Climate-vegetation interactions: 
Part II

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Outline

• Climate-vegetation feedbacks in drylands
• Feedbacks in high latitudes
• Climate effects of historical land cover changes

Will be addressed in more details in lectures of Martin Claussen (end of November)
The Use of Asphalt Coatings to Increase Rainfall

JAMES BLACK AND BARRY TARMY
J. Applied Meteorology, 1963

Arid regions near seas or lakes:
coating large area with asphalt -> thermal updrafts ->
the sea breeze circulation increased -> condensation promoted
• 2 to 3 acres of arable land produced per acre of asphalt
• the cost of the rainfall produced: 3¢ per 1000 gal
If low albedo could lead to a rain, could high albedo lead to a drought?
Baring High-Albedo Soils by Overgrazing: A Hypothesized Desertification Mechanism

JOSEPH OTTERMAN
Science, 1974

Denuded surfaces are brighter -> they are cooler under sunlit conditions -> "thermal depression" -> a decreased lifting of air necessary for cloud formation and precipitation -> regional climatic desertification

Fig. 1. The ERTS-1 image E-1091-07482, taken on 22 October 1972, band MSS-6, showing the denuded high-albedo regions of the Sinai and Gaza Strip, in contrast to the darker western Negev.
Land surface albedo, July 2003

Source: MODIS satellite platform (Schaaf et al., 2002)
Dynamics of deserts and drought in the Sahel

JULES CHARNEY, 1974:

“Lack of rainfall results in lack of vegetation. Dry, sandy or rocky soil has a much higher albedo than soil covered by vegetation. Hence desert regions reflect more solar radiation to space than their surroundings, all else being equal. Desert surfaces are hotter than surrounding regions and the air above them less cloudy. Hence deserts emit more terrestrial radiation to space. The net result is that the desert is a radiative sink of heat relative to its surroundings.
Dynamics of deserts and drought in the Sahel

JULES CHARNEY, 1974:

Since the ground stores little heat, it is the air that loses heat radiatively. In order to maintain thermal equilibrium, the air must descend and compress adiabatically. Since the relative humidity then decreases, the desert enhances its own dryness, i.e. it feeds back upon itself! A bio-geophysical feedback mechanism of this kind could lead to instabilities or metastabilities in border regions.”
• Albedo -> Rainfall: Only half of the feedback loop
• Rainfall -> Vegetation: still a missing part
Radiative balance (W/m$^2$) at the top of the atmosphere

Atmosphere-vegetation feedback in Sahara

decreased precipitation $\Rightarrow$
decreased vegetation cover $\Rightarrow$
increased albedo $\Rightarrow$
decreased averaged temperature over land $\Rightarrow$
decreased temperature contrast between land and ocean $\Rightarrow$
suppressed monsoon $\Rightarrow$
decreased precipitation

Webster et al., 1998
A Box Climate Model for monsoon areas in subtropics

Model variables:

- Surface air temperature - $T_s$
- Surface air specific humidity - $q_v$
- Zonal, meridional, and vertical wind velocities - $u, v, w$
- Cloudness - $n$
The green curve $V^*(P)$ represents the dependence of equilibrium vegetation on annual mean precipitation (feature of vegetation model). The blue line represents the linear model of precipitation as a function of vegetation cover. Cases I and III correspond to one equilibrium solution, desert $I^d$ and green $III^g$, respectively; case II corresponds to the stable desert $II^d$ and green $II^g$ equilibria as well as the unstable $II^*$ solution.
Results of the Box Climate Model for North Africa, present-day and 2xCO₂ climate
In the mid-Holocene, Sahara was covered with herbaceous/shrub vegetation.
Changes in boreal summer insolation

