PALMOD GERMAN CLIMATE MODELING INITIATIVE

Dominant role of the global monsoon intensity on large-scale Holocene vegetation transitions

Anne Dallmeyer[1], Martin Claussen[1,2], and Ulrike Herzschuh[3,4,5]

[1] Max Planck Institute for Meteorology, Hamburg, Germany
[2] Centrum für Erdsystemforschung und Nachhaltigkeit (CEN), Universität Hamburg, Germany
[3] Alfred Wegner Institute, Helmholtz Centre for Polar and Marine Research, Potsdam, Germany
[4] Institute of Environmental Sciences and Geography, University of Potsdam, Germany
[5] Institute of Biochemistry and Biology, University of Potsdam, Germany

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Methods

- **Model: MPI-ESM1.2**, including the land-surface model **JSBACH** with an **dynamic vegetation module simulating 8 natural plant functional types (PFT)**. These are: tropical and extratropical trees, that can be deciduous or evergreen, raingreen shubs and cold-resistant shrubs and C3 and C4 grass. The vegetation model uses a **tiling approach**, i.e. all PFTs can in principle co-exist in a grid-cell, but are **excluded by bioclimatic (temperature) constraints**. The dynamics of changes in the fractional coverage of the PFTs is governed by the **dynamics of the Net Primary Production (NPP)** of the competing PFTs and is **affected by natural mortality and disturbances** (wind-throw and fire)

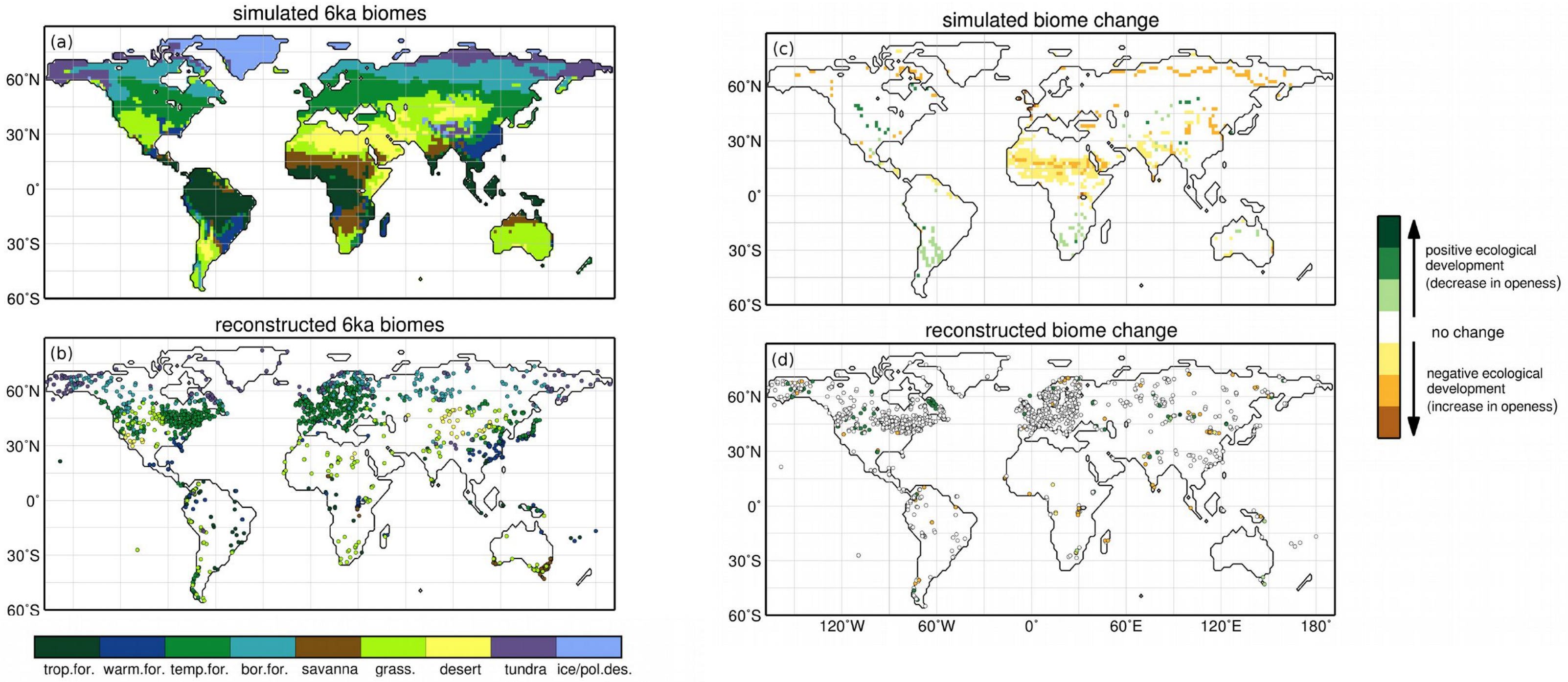
- **Resolution atmosphere/land:** T63 (approx. 200km on a Gaussian grid) with 47 levels in the vertical atmosphere.

- **Resolution ocean:** GR15 (i.e. 256x220 on a bipolar grid, 12 to 180km) and 64 vertical levels.

