Introduction to Earth System Modelling

3rd ClimEd Online Training on “Digital Tools and Datasets for Climate Change Education”

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Model

- What is a model?
  - A mathematical model is a description of a system using mathematical concepts and language (wikipedia)
- Why we use a model?
  - Make it possible to quantitatively study systems or processes which are difficult or impossible to monitor or measure
- How to make a model?
  - Obtain (mathematical) formulations from the studied system and processes
  - Get input data from measurement or generated data
  - Run the model
  - Analyse output and evaluate the model
  - Debug, calibrate, tune
  - Iterate to get a better model until satisfied
  - Use the model and interpret the model results

Model types

	Empirical (statistical)	Process-based
Based on	empirical measurements	theory or mechanism
Fit for	current datasets	current and extrapolated datasets
Difficulty	easy	hard
Other features	black box	clear and ideal
Examples	predict rainfall by cloud cover	predict species concentrations from chemical reaction equations

In many cases, these two types of models are mixed.

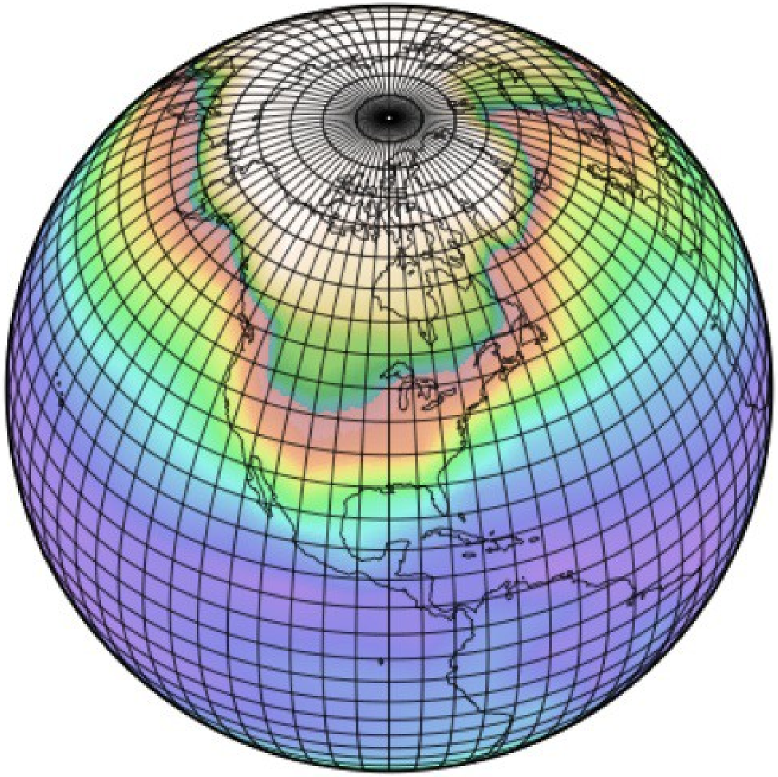
Numerical Model

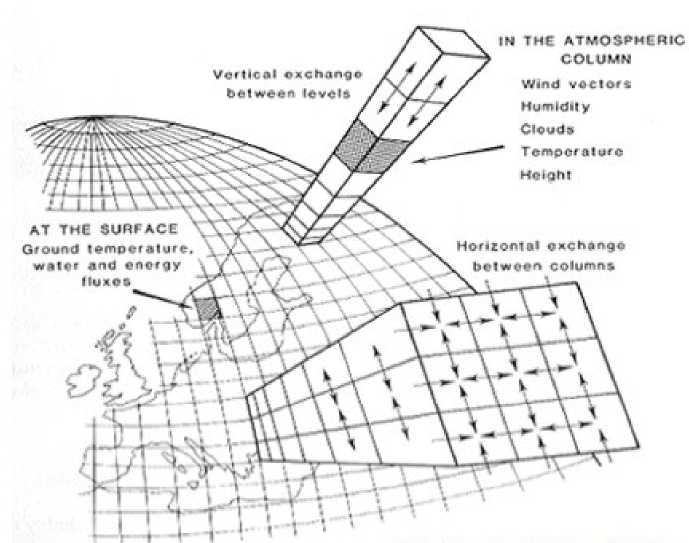
- A numerical model is a combination of a large number of mathematical equations that depends upon computers to find an approximate solution to the underlying physical problem (The Design and Manufacture of Medical Devices, 2012)
- Shortly, the model solved or run by computers (maybe you can also do it by hand)
- Characteristics
  - Continuous → discrete
  - Mathematical equations → computer languages
  - The calculation is usually impossible to do with hands

Numerical Model

- Discretizing
- Program code

Grid Point Models

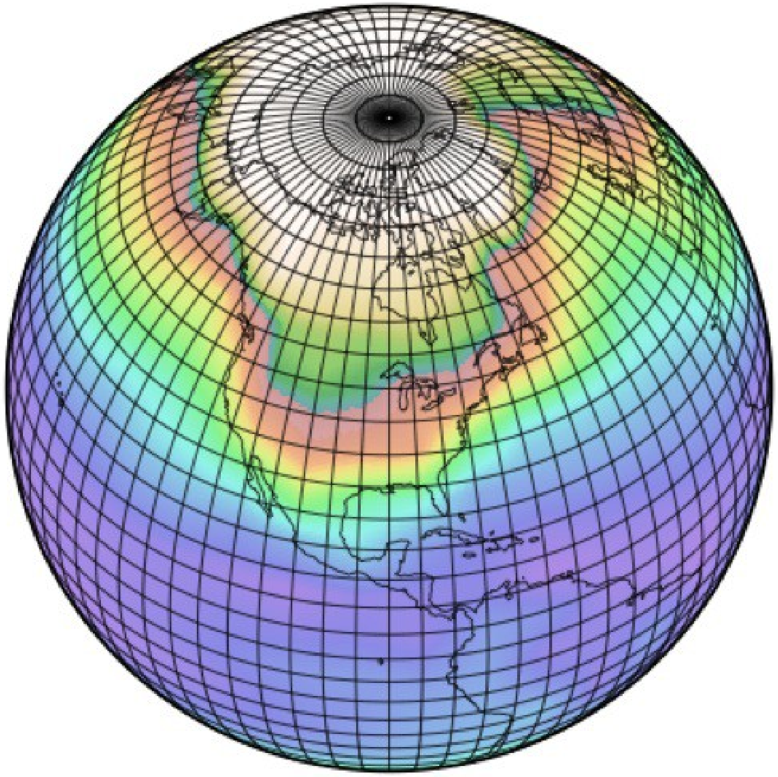




(Henderson-Sellers, 1985)

- Discretizing
- Program code

Grid Point Models



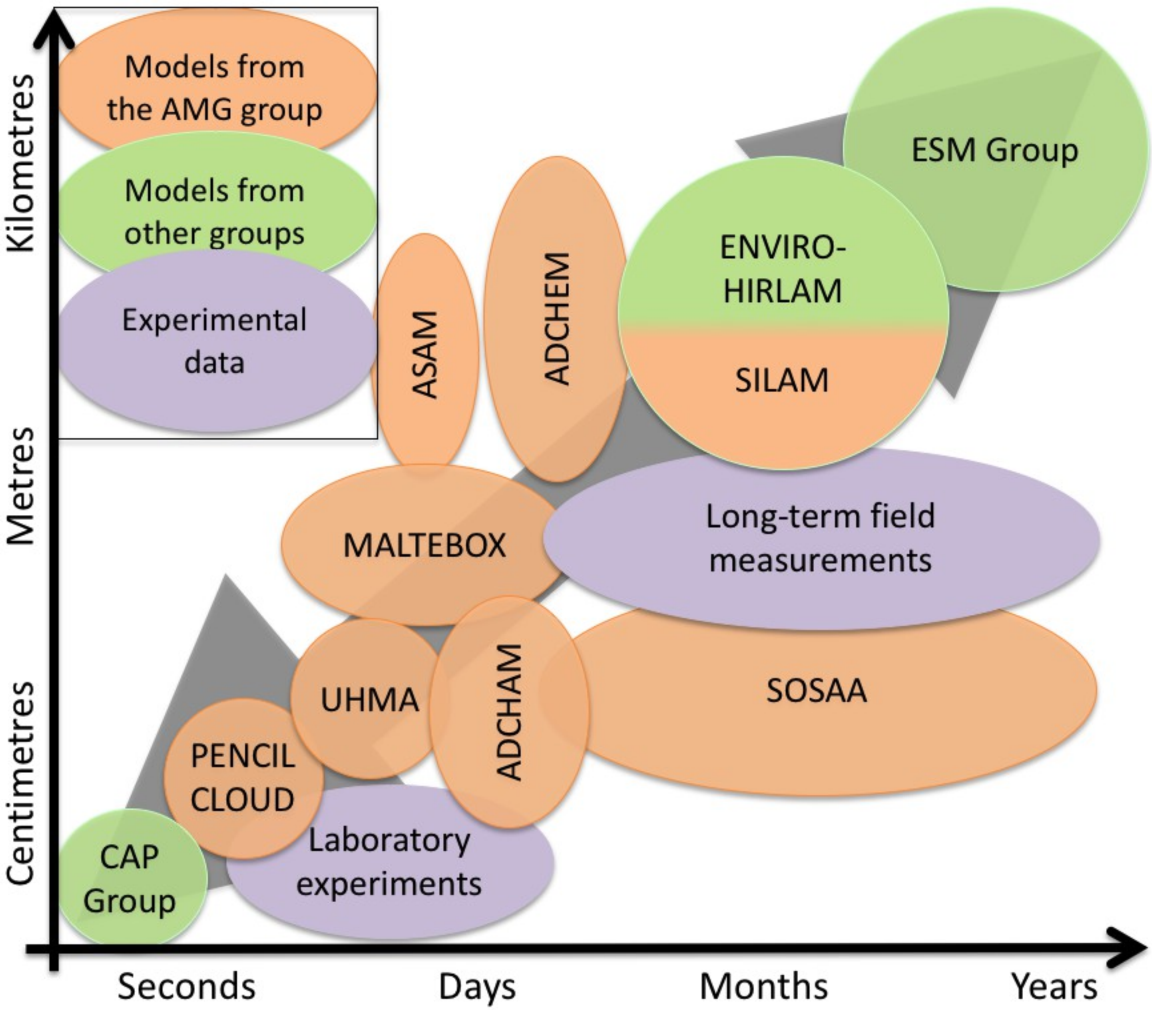
- Discretizing
- Program code

```
                ! apply convection matrix:
                do l=1,lmax_conv
#ifdef slopes
                   srzm(l)=conv1(l,l)*srzm(l)    !rzm is directly calculated
                   srxm(l)=conv1(l,l)*srxm(l) !no convection -> no multip.  !WP-Emma van der Veen
                   srym(l)=conv1(l,l)*srym(l) !no convection -> no multip.  !WP-Emma van der Veen
#ifdef secmom
                   srzzm(l)=conv1(l,l)*srzzm(l)    !rzzm is directly calculated
#endif
#endif
                   do k=1,lmax_conv

                      ! species dependent removal....
#ifndef without_wet_deposition
                      scavf = min( lbdcv(l,k)*cvsfac(n), conv1(l,k) )
#else
                      scavf = 0.0
#endif

                      ! for budgets:
                      zcnvd (l) = zcnvd (l) +  conv1(l,k)         * srm(k)
                      zwetrm(l) = zwetrm(l) +             scavf  * srm(k)  ! loss is positive

                      ! store new concentrations in zrm/zrxm/etc
                      !  using old concentrations in srm/srxm/etc
                      zrm(l)     = zrm(l)     + (conv1(l,k)-scavf) * srm(k)
#ifdef slopes
!WP-vdV!              zrxm (l) = zrxm (l) + (conv1(l,k)-scavf) * srxm(k)
!WP-vdV!              zrym (l) = zrym (l) + (conv1(l,k)-scavf) * srym(k)
#ifdef secmom
                      zrxxm(l) = zrxxm(l) + (conv1(l,k)-scavf) * srxxm(k)
                      zrxym(l) = zrxym(l) + (conv1(l,k)-scavf) * srxym(k)
                      zrxzm(l) = zrxzm(l) + (conv1(l,k)-scavf) * srxzm(k)
                      zryym(l) = zryym(l) + (conv1(l,k)-scavf) * sryym(k)
                      zryzm(l) = zryzm(l) + (conv1(l,k)-scavf) * sryzm(k)
#endif
#endif

                   end do    !k

                   ! substract original tracer mass
                   ! VH, TvN (2007-11-16)
                   zcnvd(l)=zcnvd(l)-srm(l)

                end do      !l

                ! restore concentrations:
                do l=1,lmax_conv
                   rm(i,j,l,n)=zrm(l)
#ifdef slopes
!WP-vdV!                   rxm(i,j,l,n)=zrxm(l)
!WP-vdV!                   rym(i,j,l,n)=zrym(l)
                   rxm(i,j,l,n)=srxm(l) !VDV
                   rym(i,j,l,n)=srym(l) !VDv
                   rzm(i,j,l,n)=srzm(l)
#ifdef secmom
                   rxxm(i,j,l,n)=zrxxm(l)
                   rxym(i,j,l,n)=zrxym(l)
                   rxzm(i,j,l,n)=srxzm(l)
                   ryym(i,j,l,n)=zryym(l)
                   ryzm(i,j,l,n)=zryzm(l)
                   rzzm(i,j,l,n)=srzzm(l)
#endif
#endif

                end do
```

Model Uncertainties

- Is model accurate?
- Unavoidable simplifications, so not all the processes can be included
- The mathematical formulations can not perfectly describe the phenomena in the real world (the data you use to develop the model also have uncertainties)
- Calculation can induce errors or uncertainties (e.g., 4.556 → 4.6)
- Numerical errors
  - From discretization (continuous mathematical equations compared to that in a code)
  - Finite precision (similar to calculation error) of computer

