Global climate models

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(with J. von Hardenberg, E.Palazzi, L. Filippi)

Budapest, January 2013

The difference between weather and climate

Predictions of the first and second kind (Edward Lorenz)

What is climate predictability?

Meteorological predictions and the use of numerical methods

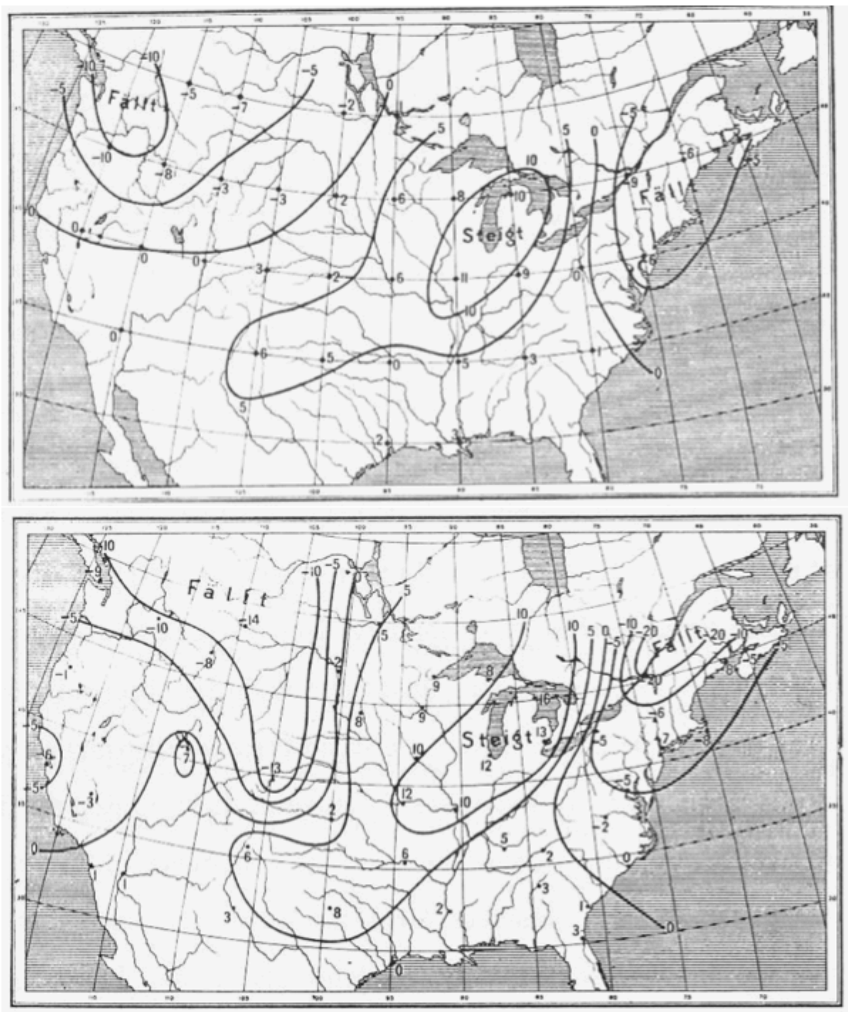
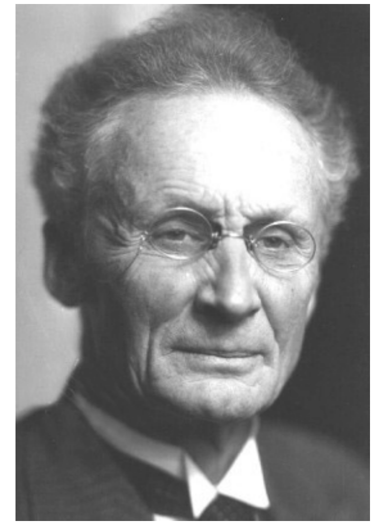


Figure 1.3 Top: Exner's calculated pressure change between 8 p.m. and midnight, 3 January 1895. Bottom: observed pressure change for the same period [Units: hundredths of an inch of mercury. *Steigt* = rises; *Fällt* = falls]. (Exner, 1908)

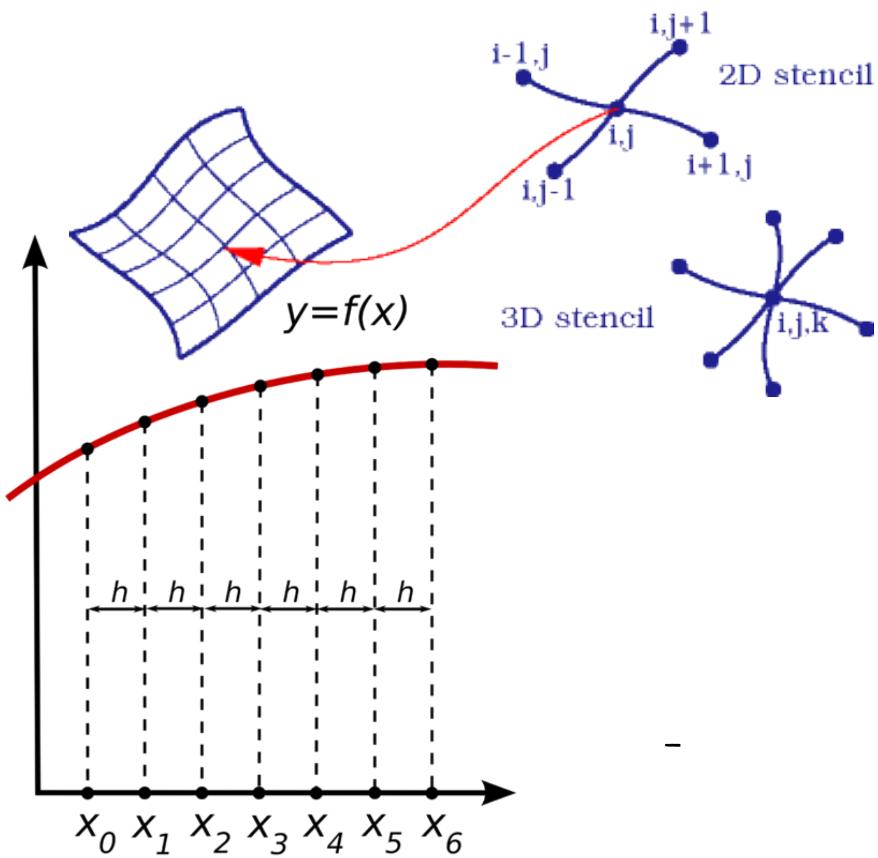


Wilhelm Bjerknes
(1862-1952)

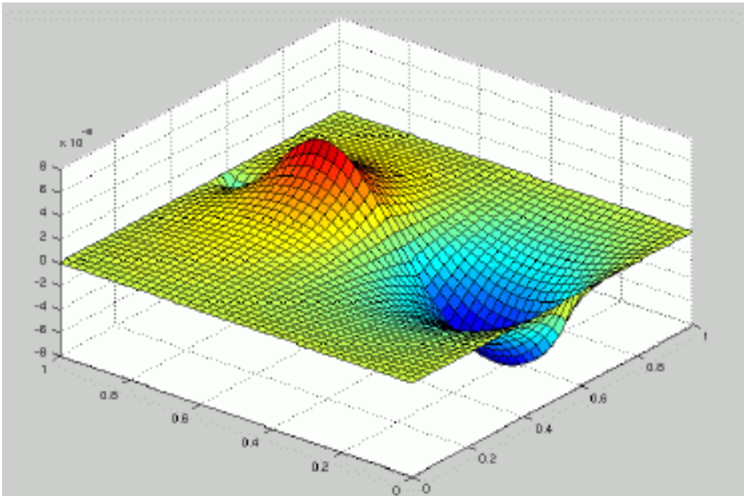
He suggested (1904) to consider weather forecast as an initial value problem, to be solved using the equations of Mathematical Physics.

Finite difference methods

- We use a discretized formulation on a grid in space and time:



$$f'(a) \approx \frac{f(a+h) - f(a)}{h}.$$



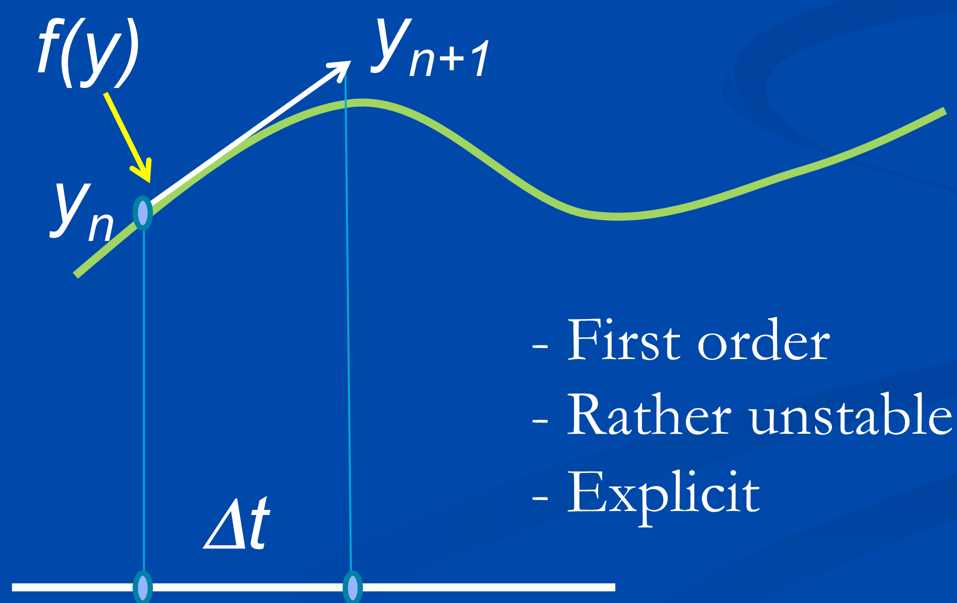
The Euler method

$$\frac{dy}{dt} = f(y)$$

$$y(t + \Delta t) = y(t) + \Delta t f(y(t))$$

$$y_{n+1} = y_n + \Delta t f(y_n)$$

+ Truncation error

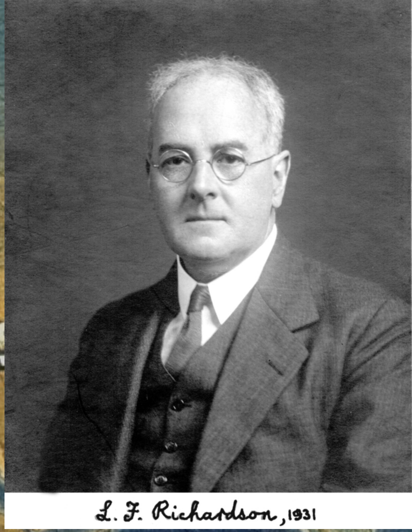


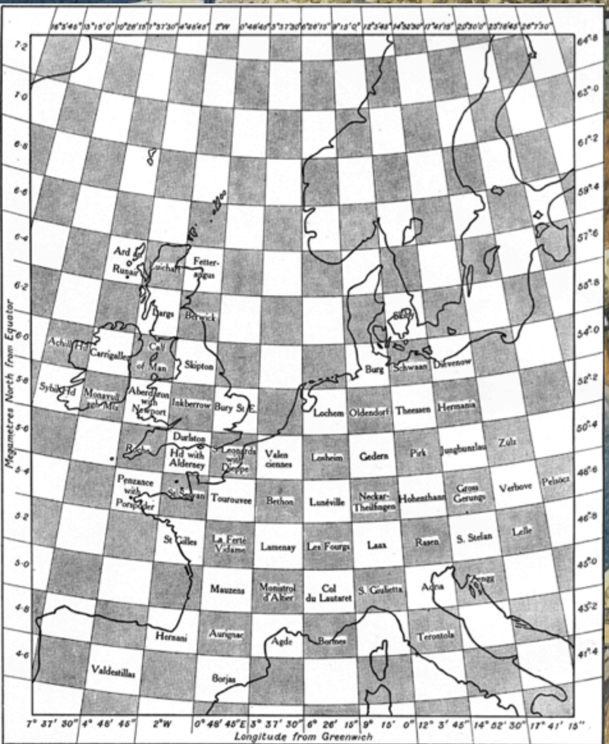
- First order
- Rather unstable
- Explicit


CHINA
SAHARA
SUDAN
ARABIA
INDIA
BRAZIL
CONGO
PACIFIC OCEAN
INDIAN OCEAN

L.F. Richardson, Weather Prediction by Numerical Process (1922):

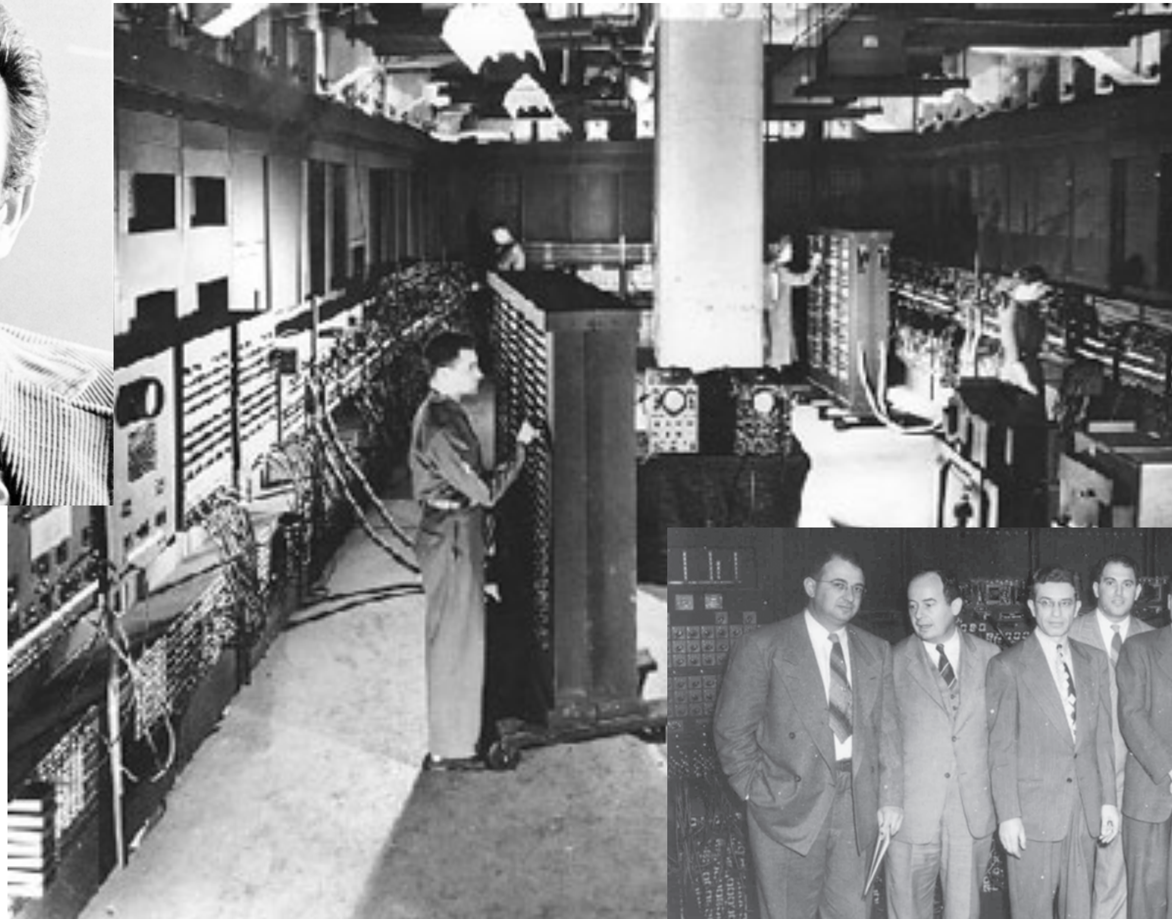
The forecast factory





"Imagine a large hall like a theater except that the circles and galleries go right round through the space usually occupied by the stage. The walls of this chamber are painted to form a map of the globe. . . . From the floor of the pit a tall pillar rises to half the height of the hall. It carries a large pulpit on its top. In this sits the man in charge of the whole theatre." (Weather Prediction by Numerical Process)

Jule Charney (1917-81)



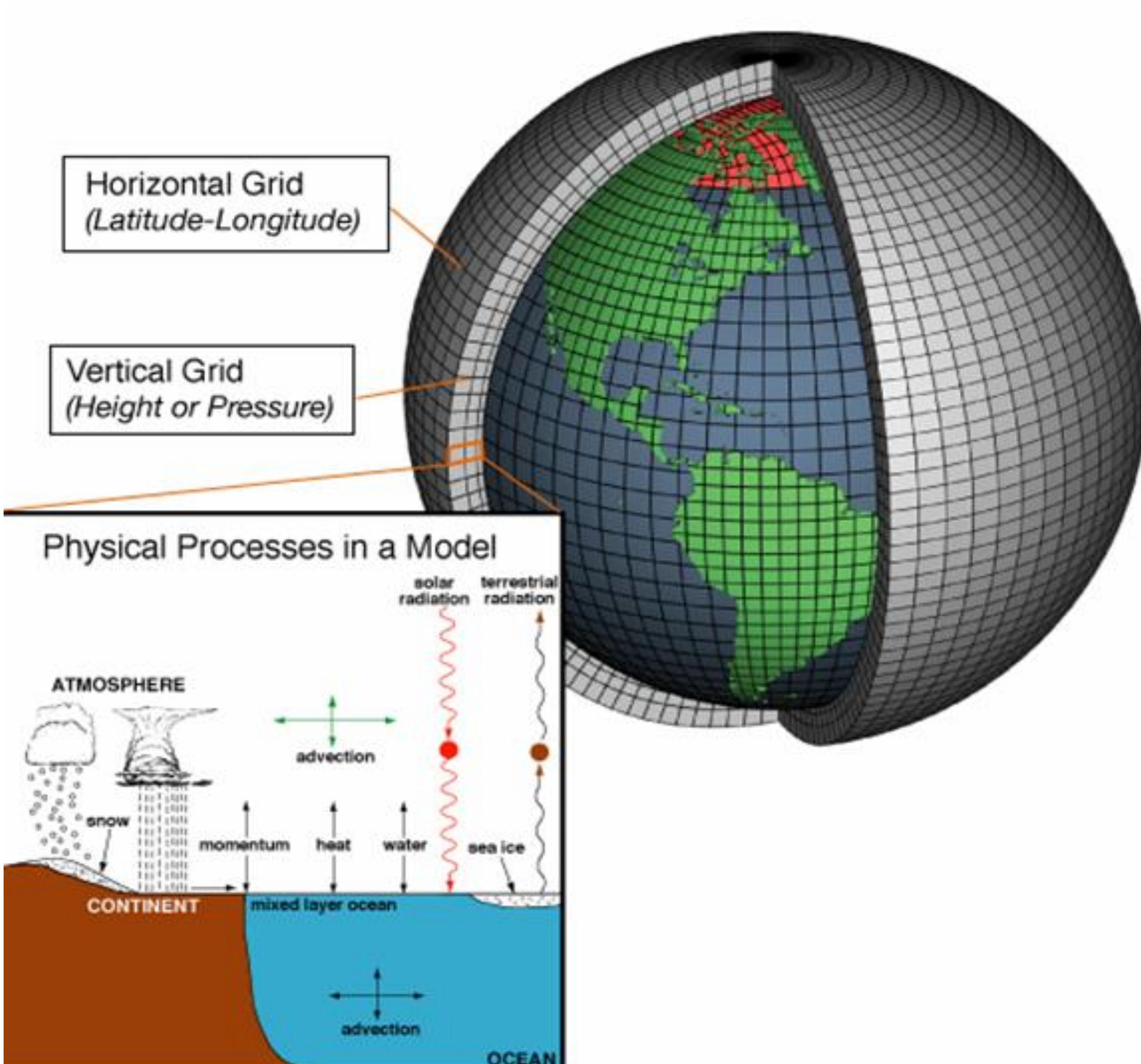
ENIAC

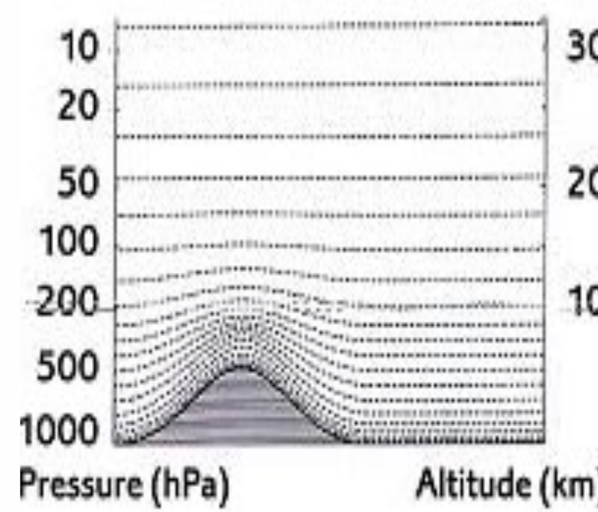
500 hPa geopotential height: solid=observed dashed=forecasted change

FIG. 1. Visitors and some participants in the 1950 ENIAC computations. (left to right) Harry Wexler, John von Neumann, M. H. Frankel, Jerome Namias, John Freeman, Ragnar Fjørtoft, Francis Reichelderfer, and Jule Charney. (Provided by MIT Museum.)

1950: First weather forecast for 24h using the first electronic computer (ENIAC) and **simplified equations for the atmosphere (QG)**

General circulation models





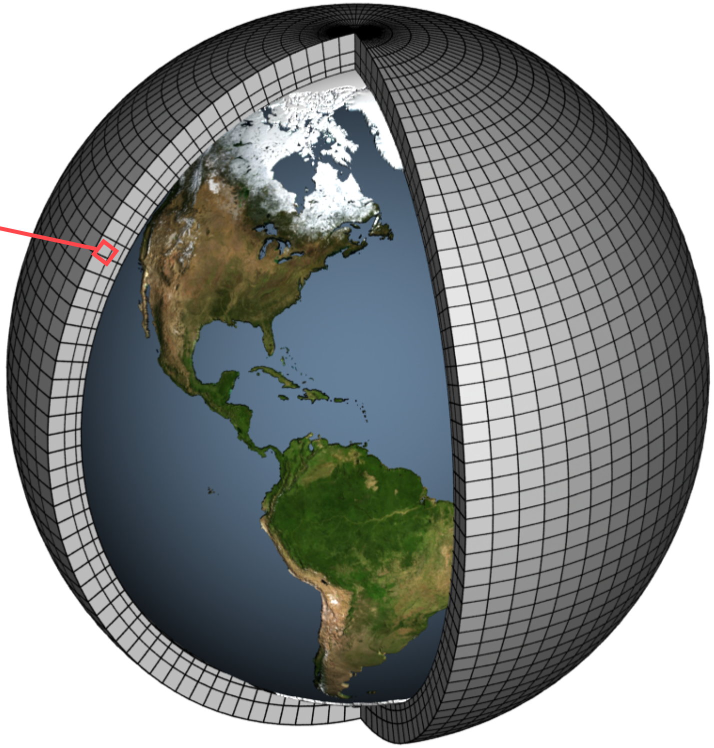
Mathematical equations that represent the physical characteristics and processes are entered for each box

Primitive equations (3D):

Hydrostatic approximation
Boussinesq approximation

Vertical coordinate:
pressure, or entropy

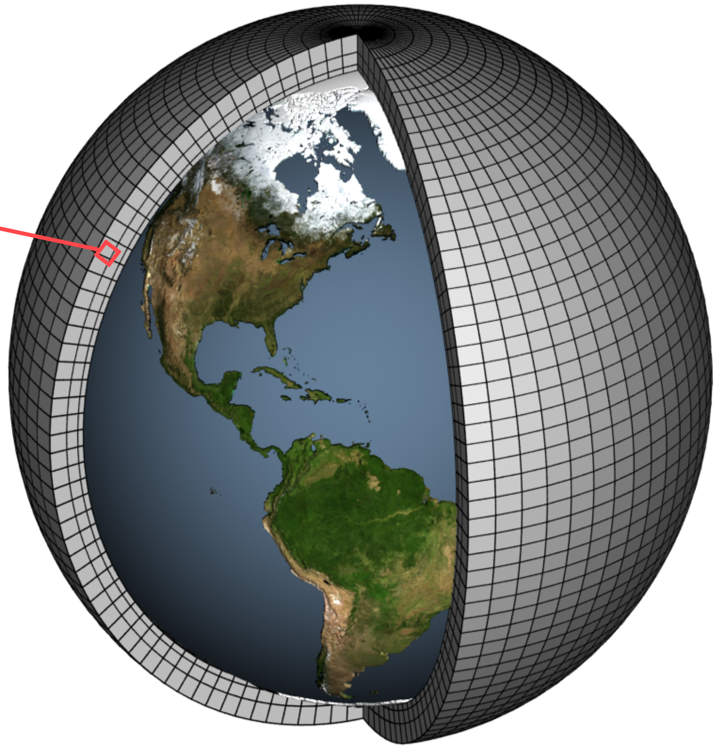
Perfect gas (atmosphere)
Thermodynamics



(from a lecture by S. Gualdi – CMCC)