- **Transient simulation: 6000 BCE to 1850 CE**, but only the period **6000 BCE (8ka) to 15BC (2.15ka)** have been analysed to exclude land use transitions

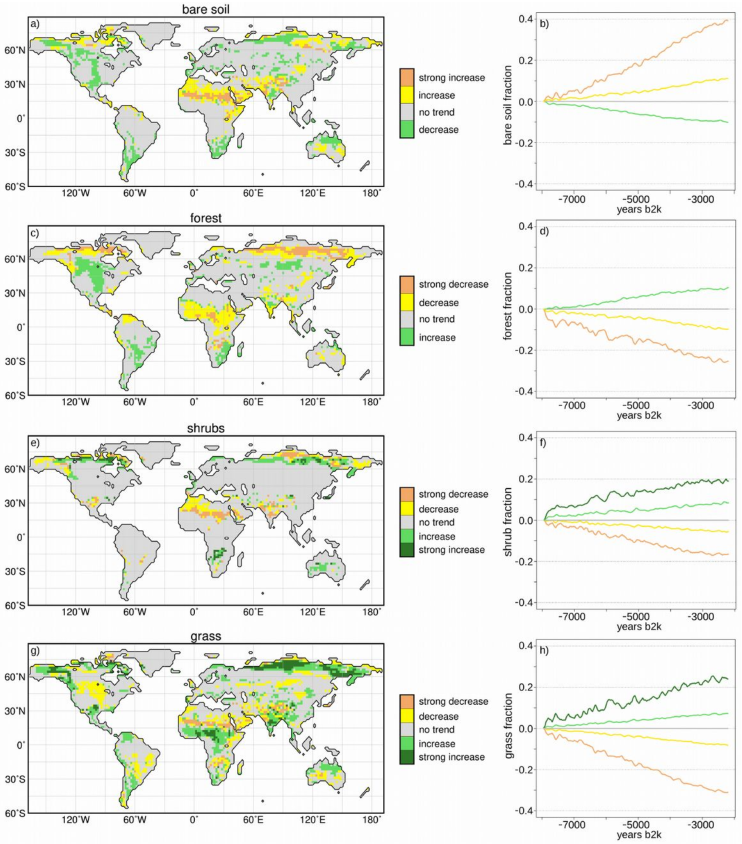
- **Forcings:** orbital-induced insolation changes, greenhouse gas concentration (methane, carbon dioxide and nitrous oxide), stratospheric sulfate aerosol injections imitating volcanic eruptions, spectral Solar Irradiance, land-use for the last 2000 yrs

Short evaluation based on biome reconstructions for 6ka and 0ka



The simulated PFT cover fractions has been converted into mega-biomes using the tool of Dallmeyer et al., 2019 (Clim. Past, 15, 335–366, https://doi.org/10.5194/cp-15-335-2019) and compared to pollen-based biome reconstructions by Harrison, 2017 (http://dx.doi.org/10.17864/1947.99). To assess the biome change, the biomes has been further grouped into the main categories forest, savannas, grassland/tundra and desert. Positive ecological development describes the transition from biomes indicating more open landscape to biomes indicating less open landscape (e.g. desert in 6ka to grasslands or to savannas or to forests in PI). Negative development describe the opposite transition (e.g. from grassland in 6ka to desert in PI).

Simulated Holocene vegetation cluster indicate rather linear trends



- **main vegetation** (forest, shrub, grass, and bare soil fraction) has been **clustered** (c-means). ***Left panel:*** cluster pattern, ***right panel:*** trend of cluster centres (range from -1 = total decrease of a vegetation type in a grid-cell to 1 = total increase)

- Model **captures the main trends** found in reconstructions:

→ strong **decrease in forest in the high northern latitudes** reflecting the southward retreat of the northern treeline since 8ka

→ (strong) increase in the subtropical northern hemispheric deserts coinciding with a **decrease and equator-ward retreat of all vegetation types in the NH monsoon regions**

→ **increase in the vegetated area in extratropical North America** (mainly 30°-60°N, 90-120°W) related to an increase in forest and partly grass

→ **increase in the vegetation** (mainly forest) in extratropical South America and South Africa including the **southern hemispheric monsoon regions**

→ **bipolar vegetation change in Australia**, mostly driven by an increase in grass on the northern and a decrease of grass on the southern part of the continent.

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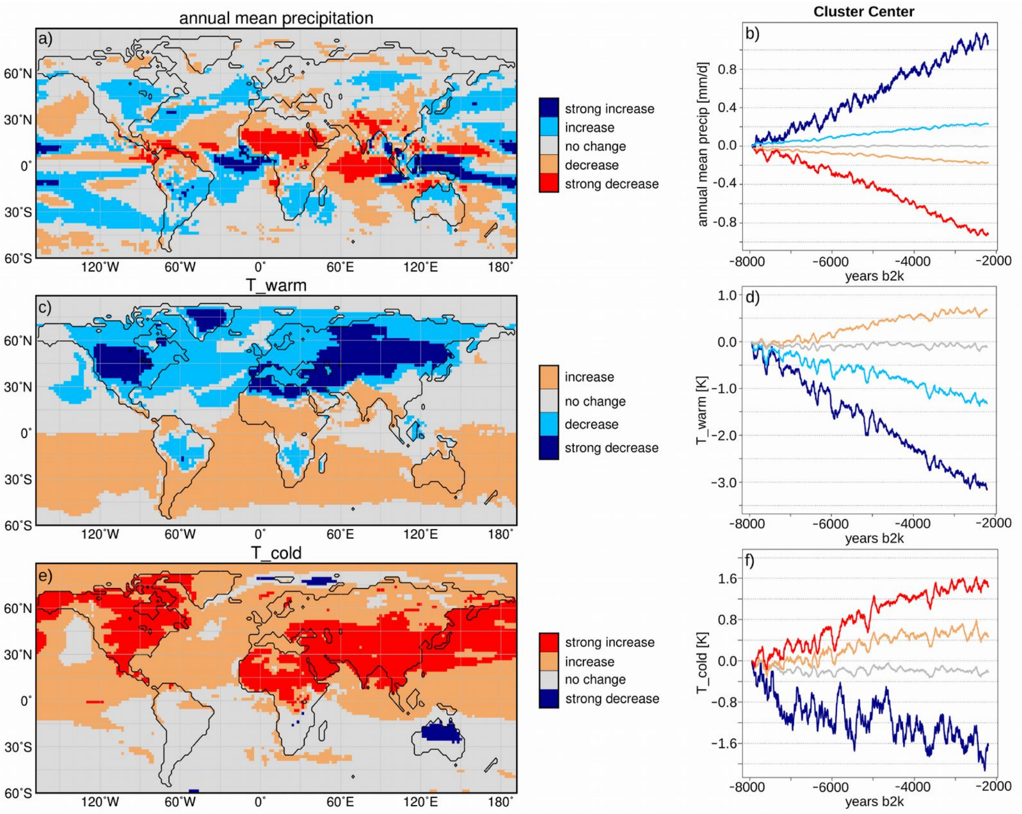
Simulated Holocene climate change summarized by cluster method