Spatial-Temporal Model Scales

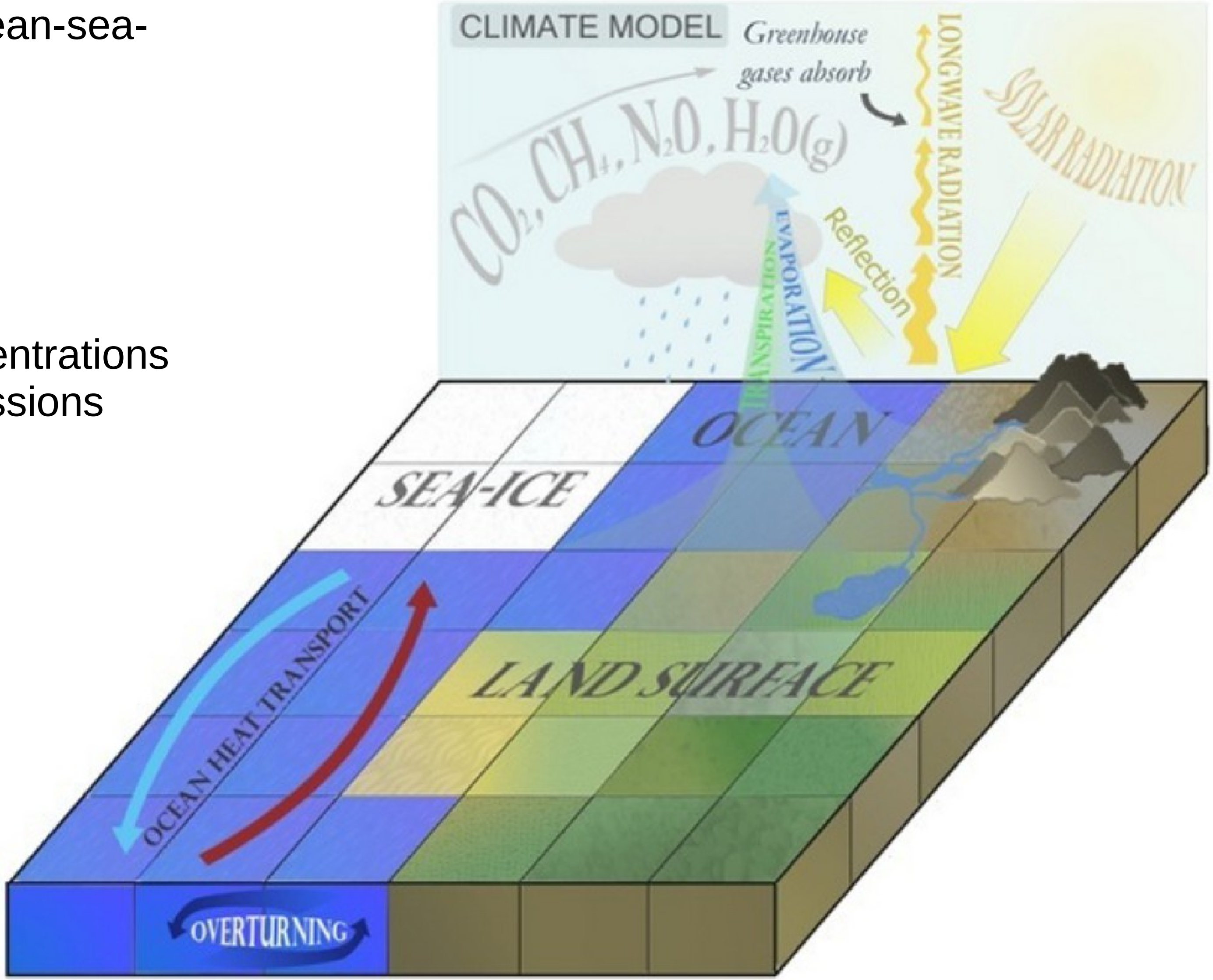


- Global model
  - ESM (EC-Earth)
- Regional model
  - ENVIRO-HIRLAM, SILAM
- 1D chemical transport model
  - SOSAA
- 2D Lagrangian model
  - ADCHEM
- Box model
  - MALTEBOX, ADCHAM, UHMA
- Large-Eddy Simulation model
  - ASAM
- Direct Numerical Simulation model
  - PENCIL CLOUD

Global Climate Models (GCMs)

Heavens et al., 2013, Nature Education Knowledge

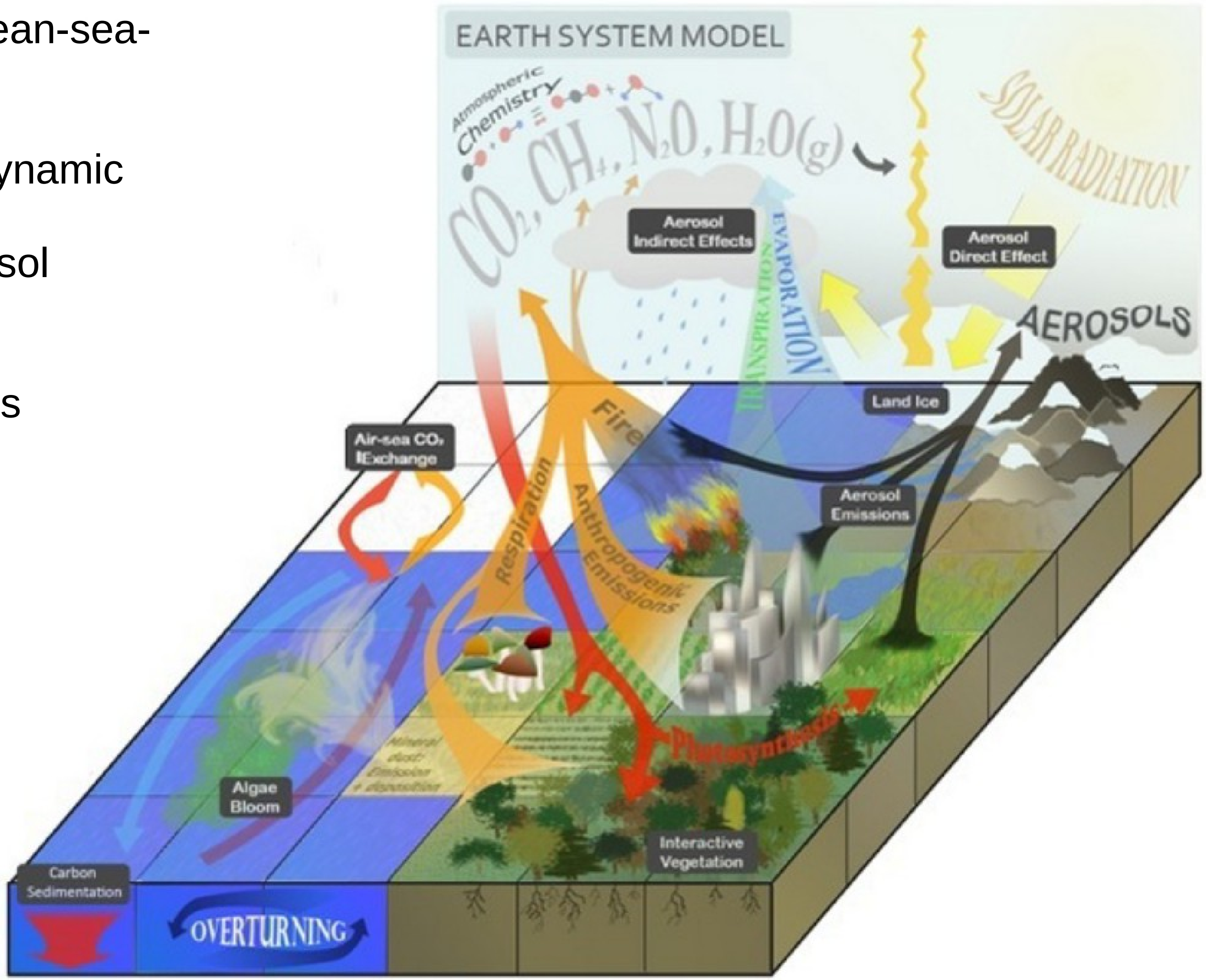
- Coupled atmosphere-ocean-sea-ice-land models
- Predicted
  - Atmospheric dynamics (meteorology)
  - Ocean currents
- Prescribed
  - Greenhouse gas concentrations
  - Aerosol precursor emissions
  - Vegetation prescribed



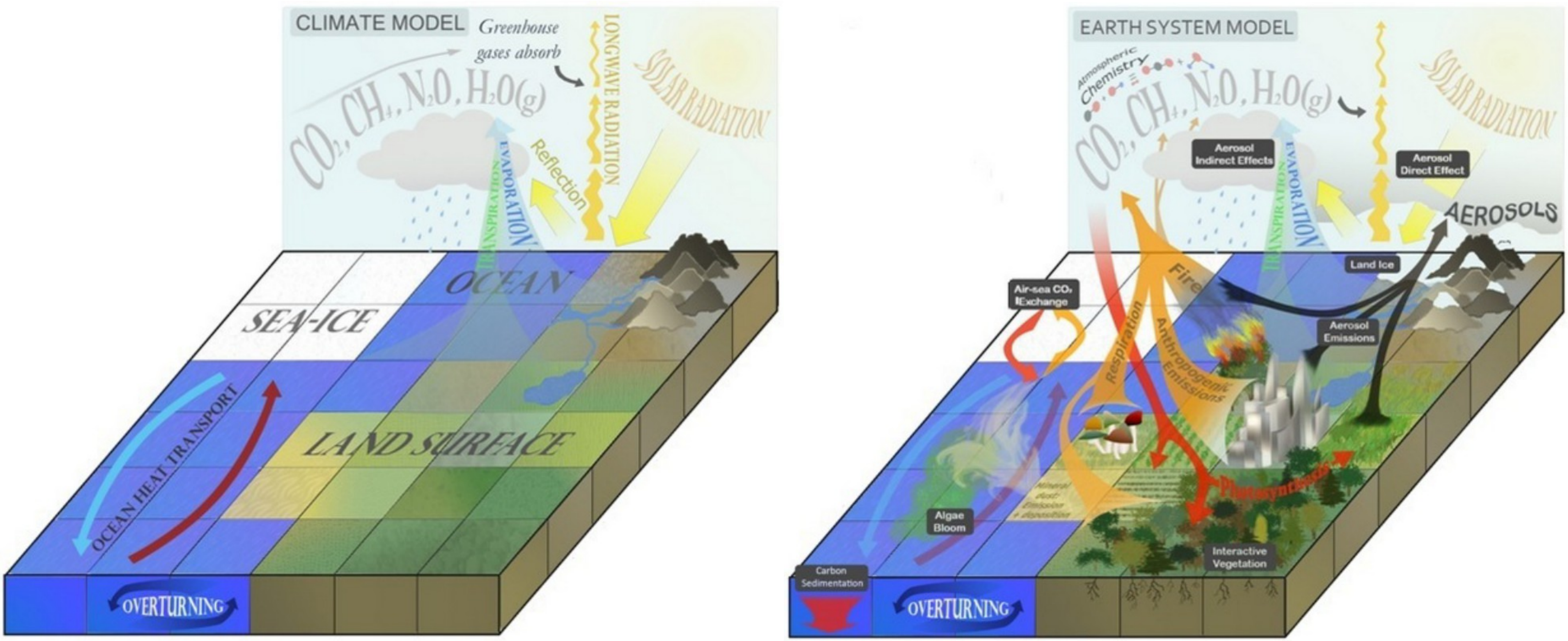
Earth System Models (ESMs)

Heavens et al., 2013, Nature Education Knowledge

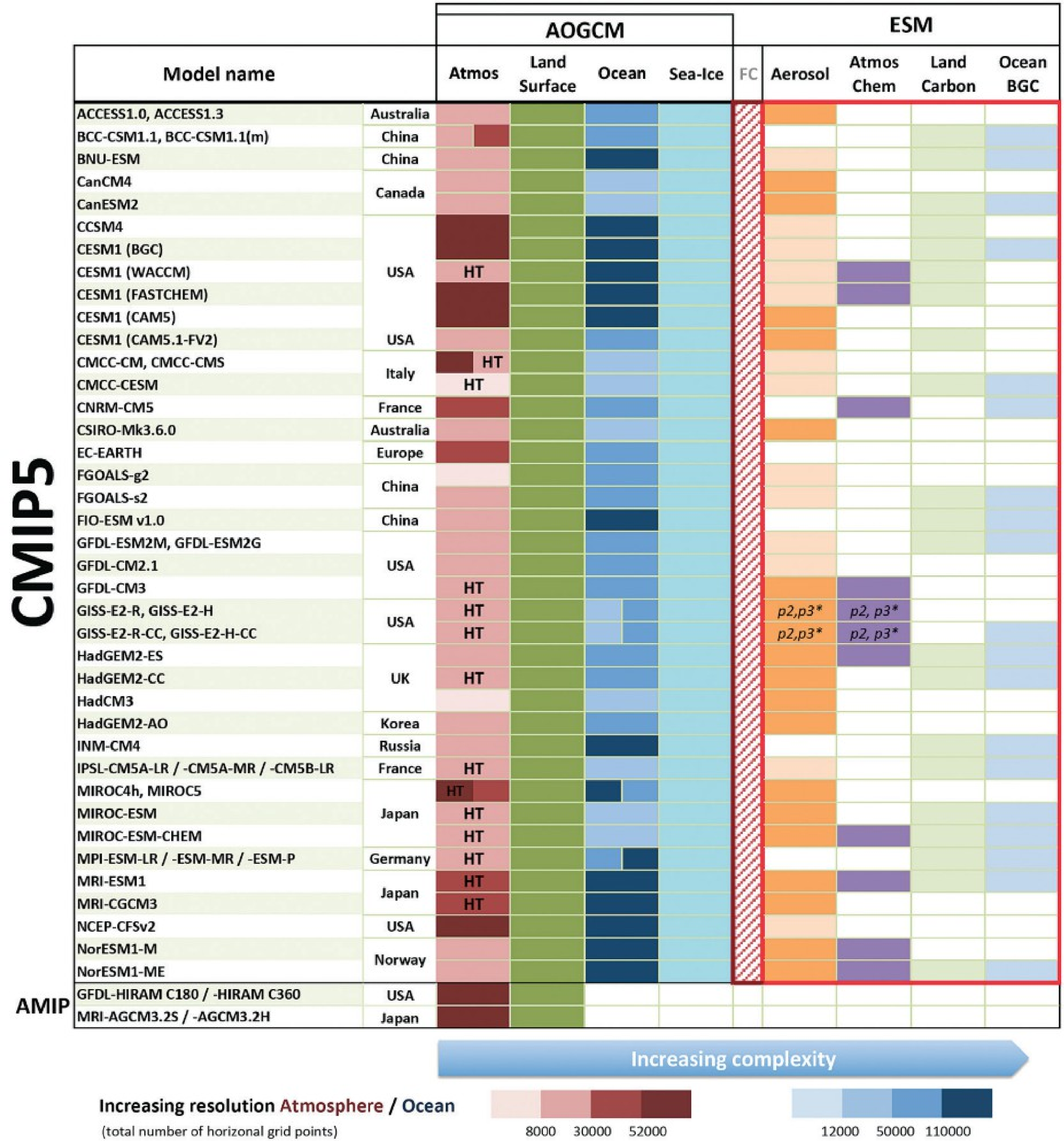
- Coupled atmosphere-ocean-sea-ice-land models
- Interactive Carbon Cycle
- Interactive Vegetation (dynamic vegetation model)
- Interactive biogenic aerosol precursor emissions
- Chemical reactions
- Aerosol-cloud interactions
- ...



