler et al. (*J. Glac.*, submitted)



Shannon et al. (*PNAS*, submitted)

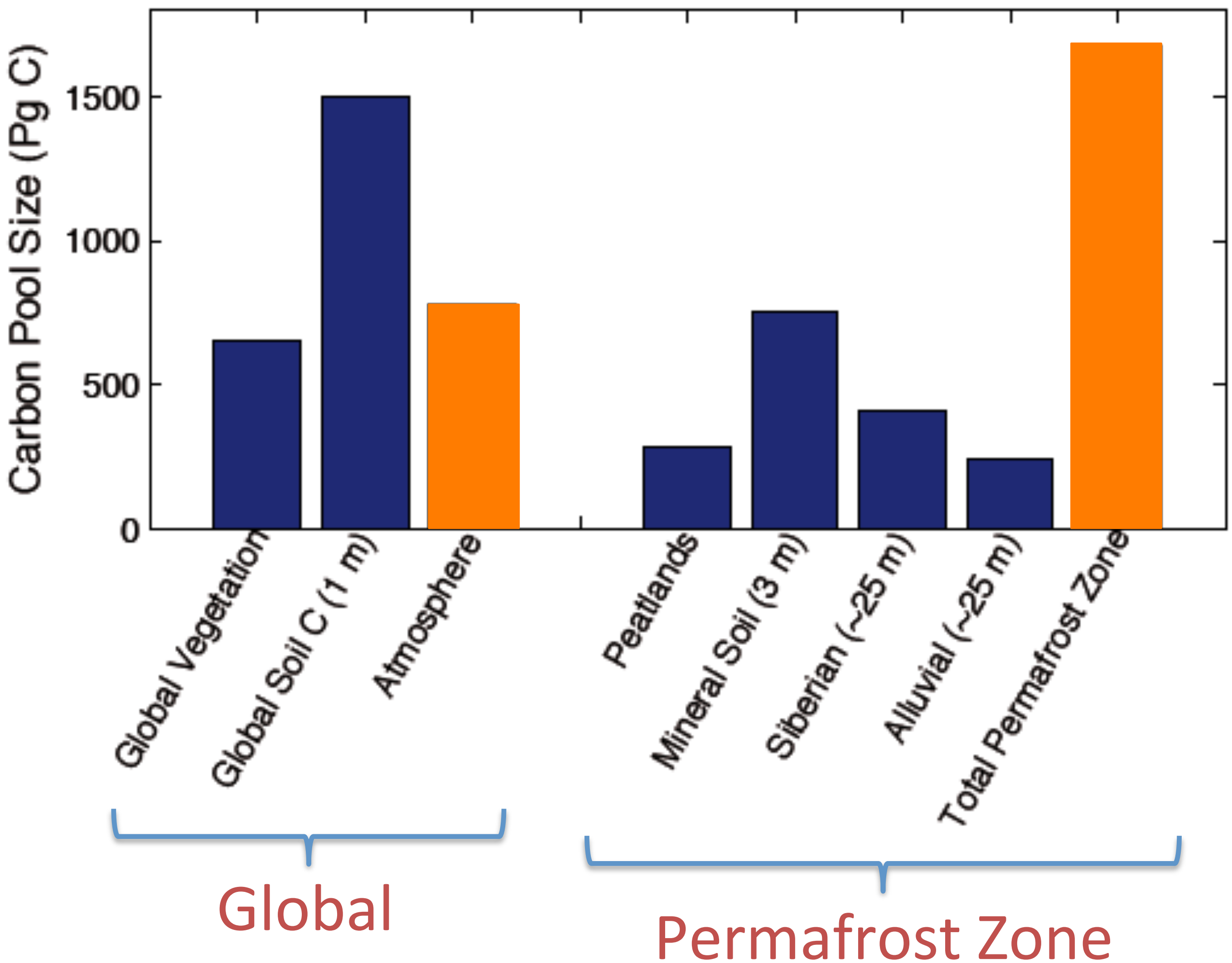
Carbon pools: A positive feedback?





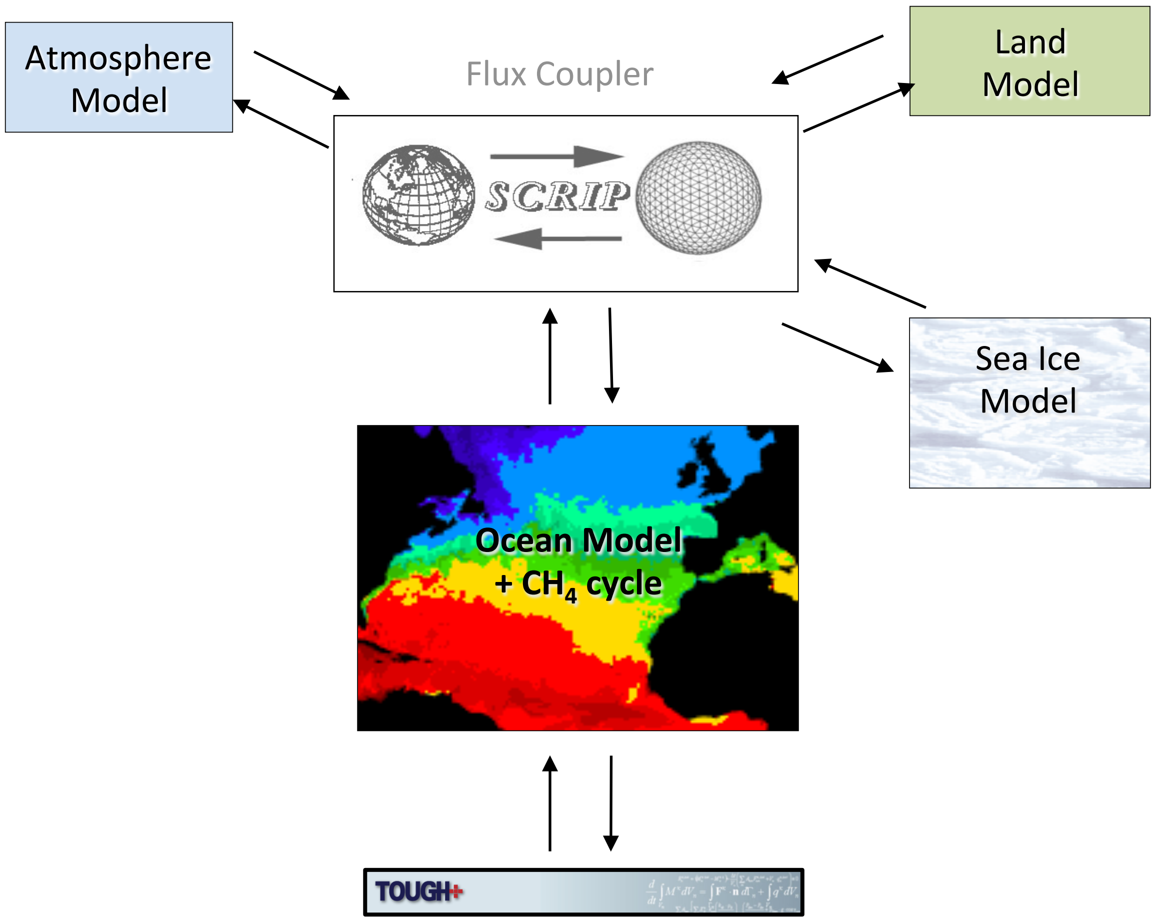
- Oceanic hydrates and permafrost are a significant reservoir of carbon.
- Could warmer oceans melt the hydrates or the permafrost?
- Could this enhance the Earth's greenhouse effect?

Carbon stored in permafrost

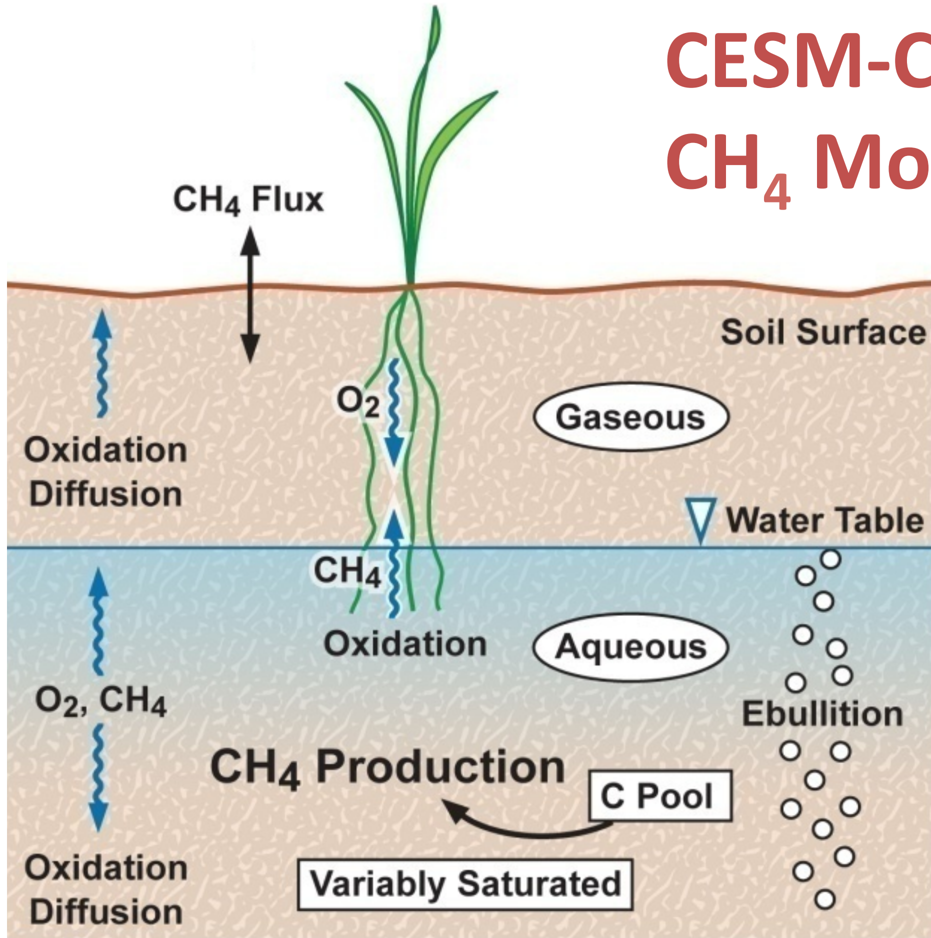


[Jobaggy 2000, Field et al. 2007, Zimov et al. 2006, Tarnocai et al. 2009, Schuur et al. 2008]

System for simulating effects of hydrates and permafrost on climate

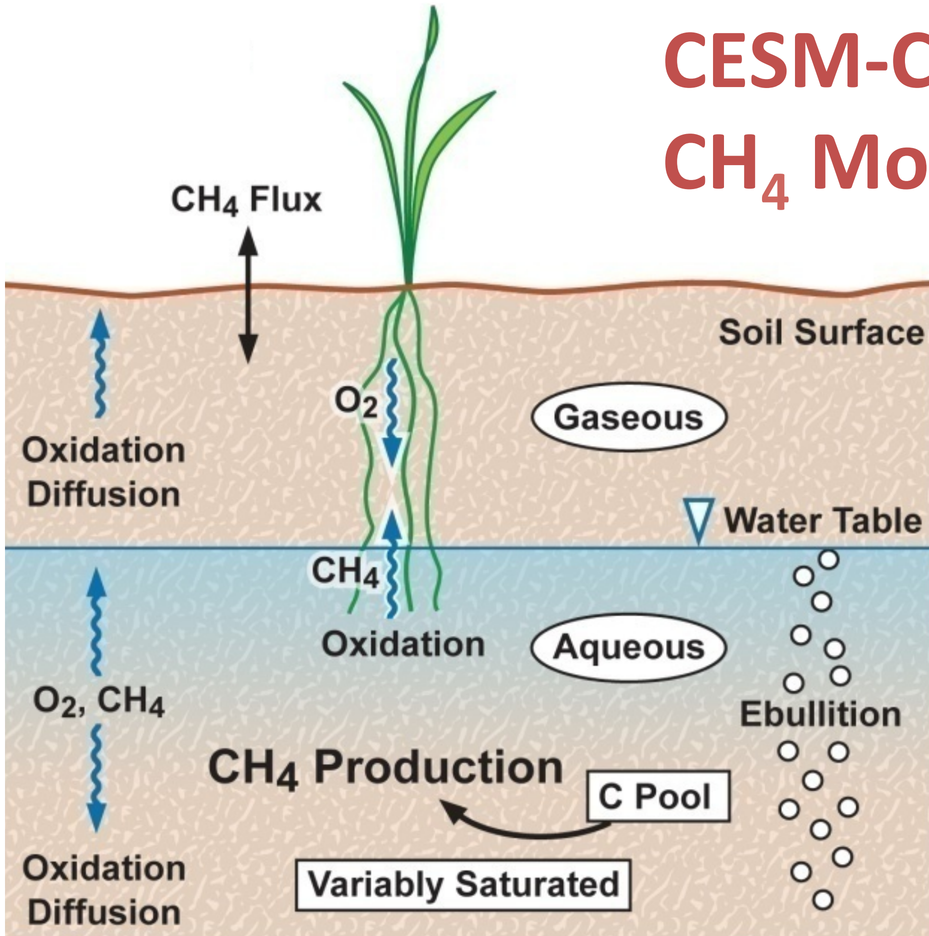


CESM-CLM4 CH_4 Model



- Production, oxidation, transport, aerenchyma, ebullition, aqueous chemistry
- Temperature, pH, and redox dependence of processes
- Fractional and seasonal inundation
- Propagation of uncertainty, sensitivity analyses