- cluster technique has also been applied to the annual mean precipitation (a,b), the temperature of the warmest month (T_{warm}) (c,d) and the temperature of the coldest month (T_{cold}) (e,f).

- **annual precipitation** decreased in the NH monsoon regions and increased in the SH monsoon regions during the Holocene. In Central Siberia and North America precipitation increases

- **T_{warm} decreased in the NH** and increased in the SH, with the exception of the SH monsoon areas in the model (increase in evaporative cooling).

- **T_{cold} increases in the NH**. In the SH, Tcold reveal no change, but decreases in Northern Australia during the Holocene

- The **temperature signal is larger over land** than over the ocean

- While the **temperature** reveals a **zonally** rather uniform trend, **precipitation varies** with continent and region

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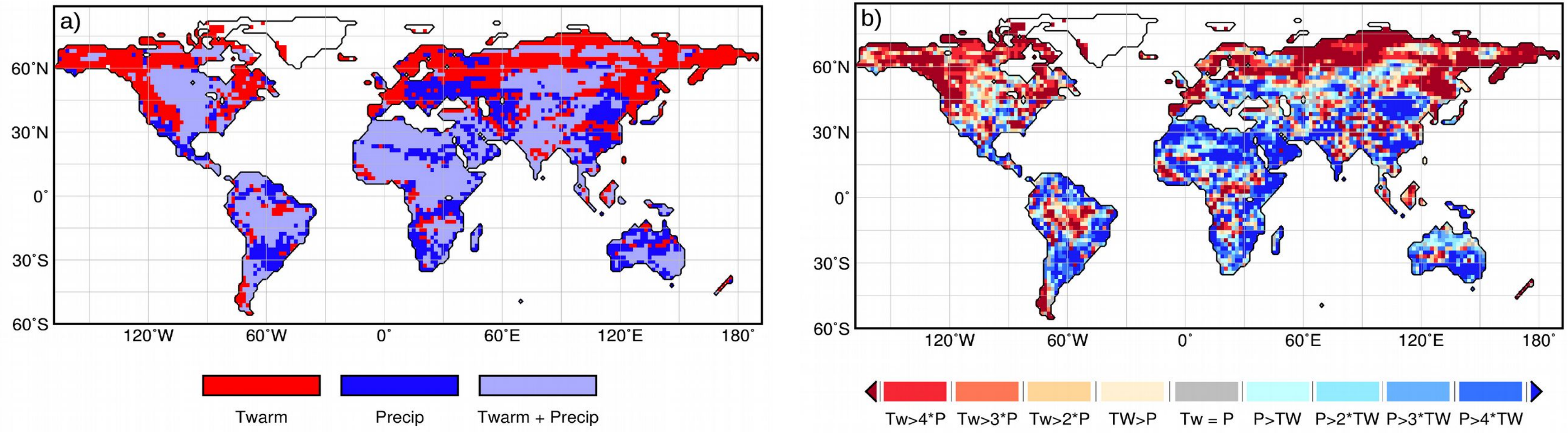
Redundancy analysis identifies **precipitation** as the **main driver** of the vegetation change outside the high northern latitudes



Results of the RDA for the vegetation groups forest, shrubs, and grass, with precipitation (precip) and temp. of the warmest month (Twarm) as explanatory variables. ***a)*** regions in which the variance in the Holocene vegetation change is mostly explained by the variance in Twarm (red), or in precipitation (blue) or in the shared variance of Twarm and P; ***b)*** ratio of the variance explained by Twarm (Tw) and by precipitation (P). For instance, P>4*Tw means that precipitation explains more than 4 times more of the variance than Twarm. Tcold explaines explains only a small part of the variance in an initial RDA and was thus excluded in the final RDA.

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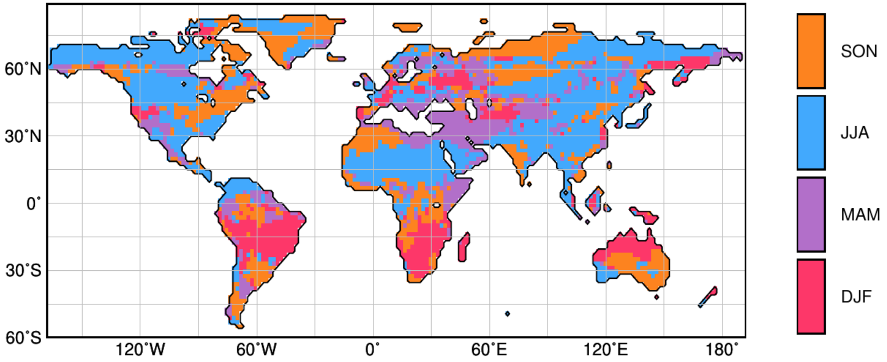

Fig. Season which contributes most to the annual mean precipitation change between 8ka b2k and 2.15ka in the model

In regions with large vegetation transitions, **summer precipitation (blue) change most** between 8ka and 2.15ka

The NH continental monsoon regions are extended by 25% and the **NH monsoon rainfall is increased by 40% at 8ka**. SH continental monsoon area is reduced by 5% and **SH rainfall is decreased by 11% at 8ka** compared to 2.15ka in the model.