GCMs and ESMs



Heavens et al., 2013, Nature Education Knowledge

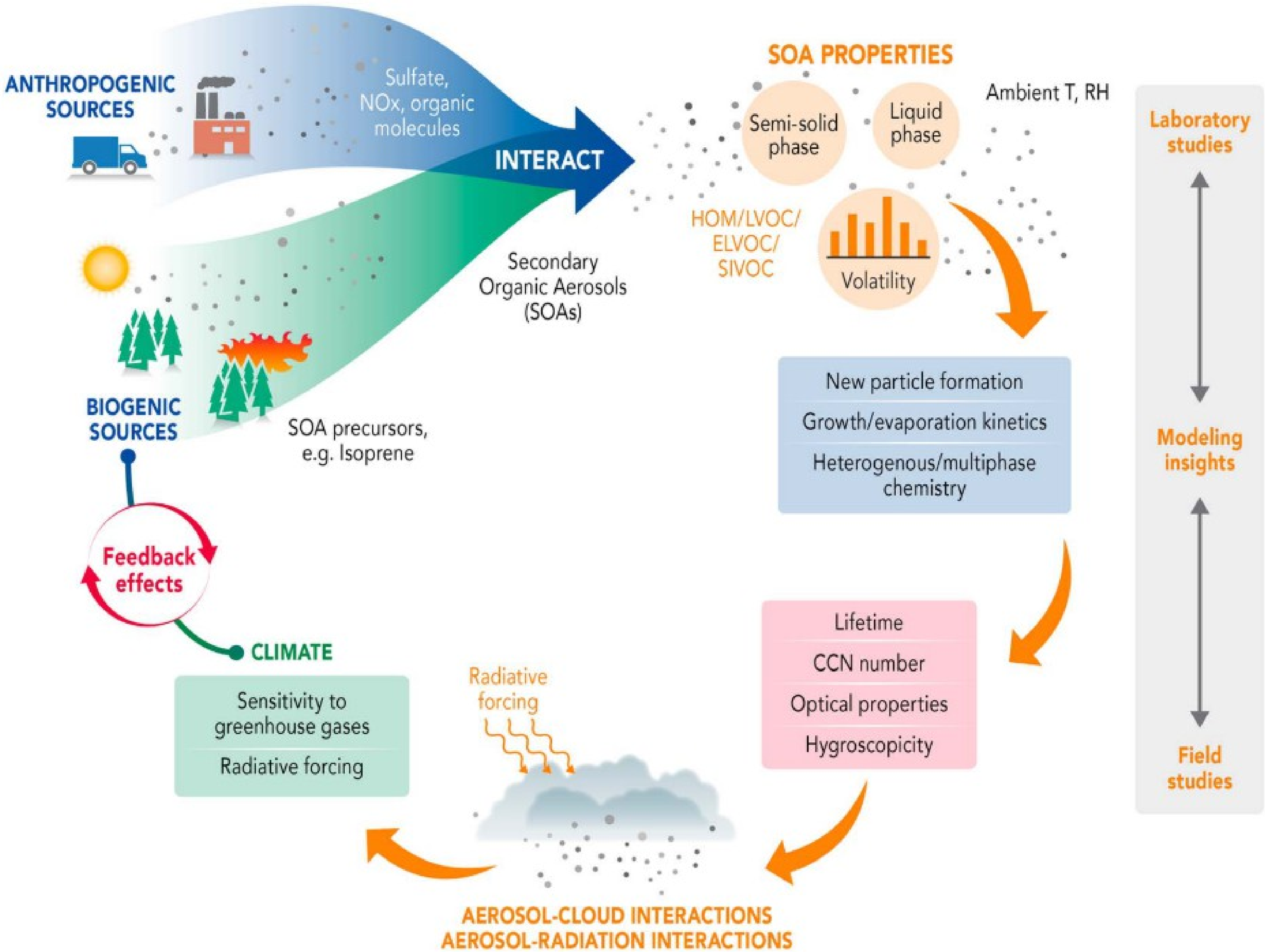


INAR

- Atmosphere-Ocean General Circulation Models (AOGCMs) and Earth System Models (ESMs) in CMIP5.
- HT: High-Top atmosphere, which has a fully resolved stratosphere with a model top above the stratopause.
- AMIP: models with atmosphere and land surface only, using observed sea surface temperature and sea ice extent.
- A component is coloured when it includes at least a physically based prognostic equation and at least a two-way coupling with another component, allowing climate feedbacks.
- For aerosols, lighter shading means 'semi-interactive' and darker shading means 'fully interactive'.
- FC: artificial flux correction (FC), not used in CMIP5

IPCC AR5, 2013, Figure 9.1

Climate feedbacks mediated by SOA



SOA: secondary organic aerosol

VOC: volatile organic compound

HOM/LVOC/ ELVOC/SIVOC: usually have low volatility and easy to condense onto existing particles

Shrivastava et al., 2017, RG

Emission Databases

- **EDGAR** (The Emission Database for Global Atmospheric Research)
  - https://edgar.jrc.ec.europa.eu/
  - CH_4, CO_2, N_2O, BC, CO, NMVOC, NO_x, SO_2, …
- **ECLIPSE** (**E**valuating the **CL**imate and Air Quality **I**m**P**acts of **S**hort-liv**E**d Pollutants)
  - http://eclipse.nilu.no/
  - SO_2, NO_x, NH_3, NMVOC, BC, OC, OM, PM2.5, PM10, CO, CH_4, ...
- **CEDS** (Community Emissions Data System) (Hoesly et al., 2018, GMD): based mostly on EDGAR v4.2 and ECLIPSE datasets, and used for CMIP6 input
  - http://www.globalchange.umd.edu/ceds/
  - CO, CH_4, NH_3, NO_x, SO_2, NMVOCs, BC, OC, CO_2, …
- **CAMS** (Copernicus Atmosphere Monitoring Service): based on national reported emissions, EDGAR, ECLIPSE, CEDS
  - https://atmosphere.copernicus.eu/anthropogenic-and-natural-emissions
- **GFED** (Global Fire Emission Database) (van Marle et al., 2017, GMD): biomass burning emissions
  - https://www.globalfiredata.org/index.html
  - BC, OC, CH_4, CO, SO_2, …
- **ECCAD** (Emissions of atmospheric Compounds and Compilation of Ancillary Data): website to download nearly all the emission datasets
  - https://eccad3.sedoo.fr/

BVOC (biogenic volatile organic compound) emissions

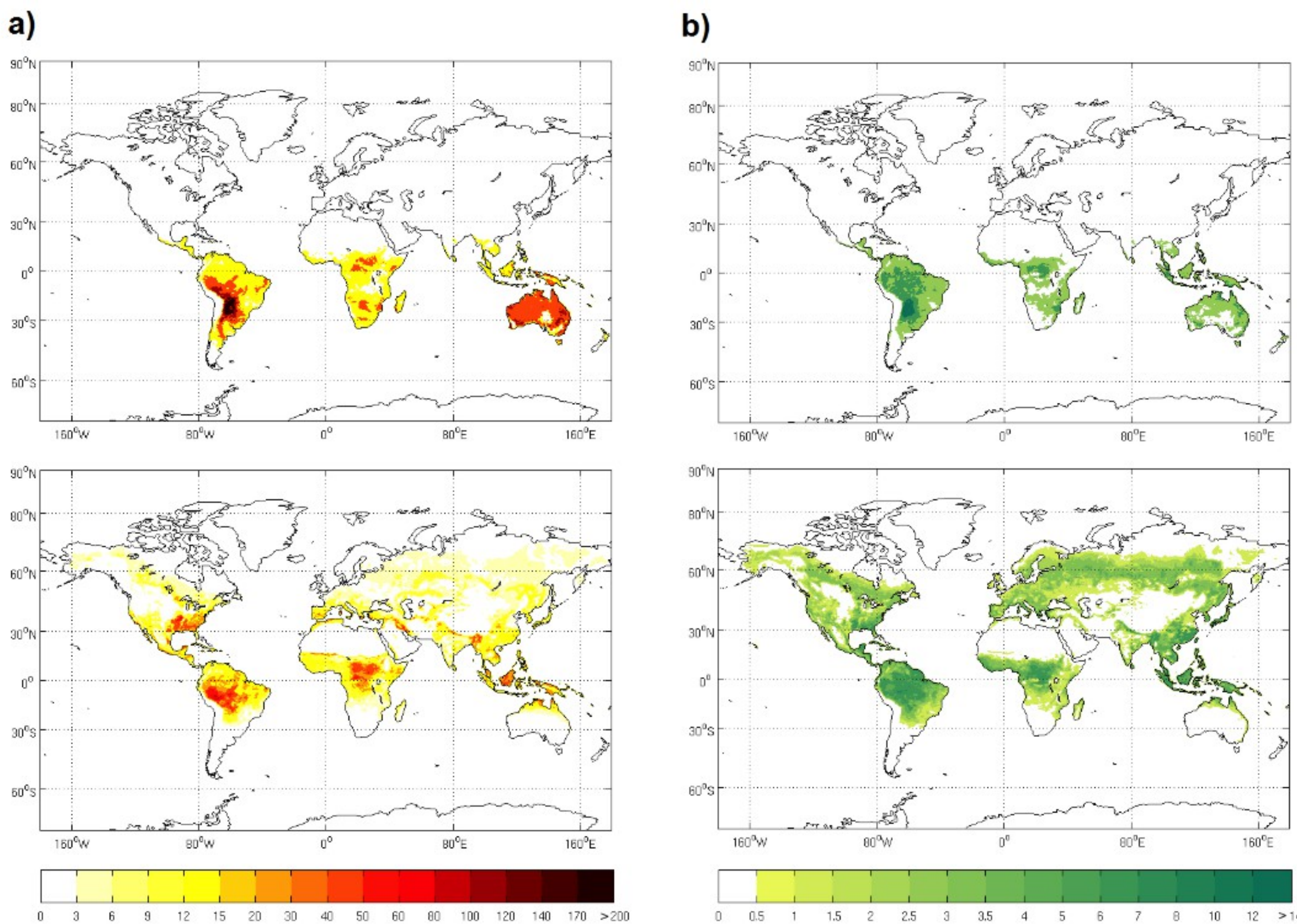


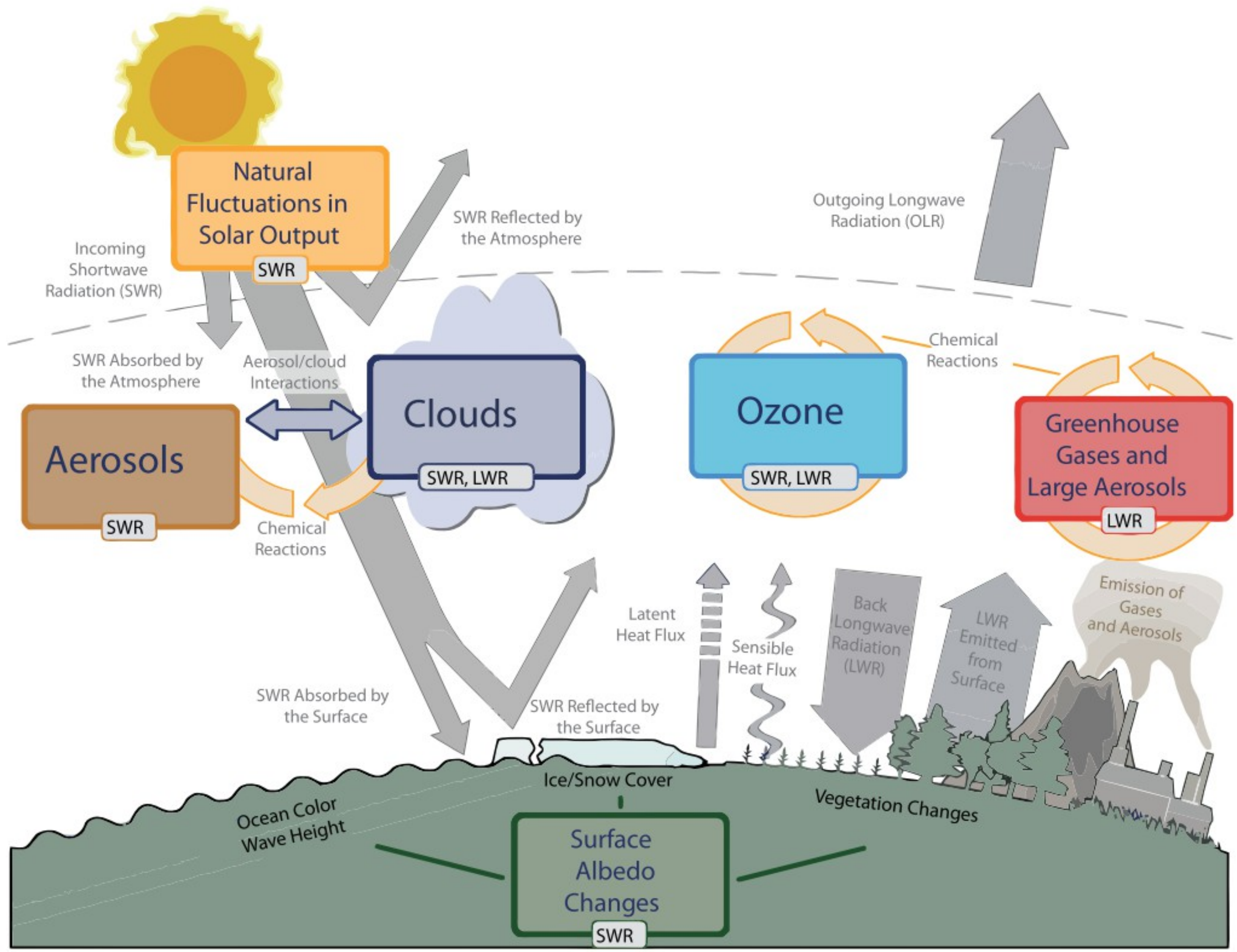
Figure 2. Spatial distribution of monthly mean emissions of **(a)** isoprene, **(b)** monoterpenes, (mg m^{-2} day^{-1}) for January (top) and July (bottom) averaged over the modelled period 1980–2010 calculated by the MEGAN model.