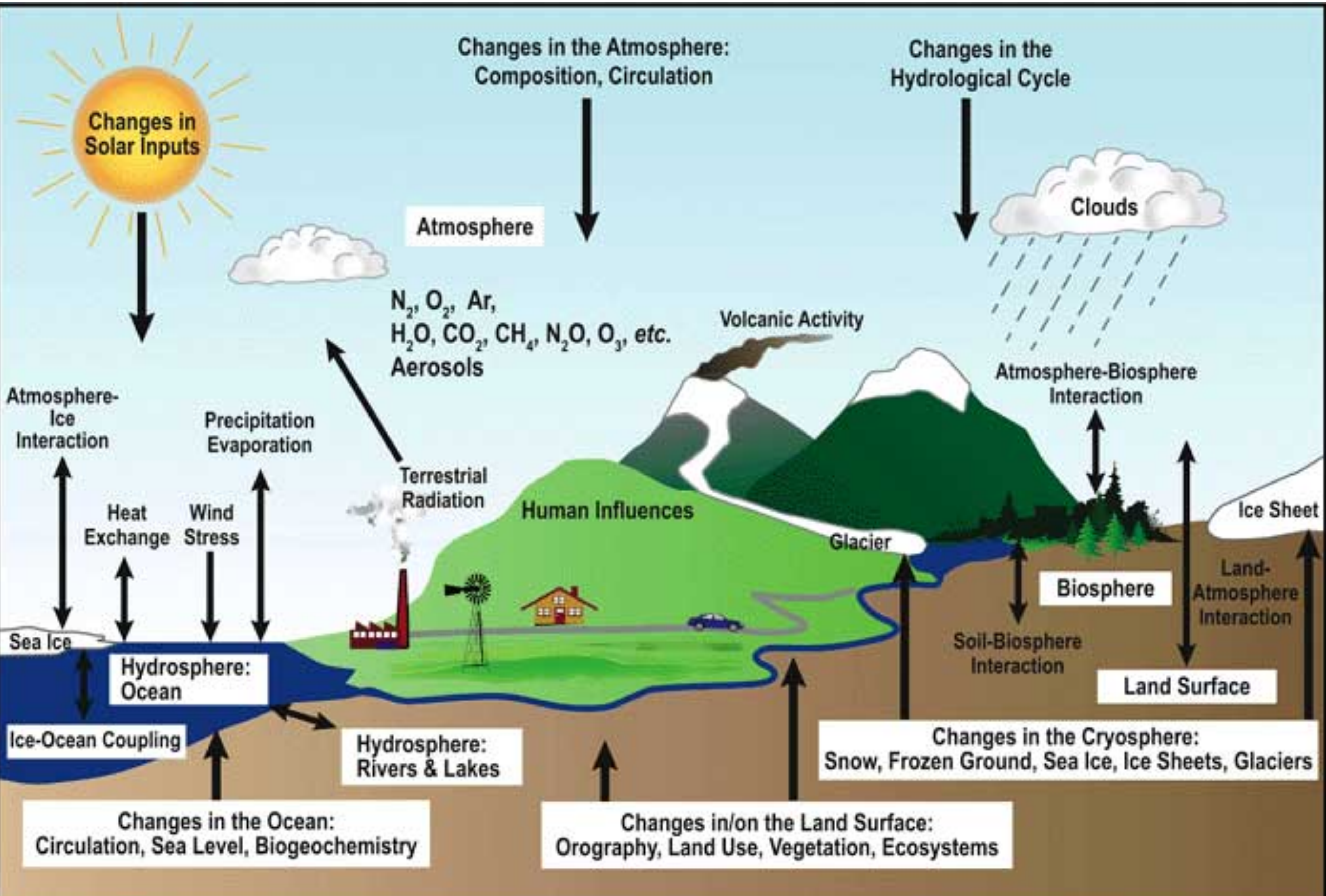
Equations are converted to computer code and climate variables are set

```
if (diagts .and. eots) then
  do 1500 m=1,nt
    do 1490 k=1,km
      fx = cst(j)*dyt(j)*dzt(k)/(c2dtts*dtxcel(k))
      do 1480 i=2,imtm1
        boxfx              = fx*dxt(i)*fm(i,k,jc)
        sddt               = (ta(i,k,m)-t(i,k,jc,nm,m))*boxfx
        svar               = (ta(i,k,m)**2-t(i,k,jc,nm,m)**2)
                             *boxfx
        n                  = 0
        termbt(k,1,m,n) = termbt(k,1,m,n) + sddt
        tvar(k,m,n)     = tvar(k,m,n)     + svar
        n      = nhreg*(mskvr(k)-1) + mskhr(i,j)
        if (n .gt. 0 .and. mskhr(i,j) .gt. 0) then
          termbt(k,1,m,n) = termbt(k,1,m,n) + sddt
          tvar(k,m,n)     = tvar(k,m,n)     + svar
```

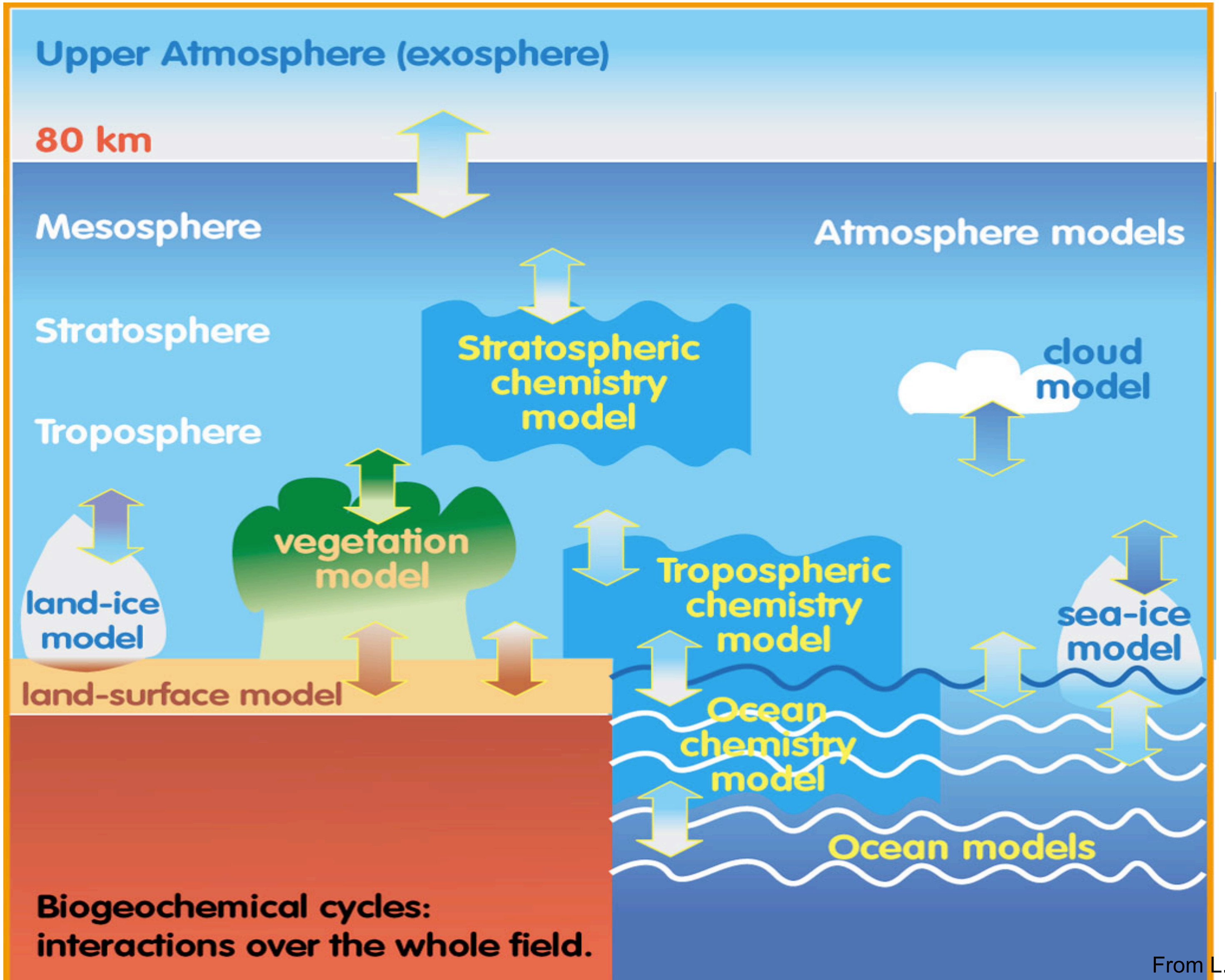


(from a lecture by S. Gualdi – CMCC)

Climatic processes

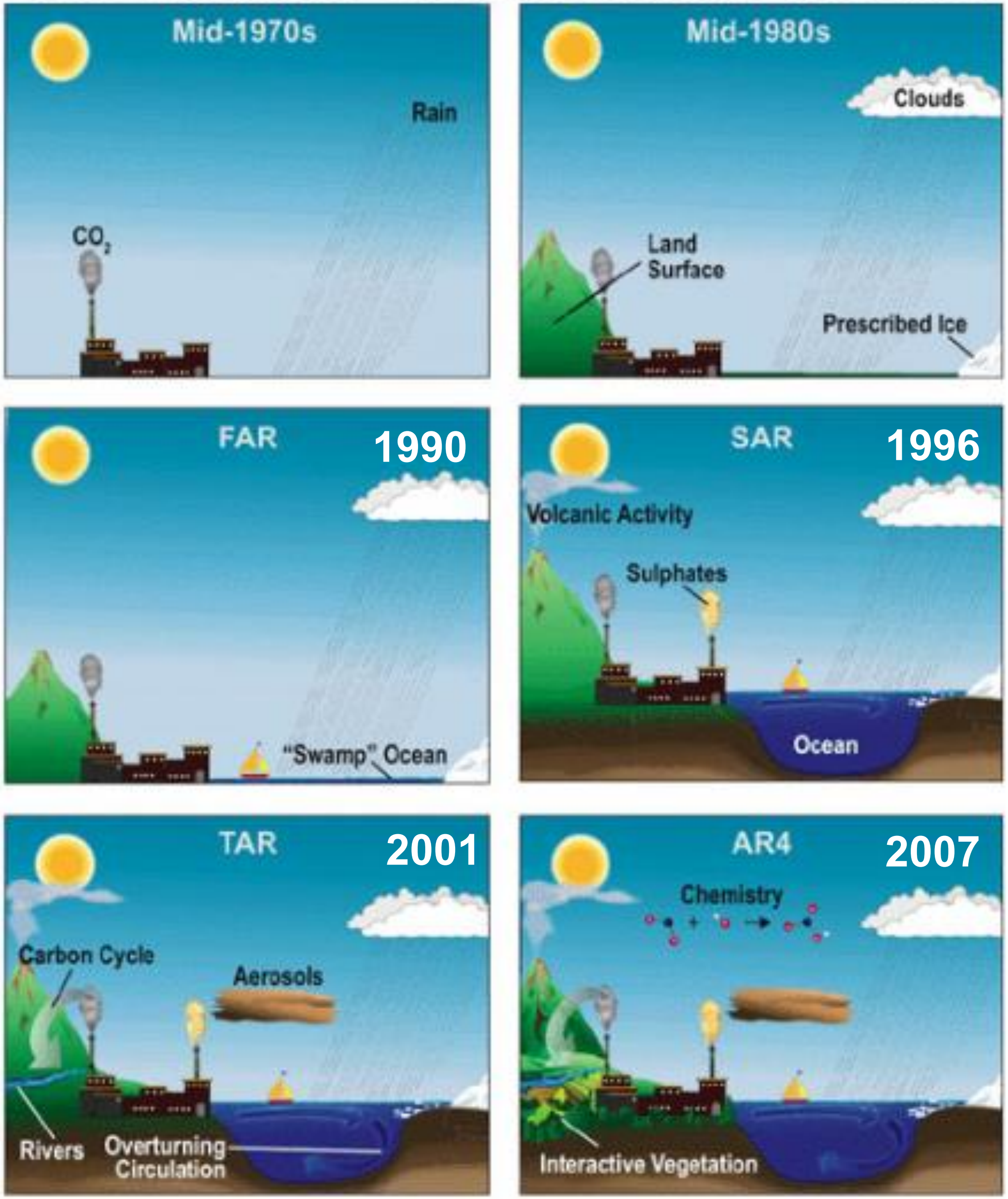


Main components of a global Earth-system model



From L. Bengtsson, 2005

The World in Global Climate Models



Le Treut et al. 2007

The Development of Climate models, Past, Present and Future

IPCC TAR, 2001

Other crucial elements of climate modelling:

External forcings

Solar variability

Orbital variability

Volcanoes

GHG concentrations

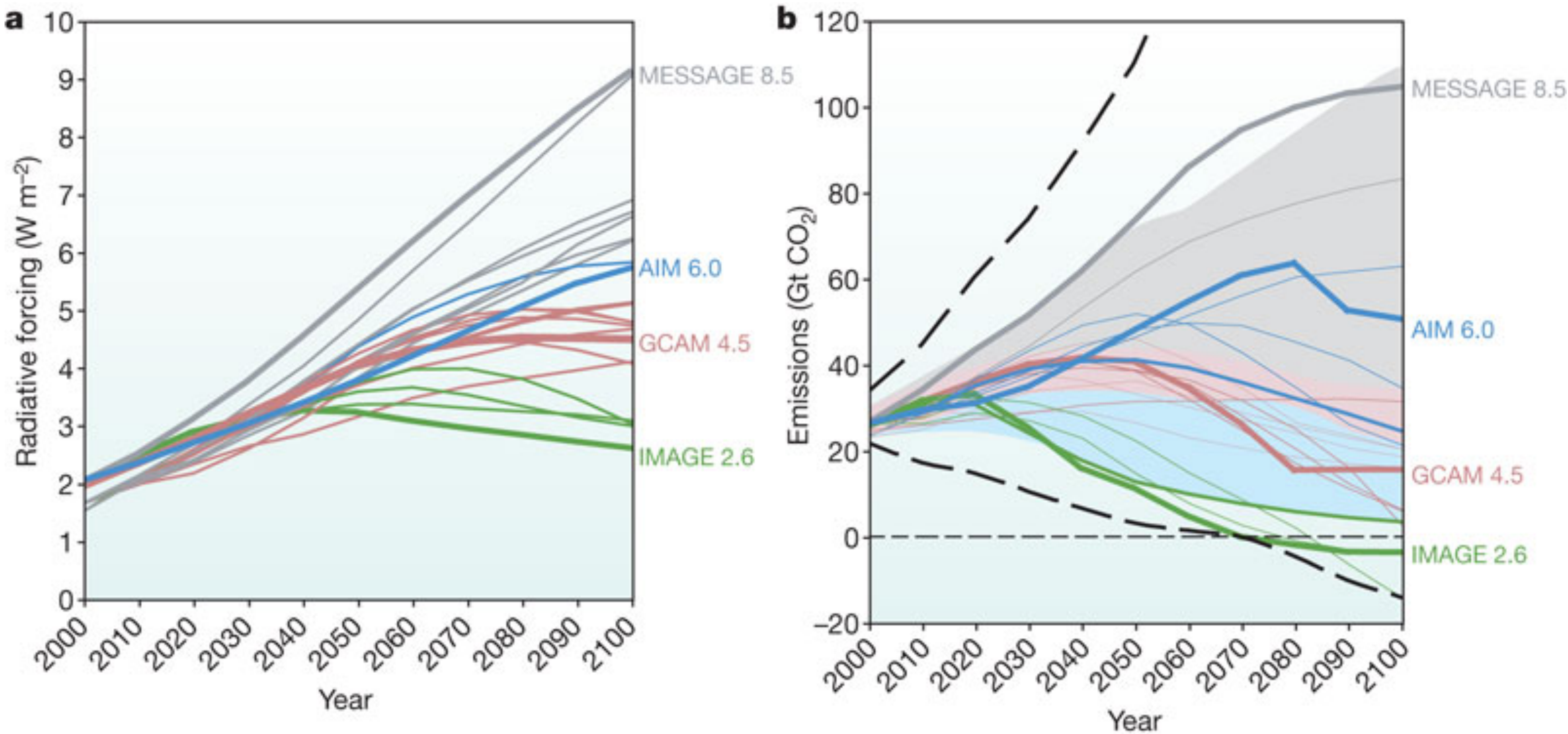
Aerosols

(often, use equivalent radiative forcing at TOA)

Initial conditions

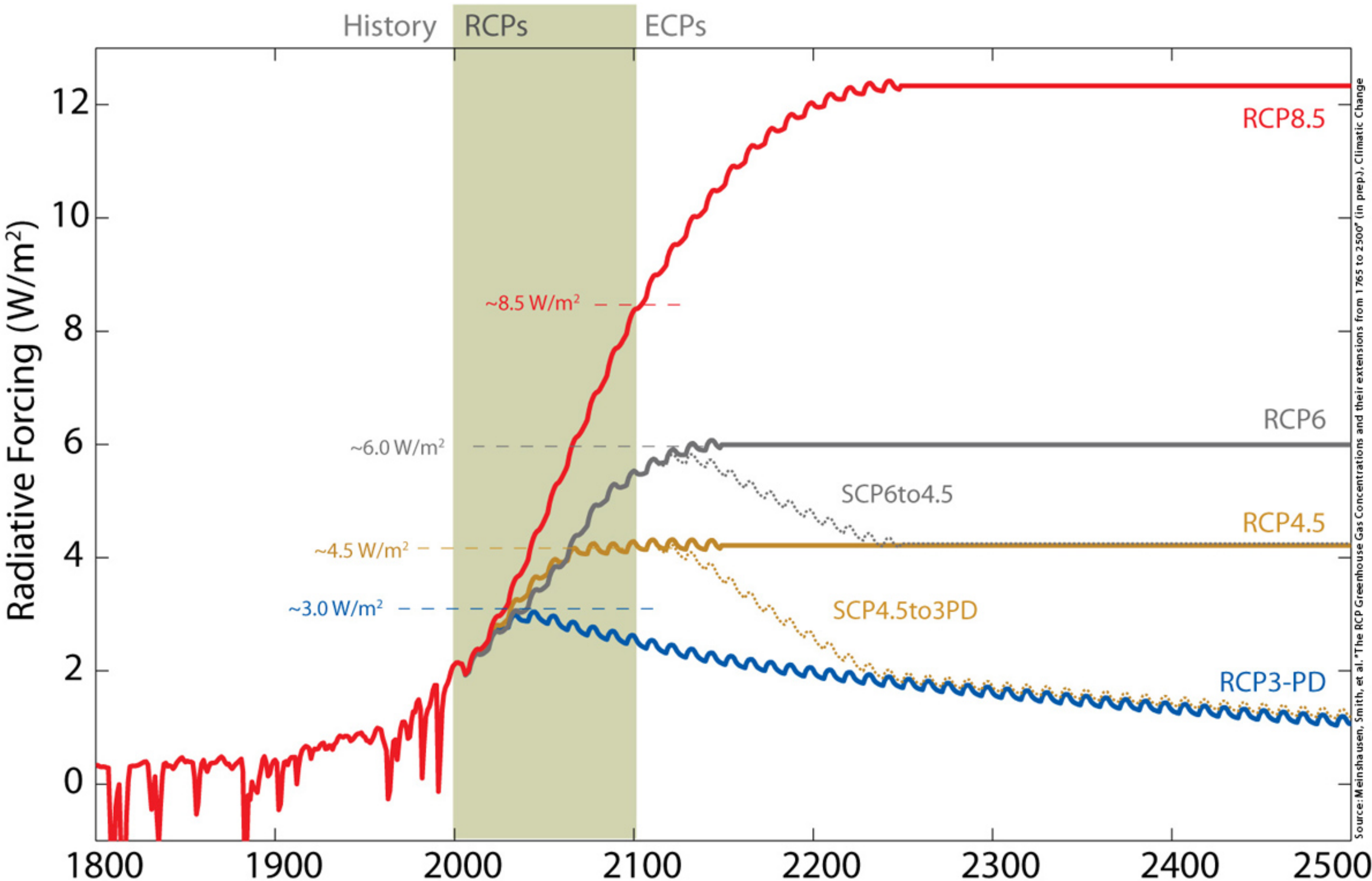
Parameterization choices

Representative concentration pathways

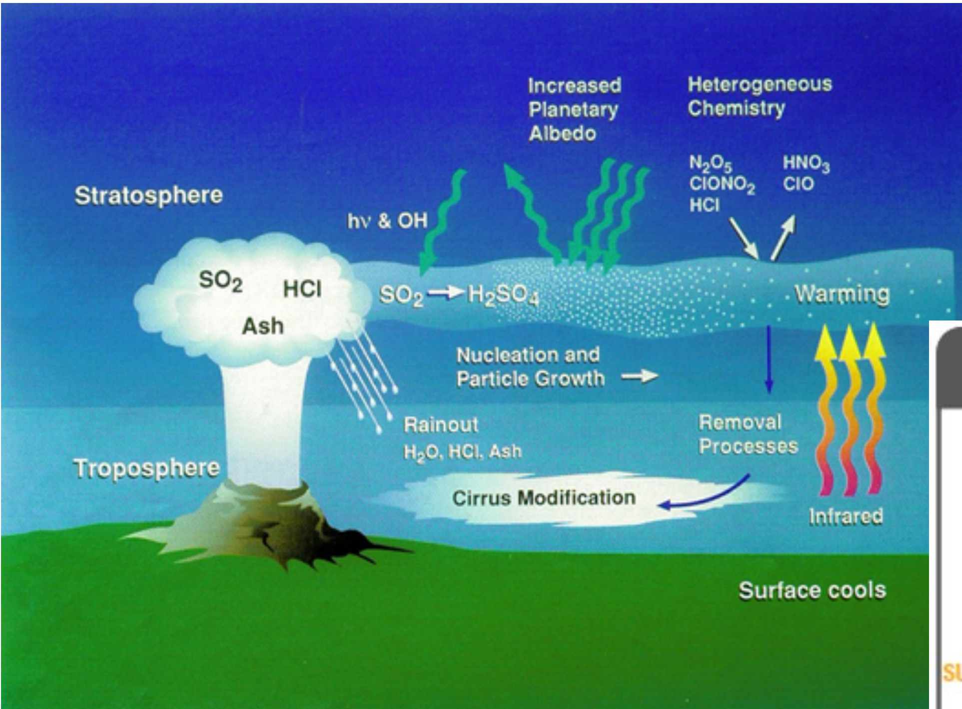


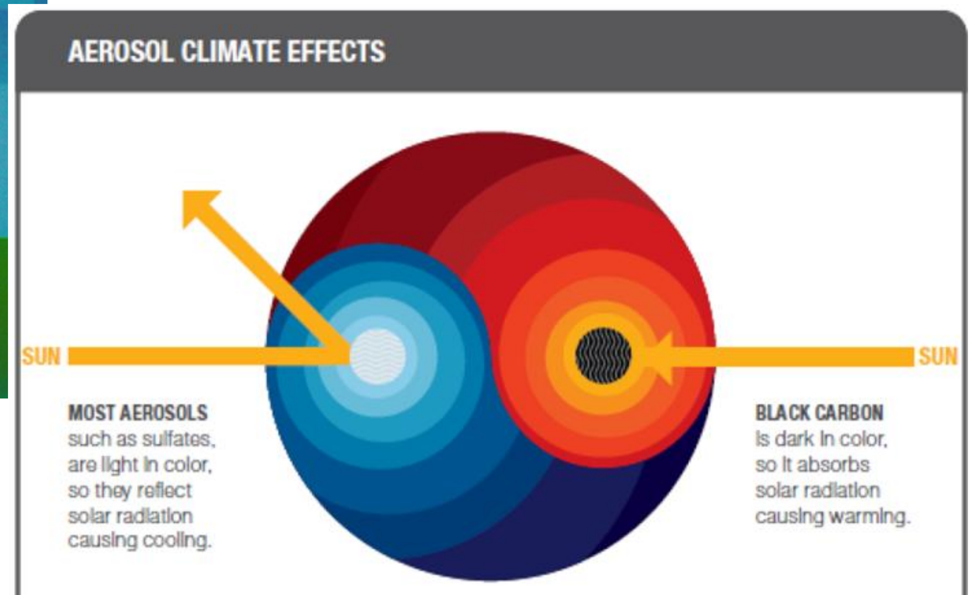
RH Moss *et al.* *Nature* **463**, 747-756 (2010) doi:10.1038/nature08823

nature


History
RCPs
ECPs
Radiative Forcing (W/m²)
~8.5 W/m²
~6.0 W/m²
~4.5 W/m²
~3.0 W/m²
RCP8.5
RCP6
SCP6to4.5
RCP4.5
SCP4.5to3PD
RCP3-PD
0
2
4
6
8
10
12
1800
1900
2000
2100
2200
2300
2400
2500
Source: Meinshausen, Smith, et al. "The RCP Greenhouse Gas Concentrations and their extensions from 1765 to 2500" (in prep.), Climatic Change

The problem of aerosols





A quick look of black carbon, IGSD, 2009.