CESM-CLM4 CH_4 Model



$$\frac{\partial (RC)}{\partial t} = \frac{\partial F_D}{\partial z} + P(z,t) - E(z,t) - A(z,t) - O(z,t)$$

Net change

Diffusion

Production

Ebullition (bubbling)

Aerenchyma (tissue)

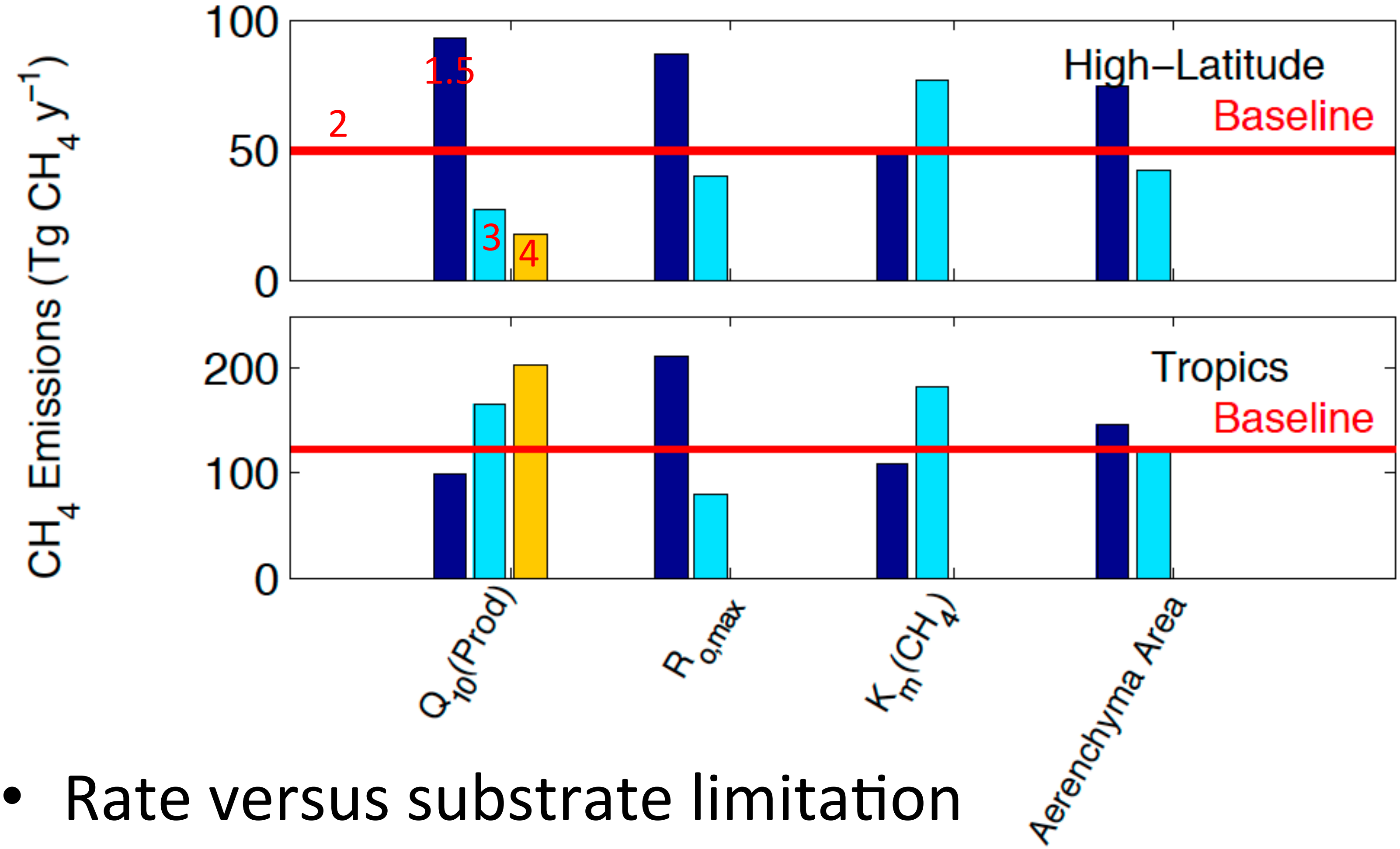
Oxidation

CH_4 Biogeochemical Models

- Of the “big three” (CO_2, CH_4, N_2O), CH_4 emissions are the most difficult to predict
  - Net emissions are often a small difference between large gross fluxes
  - Processes, and net emissions, have non-linear dependence on system properties and state variables (e.g., moisture, temperature)

- Hierarchy of model structures

CH_4 Emission Sensitivity



- Rate versus substrate limitation confounds the uncertainty
  - Tradeoff varies in time and space

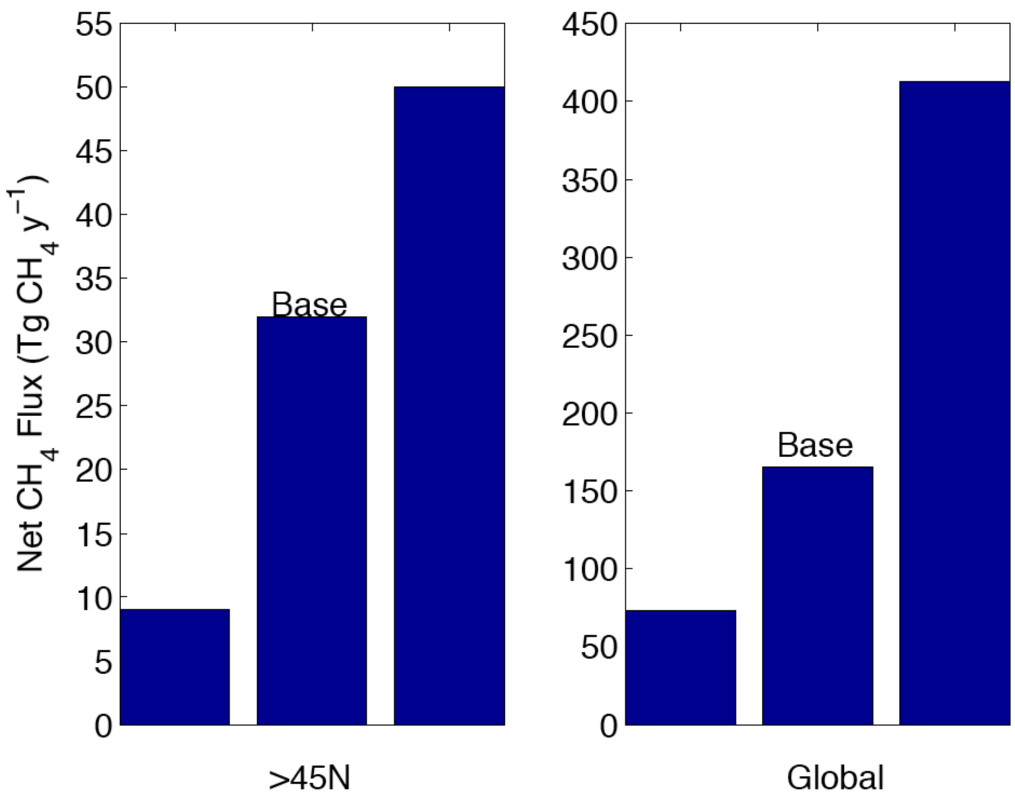
Mechanisms Not (or Poorly) Represented

- Vertically-resolved SOM pools and dynamics
- Peatlands
- Type of inundated system (marsh, bog, estuary, …)
- Aqueous chemistry (pH, redox)
- Thermokarst and 3-D hydrology
- Fractional inundation, dynamics
- Vegetation (static or dynamic)
- N cycle and interactions with C

Saturated Fraction

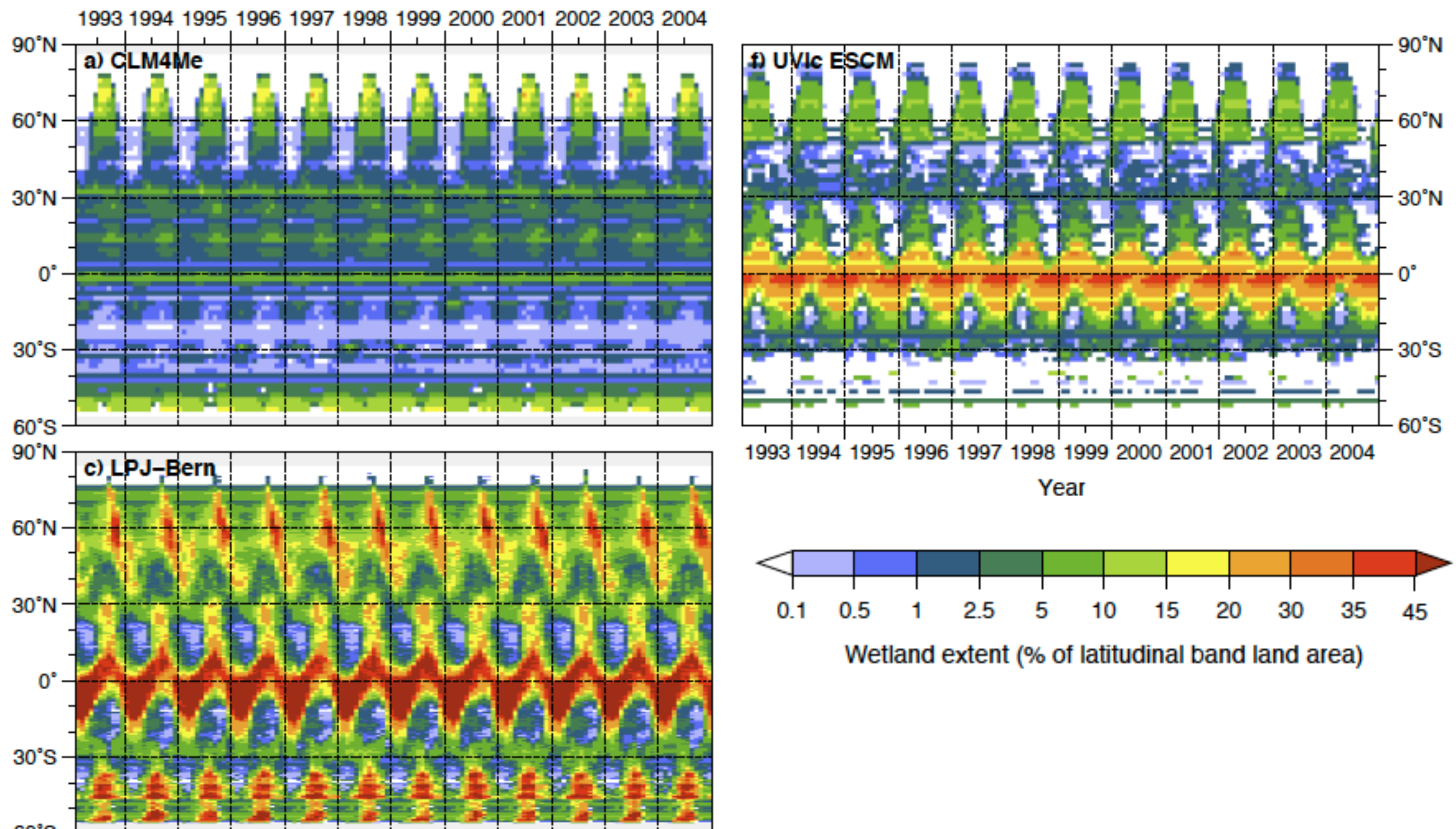
- Critical component of predicting CH_4 fluxes
  - Many types: marshes, estuaries, mudflats, mires, ponds, fens, swamps, bogs, floodplains, …
  - Seasonal variation
  - Relationship with C cycle