Mean annual total BVOC emission of 760 Tg (C) yr−1

isoprene: 70%
monoterpenes: 11%
methanol: 6%
acetone: 3%
sesquiterpenes: 2.5%
other BVOCs: each contributing less than 2%

Sindelarova et al., 2014, ACP

Drivers of Climate Systems



External drivers:

- Solar cycle
- Human activities
  - Emissions
  - Land use
- Volcano eruptions

IPCC AR5, 2013, Introduction, Figure 1.1

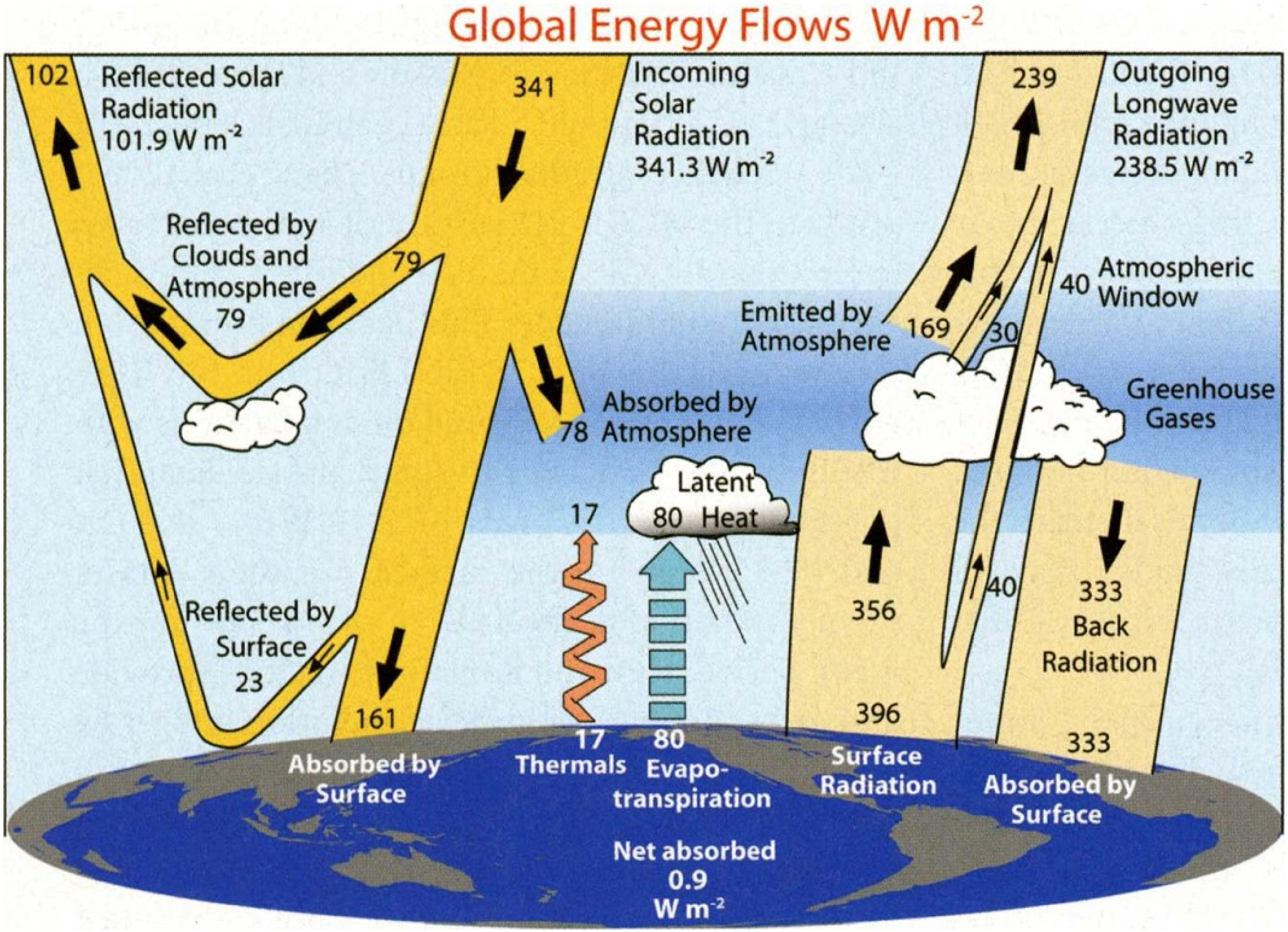
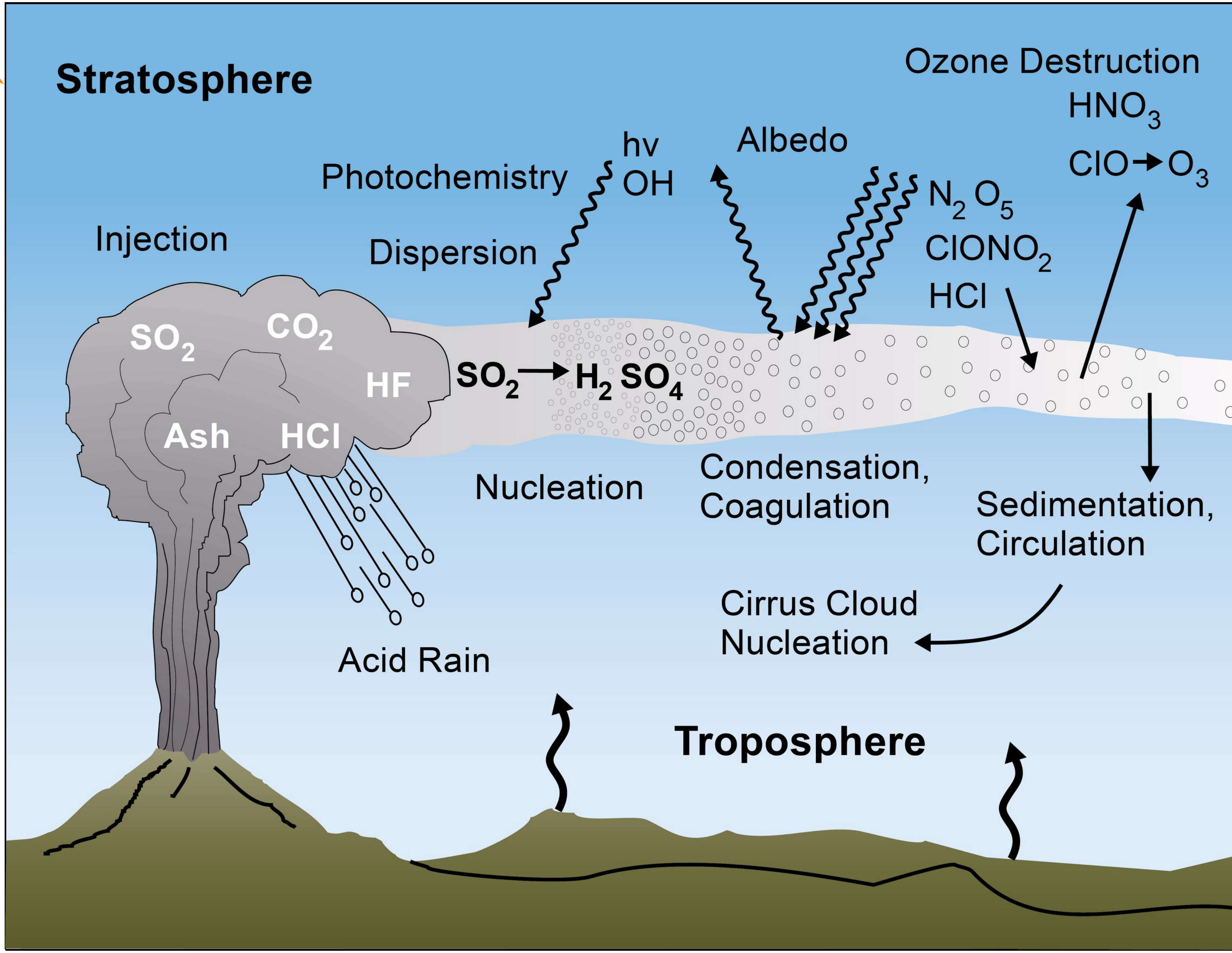


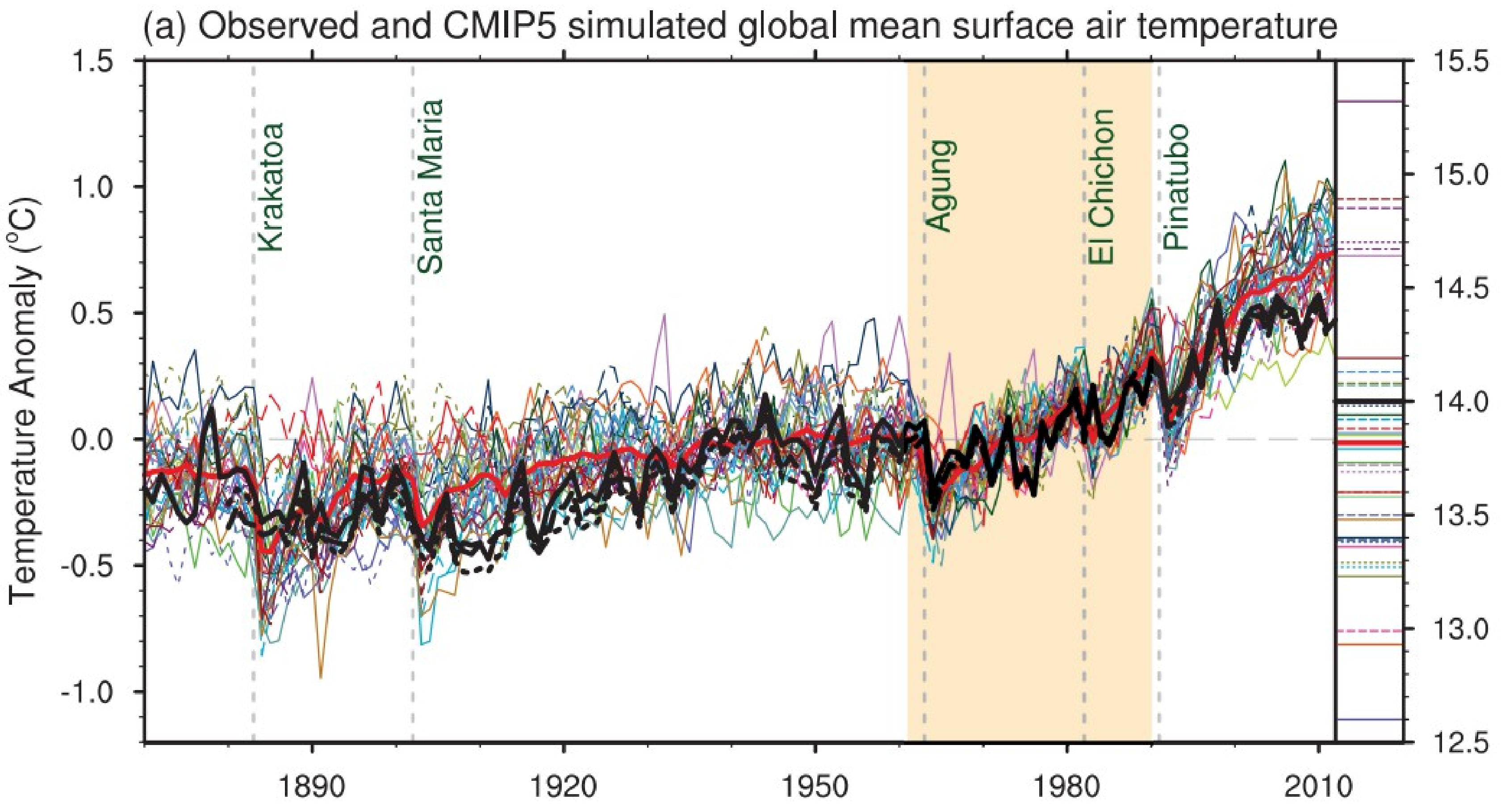
Fig. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (W m^{-2}). The broad arrows indicate the schematic flow of energy in proportion to their importance.