Berger, 1996
ECHAM3-BIOME, mid-Holocene

NO FEEDBACK ON ATMOSPHERE

INTERACTIVE ATMOSPHERE-VEGETATION

Claussen and Gayler, GEBL, 1997
ECHAM3-BIOME, mid-Holocene

„Asynchronous“ coupling, orbital forcing at 6K

7 iterations:

\[ \begin{align*}
\text{ECHAM3}(t) &= \text{ECHAM3} \left( \text{BIOME} \left( t-1 \right) \right), \text{5 yr} \\
\text{BIOME}(t) &= \text{BIOME} \left( \text{ECHAM3}(t) \right)
\end{align*} \]

- ECHAM3(BIOME(t-1)) – climate in response to 6K orbital forcing and biomes, iteration \( t \)
- BIOME(t) – biome map in response to climate, iteration \( t \)

Claussen and Gayler, GEBL, 1997
Lamerey’s „staircase“ diagramm

Vegetation cover vs. annual precipitation, mm/yr

- With feedback
- Without feedback

ECHAM response to vegetation cover
BIOME response to climate

Max-Planck-Institut für Meteorologie

Brovkin et al., JGR, 1998
Topological changes in vegetation-atmosphere system in North Africa during last 21,000 years in accordance with ECHAM3-BIOME
Spectrum of Earth system models

Integration

Conceptual Models

Processes

EMICs

Comprehensive Models

Detail of Description

Claussen et al., Climate Dynamics, 2002
Earth system Model of Intermediate Complexity (EMIC): atmosphere, ocean, vegetation, carbon cycle modules

The Earth’s geography in CLIMBER-2
CLIMBER-2: climate change in the early Holocene

Changes in temperature (°C): 8K-0K

Changes in precip (mm/day): 8K-0K

Brovkin et al., Global Biogeochem. Cycles, 2002
Regional data-model comparison: North Africa

CLIMBER-2: North Africa (20-30° N) (Claussen et al., 1999)

Marine core near western North Africa (deMenocal et al., 2000)
A abruptness of termination of the African humid period: West versus East

Fig. 1. Simulated difference between mid-Holocene and present-day vegetation cover, revealing changes mainly in the Western part of the Sahara, the focus of earlier hypotheses of abrupt ecosystem change in the Sahara. Gray shading indicates changes from mid-Holocene vegetated state to present-day desert (4); the green shaded area has more than 30% reduction in vegetation cover during the Holocene (3). A strong positive biogeochemical feedback between vegetation cover and precipitation in the Western Sahara found in (3, 4) may result in an abrupt shift from wet to dry regime. The blue shaded area indicates the area of abrupt vegetation changes attributed to a nonlinear response of vegetation to precipitation from simulation by Liu et al. (14). The stars indicate the position of Lake Yoa (19.03°N, 20.31°E) and Ocean Drilling Program site 658C (20.45°N, 18.35°W). The record from Lake Yoa does not seem to show evidence of abrupt ecosystem transitions (2), whereas the marine sediment core reveals an abrupt change in dust transport from the continent (13). Yellow circles indicate sites with mid-Holocene steppes or xerophytic shrubs from the BIOME-6000 database (10).
Changes in potential vegetation cover in Sahara, future CO$_2$ scenarios

Transient CO$_2$ scenario (1%, 1000 ppm)

Claussen et al., Clim. Dyn., 2003
How likely is a 'green Sahara' in the future?

Cook, Nature Geoscience, 2008
“Green Sahara” in CMIP5 runs

21st century (L2A8.5)

22nd-23rd century (RCP8.5)

MPI-ESM-LR

HadGEM2-ES

MIROC-ESM

Bathiany et al., J. Climate, 2014
Feedbacks in high latitudes
Land surface albedo, March 2003

Source: MODIS satellite platform (Schaaf et al., 2002)
Land surface albedo, July 2003

Source: MODIS satellite platform (Schaaf et al., 2002)
Snow-masking effect of forests

Graph showing albedo values over the course of a year for different vegetation types.
Snow Albedo Masking in SnowMIP2

Essery et al., 2009. *Bulletin of the American Meteorological Society*, 90, 1120 - 1135
Snow Albedo Masking in Deciduous Forests