Example Sensitivity Analysis



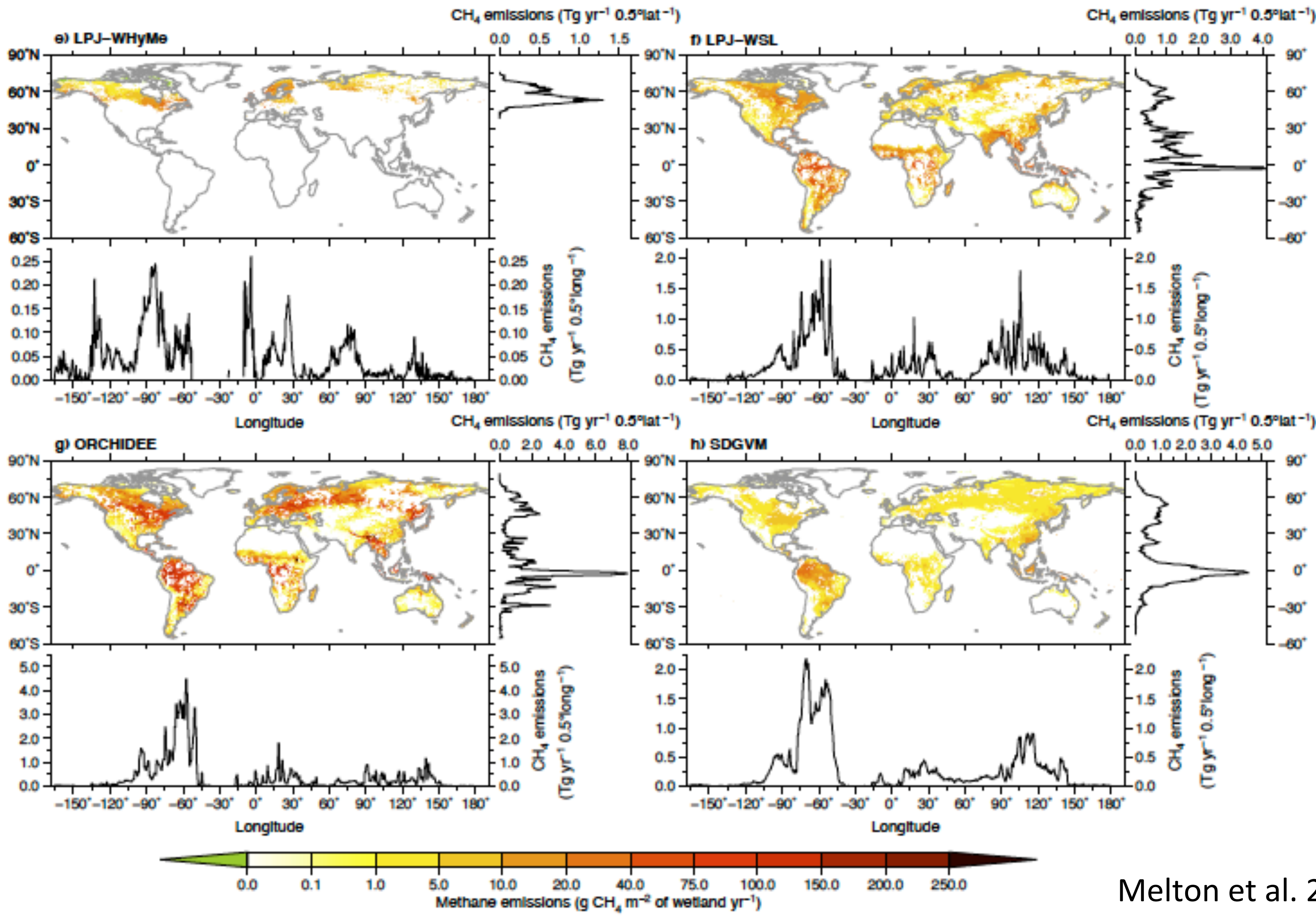
- Larger than factor of 5 response for range consistent with measured values of just three parameters
  - Half saturation coefficients for O_2 and CH_4, Aerenchyma area

WETCHIMP MIP: Wide Range of Predicted Wetland Extents



Melton et al. 2012

WETCHIMP MIP: Wide Range of Predicted CH_4 Emissions



Melton et al. 2012

CH_4 MIP Conclusions

- The ten models' simulated *wetland extents* have ~4-fold difference
  - Only slightly worse than literature estimates from inundation and wetland mapping (~3-fold)
- Simulated *global CH_4 fluxes* have ~2-fold difference across the models
  - *Mean* value is in-line with literature forward and atmospheric inverse model values
- Sensitivity of CH_4 fluxes to temperature and CO_2 increases were diverse

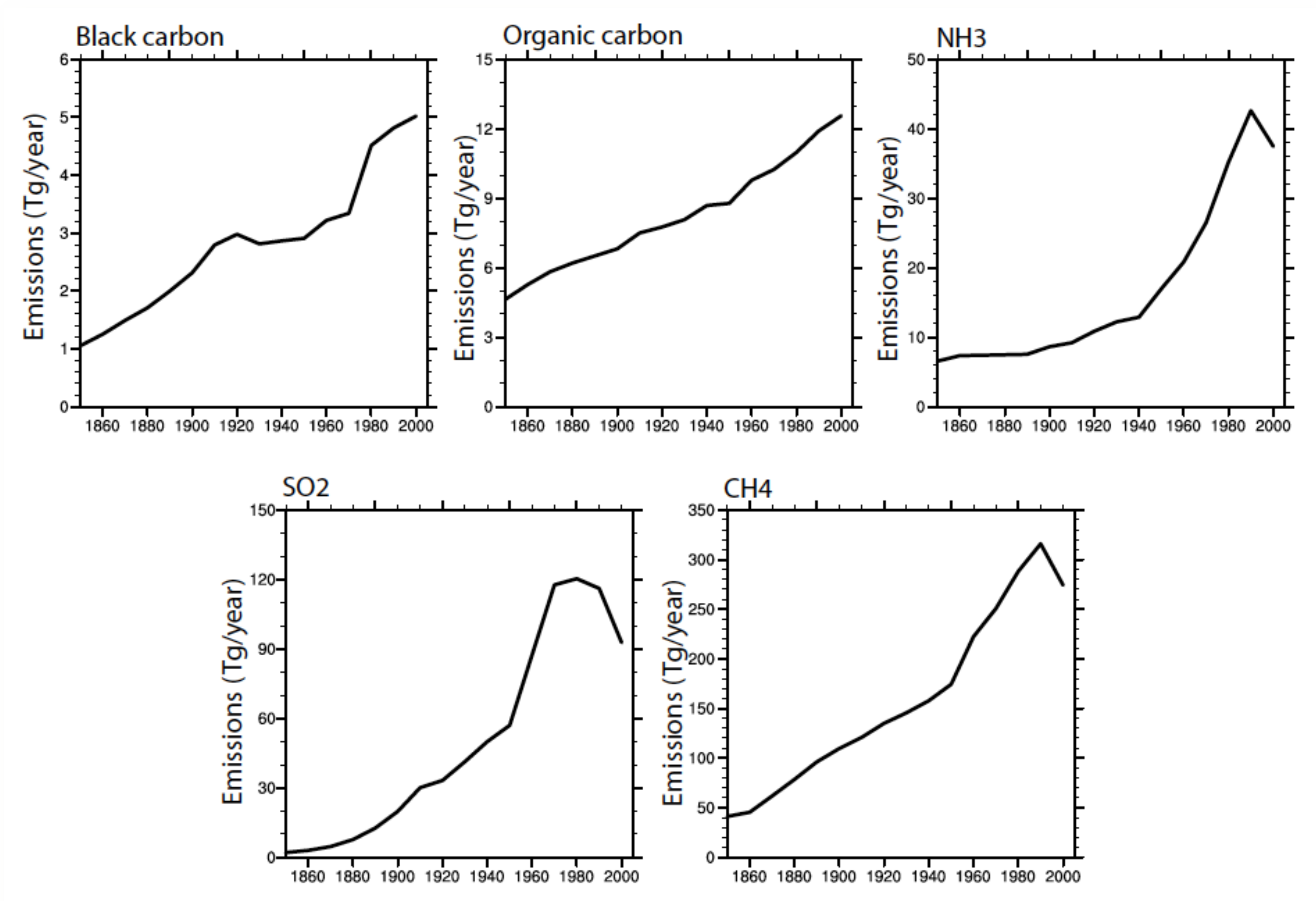
CH_4 MIP Conclusions

- We concluded that there is substantial parameter and structural uncertainty in large-scale CH_4 biogeochemistry models, even after uncertainties in wetland areas are accounted for

Aerosol Topics

- Aerosol emissions and AOD since 1850
- The Coupled Model Intercomparison Project and simulation of historical aerosol trends
- Ensemble simulations of aerosols since 1850
- Range of aerosol properties across ensemble
- Implications of simulations for CMIP5

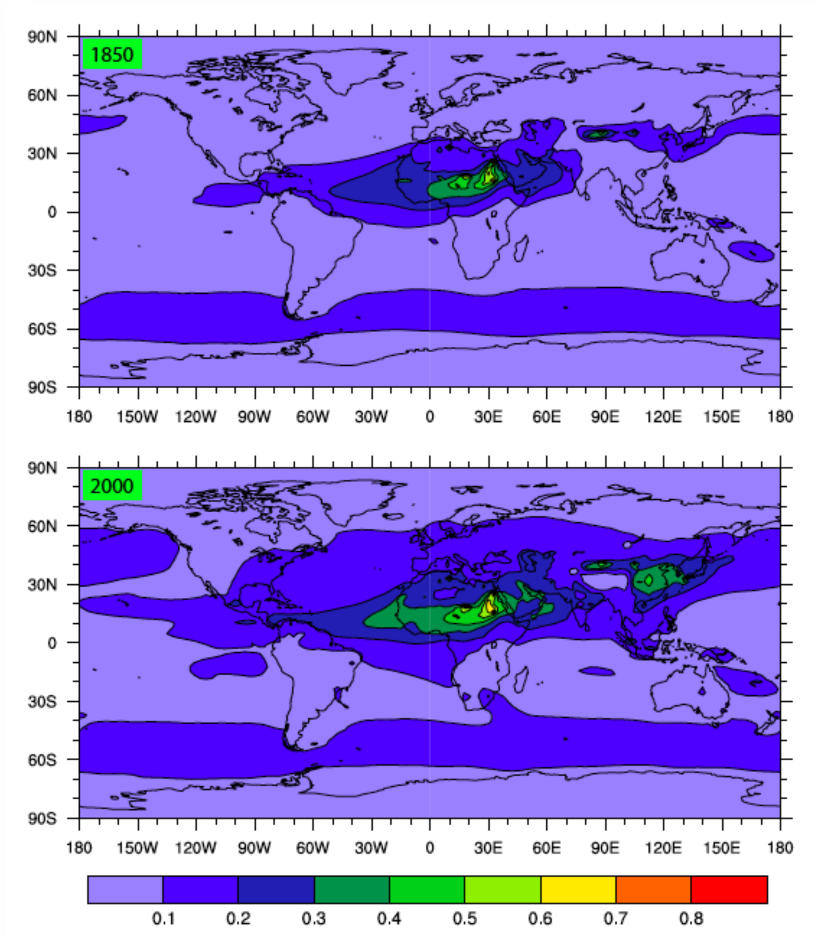
Historical Emission of Radiative Species



Lamarque et al, 2010

- Historical aerosol emissions have been developed for climate simulation.