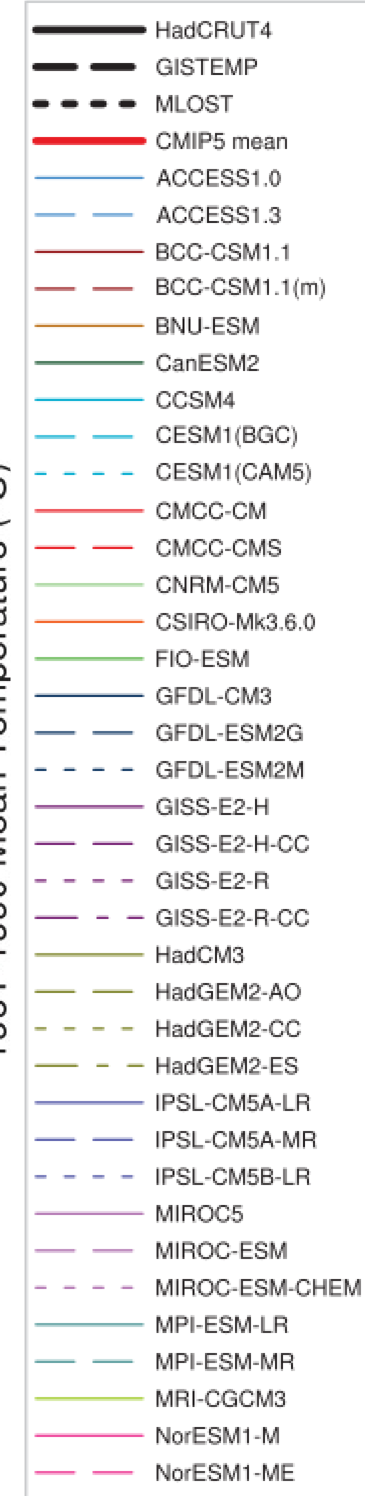
Trenberth et al., 2009, BAMS



https://volcanoes.usgs.gov/vhp/gas_climate.html; McGee et al., 1997

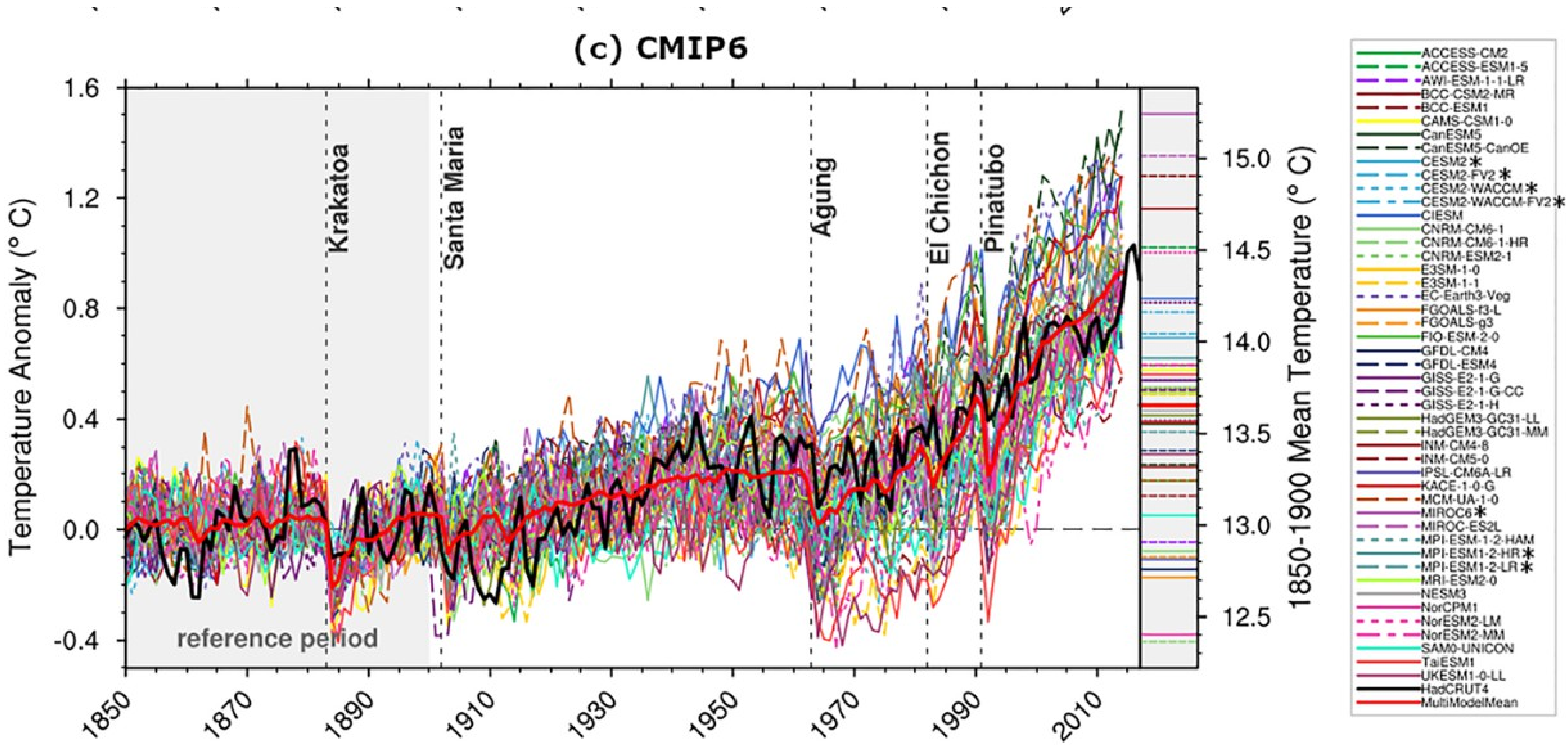
Cooling effects of volcano eruption





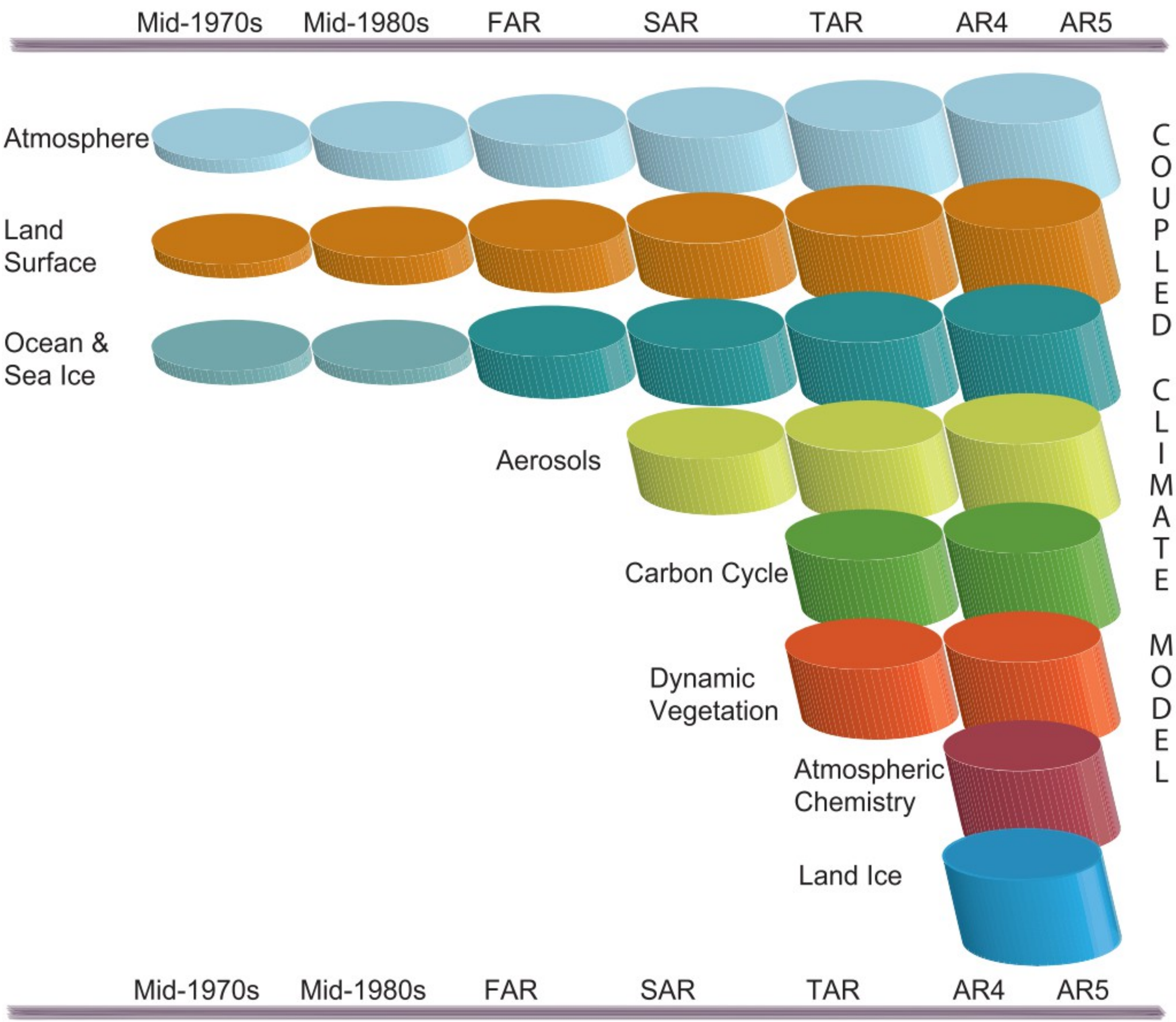
Major volcanic eruptions are marked by vertical dashed lines.

IPCC AR5, 2013, Figure 9.8



Bock et al., 2020, JGRA

Model Components



Development of climate models over the past decades

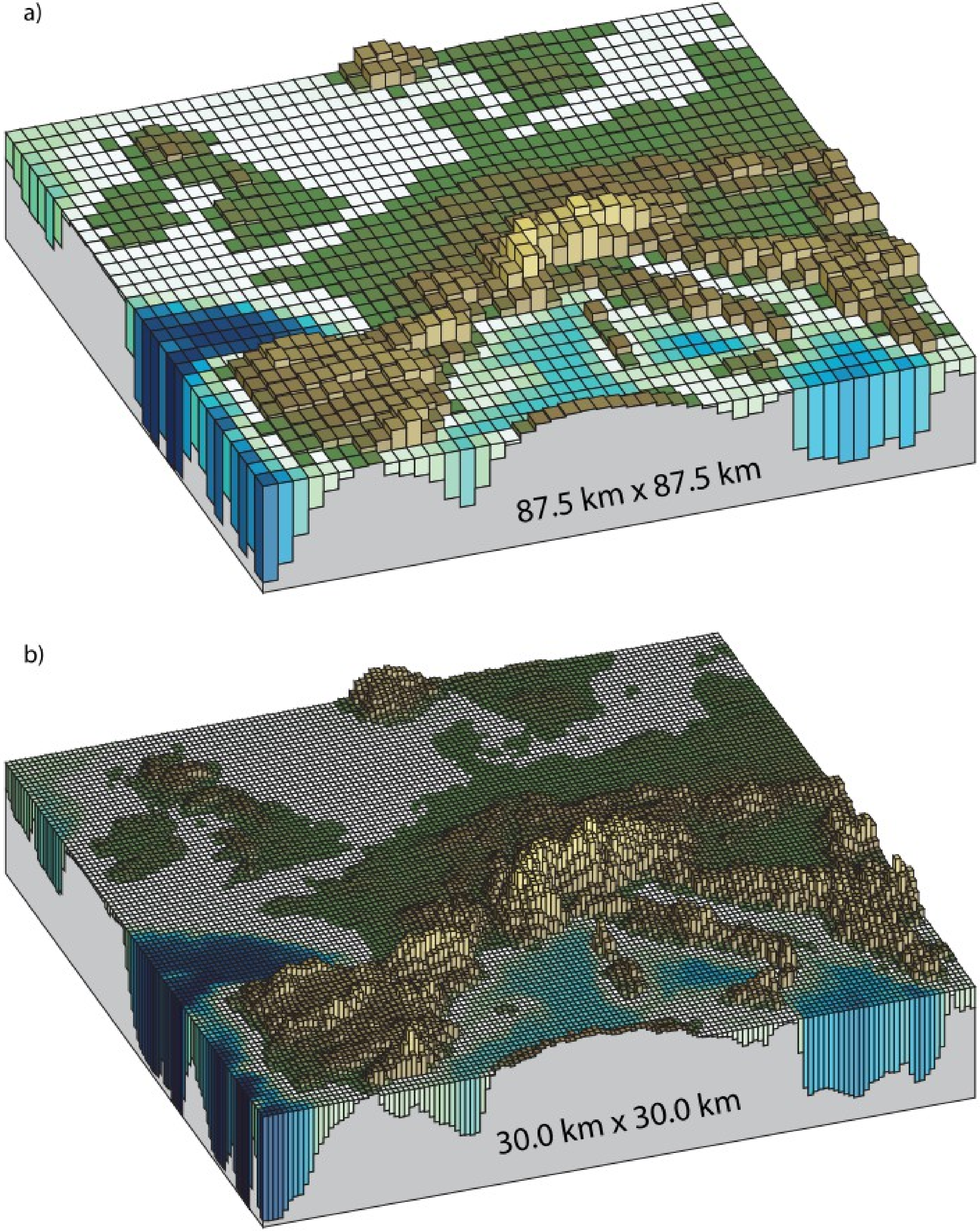
Horizontal and vertical resolution increased:

1970s: T21L9 (~ 500 km horizontal grid, 9 levels)

IPCC 2013, CMIP5: T95L95 (~ 100 km, 95 levels)

CMIP6: T255L91 (~ 50 km, 91 levels), even T799L91 (~ 25 km, 91 levels), even more (several km in the Global Cloud Resolving Models)

IPCC AR5, 2013, Introduction, Figure 1.13



Horizontal resolution comparison over Europe

IPCC AR5, 2013, Introduction, Figure 1.14

Why We Use ESMs?

- Why Earth System Models?
  - To capture the global interactions and feedbacks between the different subsystems (biosphere, atmosphere, cryosphere, hydrosphere)
  - To predict future climate and provide scientific foundation for policy makers
  - Deal with complex mechanisms and various challenges
  - Others?

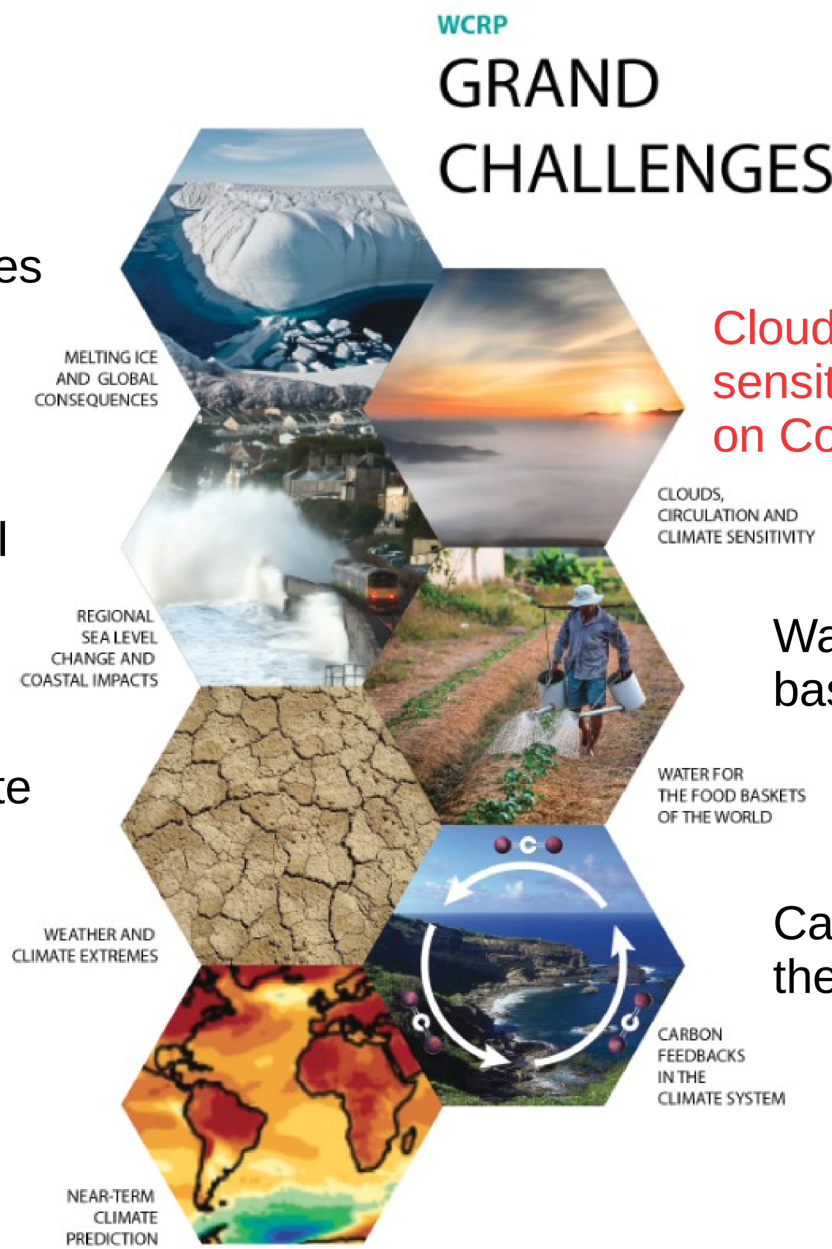
WCRP (World Climate Research Programme) Grand Challenges

Melting ice and global consequences

Regional sea level change and coastal impacts

Weather and climate extremes

Near-term climate prediction



Clouds, circulation and climate sensitivity - led by the Working Group on Coupled Modelling (WGCM)

