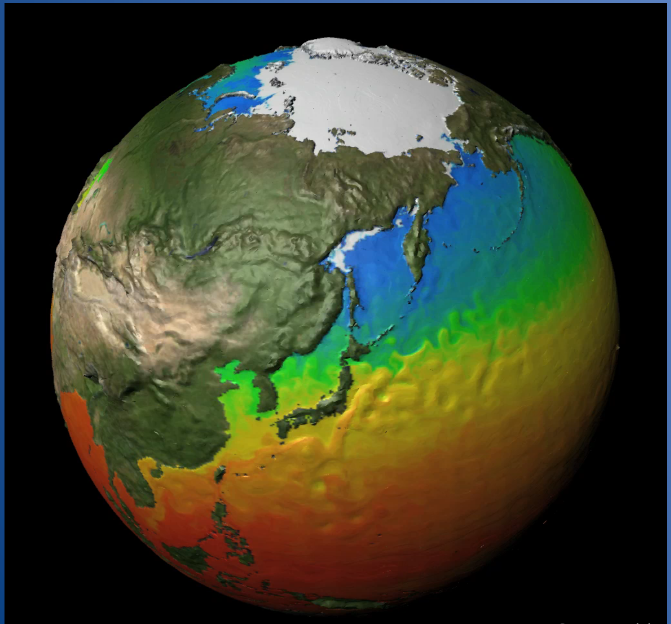
Introduction to the Community Earth System Model

Jean-François Lamarque
CESM Chief Scientist

Jean-François Lamarque
lamar@ucar.edu

Purpose of Earth System Modeling

- **To provide scientific understanding of observed climate change (historical, paleo)**
- **To simulate future climate change and its impacts**
- **Builds on our process understanding from observations and highly-detailed models (large-eddy simulations, chemical master mechanism, …)**


From J. Small

High-resolution (25 km atmosphere, 0.1^{o} ocean) coupled simulation captures short-term variability (hurricanes) and seasonal variations (sea-ice)

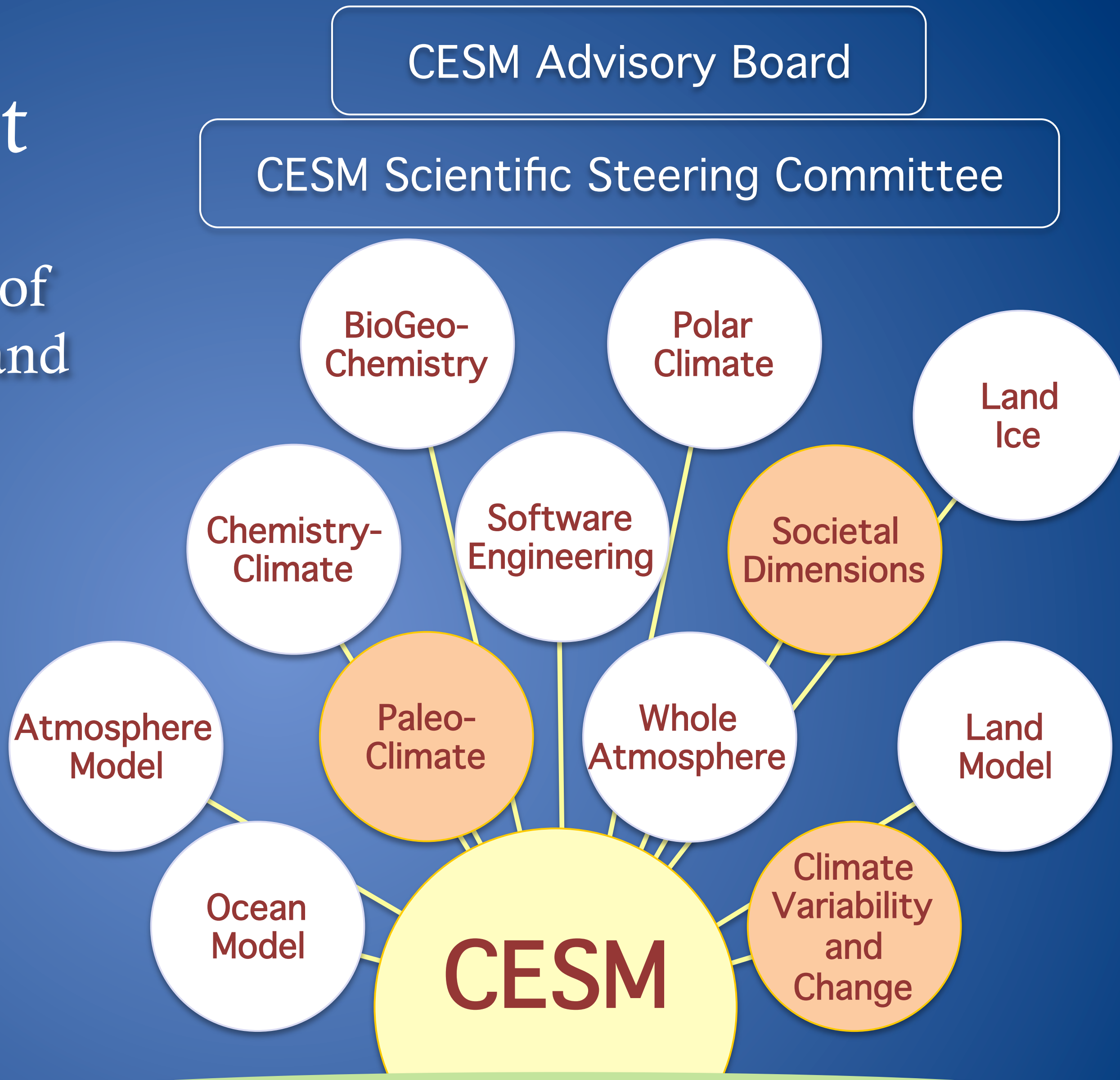
Jean-François Lamarque
lamar@ucar.edu

CESM Project

Based on 20+ Years of Model development and application

CESM is primarily sponsored by the National Science Foundation and the Department of Energy

Most working groups have winter/spring meetings. Annual meeting in June.



http://www.cesm.ucar.edu/management

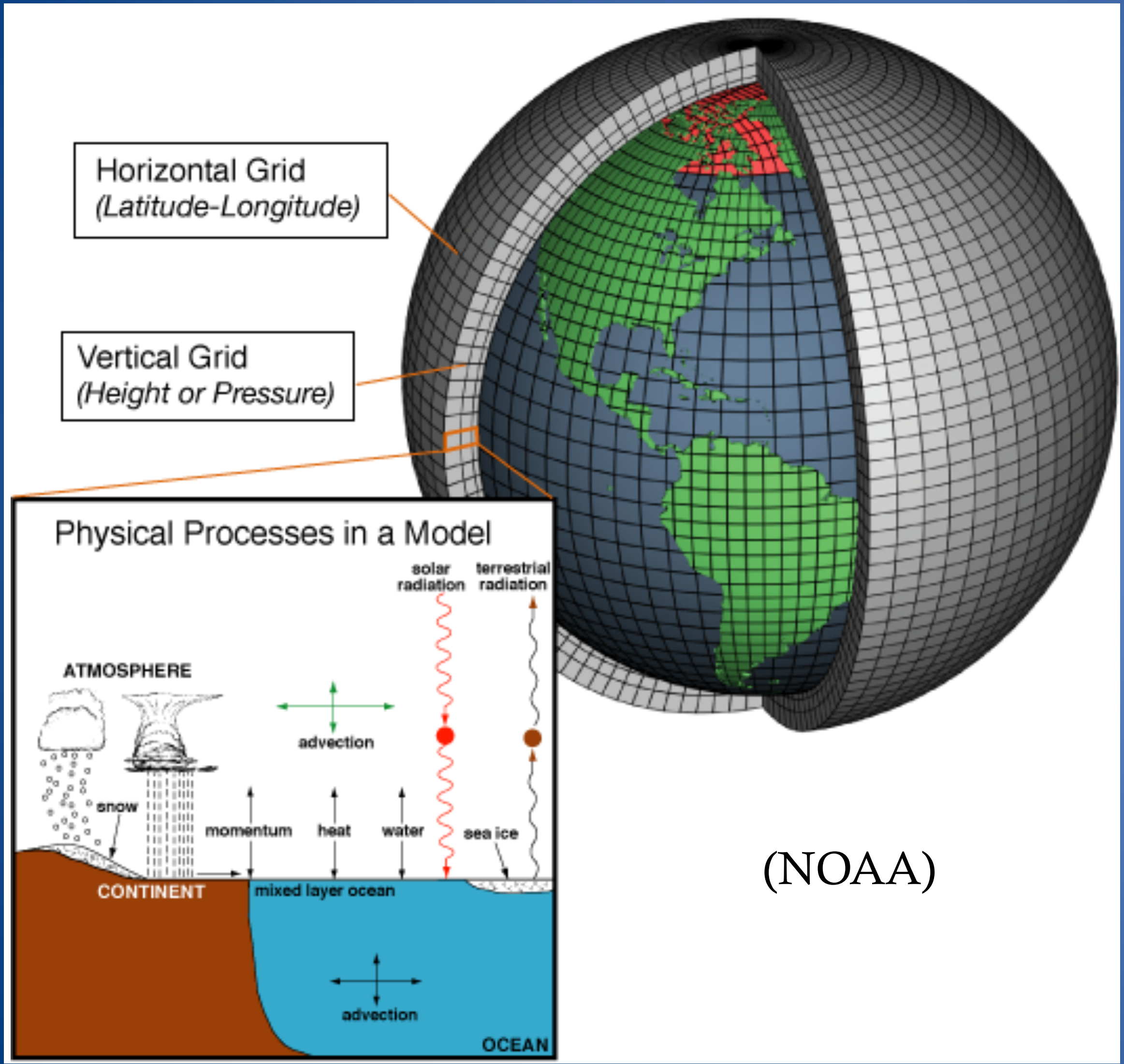
Jean-François Lamarque
lamar@ucar.edu

A truly global community

Locations of released version downloads since 2010

Jean-François Lamarque
lamar@ucar.edu

Community Earth System Model



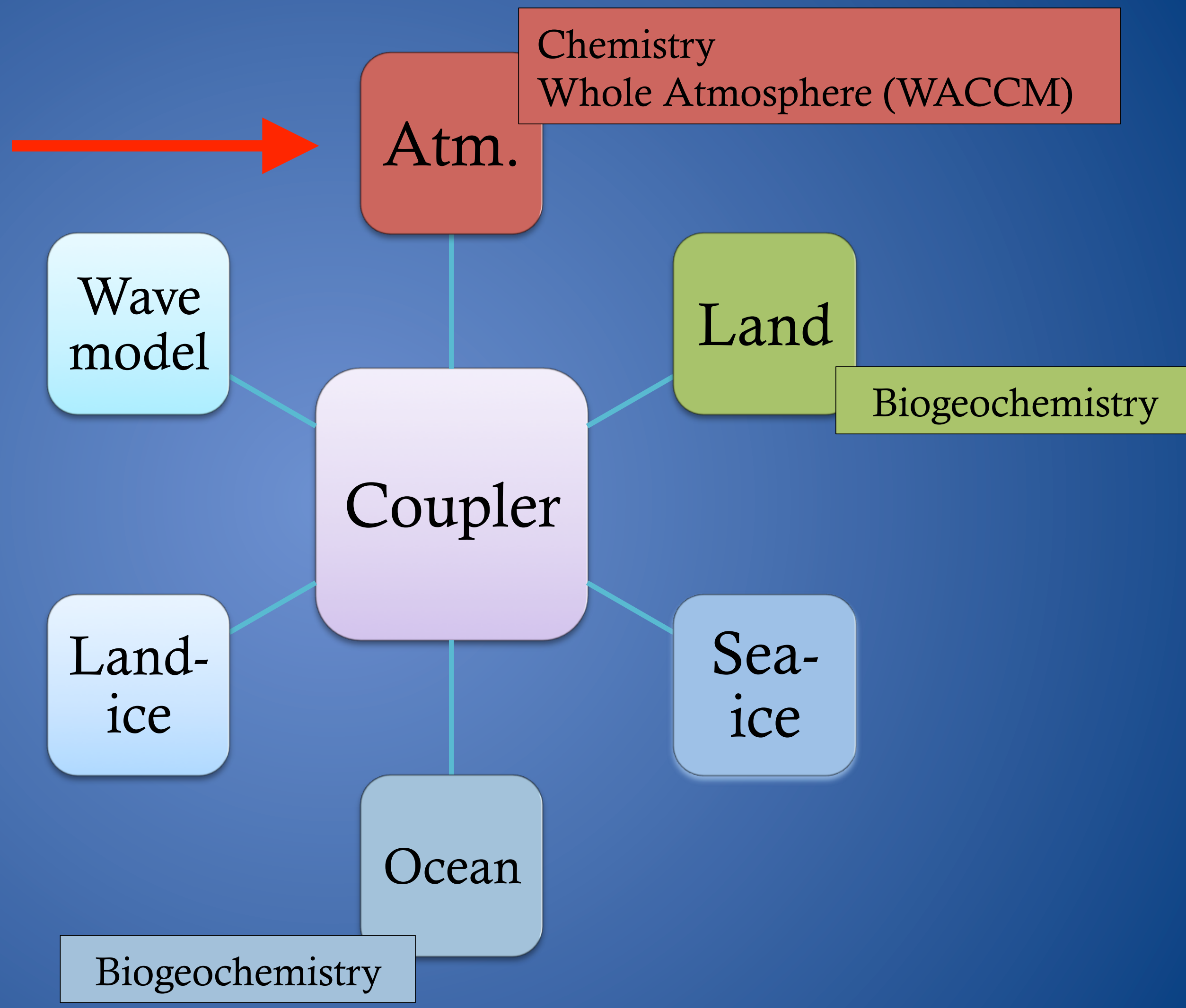
(NOAA)

- Systems of differential equations that describe fluid motion, radiative transfer, chemical composition, etc.
- Planet divided into 3-dimensional grid to solve the equations
- Atmosphere and land traditionally on same horizontal grid
- Similarly for ocean/sea-ice
- Sub-gridscale processes are parameterized

Jean-François Lamarque
lamar@ucar.edu

Current structure of CESM

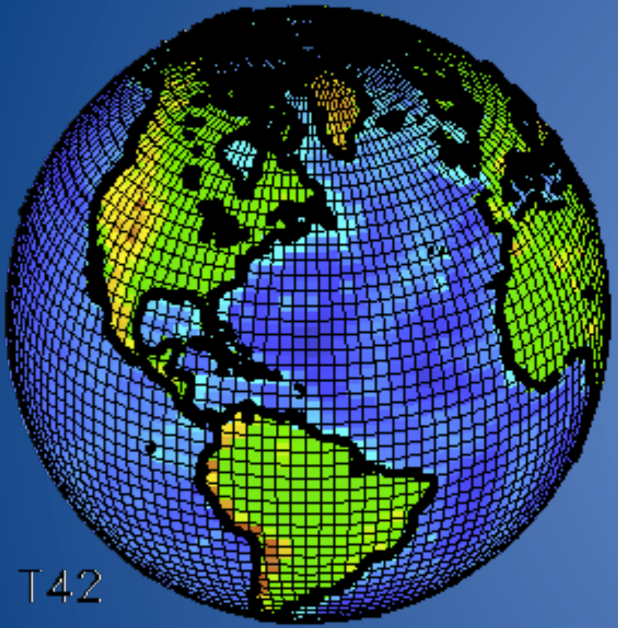
Forcings:
- Greenhouse gases
- Manmade aerosols
- Volcanic eruptions
- Solar variability
- Land-use change



CESM contains a hierarchy of models that can be configured for specific scientific explorations: single column, aquaplanet, dynamical cores, ocean-only, …

Jean-François Lamarque
lamar@ucar.edu

Community Earth System Model (CESM1)