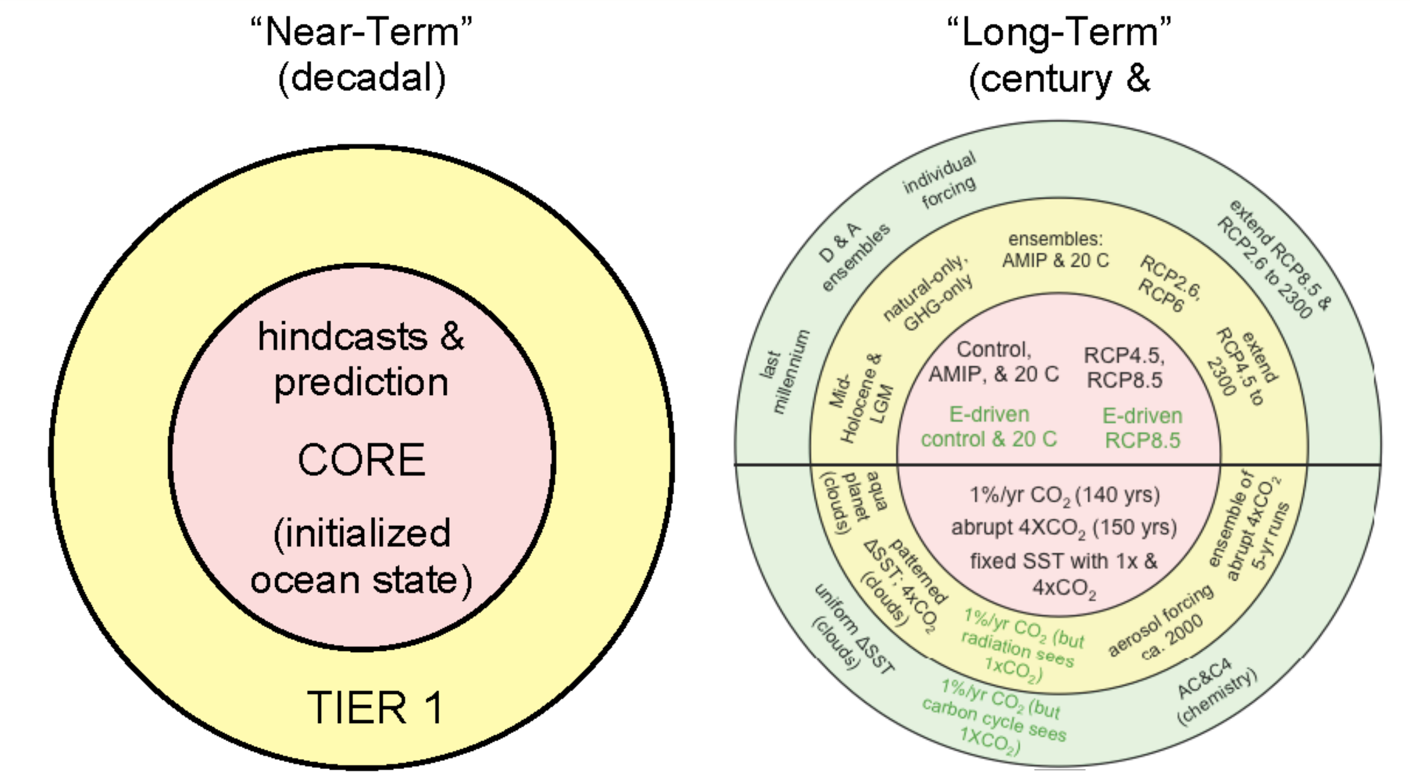
Historical Evolution of AOD



Lamarque et al, 2010

- The emissions produce significant increases in AOD across northern hemisphere.

The CMIP5 climate simulation protocol



Taylor et al, 2011

- The Coupled Model Intercomparison Protocol (CMIP5) is the basis for AR5.
- It includes a new set of simulations for the historical record: 1850 - 2005.

The CMIP5 Models

- To address process uncertainties, CMIP5 includes output from >22 different centers.
- Same forcings are used in these models for a uniform ensemble.

Modeling Center	Model	Institution	term of use
BCC	BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration	unrestricted
CCCma	CanAM4 CanCM4 CanESM2	Canadian Centre for Climate Modelling and Analysis	unrestricted
CMCC	CMCC-CM	Centro Euro-Mediterraneo per I Cambiamenti Climatici	non-commercial only
CNRM-CERFACS	CNRM-CM5	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	non-commercial only
CSIRO-BOM	ACCESS1.0 ACCESS1.3	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia)	non-commercial only
CSIRO-QCCCE	CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence	non-commercial only
EC-EARTH	EC-EARTH	EC-EARTH consortium	non-commercial only
GCESS	BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University	unrestricted
INM	INM-CM4	Institute for Numerical Mathematics	unrestricted
IPSL	IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR	Institut Pierre-Simon Laplace	unrestricted
LASG-CESS	FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences; and CESS, Tsinghua University	unrestricted
LASG-IAP	FGOALS-gl FGOALS-s2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	unrestricted
MIROC	MIROC4h MIROC5 MIROC-ESM MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	non-commercial only
MOHC	HadCM3 HadGEM2-A HadGEM2-CC HadGEM2-ES	Met Office Hadley Centre	unrestricted
MPI-M	MPI-ESM-LR MPI-ESM-MR MPI-ESM-P	Max Planck Institute for Meteorology (MPI-M)	unrestricted
MRI	MRI-AGCM3.2H MRI-AGCM3.2S MRI-CGCM3	Meteorological Research Institute	non-commercial only
NASA GISS	GISS-E2-H GISS-E2-R	NASA Goddard Institute for Space Studies	unrestricted
NASA GMAO	GEOS-5	NASA Global Modeling and Assimilation Office	unrestricted
NCAR	CCSM4	National Center for Atmospheric Research	unrestricted
NCC	NorESM1-M NorESM1-ME	Norwegian Climate Centre	unrestricted
NCEP	CFSv2-2011	National Centers for Environmental Prediction	unrestricted
NOAA GFDL	GFDL-CM2.1 GFDL-CM3 GFDL-ESM2G GFDL-ESM2M GFDL-HIRAM-C180 GFDL-HIRAM-C360	Geophysical Fluid Dynamics Laboratory	unrestricted

Representative Concentration Pathways (RCPs)

Name	Radiative forcing	Concentration(p.p.m.)	Pathway	Model providing RCP*	Reference
RCP8.5	>8.5 Wm^{-2} in 2100	>1,370 CO_2-equiv. in 2100	Rising	MESSAGE	55, 56
RCP6.0	~6 Wm^{-2} at stabilization after 2100	~850 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	AIM	57, 58
RCP4.5	~4.5 Wm^{-2} at stabilization after 2100	~650 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	GCAM	48, 59
RCP2.6	Peak at ~3 Wm^{-2} before 2100 and then declines	Peak at ~490 CO_2-equiv. before 2100 and then declines	Peak and decline	IMAGE	60, 61

***MESSAGE, Model for Energy Supply Strategy Alternatives and their General Environmental Impact, International Institute for Applied Systems Analysis, Austria; AIM, Asia-Pacific Integrated Model, National Institute for Environmental Studies, Japan; GCAM, Global Change Assessment Model, Pacific Northwest National Laboratory, USA (previously referred to as MiniCAM); IMAGE, Integrated Model to Assess the Global Environment, Netherlands Environmental Assessment Agency, The Netherlands.**

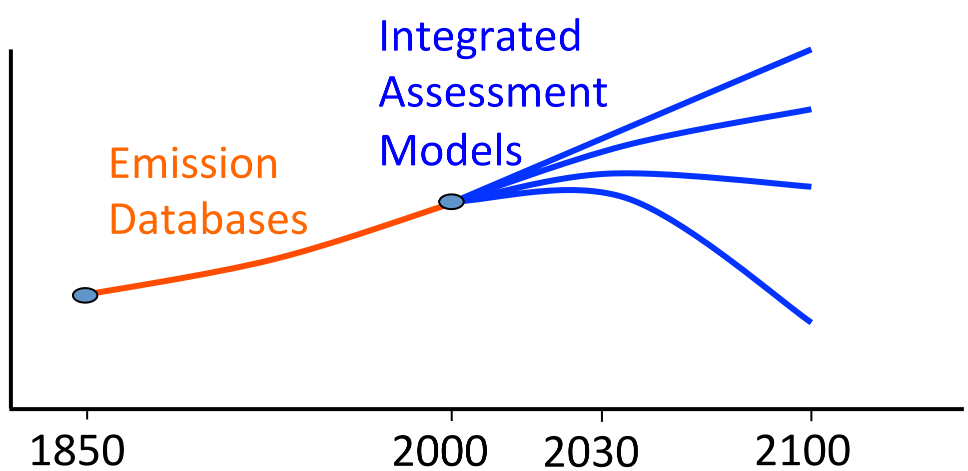
Moss et al, 2010

- The RCPs include several mitigation scenarios with range of 2100 forcings.
- The RCP emissions are harmonized with the historical emissions.

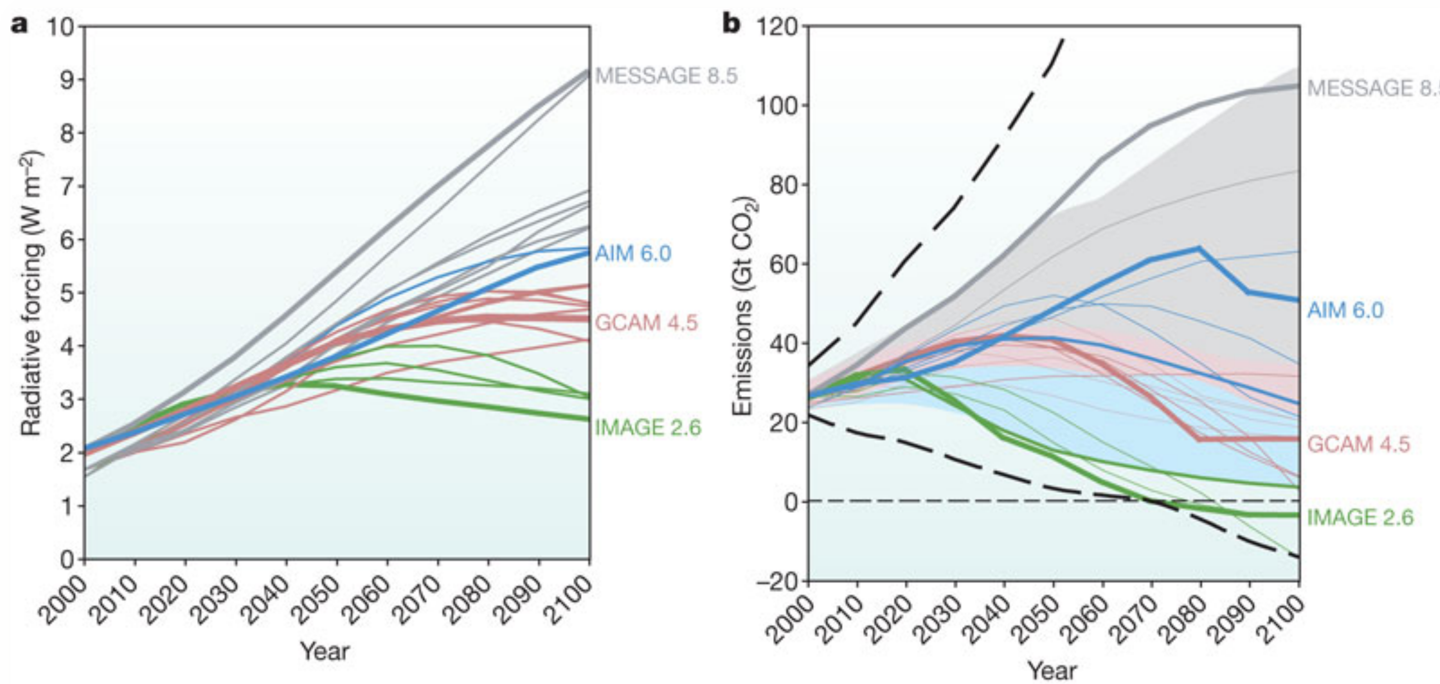
Air pollutants in RCPs

- Decadal estimates, harmonized for 2000, of anthropogenic (land, ship and aircraft) and biomass burning emissions of ozone precursors, aerosols and ODSs:
    1. 1850-2000 (from available emission estimates)
    2. 2000-2100 for each RCP
- AP emissions output of IAM RCP projections

