Climate-Vegetation-Feedbacks as a Mechanism for Accelerated Climate Change: The Greening Sahara Case

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Introduction:

Paleo-environmental records and extensive modeling studies have demonstrated that the Sahara was largely covered by grass and steppe vegetation in the early to mid Holocene. The orbitally controlled incoming summer insolation is the primary forcing factor during the Holocene. It is well-documented that internal feedback-mechanisms between the vegetation and the atmosphere-ocean system caused a sudden shift from the vegetated humid Sahara state to a arid desert climate about 5000-4000 years ago. Proxy evidence suggests also an abrupt onset of the African Humid Period between 14,000 and 11,000 BP. However, the attribution of the rapid onset to orbitally driven insolation anomalies or to the Bølling-Allerød, Younger-Dryas transitions non-trivial. Here we show in transient simulations with climate and vegetation models of different complexity that the abrupt change of the African Monsoon/Vegetation system from dry/deserted glacial state to wet/green conditions is accelerated by the vegetation-albedo feedback. The non-linear response of the climate-vegetation system to precessional forcing leads to a 'rapid' onset of the African Humid Period at ~11,000BP.

Temperature, Rainfall, and Vegetation in Western North Africa

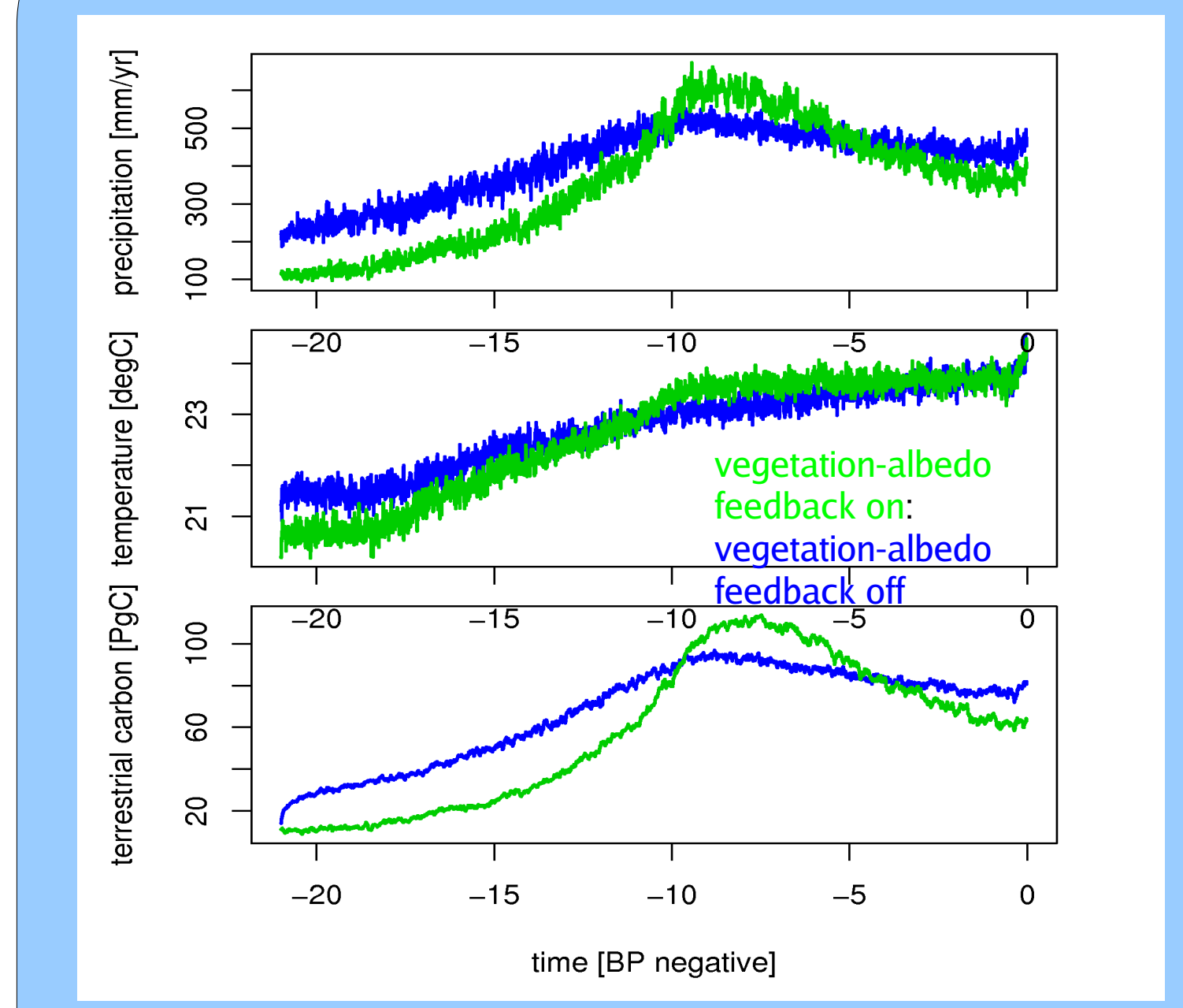


Fig 1: Temperature, precipitation and carbon stock over western North Africa (15°N-30°N/15°W-35°E) in the LOVECLIM simulations with/without vegetation feedback (green/black, respectively). The vegetation feedback enhances the precipitation anomalies over the greening Sahara, which leads to a further northward expansion of the vegetation. As a result the **vegetation-albedo feedback accelerates the northward movement of the ITZC and increases the precipitation and the terrestrial carbon storage at ~12,000 BP**. The wet and green Sahara climate state reaches peak values during the early Holocene (~8000 BP).

