The Earth System and Earth System Models (ESMs)

Marco A. Giorgetta

EaSyMS 2010
Hamburg
27.8.2010
Content

• The Earth system, what is it?

• Earth system questions
  – The energy balance of Earth
    • 0-dimensional model, analytic solution
  – Allowable anthropogenic CO\textsubscript{2} emissions
    • 3-dimensional atmosphere ocean land model, numerical solution
The ES - what is it?

• A relatively modern term describing atmosphere, ocean, ice and land with sufficient details, and processes that are necessary to explain the climate variations of the past several thousand years

• Typically this means that biogeochemistry in the oceans and vegetation on land and the processes by which they modify the atmospheric composition and the surface properties must be considered.

• Humans are part of the Earth system
The ES – what is it?

• **The physical climate system**, in which the climate state is described by **temperature**, **circulation**, **water** (gas, liquid, ice), **salinity** (for density), and its evolution results from dynamics, transport, and thermodynamics.

• **Biological, chemical and micro-physical processes** that modify the properties of air, water and soils, and hence influence the radiation budget and the transfer of energy through the system.

• Interactions between **climate** and **processes**, and feedbacks.
The (changing) Earth system

Source: IPCC AR4 WG1 Ch.1, Fig. …
Essential: Regulation of energy fluxes in the Earth system

• Processing of solar irradiation by the Earth system
  – Reflection  → planetary albedo
  – Absorption  → thermal energy
  – Turbulent and advective transport of heat and matter (H$_2$O, salt)
  – Phase changes of H$_2$O
  – Chemistry: ozone layer, …
  – Biology: flora & fauna, soil organisms, plankton)
  – Thermal radiation → cooling to space

• Transfer of energy depends on system properties
  – Surface properties: albedo, roughness, sources and sinks
  – Atmosph. composition: H$_2$O(g,l,i), CO$_2$, CH$_4$, O$_3$, aerosols
  – Dynamics of the atmosphere and the ocean on a rotating planet, for given land sea distribution and orography and bathymetry.
  – Dynamics of vegetation and soils
Energy flux in the global atmosphere

Source: IPCC AR4 WG1 Rep., Ch. 1, FAQ Fig.1
Energy flux in the global atmosphere

Source: Czaja A., and J. Marshall, J. Atmos. Sci., 63, 1498 – 1511, 2006, Fig.1

(a) Estimates of oceanic ($H_O$, gray) and atmospheric ($H_A$, black) heat transport in PW ($1 \text{ PW } = 10^{15}\text{ W}$)

(b) Relative contribution of ocean (gray) and atmosphere (black) to the total energy transport $H=H_O+H_A$

Continuous curves: NCEP-based estimates; dashed curves: ECMWF-based estimates.

The ratios in (b) were not plotted in the deep Tropics ($2^\circ$S–$2^\circ$N) where $H_O + H_A$ vanishes.
How to test the understanding of the observed variations of the ES?

• Develop models of the ES, based on theory and observations, which can be used for verifiable predictions.

• What is a model?
  – an idealized or simplified representation or abstraction of an object …
  – … with the purpose to demonstrate the most relevant or selected aspects …
  – … to make the object accessible to studies
  – … to find answers on particular questions

• Models are used in many fields:
  – architecture
  – fashion industry
  – teaching,
  – science, …
Earth system models – ESMs

• What should an ESM describe / predict?
  – Depends on timescales, spatial scales, questions, experimental design etc.

• The energy balance of Earth
  – \( (1 - a)S \pi r^2 = 4\pi r^2 \sigma (T_{em})^4 \)
    - \( S = \) solar irradiation at the top of the atmosphere = 1361 W/m\(^2\),
    - \( r = \) Earth radius = 6371 km,
    - \( a = \) planetary albedo = 0.3,
    - \( T_{em} = \) emission temperature of Earth = 255 K = -18\(^\circ\)C < \( T_{srf} \)
  – Global mean, constant in time
  – \( \pi \) and \( \sigma \) are constants
  – \( S \) and \( r \) are assumed constants
  – All complications hidden in the albedo \( a \)
  Why is \( a = 0.3 \) and why is it nearly constant in time?
Allowable anthropogenic CO$_2$ emissions

- How much CO$_2$ can mankind emit so that the CO$_2$ concentration follows a given path, and global warming is likely to stay beyond 2°C until 2100?

