Clim Dyn (2011) 37:171–186
DOI 10.1007/s00382-010-0862-7

Global and regional coupled climate sensitivity to the parameterization of rainfall interception

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Received: 1 December 2009 / Accepted: 28 May 2010 / Published online: 10 June 2010

Abstract A coupled land–atmosphere model is used to explore the impact of seven commonly used canopy rainfall interception schemes on the simulated climate. Multiple 30-year simulations are conducted for each of the seven methods and results are analyzed in terms of the mean climatology and the probability density functions (PDFs) of key variables based on daily data. Results show that the method used for canopy interception strongly affects how rainfall is partitioned between canopy evaporation and throughfall. However, the impact on total evaporation is much smaller, and the impact on rainfall and air temperature is negligible. Similarly, the PDFs of canopy evaporation and transpiration for six selected regions are strongly affected by the method used for canopy interception, but the impact on total evaporation, temperature and precipitation is negligible. Our results show that the parameterization of rainfall interception is important to the surface hydrometeorology, but the seven interception parameterizations examined here do not cause a statistically significant impact on the climate of the coupled model. We suggest that broad scale climatological differences between coupled climate models are not likely the result of how interception is parameterized. This conclusion is inconsistent with inferences derived from earlier uncoupled simulations, or simulations using very simplified climate models.

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1 Introduction

The terrestrial surface is a key component of climate models and is now typically resolved using land surface models (LSMs) that explicitly represent the plant canopy (Randall et al. 2007). One component of LSMs is the interception of rainfall by leaves, and the subsequent redistribution of intercepted rainfall to throughfall or re-evaporation. The amount of rainfall interception in a climate model is parameterized based on attributes including canopy characteristics, rainfall intensity and duration (Dickinson et al. 1986) and wind.

The nature of climate models forces limitations in how rainfall interception is parameterized. While detailed modeling of rainfall interception (that might account for plant canopy architecture, rain droplet size, or specific leaf attributes) does exist within specific research communities, climate models simplify this detail to meet the limitations imposed by spatial resolution, pre-defined numbers of vegetation types, available globally resolved observational data and computational constrains. This paper focuses on these climate model-relevant interception schemes and their impact on the climate model.

The decision to include rainfall interception in climate models is linked to the timescales in which rainfall is returned to the atmosphere of a climate model. Intercepted water which fails to fall through to the soil re-evaporates rapidly, commonly on time scales of minutes to hours, due to the large aerodynamic roughness of canopies, high ventilation and large surface area in contact with the atmosphere. In contrast, precipitation which infiltrates into the soil tends to remain there for much longer periods (days to months) and may reach rivers or ground water to be effectively lost to the atmosphere, potentially for years to centuries. A key rationale for incorporating canopy interception into LSMs is therefore to capture the higher time frequency response driven by canopy interception (Scott et al. 1995), which could trigger changes in the diurnal cycle of clouds and affect radiation, in comparison to the slower timescale response of soil-based processes.

There are a variety of models available for interception parameterization (e.g. Rutter et al. 1971, 1972; Massman 1980). Methods similar to these are incorporated in most second and third generation LSMs (see Sellers et al. 1997; Pitman 2003). There is clear evidence that representing rainfall interception in a climate model is important (Wang and Eltahir 2000). However, there are various methods used in climate models and the question posed by this paper is *do different methods differ enough to cause an impact on the climate of the model*? The capacity of climate models to simulate the climate varies (Randall et al. 2007) and this paper explores whether these differences might in part be related to the parameterization of rainfall interception.

There have been several modeling experiments to explore the impact of interception parameterization on surface hydrometeorology and on climate. Pitman et al. (1990), for example, showed considerable sensitivity depending on the spatial scale of the rainfall forcing. However, Dolman and Gregory (1992) noted a fundamental limitation in the earlier study (and indeed similar off-line studies) due to the lack of land–atmosphere feedbacks. Dolman and Gregory (1992) used a single column model to highlight that interception losses were sensitive to the spatial scale of the rainfall forcing and to the precise formulation of the interception in the LSM but their modeling experiments were limited to Amazonian case studies. Wang and Eltahir (2000) extended the one-dimensional single column model approach to a zonal (a two-dimensional) approach. Their results pointed to considerable sensitivity in rainfall interception depending on the spatial scale of rainfall and they noted impacts from the surface to low level cloud, solar radiation, atmospheric circulation and the distribution of rainfall. Wang and Eltahir (2000) focused their analysis on West Africa—and found important sensitivities to how these processes were represented in the surface hydrometeorology. In particular, they identified that while neglecting sub-grid variability in rainfall interception might not affect the total evapotranspiration, it could change the partitioning of available water between interception loss, transpiration, and runoff. These changes could cause significant differences in the simulated atmosphere with a moister atmosphere, more low-level clouds and a weaker monsoon circulation. While Wang and Eltahir (2000) used a carefully evaluated model, it was a zonal model that was necessarily simplified in terms of the atmospheric response to the imposed changes.