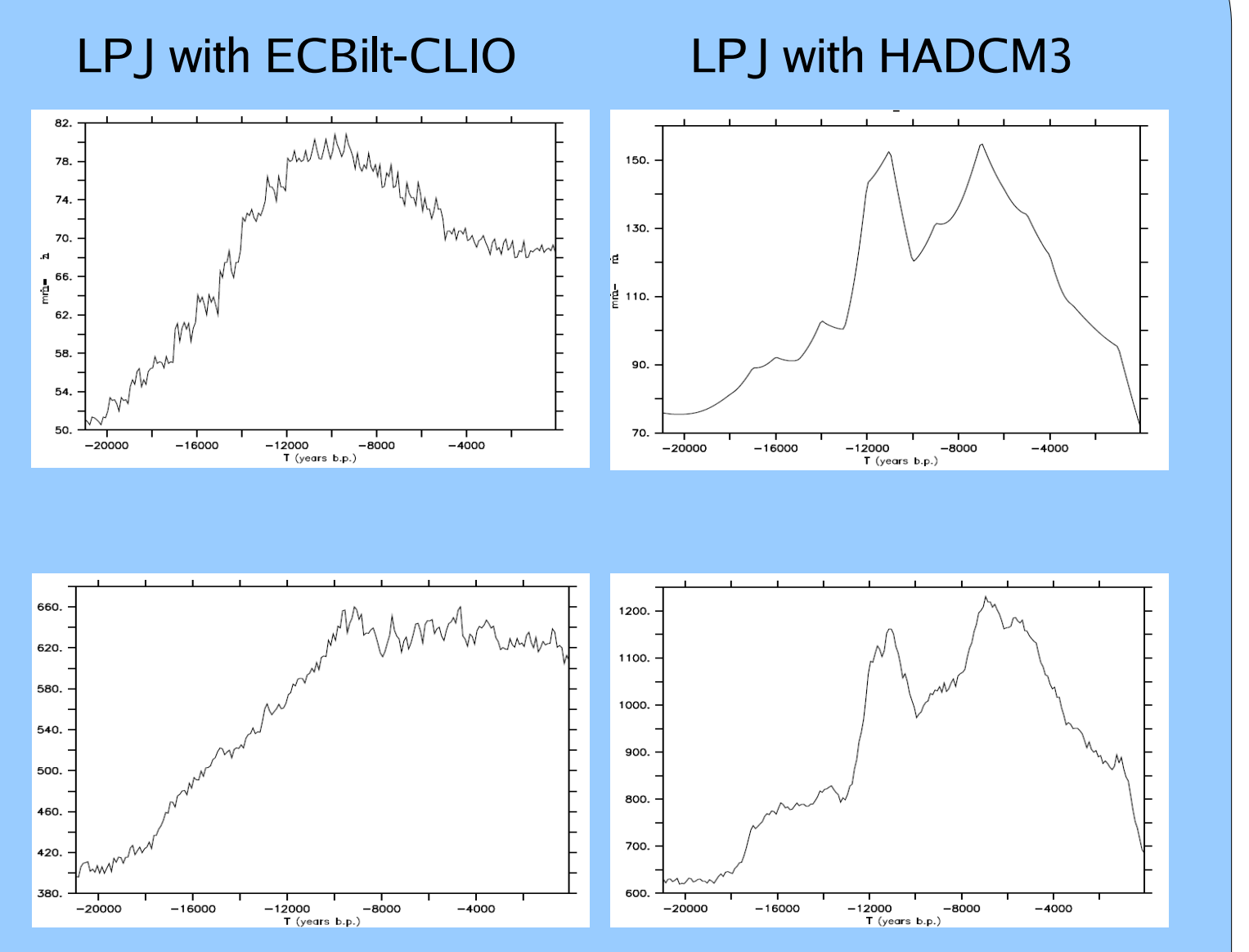
