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The Planet Simulator: Green planet and desert world

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Abstract

An application of the Planet Simulator is presented to estimate the maximum effect of vegetation on the Earth's climate. Four sets of sensitivity experiments are performed: (1) All vegetation related land surface parameters are changed simultaneously. (2) Only one effect of vegetation on climate is considered: albedo, surface roughness and soil hydrology. To identify the nature of vegetation-climate interaction, linear superposition and non-linear interaction of these three effects are compared. (3) The first experimental set-up is repeated but with mixed-layer ocean and thermodynamic sea-ice. (4) The effect of enhanced greenhouse gas concentrations on extreme vegetation climates is analysed repeating the preceding experimental setup with twice the CO_2 concentration (compared to set-3).

Zusammenfassung

Der Planet Simulator wird hier benutzt, um den maximalen Effekt der Vegetation auf das Erdklima abzuschätzen. Es werden vier Gruppen von Sensitivitätsexperimenten durchgeführt: (1) Alle vegetationsbezogenen Landoberflächenparameter werden simultan geändert. (2) Nur jeweils einer der Vegetationseffekte Albedo, Rauhigkeit und Bodenhydrologie wird geändert. Um die Art der Vegetation-Klima Wechselwirkung zu ermitteln werden die lineare Superposition und die nichtlinearen Wechselwirkungen der drei Effekte miteinander verglichen. (3) Die Experimente der ersten Gruppe werden nach Hinzufügen von Mixed-Layer-Ocean und thermodynamischem Eismodell wiederholt. (4) Die Experimente der Gruppe 3 werden mit doppelter CO_2 Konzentration wiederholt.

1 Introduction

The performance of the Planet Simulator (FRAEDRICH et al., 2005) is illustrated by four sets of experiments to quantify the relevance of vegetation for the climate system. Two extreme scenarios of vegetation are prescribed as fixed boundary conditions: In the green planet all the continents are covered by forest while, in the desert world, no vegetation is present. The setup and the motivation follow the study FKL-99 FRAEDRICH et al. (1999) and KFH-00 KLEIDON et al. (2000) with the atmospheric GCM ECHAM4 (see also BEESE et al. (2000)). In these studies ocean feedback has not been considered explicitly, although flux anomalies at sea surface indicate a potentially significant effect. Therefore, the present application includes these aspects by adding an interactive ocean/sea ice module. Furthermore, the sensitivity to greenhouse forcing is analyzed.

The outline of the paper is as follows: Section 2 describes the experimental design and section 3 presents the results. We conclude with a summary and outlook.

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2 Experimental design

A T21 version of the Planet Simulator with 10 non equally spaced sigma levels is used. This version needs about 15 minutes for one model year on a Linux-PC with two 3.0 GHz Pentium-IV processors. In the model, vegetation is represented by four parameters in the land surface scheme: (i) the surface background albedo effecting the surface solar radiation, (ii) the surface roughness (given by the roughness length) with direct implication for the exchange of moisture (latent heat), sensible heat and momentum, and two parameters representing the effect of vegetation on the soil hydrology: (iii-a) the maximum water storage of the soil (the bucket size) W_S and (iii-b) a parameter, w_f, controlling the fraction of actual and potential (maximum) evapotranspiration (i.e. the fraction of soil water which is available). This fraction, F, is given by

$$F = min(1.0, \frac{W}{w_f W_S}) \qquad (2.1)$$

where W is the actual amount of water in the bucket. For all three quantities, surface albedo, roughness and soil hydrology, specific parameter settings define the green

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Table 1: Definition of the green planet and desert world experiments.

Land surface parameter	Green planet	Desert world
Background albedo	0.12	0.28
Roughness length (vegetation)	2 m	0.01 m
Soil hydrology:		
Fraction parameter w_f	0.01	0.4
Bucket size W_S	0.5 m	0.1 m

planet and desert world scenarios (Table 1). Although the land surface module of the Planet Simulator is somewhat simpler than the ECHAM scheme, the values prescribed are as close as possible to the ECHAM specifications used in FKL-99 and KFH-00.

To determine the effect of vegetation extremes on the climate, the following sets of simulations are performed using global forest and global desert boundary conditions over land. That is, in the green planet and desert world simulation all land points (except glaciers) are fixed to one of the extremes.

Set-1: All vegetation related surface parameters are changed simultaneously.

Set-2: Sensitivity experiments, where only one effect of vegetation on climate in the model is considered: (a) albedo, (b) surface roughness, and (c) soil hydrology.

In these two sets the same annual cycle of SST and sea ice distributions is prescribed which is in accordance to the ECHAM experiment. The results of these sets are used to estimate the maximum effect of vegetation in the Planet Simulator in comparison to ECHAM and to separate the effects of the individual vegetation related parameters. The aim of this experimental set is, to analyze the nature of the vegetation-climate interaction: Is it simply a linear superposition of the vegetation attributes, (a) albedo, (b) surface roughness, (c) soil hydrology, or do non-linear interactions with the climate system, its water and energy-radiation balance, matter?

Set-3: Here set-1 is repeated but with a mixed-layer ocean and thermodynamic sea ice coupled to the atmosphere, to include potential feedbacks with the ocean.

Set-4: The effect of enhanced greenhouse gas concentration on the extreme vegetation climates is investigated by repeating set-3 but with twice the CO_2 concentration (defined by the present day value of 360ppm as in set-1 to set-3).