- Data for past and future CO$_2$ concentrations
  - Future: different scenarios possible

- Model:
  - Climate model describing atmosphere, ocean and land
  - Circulation in atmosphere and ocean + sea ice
  - Heat, water and carbon fluxes and storage
    - CO$_2$ flux between atmosphere and land and atmosphere and ocean
  - Feedback mechanisms coupling climate and the C-cycle
  - ... (effects of other substances like N, P, S on C-cycle?)
Schematic view of the ES

Energy
Momentum

Atmosphere

Land

Ocean

Health
Wealth
Food
e.tc.

Substance cycles
H₂O, C N S P ...

Society

Use & management
of the environment
... and of the model used here

Energy Momentum

A: ECHAM

L: JSBACH

O: MPIOM + HAMOCC

Substance cycles
H2O, C

Society

X
(no feedback)

Prescribed BCs from observations+scenarios
Methodology

ESM: Carbon cycle - climate model

\[ \frac{d\text{CO}_2}{dt} = E_{\text{foss}} + E_{\text{lcc}} + F_{\text{O-A}} + F_{\text{L-A}} \]

\[ E_{\text{foss}} = \frac{d\text{CO}_2}{dt} - E_{\text{lcc}} - F_{\text{O-A}} - F_{\text{L-A}} \]

Scenario, ESM

Hibbard et al., 2007
Scenario for future CO$_2$ concentrations

Scenario $\rightarrow$ boundary conditions including CO$_2$ concentrations

- **SRES scenarios**: no political action to mitigate climate change
- **E1**: mitigation with a target of 2°C global warming in 2100.

<table>
<thead>
<tr>
<th>CO2 [ppmv]</th>
<th>2050</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRES A2</td>
<td>522</td>
<td>836</td>
</tr>
<tr>
<td>SRES A1B</td>
<td>522</td>
<td>703</td>
</tr>
<tr>
<td>SRES B1</td>
<td>482</td>
<td>540</td>
</tr>
<tr>
<td><strong>E1</strong></td>
<td><strong>435</strong></td>
<td><strong>421</strong></td>
</tr>
</tbody>
</table>
Experimental design

- **Control**
  - "1860"
  - 1000 yr

- **Historic**
  - 1860-2005

- **SRES A1B**
- **E1 450 ppm**

- Ensembles of 5 realizations
Pre-industrial control simulation

Global annual mean surface air temperature (°C) and CO₂ concentration (ppmv)

Pre-industrial conditions, thick lines: 11-year running means

Climate of undisturbed system stable over 1000 years, no systematic drift in surface air temperature or CO₂ concentration
Global annual mean surface air temperature

Global annual mean surface air temperature anomalies w.r.t. 1860-1880 (°C)
5 year running means

• Simulated surface air temperature less variable than observed.
• Natural sources of variability like volcanic forcing or the 11 year solar cycle are excluded from the experiment.
• Simulated warming in 2005 slightly underestimated.
Global annual mean CO$_2$ emissions 1860 to 2005

- Model allows for relatively higher emissions before 1930.
- Minimum in 1940s
- Similar emissions in 2000.
Global surface air temperature anomalies

- Initially stronger warming in E1 than in A1B because of faster reduction in sulfate aerosol loading, hence less cooling.
- Reduce warming in E1 after 2040
- Warming in 2100: ~4°C in A1B and ~2°C in E1
- Climate – carbon cycle feedback will differ after 2050
• Implied CO$_2$ emissions of E1 scenario drop sharply after ~2015
• Implied emissions reduced by feedback of climate warming on carbon cycle
  In 2100: -2 GtC/yr in E1 and -4.5 GtC/yr in A1B
• Implied emissions of E1 close to 0 in 2100 (still positive).
Conclusions

• The Earth system, as understood currently in climate science, includes biological, chemical and microphysical processes interacting with climate (T, circulation, H$_2$O, salt)

• ESMs are simplified numerical representations of the ES
  – Limits of understanding
  – Computational limits
  – Experimental choice

• What was neglected in the presented study?
  – Dynamics of vegetation maps
  – Interactive aerosols
  – Chemistry of the atmosphere
  – …