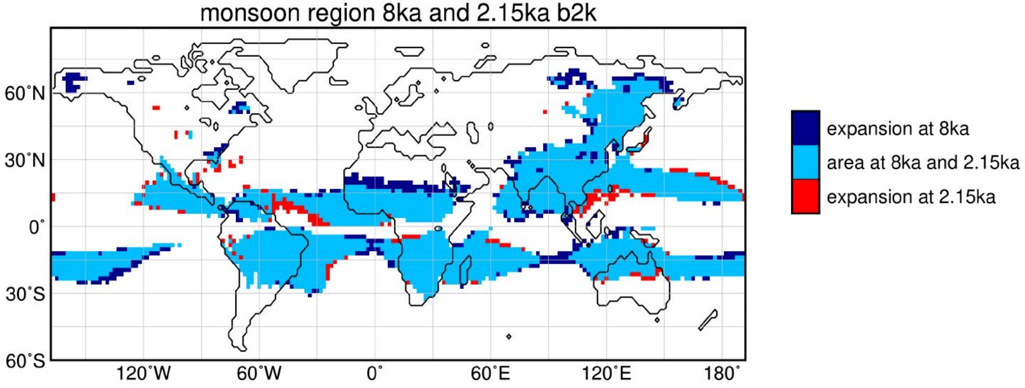

Fig: Monsoon area that does not change from mid-to late Holocene (light blue), additionally assigned monsoon domain at 8ka, but not at 2.15 ka (dark blue) and additionally assigned monsoon domain at 2.15 ka, but not at 8ka b2k.

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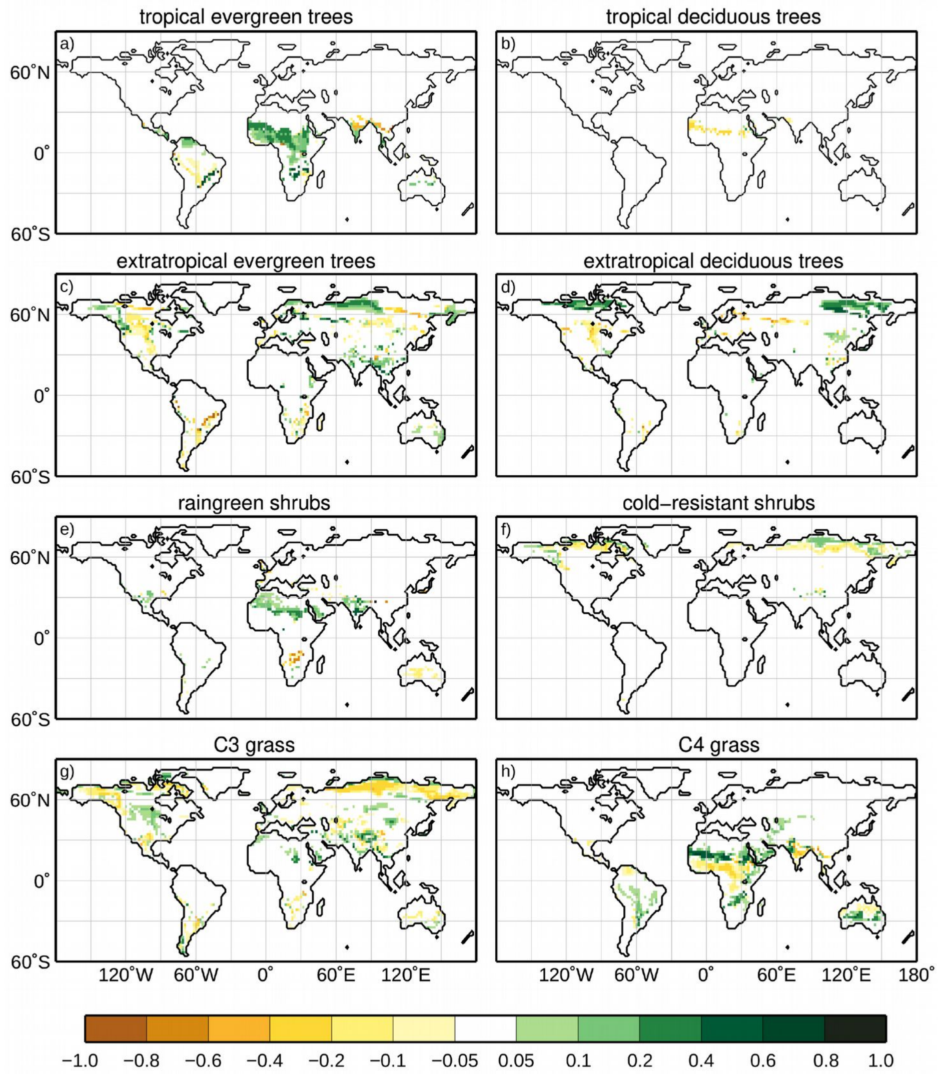

Fig. ***Simulated changes in plant functional types (PFT)*** *for the mid-Holocene (8ka) compared to the late-Holocene (2.15ka)*

yellowish colour*: decreased PFT cover fraction at 8ka compared to 2.15ka.*

greenish colour*: increased PFT cover fraction at 8ka compared to 2.15ka.*

Values of '1.0' mean that the grid-box is fully covered by the PFT during 8ka, but does not occur at 2.15ka in this grid-cell, and vice versa for values of '-1.0'.