3 Results: Green planet versus desert world

The four sets of numerical experiments with the Planet Simulator are simulated for half a century. Results are reported in the following. The comparison with ECHAM is confined to set-1, while the other sets extend the previously analyzed results of the effect of vegetation extremes on the general circulation and, in particular on the climate of the Earth with a focus on the water cycle and the energy balance at the surface. A local t-test has been applied to all figures which shows that the contour lines capture areas with more than 90 or 95 % significance. Note that in the Planet Simulator all fluxes are defined positive in downward direction. E. g. precipitation is positive and evapotranspiration is negative.

Set-1: Total effect and Planet Simulator-ECHAM comparison

The difference between the climates of the green planet and the desert world is dominated by the changes of the hydrological cycle, which is intensified substantially. Enhanced evapotranspiration over land reduces the near surface temperatures; enhanced precipitation leads to a warmer mid- and upper troposphere extending from the subtropics to the mid-latitudes. In the inner tropical troposphere, temperature changes are negligible. In addition, the regional changes of the surface water and energy balances, and of the atmospheric circulation indicate potential impact on the ocean and the atmospheric greenhouse (FKL-99). In general, a good agreement can be found for both the spatial patterns and for the magnitudes of these changes. For some parameters and specific regions, however, differences to the FKL-99 and KFH-00 results appear, which will be emphasized in following. In particular, differences in the water cycle and in the surface energy balance for JJA and DJF need to be discussed; in addition, Planet Simulator results are compared with the respective ECHAM experiments in KFH-00 (their Figures 2 and 4).

The water cycle (Figure 1): Evapotranspiration is enhanced over most parts of the continents with largest values (up to 4 mm/day) in the tropics persisting over the whole year. For higher latitudes, more evapotranspiration is obtained during summer. Only a few regions show a decrease in evapotranspiration on the green planet: During JJA the east coast of America, southern Europe and a region extending from the monsoon areas of India/Southeast Asia up to Japan. The latter also persists in DJF. While for JJA the results are very similar to KFH-00 except that the decrease over southern Europe is less intense, ECHAM shows more decrease of evaporation over the ocean downstream of the continents for DJF.

In the green planet, precipitable water (the vertically integrated moisture content of the atmosphere) increases over almost all continental areas with peak values over Africa and, for JJA, across the Middle East towards the Pacific (up to 16 kg/m^2). Reductions are observed locally over the oceans and the Southeast Asia/India monsoon area where the latter is not present in the ECHAM simulation.