In this paper, we use a three-dimensional climate model to assess seven approaches to interception parameterization. There are two major themes to our analysis: first, does the method used to simulate rainfall interception affect the surface hydroclimatology? This would be important if results from climate models were used to explore land surface phenomena, such as water availability. Second, does the interception method affect the net evaporation flux enough to affect broad scale atmospheric variables? The atmosphere of a climate model is not affected separately by re-evaporation intercepted water, transpiration or soil evaporation; these are combined before they are passed to the atmosphere. We therefore explore whether this combined flux is affected by rainfall interception choices and whether this in turn perturbs atmospheric variables and modeled climatology at timescales longer than a single day (we do not examine potential impacts of interception choices at sub-daily timescales).

2 Model description

2.1 The basic climate model

This paper uses an upgraded version of the Commonwealth Scientific and Industrial Research Organization (CSIRO) Mark 3 model (Mk3L; Phipps 2006). Mk3L is a low-resolution climate model; its parameterization and resolution would have been state-of-the-art for the second assessment report (Houghton et al. 1996). The atmosphere model (Gordon et al. 2002; Phipps 2006) uses a horizontal resolution of $\sim 3.18°$ latitude and $\sim 5.63°$ longitude with 18 vertical levels. Semi-Lagrangian transport is used to advect moisture (McGregor 1993), and gravity wave drag is parameterised following Chouinard et al. (1986). Shortwave (based on Lacis and Hansen 1974) and longwave [based on Fels and Schwarzkopf (1981) and Schwarzkopf and Fels (1985)] radiation are treated separately with both the annual and diurnal cycle resolved. A cumulus convection scheme (Gregory and Rowntree 1990) is coupled to the prognostic cloud scheme of Rotstayn (1997, 1998).

2.2 The land surface model

The community atmosphere biosphere land exchange (CABLE) land surface scheme (Wang and Leuning 1998; Kowalczyk et al. 2006) is a "third-generation" (Sellers et al. 1997) LSM. CABLE has been extensively evaluated (Kowalczyk et al. 2006; Wang et al. 2007a; Abramowitz et al. 2008).

CABLE represents canopy processes, soil, snow, carbon pool dynamics and soil respiration. It builds on Raupach et al. (1997), utilizing near field theory of turbulent transfer between soil, vegetation and atmosphere and calculations of canopy aerodynamic properties as a function of canopy height and canopy leaf area index. CABLE uses a one-layer two-leaf canopy model formulated by Wang and Leuning (1998) based on the multilayer model of Leuning et al. (1995). The stomatal model of Leuning et al. (1995) is extended to include the effects of soil water deficit on photosynthesis and respiration (Wang et al. 2001). A multilayer soil model is used, with Richards' equation solved for soil moisture and the heat conduction equation solved for soil temperature. The snow scheme was also improved by including up to three layers of dynamic-density snow above the soil (Kowalczyk et al. 2006).

3 Experimental methodology

3.1 Basic experimental design

Seven simulations were conducted, each integrated for 30 years, with the only differences being the canopy interception parameterization. All runs were initialized from the equilibrated state reached at the end of an earlier 500-year experiment. The atmosphere model used an atmospheric carbon dioxide concentration of 350 ppmv, a solar constant of 1,365 W m^{-2} and modern values for the Earth's orbital parameters. Climatological sea surface temperatures for 1982–2001 were used based on Reynolds et al. (2002).