- 0.25°, 1° , 2° resolutions, +regional-refinement
- 30 minute time step (for 1° and 2°)
- 32 atmosphere levels (72 for WACCM)
- 60 ocean levels (0.1° or 1°)
- 25 ground layers
- ~5 million grid boxes at 1° resolution
- >1.5 million lines of computer code
- Data archived (monthly, daily, hourly) for hundreds of geophysical fields

CESM2 will be released in December 2016

Jean-François Lamarque
lamar@ucar.edu

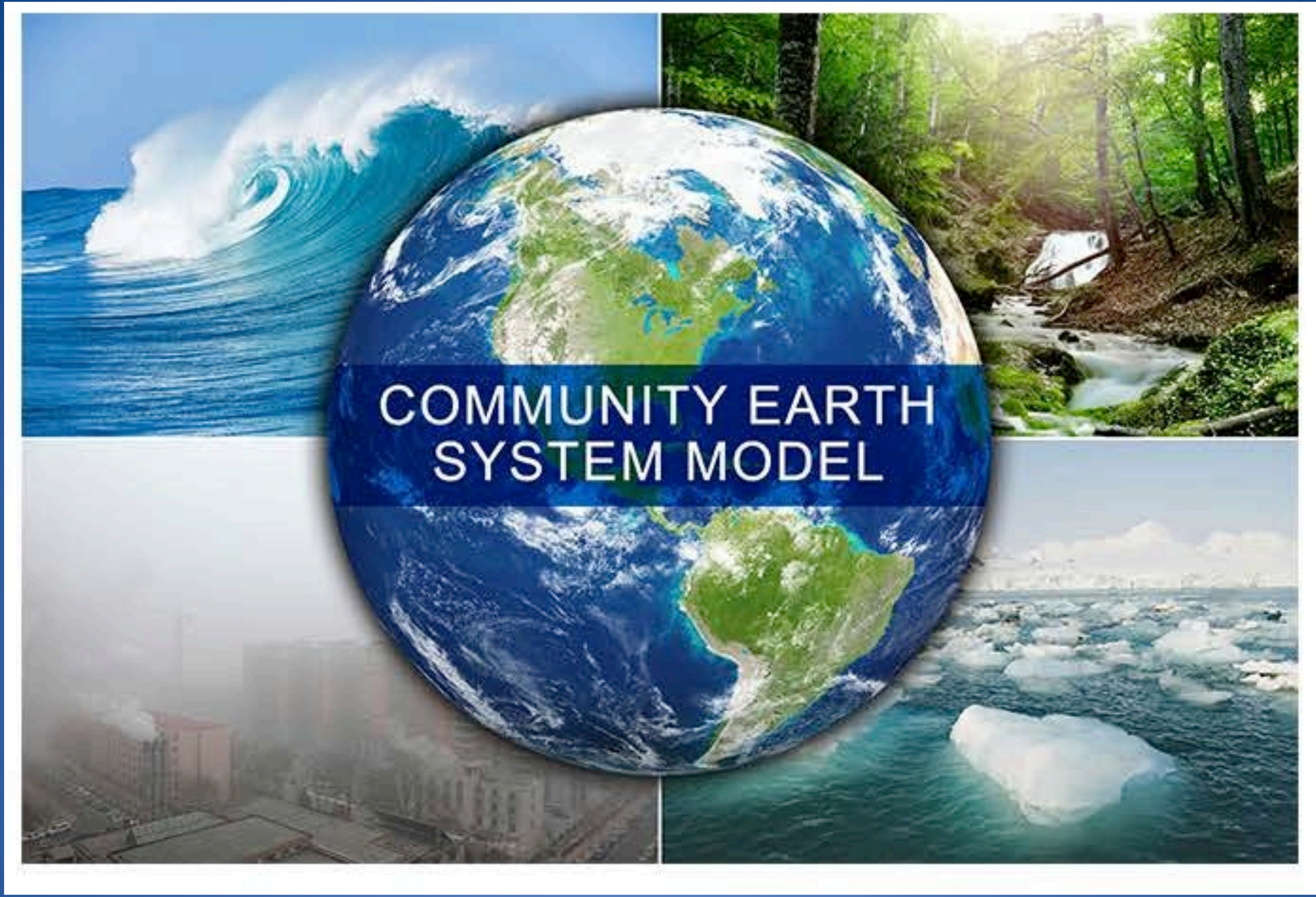


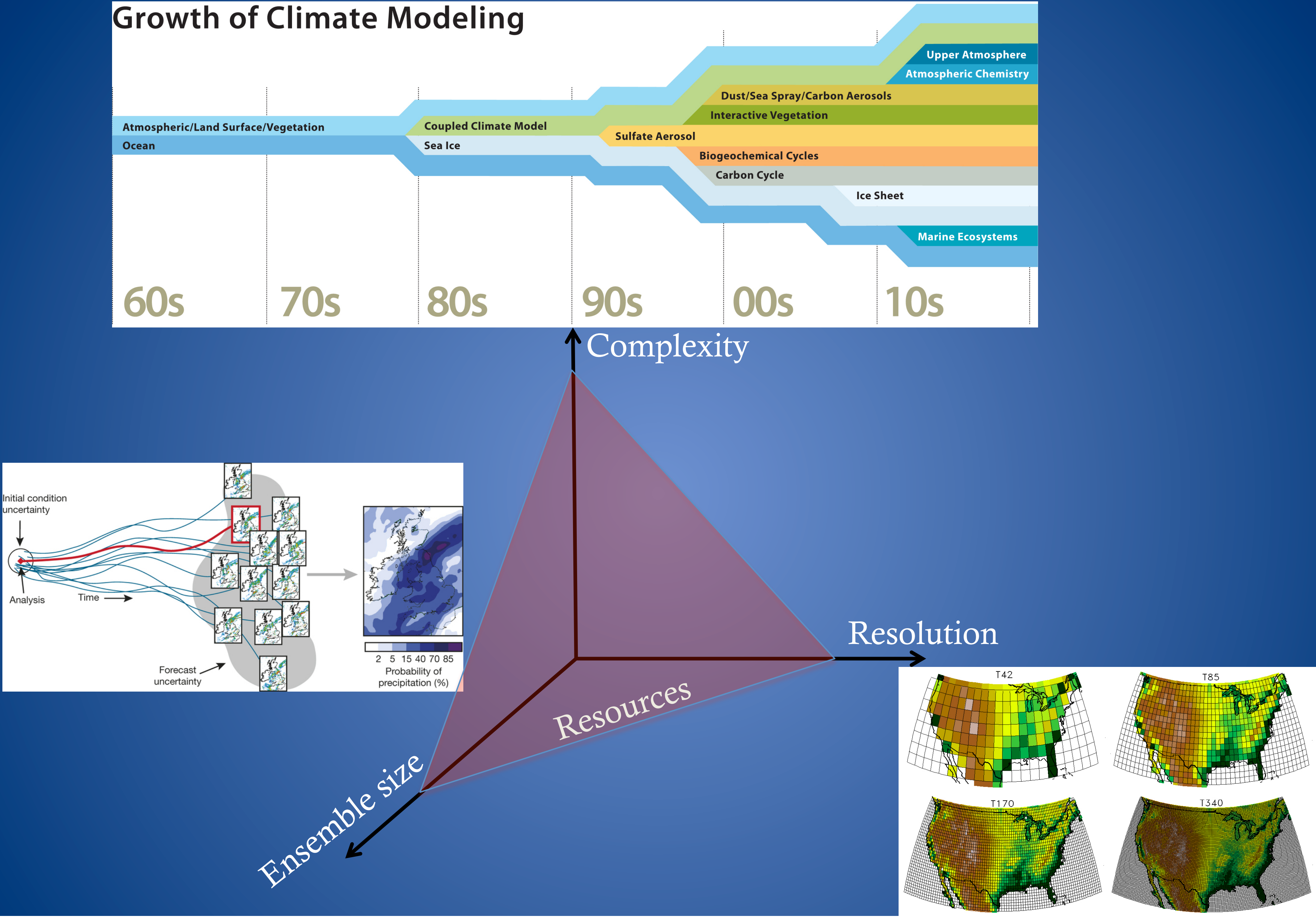
Figure courtesy of Steve Ghan and DOE Graphics team

BAMS Article:

The Community Earth System Model: A Framework for Collaborative Research

J.W. Hurrell, M.M. Holland, P.R. Gent, S. Ghan, J.E. Kay, P.J. Kushner, J.-F. Lamarque, W.G. Large, D. Lawrence, K. Lindsay, W.H. Lipscomb, M.C. Long, N. Mahowald, D.R. Marsh, R.B. Neale, P. Rash, S. Vavrus, M. Vertenstein, D. Bader, W.D. Collins, J.J. Hack, J. Kiehl, S. Marshall, 2014