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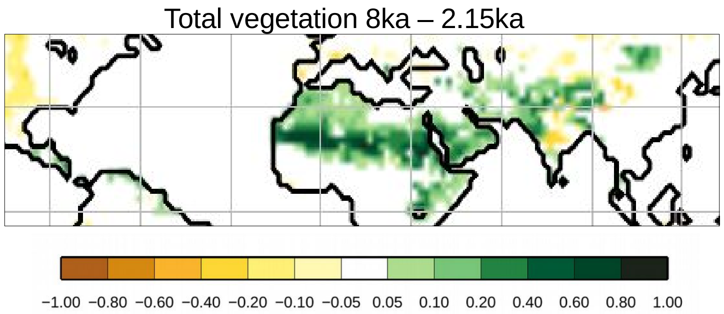
Northern hemispheric monsoon region

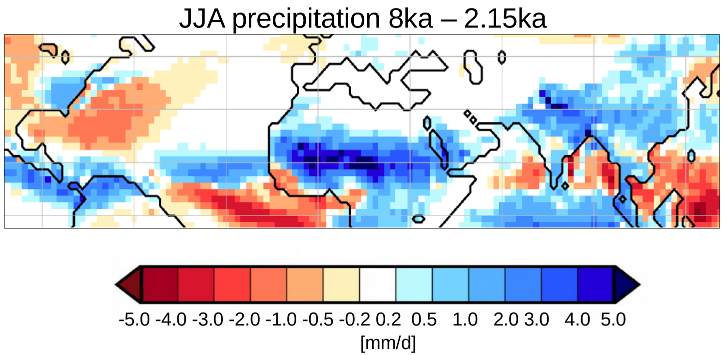
North Africa: monsoon area is expanded northward by ~ 600 km and allows for a widespread vegetation cover at 8ka. Raingreen shrubs are increased by up to 30%, the grass fraction by up to 60%. The overall non-vegetated area north of 15°N is diminished by 22% in the mean at 8ka, ranging up to 82% in the Central Sahel.

East Asia: monsoon area is expanded to the northwest into Western Mongolia by up to 800km at 8ka, increased total vegetation cover (mainly grass) by up to 27% per grid-cell

South Asia: monsoon is expanded at its northwestern rim by about 1-2 grid-cells (ca. 200km) into western South Asia and onto the Tibetan Plateau, leading to an increased total vegetation cover by up to 50% at 8ka. Our model reveals less vegetation in Central South Asia during the mid-Holocene, driven by a tropical evergreen forest cover decreased by up to 40 % and a C4 grass cover reduced by up to 35%. In this region, precipitation is decreased at 8ka during mid-summer, caused by a high pressure anomaly in the lower atmosphere above South Asia and Indochina and related low level easterly wind and subsidence anomalies.

North America: monsoon area is expanded south- and westward by approx. 200km at mid-Holocene. Summer precipitation is substantially increased in Central America and the north western part of the South American continent, leading to a larger area covered by tropical evergreen forests.





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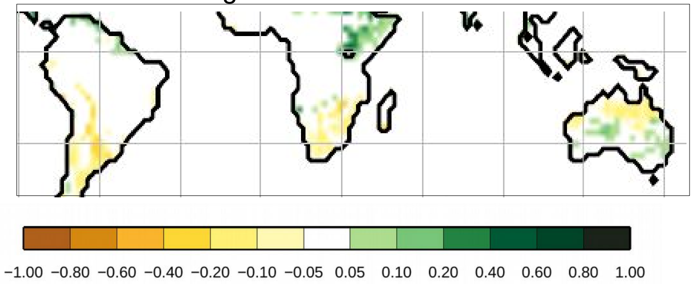
Southern hemispheric monsoon region

South America: precipitation is reduced in most regions at 8ka, due to a generally northward displaced ITCZ and diminished uplift of moist air over the central continent during the monsoon season. Both is also mirrored in the slightly increased precipitation on the north-easternmost continent. The total vegetation cover is only slightly decreased along the foot of the Bolivian Andes, but the PFT composition change (among trees types). The vegetation in the Amazon rainforest region is relatively stable over the Holocene. The Atlantic rainforest is decreased and the landscape more open at 8ka.

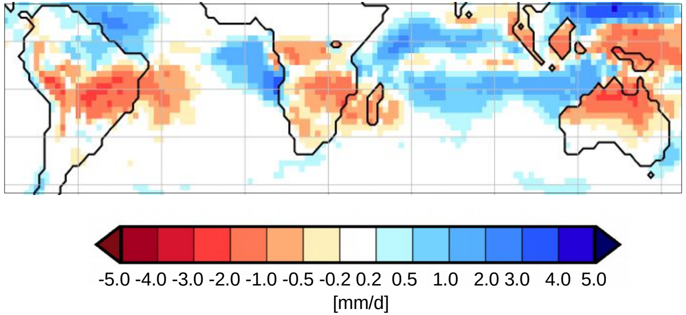
South Africa: precipitation is diminished in the entire monsoon domain at 8ka due to a less powerful monsoon. The Angola low is weakened and the South Atlantic high is shifted northwards (Fig. 9d), reducing the moisture flux to the continent. The total vegetation is only decreased on the southern continent at 8ka, but PFT composition change. C3 grass and extratropical trees increase from 8ka on.

Australia: monsoon region is shrunk at its south-eastern rim by approx. 200km at 8ka due to a weakened monsoon-related moisture flux and less precipitation during austral summer at 8ka. The total vegetation is decreased by up to 19% during the mid-Holocene, mainly due to a decreased C4 grass cover and less tropical evergreen trees.

Total vegetation 8ka – 2.15ka



DJF precipitation 8ka – 2.15ka



Extratropical North America (<60°N)

Total vegetation cover in large parts increases from 8ka to 2.15ka, resulting from a vast expansion of trees. In total, the Great Plains receive less precipitation at 8ka, mainly during summer. The precipitation response to the orbital forcing in the model is a complex mixture of several interacting processes:

→ The Bermuda high is strengthened in the core at 8ka (s. PSI*) leading to a rerouting of the moisture transport from the Gulf of Mexico along the Atlantic coast, thereby enhancing the precipitation along the Appalachian mountain range. The subtropical anticyclones are stated to be related to Kelvin and Rossby wave responses to the heating in the monsoon rainband. The strongly intensified northern hemispheric monsoon circulation thus may also strengthen the Bermuda high

→The moisture flux is more divergent in the Great Plains and the atmosphere is generally drier, inhibiting convection and rainfall.