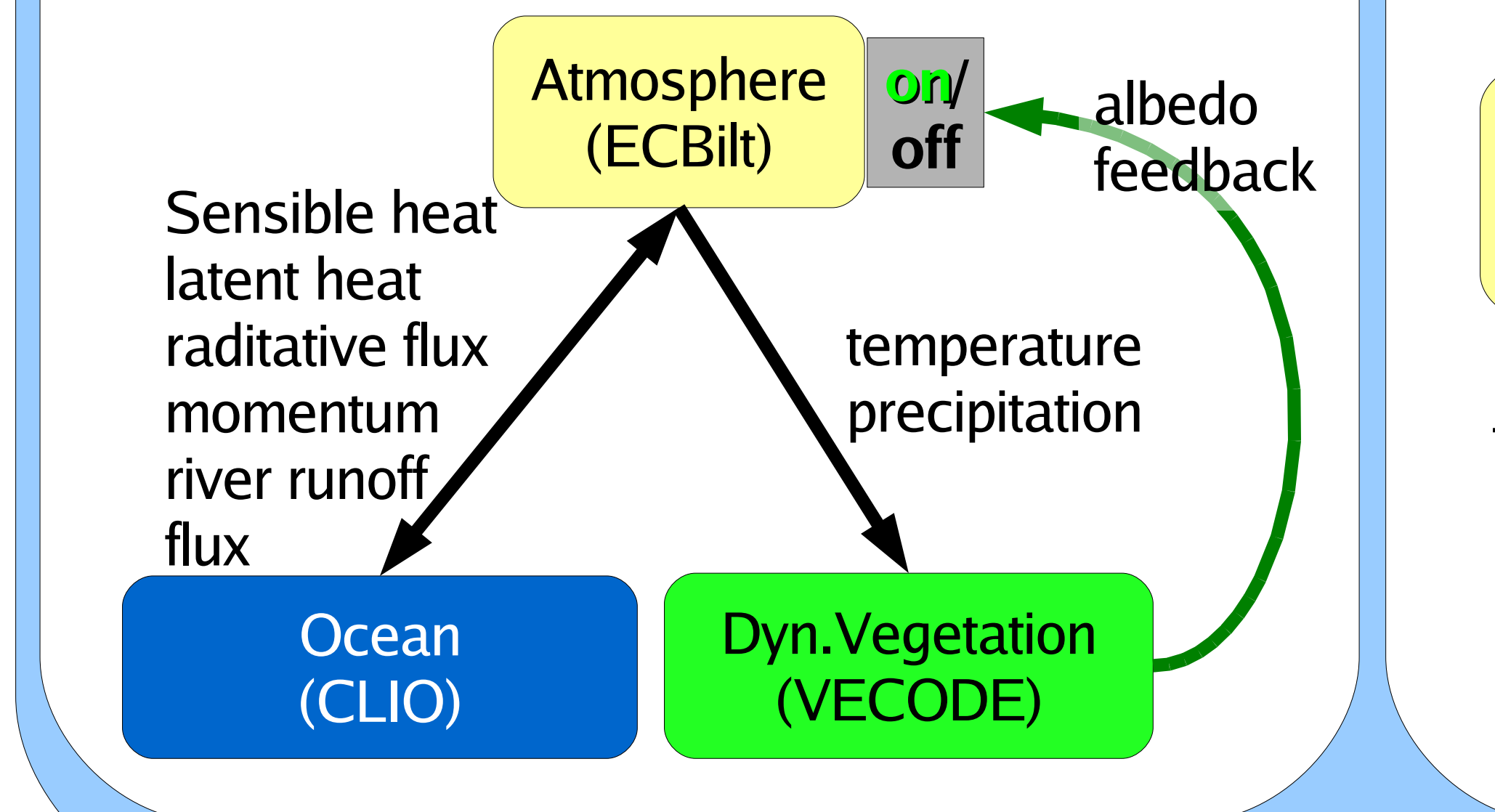