Specific codes for climate/weather models: HAM, TM5

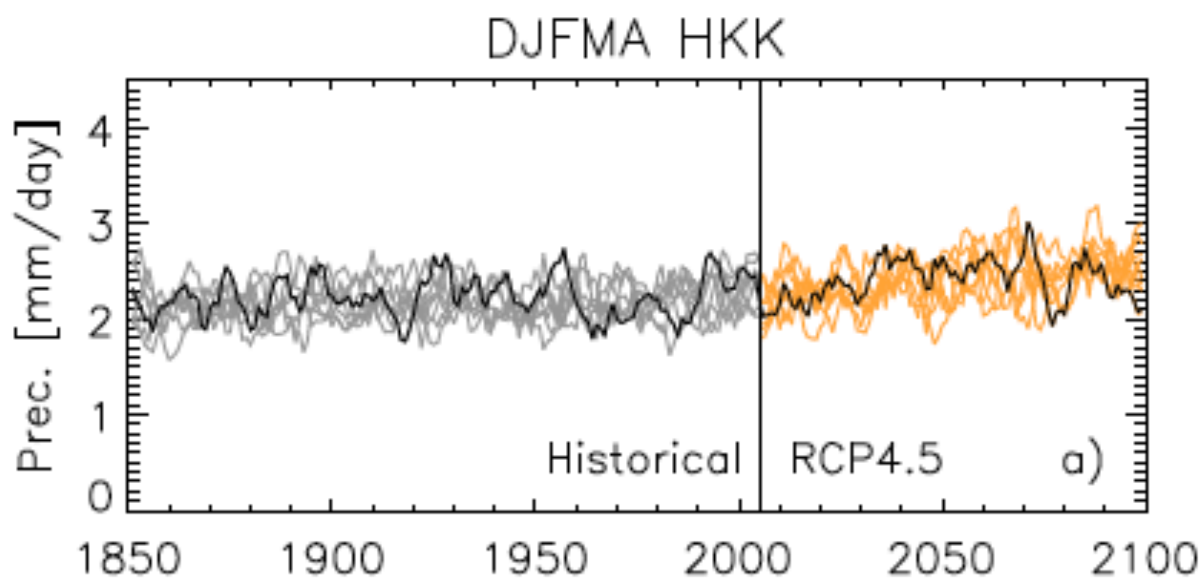
Climate simulations are statistical

A given year in a climate simulation does not mean anything

Only trends and statistical quantities (PDFs) are meaningful

Climate ensemble predictions

Start from different initial conditions
and generate an ensemble of simulations
with the same model and same parameters/forcing
or with different models (multimodel superensemble)
and/or with different parameter choices



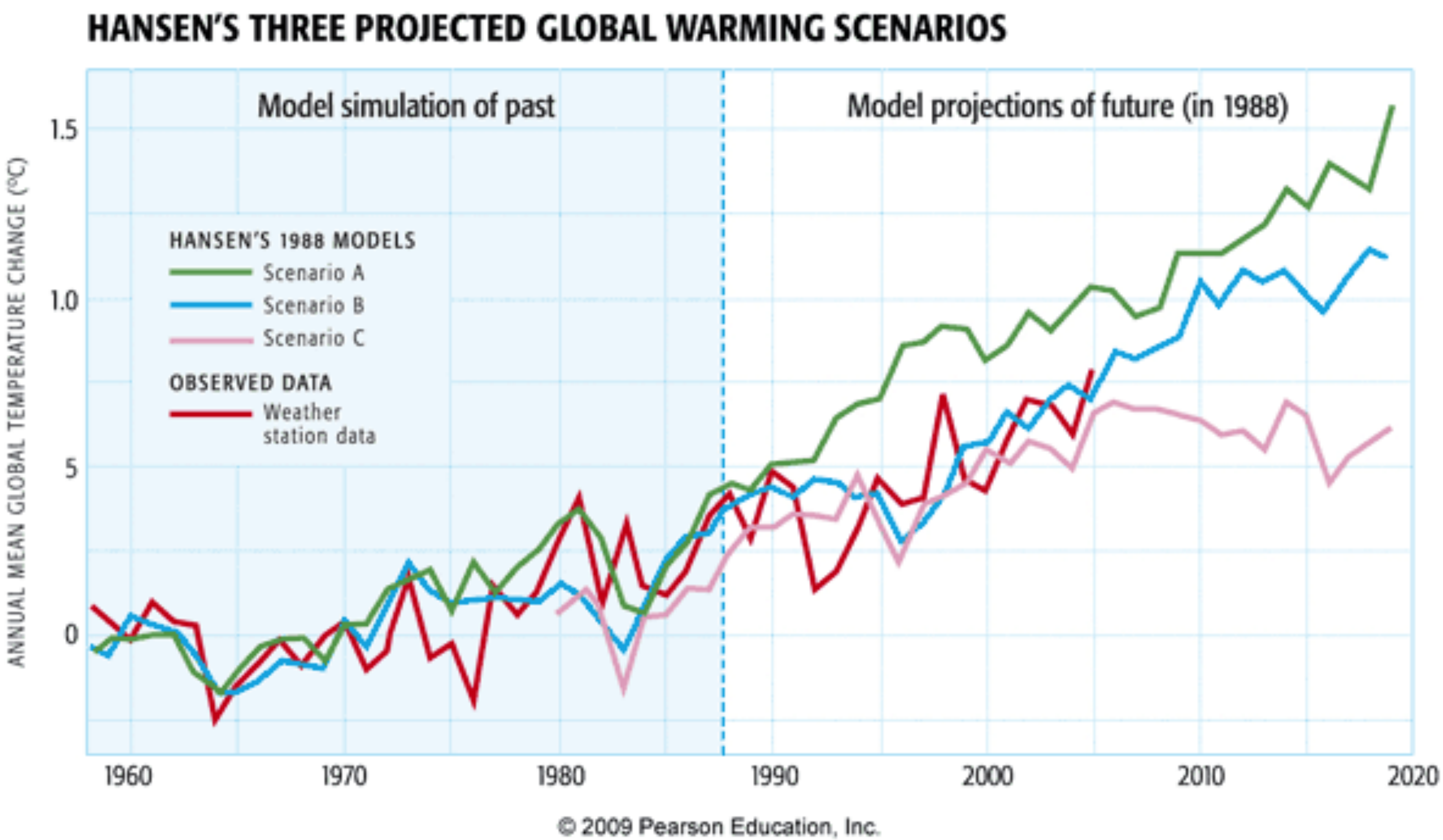
The concept of reanalysis

Include DATA ASSIMILATION into the model
to stay as close as possible to reality

ERA-40 (1957-2002), 1.125°, 2.5°
ERA-Interim (1979-2012) 0.75°
NCEP2 (1979-2012)

Paleo simulations with data assimilation

Model validation



Model validation

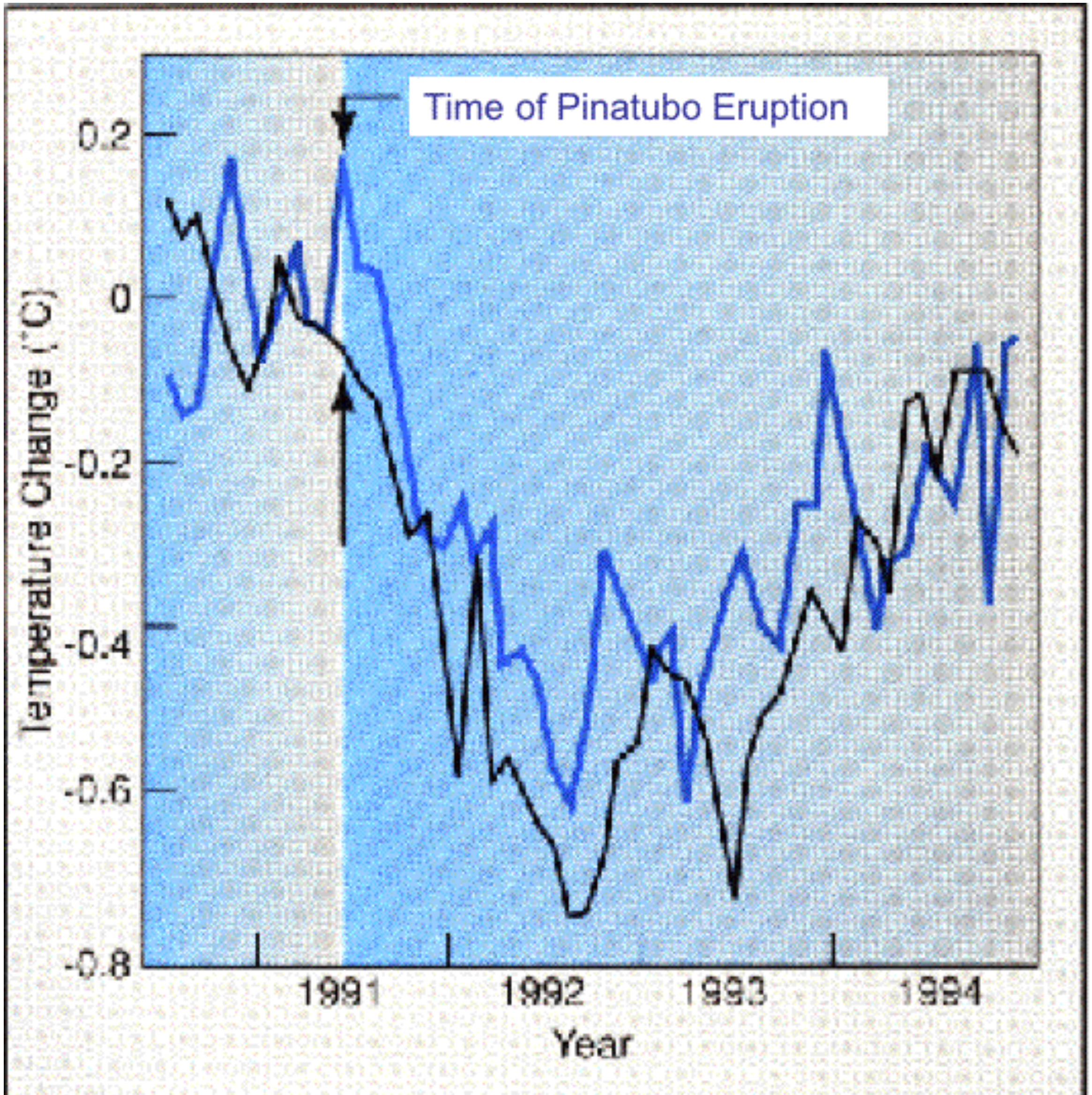


Figure 1 Comparison of modeled (black line) and observed (blue) impact of a major volcanic eruption on the temperature of the lower atmosphere. The eruption of Mt. Pinatubo in the Philippines, during June 1991, injected vast amounts of sulfur dioxide directly into the stratosphere. The gas quickly transformed into sulfuric acid particles that enshrouded the Earth and blocked part of the incoming solar radiation. The apparent effect is a drop of about 0.6°C in the globally-averaged temperature, lasting about two years. From J. Hansen *et al.*, in National Geographic Research and Exploration, vol 9, no 2, pp 142-158, 1993.

Reconstruction of past climates

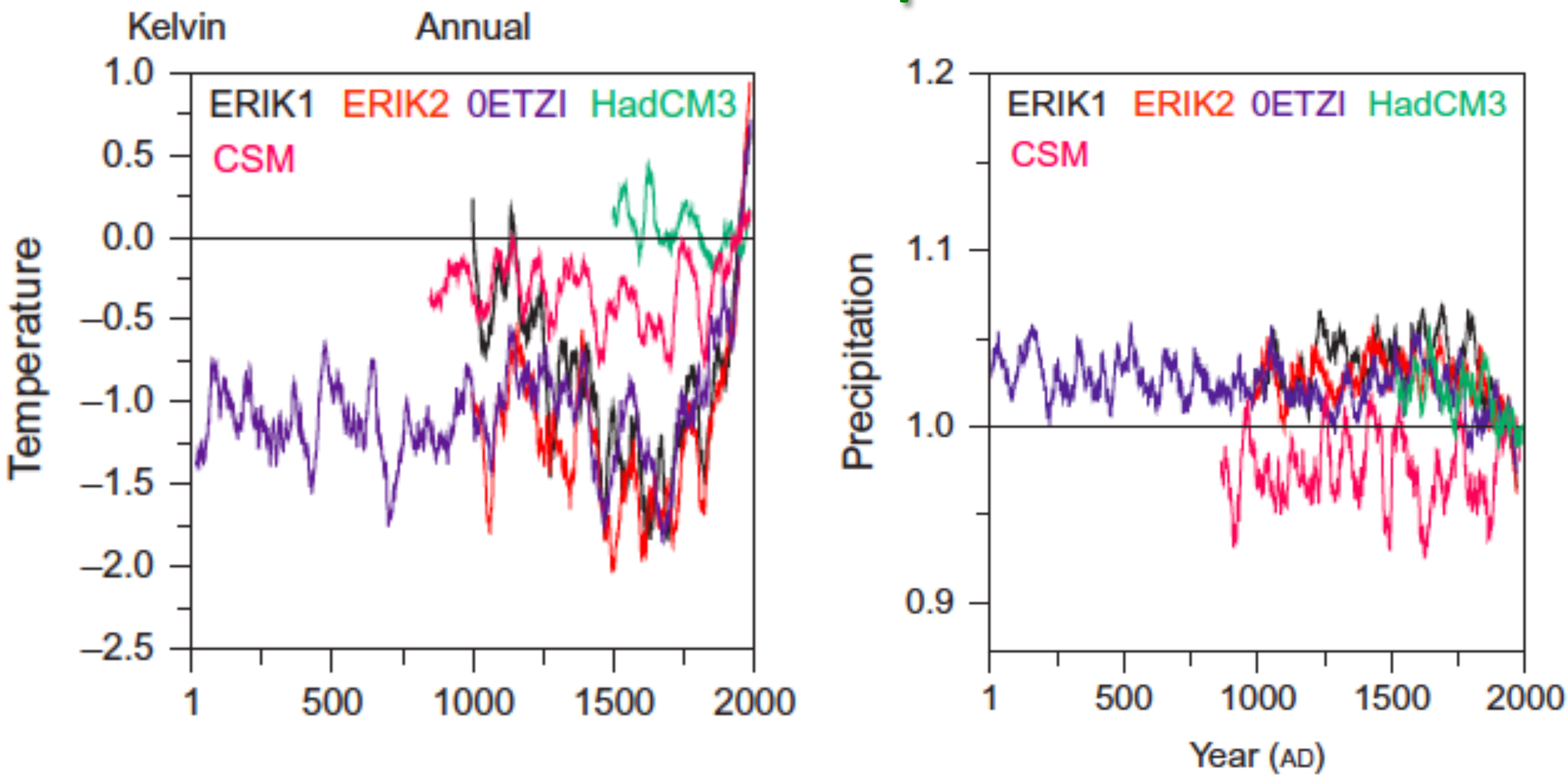


Figure 2.20 Evolution of the air temperature and precipitation in the Mediterranean region (30°N–45°N; 10°W–40°E) simulated by ECHO-G, HadCM3, and CCSM. The curves represent the respective temperature anomalies or the ratio to the mean precipitation in 1900–1990. All are smoothed with a 31-year running mean.

Luterbacher et al., Chapter in the 2012 MedCLIVAR book
A Review of 2000 Years of Paleoclimatic Evidence in the Mediterranean

Reconstruction of past climates

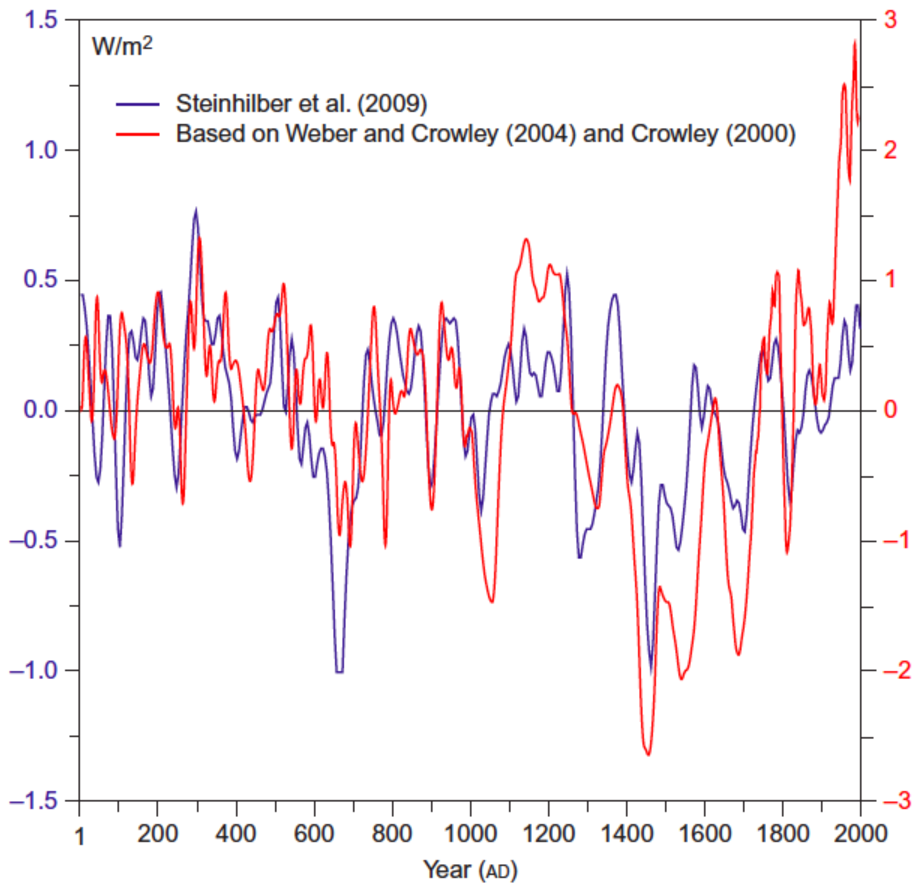
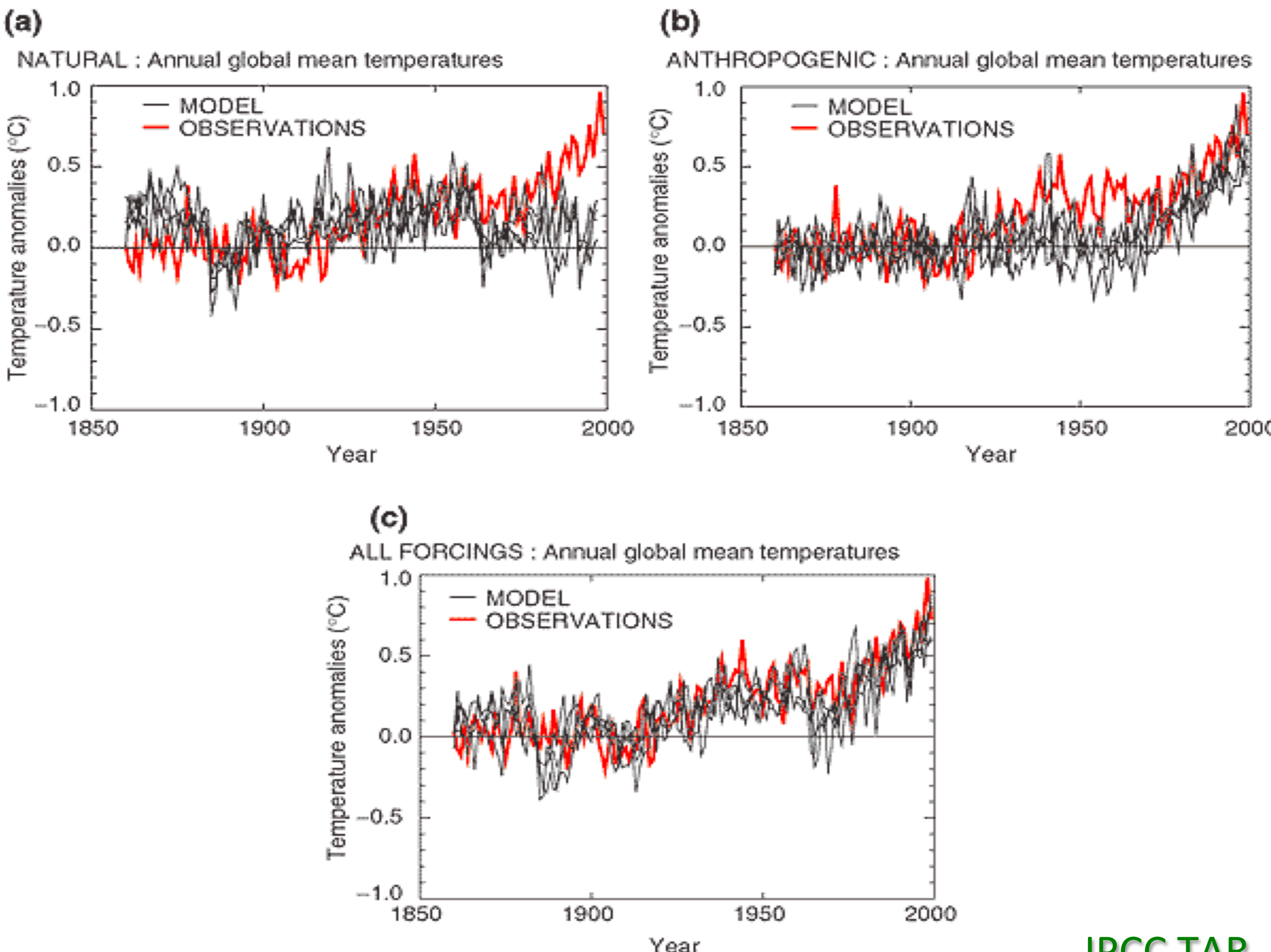


Figure 2.19 Reconstructions of total solar irradiance in the last 2k years. The record by Steinhilber et al. (2009) is based on the ^{10}Be record. The red line is based on the ^{14}C record in tree rings in 0–1000 and on ^{10}Be thereafter. Note the different scaling for both curves. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.)

Luterbacher et al., Chapter in the 2012 MedCLIVAR book

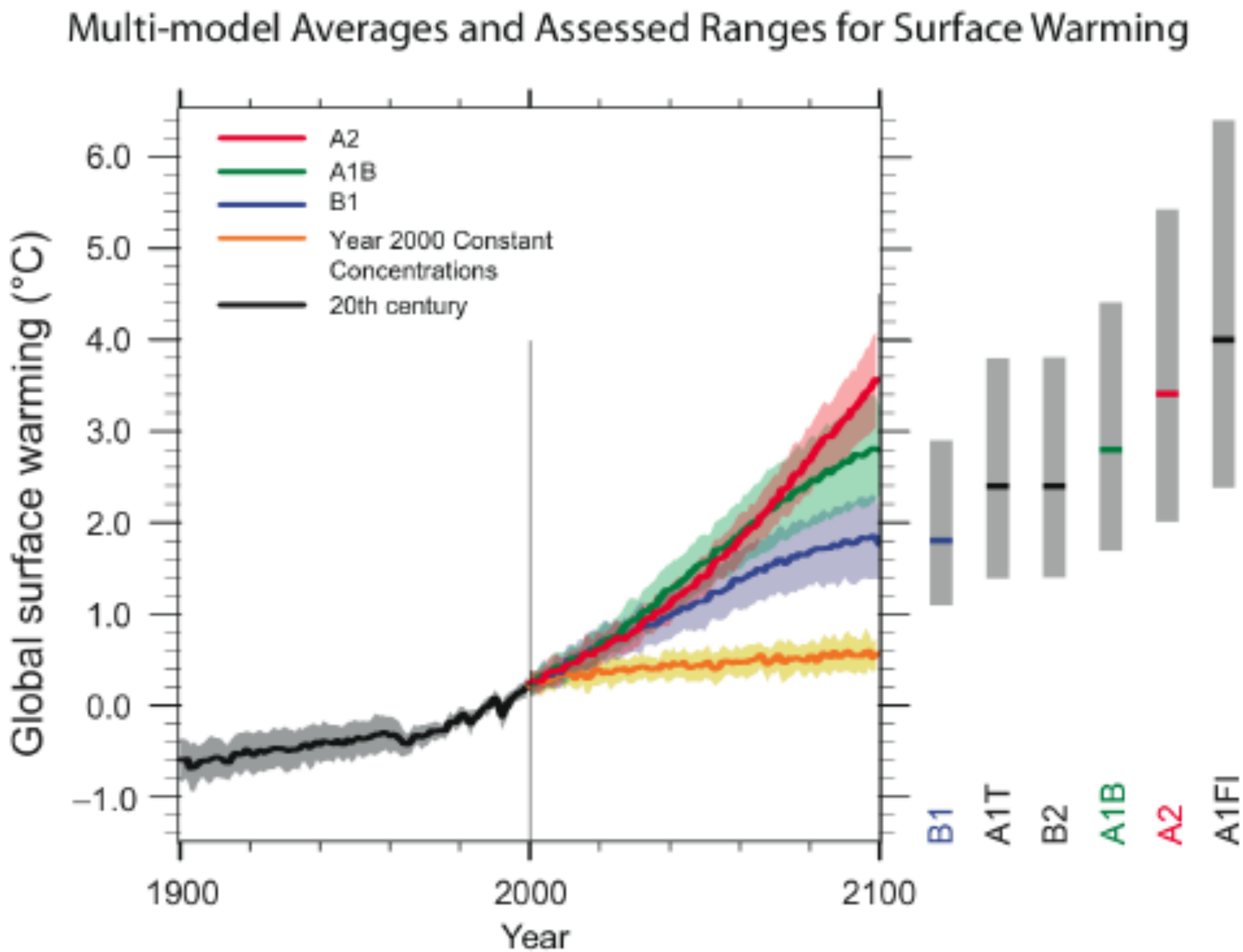
A Review of 2000 Years of Paleoclimatic Evidence in the Mediterranean

"What-if" experiments

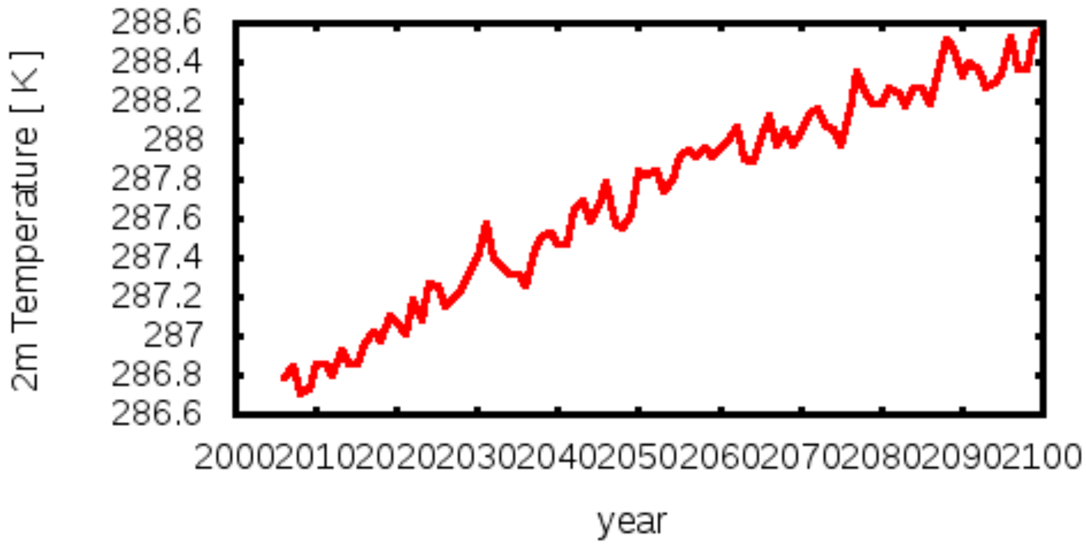


IPCC TAR, 2001

Simulations of future climate



Simulations of future climate (eg RCP4.5)



EC EARTH

an Earth-System-Model for climate studies

ISAC

The concept of seamless predictions

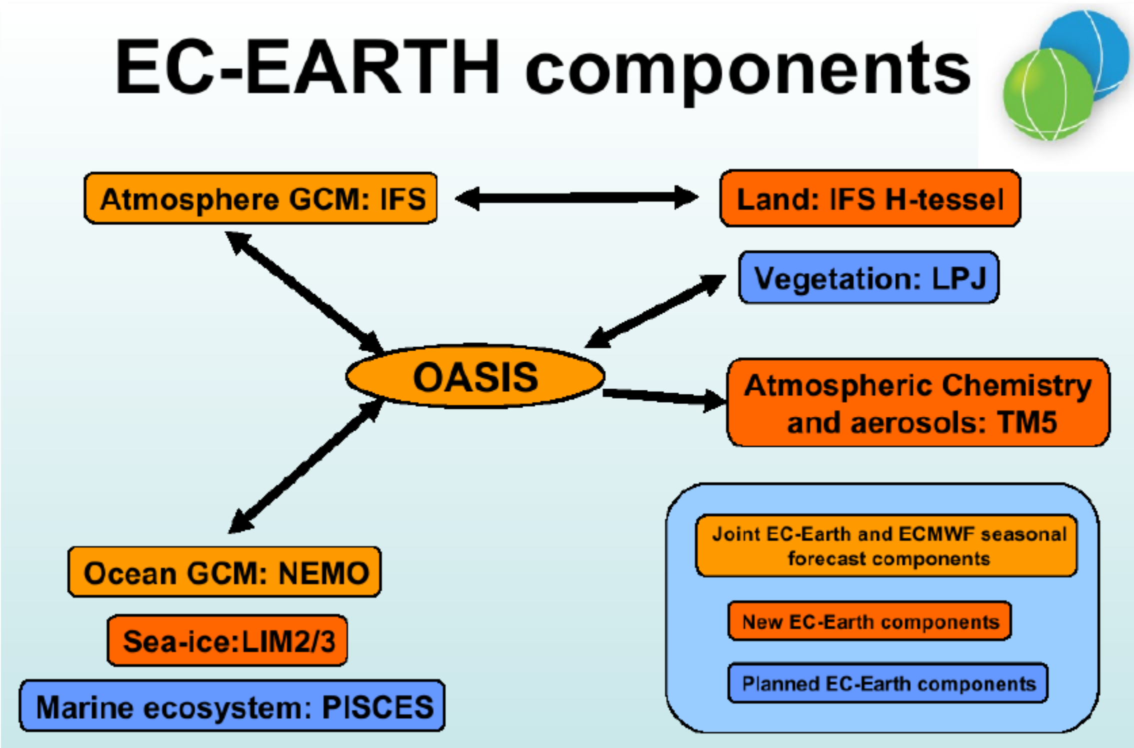
- Weather and Climate: Same physical processes (but acting on different space and time scales)
- Initial conditions vs boundary conditions (predictability of the first or second kind)
- From weather → to seasonal → to decadal predictions
- Advantages: climate models profit from advances in NWP and vice-versa

Ref.: Hazeleger, W. et al., 2009. EC-Earth: A Seamless Earth System Prediction Approach in Action. *Bull. Amer. Meteor. Soc.*, in press.