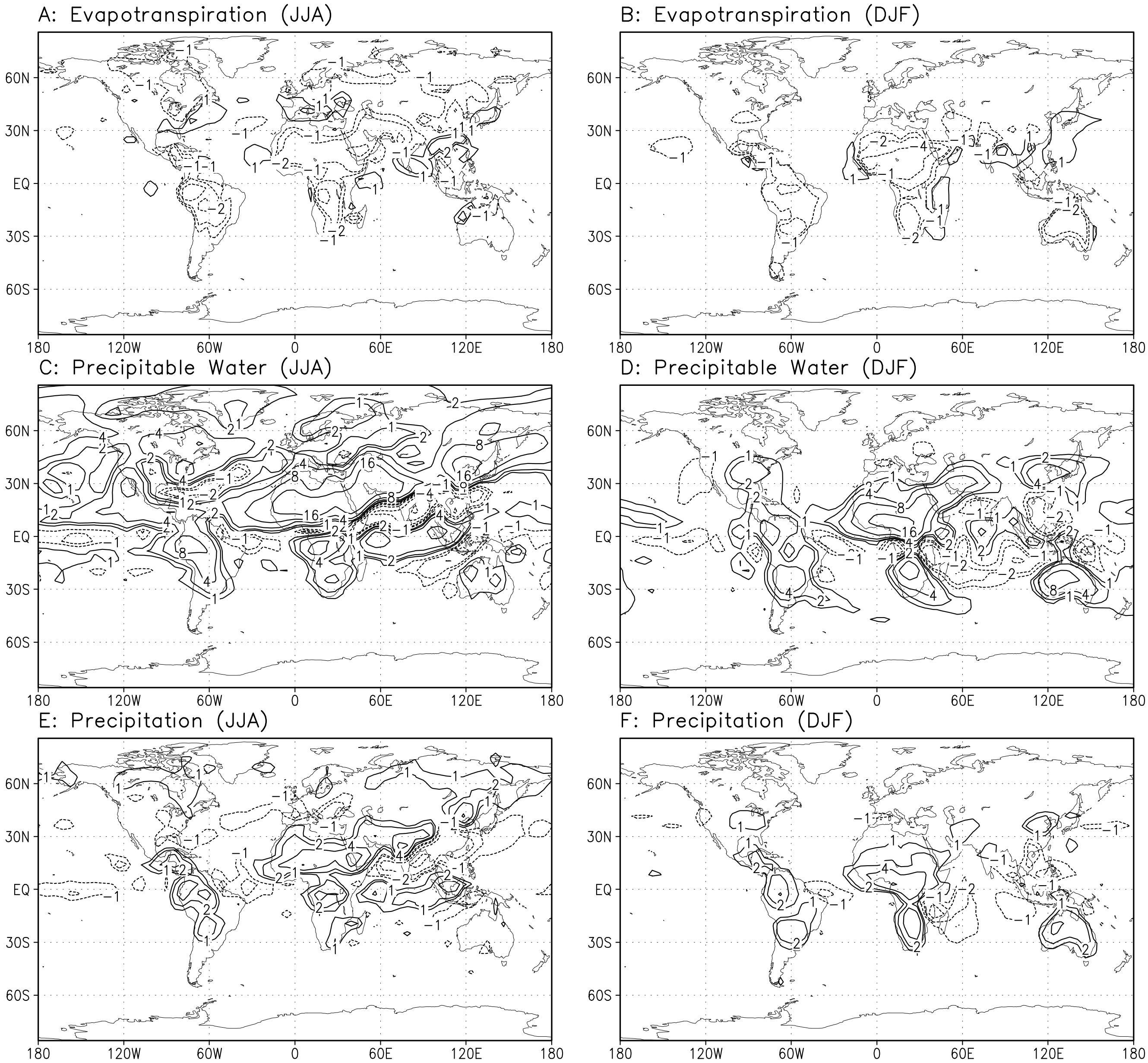

Figure 1: Differences in the water cycle for set-1: Seasonal differences between the green planet and desert world climates for June-August (JJA, left) and December-February (DJF, right). A, B: Evapotranspiration (in mm day^{-1}), C, D: Precipitable water (in kg m^{-2}), and E, F: Precipitation (in mm day^{-1}). Contours are $\pm$1, 2, 4, 8, 16 mm day^{-1} or kg m^{-2}. Negative contours are dashed.

Precipitation increases over the continents in the tropics except for the monsoon regions of southern India and Southeast Asia, where a decrease can be found consistent with the ECHAM results. Over the tropical oceans the precipitation is slightly weaker on the green planet but substantial shifts of the ITCZ over the tropical Pacific, as simulated by ECHAM, do not appear. In higher latitudes, enhanced precipitation can be found over the continents in summer except for central North America and southern Europe where a decrease is visible during JJA which, in particular for America, is different to ECHAM, where the decrease of precipitation is more confined to the east coast of America.

The surface energy balance (Figure 2): On the green planet net surface solar radiation increases by up to 40 W/m^2 over most of the continents. Only over Africa solar radiation is reduced in regions where total cloud cover increases (not shown) and thus overcompensates for the surface albedo effect. Over the oceans significant changes occur only during JJA with decreasing insolation over the North Atlantic/Arctic ocean and along the western Pacific. Compared with the ECHAM simulation some differences are noted: Changes over the oceans are in general larger in ECHAM and appear in both seasons emphasizing summer hemispheres. Over the continents ECHAM simulates negative radiation anomalies for higher latitudes in summer; positive changes are confined to the subtropics.