Fig 2: precipitation and terrestrial carbon stock over western North Africa (15°N-30°N/15°W-35°E) in the LPJ simulations with LOVECLIM (ECBilt-CLIO) atmospheric forcing (left) and HADCM3 forcing (right). The precipitation forcing shows some differences in the absolute values with less annual precipitation in ECBilt-CLIO. Strikingly, the HADCM3 precipitation has a sharp decrease in the late Holocene. The terrestrial vegetation response follows the more closely the precipitation forcing in the HADCM3 run rather than in the ECBILT-Clio run, where the Holocene vegetation cover does not decrease in the late Holocene. The results show that **the mean precipitation fields control the response of the vegetation to rainfall anomalies.**

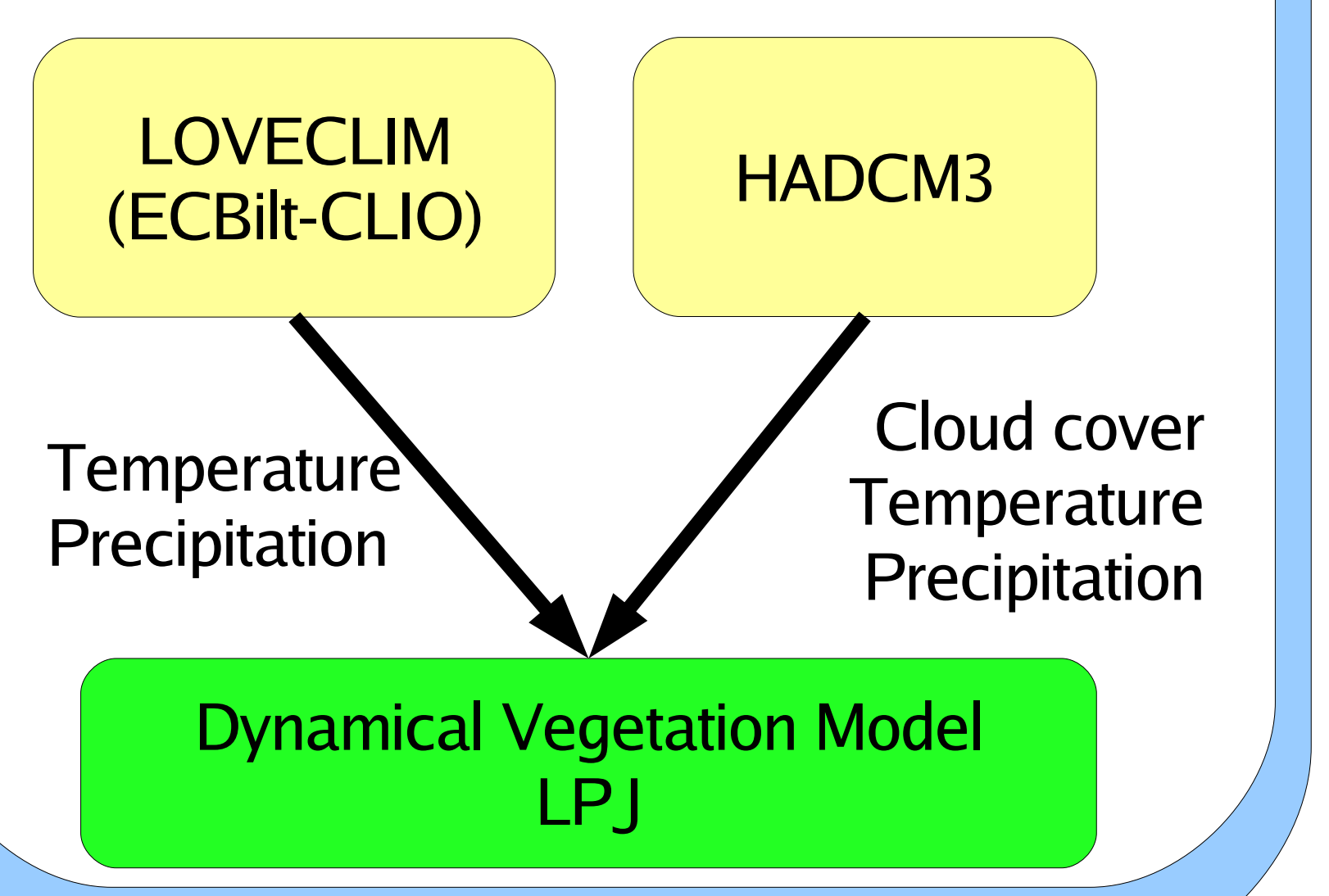
Model Simulations:

To understand the vegetation-climate feedback we used two different models: the dynamical vegetation model LPJ was forced with 2m air temperatures, precipitation, and cloud cover from time slice experiments with the HADCM3 model 21,000BP-0BP [Koehler et al.]. In a second experiment, the LPJ was forced with temperatures and precipitation data from a transient simulation with ECBilt-CLIO [Timm and Timmermann, 2007].

Earth System model LOVECLIM


Atmosphere (ECBilt)
on/ off
albedo feedback
Sensible heat
latent heat
raditative flux
momentum
river runoff
flux
temperature
precipitation
Ocean (CLIO)
Dyn.Vegetation (VECODE)

Dynamical Vegetation Model LPJ


LOVECLIM (ECBilt-CLIO)
HADCM3
Temperature
Precipitation
Cloud cover
Temperature
Precipitation
Dynamical Vegetation Model LPJ

Summary and conclusion:

1) The initial intensification and northward shift of the ITCZ rainfall is triggered by the increased incoming solar radiation during boreal summer (June-September).

2) The transition from desert to grass-shrub vegetation in western and central North Africa enhances the convergent flow of low-level moist air masses from the sub-/tropical Atlantic into the Sahara.

3) The response of the vegetation (within ~100 years) is relatively fast compared with the orbital precessional forcing (~21,000 yr) period. The vegetation feedback leads to a 'rapid' climate response.

4) The described mechanism is comparable with the abrupt cessation of the African Humid Period about 5000-4000 BP. In the simulation with the vegetation-albedo increases the carbon storage in the terrestrial vegetation.

5) Coupled climate-vegetation-carbon-models are crucial for the estimation of carbon budgets in atmosphere, ocean, and on land.

6) The comparison of the model results with proxy records is challenging.
The large millennial climate transitions, Boelling-Allerod and the Younger Dryas,mask signals resulting from the feedback between atmosphere-vegetation.