BERMS Old Aspen

Essery et al., 2009. *Bulletin of the American Meteorological Society*, 90, 1120 - 1135
Snow-maskimg effect of forests

Bonan, Science, 2008
Taiga-tundra feedback

increased tree fraction ➔
decreased surface albedo during snow season ➔
increased air temperature and earlier snow melt ➔
longer and warmer growing season ➔
increased tree fraction
The arrows on the left indicate relations between variables, including amplification (+) or dampening (−) of the original change Δ. F refers to the tree fraction; T, to surface air temperature; R, to the net radiation at the surface; E, to evapotranspiration; SST, to sea surface temperature; SI, to sea ice; H, to heat fluxes out of the ocean and into the atmosphere; \( \Psi_{NADW} \), to the intensity of the thermohaline circulation. The boxes in the middle indicate model compartments necessary to investigate feedbacks shown on the left.

Brovkin et al., Climatic Change, 2003
Taiga-tundra feedback: no multiple equilibria

External warming $\rightarrow$ increased tree fraction $\rightarrow$ decreased surface albedo during snow season $\rightarrow$ increased air temperature and earlier snow melt $\rightarrow$ Enhanced warming

Tree fraction at 60-70° N
GDD0 - Growing degree days above 0

- $F^*(T)$, tree dependence on temperature
- $T^*(F)$, temperature dependence on tree fraction

Brovkin et al., Climatic Change, 2003
Temperature changes (°C) relative to the control simulation, MPI-ESM

Winter (DJF)

Summer (JJA)

FOREST world

GRASSLAND world

Brovkin et al., GRL, 2009
Climate response to global forest or grass cover

Global annual mean temperature, °C

- Forest
- Grass
- Fixed vegetation
- Interactive vegetation

Corrected for climate response to global forest or grass cover

Brovkin et al., GRL, 2009
Global climate-forest interactions: no multiple states in the MPI-ESM

Tree cover after 500 years of interactive dynamics started from complete tree (A) or grass (B) cover

Brovkin et al., GRL, 2009
Changes in North American tree cover during the last 21,000 yr
Role of taiga-tundra feedback in the last glacial inception

Ice-area (North America)

Atm. + oce. + veg.
Atm. + oce.
Atm. + veg.
Atm.

Area [10^6 km^2]

Time [kyr BP]

Kubatzki et al., 2006; Calov et al., Clim Dyn, 2005
Land biosphere as „climate amplifier“ in Quaternary dynamics

Original climate signal

Amplified climate change: threshold crossed

Vegetation response
Biogeophysical + biogeochemical effects of boreal deforestation

-0.8°C
Boreal deforestation

-0.25° C
So... historical land cover change caused global warming?

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<tbody>
<tr>
<td>Biophysical</td>
<td>-0.26</td>
<td>-0.16</td>
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<tr>
<td>Biogeochemical</td>
<td>0.18</td>
<td>0.30</td>
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<tr>
<td>Overall effect</td>
<td>-0.05</td>
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Effect of historical land cover changes on temperature, CLIMBER-2

Cropland fraction
Ramankutty and Foley, GBC, 1999

Brovkin et al., Global Change Biology, 2004
Deforestation effect on climate:
Biogeophysics versus biogeochemistry

Brovkin et al., Global Change Biology, 2004
Radiative forcing of land use: 1750-2010

Myhre et al., IPCC AR5, 2013
Summary of climate-vegetation interactions

• The biogeophysical feedbacks between vegetation and climate are positive (i.e. they amplify external changes)
  – North Africa is a „hot spot“ of atmosphere-vegetation interaction; This interaction leads to multiple equilibrium states in climate-vegetation system in the region;
  – forested world is warmer in the northern high latitudes; current models suggest no feedback-generated multiple states in the northern high latitudes
  – Historical land cover changes cooled the climate through biogeophysical effects, while warmed via biogeochemical effect

• These feedbacks amplified past climate changes and their quantification is important for the future projections