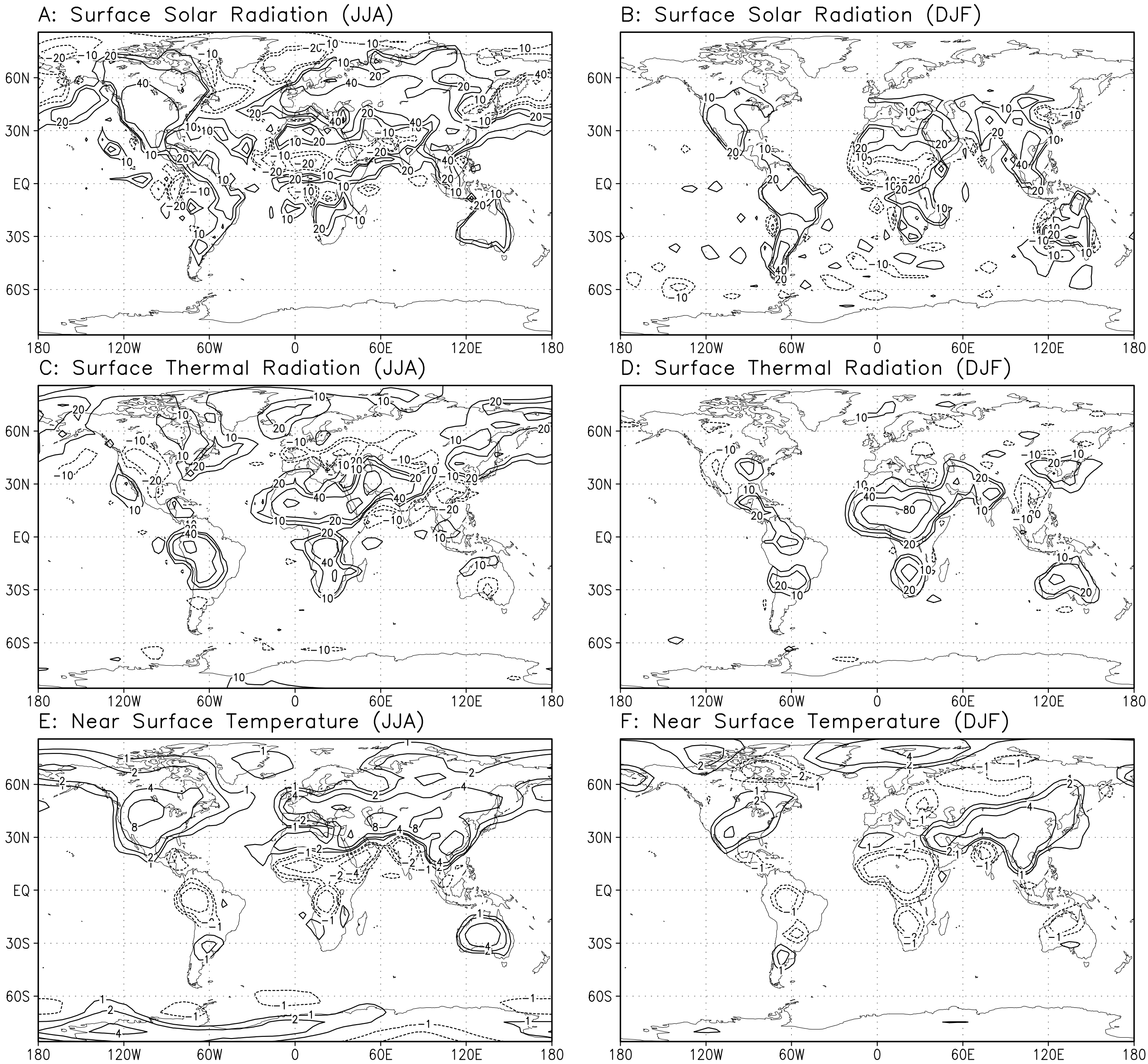

Figure 2: Differences in the surface energy cycle for set-1: Seasonal differences between the green planet and desert world climates for June-August (JJA, left) and December-February (DJF, right). A, B: Net solar radiation (in W m^{-2}), C, D: Net longwave radiation (in W m^{-2}), and E, F: Near surface temperature (in K). Contours are $\pm$10, 20, 40, 80 W m^{-2} and $\pm$1, 2, 4, 8 K, respectively. Negative contours are dashed.

For the net thermal radiation at the surface, positive anomalies dominate the green-desert world differences with values of about 80 W/m^2 over Africa. Negative anomalies occur in higher Northern Hemisphere latitudes (during DJF) and over central North America and southern Europe/Eurasia (during JJA); such negative anomalies are hardly noticeable in ECHAM.

The green-desert world differences in surface latent heat flux reflect the modifications due to increasing evapotranspiration; the differences in sensible heat flux reveal similar spatial patterns, but they are of opposite sign and smaller magnitude (not shown).

The cumulated effect of the surface energy budget difference (green-desert world) is realized in the near surface temperature. Since SST is fixed, no significant changes occur over the ice free oceans. Over land, however, a new balance of the total energy flux is attained due to temperature change: A general cooling in the tropics (up to 4 K), higher temperatures in the subtropics during summer and a slight cooling of the Northern Hemisphere high latitudes during winter (DJF). While the changes in the tropics are consistent with ECHAM, the extra tropical changes are not; the strong warming of the Northern Hemisphere continents during summer

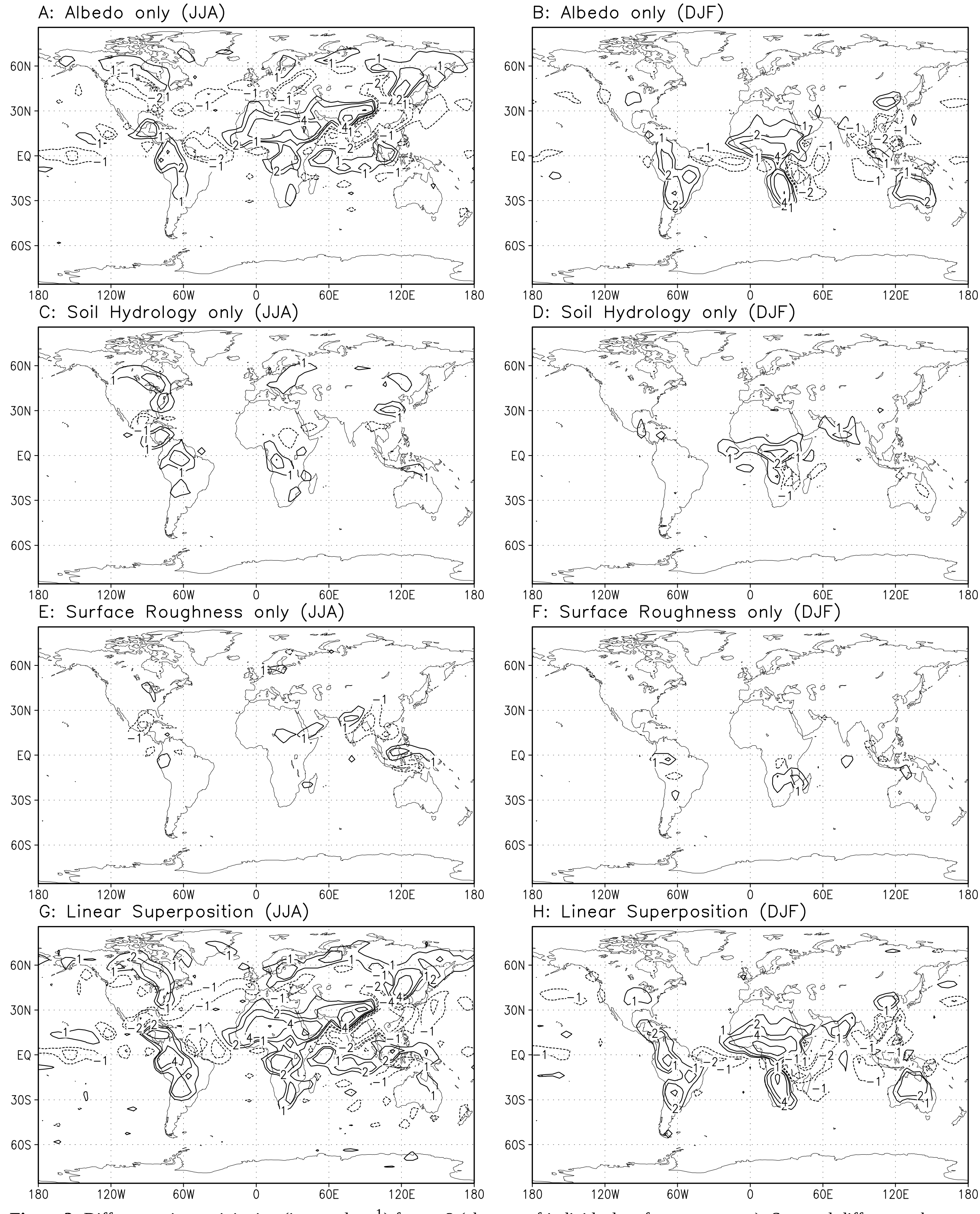

Figure 3: Differences in precipitation (in mm day^{-1}) for set-2 (changes of individual surface parameters): Seasonal differences between the green planet and desert world climates for June-August (JJA, left) and December-February (DJF, right). A, B: Changes in albedo only, C, D: Changes in hydrological cycle only, E, F: Changes in surface roughness only, and G, H: Linear superposition. Contours are ±1, 2, 4, 8, 16 mm day^{-}1. Negative contours are dashed.