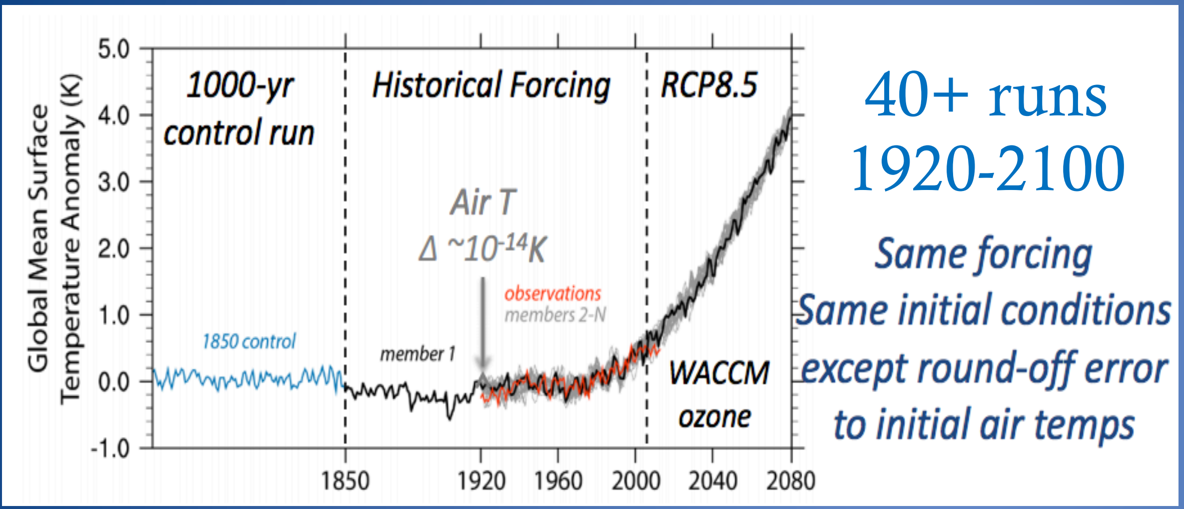
Jean-François Lamarque
lamar@ucar.edu



CESM Tutorial August 2016

Jean-François Lamarque
lamar@ucar.edu

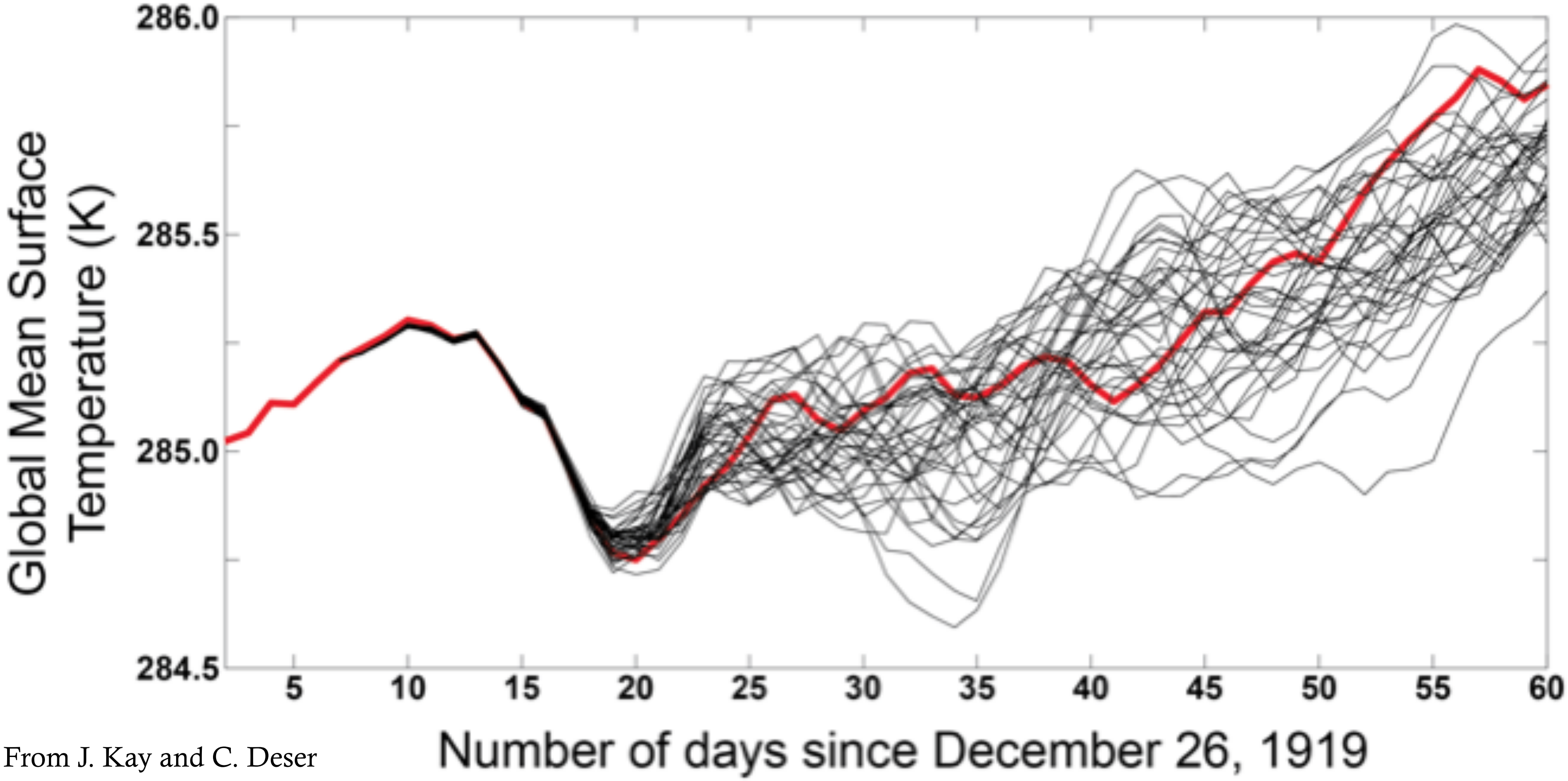
Internal variability and ensemble



Slide from C. Deser

Jean-François Lamarque
lamar@ucar.edu

Internal variability and ensemble

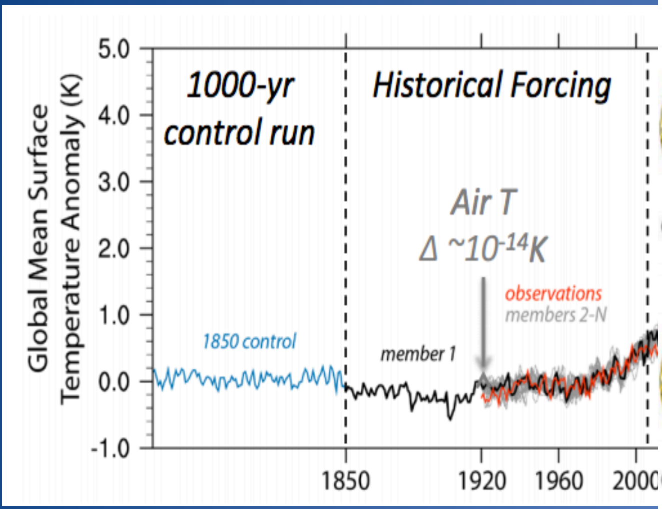


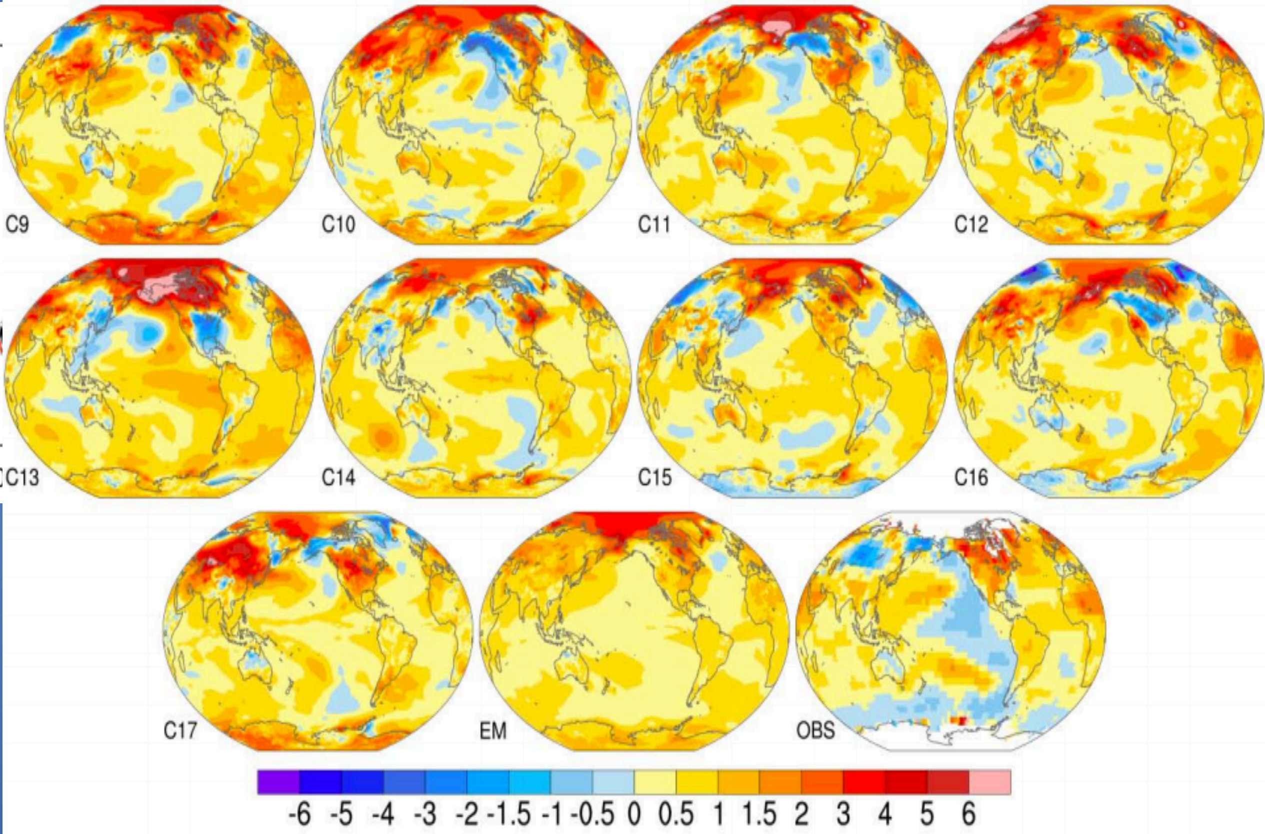
From J. Kay and C. Deser

Slide from C. Deser

Jean-François Lamarque
lamar@ucar.edu

Internal variability and ensemble





Panels show 1979-2012 DJF surface temperature trends for 9 ensemble members, the ensemble mean, and observations.

Slide from C. Deser

Jean-François Lamarque
lamar@ucar.edu

What can we learn from comparing observed and modeled September sea ice trends?

1. Observed sea ice loss cannot be explained by natural variability alone.

2. Individual ensemble members can reproduce the observed ice loss, but the ensemble spread is large.

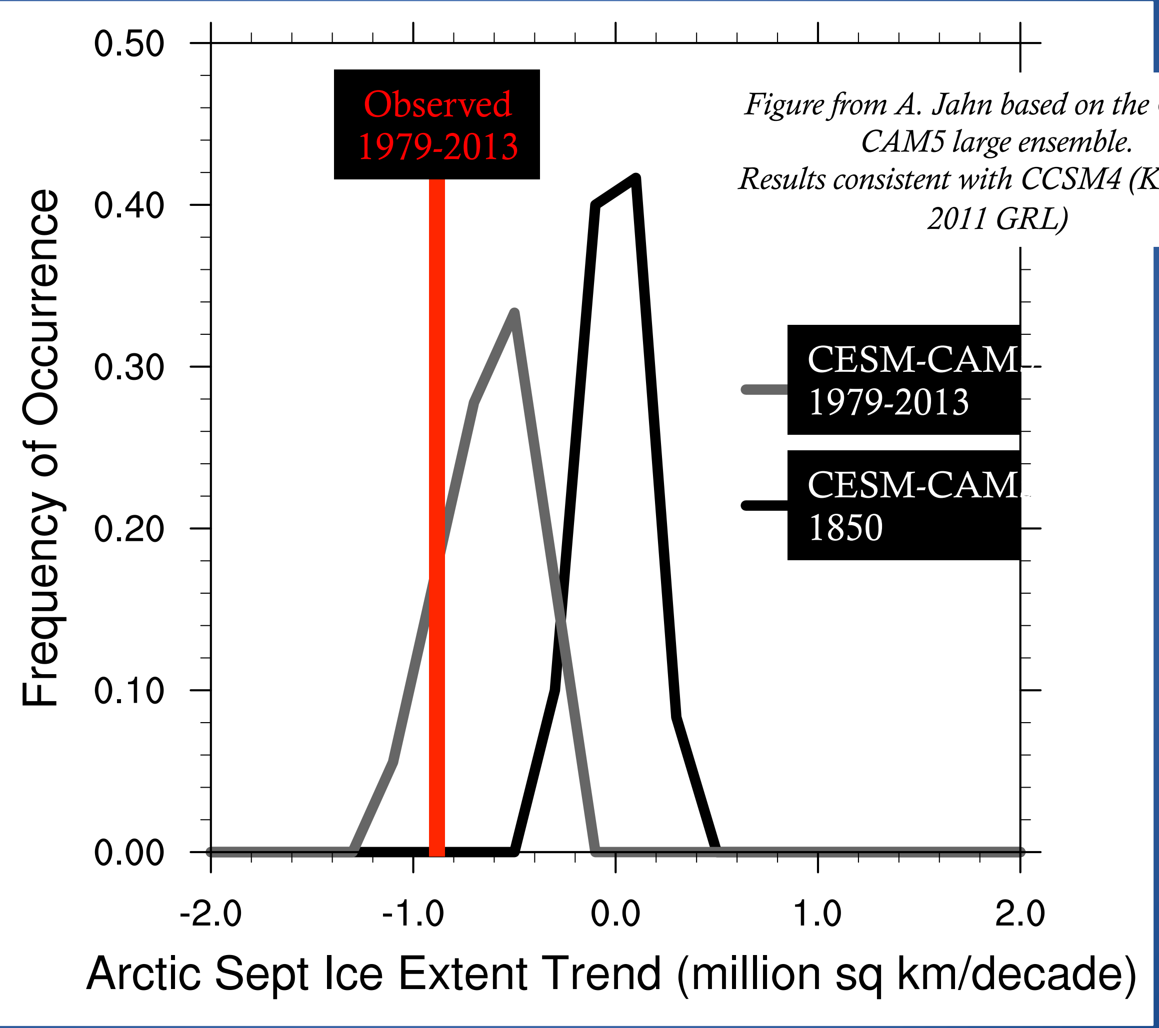
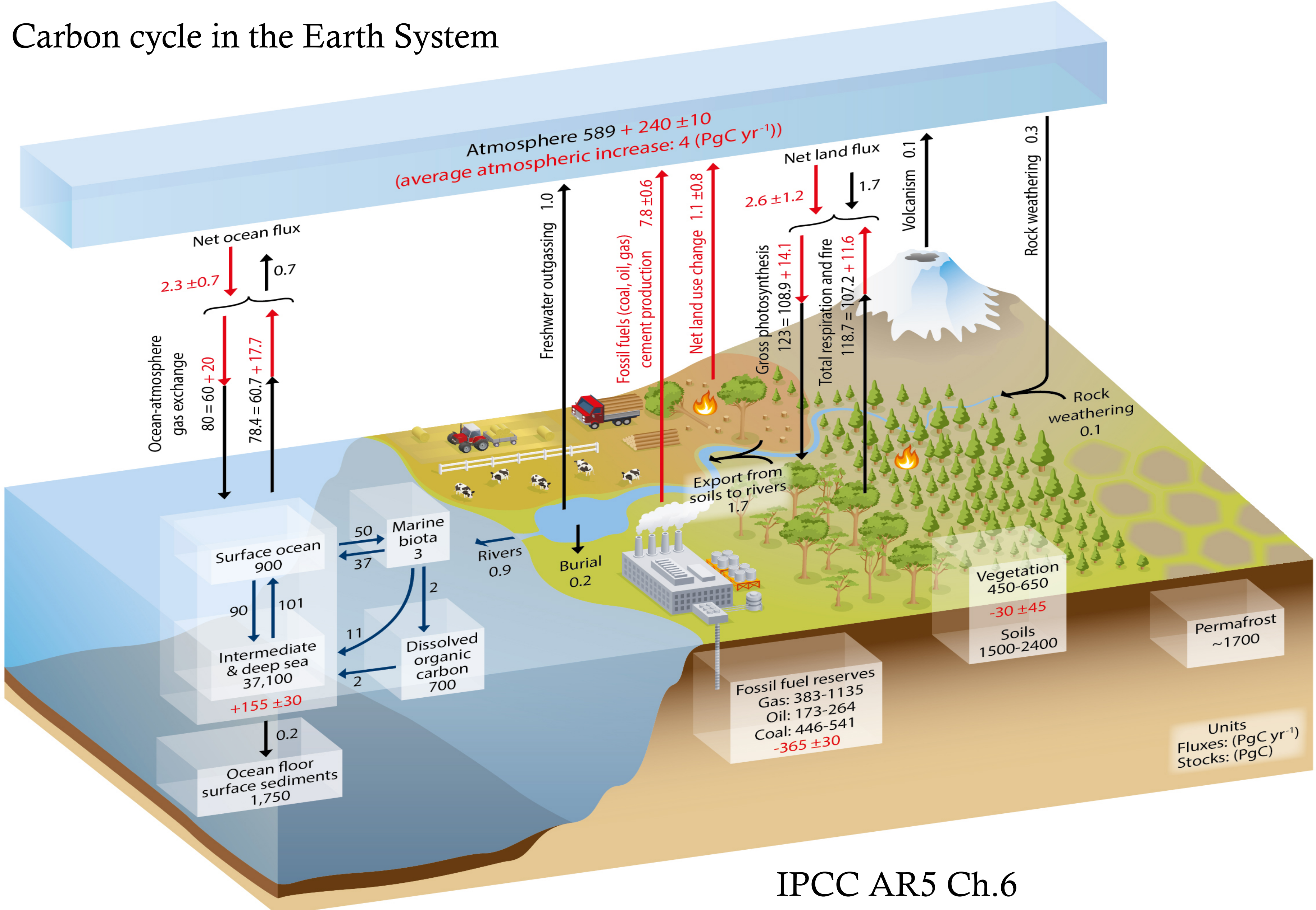


Figure from A. Jahn based on the CESM-CAM5 large ensemble. Results consistent with CCSM4 (Kay et al. 2011 GRL)