The EC-Earth Model

Based on the idea of “seamless predictions”

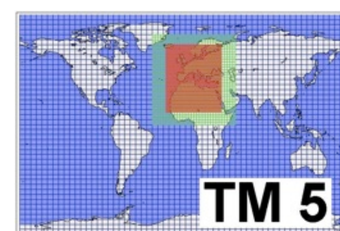
ECMWF IFS atmosphere (31r1 - T159L62/N80)+ Land/veg module
+ NEMO2 ocean (OPA/ORCA1) (1° L32)
+ TM5 chemistry/aerosols (6°x4° / 3°x2°)



Integrated Forecast System
ECMWF

NEMO

Nucleus for European
Modelling of the Ocean



TM5 atmospheric chemistry
and transport model

Ref.: Hazeleger, W. et al., 2009. EC-Earth: A Seamless Earth System Prediction Approach in Action. *Bull. Amer. Meteor. Soc.*, in press.

The Atmosphere: IFS

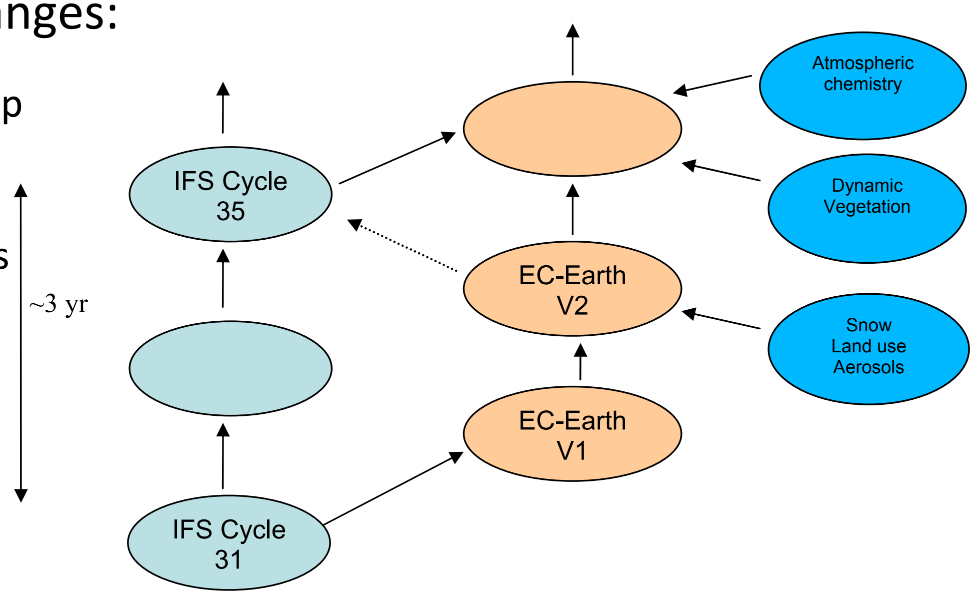
- The "Integrated Forecast System" is the NWP system in use at the European Centre for Medium-Range Weather Forecasts
- Spectral primitive equation model
- Semi-Lagrangian advection , 1h time step
- Current resolution for EC-Earth:
  T159 / N80 (1.125° ~ 125 km) reduced Gaussian grid /
  62 vertical levels up to 5 hPa.
- Cloud and radiation physics + aerosol direct and indirect effects.
- Based on IFS cycle 31r1, some changes:

  ✓ Better description of entrainment in deep convecting plumes
  (from cycle 32r3) →
  better precipitation patterns over tropics

  ✓ Better mass conservation correction scheme from cy33R2 →
  better mean atmospheric state

  ✓ Time-varying aerosols

  ✓ Ocean wave model not used



Ref.: Hazeleger et al. EC-Earth V2: description and validation … http://ecearth.knmi.nl/index.php?n=PmWiki.Papers

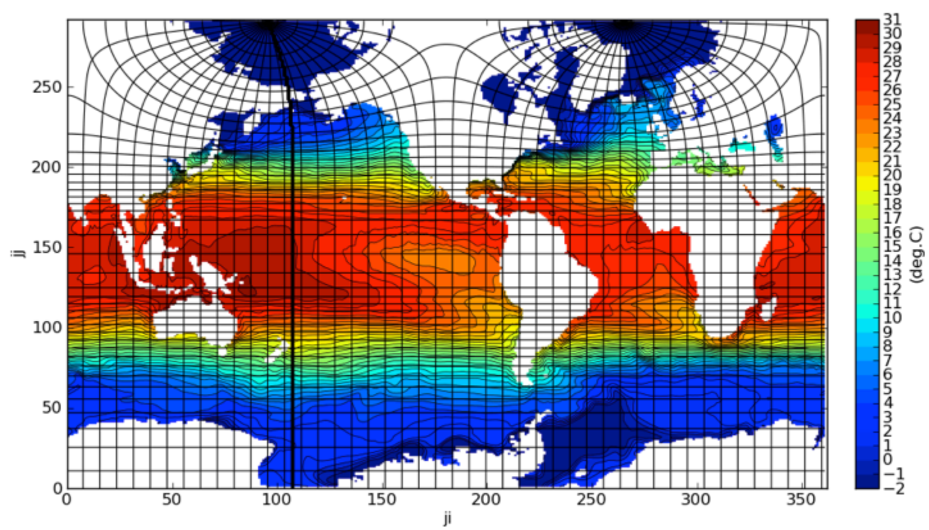
The Ocean: NEMO

The "Nucleus for European Modelling of the Ocean" is based on the OPA 9 (Océan Parallélisé) model:

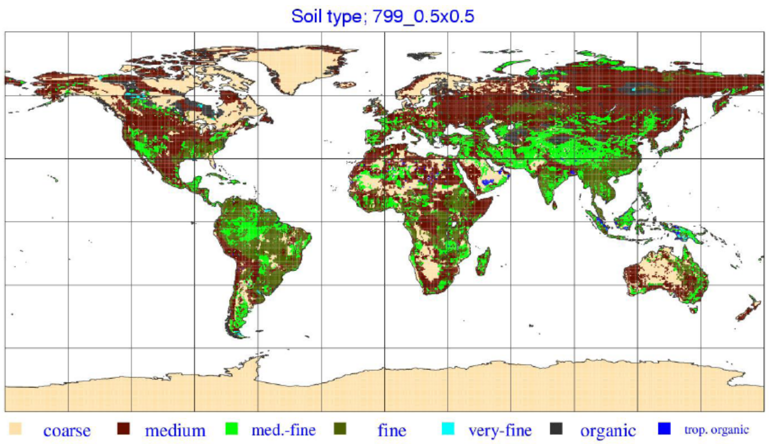
- NEMO2: Primitive equations, free surface, energy and enstrophy conserving momentum advection.
- TVD advection scheme (Zalesak 1979). Free slip lateral BCs.
- Gent and McWilliams (1990) vertical adiabatic mixing scheme for T and S
- Vertical eddy diffusion using TKE scheme (Gaspar et al. 1990).

- ORCA1 grid: Arakawa-C, about 1° resolution (not constant), higher resolution (1/3°) near the equator. Tripolar grid. 42 levels.

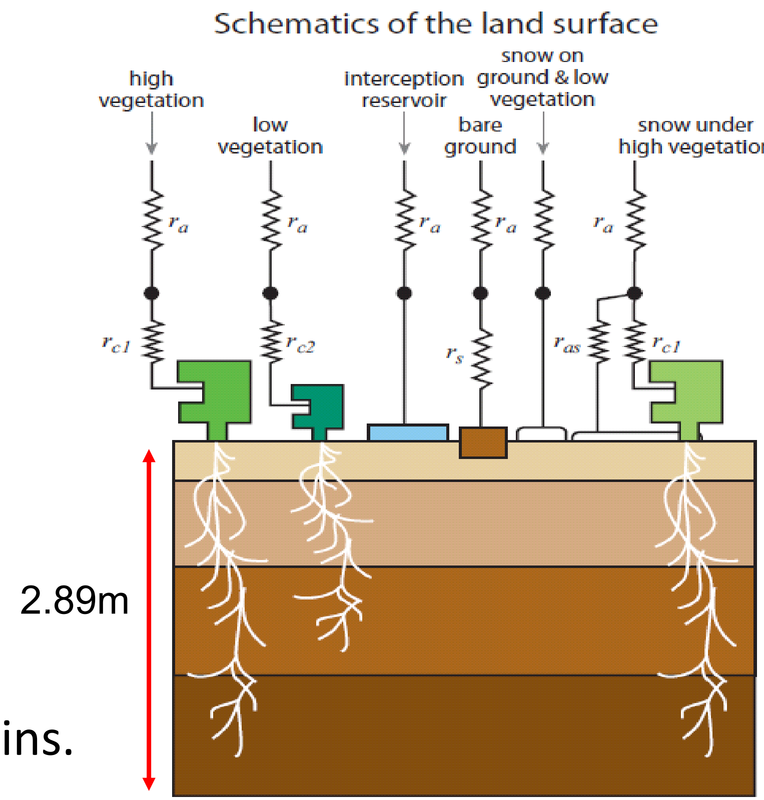
- + Louvain La Neuve Ice Model (LIM2) for sea-ice (3-layer thermodynamic model)



Land Surface: H-TESSEL



- Water + heat exchanges
- 6 land tiles: bare ground, low and high vegetation, intercepted water, shaded and exposed snow

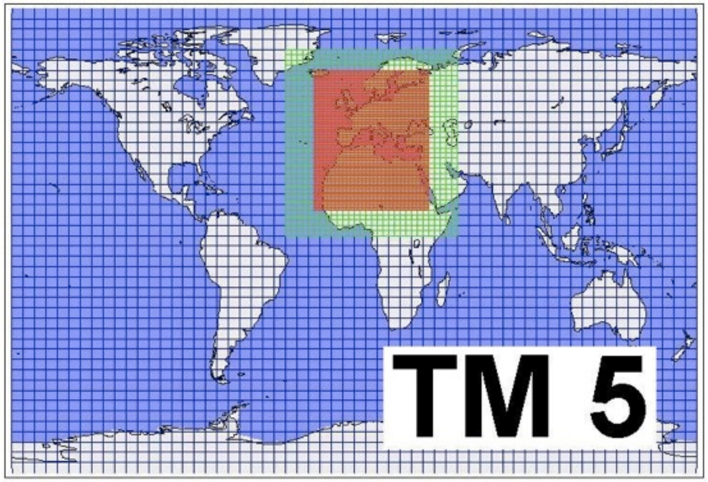


- Energy balance for each tile w/ vegetation evaporation, roughness and snow properties
- Snow albedo and density prognostic
- Parametrization of fast surface runoff
- Spatially varying soil textures + soil hydraulic properties
- Soil water flow: Richard's equation + van Genuchten for conductivity and diffusivity + 4 soil layers
- Instantaneous collection of runoff in river basins.

Refs:: van den Hurk et al. 2000, ECMWF tech. memo 295 + Balsamo et al. 2009, ECMWF tech. memo 563

To be coupled in the next versions:

Atmospheric chemistry and aerosols: TM5



- Tropospheric chemistry + aerosols
- Direct and indirect radiative forcing computed in IFS
- 3°x2° and 6°x4° resolutions
- Tropospheric photochemistry based on CBM (carbon bond mechanism) IV
- Aerosol mass and number concentration computed with M7 (Vignati et al. 2004)
- Online parametrizations for biogenic emissions.

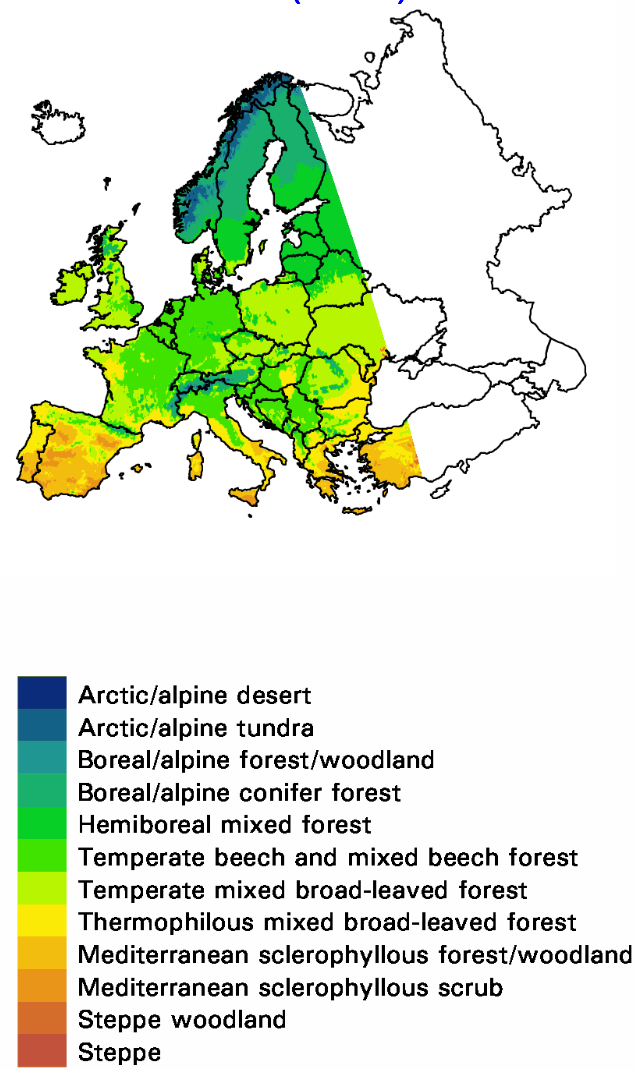
Ref.: Krol et al. 2005 ACP 5, 417-432.

To be coupled in the next versions:

Vegetation and biogeochemistry: LPJ-GUESS

General Ecosystem Simulator (GUESS), +
Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ)

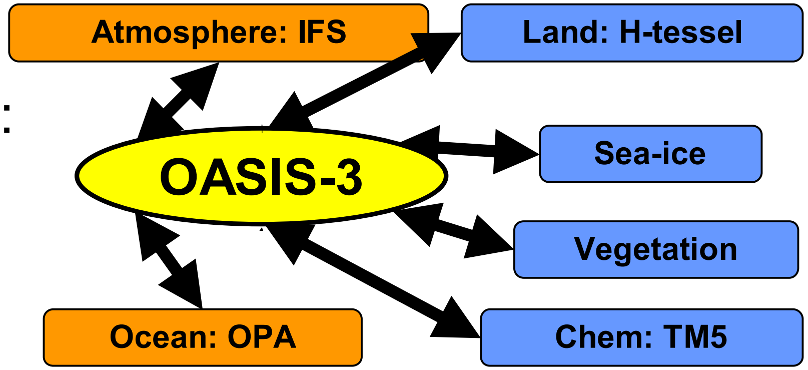
- Plant physiology + ecosystem biogeochemistry
- Functional types, vegetation dynamics + canopy structure
- Stochastic establishment, individual tree mortality and disturbances → successional vegetation dynamics
- Process-based description for the main biogenic volatile organic compounds



Ref.: Smith et al. 2001. Global ecology and biogeography, vol 10 (6).

The coupler: OASIS3

- All communication between Atmosphere, Ocean and Chemistry models occurs through the coupler.
- The coupler synchronizes the models, interpolates and transforms variables between the surface grids of the models.
- 39 2D coupling fields exchanged btw atmosphere and ocean, including:
  - Atmosphere→ ocean:
    wind-stresses, ocean temperature, heat flux, E-P, snow, runoff
  - Ocean→atmosphere:
    currents, SST, sea-ice temperature, albedo and thickness, snow thickness



- OASIS3 is single-processor. A parallel version is under development.

Boundary conditions and forcings

- Land and vegetation:
  - ✓ Low and high vegetation cover prescribed: GLCC database
  - ✓ Land-use scenarios for RCPs
  - ✓ Monthly varying albedo for each veg. type

- Anthropogenic and natural aerosols:
  - ✓ Sulfates, BC, OC, Sea-salt and desert dust concentrations are taken from the Community Atmosphere Model with IPCC emissions.
  - ✓ Monthly averages, 26 levels, 35x71 points.

- Volcanic aerosols:
  - ✓ Monthly fields of volcanic AOD based on GISS data (1850-2010) including major eruptions.

- Greenhouse gases:
  - ✓ Global averaged annual values for CO2, CH4 and N2O based on IIASA concentrations.
  - ✓ CFC-11 and CFC-12 computed based on annual emissions.

- Solar forcing:
  - ✓ Forcing data (SPARC) based on reconstruction w/ solar flux model based on sunspot and facular timeseries. Before 1850 mean of reconstructed 1844-1856 irradiance. After 2008 last solar cycle is repeated.

Implementation on Matrix (CINECA) and benchmark

- Implemented on the Matrix cluster @CASPUR:
  - ✓ 22TFlop Linux Clustervision cluster
  - ✓ 640 Quad core AMD nodes
- Typical EC-Earth configuration:
  - ✓ 96 cores: 63 cores (IFS) + 4x8 (NEMO) + 1 OASIS3
  - ✓ 1 model year = 600 cpu-hours = 6 hours wall time
- Benchmark run:
  - ✓ Same initial conditions for all consortium members
  - ✓ 10 years (1990-1999)

Results for year 1999 (calculated the same way as for 1990)

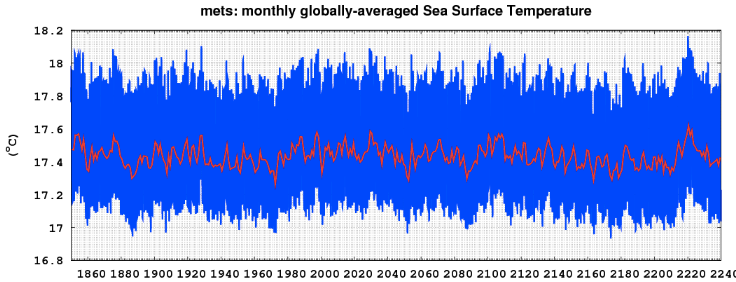
	T2M (K)	TCC (fraction)	TTR (W/m2)	TSR (W/m2)	SSHF (W/m2)	SLHF (W/m2)	MSL (hPa)	TP (mm/day)	SST (ºC)	SSS (psu)	SSH (m)
MISU	286.484	0.6325	-241.055	242.026	-18.397	-82.248	1010.96	2.856	12.969	24.800	0.926
ISAC	286.503	0.6342	-240.941	241.767	-18.473	-82.091	1010.965	2.850	12.954	24.796	0.926
UL	286.36	0.636	-240.6	241.36	-18.349	-82.118	1011.0	2.851	12.897	24.771	0.923
fjka - c1a prepIFS	286.478	0.6336	-240.872	241.773	-18.451	-81.989	1010.946	2.847	12.955	24.805	0.927
BSC/IC3 (MareNostrum)	286.323	0.634	-240.652	241.501	-18.407	-81.986	1010.940	2.848	12.893	24.774	0.926
DMI	286.474	0.633	-240.863	241.839	-18.490	-81.922	1010.96	2.846	12.971	24.815	0.926

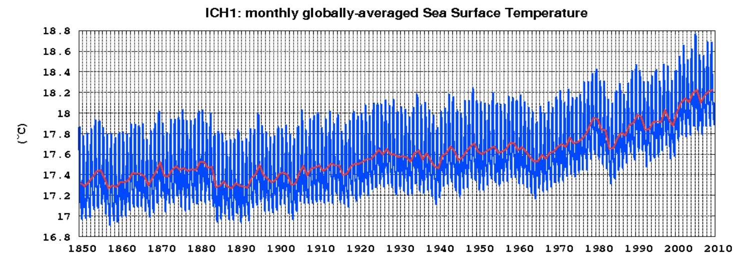
Current simulations (ISAC) Historical runs and scenarios (CMIP5)

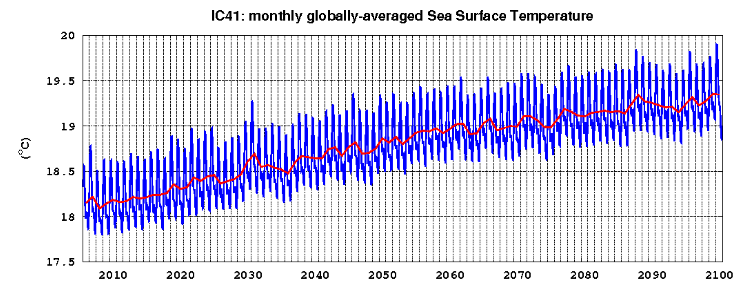
- Pre-industrial spin-up and control run (700 yrs – by MetEireann)

- Industrial simulation 1850-2005 (using historical GHG and aerosol concentration fields) (16 member ensemble created by consortium partners)

- RCP 4.5, RCP 8.5 + RCP 2.6 scenarios 2006-2100



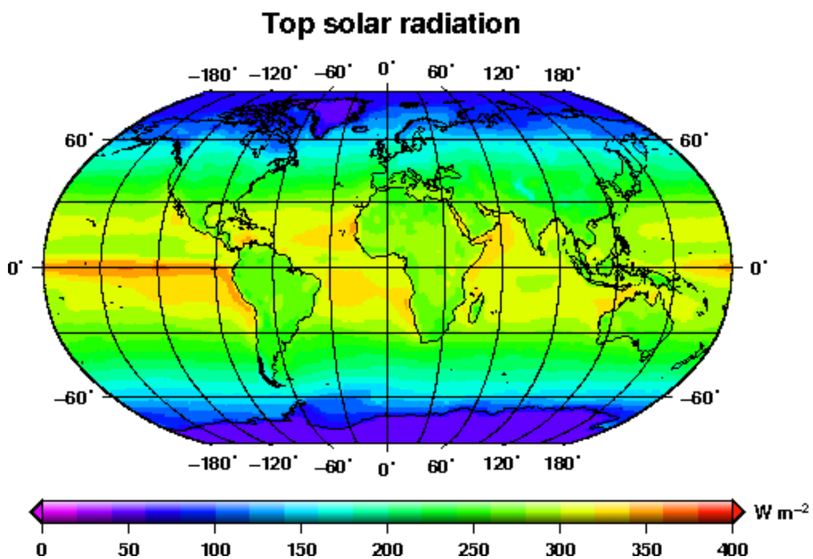




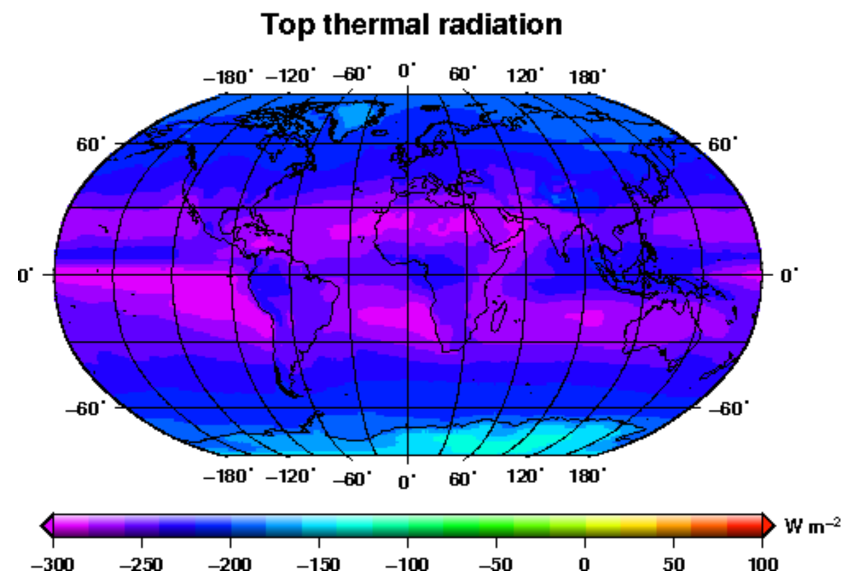
Data produced (historical): 15TB+ 30TB (scenarios)