  ↳Concentration of radiatively-active gases and aerosols computed by chemistry-climate models



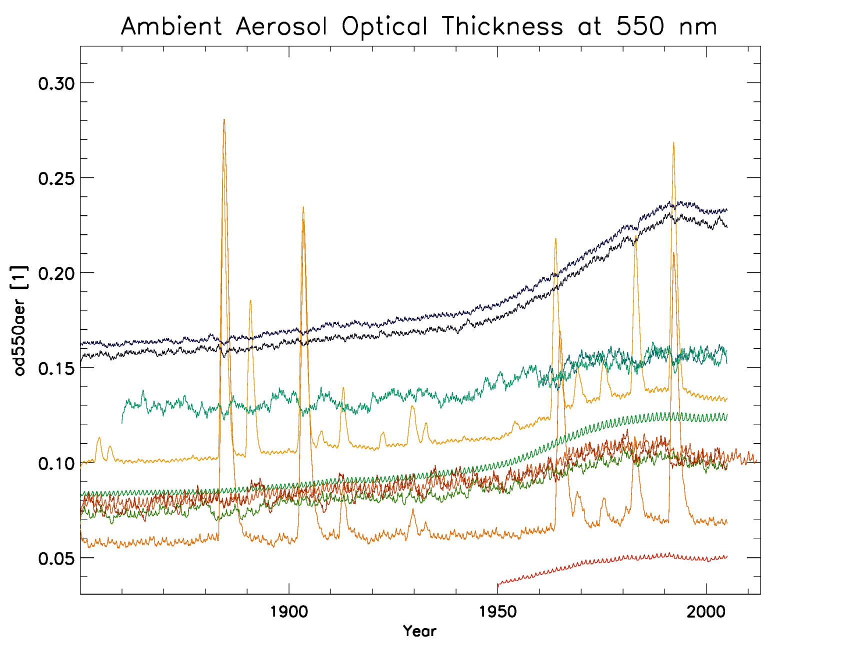
Radiative Forcing and CO_2 in the RCPs

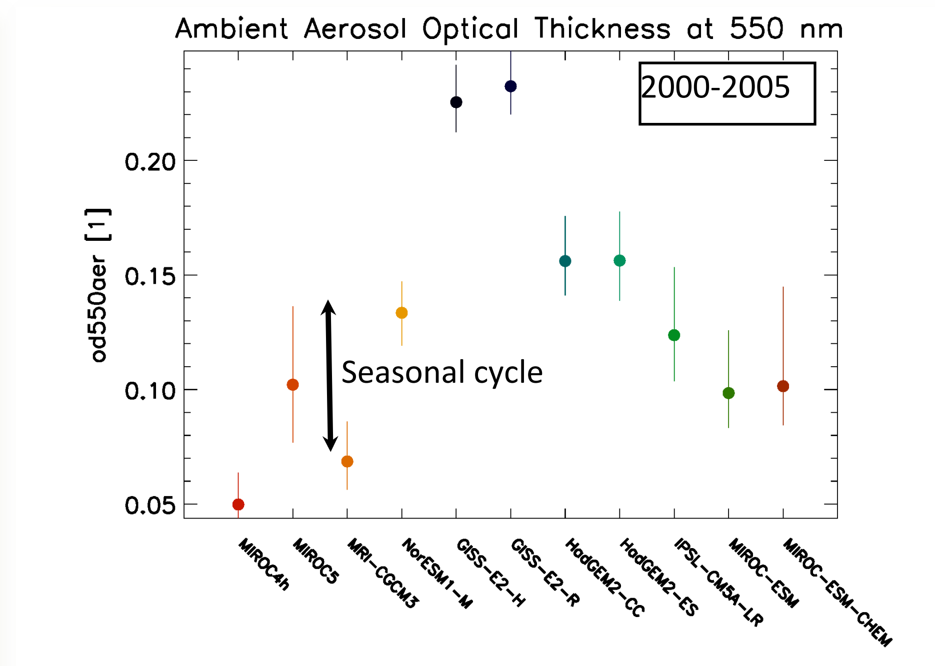


Moss et al, 2010

- Consistency in GHG+aerosol forcing is a key element of CMIP5 design.
- Roughly 2/3 to 3/4 of warming to 2025 is due to historical emissions.
- We have analyzed ~15 models available now in CMIP5 archives.

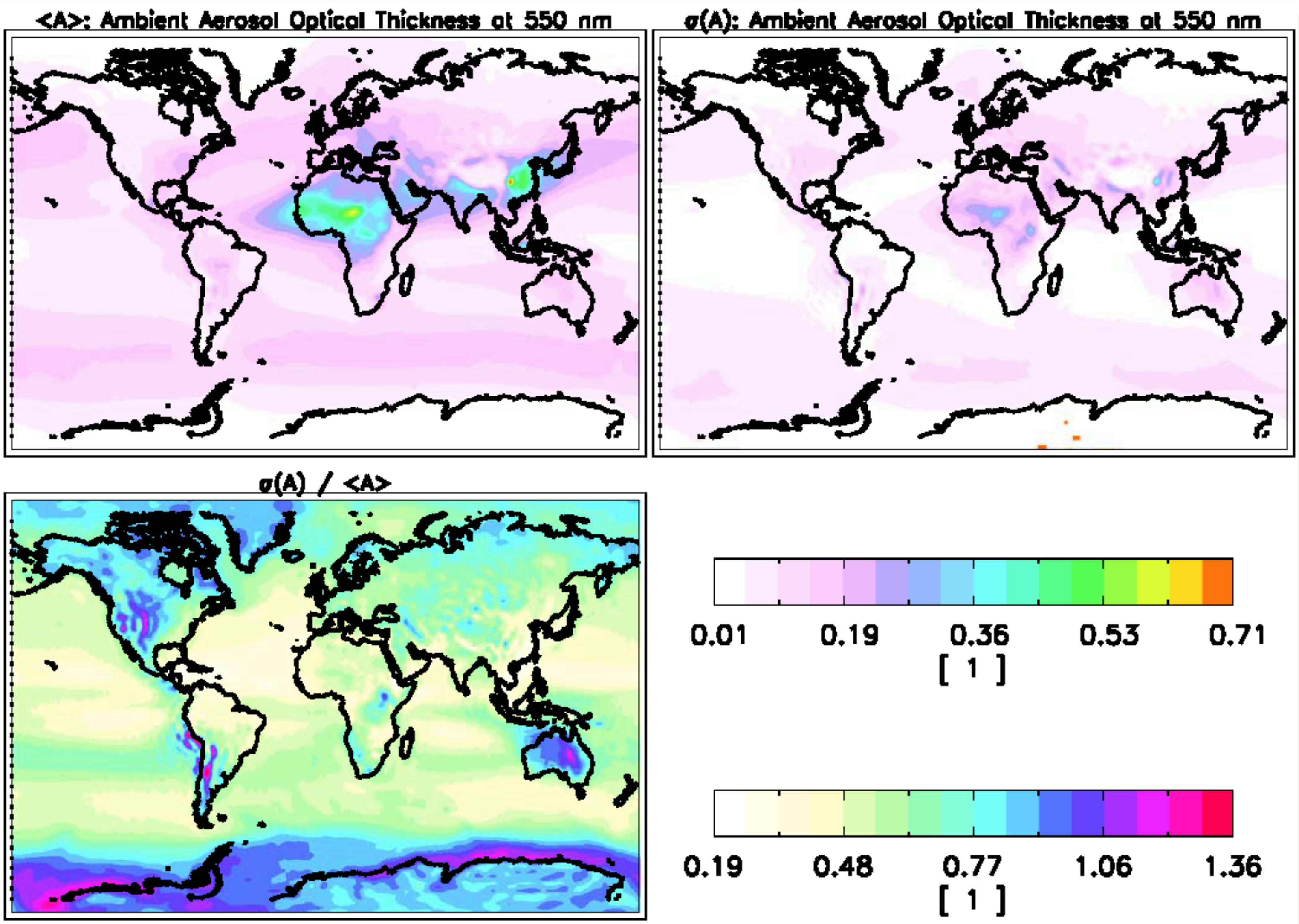
Present-Day Aerosol Optical Depth



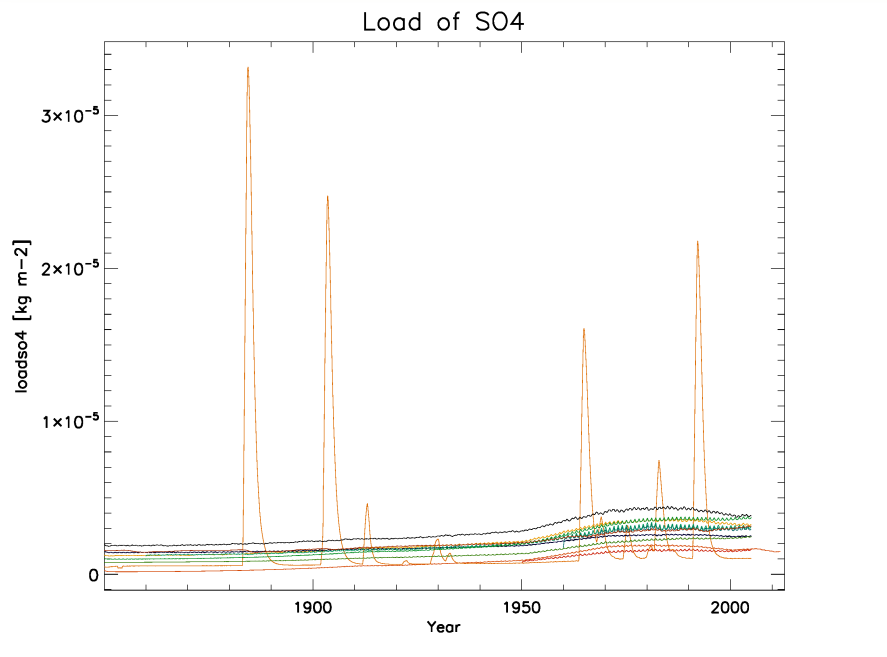


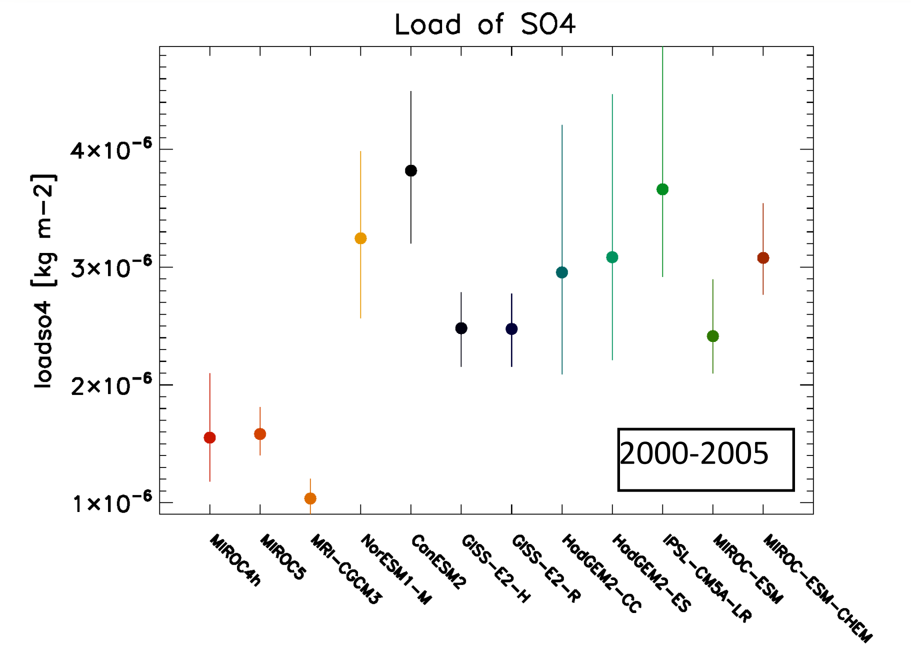
- AOD for all species has differed since start of simulations in 1850.
- Current AODs vary across ensemble by factor of >4.
- Resulting variation in clear-sky direct forcing is O(5 W/m^2).