→ the model shows a rainfall-reducing subsidence anomaly over the Great Plains south of 45°N at 8ka (omega) that could at least partly be attributed to a Rodwell&Hoskins-like Rossby wave response to the enhanced updrafts in the North American summer monsoon

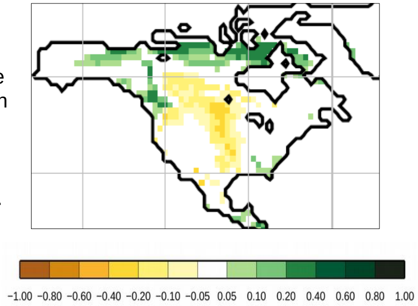
→ The northward shifted upper level westerly Jet during the mid-Holocene coincides with a northward replacement of the storm tracks, which probably results in less transient eddy transport to the northern Great Plains at 8ka compared to 2.15ka.

→ The model also reveals less precipitation during spring and therefore limited evaporation during mid-Holocene summer, reducing water recycling and the northward transport of moisture in the Great Plain low level Jet. The influence of evaporation on vegetation change may also explain the relatively large proportion of vegetation variance explained by the temperature of the warmest month.

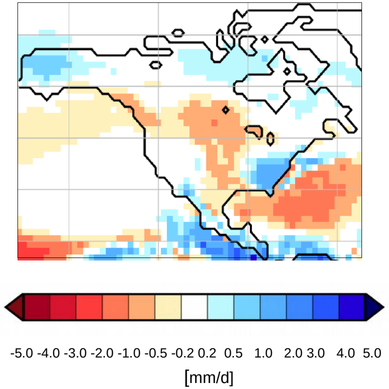
→ The more La Nina like sea surface temperature pattern may also contribute to the drier surface conditions in the Great Plains at 8ka

→ The reduced precipitation above the Canadian interior Plains and northeastern Rockies at 8ka is probably related to the strengthened and westward shifted North Pacific subtropical high. This leads to enhanced northerly winds transporting rather dry continental air inland. The subsidence is increased in large parts during mid-Holocene summers, further limiting the convection.

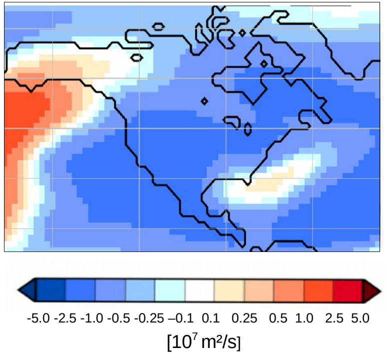
Tree cover 8ka – 2.15ka



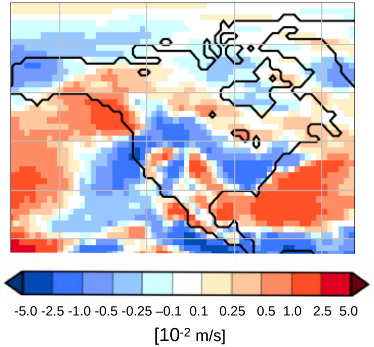
JJA precipitation 8ka – 2.15ka



JJA PSI* 850hPa 8ka – 2.15ka



JJA omega 500hPa 8ka – 2.15ka



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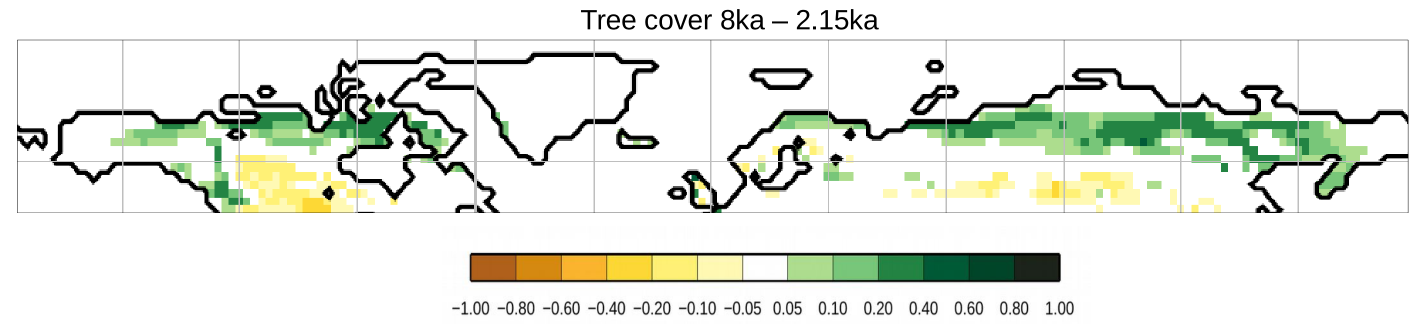
Taiga-Tundra region



- The main signal is the decrease of tundra along the Arctic coast and the strong decrease of boreal forest further south, both reflecting the southward shift of the boreal vegetation zones over the course of the Holocene. The model shows the following reduction in boreal forest and retreat of the northern treeline from 8ka to 2.15ka :

	Forest decrease	Retreat of treeline
North America	25.5%	2°
Europe	5.9%	0.5°
Asia	32.9%	3°

-The main forcing is the insolation-induced cooling of the summer climate during the Holocene