Cpu time used: 95000 cpu-hours (historical run)
+ 60000 hours / scenario
63 cpus (IFS) + 32 cores (NEMO)

Present day climatology:
Top of atmosphere balance and meridional heat transport

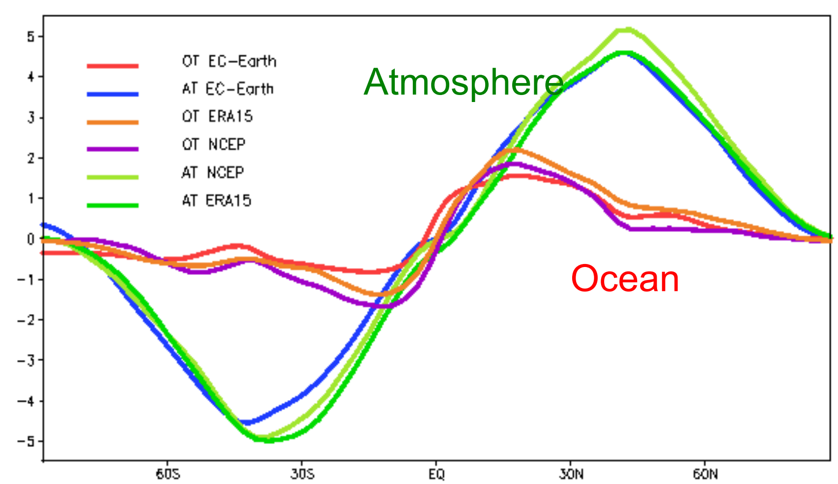


Top net shortwave: 242.6 W/m^2



Top net longwave: -242.7 W/m^2

Meridional heat transport (10^{15} W)



Based on 440 year present-day (2000) run:

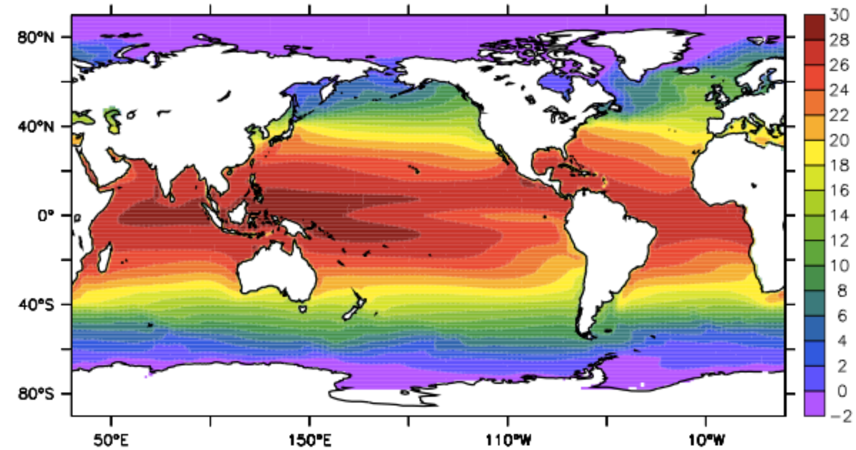
Ref.: Hazeleger, W. et al.,
EC-Earth v2: description and validation.
Submitted to Climate Dynamics (2011)

Present day climatology: Ocean

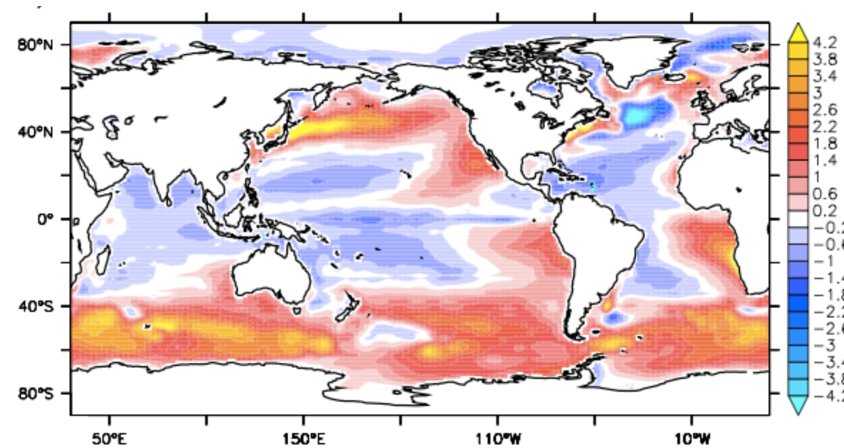
Transport through straits and AMOC

Section		PI	PD	observation
Drake Passage	annual	103	109	134
Indonesian	Jan	7.2	7	
Throughflow	Jul	20.2	16	
	annual	13.3	12.6	15
Florida Strait	annual	19.4	19.5	25
Bering Strait	annual	1.3	1.5	0.8-1
Strait of Gibraltar	inflow	1.77	1.78	0.78
	outflow	1.73	1.74	0.67
NAC	annual	40.8	44.5	51
AMOC (30°N)	March	14.2	11.8	≈ 14
	Jul	19.4	16.3	≈ 21
	annual	16.5	14.5	18.7 ± 2.1

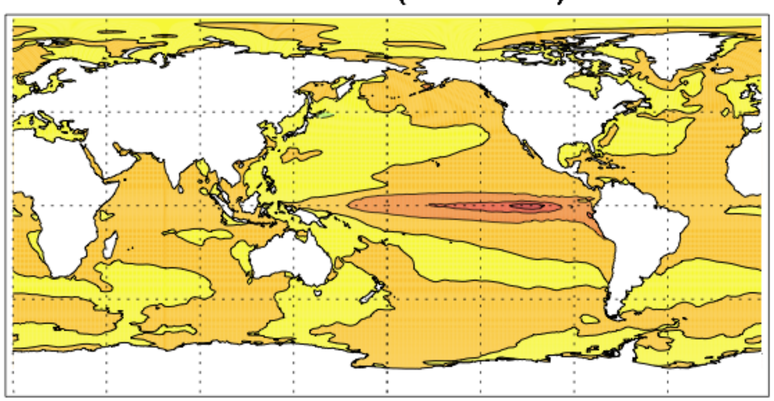
SST



SST-observed



El Nino (model)

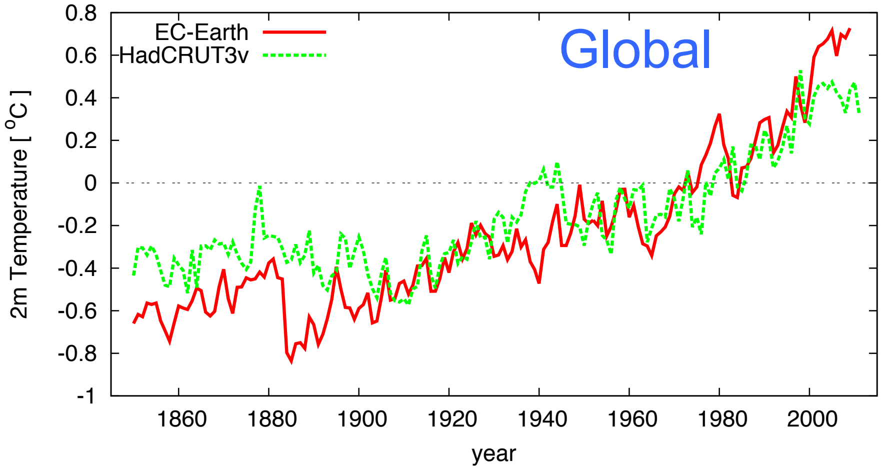


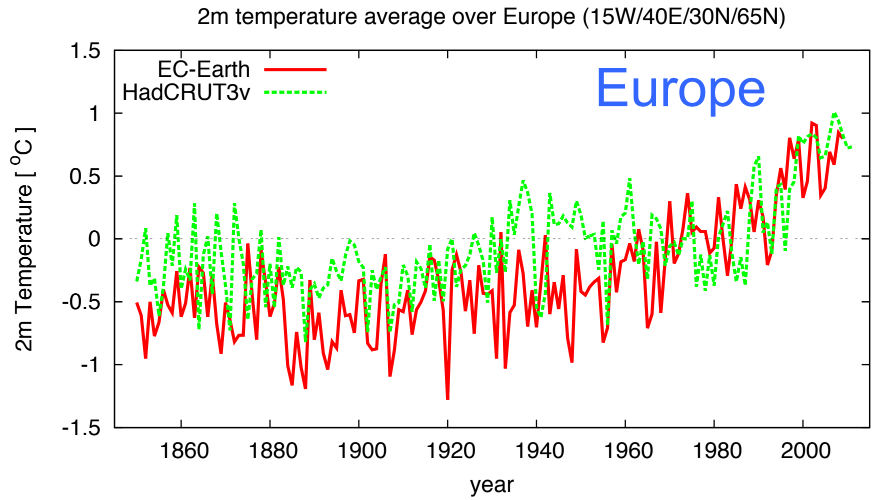
Ref.:

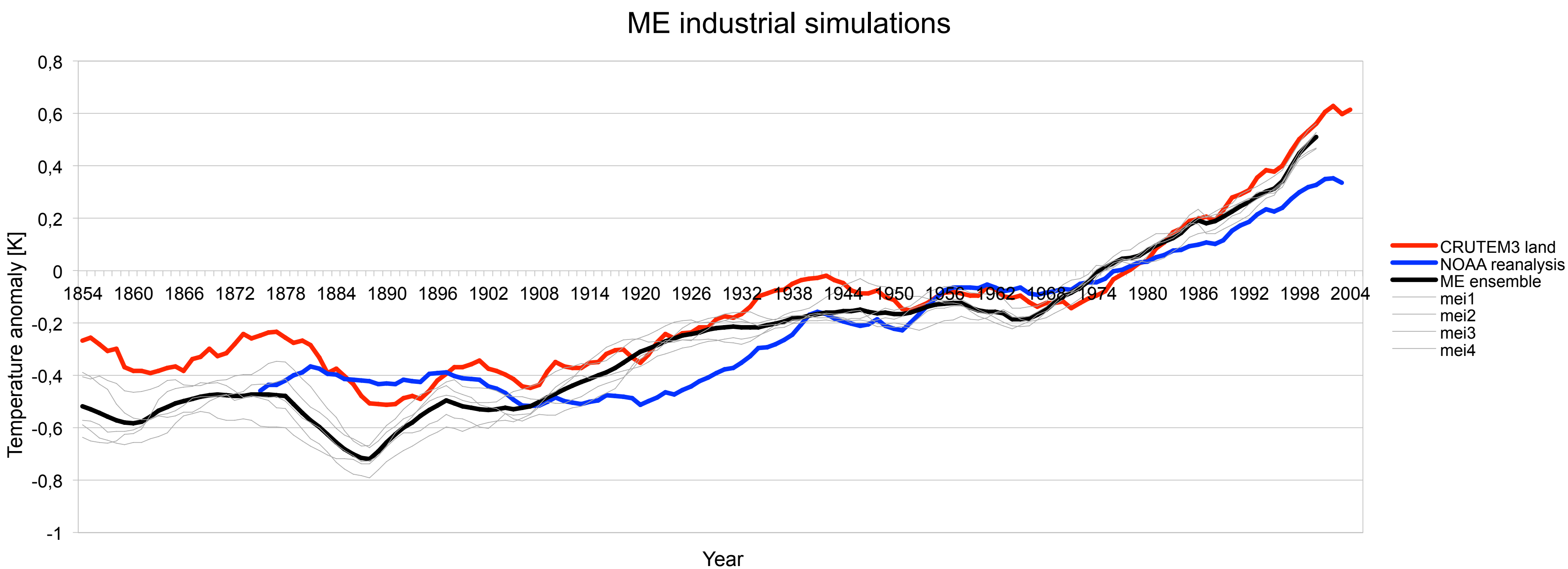
Sterl et al.

A look at the ocean in the EC-Earth climate model. Climate Dynamics (2011)

Historical run: surface temperatures

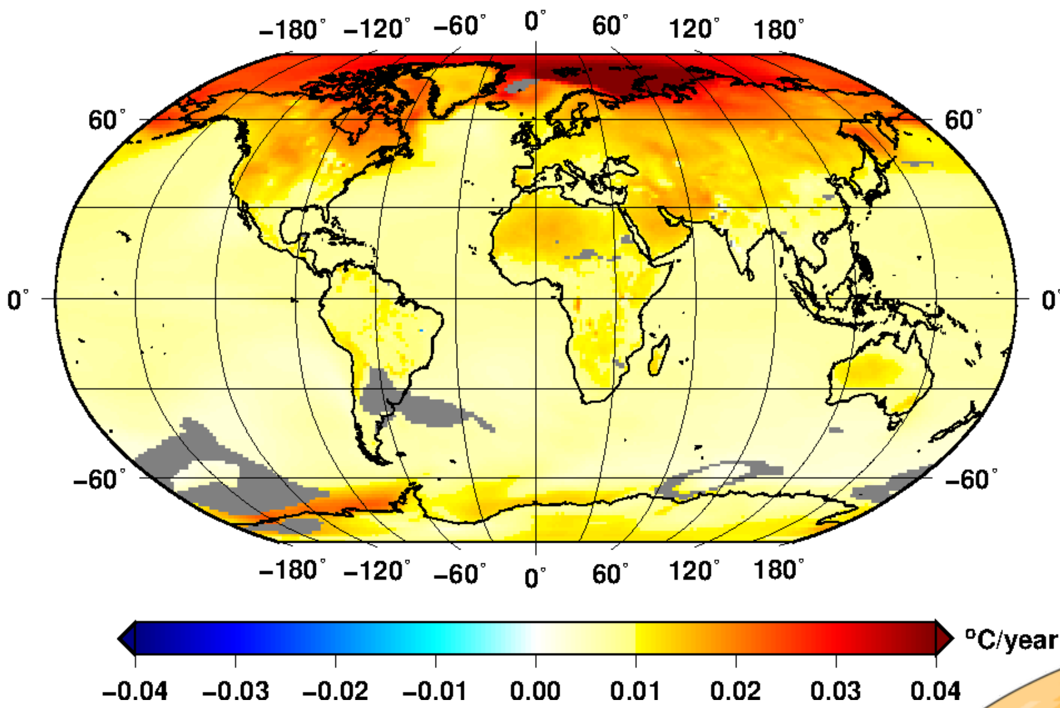




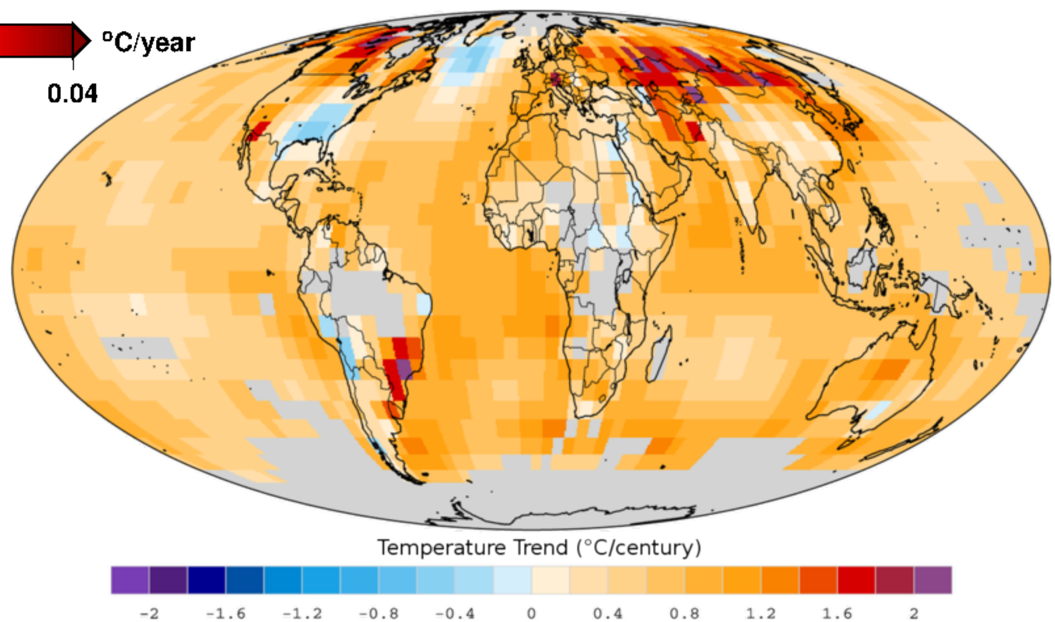


Global temperature trends

EC–Earth – Temperature trend 1880–2009

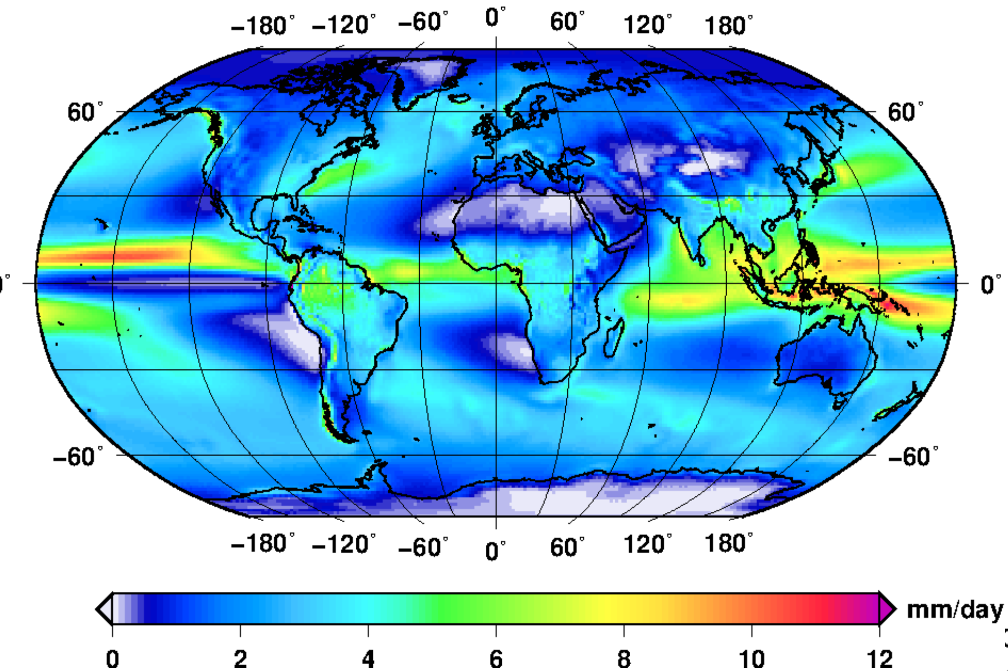


NCDC 1901-2008 trend



EC-Earth 2.3 climatology: Global precipitation

Total precipitation annual mean 1951–2007

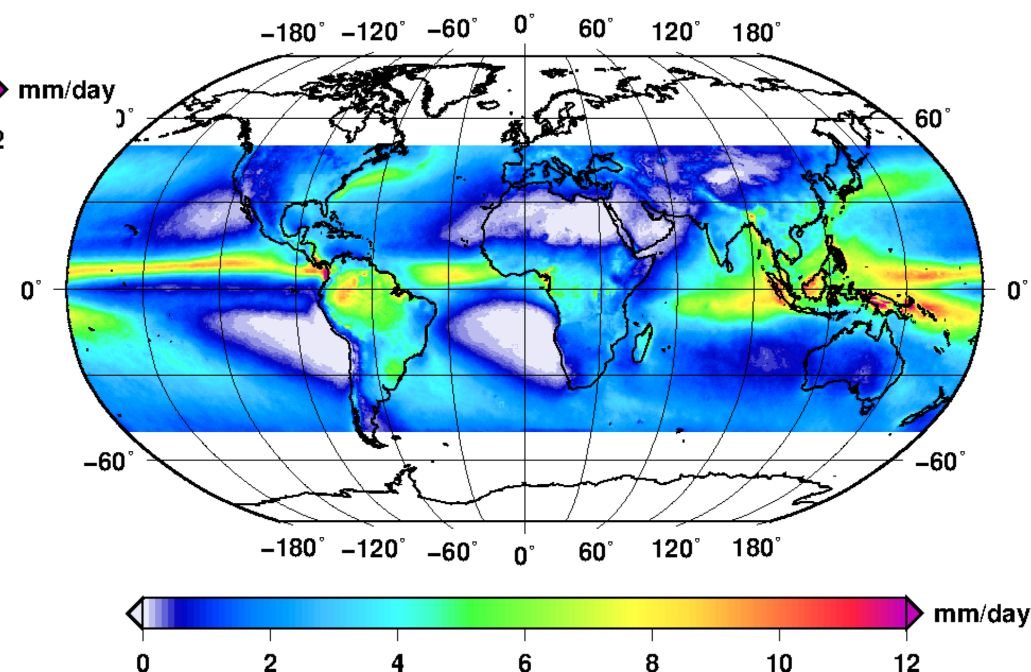


EC-Earth 2.3

TRMM (Tropical Rainfall Measuring Mission)

Product: 3B42: 3-Hour 0.25 x 0.25 ° (30x30 km) from 50°S-50°N

Total precipitation annual mean 1998–2008



EC-Earth 2.3 validation: Global precipitation

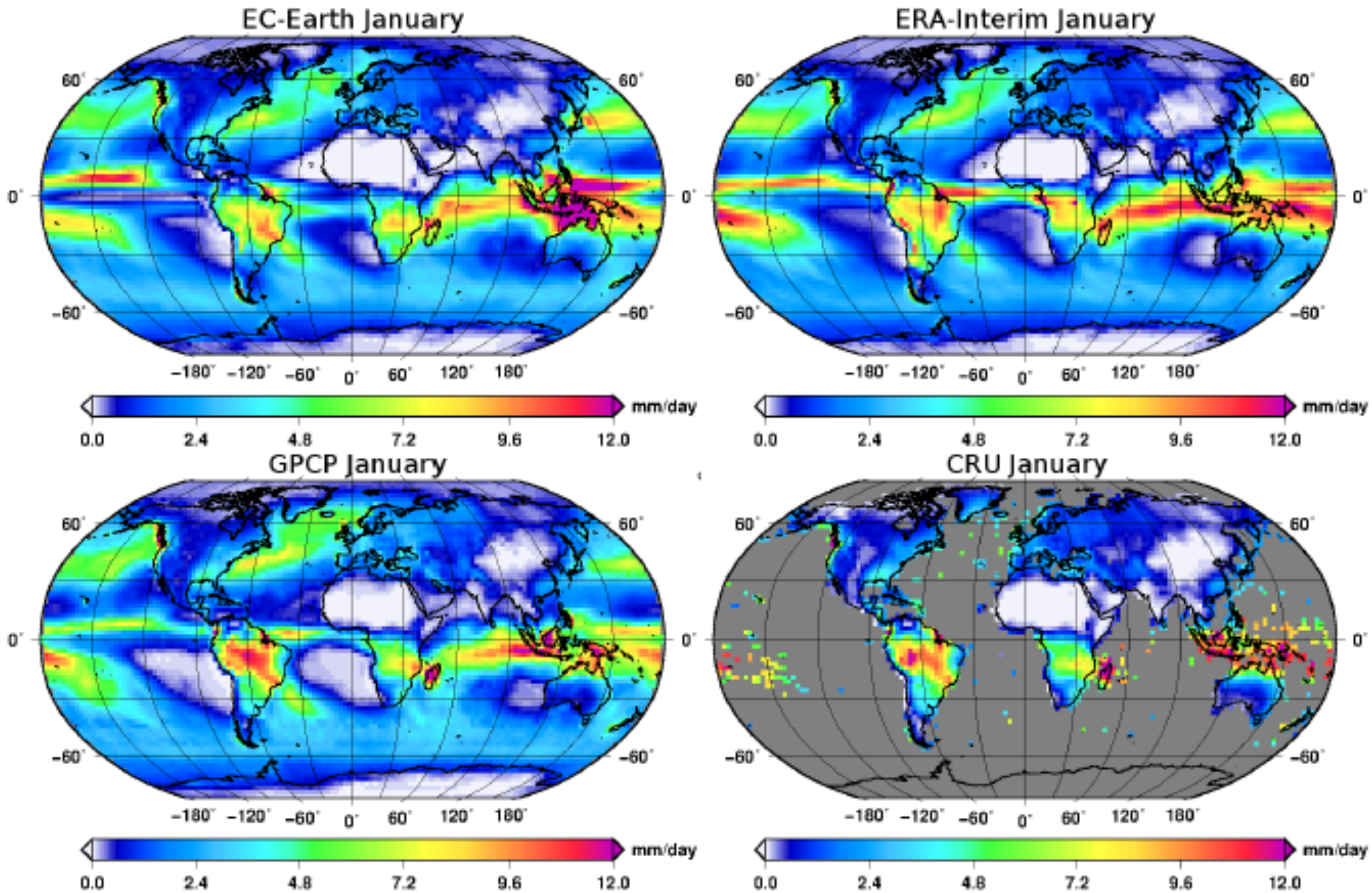


Figure 1: Multiannual mean (1980-2005) January precipitation from EC-Earth, ERA-Interim, GPCP and CRU.