The statistical significance in the global plots was determined with a two-sample F- and t test at a 90% significance level. The percentage area of the 90% statistically significant differences was also taken over all land points. Following Findell et al. (2006), we note that more than 10% of the area of interest must pass the significance test at the 90% level locally for a field to be considered statistically significant on the whole, to account for spatial correlation within the field.

3.2 Canopy interception methods: control parameterization

In the default version of CABLE, interception is calculated as the minimum of potential canopy surface water storage and the amount of precipitation. That is,

$$I = \min[[\min(P, P_{\max})], S_{\max}L - S] \quad (1)$$

where P is the liquid precipitation in a model time step (mm), $P_{\max}$ is the maximum liquid precipitation that can be intercepted in a time step as a function of time step size (mm), $S_{\max}$ is the maximum canopy storage capacity (mm per unit leaf area index), L is the leaf area index (m^2 m^{-2}) and S is the intercepted canopy reservoir from the previous time step (mm). The units of I, the intercepted rainfall in a model time step, are therefore mm.

A series of experiments were conducted that perturbed the formulation of I. In each case, this involved replacing the default parameterization used in CABLE with an alternative method.

3.3 Canopy interception methods: following Lawrence et al. (2007)

This method is based on Lawrence et al. (2007) (hereafter L07) and is currently used in the NCAR CLM. Precipitation arriving at the vegetation top is either intercepted by foliage, or directly falls through the gaps of leaves to ground. The water intercepted by the canopy in a model time step (mm) is:

$$I = P\left(0.25(1 - e^{-L/2})\right) \quad (2)$$

where 0.25 is implemented to scale the parameterization of interception from point to grid cells (Lawrence et al. 2007).

3.4 Canopy interception methods: following Kergoat (1998)

This method is based on Kergoat (1998) (hereafter K98) and is used in an updated version of LPJ (Gerten et al. 2004). Canopy interception in a model time step (mm) is defined as a function of biome, leaf area index, and precipitation:

$$I = PLi \quad (3)$$

where i is a dimensionless biome-dependent proxy for the rainfall regime. This varies from 0.01 for grassland and crops to 0.06 for evergreen needleleaf and deciduous broadleaf forest.

3.5 Canopy interception methods: following Sellers et al. (1986)

This formulation is based on Sellers et al. (1986) (hereafter S86) and has been used by Dai et al. (2003). Canopy interception is assumed to be similar to the treatment of the transmission of solar beam for spherically distributed leaves, which takes into account the factor of leaf angle distribution:

$$I = P\left(0.25(1 - e^{L(p_1+p_2)})\right) \quad (4)$$

where p_1 and p_2 are vegetation-type dependent parameters that depend on leaf angle parameters (Sellers et al. 1986). Note that Eq. 4 collapses to Eq. 2 when $p_1 + p_2 = 0.5$.

3.6 Canopy interception methods: incorporating sub-grid scale rainfall forcing

While interception in a LSM is driven by many factors (e.g. precipitation intensity and duration, canopy temperature, canopy characteristics, wind velocities), an established sensitivity exists relating to the sub-grid scale of the precipitation forcing. There is a long history of exploration of sub-grid scale precipitation and its impact on interception and surface hydrometeorology (Shuttleworth 1988, Entekhabi and Eagleson 1989, Pitman et al. 1990). Dolman and Gregory (1992) and Pitman et al. (1993) noted that off-line simulations of the impact of sub-grid scale precipitation forcing likely overestimated the impact of how sub-grid scale rainfall was parameterized on the surface hydrometeorology. Despite this, Wang and Eltahir (2000) highlighted large-scale responses from the sub-grid scale parameterization of rainfall interception using a zonal climate model. Clearly, there is value in exploring the scale of response of sub-grid scale rainfall parameterization in a coupled climate model.

Following Wang et al. (2005), for a given rainfall coverage fraction and a given probability density function (PDF) of rainfall, the grid-averaged canopy interception can be expressed as:

$$I = P - \Delta t\left(\mu \int_{(S_{\max}L-S)/\Delta t}^{\infty} (P_a - (S_{\max}L - S)/\Delta t) f(P_a)\, dP_a\right) \tag{5}$$

where μ is the rainfall coverage fraction ($\mu = P/\Delta t/P_a$), P_a is the conditional mean rain rate derived from observations (mm s^{-1}), and $f(P_a)$ is the PDF of the rain rate P_a.