Jean-François Lamarque
lamar@ucar.edu

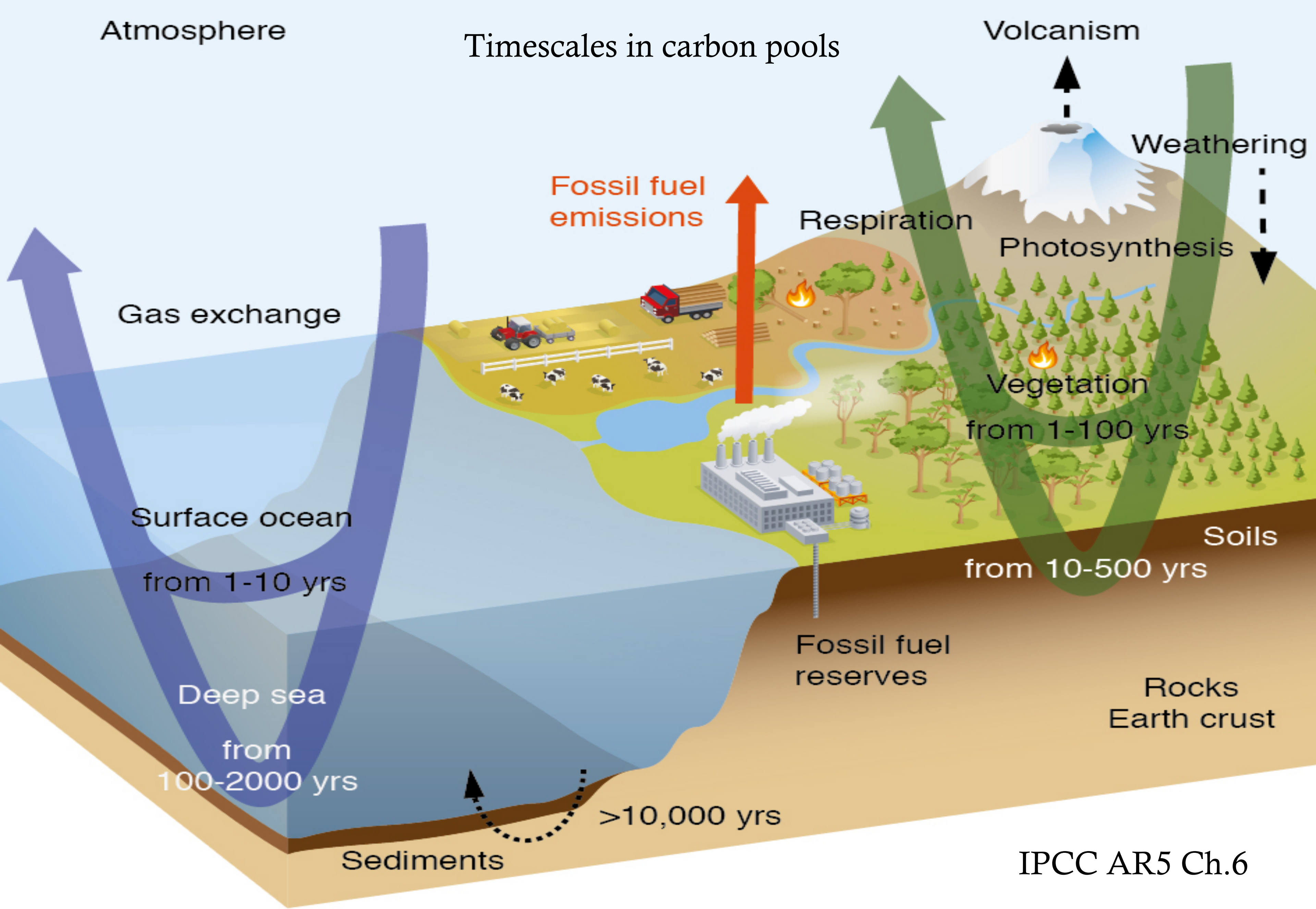
Carbon cycle in the Earth System



IPCC AR5 Ch.6

Jean-François Lamarque
lamar@ucar.edu

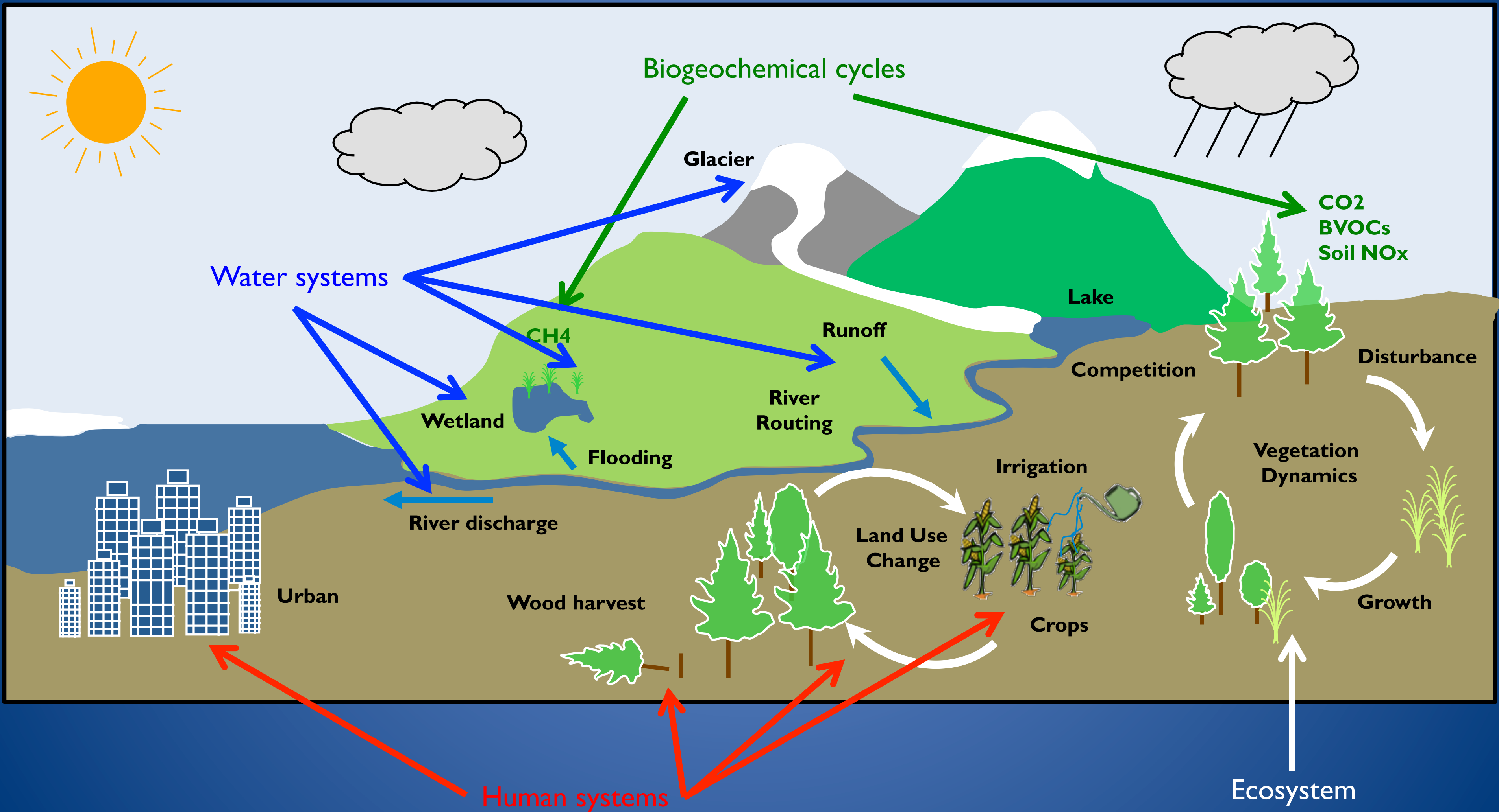
Timescales in carbon pools



IPCC AR5 Ch.6

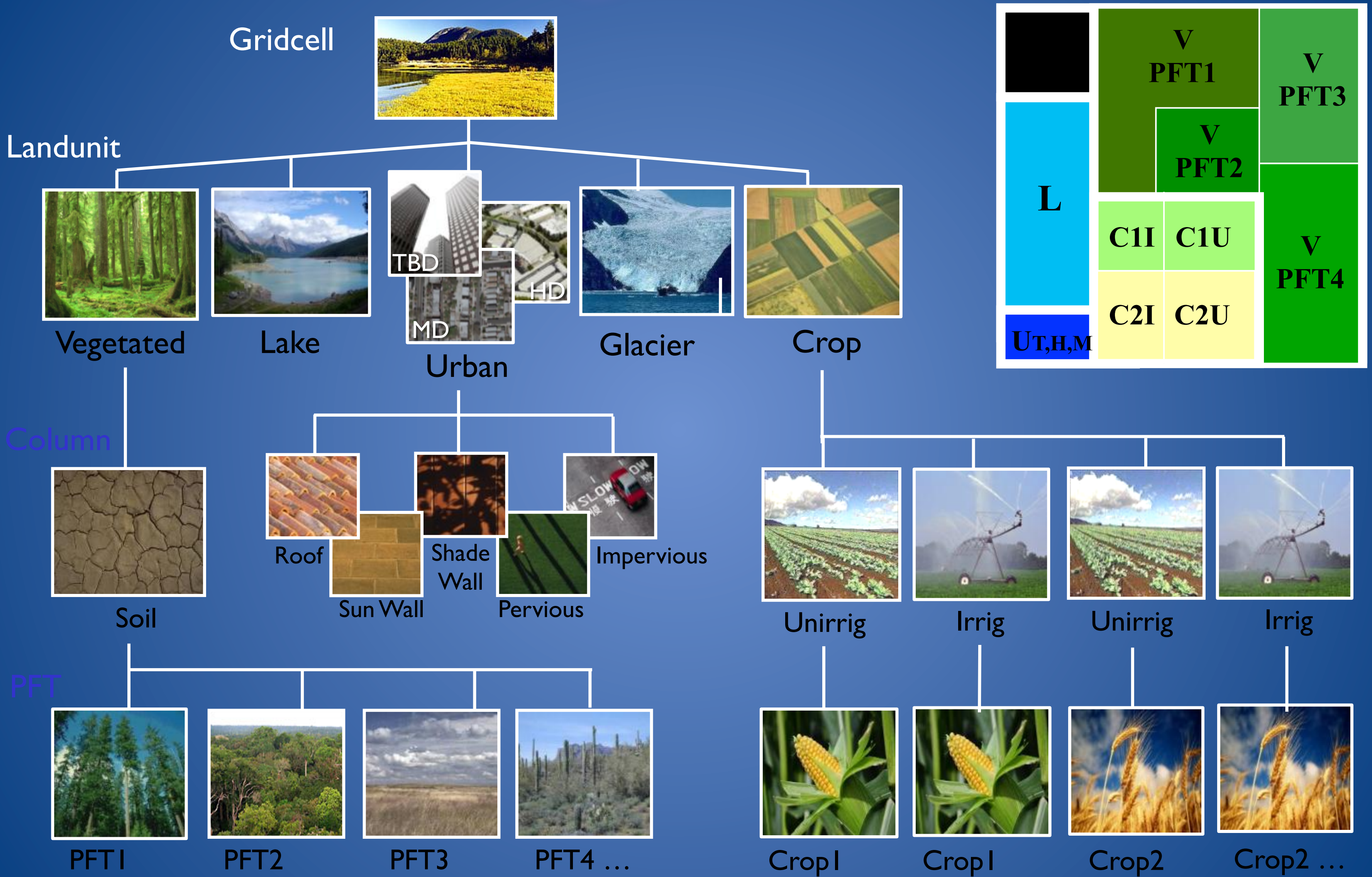
Jean-François Lamarque
lamar@ucar.edu

Processes in the CESM land model



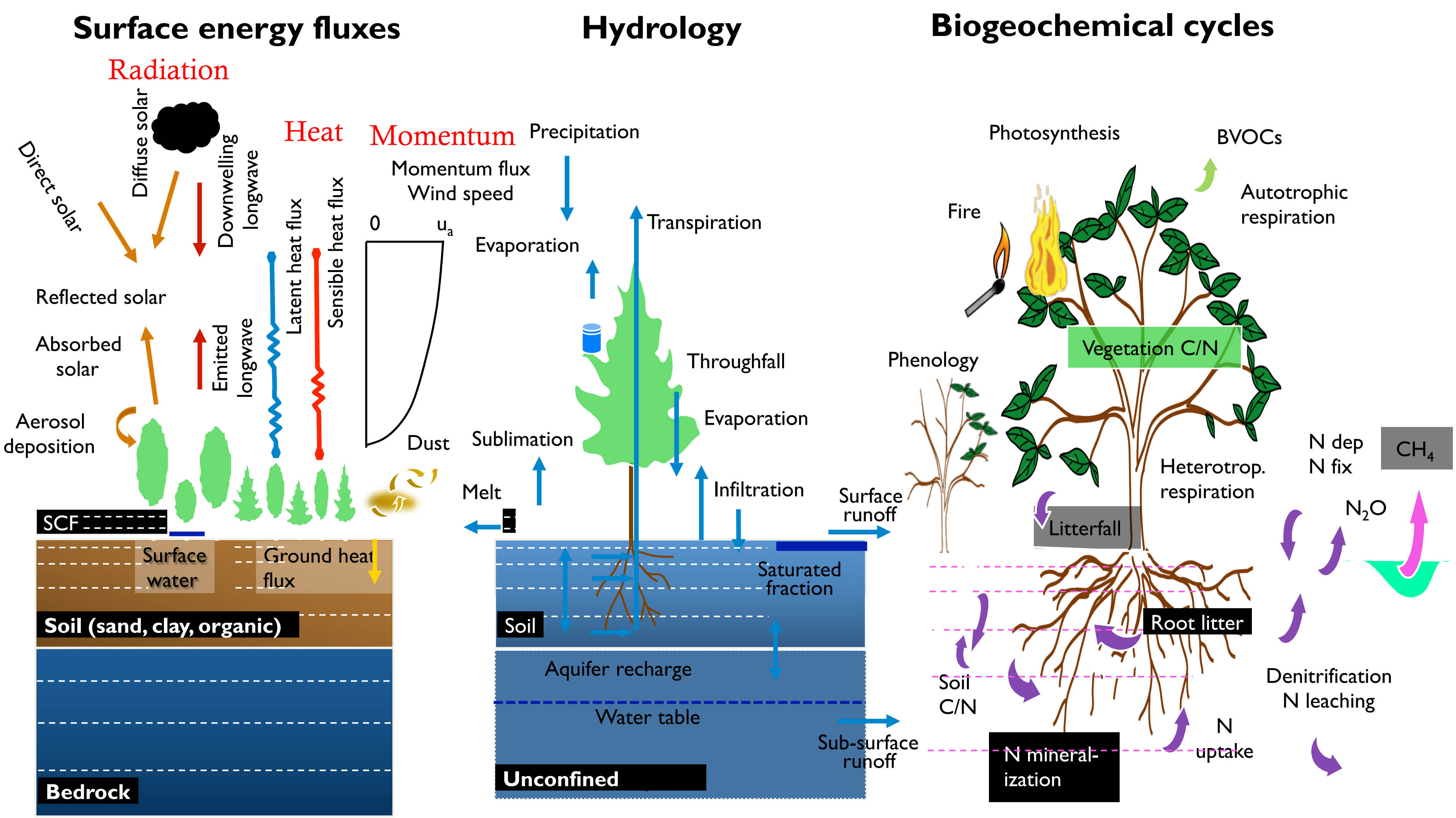
Jean-François Lamarque
lamar@ucar.edu

CLM tiling structure



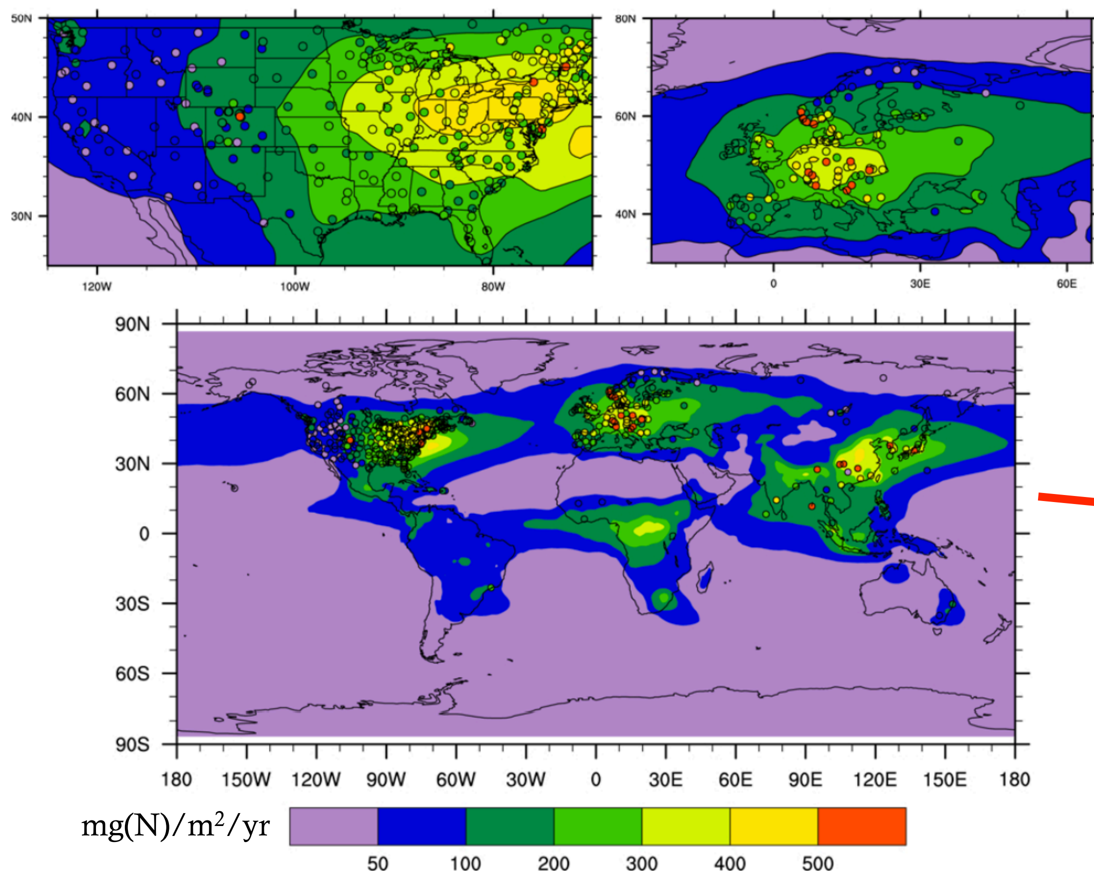
Jean-François Lamarque
lamar@ucar.edu

Current processes in CLM

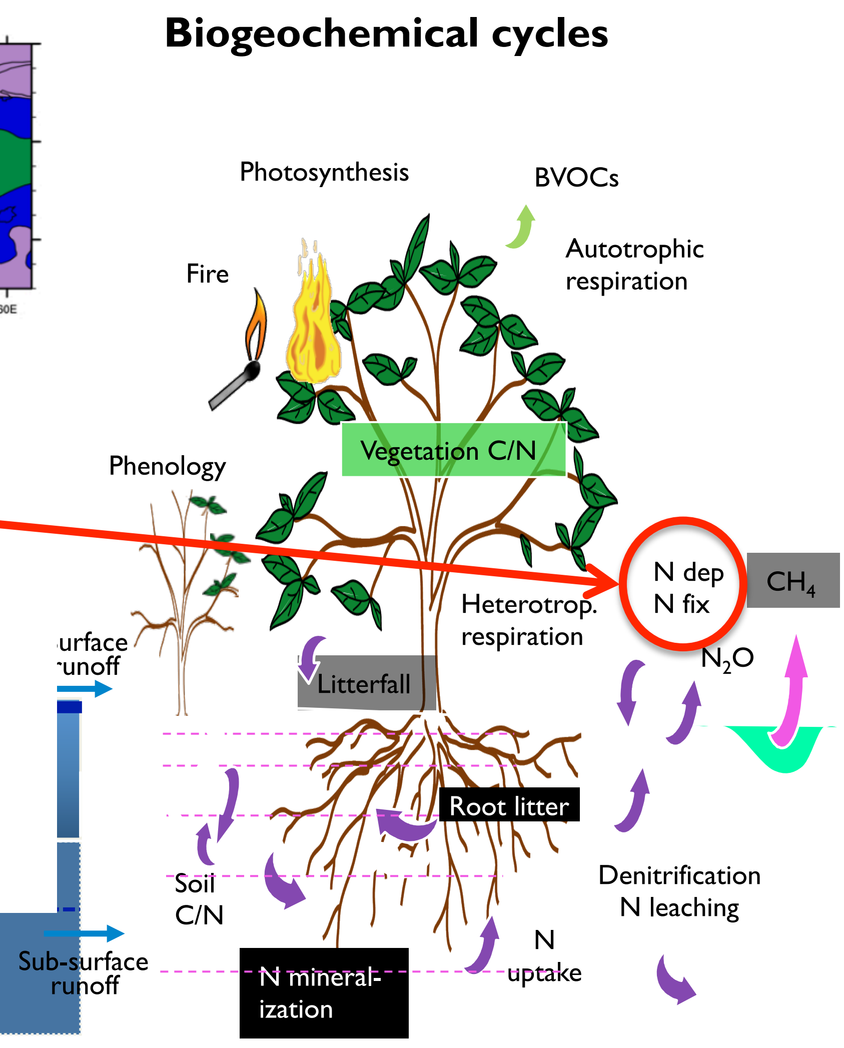


Jean-François Lamarque
lamar@ucar.edu

Current processes in CLM

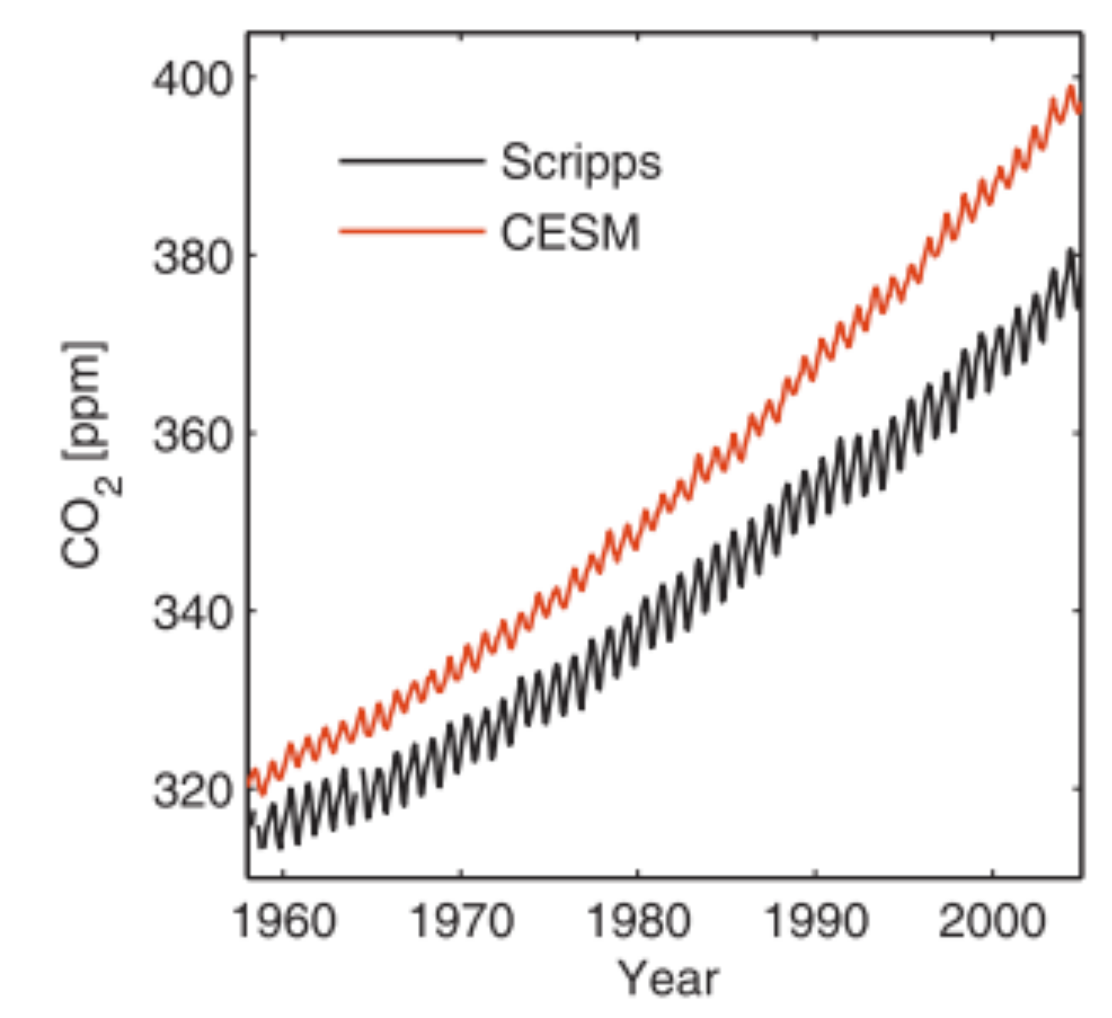


Lamarque et al., 2013



Jean-François Lamarque
lamar@ucar.edu

CO_2 over historical period in CESM1

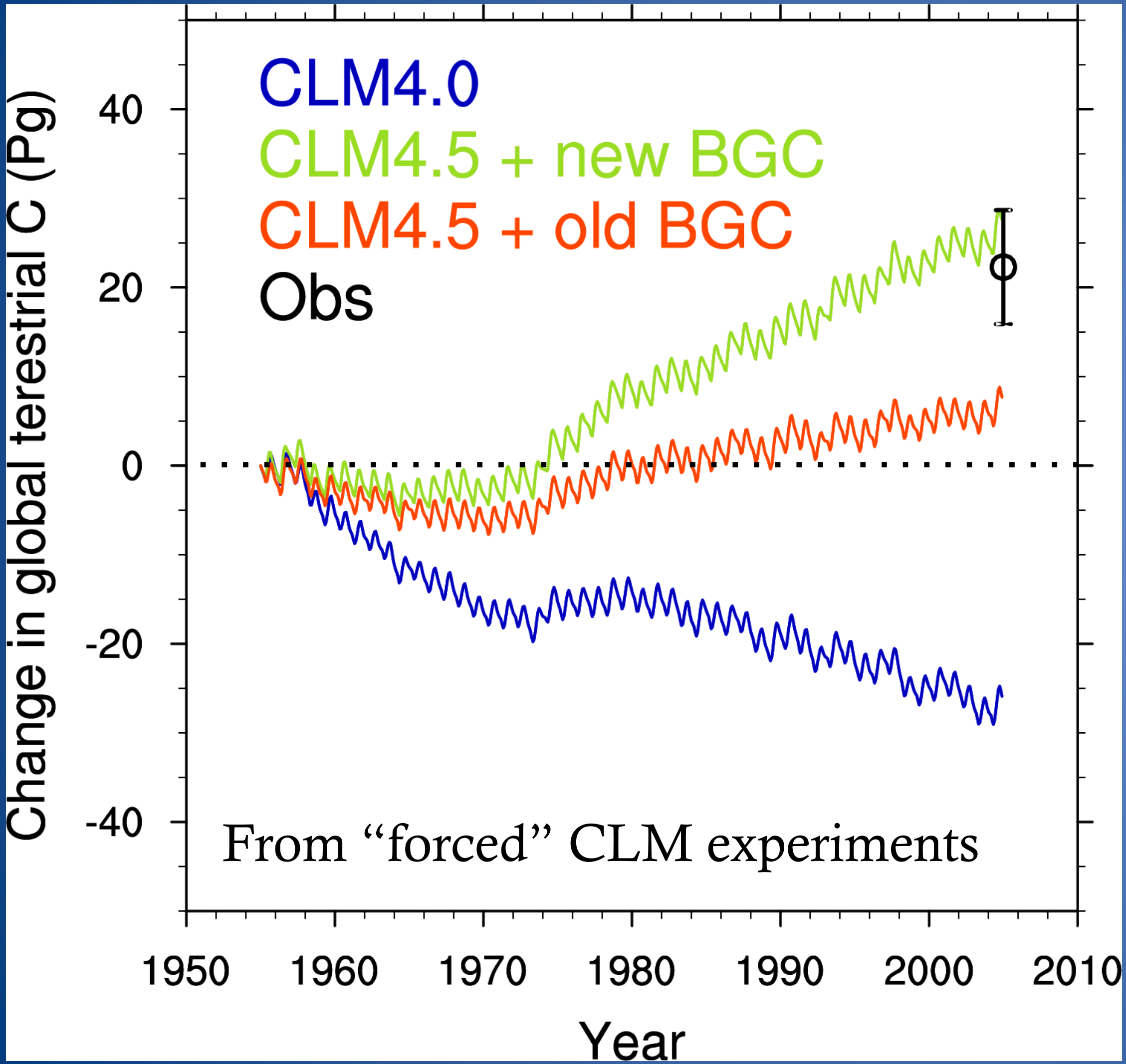


Mauna Loa

Keppel-Aleks et al., 2013

Jean-François Lamarque
lamar@ucar.edu

Changes in the Global Terrestrial Carbon Budget



Accumulated carbon from

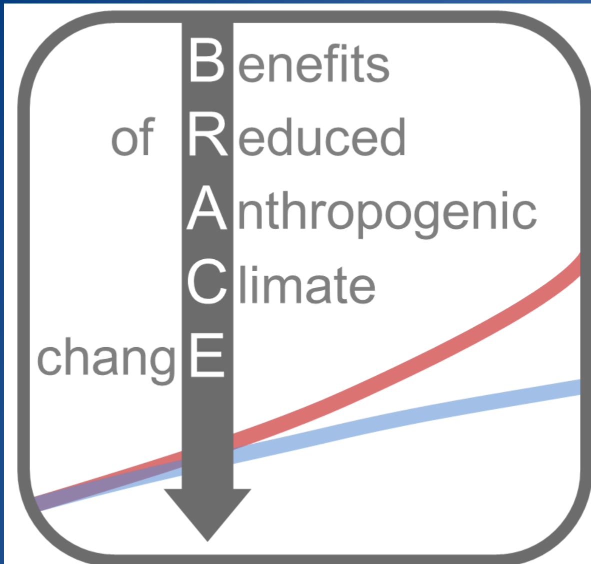
- losses due to land cover change,