Water of the food baskets of the world

Carbon feedbacks in the climate system

https://www.wcrp-climate.org/grand-challenges/grand-challenges-overview

About CMIP

- CMIP is short for Coupled Model Intercomparison Project
- CMIP is a project of the WCRP WGCM
- Since 1995, CMIP has coordinated climate model experiments involving multiple international modeling teams worldwide
- CMIP has led to a better understanding of past, present and future climate change and variability in a multi-model framework
- CMIP defines common experiment protocols, forcings and output
- CMIP has developed in phases, now CMIP6 is ongoing
- CMIP's central goal is to advance scientific understanding of the Earth system
- CMIP is not done for the IPCC, or run by the IPCC
- CMIP model simulations, constituting the current state-of-the-art of climate science formulated by the climate science community through WCRP, are assessed as part of the IPCC Climate Assessment Reports and various national assessments.

https://www.wcrp-climate.org/JSC38/presentations/CMIP6_JSC38_2017.pdf

IPCC and CMIPs

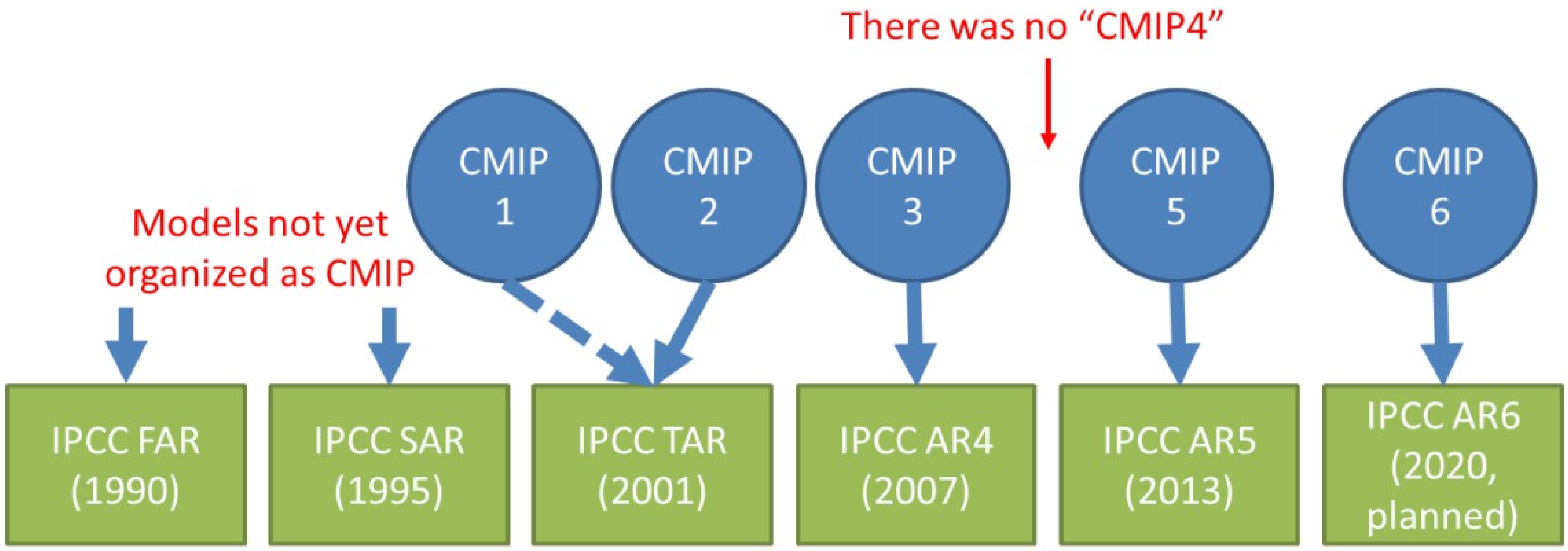
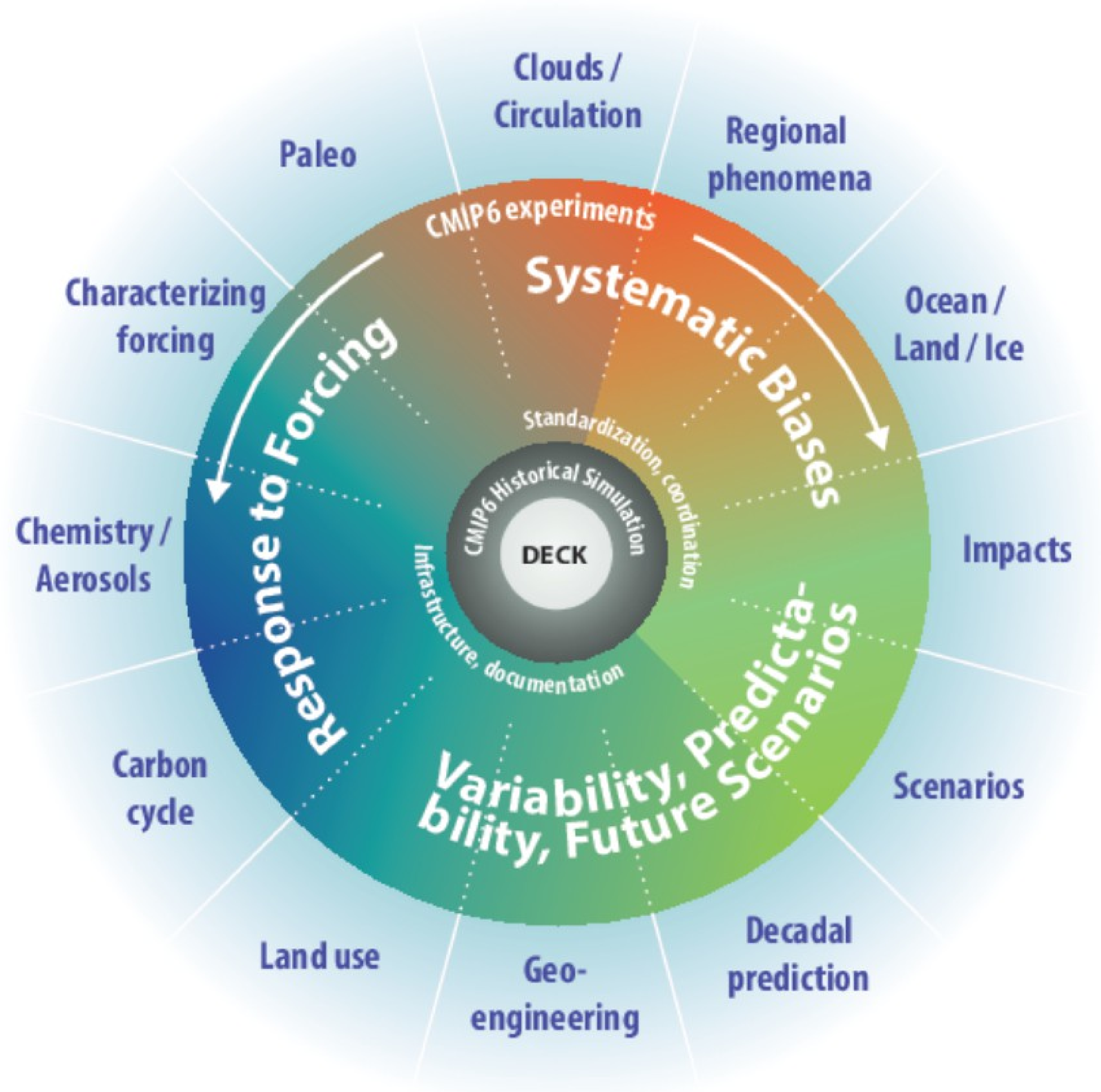


***Figure 1**. History of CMIPs and their contributions to IPCC Assessment Reports (ARs). Note that there was no CMIP4. As an initial attempt, CMIP1 only contains "control" (constant external conditions) simulations and contributed to the Third Assessment Report (TAR) through model evaluation together with CMIP2. The year given is the publication year of the Working Group I contribution to each Assessment Report.*

https://www.ipcc-data.org/docs/factsheets/TGICA_Fact_Sheet_CMIP5_data_provided_at_the_IPCC_DDC_Ver_1_2016.pdf

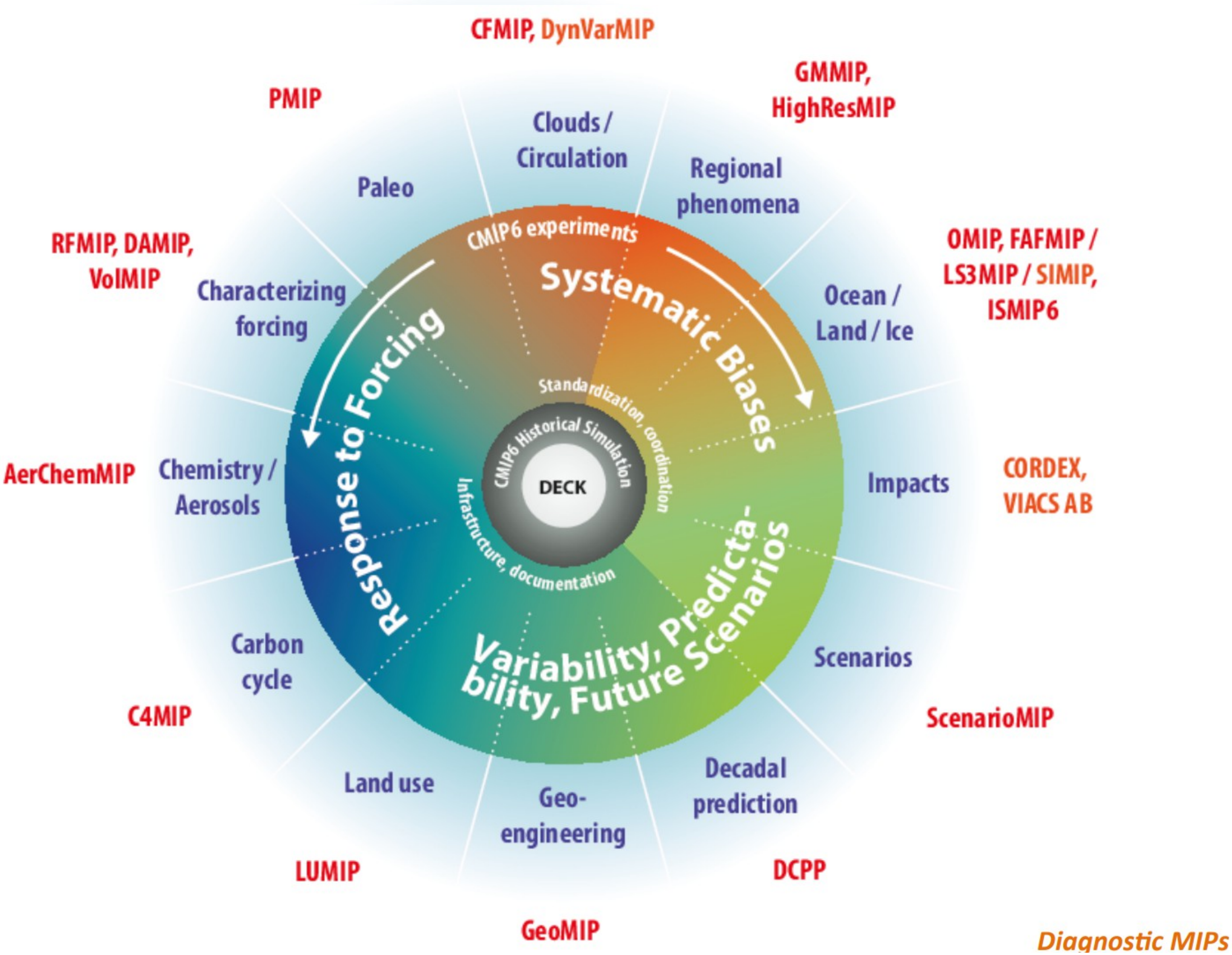
CMIP6 Experiment Design



- DECK (Diagnosis, Evaluation, and Characterization of Klima; entry card for CMIP)
  - AMIP simulation (~1979-2014)
  - Pre-industrial control simulation
  - 1%/yr CO2 increase
  - Abrupt 4xCO2 run
- CMIP6 Historical Simulation (entry card for CMIP6)
  - Historical simulation using CMIP6 forcings (1850-2014)
- Another entry card: use of CMIP6 data standard
- CMIP-Endorsed MIPs selected according to 10 criteria

Eyring et al., 2016

CMIP6 Experiment Design



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standard

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10 criteria

Eyring et al., 2016

Scale of Model Results

- CMIP3: 17 institutes (groups) and 25 models (40 TB)
  - total years simulated: 70000
  - individual models simulated 500 to 8400 years with a median of 2200 and a mean of 2800
  - individual groups simulated on average 70000/17 = 4,100 years
- CMIP5: 26 institutes (groups) and 60 models (2 PB)
  - numbers estimated on 10/1/2014 (to within about 20%)
  - total years simulated: 330000
  - individual models simulated on average 330000/60 = 5500 years
  - individual groups simulated on average 330000/26 = 13,000 years
- CMIP6: 32 institute (groups) and many model versions, more with higher resolution models, 23 MIPs, many experiments (<10 PB)

https://www.wcrp-climate.org/JSC38/presentations/CMIP6_JSC38_2017.pdf

CMIP6 Controlled Vocabularies

- How do we separate the results from individual models, experiments, MIPs, etc., and how do we have a common name for a variable?
- Write global attributes with the values from CMIP6 Controlled Vocabularies (CVs) in the output file
- Homepage
  - https://github.com/WCRP-CMIP/CMIP6_CVs
  - Find more or nearly all details from “CMIP6 Global Attributes, DRS, Filenames, Directory Structure, and CV's document”
  - DRS: data reference syntax
  - Example
    - tas_Amon_GFDL-CM4_historical_r1i1p1f1_gn_196001-199912.nc
    - pr_day_CNRM-CM6-1_dcppA-hindcast_s1960-r2i1p1f1_gn_198001-198412.nc