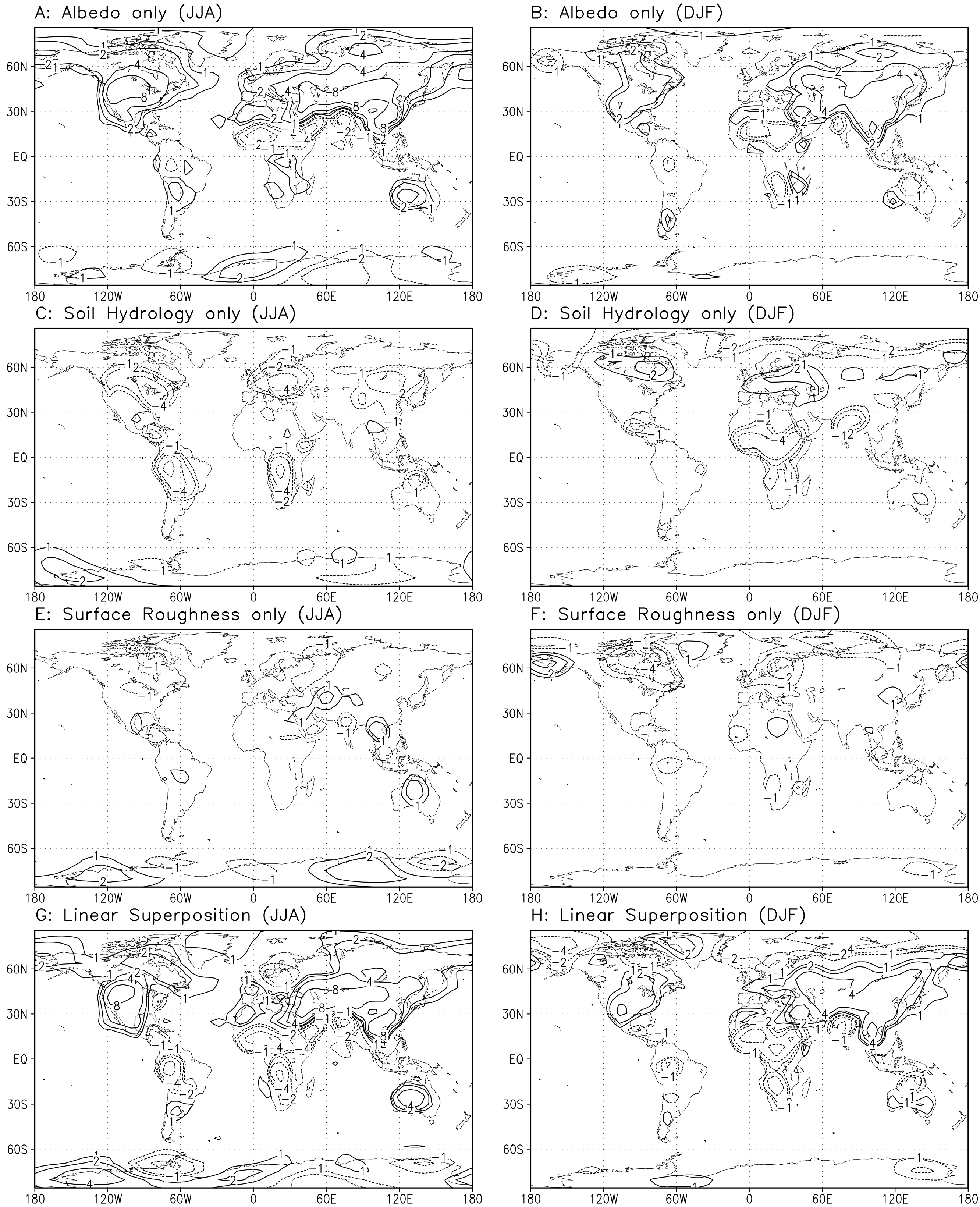

Figure 4: Differences in near surface temperature (in K^{-1}) for set-2 (changes of individual surface parameters): Seasonal differences between the green planet and desert world climates for June-August (JJA, left) and December-February (DJF, right). A, B: Changes in albedo only, C, D: Changes in hydrological cycle only, E, F: Changes in surface roughness only, and G,H: Linear superposition. Contours are ±1, 2, 4, 8, 16 K. Negative contours are dashed.