Ensemble AOD for 2000-2005



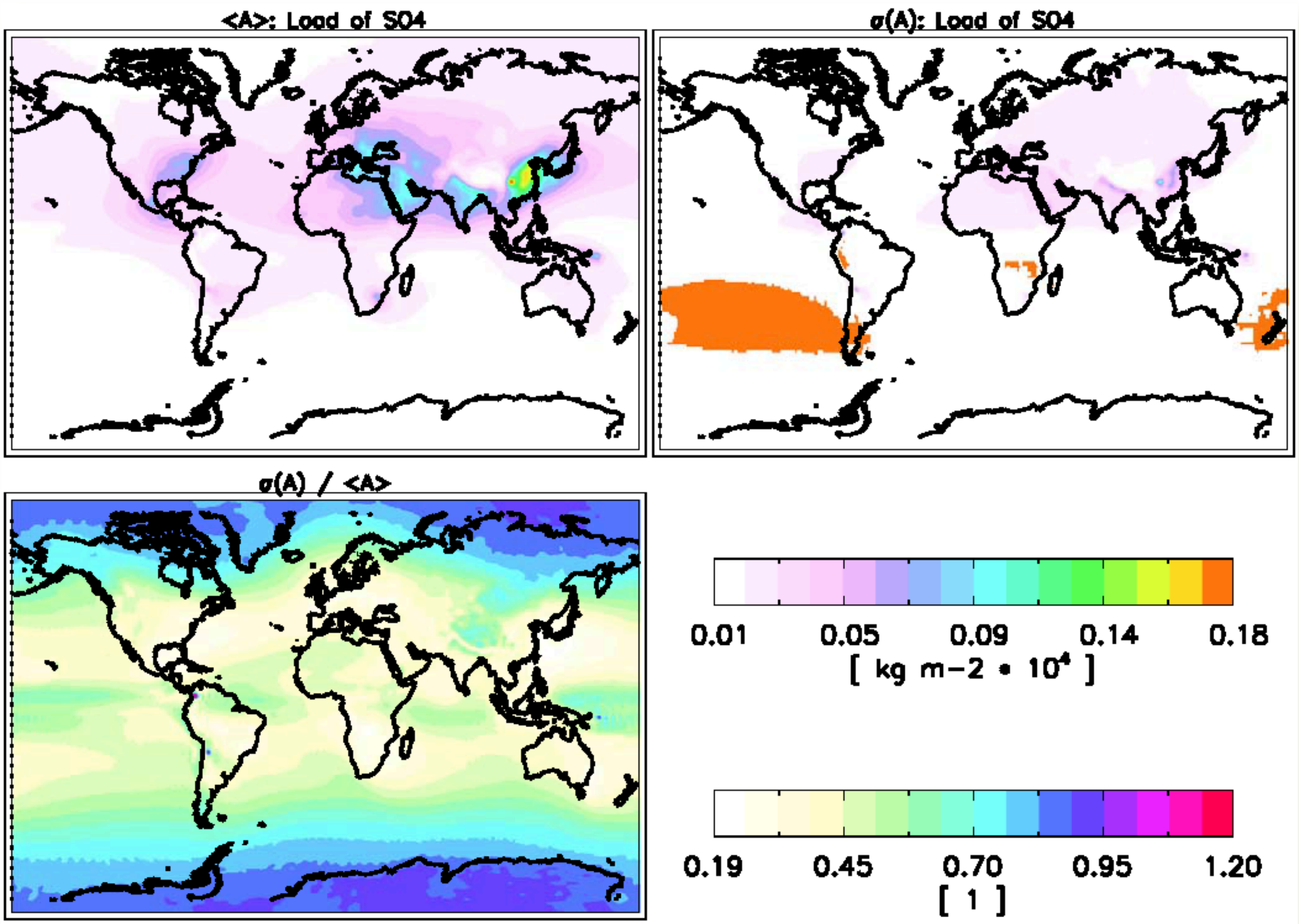
Load of SO_4



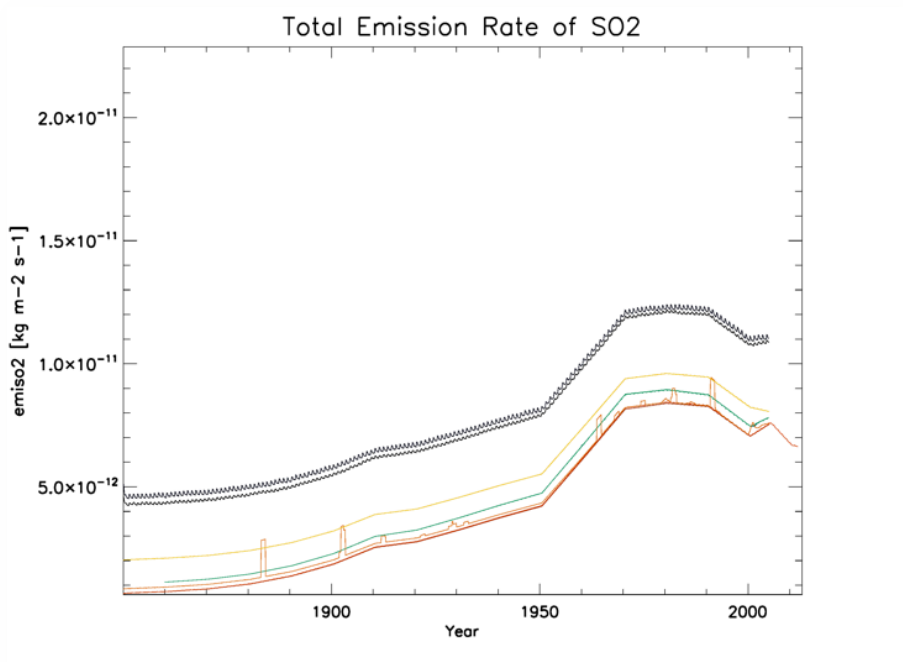


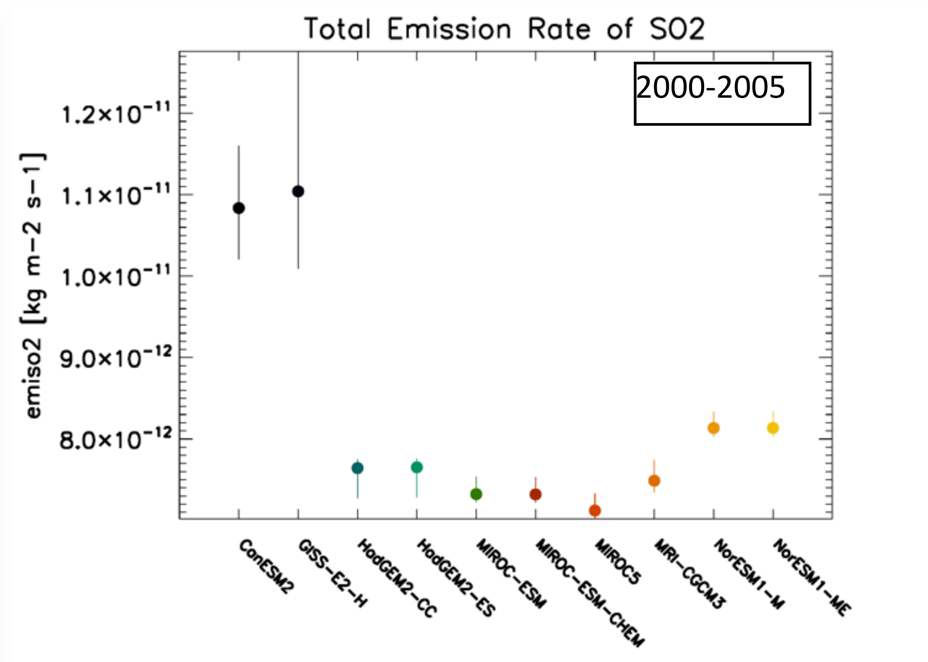
- Despite supposedly common emissions data, SO_4 loads vary by factor of ~3.
- There are also large variations in the seasonal cycle magnitude.

Ensemble Load of SO_4



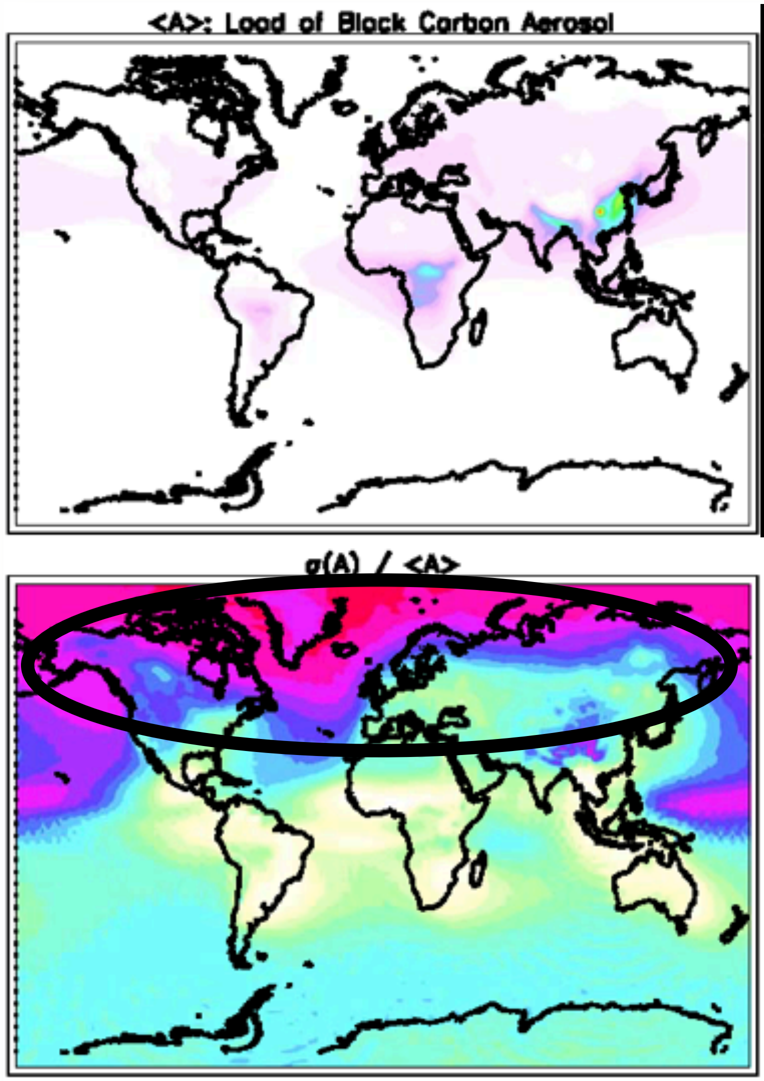
Emissions of SO_2





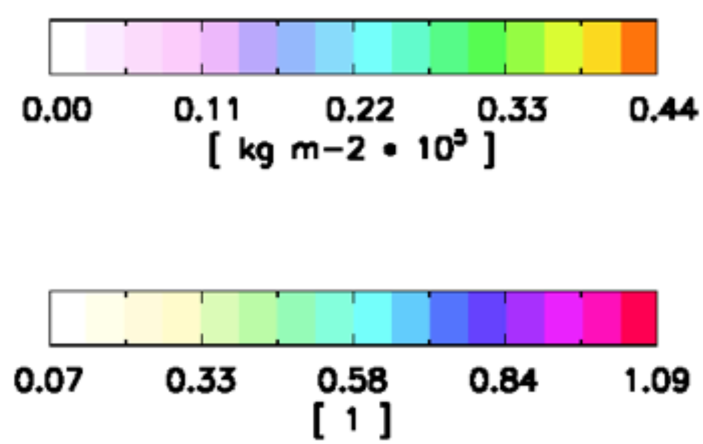
- There are ~33% differences in SO_2 emissions for present day.
- This explains a small fraction of variation in SO_4 loads across ensemble.