Three simulations were undertaken based on observations from Wang et al. (2007b) using three distributions of rainfall based on Wang et al. (2005). We used an exponential distribution (hereafter W05e), a distribution assuming a spatially uniform rainfall rate (W05u) and a modified step function approximation to a lognormal (hereafter W05l) within the rain-covered area. The definitions and expressions for W05e and W05u are precisely as given in Wang et al. (2005). As Wang et al. (2005) noted little difference between the default exponential and lognormal distributions, we use a modified step-function version of their lognormal distribution as a boundary condition example. More precisely, W05l is given by

$$I = P - \Delta t\left[\frac{\mu}{3,600}\mathrm{INT}\left(\int_{(S_{\max}L-S)/\Delta t}^{\infty} 3,600(P_a - (S_{\max}L - S)/\Delta t) f(P_a)\, dP_a\right)\right] \tag{6}$$

where INT is a function that takes the value of the integer part of its argument. The effect Eq. 6 and W05l is therefore to only allow throughfall for heavy rainfall—all lighter

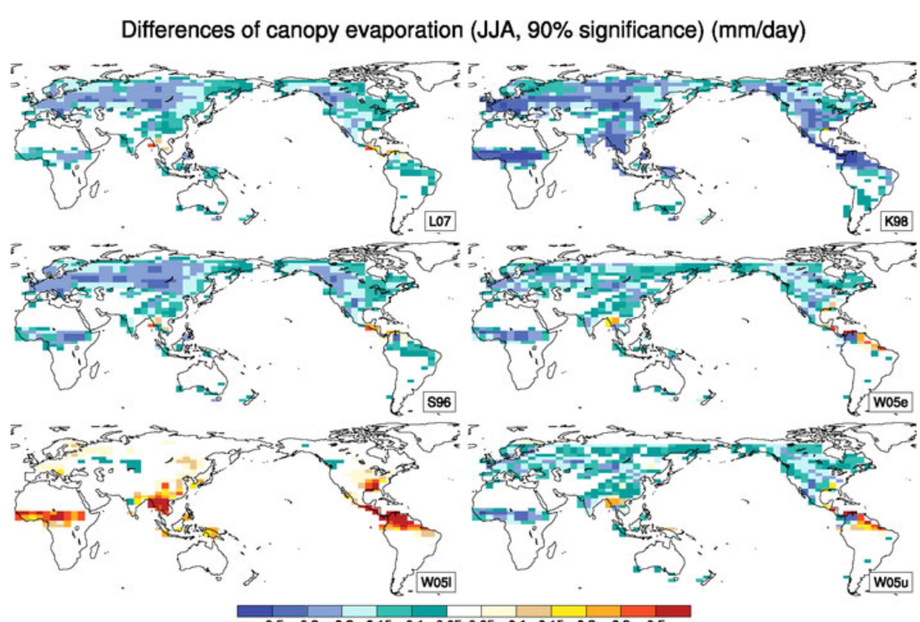


Fig. 1 Differences from the control (CTL) for each interception parameterization for JJA canopy evaporation (mm day^{-1}). Only differences statistically significance at a 90% confidence level are shown

rainfall will be stored by the canopy. It provides an extreme example of canopy interception.

4 Global scale results

Figure 1 shows the impact of the six different interception parameterizations on the global-scale June–July–August (JJA) canopy evaporation (interception loss) climatology. Large reductions in canopy evaporation are commonly simulated over regions of significant rainfall compared to the control run in all simulations except the extreme W05l case. These differences are statistically significant at a 90% confidence level. Simulation W05l, as well as parts of northern South America in simulations W05e and W05u, shows significant increases in canopy evaporation compared to the control run. Table 1 shows that a large percentage of land points simulate statistically significant changes due to the interception methodology, reaching 90% in K98 and 41% in the least sensitive simulation (W05l). Table 1 shows that this is not seasonally dependent—the sensitivity of canopy evaporation to the interception parameterization greatly exceeds the ~10% of points that would be expected to be statistically significant by chance. Note that the increase in canopy evaporation in simulation W05l is largely limited to tropical regions of the summer hemisphere.