L. Filippi, Master Thesis

EC-Earth 2.3 validation: Global precipitation

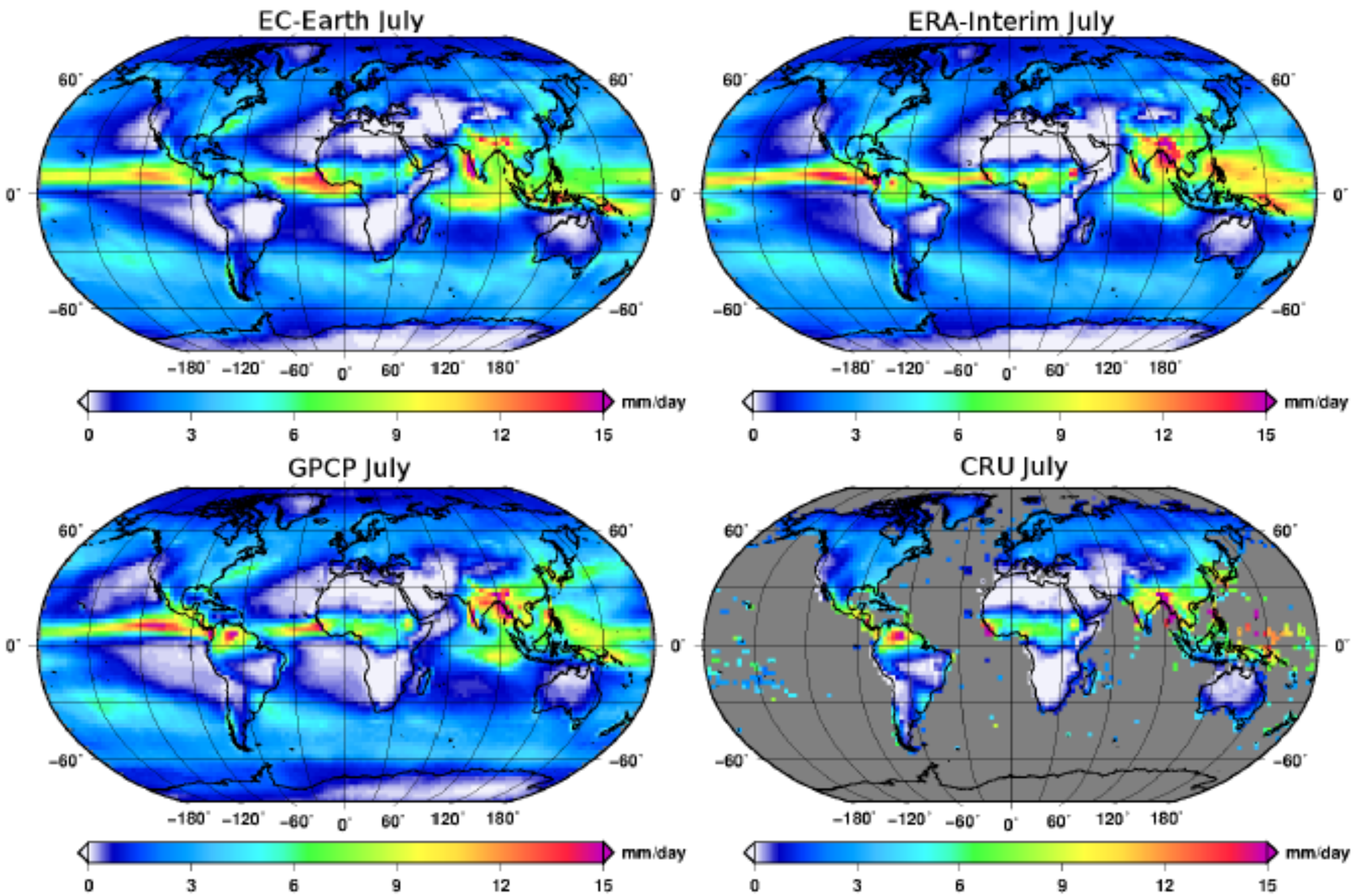
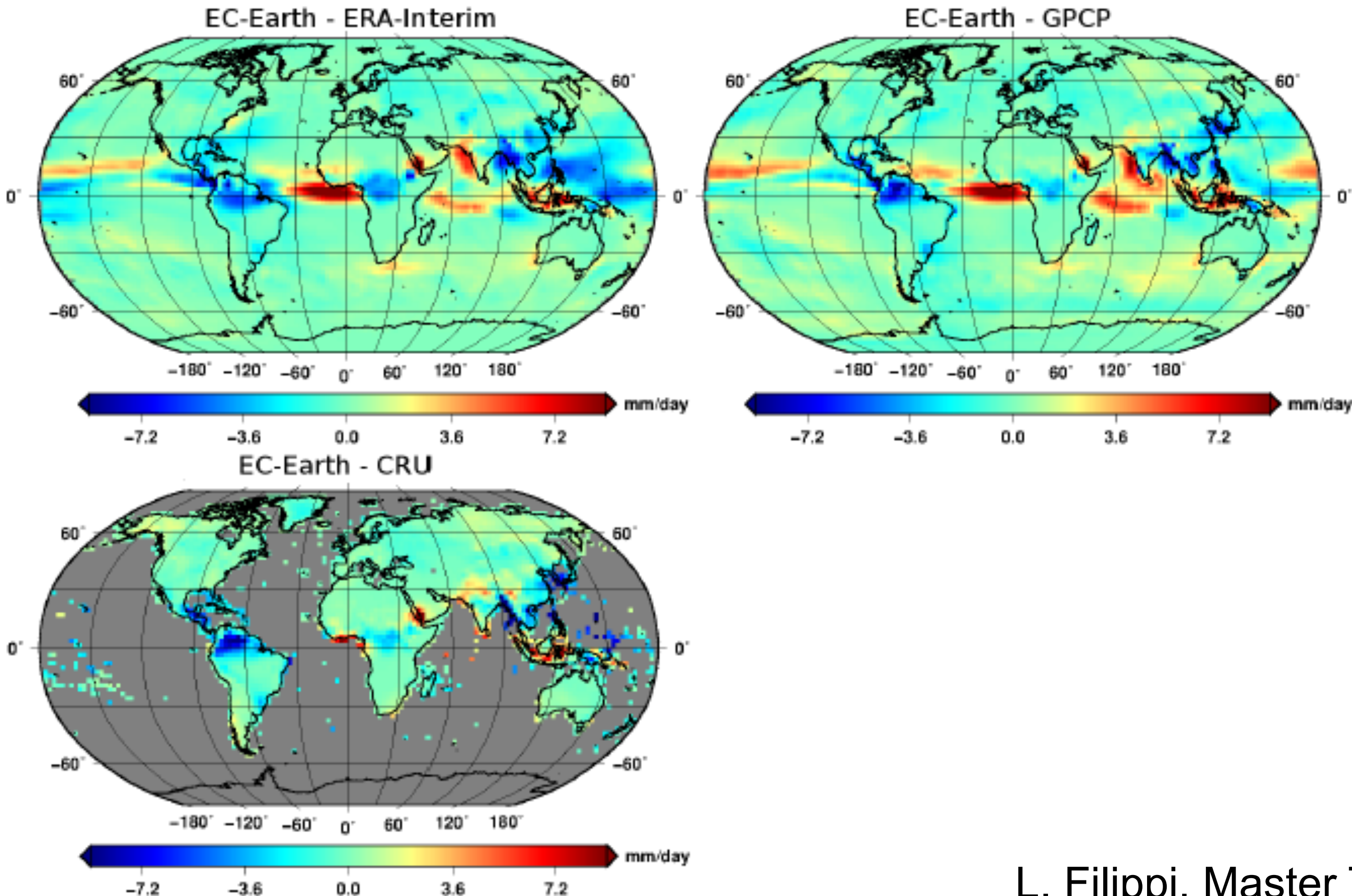


Figure 2: Multiannual mean (1980-2005) July precipitation from EC-Earth, ERA-Interim, GPCP and CRU.

L. Filippi, Master Thesis

EC-Earth 2.3 validation: Global precipitation



L. Filippi, Master Thesis

Figure 4: Differences of multiannual mean (1980-2005) July precipitation between EC-Earth and ERA-Interim, GPCP and CRU respectively.

EC-Earth 2.3 validation: Global precipitation

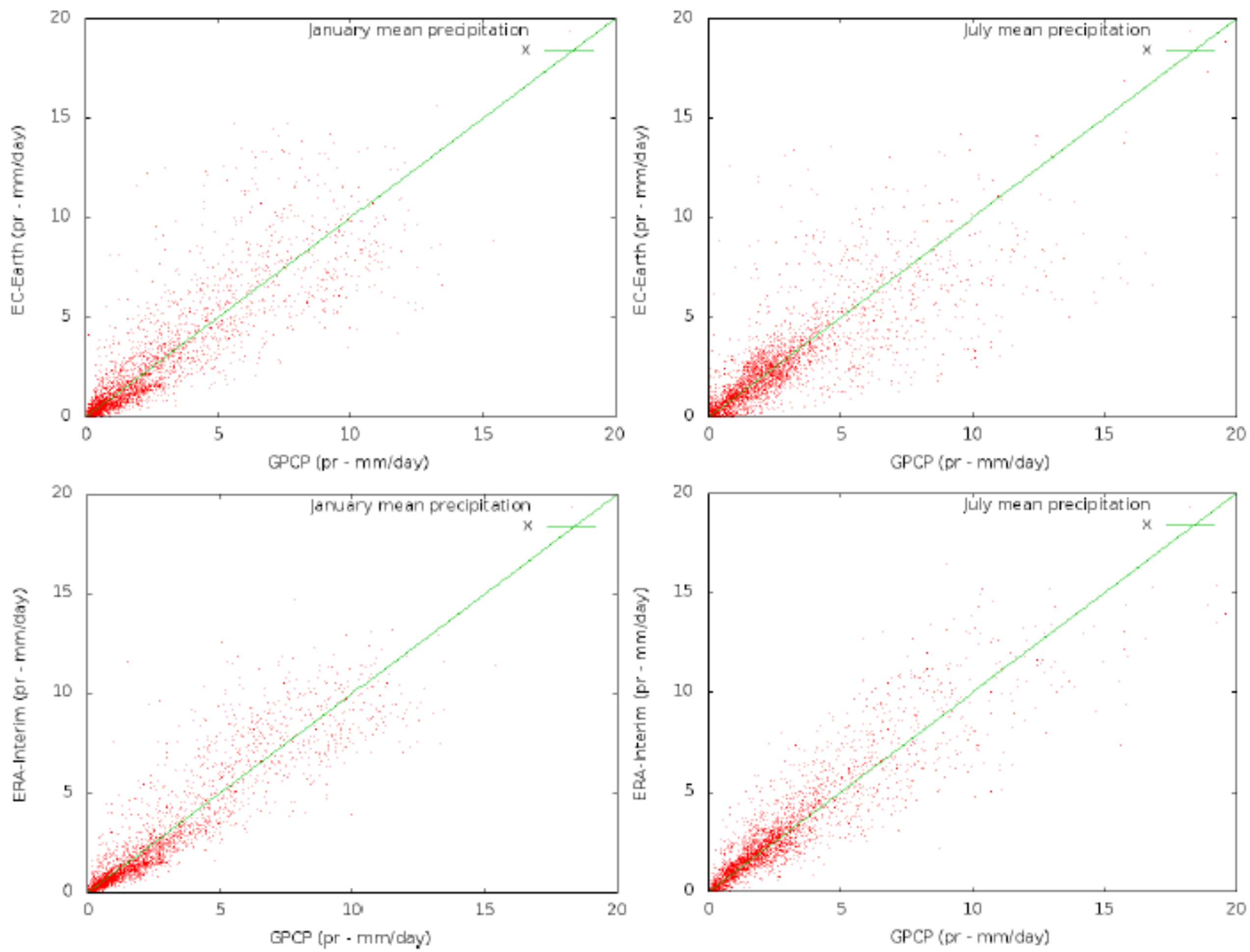


Figure 5: Scatterplots of multiannual mean (1980-2005) monthly precipitation between EC-Earth and GPCP (top) and ERA-Interim and GPCP (bottom) in January (left) and July (right). These scatterplots include only land grid points.

L. Filippi, Master Thesis

EC-Earth 2.3 validation: Global precipitation

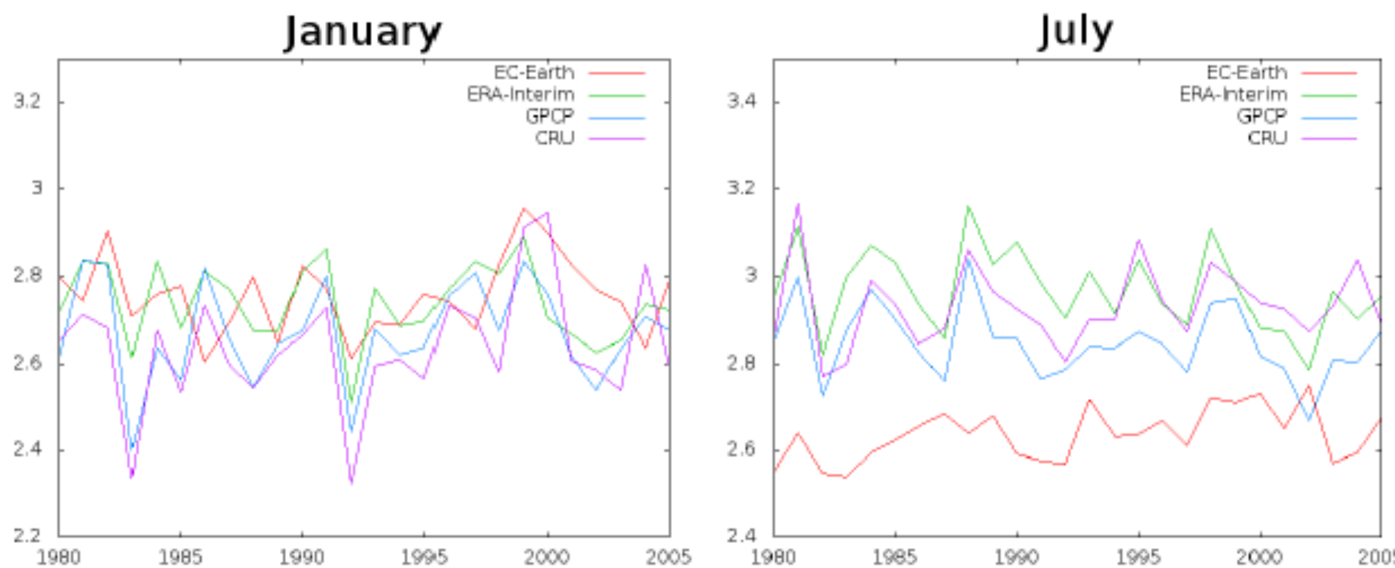


Figure 10: Time series of January (left) and July (right) precipitation spatially averaged over land for EC-Earth, ERA-Interim, GPCP and CRU.

L. Filippi, Master Thesis

EC-Earth 2.3 validation: Global precipitation

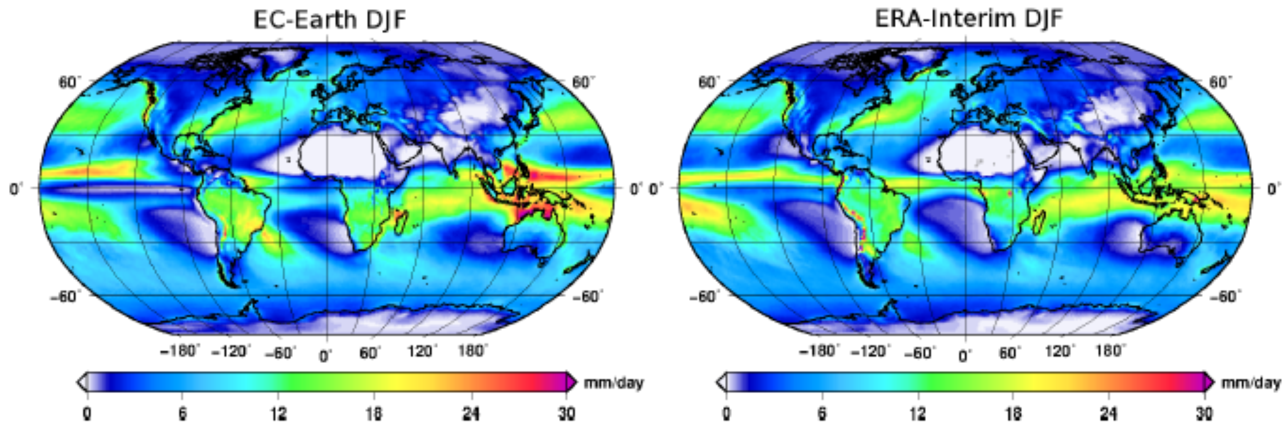


Figure 11: 90th percentile of daily precipitation distribution in winter (DJF) in EC-Earth (left) and in ERA-Interim (right).

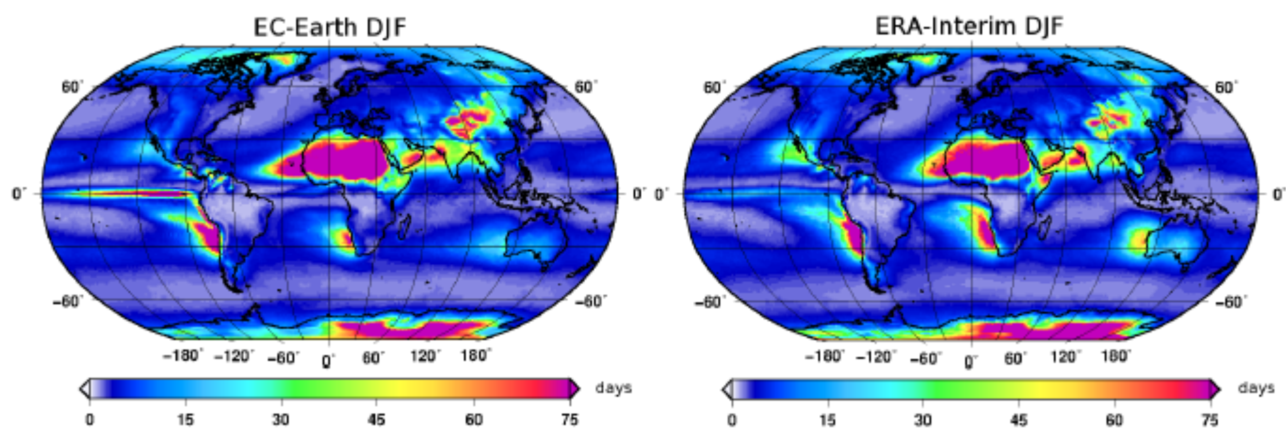


Figure 12: Average length of dry periods in winter (DJF) in EC-Earth (left) and in ERA-Interim (right).

L. Filippi, Master Thesis

Scenario runs:

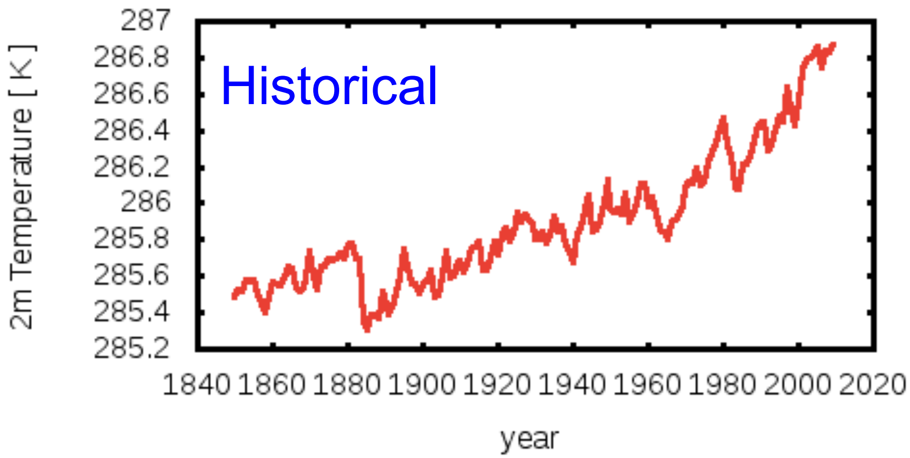
RCP 4.5

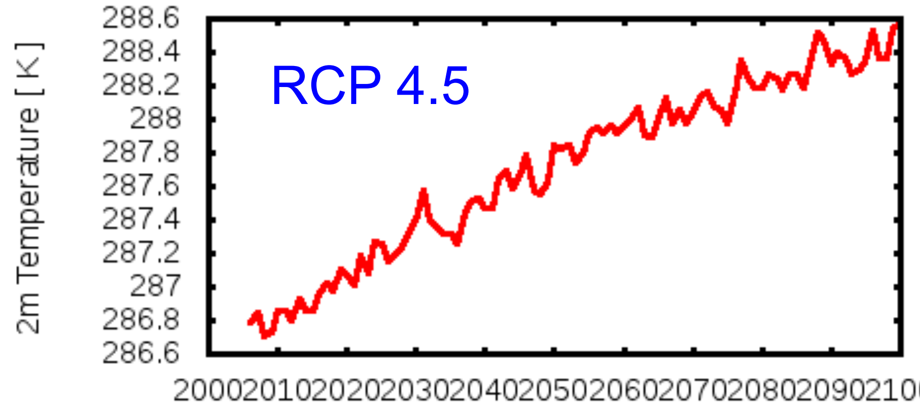
(stabilization of anthropogenic radiative forcing at 4.5 W/m^2 wrt to pre-industrial in 2100)

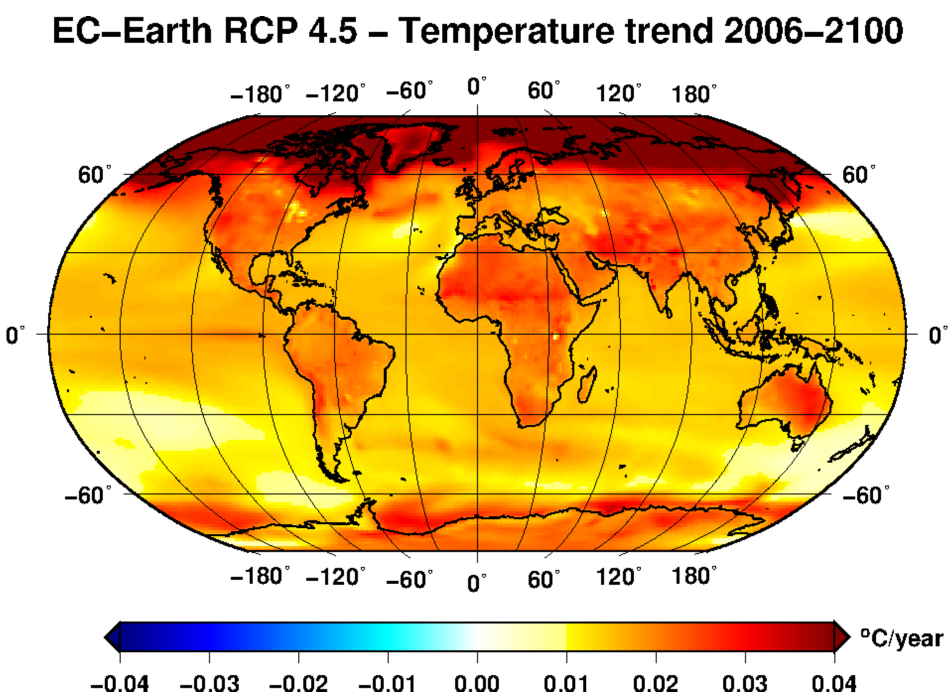
RCP 8.5

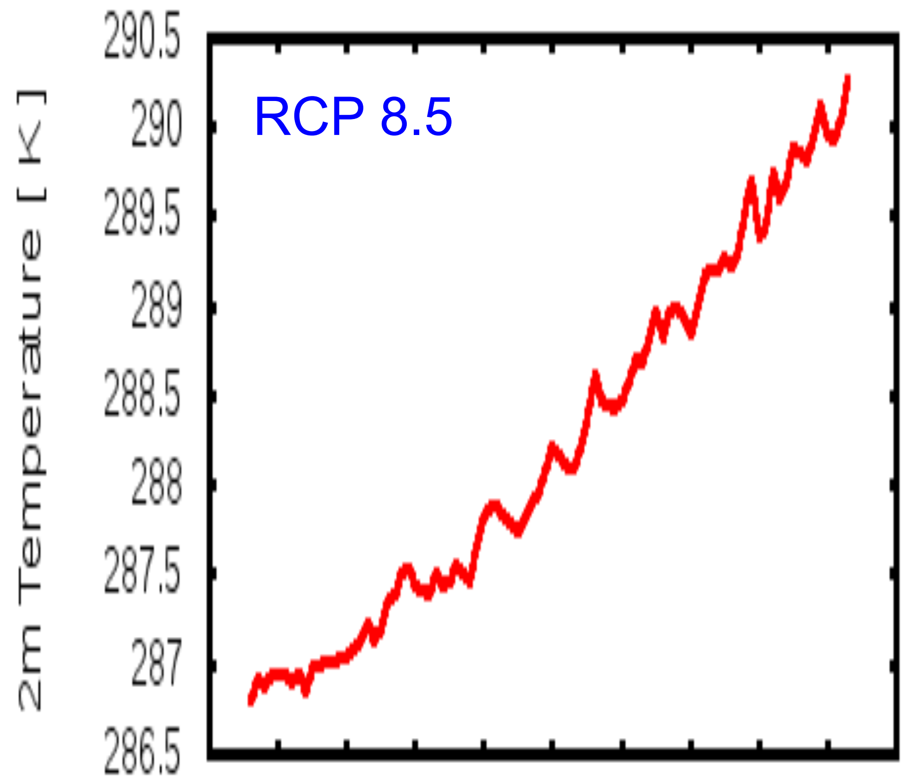
(increase of anthropogenic radiative forcing to 8.5 W/m^2 wrt to pre-industrial in 2100)