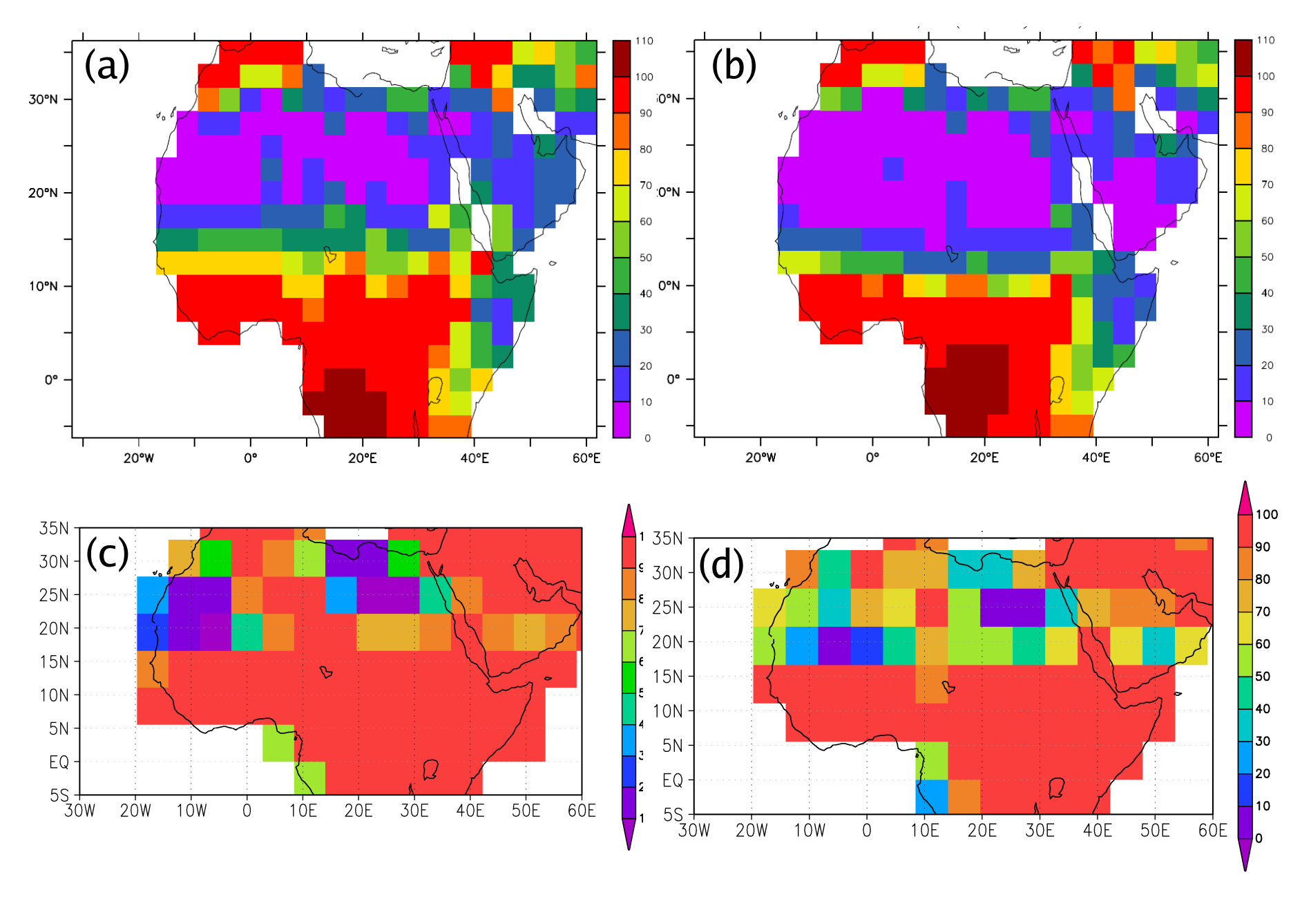
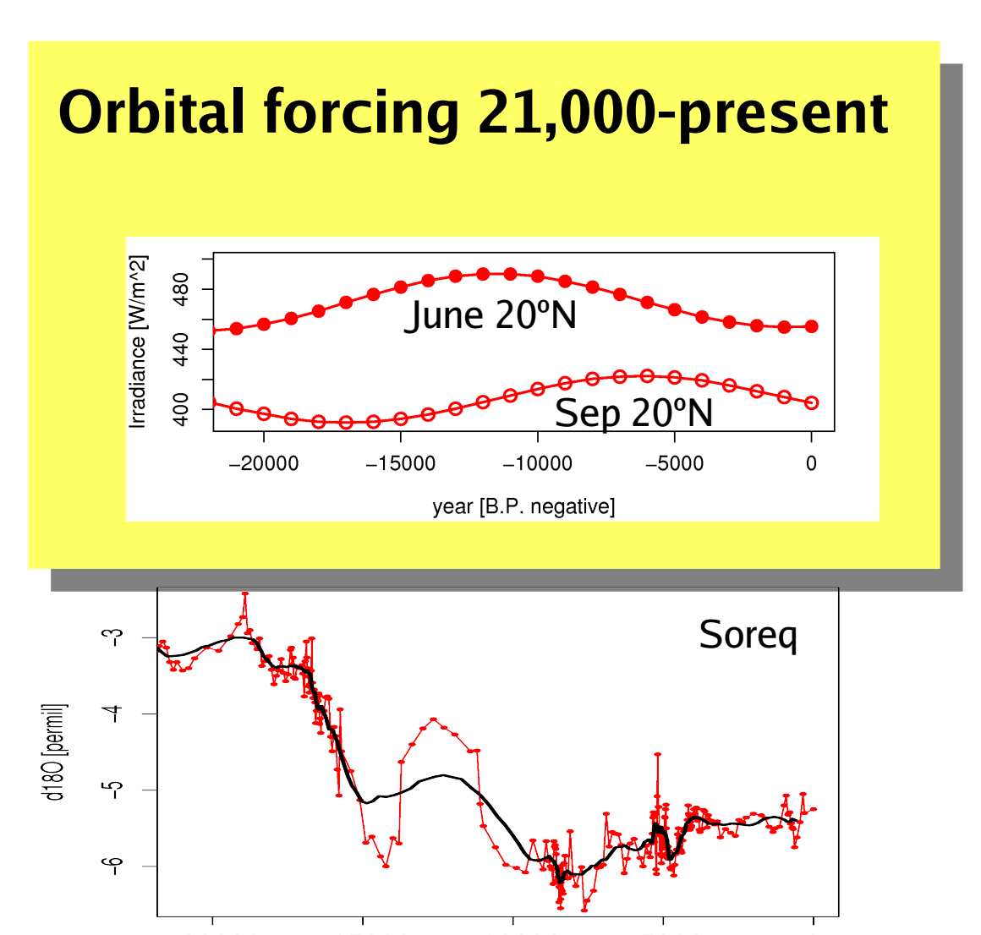