Figure 2 shows the sensitivity of canopy transpiration to the interception parameterization. The impact of the interception parameterization is, as expected, a near mirror image of Fig. 1. If a canopy is covered by water it cannot transpire in a LSM parameterization and thus less interception tends to be associated with an increase in transpiration. Approximately half the land-based grid points simulate statistically significant changes in transpiration compared to canopy evaporation (Table 1). This is a seasonal impact.

Total evaporation (the sum of canopy evaporation, transpiration and soil evaporation) is shown in Fig. 3. Total evaporation is the only moisture flux that actually drives atmospheric processes in a climate model—the climate model is not forced separately by each component of evaporation. Figure 3 shows how the increase in one of the terms is counter-balanced by a decrease in the other. That is, canopy evaporation changes are compensated for by a change in soil evaporation, even in the extreme W05l case. The changes in total evaporation are smaller and less regionally coherent than the changes in transpiration or canopy evaporation. The maximum number of points showing statistically significant changes reaches 20% only once (Table 1) but exceeds 10% (the percentage expected by chance at a 90% confidence level) for all simulations in all seasons.

Table 1 Percentage of land grid points where a simulated change passed a 90% statistical significance confidence test

	L07	K98	S96	W05e	W05l	W05u
Canopy evaporation						
DJF	57	62	58	52	30	51
MAM	80	90	83	77	38	77
JJA	86	90	86	75	41	71
SON	84	91	85	81	34	79
Canopy transpiration						
DJF	15	25	18	20	19	21
MAM	36	55	37	34	25	37
JJA	48	59	49	42	29	42
SON	40	56	41	41	24	41
Evapotranspiration						
DJF	11	16	12	14	15	16
MAM	14	19	18	18	18	20
JJA	16	17	18	17	18	16
SON	17	17	16	15	16	19
Precipitation						
DJF	10	10	8	10	8	7
MAM	9	7	10	10	9	11
JJA	10	12	13	14	11	10
SON	8	10	11	10	10	11
Net radiation						
DJF	9	9	9	10	10	8
MAM	12	9	12	8	13	11
JJA	10	12	13	12	10	12
SON	8	10	11	8	10	12
Maximum daily temperature						
DJF	8	14	8	12	8	11
MAM	12	10	13	9	11	11
JJA	16	8	10	11	9	11
SON	8	11	11	18	7	14
Minimum daily temperature						
DJF	10	10	7	10	8	6
MAM	9	7	9	5	12	9
JJA	15	11	13	10	10	14
SON	10	7	10	12	9	8

There is no large-scale or coherent impact of the interception parameterizations on the simulated precipitation (Fig. 4). The changes in rainfall are small and are not biased to an increase or decrease in any individual simulation. Table 1 shows that the strongest impact occurs in JJA, but given 10% of grid points should show a statistically significant change by chance at a 90% confidence level, Table 1 and Fig. 4 do not provide convincing evidence that rainfall is affected at the large (e.g. continental) scale.

Figure 5 shows the impact on maximum temperature. While Table 1 suggests that too few grid points display