Ensemble Load of Black Carbon



The largest relative variability occurs northern polar regions.

Implications for forcing by BC on snow, sea ice,and land ice?



Conclusions on Aerosols

- The CMIP5 simulations are broadly consistent with historical emissions.
- In improvement to CMIP3, emissions and AOD are continuous at present day.
- There is considerable diversity in the simulated aerosol properties, including:
  - Aerosol optical depth
  - Load of sulphate aerosol
  - Transport of anthropogenic aerosols to polar regions, esp. the Arctic.
- This diversity imply the aerosol forcing in historical simulations is not uniform.
- The differences will carry forward into decadal projections of climate change.

Advancing solutions for climate change

- "Human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future."

  [Roger Revelle, 1957]

- "Look before you leap."

  [Anonymous, ca. 1546]

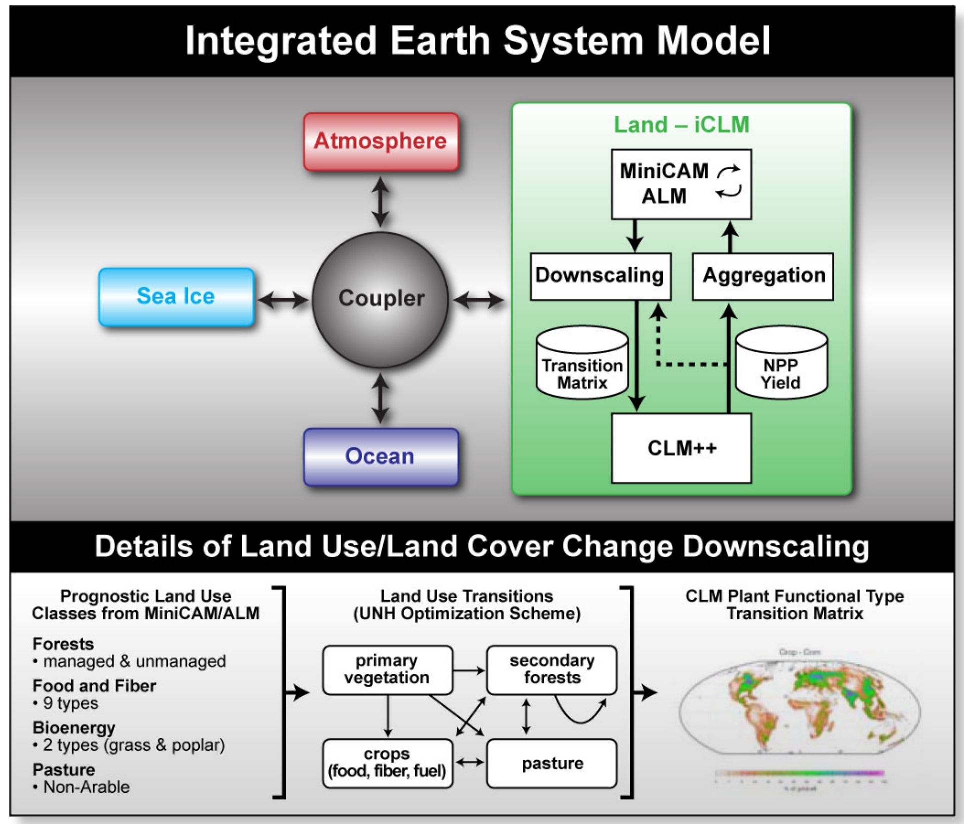




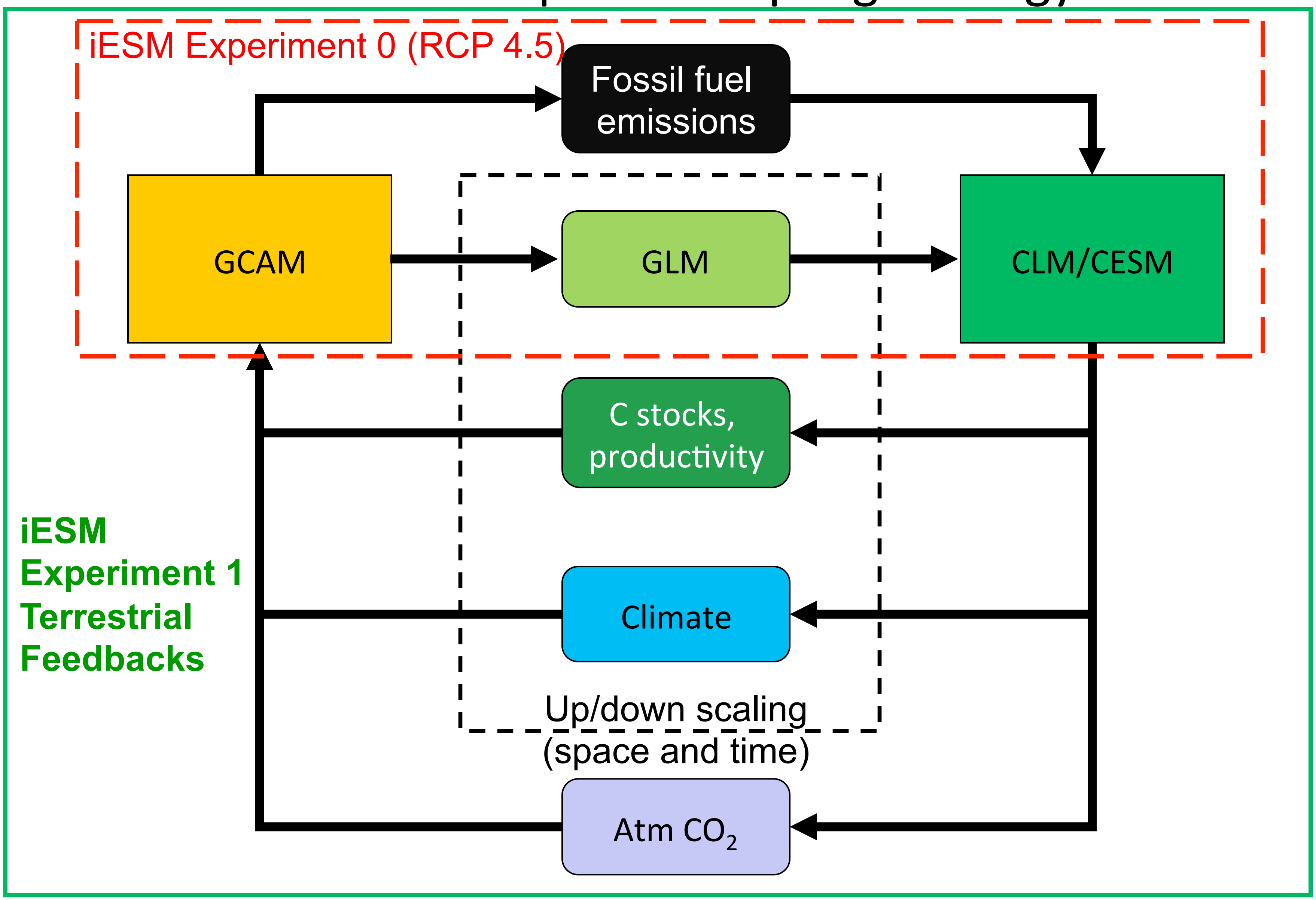

Improved projection of human-Earth system interactions

Major objectives of our project:

- Create an integrated Earth System Model with energy-climate interactions
- Apply the model to the coupled physical, ecological, and human system
- Test sustainability of new technologies



iESM multi-phase coupling strategy

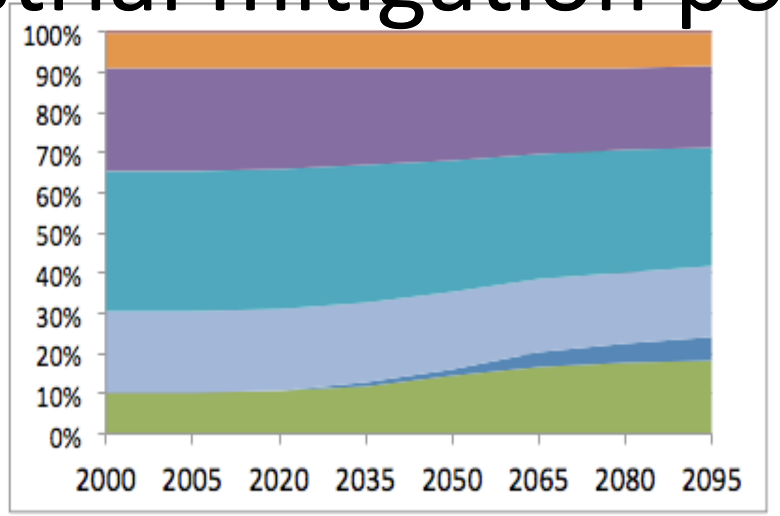


iESM Experiment 0: Bioenergy Scenarios with 1-Way Coupling

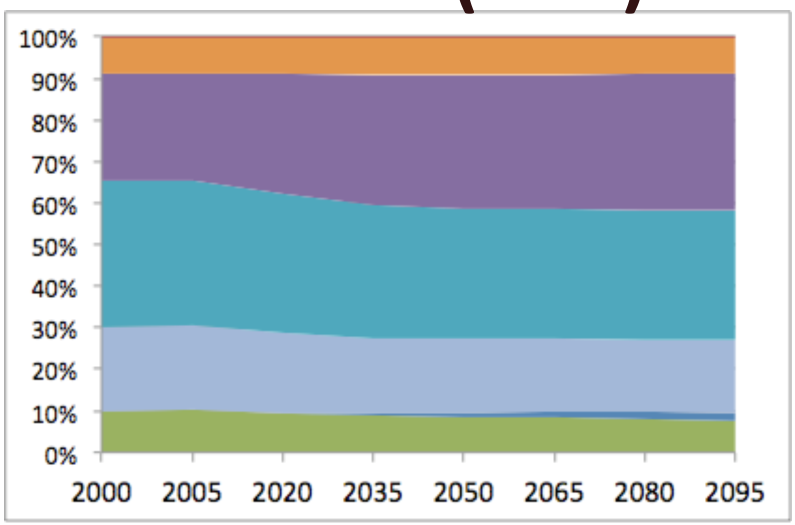
- If we now add a different policy scenario, but keep the same concentration pathway, does the evolution of the climate system differ?
- Two scenarios evaluated:
  - RCP4.5 – carbon price on all carbon (UCT)
  - RCP4.5 – carbon price ONLY on fossil carbon (FFCT)

RCP 4.5 and a Replication without terrestrial mitigation policy

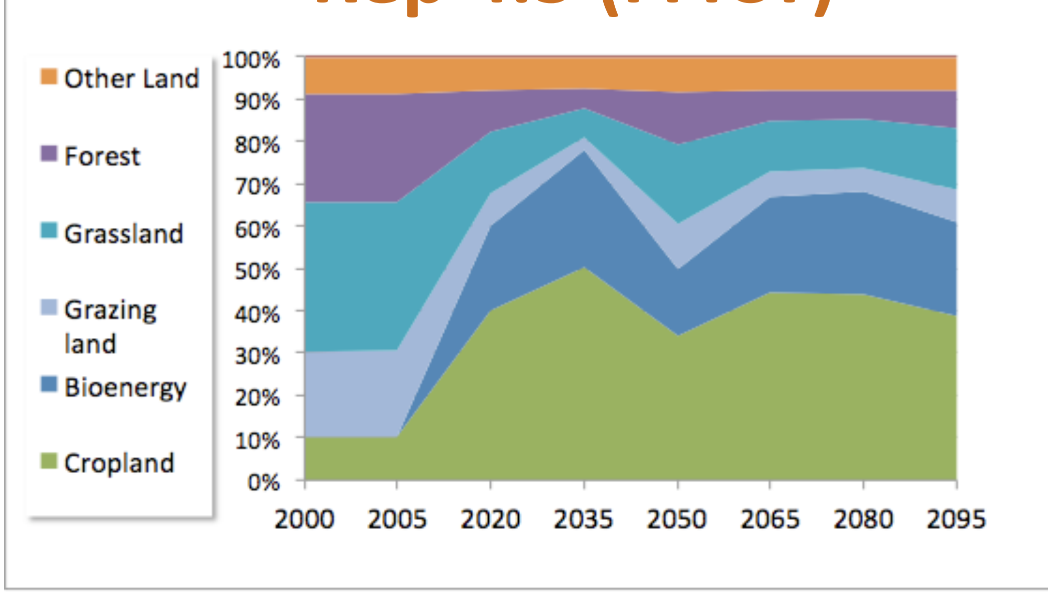
No Policy



RCP4.5 (UCT)