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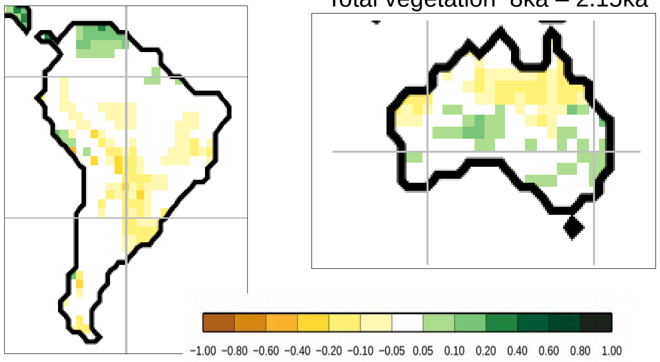
Extramonsoonal Australia and South America

Australia: South of 22°S vegetation decreases during the Holocene. At 8ka extratropical evergreen trees are more widespread. Along the eastern coast, the cover fraction of extratropical forests is increased by up to 16%. In central Australia, forest fraction is raised by up to 6%. The grass cover is enhanced in large parts of the (today) rather dry continental interior. These vegetation changes are related to a slightly wetter climate during the mid-Holocene due to a weaker subtropical ridge and less subsidence. In addition, the moisture influx from the western Pacific is increased. The enhanced low pressure system over northwestern Australia during austral spring causes monsoon-like conditions and suggest an earlier onset of the Australian summer monsoon at 8ka, coinciding with an enhanced precipitation level in entire Australia. The warmer sea surface temperatures in the Indonesian ocean may additionally favour increased winter precipitation during mid-Holocene.

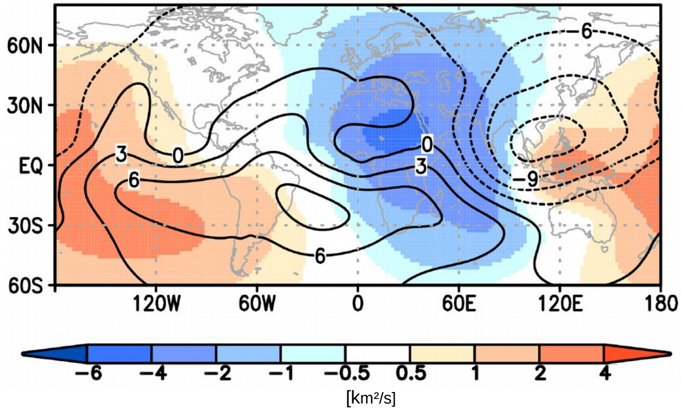
South America: The Gran Chaco and Pampas regions east of the South American Andes experience an increase in vegetation during the Holocene, mainly due to an increase in grass cover. On the Southern continent, extratropical evergreen trees cover up to 27% less area at 8ka compared to 2.15ka. These vegetation changes are probably related to the increase in both, austral wintertime and summertime precipitation during the Holocene. Large parts of the region get precipitation mainly due to the moisture influx in the north-easterly branch of the Subtropical Atlantic High. During 8ka austral winters, this anticyclone is shifted equatorwards leading to diverging easterly wind anomalies in the lower level and a decrease in moisture flux convergence. The upper tropospheric westerly jet is squeezed and intensified along the core (ca.30°S), probably enhancing the subsidence in the lee of the Andes. The subsidence is furthermore enhanced by the updraft of the Afro-Asian monsoon that forces a strong convergence anomaly above South America during austral winter. The continental summer low is weakened at 8ka, in line with the weakened South American monsoon, whose outflow touches this region at 2.15ka but not at 8ka. The model indicate a southwind anomaly in the lower troposphere (i.e. a reduced low level jet), diminishing the inflow from the monsoon area.

Tree cover 8ka – 2.15ka

Total vegetation 8ka – 2.15ka



JJAS velocity potential 8ka -2.15ka



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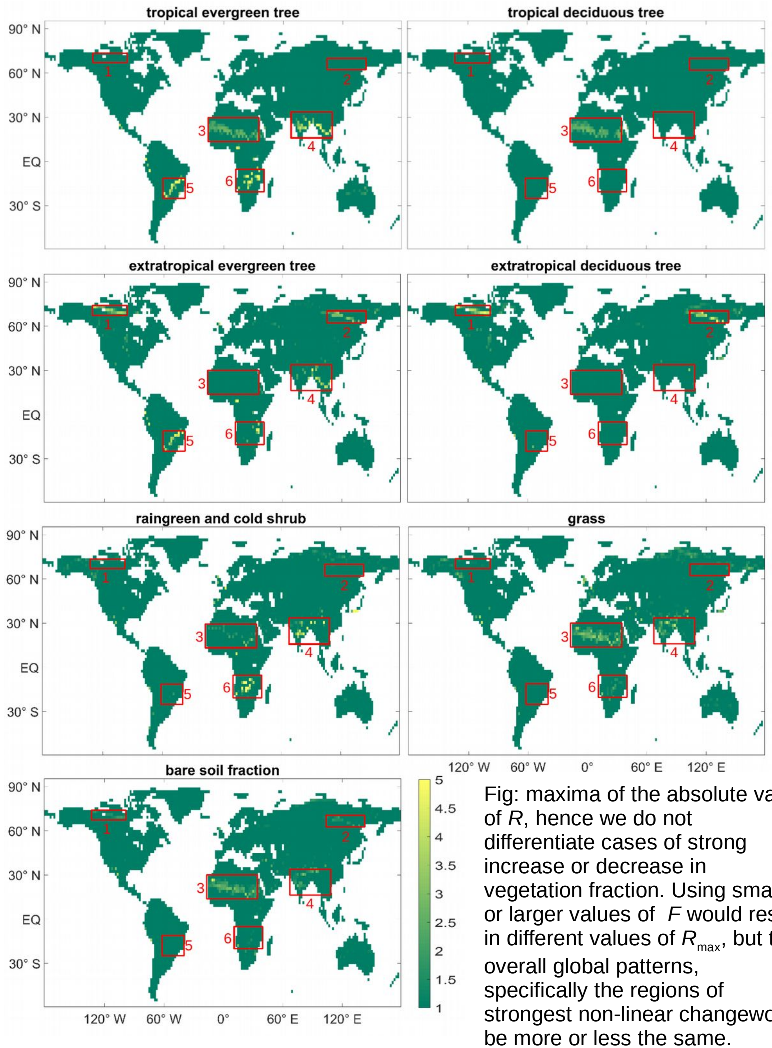