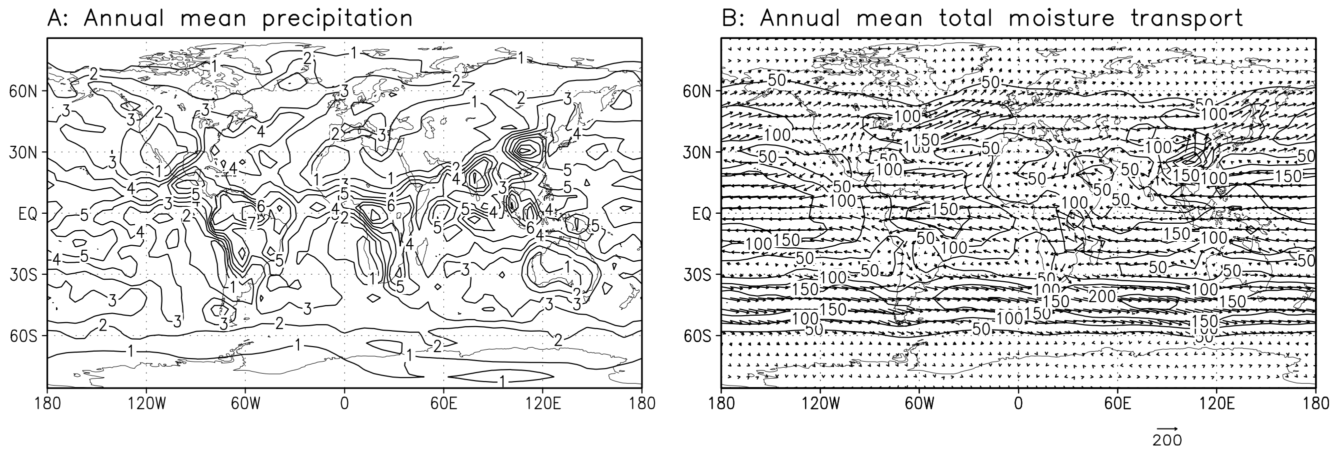

Figure 5: Annual mean precipitation (A, in dm) and water vapor transport (B, the sample arrow represents 200 kg m^{-1} s^{-1}) of the control run with mixed layer ocean.

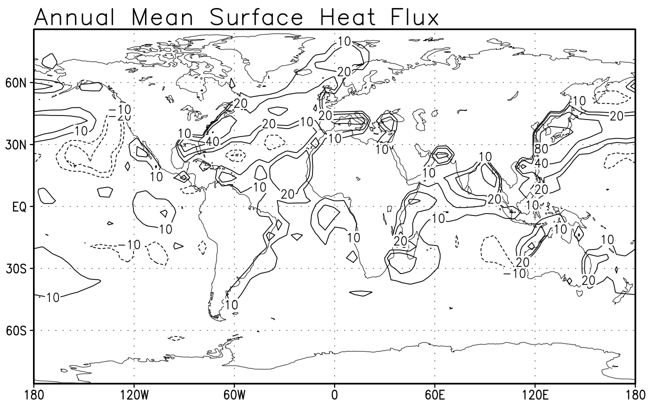

Figure 6: Annual mean net surface heat flux differences (in W m^{-2}) between the green planet and desert world climates in set-1 (without interactive ocean). Contours are ± 10, 20, 40, 80 W m^{-2}. Negative contours are dashed.

(JJA) is not present in ECHAM, where most of the areas north of 30°N cool.

Set-2: Sensitivity studies

To investigate the contribution and the relative importance of the individual vegetation parameters, these are albedo, soil hydrology, and surface roughness, additional systematic simulations are conducted. Only one of the parameters is modified while the others are set to normal (present day) conditions. It appears that, with some exceptions, the differences between green planet and desert world result from a linear superposition of the individual parameter changes. Depending on the region and the season, however, counteracting effects may occur. Albedo related changes dominate these responses. Regionally, however, they can be enhanced, diminished or, sometimes, overcompensated by the effect of soil hydrology. Surface roughness has the smallest impact.

For the water cycle (evapotranspiration, precipitation and precipitable water content) this linear superposition is a good approximation for the effect of the combined modifications. A closer inspection shows that during summer (JJA) the linear response is dominated by the changes of the surface albedo. But the changes of the soil hydrology play a minor role except for the subtropics in the Northern Hemisphere where albedo changes mostly act to decrease the water cycle leading to less evapotranspiration, precipitation and precipitable water (for precipitation, see Figure 3). Changes in soil hydrology counteract the albedo effect in these regions. During winter (DJF) the effect of albedo and soil hydrology are of comparable size in the tropics and act in the same direction, that is, they enhance the water cycle. Outside the tropics albedo related changes prevail in the response.

For the energy cycle, the green-desert world changes are dominated by the albedo modifications. The effect of soil hydrology is of regional importance. Besides an enhancement of net solar radiation due to the lower albedo of the green planet, changes of cloud cover influence the energy budget. The net effect can be measured by the near surface temperature changes (Figure 4): In the tropics and subtropics these changes are, to a large extent, achieved by a linear superposition of the albedo, soil hydrology, and surface roughness effect, with slightly higher magnitudes than the total non-linear set-1. At higher latitudes, in particular of the Northern Hemisphere, however, a view of linear superposition is not sufficient. While the linear superposition over northern European summer (JJA) is negative, the reference experiment (set-1) shows positive anomalies.

For DJF, positive anomalies extend mostly throughout Eurasia in the linear superposition case, while negative anomalies over Europe and the northern part of Asia characterize the reference experiment. In contrast, negative anomalies result from the linear superposition for the Arctic ocean while in the reference experiment the green planet is warmer than the desert world in this region. Both, albedo and soil hydrology contribute to the linear superposition effect. Changes of surface roughness only matter for high latitudes in winter, leading