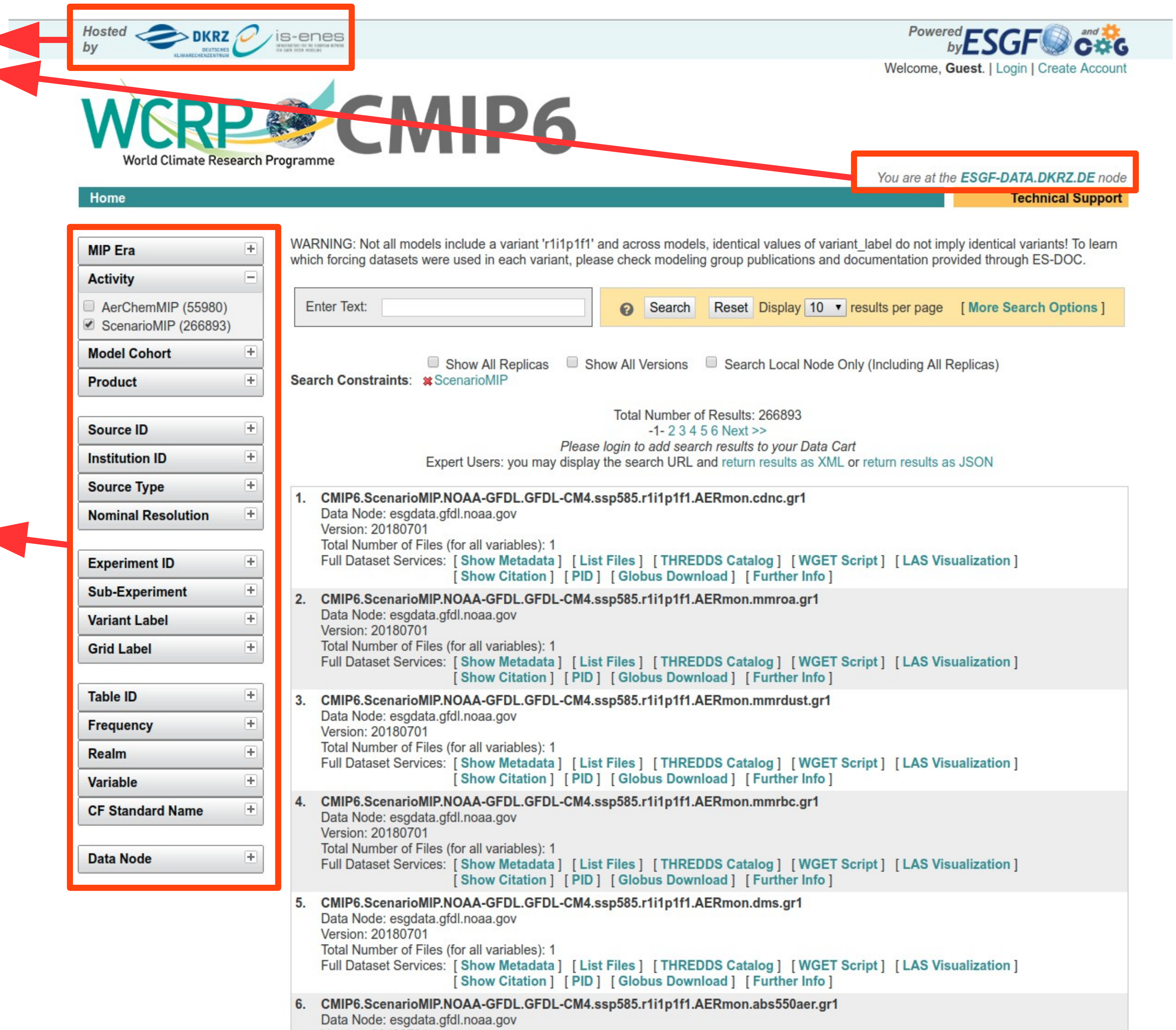
ESGF

- ESGF: Earth System Grid Federation
- A data platform where CMIP data are saved and managed
- Everyone can search and download the CMIP data from ESGF
- Homepage: https://esgf.llnl.gov/
- Federated ESGF-CoG Nodes
  - LLNL: USA
  - CEDA: UK
  - DKRZ: Germany
  - GFDL: USA
  - IPSL: France
  - LIU: Sweden
  - NCI: Australia
  - NCCS: USA

ESGF

Node information

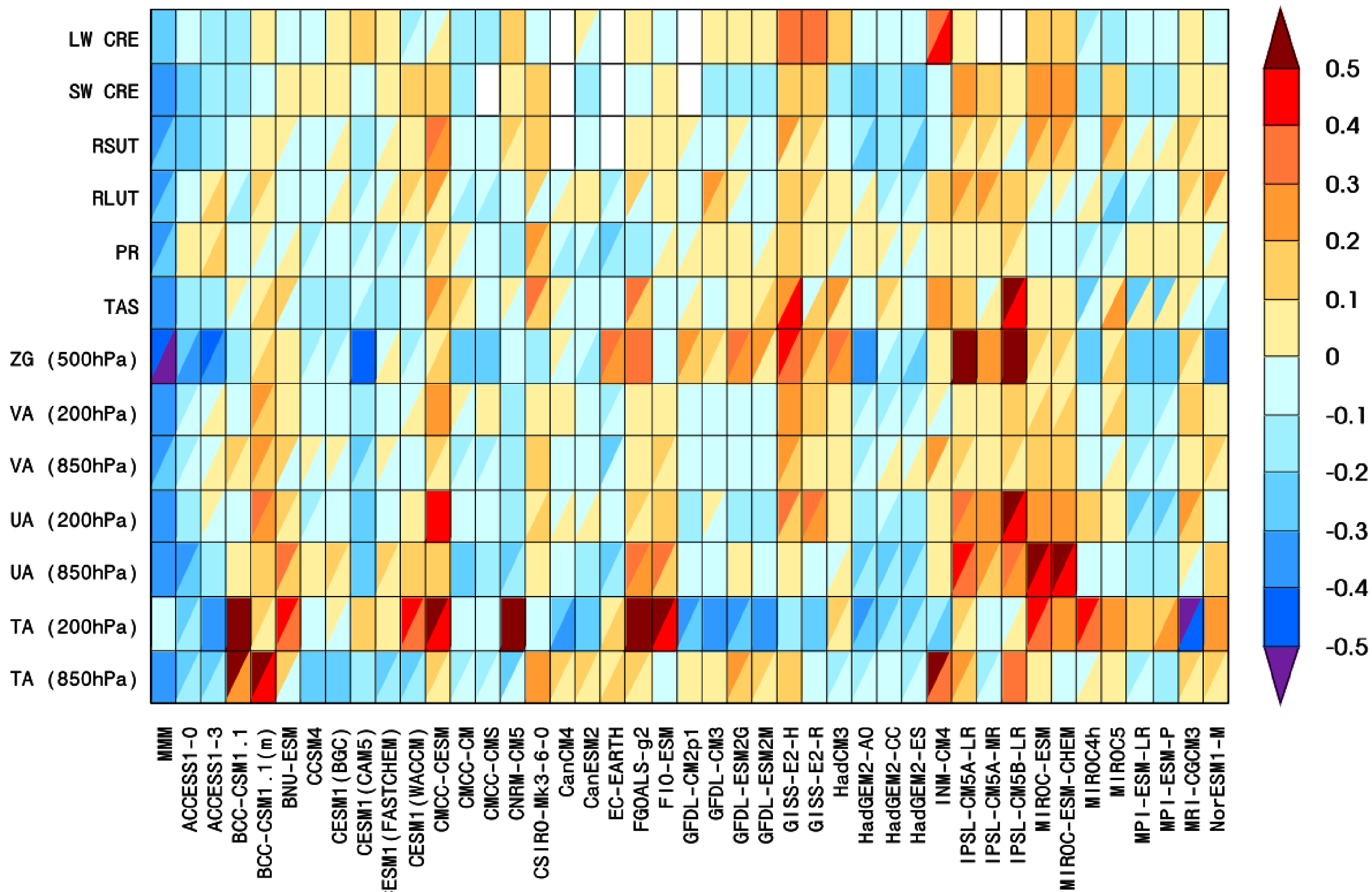
You can search by using global attributes and CMIP6 CVs



ES-DOC

- ES-DOC: Earth System Documentation
- Homepage: https://es-doc.org/
  - A more useful entry: https://documentation.es-doc.org/cmip6/experiments
- For example, it includes all the set-up information and forcing data for an experiment
- Errata: report any problems discovered after publication to ESGF
  - https://errata.es-doc.org/static/index.html

CMIP5 Model Performance

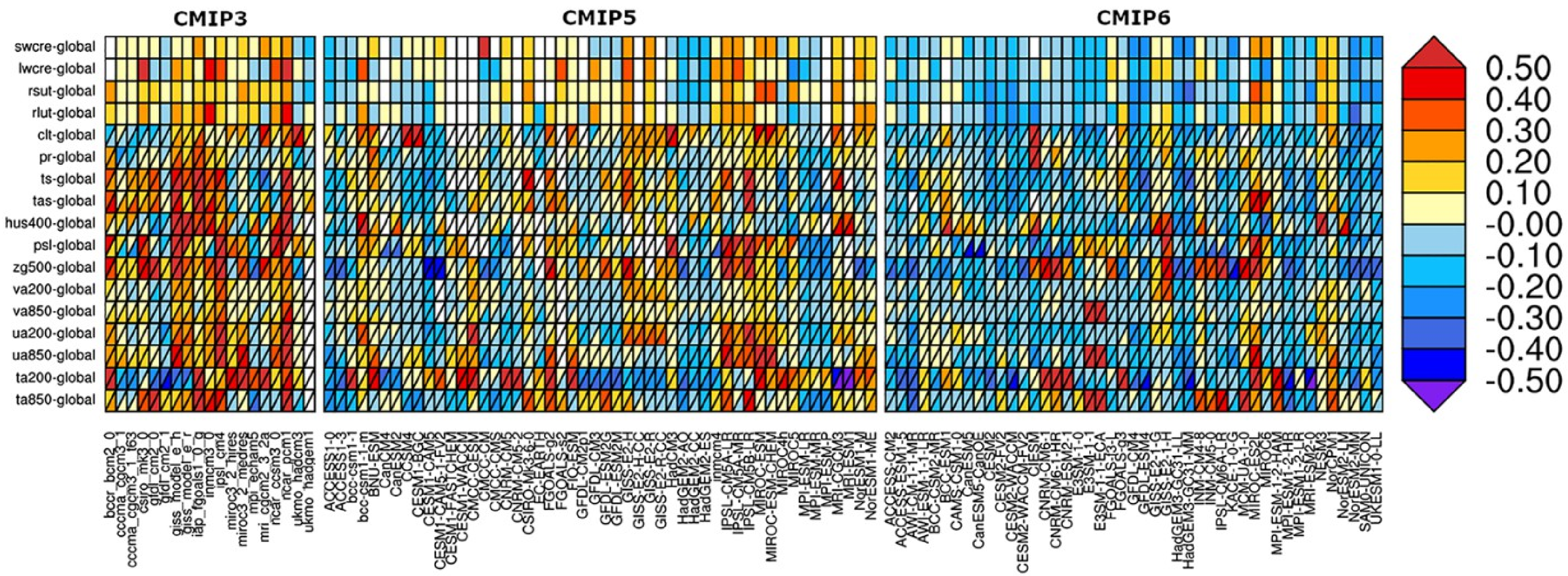


Relative space-time root-mean-square deviation (RMSD)

Red: worse
Blue: better

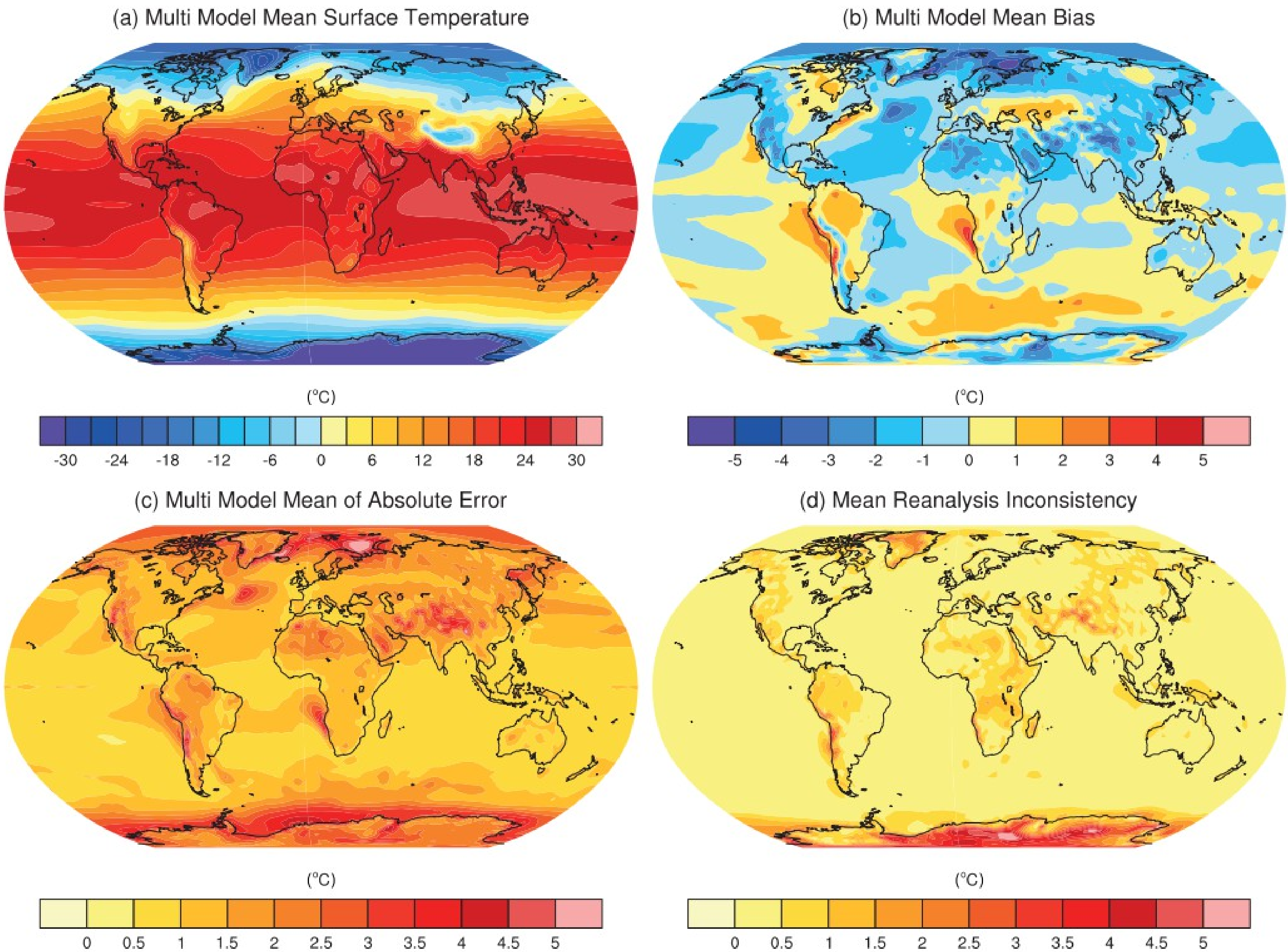
MMM (multi-model mean) shows better performance in nearly all the variables