- gains due to CO_2 fertilization
- regional losses or gains due to climate-carbon feedbacks.

More realistic land carbon uptake results from reduced N-limitation on CO_2 fertilization.

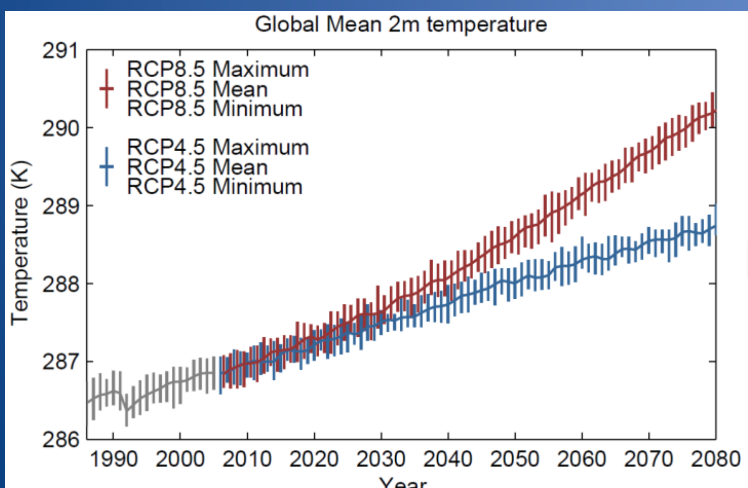
Koven et al., 2013

Jean-François Lamarque
lamar@ucar.edu

BRACE: Benefits of Reduced Anthropogenic Climate changE



- Explore differences in physical and societal impacts between RCP8.5 and RCP4.5 using CESM ensembles
- 21 papers, special issue of *Climatic Change* (in progress)
- 50+ participants, from NCAR and 18 other institutions

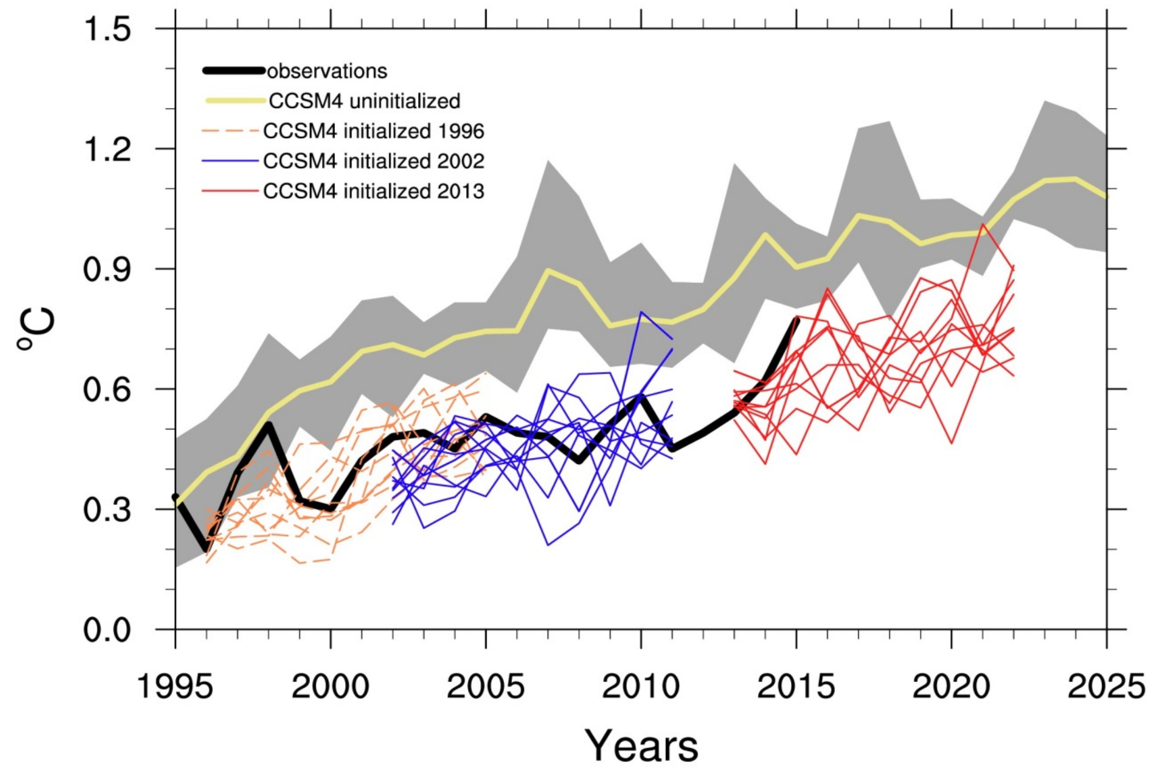


Biophysical & Societal Impact Models

Avoided Impacts
Health
Ag. and Land use
Heat extremes
Tropical cyclones
Drought
Sea-level rise

Jean-François Lamarque
lamar@ucar.edu

Decadal prediction



Predicted rate of global warming from 2013 initial year greater than during early-2000s slowdown and greater than uninitialized:

Observed 2001-2014: +0.08±0.05°C/decade

Predicted 2013-2022: +0.22±0.13°C/decade

Uninitialized 2013-2022: +0.14±0.12°C/decade

(Meehl et al., 2016, Nature Communications)