Fig: maxima of the absolute value of R, hence we do not differentiate cases of strong increase or decrease in vegetation fraction. Using smaller or larger values of F would result in different values of R_{max}, but the overall global patterns, specifically the regions of strongest non-linear changewould be more or less the same.

How rapid are the changes?

We evaluate the temporal change *dV/dt* of the simulated vegetation fraction *V* of a PFT relative to an overall amplitude *ΔV (here = maximum possible change = 1)* and over the entire period *ΔT* considered (here: *ΔT* = 6000 y). We define the relative change *R* and the absolute maximum of R (R_{max}) by:

$$R=\left(\frac{dV}{dt}\right)\left(\frac{\Delta V}{\Delta T}\right)^{-1} \qquad R_{max}=\left|\frac{dV}{dt}\right|_{max}\left(\frac{|\Delta V|}{\Delta T}\right)^{-1}$$

A Butterworth filter of the order 5 with a cut-off frequency 1/ *F* > 1/500y is used to get rid of fluctuations in V.

→ global shifts in vegetation appear to follow the rather linear, orbital forcing

→ Six regions with rapid, strongly nonlinear changes in PFTs: Canada and mid-Siberia, four regions in the monsoon margin area on both hemispheres (Sahel-Sahara, India & South East Asia, South America and South Africa).

→ most striking: Sahel-Sahara domain with rapid vegetation transitions to a rather desertic state induced by a strong decrease in precipitation since 8ka

→ The other rapid changes are mainly triggered by changes in the winter temperatures, which go into, or move out of, the bioclimatic tolerance range of individual PFTs in the model. These rapid changes have to be interpreted with care and should be taken as an indicator of possible rapid changes in the vegetation, rather than a precise prediction of rapid changes themselves.

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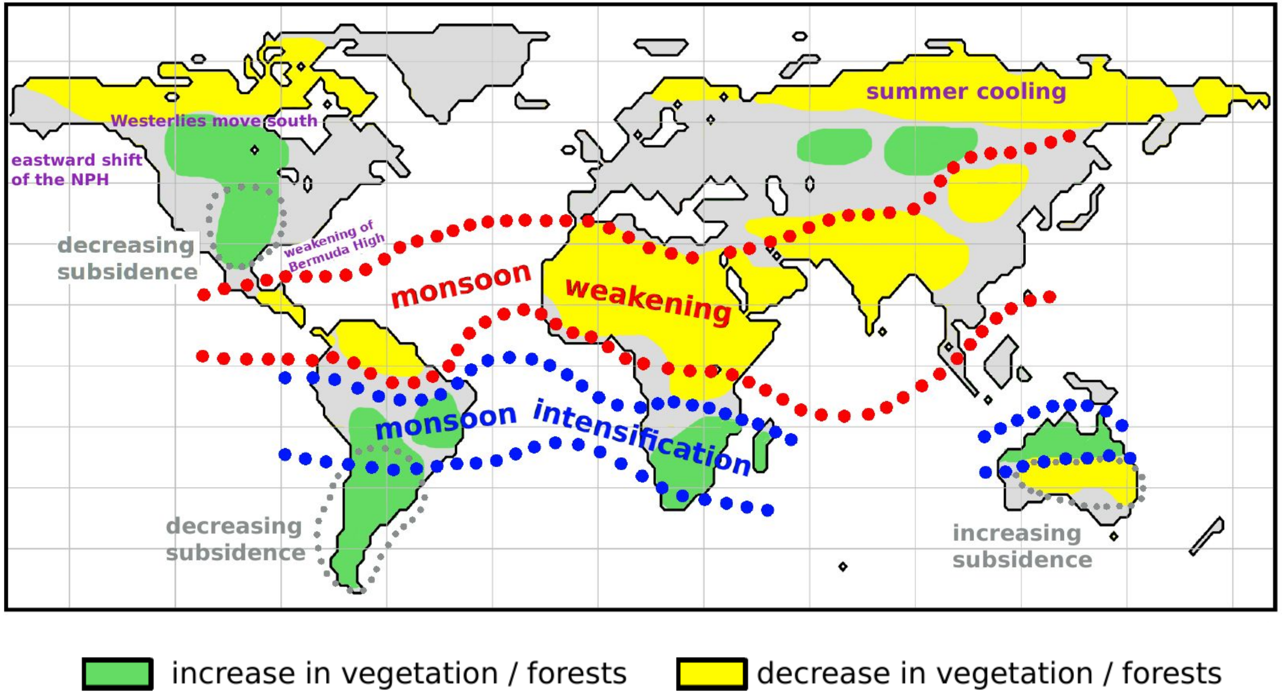

Summary

- a transient MPI-ESM 1.2 simulation shows that **precipitation is the main driver** for the veg. change south of 60°N

- precip. changes can mostly be **related to** the **weakening of the NH monsoon** and **strengthening of the SH monsoons** and **their remote effects on the large-scale circulation**

- vegetation trend follows the **almost linear** orbital forcing, but for **six regions rapid changes** are simulated

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anne.dallmeyer@mpimet.mpg.de

This study will be submitted to Climate of the Past end of April 2021

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