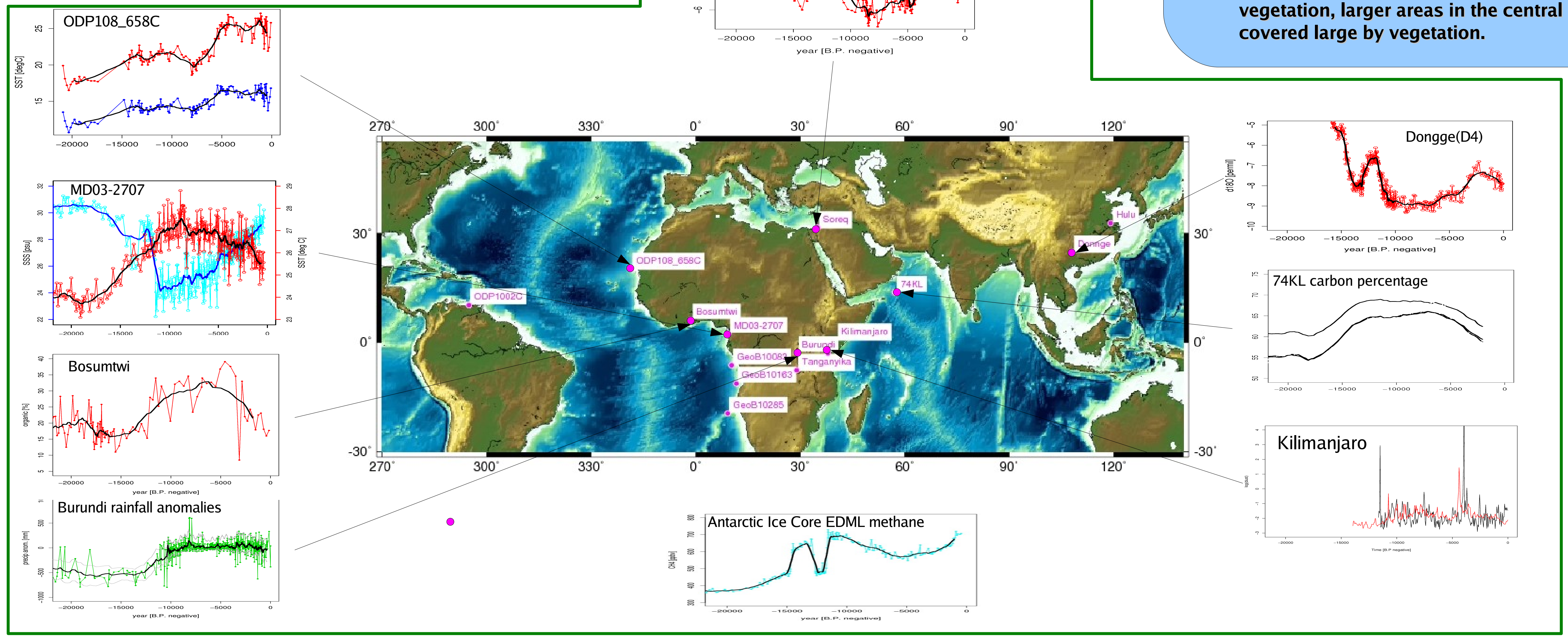