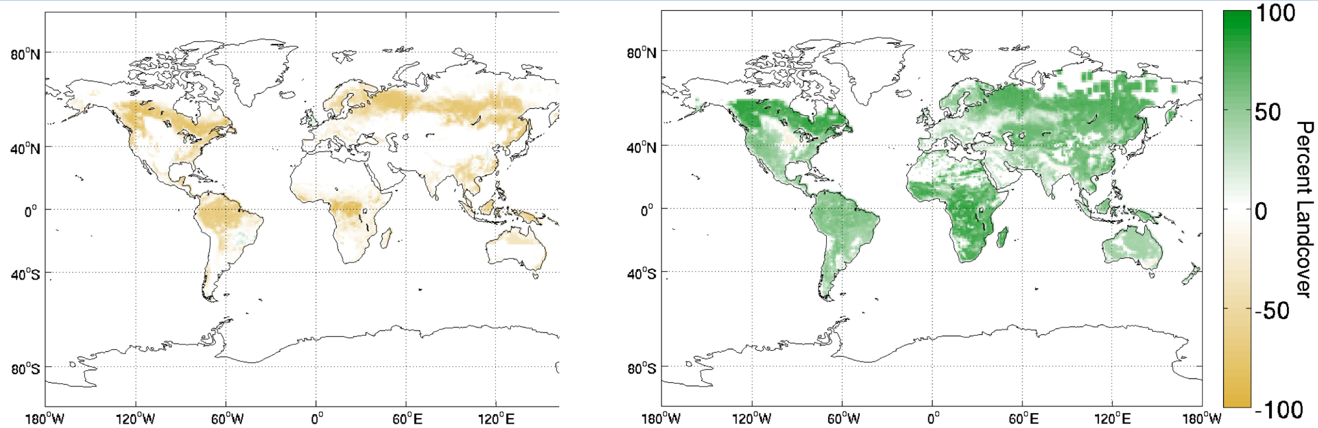


Rep 4.5 (FFICT)



Change in Landcover under the RCP4.5 FFICT Scenario

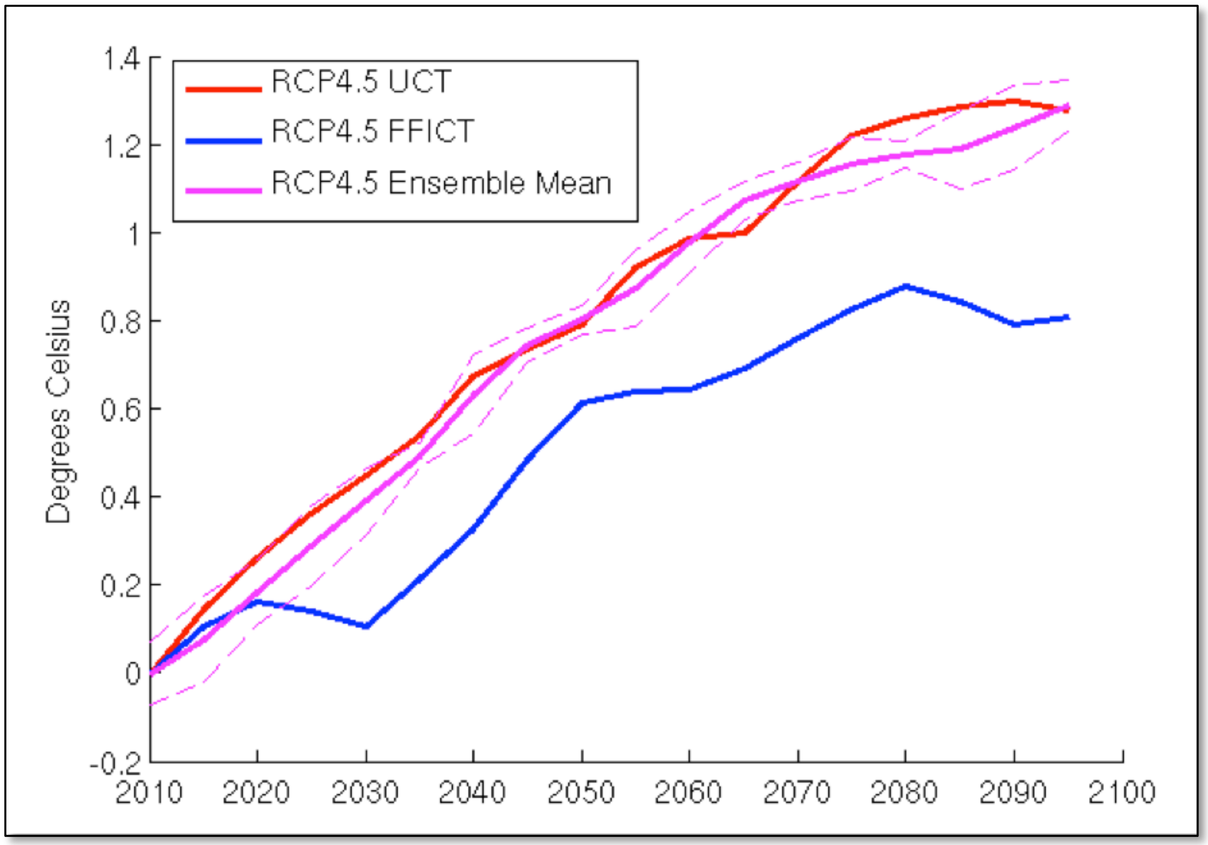
FFICT: Change in Forest Cover FFICT: Change in Crop Cover



Jones et al, 2012

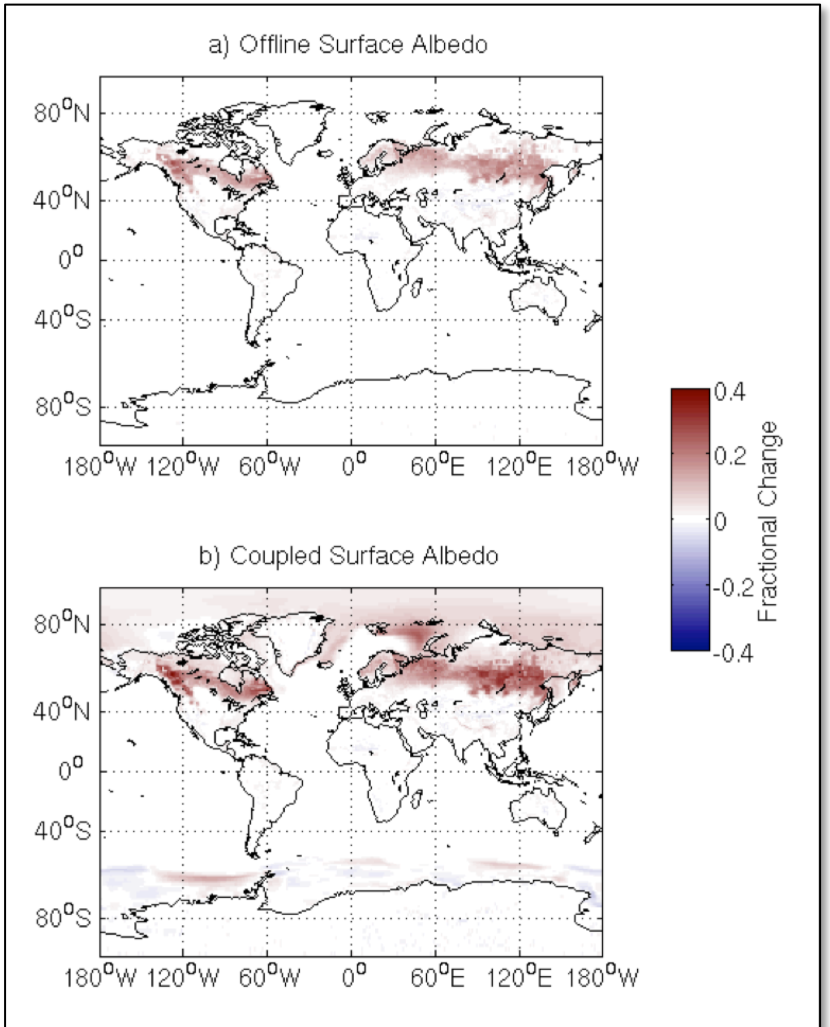
Change in Landcover from 2005 to 2100

Effect of Land cover scenario on global mean temperature

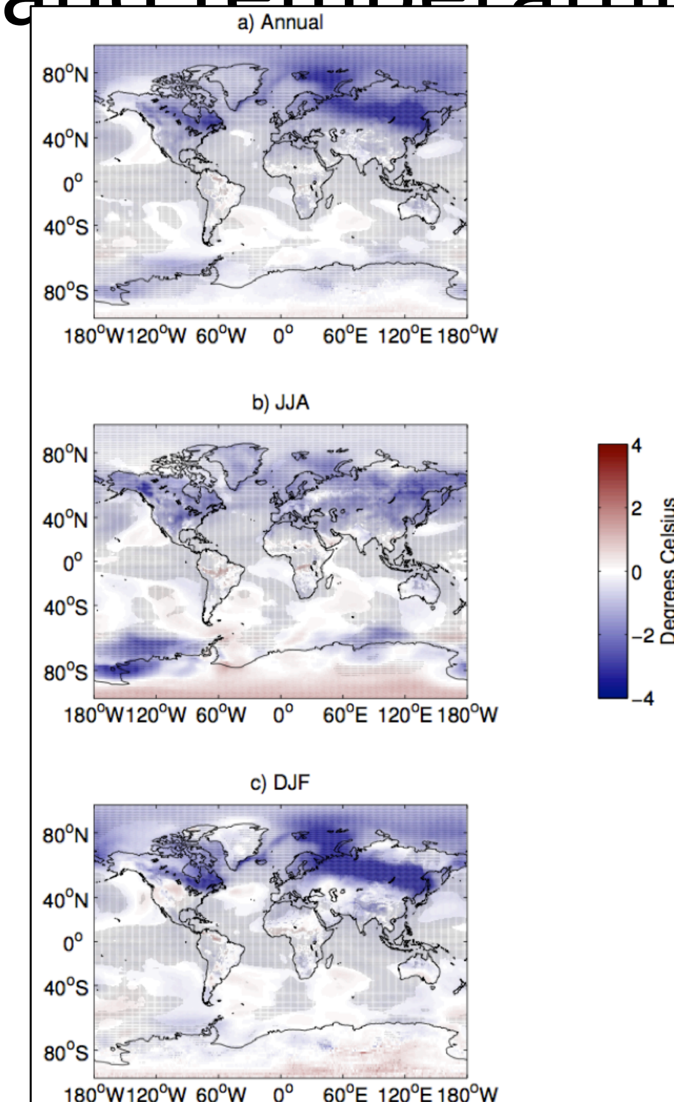


Jones et al, 2012

Link between albedo and temperature



Jones et al, 2012



Jones et al, 2012

Next steps on ESM Uncertainty

- Integrate process models and data at the relevant scales
- Develop seamless traceability from these process models to the parameterizations.
- Example: DOE's Next Generation Ecosystem Experiments
- Most fundamentally, the ESM community needs to develop robust measures of predictive skill.