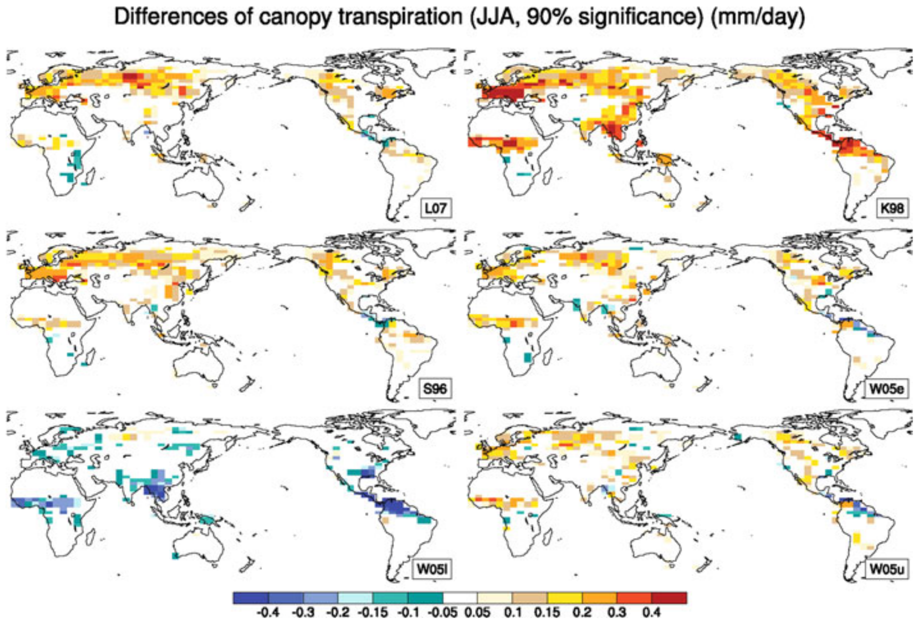


Fig. 2 As Fig. 1 but for canopy transpiration

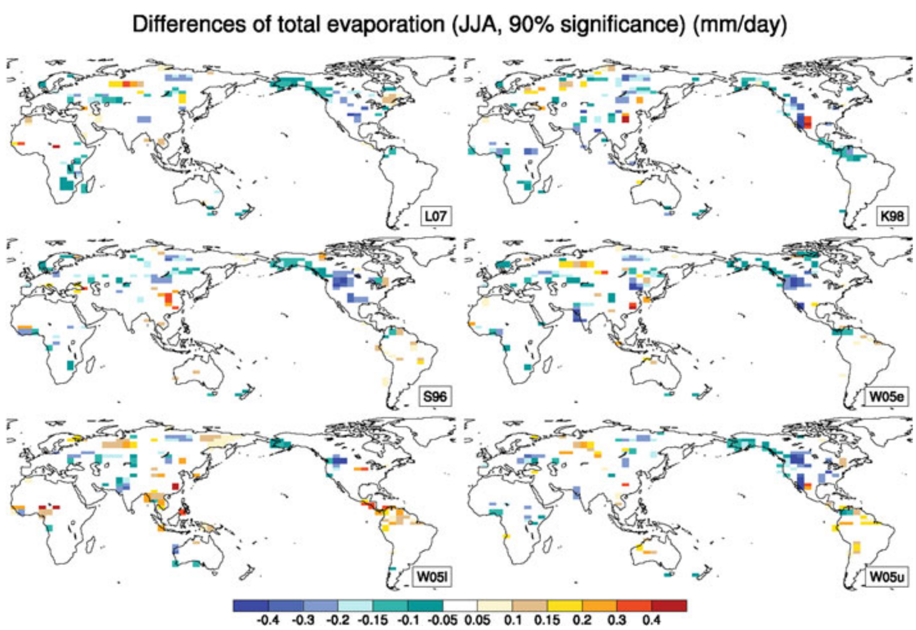


Fig. 3 As Fig. 1 but for total evaporation

statistically significant changes to conclude that an impact occurs, Fig. 5 hints at a coherent increase in temperature over North America. The changes are coincident with the decrease in total canopy evaporation (Fig. 3) and to a lesser degree reductions in rainfall (Fig. 4). It is most likely that the changes in maximum temperature are the result of reductions in available water from rainfall leading to lower evaporation and thereby warming.

We explored a suite of other variables, some of which are shown in Table 1. The scale of impact of changes in the interception parameterization did not exceed the levels expected by chance in minimum temperature or net radiation.

5 Regional scale results

Six regions were chosen to explore the impact of the canopy interception parameterization in more detail: Africa, Mackenzie basin, Amazon basin, Mississippi basin, Baltic and Murray-Darling basin (MDB) (see Table 2). A regional analysis can highlight processes that dominate a regional response that are lost in global averages. Rather than showing just the change in the seasonal or monthly mean, we focus on PDFs based on daily data. This allows us to identify changes that may be hidden in the mean but would be important, such as a systematic change in extremes.