Fig 3: Simulated plant fraction coverage [%] during the maximum of the African humid period 9000-8000 BP:
(a) LPJ with HADCM3 forcing , (b) LPJ with ECBILT forcing, (c) LOVECLIM with vegetation-albedo feedback, (d) LOVECLIM without vegetation-albedo feedback. **With the albedo-feedback from the vegetation, larger areas in the central and western Sahara are covered large by vegetation.**

Orbital forcing 21,000-present





Vegetation-Atmosphere feedback dynamics

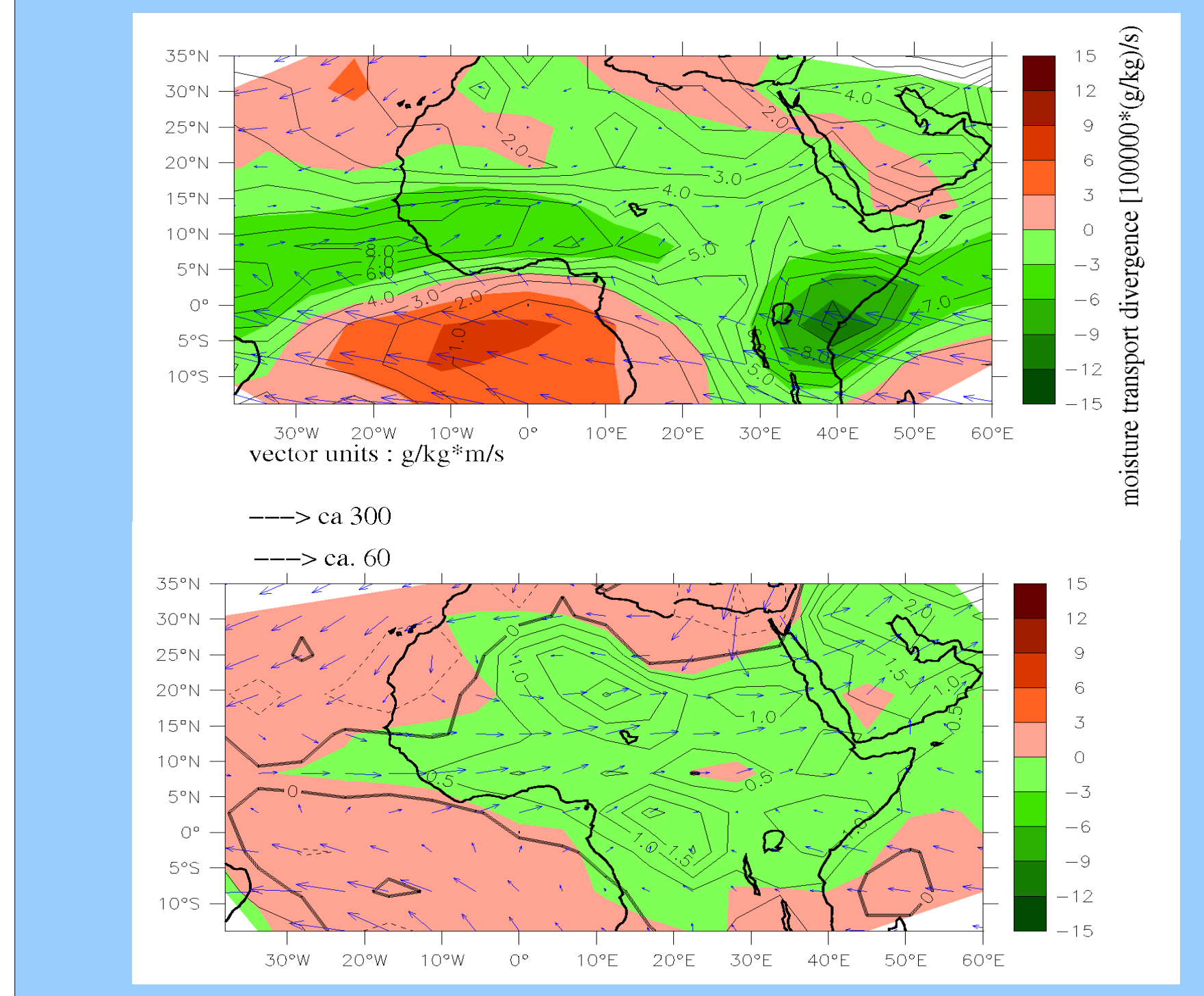


Fig 4: **(a)** Moisture flux (vectors) and moisture flux convergence (divergence) in green (red) colors for the northern hemisphere summer (June-September) in the LOVECLIM simulation without vegetation-albedo feedback during the peak African Monsoon 9,000-8,000 BP. Black contours depict the precipitation [mm/day]. **(b)** Difference between LOVECLIM simulation with and without vegetation-albedo feedback. Green colors mark regions of more moisture convergence and increased precipitation (contours) with vegetation-albedo feedback. T**he vegetation feedback increases the inflow of moist air masses from the tropical Atlantic into the continent.**