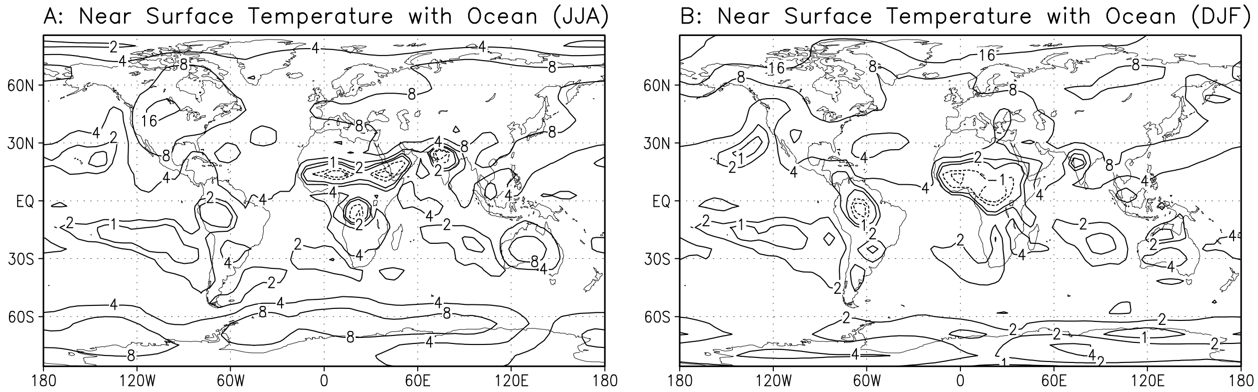

Figure 7: Differences in near surface temperature (in K^{-1}) for set-3 (with interactive ocean): Seasonal differences between the green planet and desert world climates: June–August (JJA, left) and December–February (DJF, right). Contours are ± 1, 2, 4, 8, 16 K. Negative contours are dashed.

mostly to cold anomalies in the Arctic (DJF) and warm anomalies in the Antarctic (JJA). For JJA the soil hydrology modifications result in colder temperatures in the green world in the Northern Hemisphere mid-latitudes and the Southern Hemisphere tropics while the albedo differences lead to a strong warming in the subtropics and mid-latitudes, with strongest response in the summer hemisphere, and colder temperature in the Northern Hemisphere tropics, the latter being caused by enhanced cloud cover. During DJF the anomaly pattern induced by the albedo changes persists with reduced magnitude. The effect of the soil hydrology is a cooling in the Northern Hemisphere tropics and in the Arctic together with a warming of the mid-latitudes.

Set-3: Impact of the ocean

Although the effect of vegetation on the surface climate (discussed above) is most distinct over land, it turns out that also the ocean surface is significantly influenced. In particular the energy balance at the ocean surface is modified, which implies a potential feedback between land vegetation and ocean. Before analyzing the green planet and desert world differences in heat flux and temperature, we show annual mean precipitation and atmospheric water vapor transport for the control run (Figure 5), which represents a satisfactory geographical distribution JAMES (1995) with an underestimation of the magnitude in the tropics not uncommon for low resolution spectral GCMs.

Figure 6 displays the difference in total annual surface heat flux between green planet and desert world runs of the experimental set-1 and set-2 (climatological SST). Large differences can be found over the oceans with positive anomalies up to 80 W/m^2. The anomalies add up to a global oceanic gain of about 7.8 W/m^2 for the green planet compared to the desert world. However, since SST and sea ice is fixed in set-1 and set-2, the ocean cannot react. To investigate the oceanic response and potential feedbacks an additional set of simulations (set-3) is performed using the same design as in set-1, but with an oceanic mixed-layer/thermodynamic sea ice model coupled to the atmosphere. In this simulation SST and sea ice are allowed to vary whereas the annual cycle of the oceanic heat transport is prescribed. Computed from a Planet Simulator present-day control simulation this transport is the same for the green planet and the desert world.

In principle, the interactive ocean enhances the effect of vegetation. Figure 7 shows the near surface temperature difference between the green planet and the desert world of set-3 (JJA and DJF). On the green planet, the ocean shows globally warmer temperatures than in the desert world with a difference of about 2–4 K over the oceans reaching 16 K in high latitude winters. The latter is related to a retreat of sea ice cover on the green planet. Over land, the green-desert difference patterns are similar to set-1, but positive anomalies show a substantial increase of magnitude (up to a factor of 2) and negative anomalies diminish.

Set-4: Sensitivity to greenhouse gas forcing

The possible effect of enhanced greenhouse gas concentration on the earth's climate is one of the most discussed numerical experiments. Therefore, and following the focus of this investigation, the sensitivity of the extreme vegetation climates to greenhouse gas forcing is studied in the experimental set-4. That is, the experimental set-3 is repeated but with twice the atmospheric CO_2 concentration (i.e. 720 ppm instead of 360 ppm used in set-3). The experiments start from the equilibrium climates of set-3. In addition, the same CO_2 scenario is carried out for a present day vegetation. For this present day vegetation setup, the model response to CO_2 doubling lies within the range of atmosphere-mixed-layer models (see, for example, HOUGHTON et al., 1990). The annually averaged global sensitivity of the model is 4.9 K. The horizontal distribution of the near surface temperature changes for the present day vegetation setup is