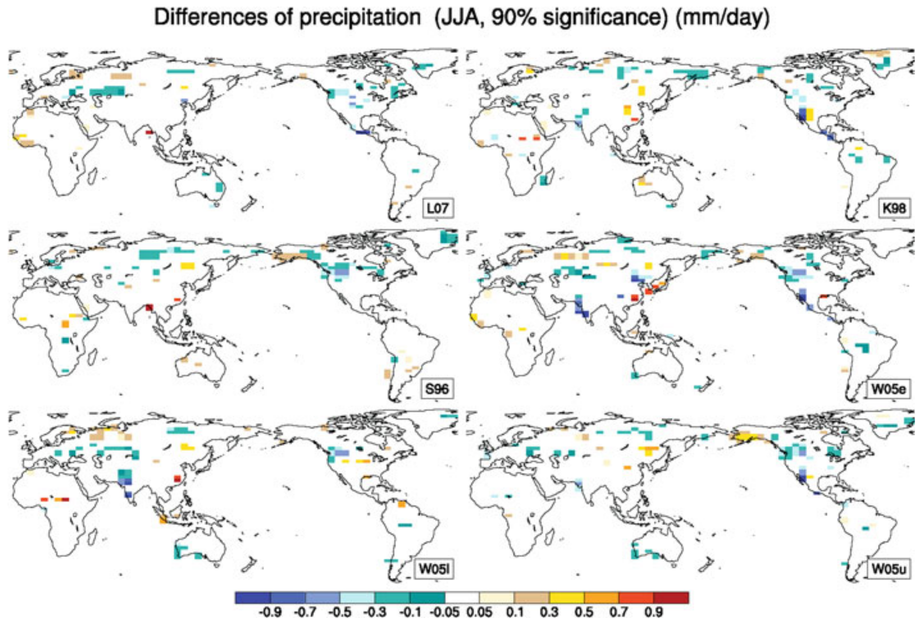


Fig. 4 As Fig. 1 but for precipitation

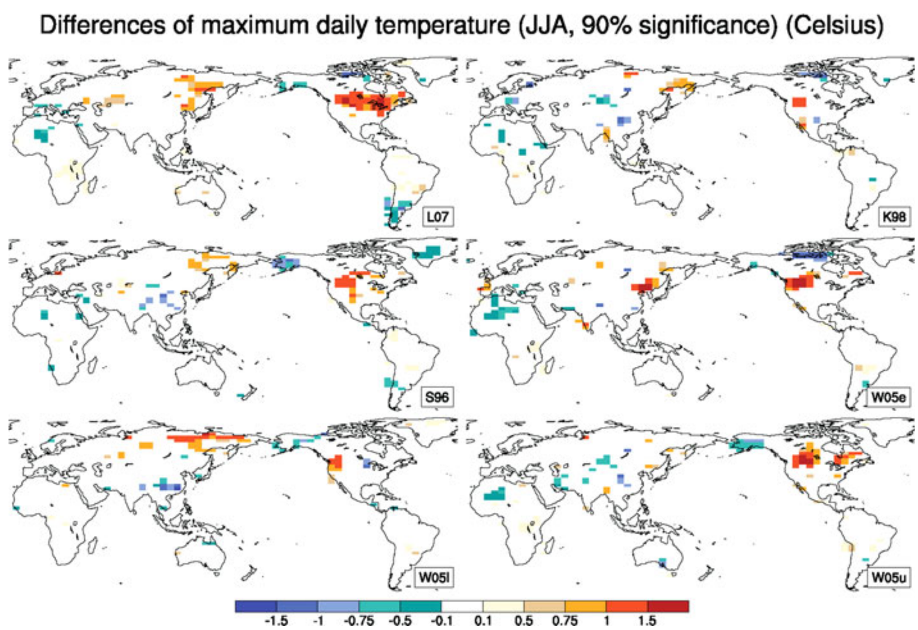


Fig. 5 As Fig. 1 but for maximum daily temperature (°C)

Table 2 Latitude and longitude of the regions discussed in the text

Region	Latitude; longitude
Africa	6°N–19°N; 14°W–14°E
Mackenzie Basin	60°N–70°N; 129°W–107°W
Amazon Basin	11°S–3°N; 75°W–50°W
Mississippi Basin	30°N–40°N; 95°W–82°W
Baltic	51°N–66°N; 16°E–29°E
Murray-Darling Basin	23°S–38°S; 138°E–151°E

A change in the shape of the PDF of canopy evaporation is clearly visible in Fig. 6. Not surprisingly, simulation W05l has a higher probability of higher canopy evaporation, particularly over Africa and the Amazon, while K98 clearly peaks at lower evaporation rates. K98 has a peculiar distribution over the MDB and Mackenzie. These differences are not caused by differences in rainfall, rather they relate to the use of an integer index in Eq. 3 which causes a non-continuous set of solutions. The differences in regional rainfall means are small ($\sim$5% of the control). However, there is a clear association between the PDF of rainfall (Fig. 7) and the impact of interception parameterization. In those regions where simulations L07, K98, S96, W05e and W05u simulate lower interception, the simulated PDF of rainfall is within the range from 0 to 6 mm day^{-1} (Baltic,