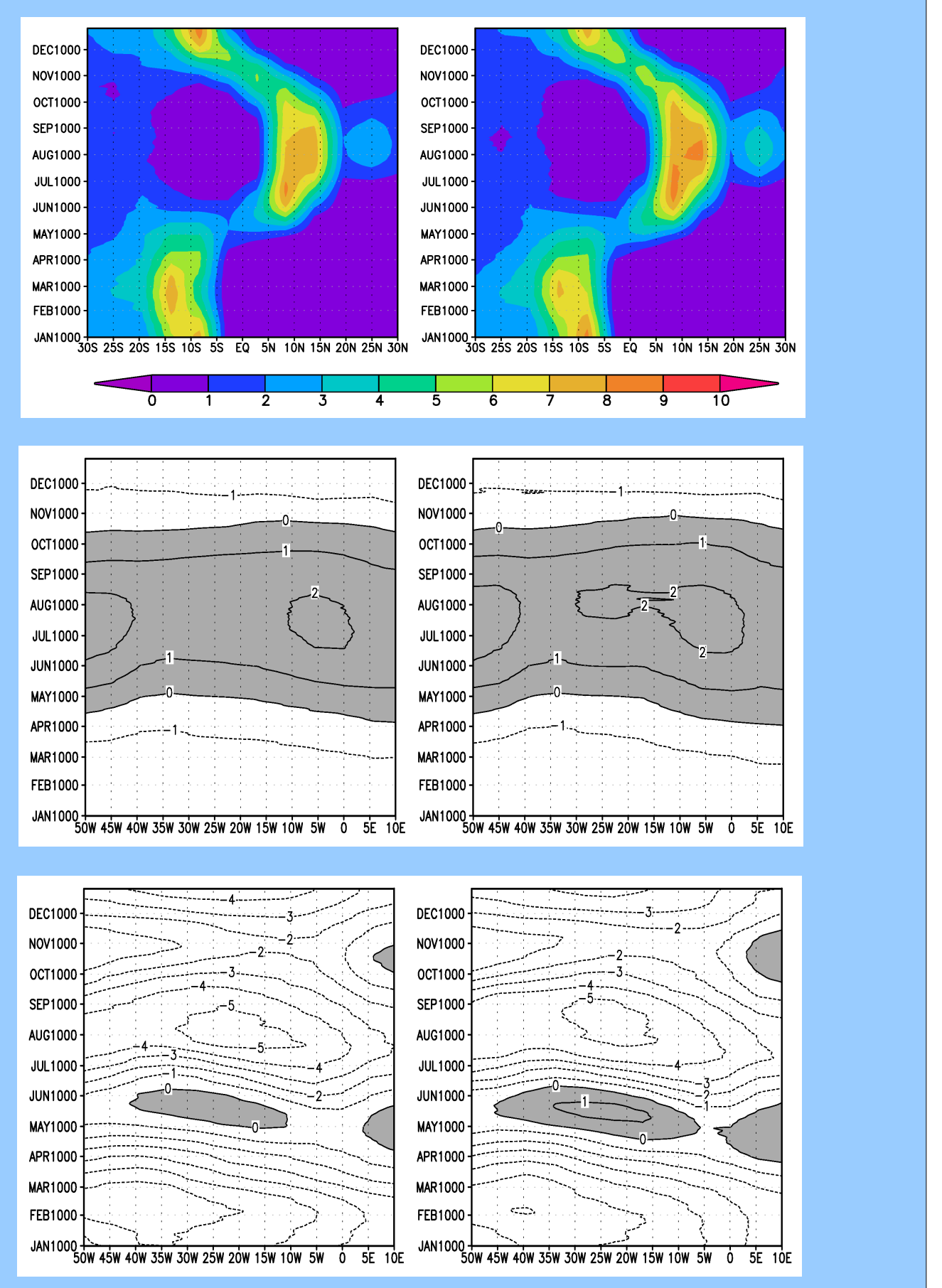


Fig 5 (top): Average seasonal cycle in western Africa (10W-10E) for the time of the Holocene maximum precipitation at 9,000-8,000 BP. Left (right), LOVECLIM simulation without (with) vegetation-albedo feedback (units in mm/day). The albedo-feedback has largest effect on the July-August months and leads to more intense rainfall.
(middle) Average seasonal cycle in the meridional winds across the equator for 9,000-8,000 BP. The July-August month have enhanced cross equatorial flow with vegetation feedback
(bottom) Average seasonal cycle in the zonal winds on the equator for 9,000-8,000 BP.

Acknowledgments:

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