With funding from DOE RGCM program

Jean-François Lamarque
lamar@ucar.edu

ROAD TO CESM2

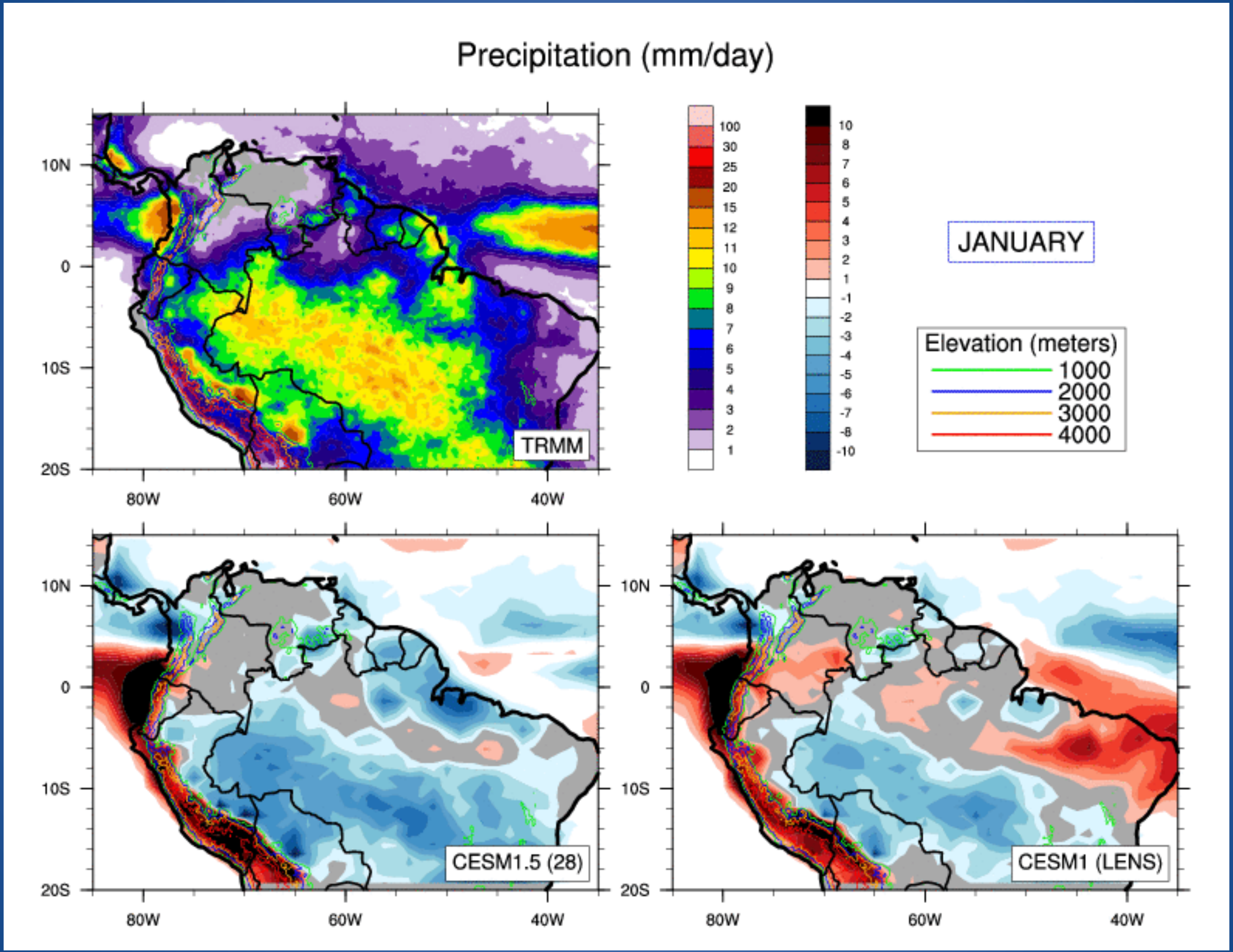
Jean-François Lamarque
lamar@ucar.edu

Where we were in Feb. 2016

- 4-day all-WGs meeting in Boulder
- Had generated 100+ year control and 20th century simulation w/ intermediate configurations
- Identified 3 main areas of strong concern
  - > Amazon precipitation
  - > Surface wind over ice sheet
  - > Arctic ocean warming at depth

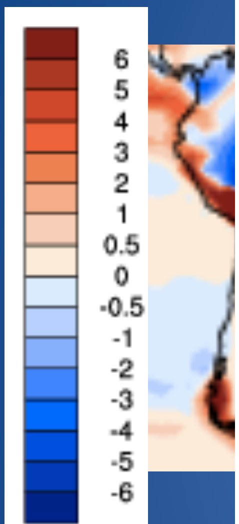
Jean-François Lamarque
lamar@ucar.edu

Amazon problem

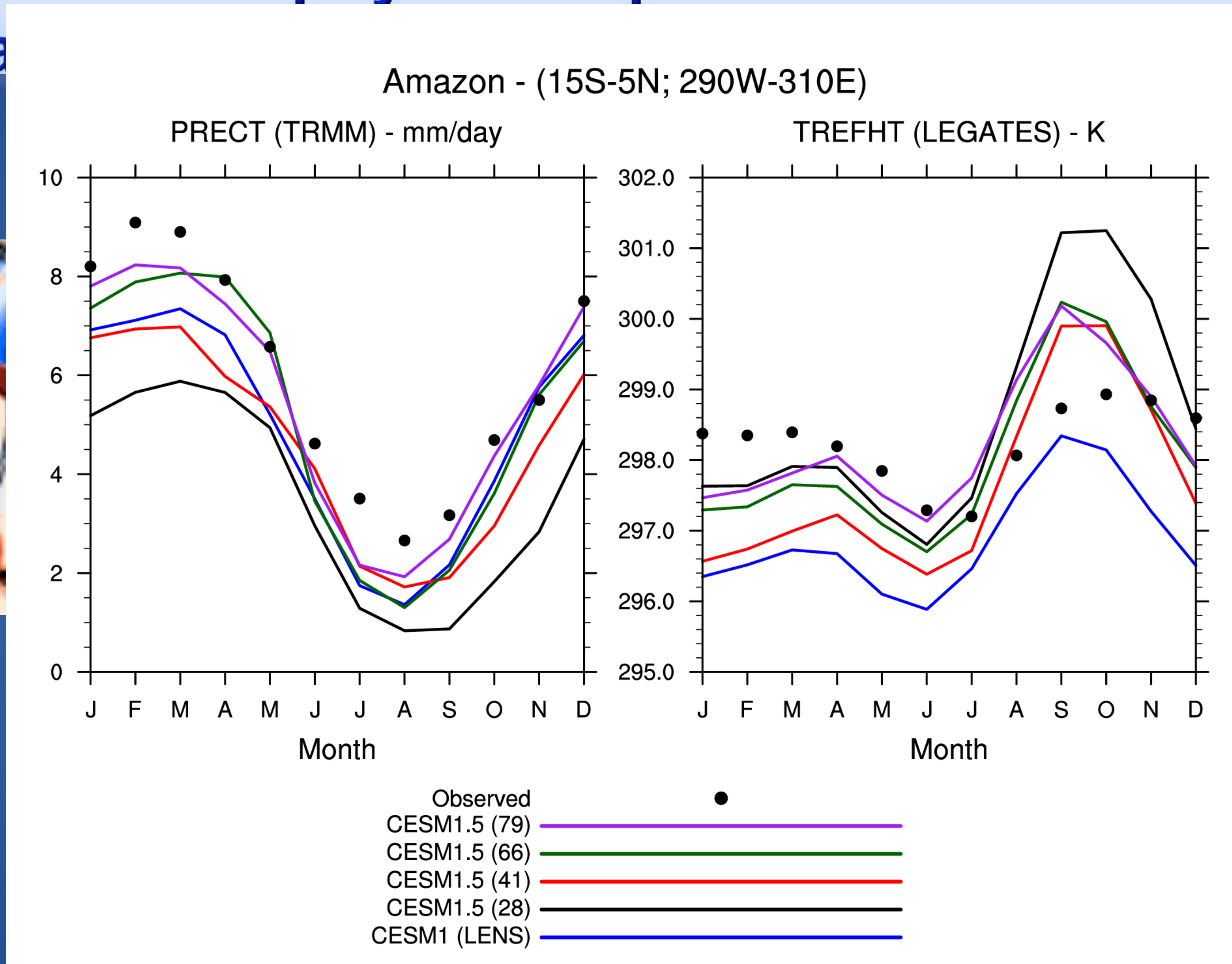


Jean-François Lamarque
lamar@ucar.edu

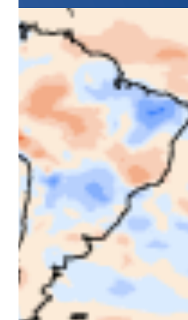
Parameter and physics exploration – Amazon DJF Rainfa



mm/day



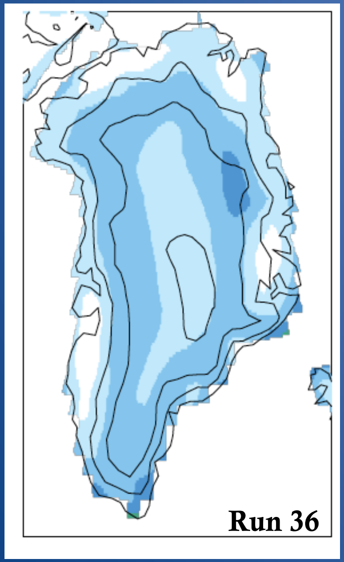
eten



Jean-François Lamarque
lamar@ucar.edu

Reduced surface biases for ice sheets

- CESM2 can now generate a realistic surface mass balance for either Greenland or Antarctica.
  - However, surface melting is sensitive to snow physics. Still working on uniform physics that gives good results for both ice sheets.
- Surface winds over both ice sheets are much improved.
- CAM still generates too much liquid precipitation in cold regions.

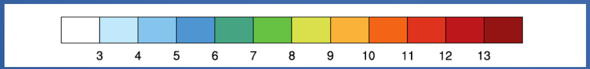


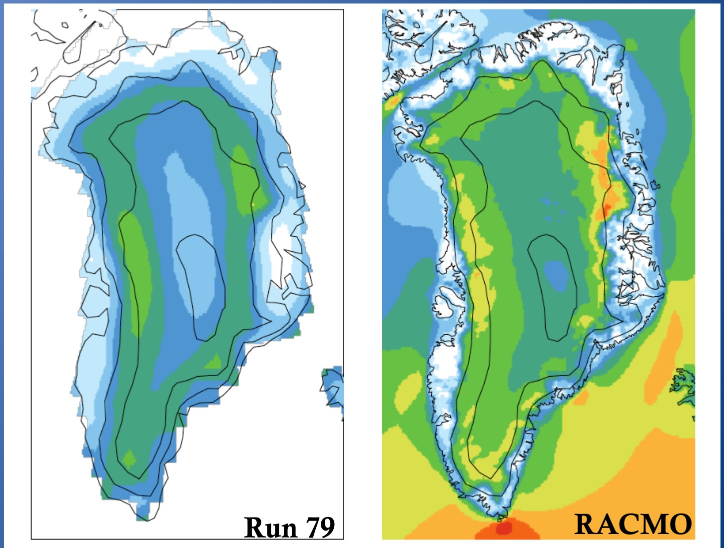
10 m wind speed (m/s) over the Greenland ice sheet.

Left: Run 36, with turbulent mountain stress.

Right: Run 79, with Beljaars form drag.

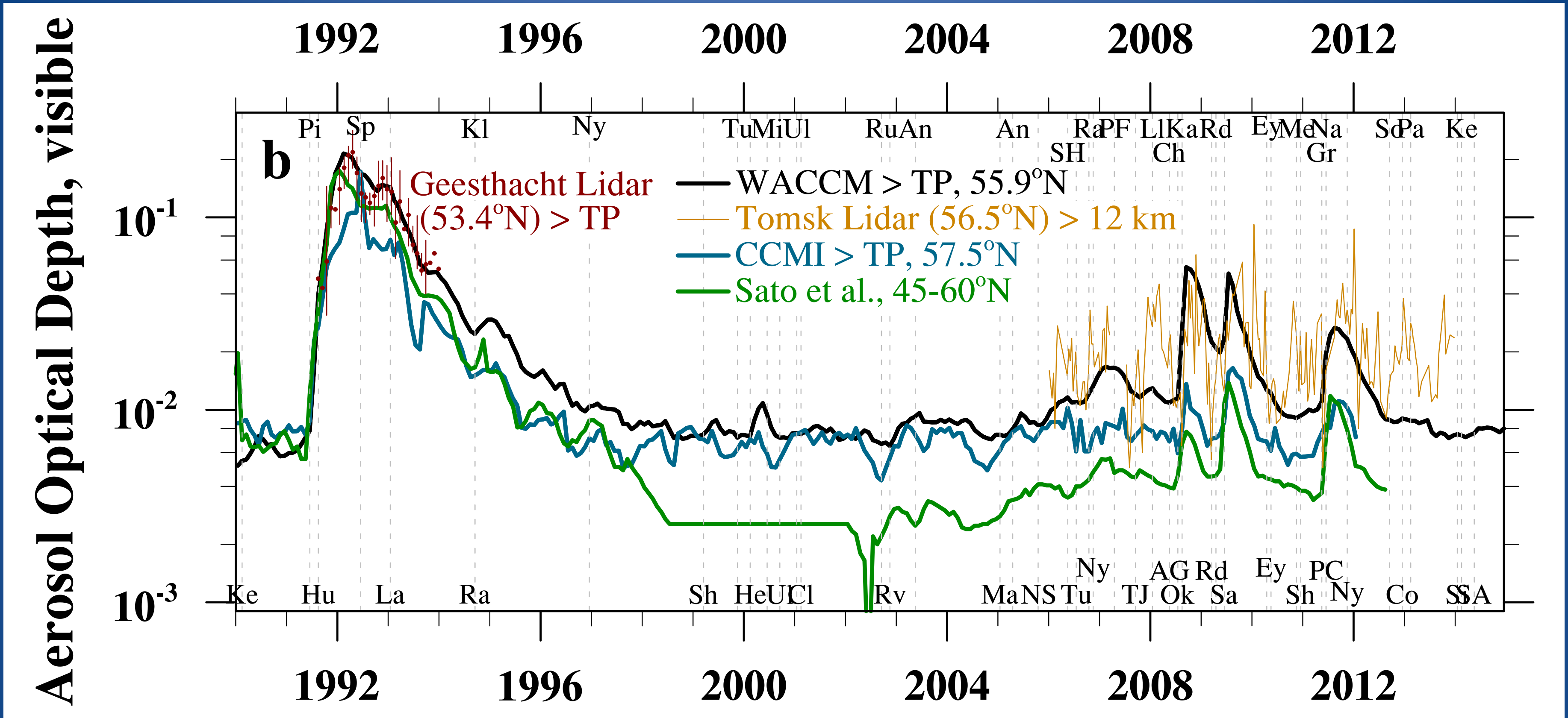
Far right: RACMO2.3 regional model.