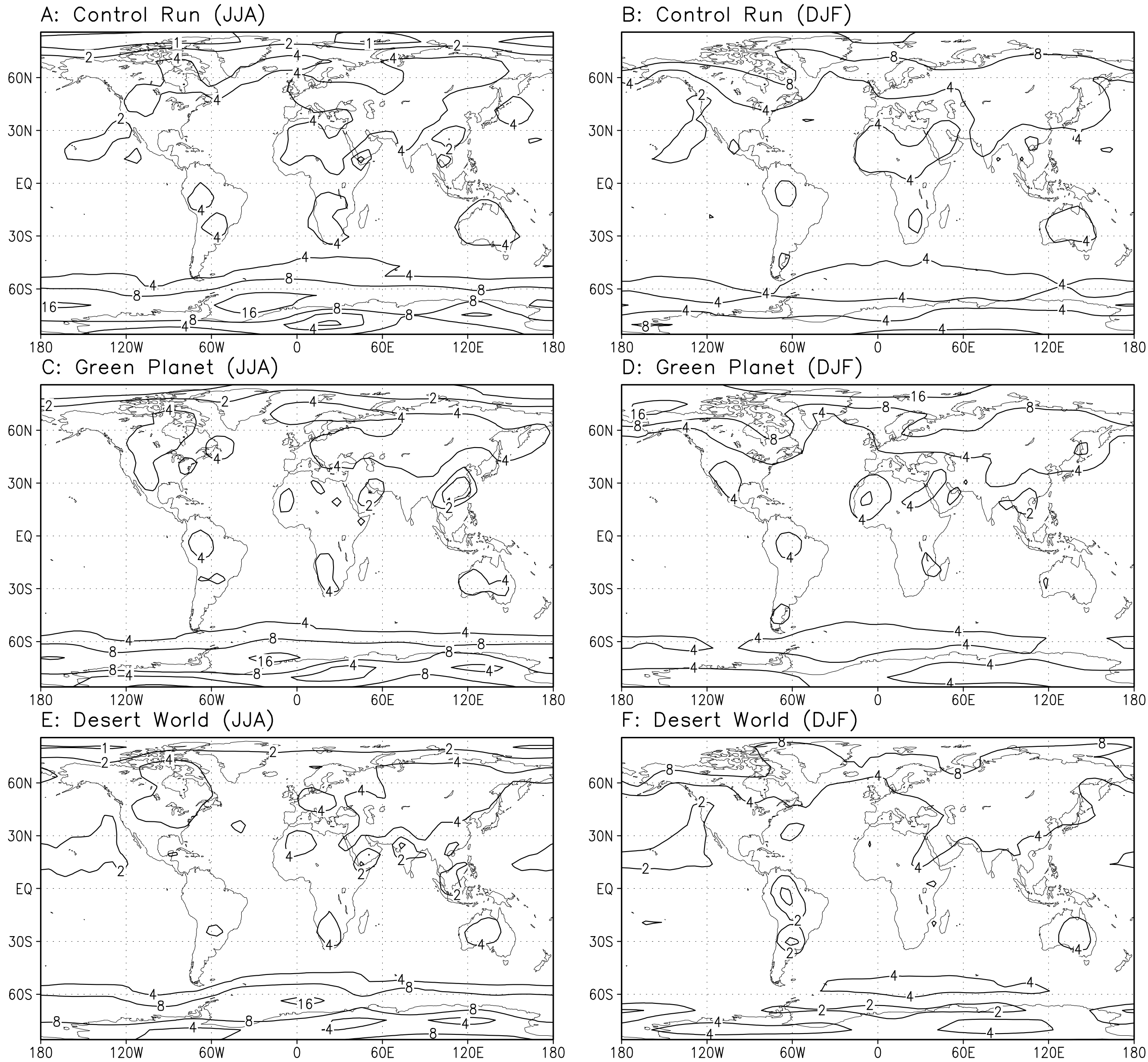

Figure 8: Differences in near surface temperature (in K) for set-4 (CO_2 sensitivity): Seasonal differences between two times CO_2 and present day CO_2 climates for June-August (JJA, left) and December-February (DJF, right). A, B: Present day vegetation, C, D: Green planet, and E, F: Desert world. Contours are ± 1, 2, 4, 8, 16 K. Negative contours are dashed.

shown in Figure 8A,B for DJF and JJA. The largest response is obtained over sea ice and high latitude land surfaces during the respective winter season. Maximum magnitudes of the warming are about 16 K over sea ice and 6–8 K over land surfaces.

The sensitivity of both, green planet and desert world, climates to greenhouse gas forcing is basically similar to the control climate with present day vegetation. However, some differences are noteworthy: (i) The annually averaged global sensitivity is about 1 K smaller for both, the green planet (3.7 K) and for the desert world (3.5 K). (ii) Related to reduced sea ice in the undisturbed simulation, the warming over the sea ice covered regions is larger on the green planet during the respective winter seasons (Figure 8). The opposite holds for the desert world, where the undisturbed simulation shows more sea ice, which leads to less warming. (iii) Over land, the differences between the three cases are small with a tendency that both, the green planet and the desert world, show less warming in tropics and stronger warming in higher latitudes compared with the present day vegetation set up.

4 Summary and outlook

A first application of the Planet Simulator describes the effect of vegetation extremes on the general circulation and, in particular the climate of the Earth with a focus on the water cycle and the energy balance at the surface. Investigations of these extreme vegetation states have been missing in most vegetation-related GCM experiments, although they are prerequisite for an analysis of the forces or feedbacks, which drive the climate-vegetation system towards its equilibria.

The Planet Simulator is applied to assess the relevance of vegetation in the climate system comparing a green planet with a desert world focussing on the water cycle and the surface energy balance. The strategy, suitable for comparing systematic differences between models, is composed of two steps: The comprehensive analysis (all parameter effect) versus the stepwise evaluation (individual parameter effects and their linear superposition) allows an identification of the non-linear contribution. Interpretation of the causes and isolating the underlying dynamical and physical processes requires a further step (which will be reported on later). An experimental strategy needs to be applied comparing dynamical cores and physical columns representing the radiative-convective processes. Here a note of caution is in order. The analysis of extreme boundary conditions like green planet versus desert world clearly exhibits potential model inadequacies. Thus, model intercomparison for such cases may improve the insight into possible model deficiencies notwithstanding a better view on the underlying physical processes and feedbacks at work with a strategy outlined here.

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