Global 2m temperatures

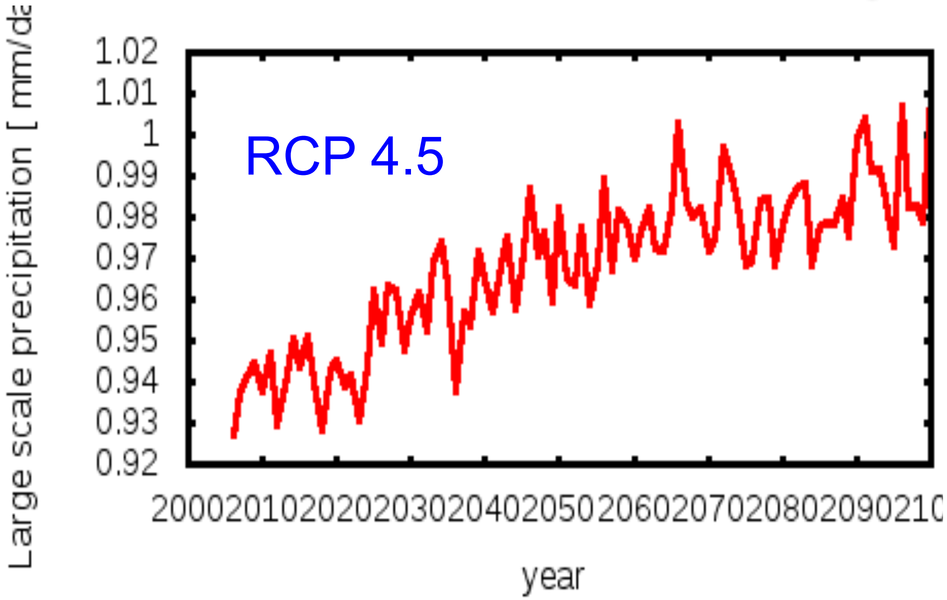


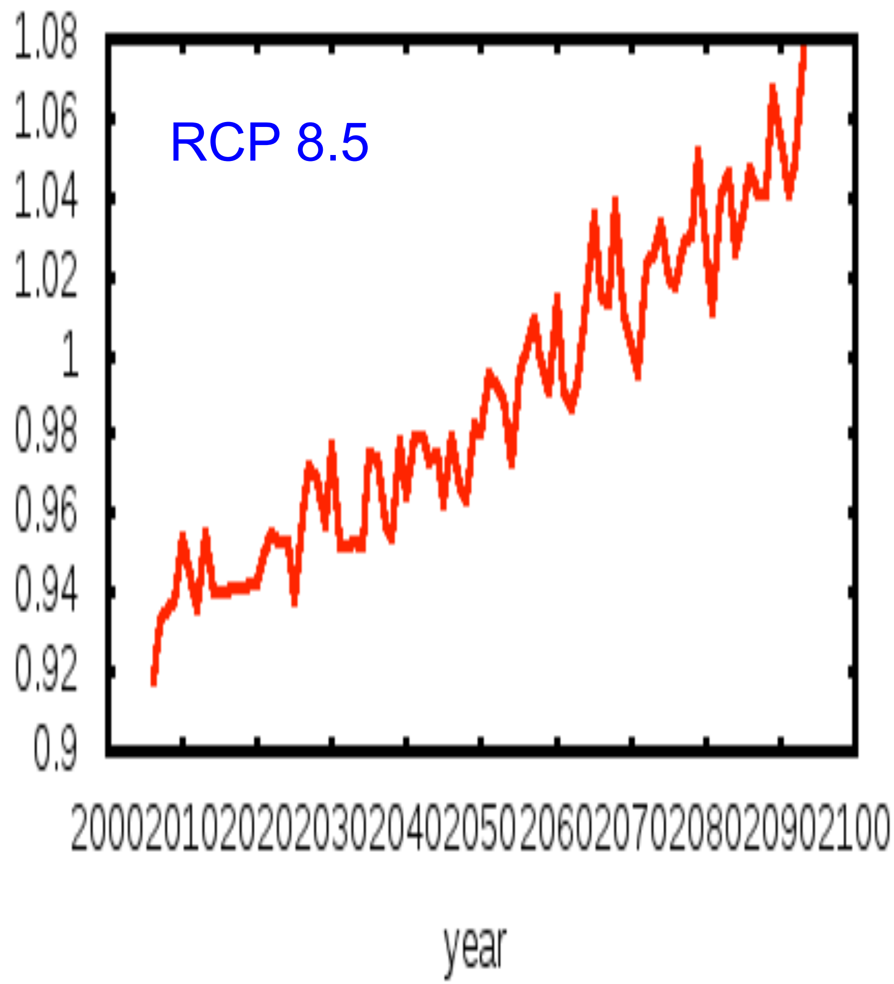


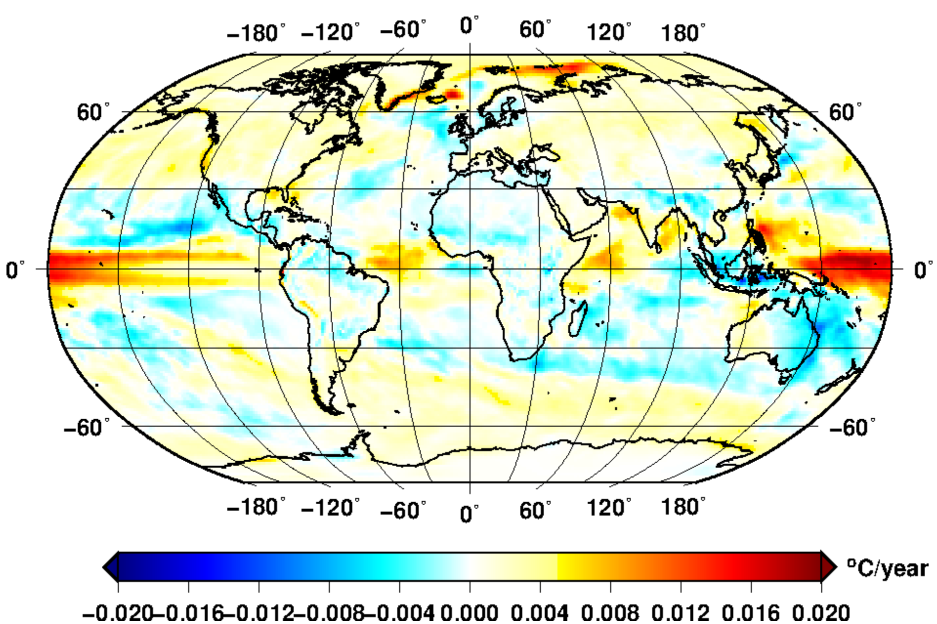




Precipitation

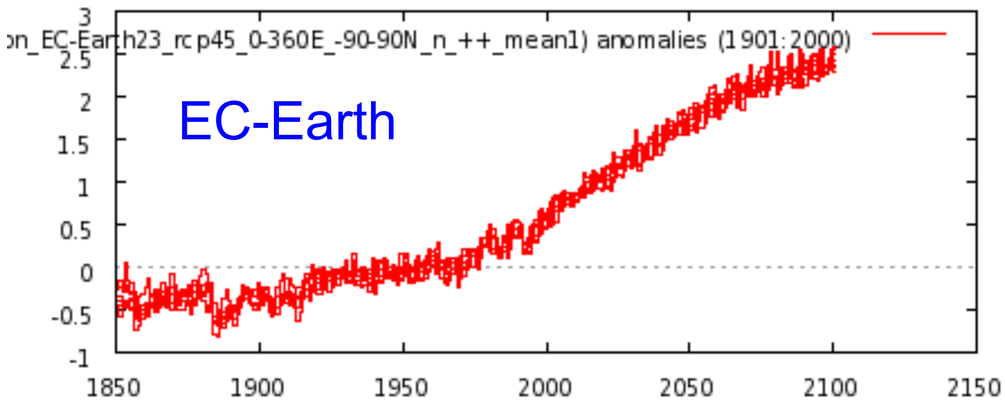


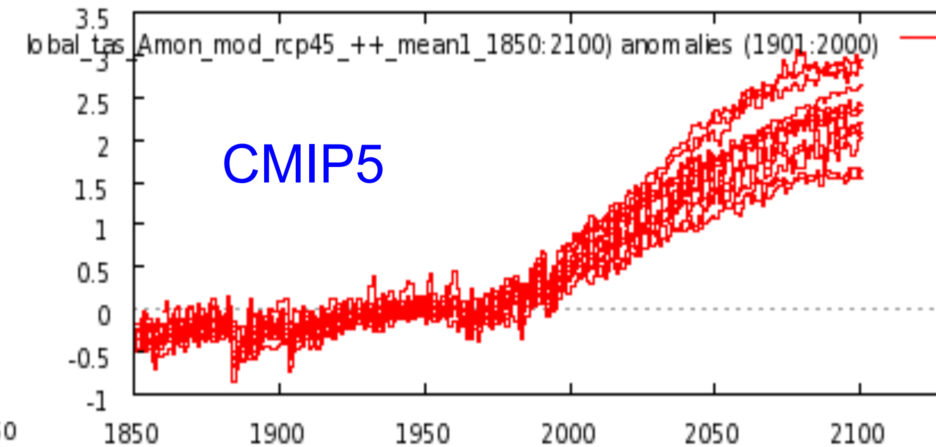




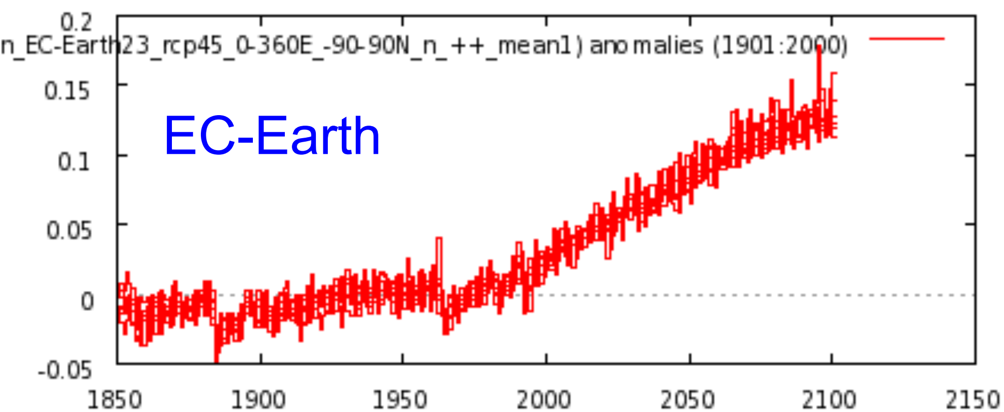
Comparing EC-Earth with other 12 CMIP5 models (RCP 4.5)

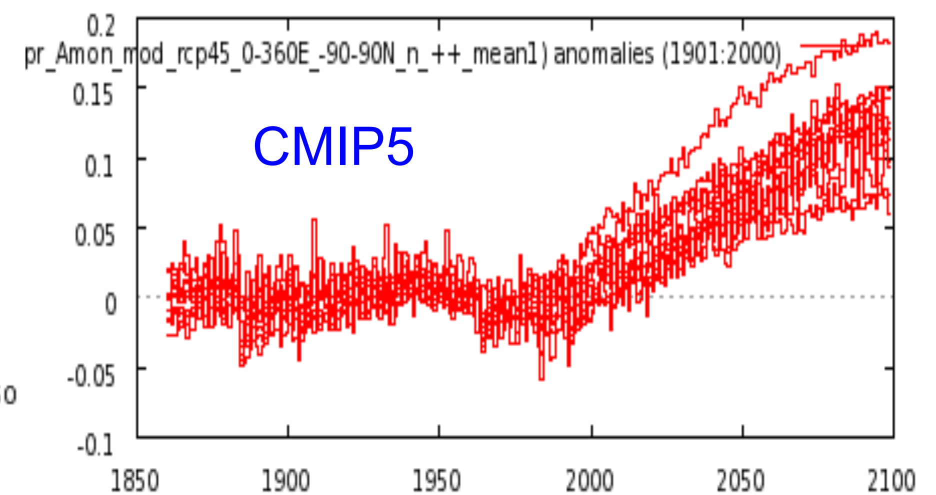
Temperature at soil





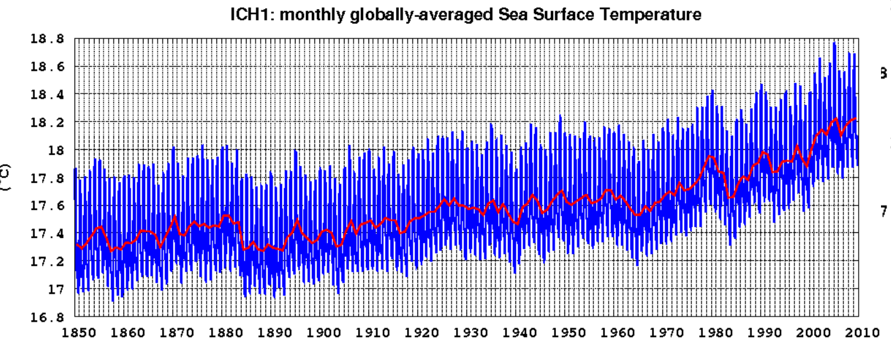
Precipitation

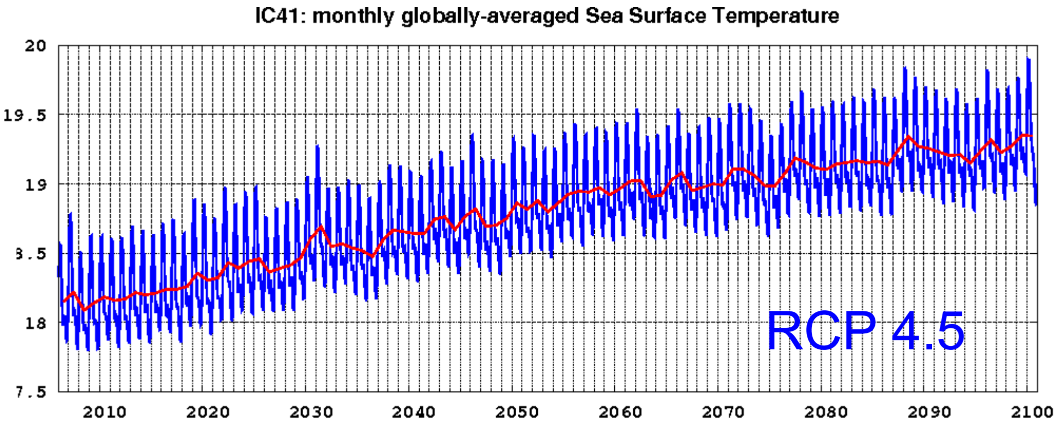


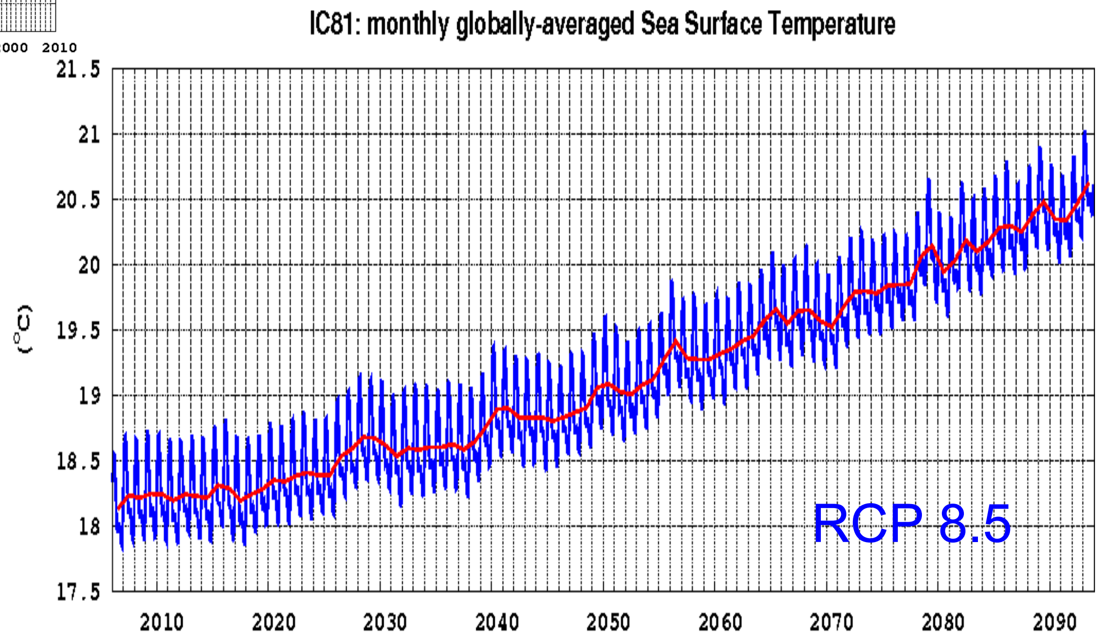


Ocean temperature (SST)