Jean-François Lamarque
lamar@ucar.edu

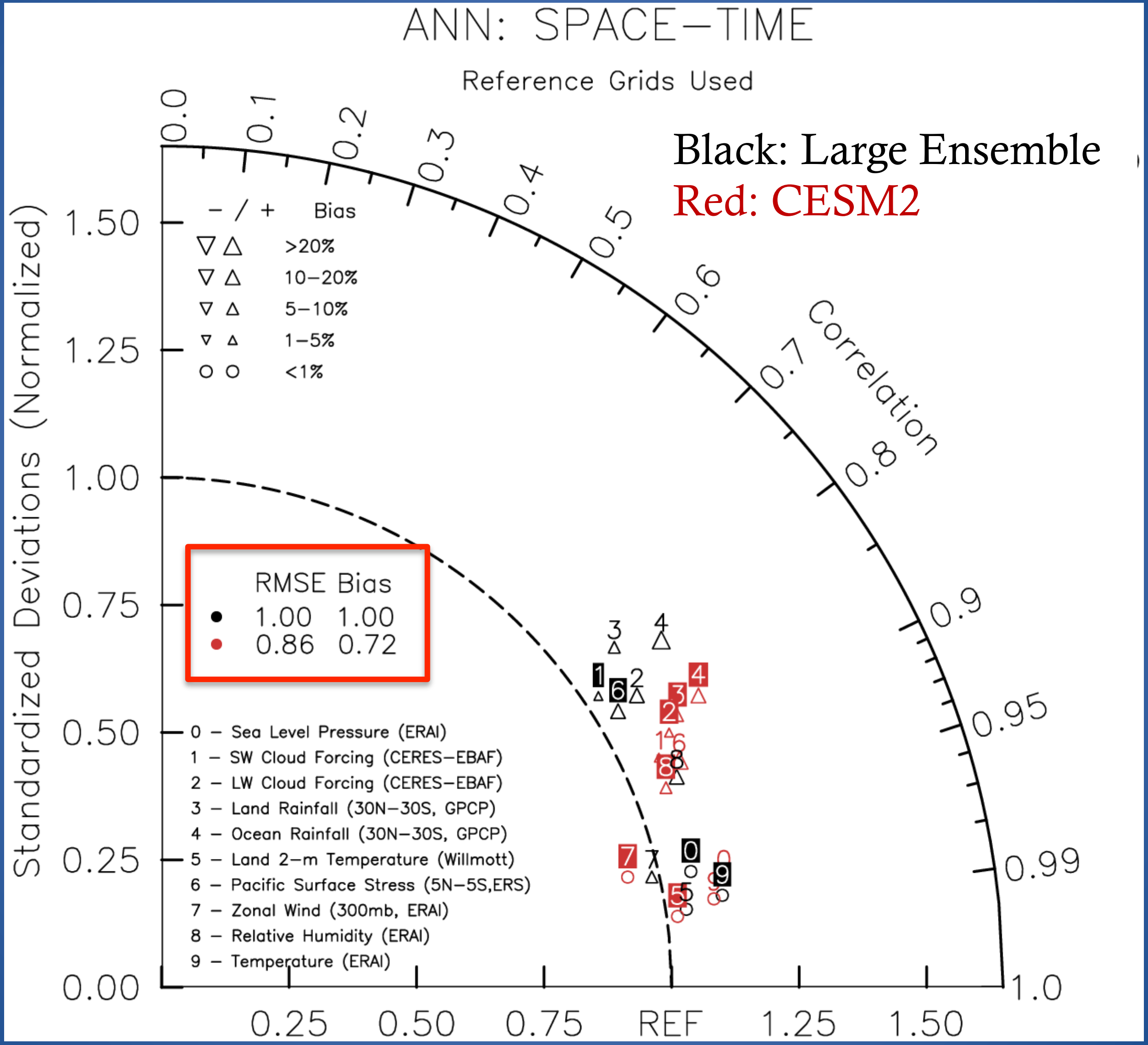
Stratospheric AOD at Northern Mid-Latitudes



Prognostic stratospheric aerosols with volcanic SO_2 database match lidar observations much better than existing climatologies.

Jean-François Lamarque
lamar@ucar.edu

Overall score



Jean-François Lamarque
lamar@ucar.edu

Where we are now:

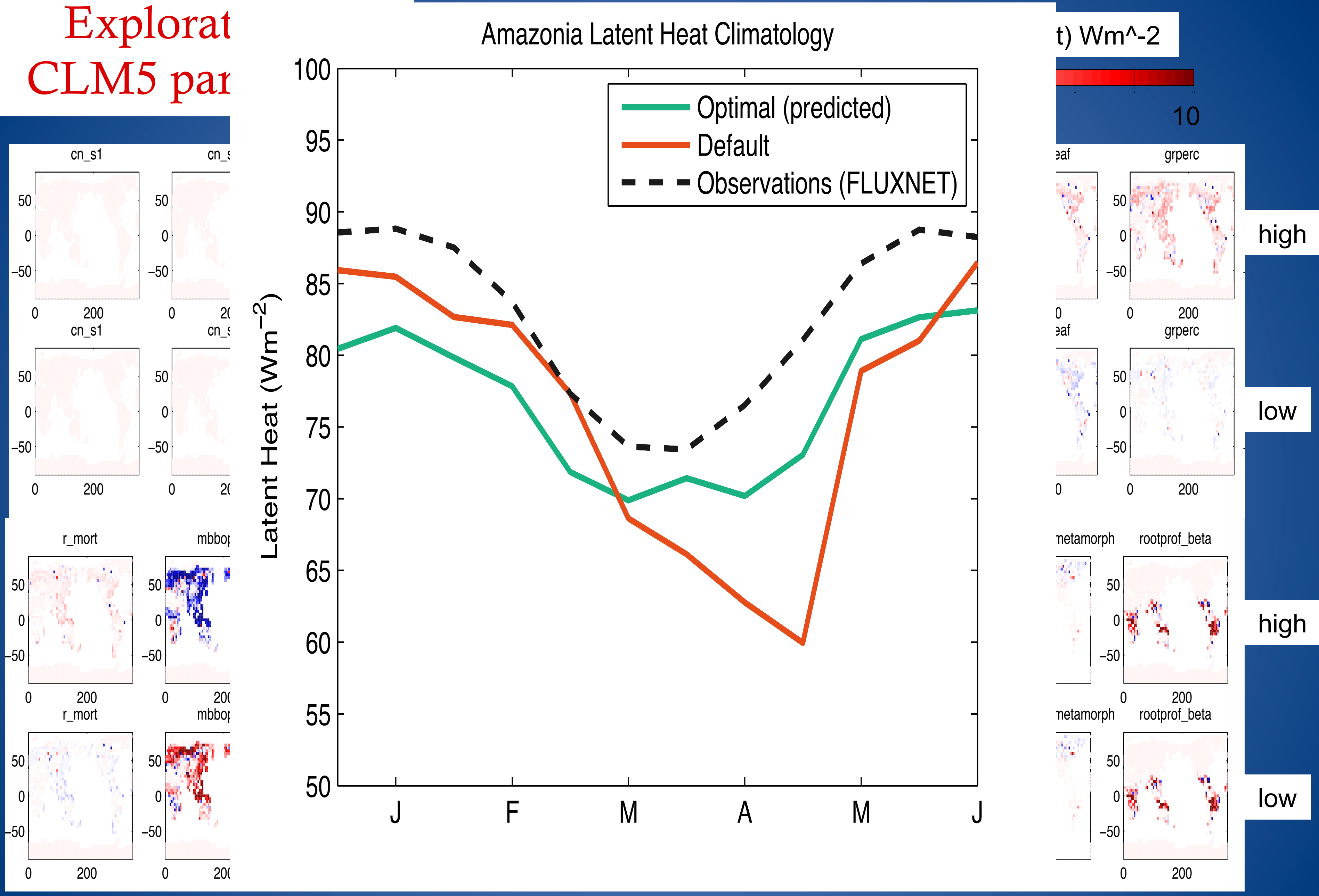
- Nearing completion of ALL components
- Targeted coupled issues identified in Feb.

✓ CESM2 is improved over LENS

- Additional work going on
  - ➢Secondary-organic aerosols
  - ➢Land optimization

Jean-François Lamarque
lamar@ucar.edu

Explorat
CLM5 par



Jean-François Lamarque
lamar@ucar.edu

Where we are now:

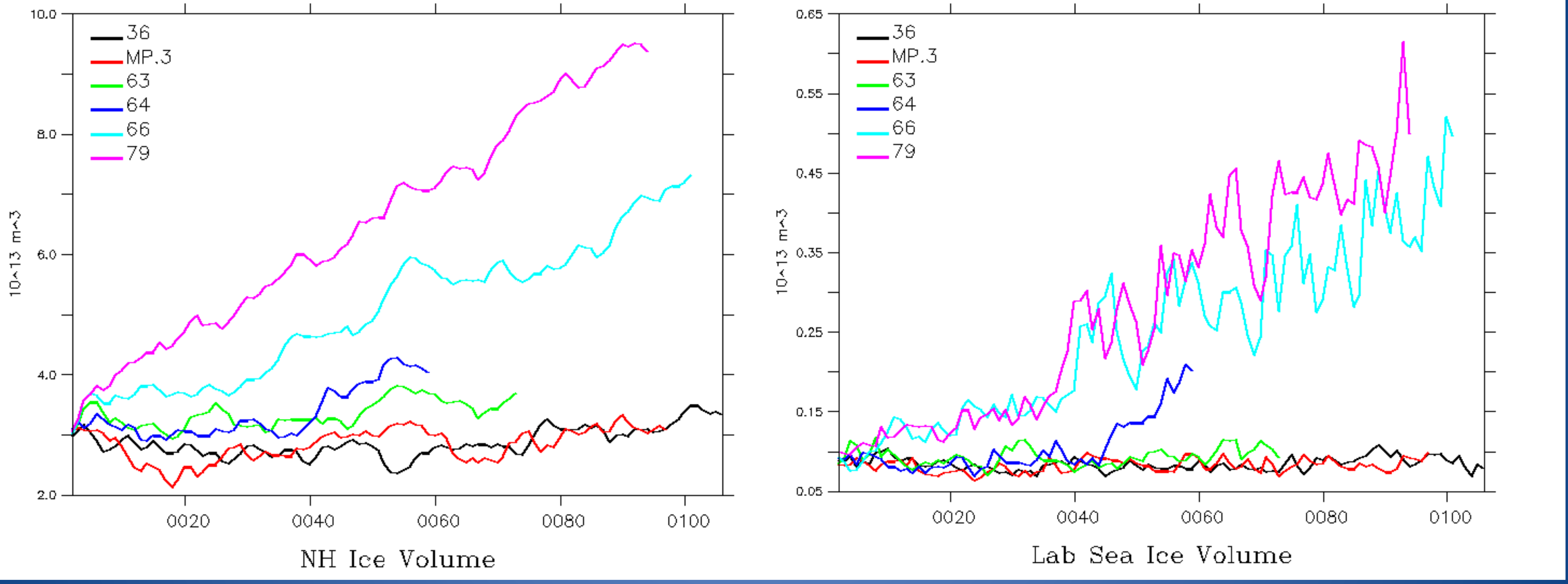
- Nearing completion of <u>ALL</u> components
- Targeted coupled issues identified in Feb.

✓ CESM2 is improved over LENS

- Additional work going on
  - Secondary-organic aerosols
  - Land optimization
  - Performance optimization (20+ sypd!)
  - …

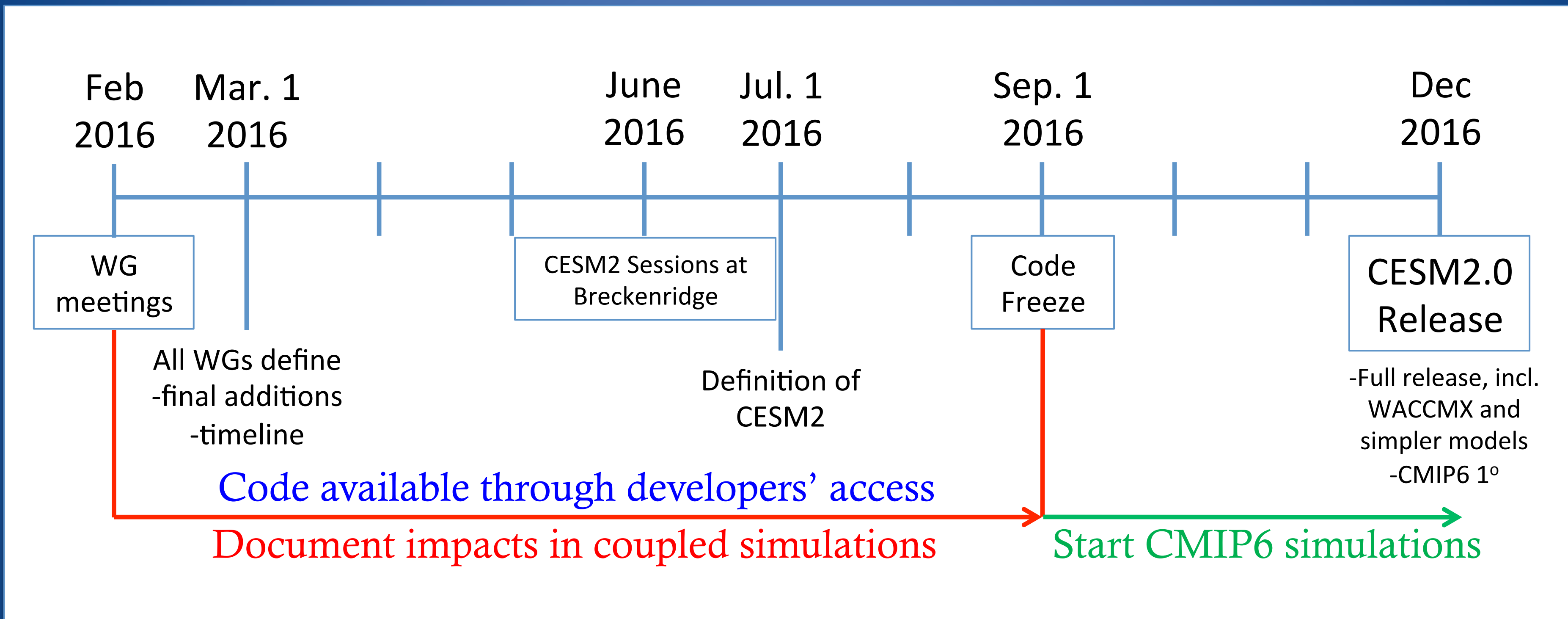
Jean-François Lamarque
lamar@ucar.edu

Sea-ice issue in very recent experiments



Jean-François Lamarque
lamar@ucar.edu

Timeline until release



Jean-François Lamarque
lamar@ucar.edu

CESM Model Releases

- Configurations in multiple categories
  - Scientifically vetted (with runs/"assessment")
  - Functionally vetted (routine testing)
  - Development only (no testing; use at own risk)
- Webpage with "scientifically supported" compsets: http://www2.cesm.ucar.edu/models/scientifically-supported
- Bulletin board (DiscussCESM Forum) for updates on releases and other model support – encourage subscription

Jean-François Lamarque
lamar@ucar.edu

Future Directions and Remaining Challenges

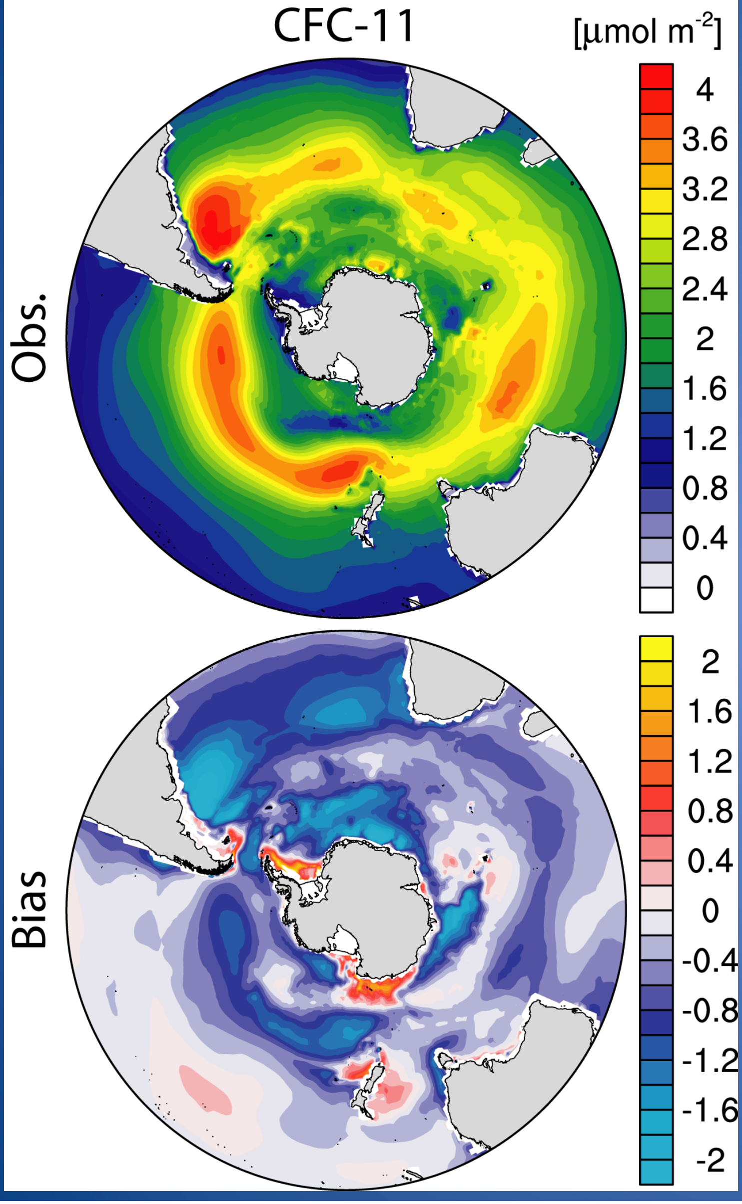
A need for continued scientific understanding and model improvements

Investigation of small-scale phenomena

Incorporation of New Capabilities

Jean-François La
lamar@ucar.