IPCC AR5, 2013, Figure 9.7



Apparent general improvement from CMIP3 to CMIP6

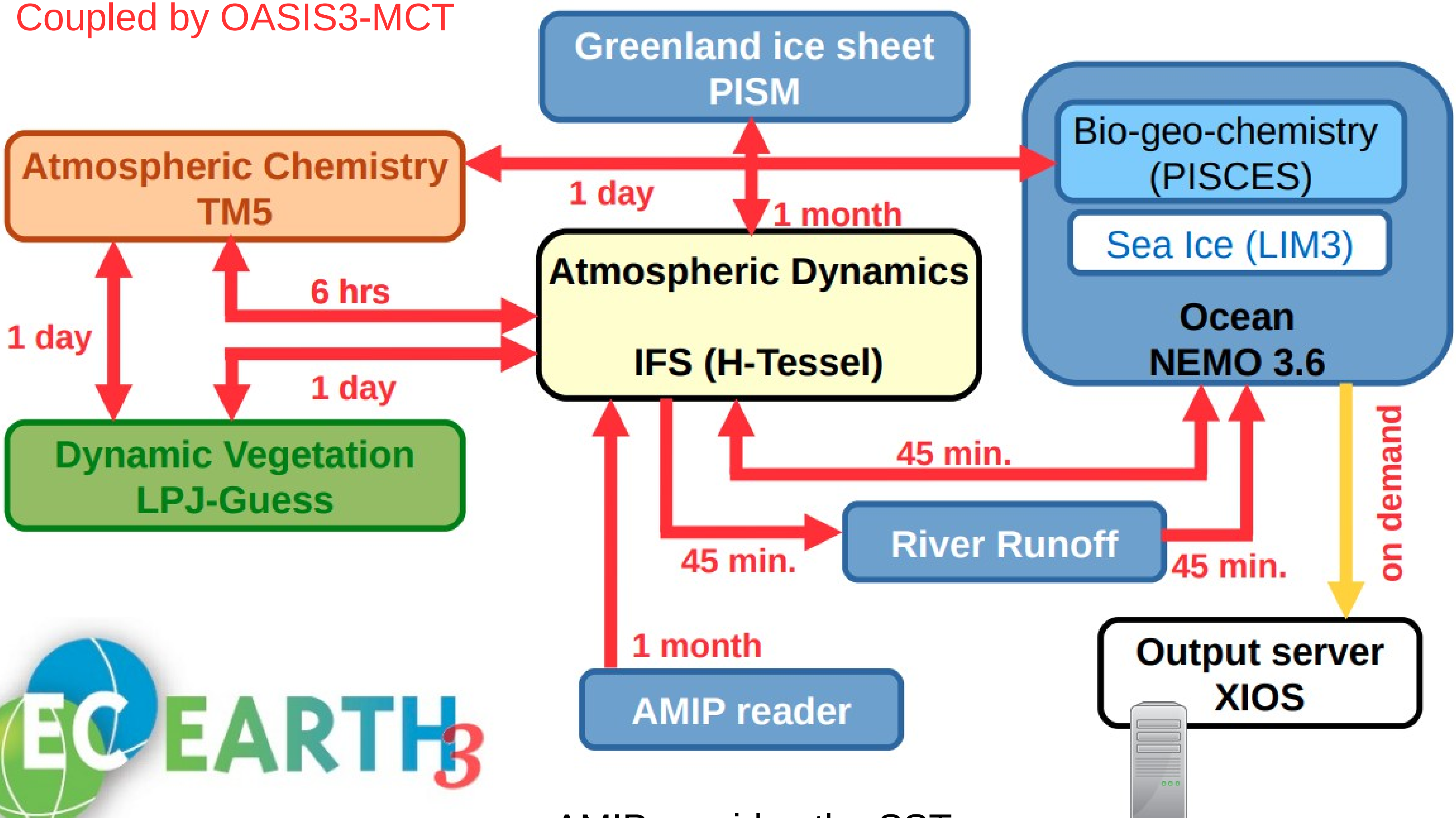
Model Validation



IPCC AR5, 2013, Figure 9.2

ESM example: EC-Earth

Coupled by OASIS3-MCT

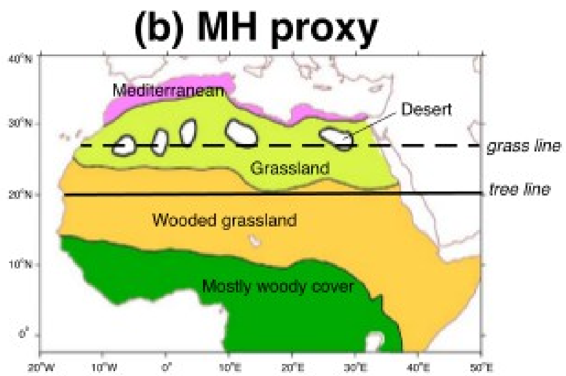


AMIP provides the SST boundary conditions

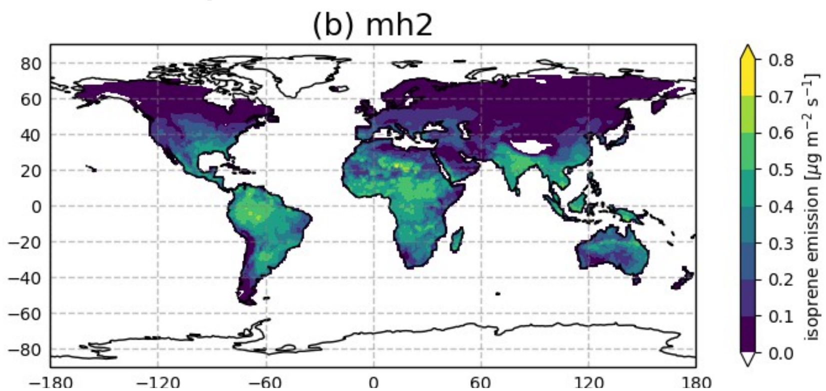
https://dev.ec-earth.org/attachments/download/2588/BOG_summary_TechnicalWG.pdf

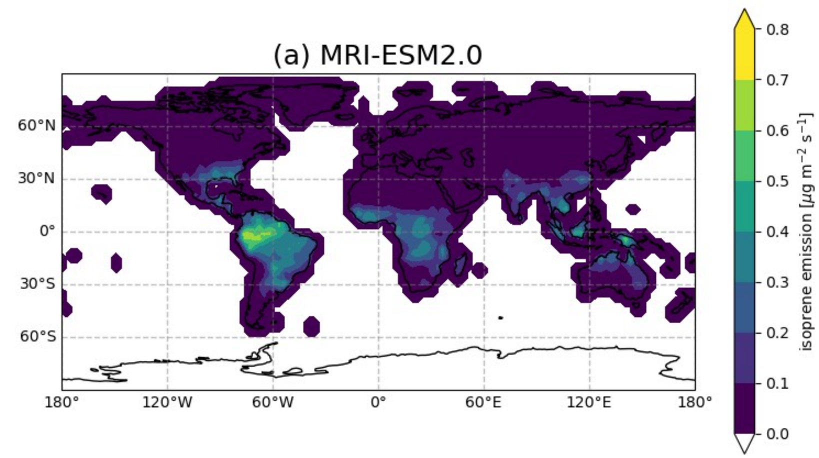
Green Sahara in Mid-Holocene (6000 years ago)

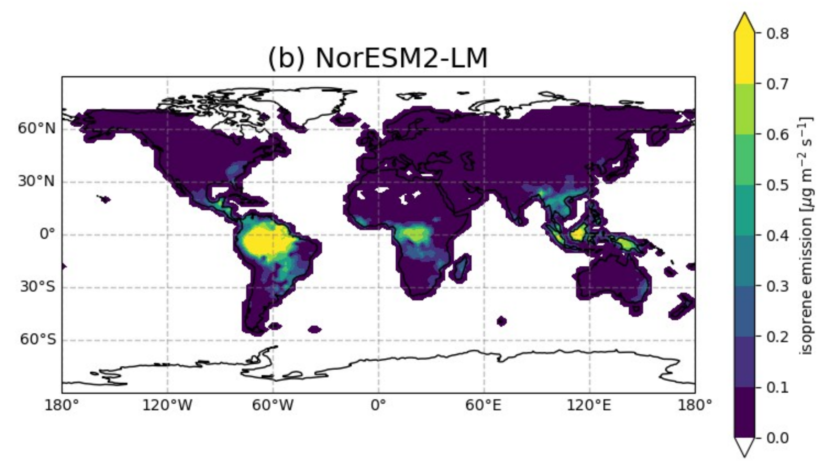
Reconstructed data (Hély et al., 2014, CP)



Our simulation results with LPJ-GUESS, which will be used as TM5 input for further simulations.



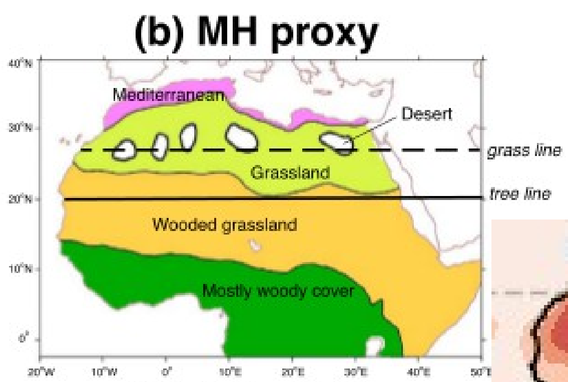


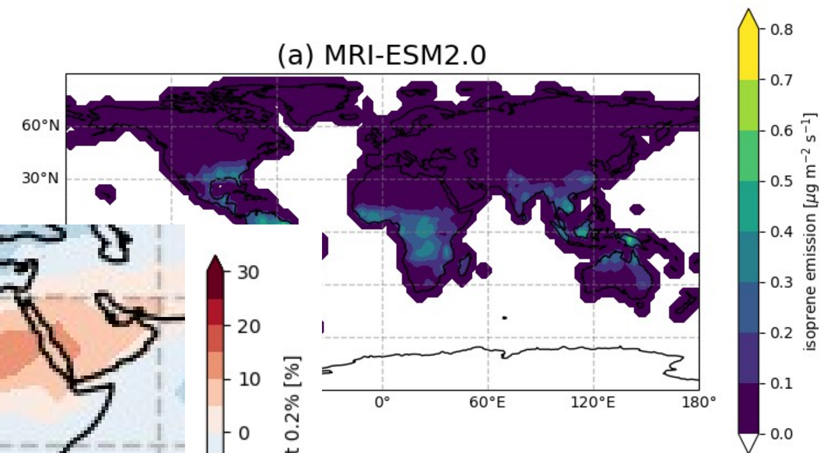


Zhou et al., in preparation

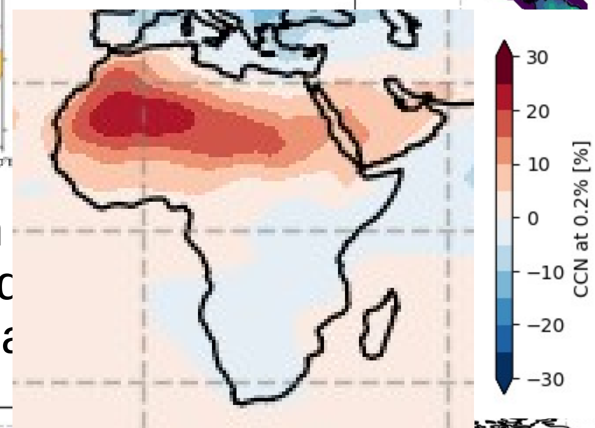
Green Sahara in Mid-Holocene (6000 years ago)

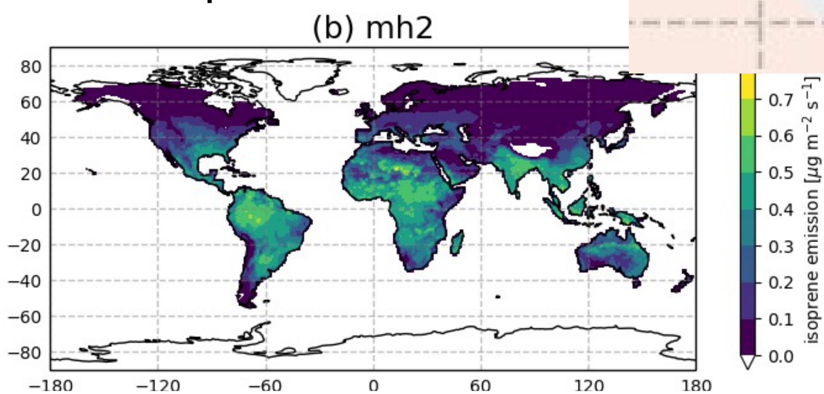
Reconstructed data (Hély et al., 2014, CP)

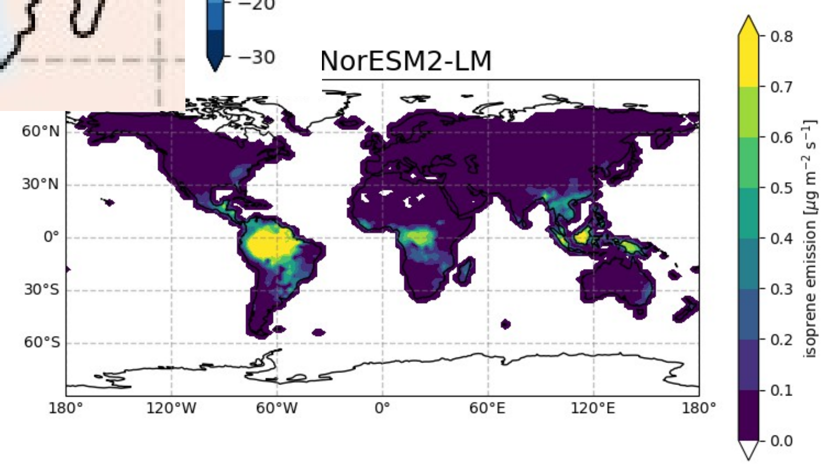




Our simulation results with
GUESS, which will be usec
TM5 input for further simula







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Thank you!

Backup

EC-Earth

- EC-Earth: A European Community Earth-System Model
- A global coupled climate model, which integrates a number of component models in order to simulate the earth system
- Developed by a consortium of European research institutions
- Homepage: http://www.ec-earth.org/
- Development Portal: https://dev.ec-earth.org/
- First paper
  - Hazeleger et al., 2010, BAMS, EC-Earth: a seamless earth-system prediction approach in action
- Current version: EC-Earth 3.3.3.1 (van Nojie et al., 2021, GMD)
- Forthcoming: EC-Earth 4
- CMIP5 and CMIP6
  - AerChemMIP, C4MIP, DAMIP, HighResMIP, PMIP, LUMIP, ...

EC-Earth Consortium

Core partners:
- SMHI, Sweden
- KNMI, The Netherlands
- DMI, Denmark
- AEMET, Spain
- Met Éireann, Ireland
- CNR-ISAC, Italy
- Instituto de Meteorologia, Portugal
- FMI, Finland

Partners

- BSC, Spain
- Centro de Geofisica, University of Lisbon, Portugal
- Lund University, Sweden
- Meteorologiska Institutionen, Stockholm, Sweden
- Universiteit Wageningen, The Netherlands
- University of Helsinki, Finland
- ...