Historical

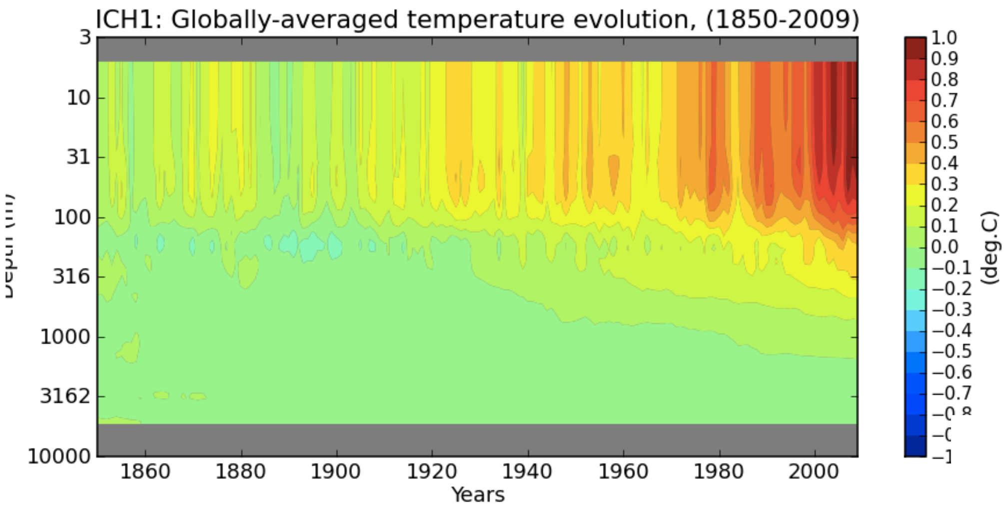




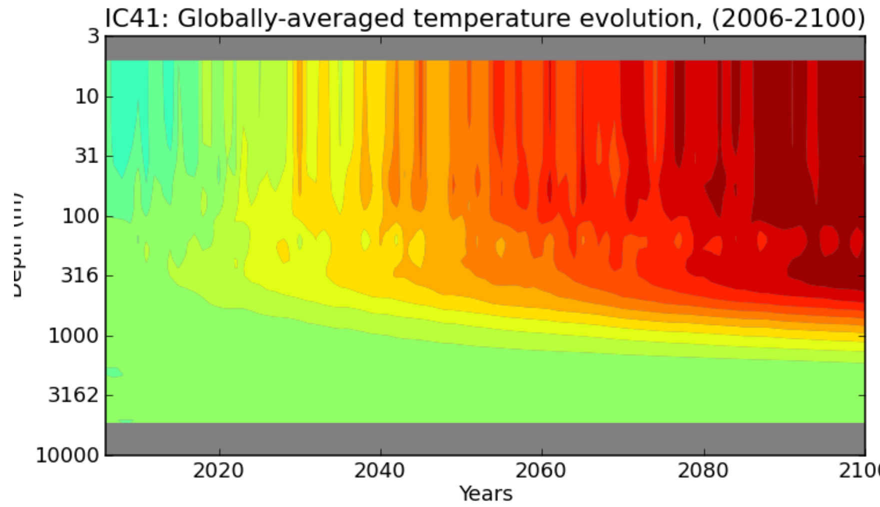


Ocean temperature

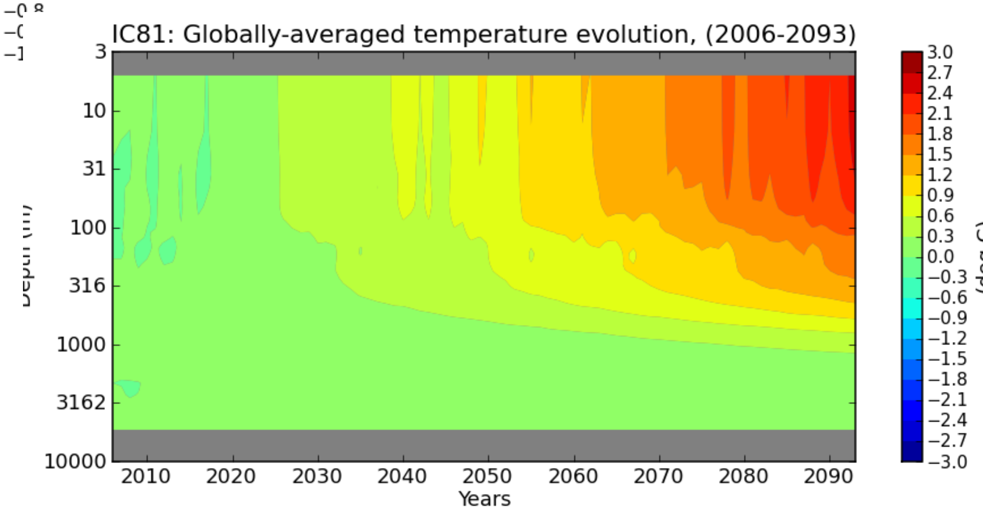
Historical



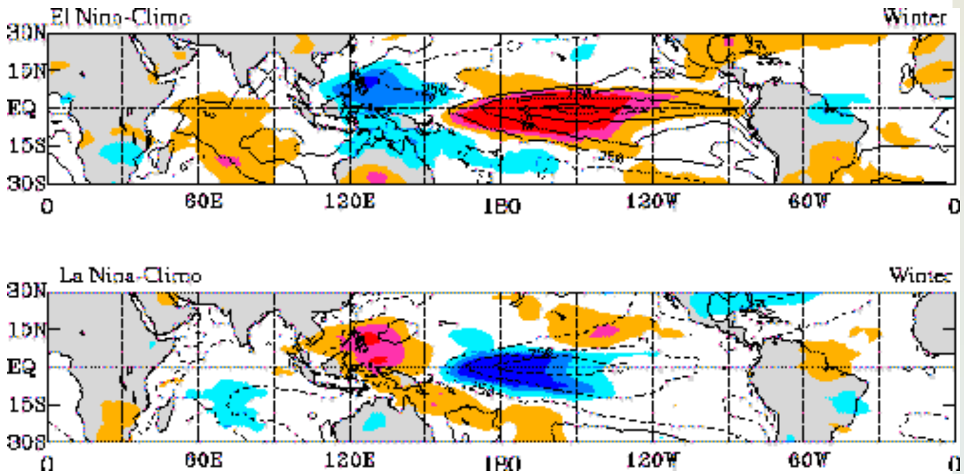
RCP 4.5

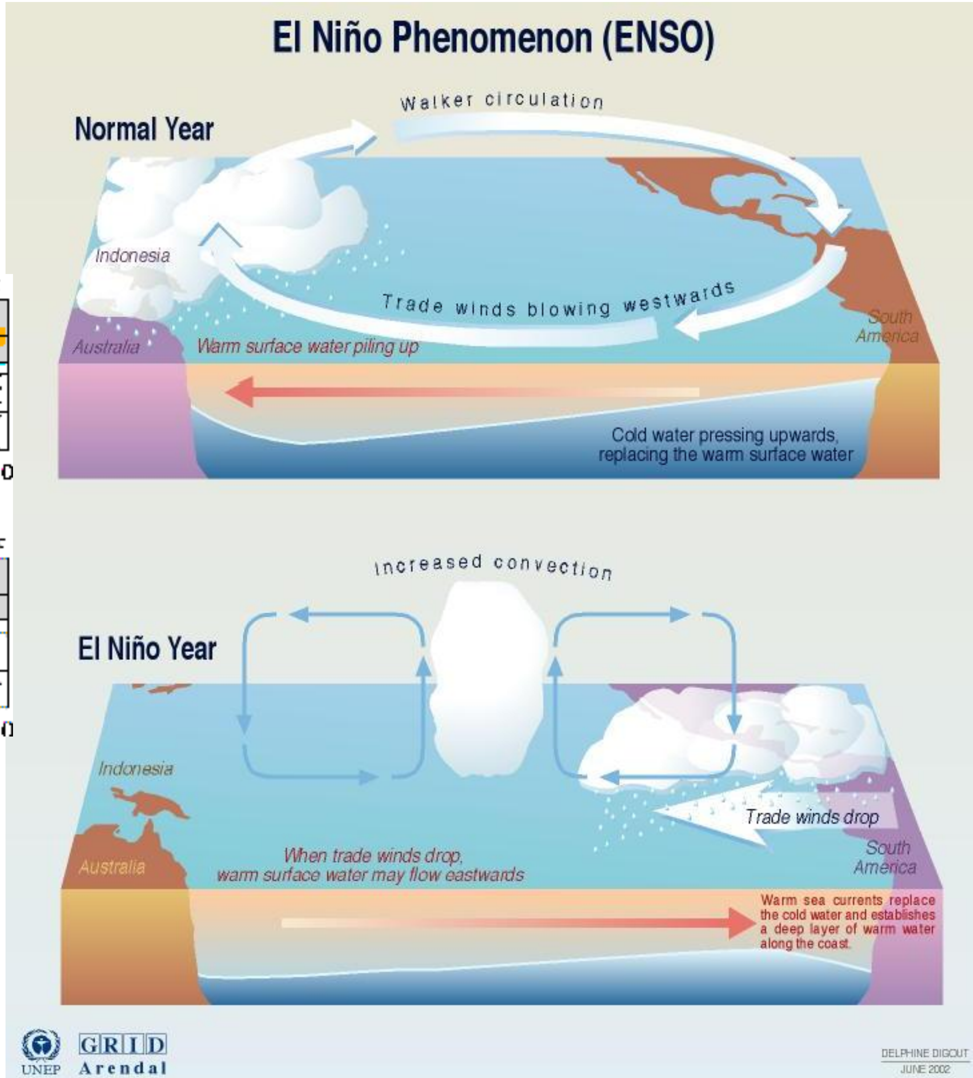


RCP 8.5



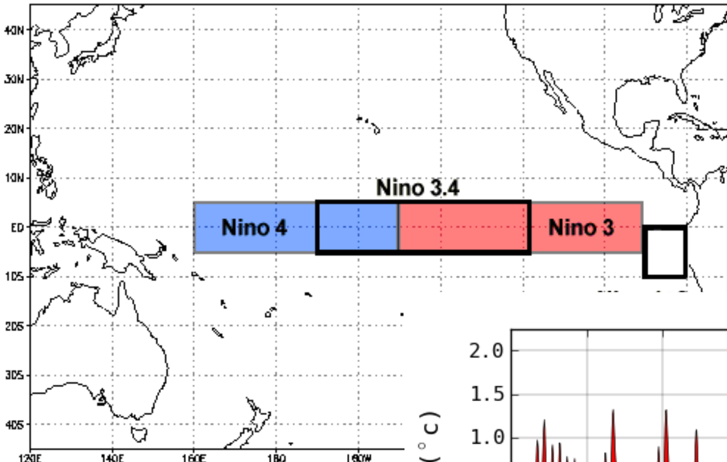
El-Niño – Southern Oscillation



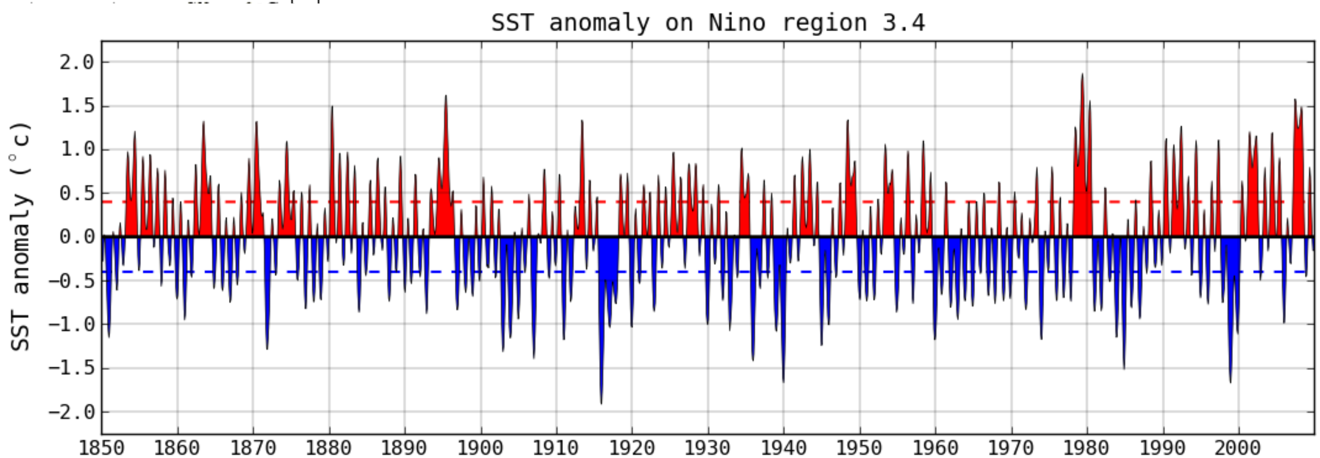


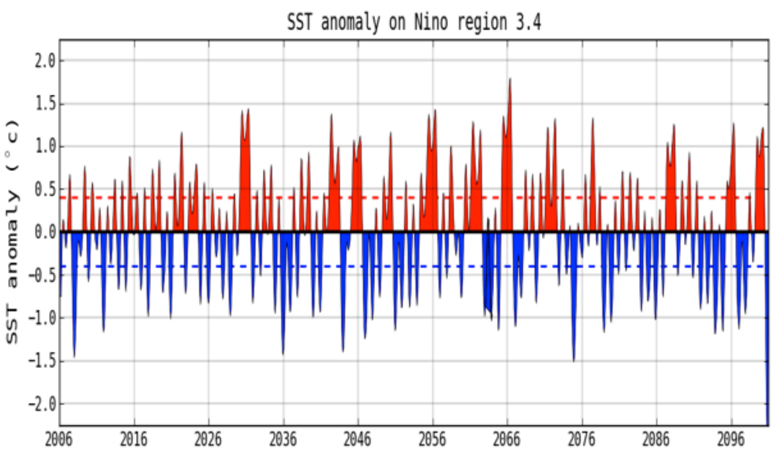
Sources: Climate Prediction Center-NCEP; NOAA.

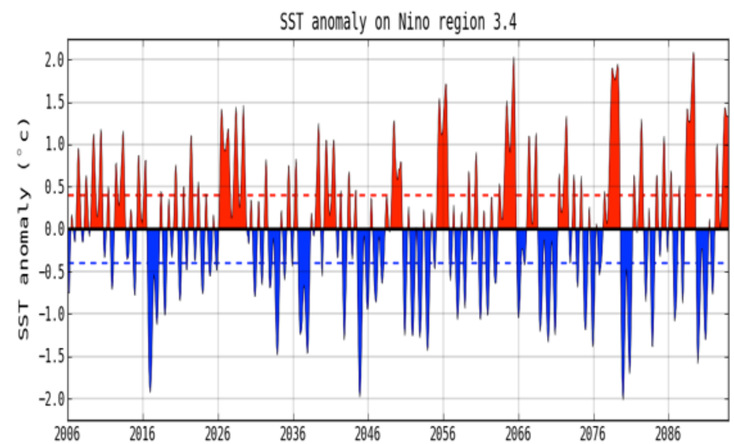
El-Niño – Southern Oscillation



Historical





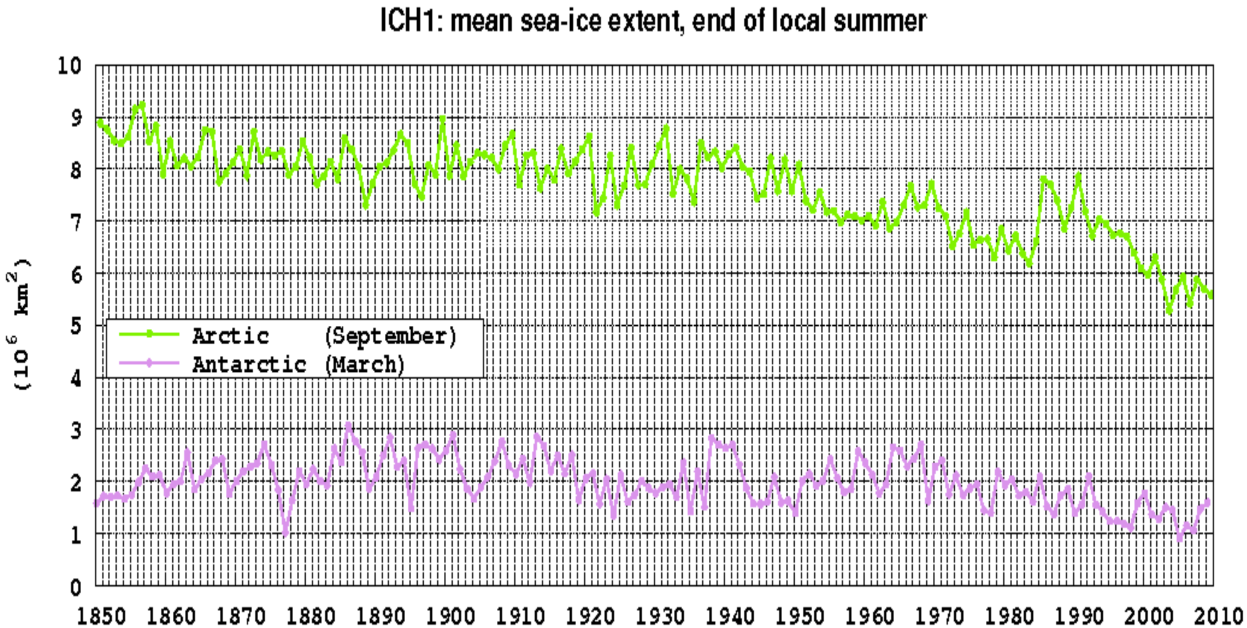


RCP 4.5

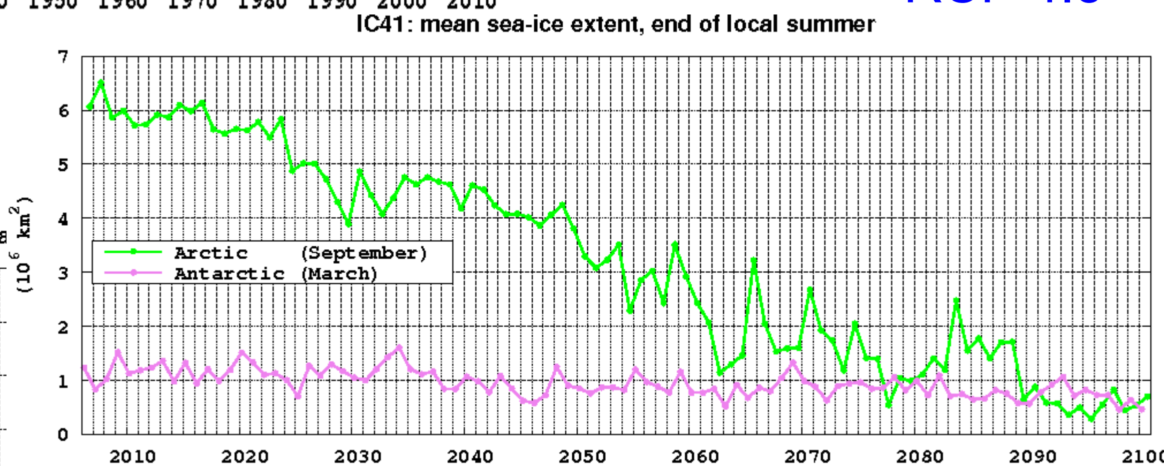
RCP 8.5

Arctic sea-ice cover – end of summer

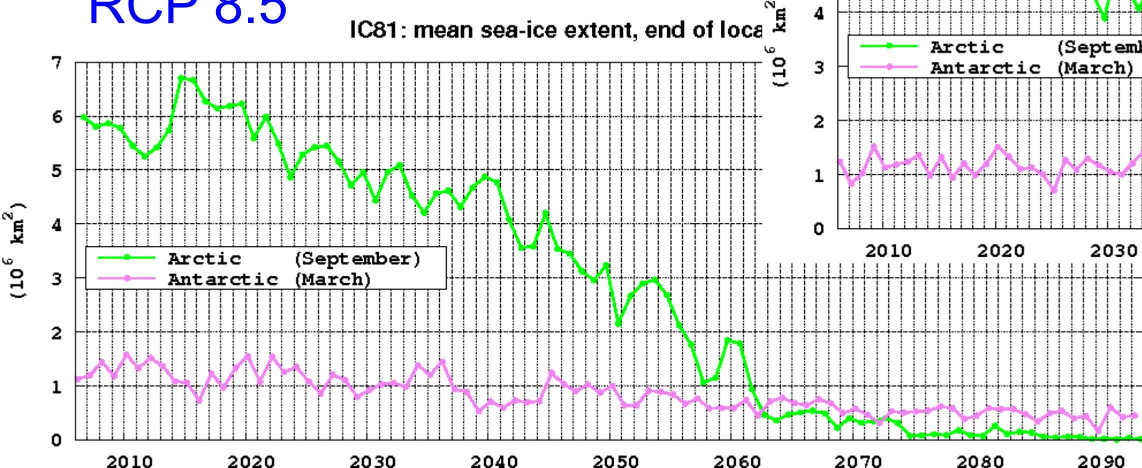
Historical



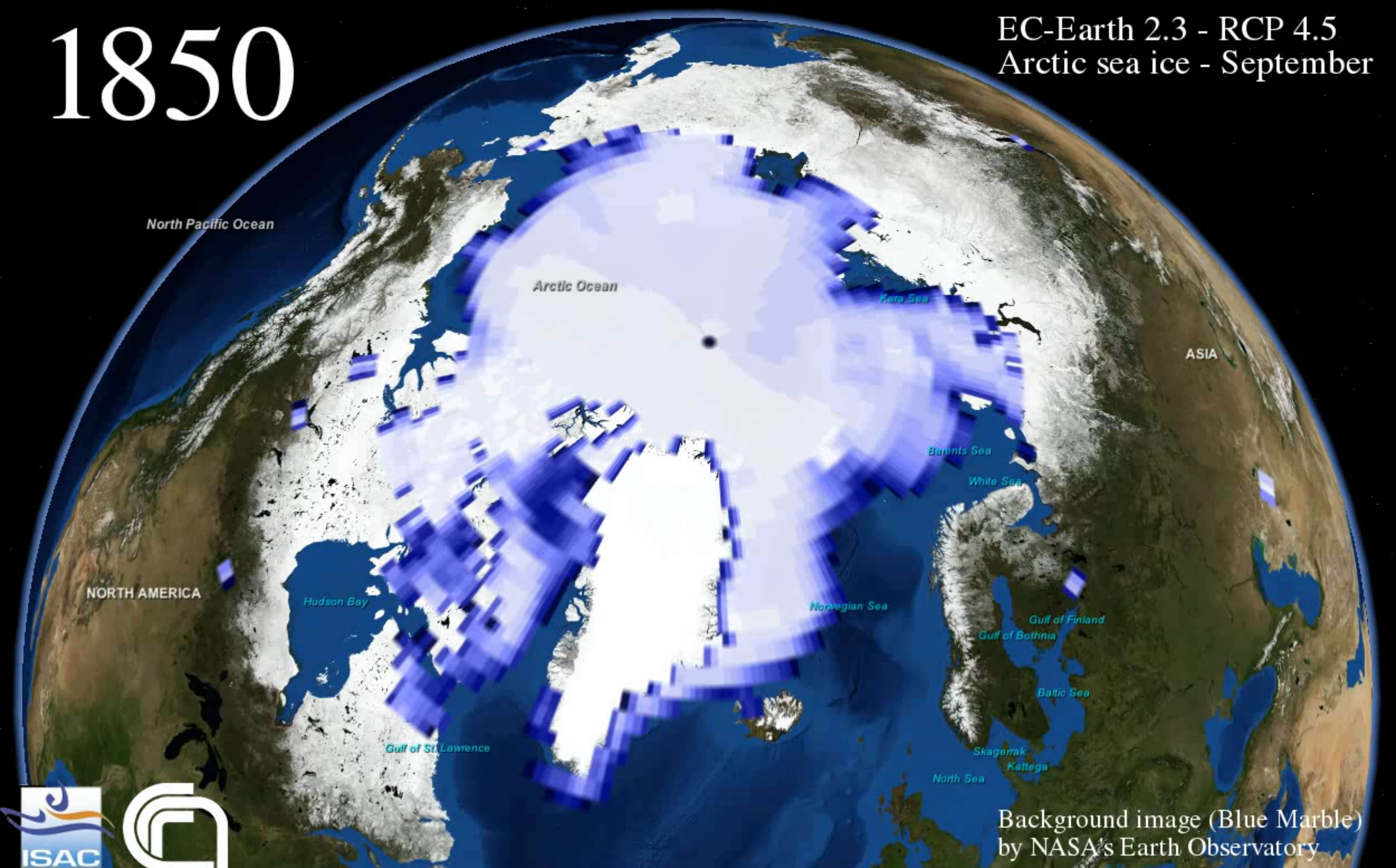
RCP 4.5



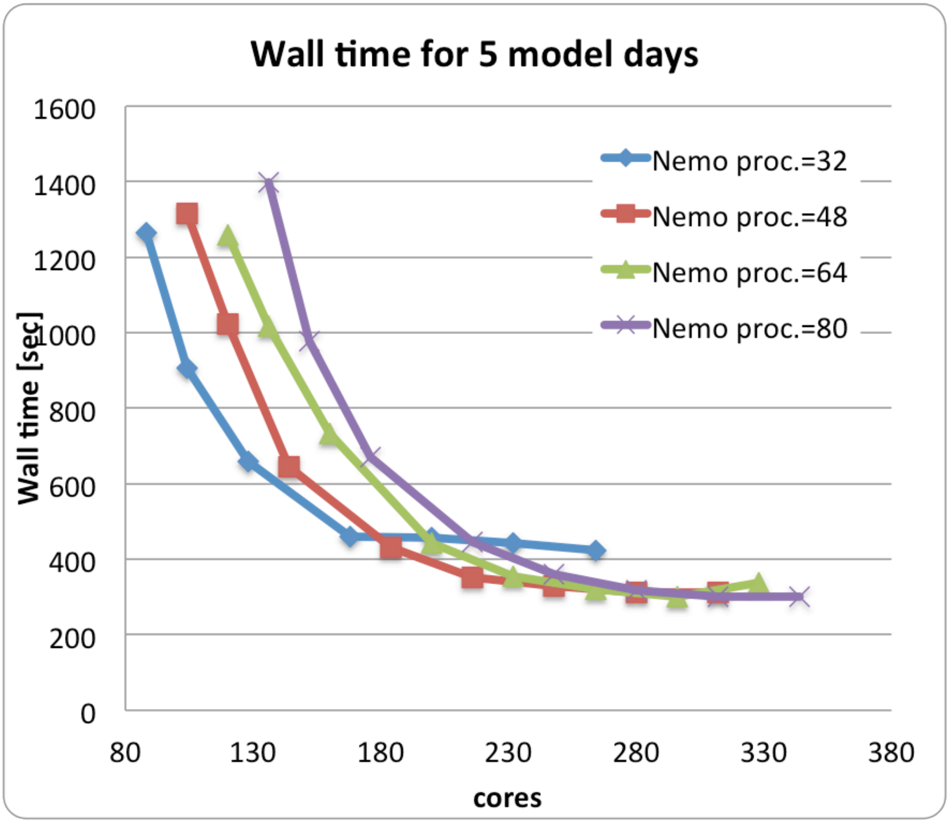
RCP 8.5

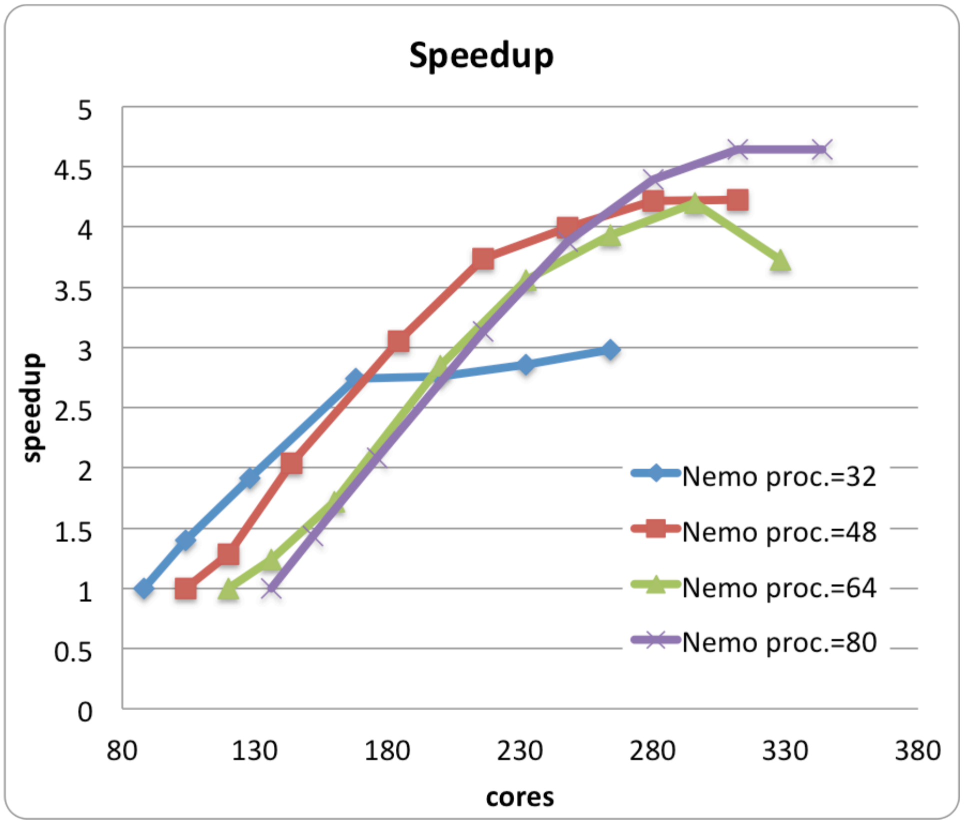


EC-Earth – RCP 4.5 scenario
September Arctic sea-ice coverage



Huge computational requirements
Huge storage requirements





Matrix Cluster at CINECA/CASPUR

EC-EARTH

Home Page

EC EARTH

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Go!

Welcome to EC-EARTH Wikipages !

You reached the EC-Earth Wiki. EC-Earth is a project, a consortium and a model system. The EC-Earth model is a state-of-the-art earth system model based on ECMWFs Seasonal Forecasting System. The baseline model is further developed into an earth system model by different partners in the consortium. Currently, the EC-Earth consortium consists of 22 academic institutions and meteorological services from 10 countries in Europe.

EC-Earth will contribute to different model intercomparison projects (CMIP5, CFMIP, ...) and features in many national and international projects.

EC-EARTH leaflet

News

28-07-2011 International EC-Earth meeting in Copenhagen at 7-8th of September 2011. See link to Meetings on the right side of this page.

Special Issue EC-Earth
The EC-Earth consortium is preparing for submitting papers to EC-Earth Special Issue Climate dynamics. See link to Papers on the right side of this page.

CMIP5
CMIP5 runs are underway. For information over status of the the runs click link.

04-01-2011 International EC-Earth meeting in Reading at 17-18th of January 2011. See link to Meetings.

14-12-2010 EC-Earth team publishes paper in the Bulletin of American Meteorological Society: EC-Earth: A

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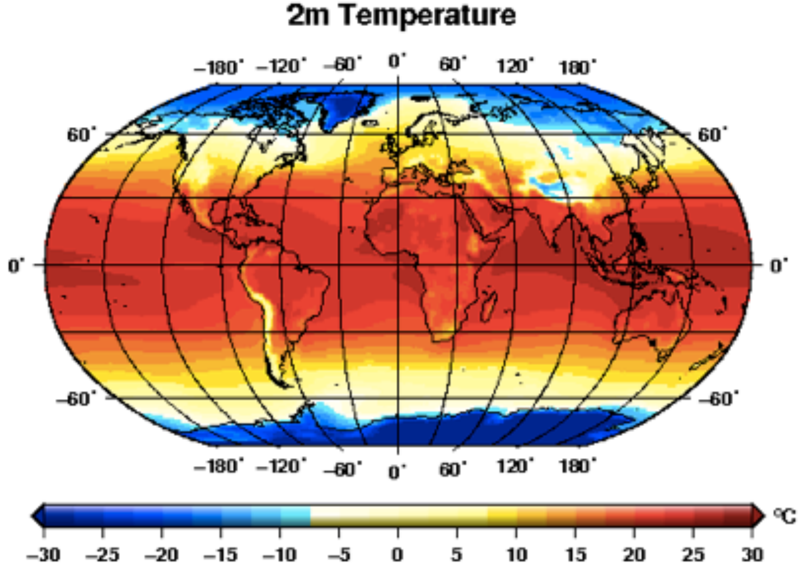
http://ecearth.knmi.nl/

RCP 4.5 simulation 2006-2100

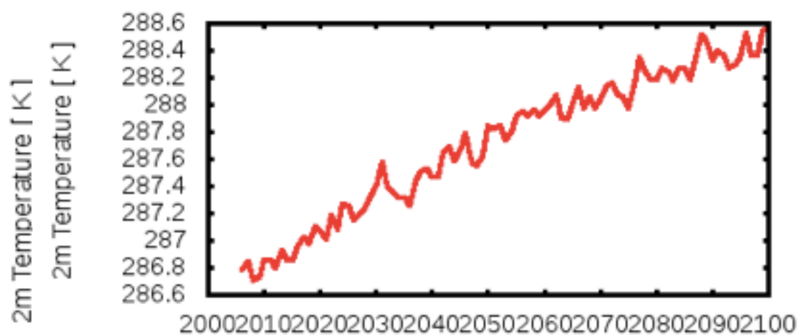
Home | Historical | RCP 4.5 | RCP 8.5 | RCP 3-PD | Benchmark | Video

Yearly mean 2006



Select variable: 2m Temperature Select year: 2006

Global average



http://www.to.isac.cnr.it/ecearth

Appendix

Simplified models and EMICs

for process studies and
long paleo simulations
EMICs can be valuable

A well-known player: PLASIM