Bias Example: Southern Ocean Ventilation



CESM1-CAM5 20th Century Simulation

Comparisons of simulated and observed ocean CFCs

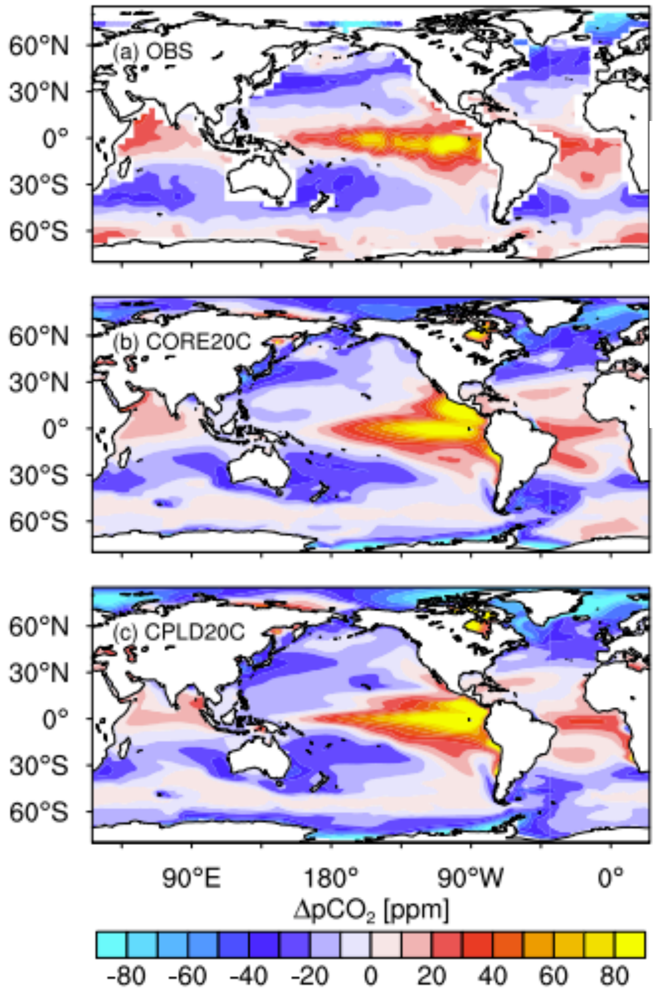
Indicate too little Southern Ocean uptake

Has implications for simulated ocean heat and carbon uptake

Courtesy of Matt Long

Jean-François Lamarque
lamar@ucar.edu

Air-sea exchange of CO_2



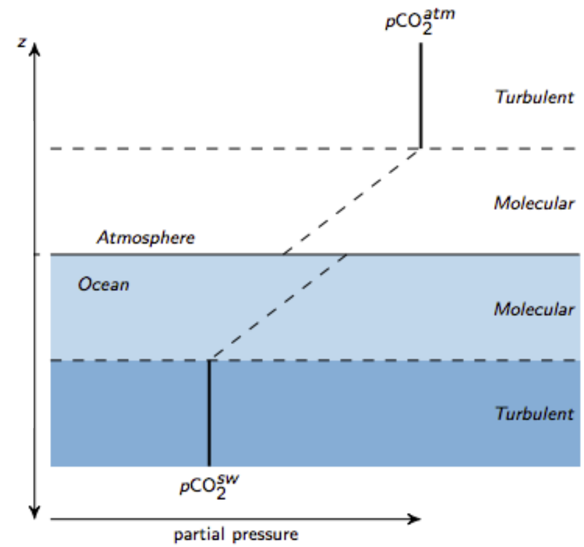
Obs: Takahashi et al. 2009

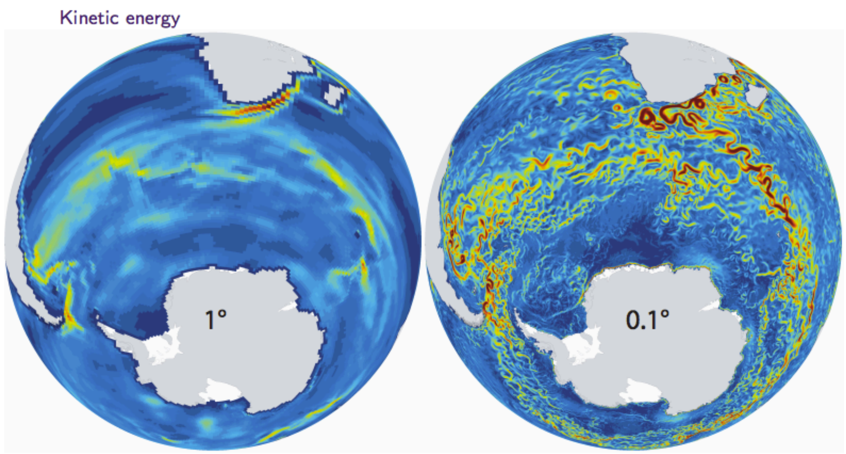
Air-sea exchange:

$$J_{co_2} = (1 - A_{ice})k\alpha\left(pCO_2^{sw} - pCO_2^{atm}\right) = (1 - A_{ice})k\alpha\Delta pCO_2$$

where
k = piston velocity (empirical), and
α = solubility, $f(T, S)$

negative := ocean uptake



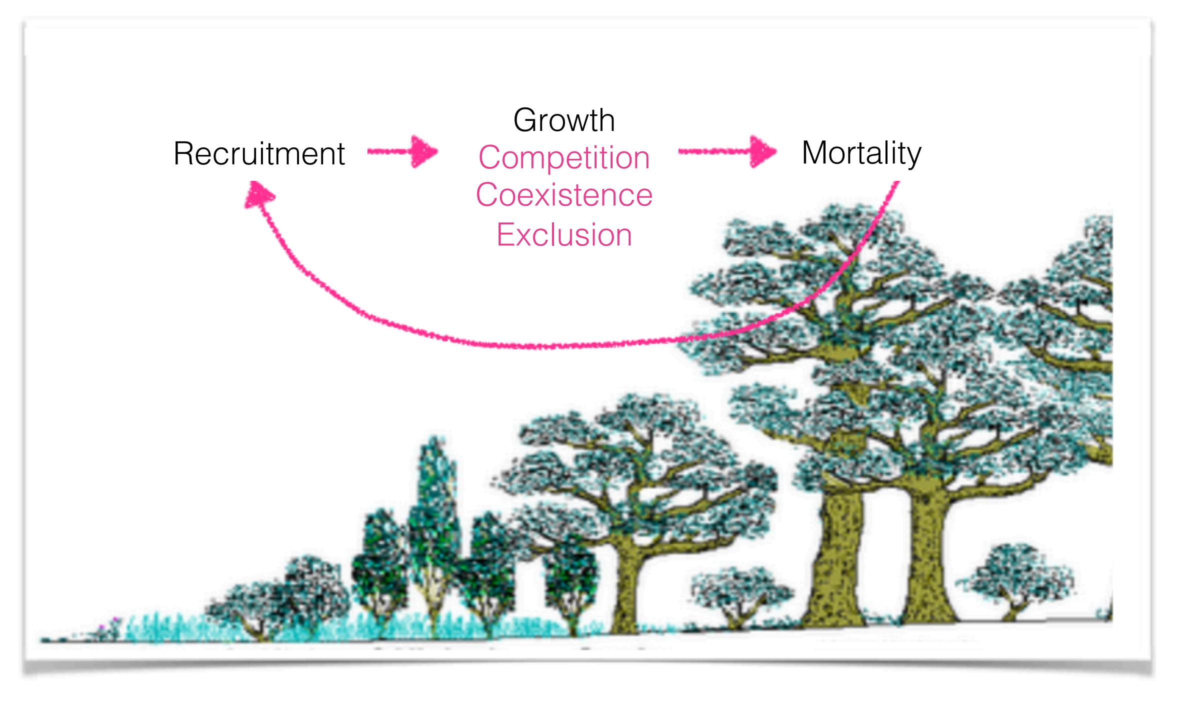


Slide courtesy of M. Long

Jean-François Lamarque
lamar@ucar.edu

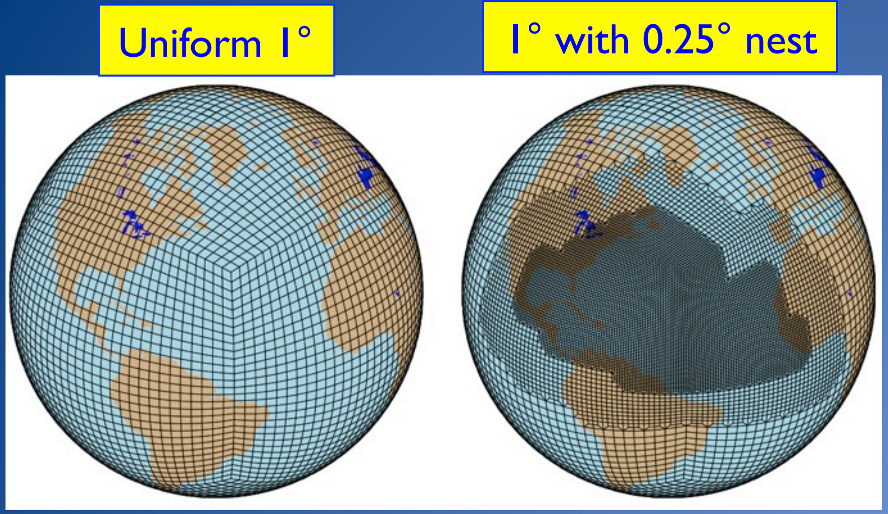
CLM(ED) ecosystem demography

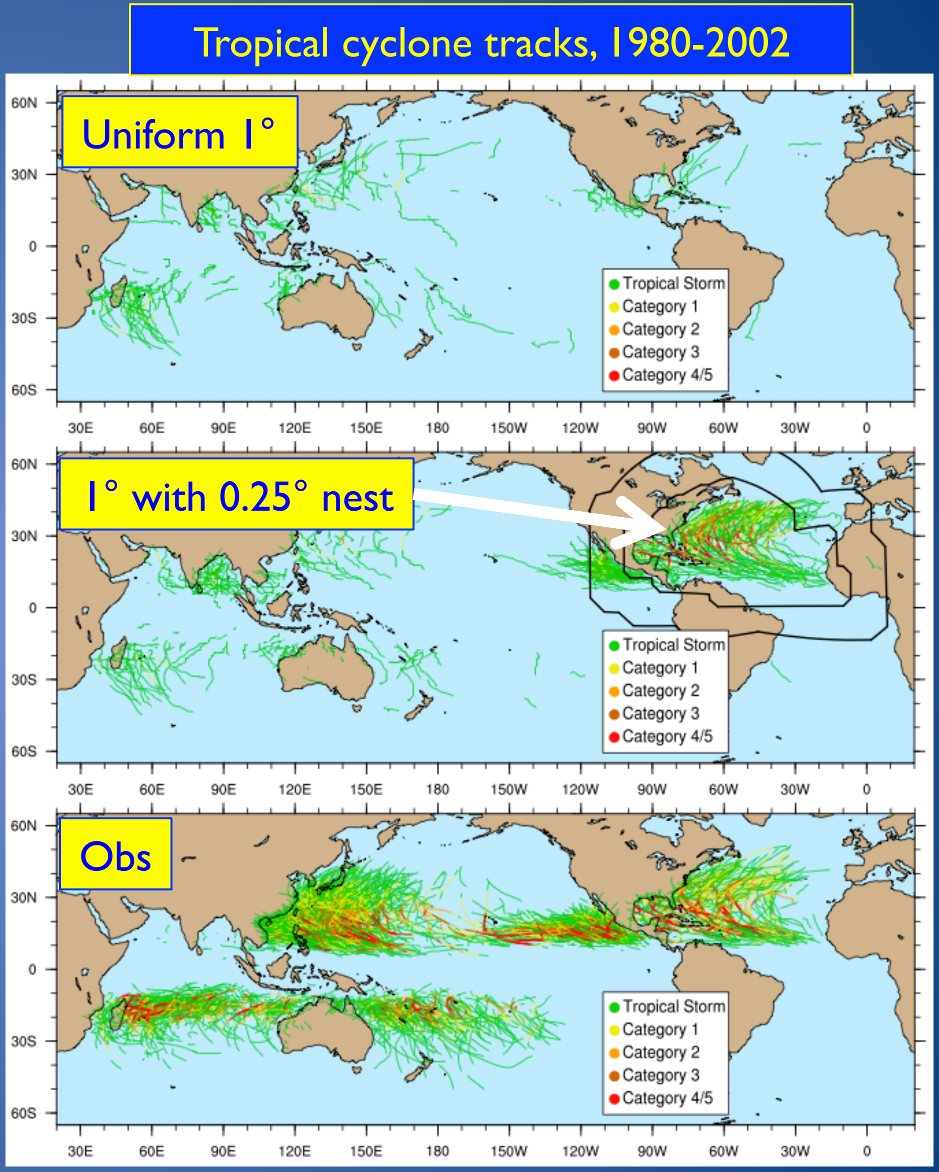
- Next-generation biogeophysical and biogeochemical core for the CLM
  - Landscape structured according to disturbance history.
  - Height resolved competition between plants for light.
- Plant distribution emerges from plant functional properties.



Jean-François Lamarque
lamar@ucar.edu

High resolution: Regionally refined grids





- Variable-resolution CAM-SE (CAM5) simulations -> dramatically improved tropical cyclone representation at regional scale
- 0.25° nest produces realistic storm counts/ intensities in North Atlantic at 1/6th compute cost of globally-uniform 0.25° mesh
- Challenges: Streamlining generation of new grids; Ensuring that physics parameterizations work across resolutions

Slide from Colin Zarzycki

Jean-François Lamarque
lamar@ucar.edu

In summary:

- CESM is a flexible, extensible and well supported community tool
- CESM applications continue to increase
- Numerous CESM simulations are currently available through CMIP5 for analysis; additional community runs becoming available
- Model developments and improvements are ongoing

NCAR is sponsored by the National Science Foundation

Jean-François Lamarque
lamar@ucar.edu

Questions? Comments?

Purple: precipitation

Slide courtesy of R. Knutti and O. Stebler

Jean-François Lamarque
lamar@ucar.edu