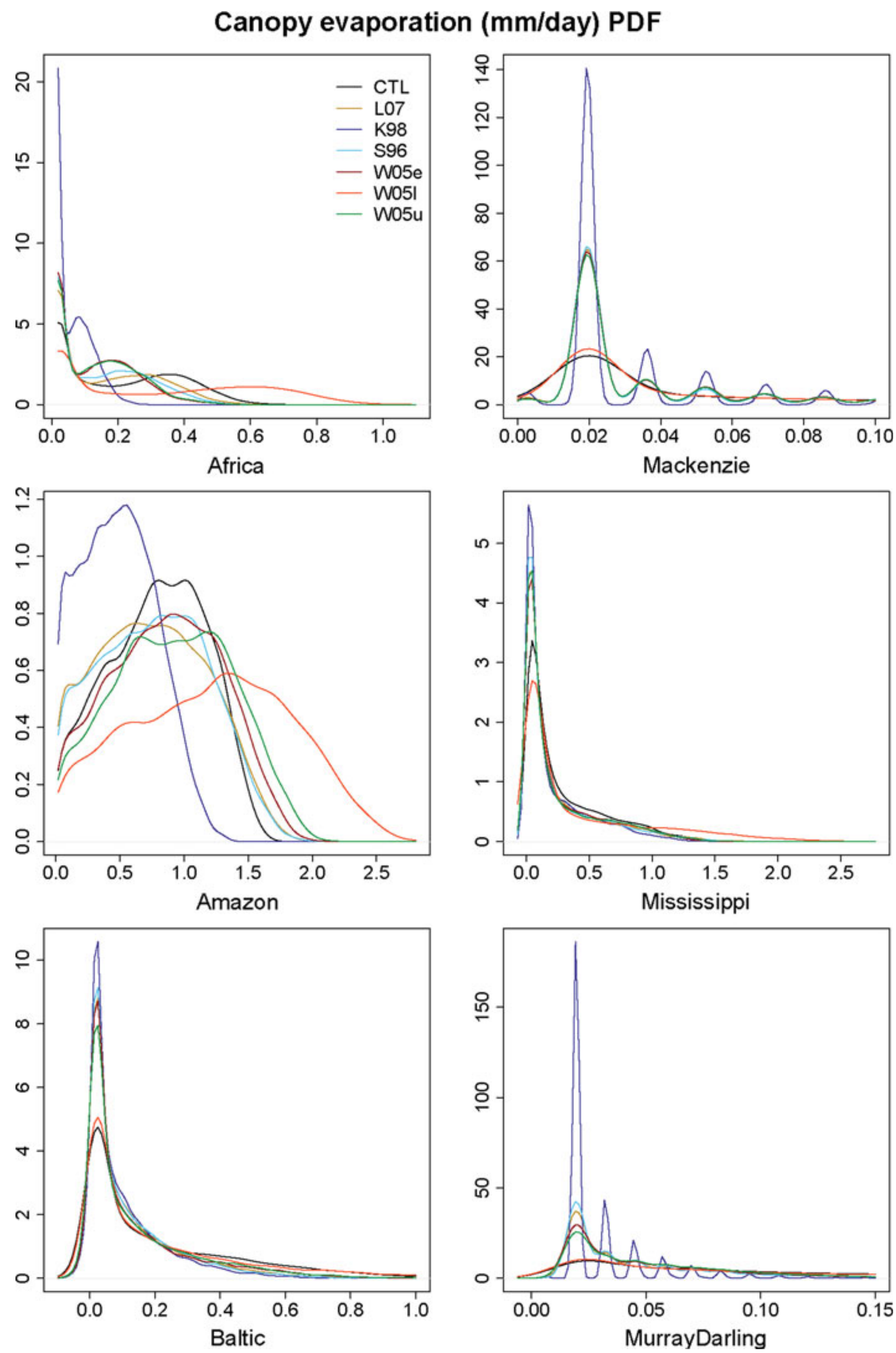


Fig. 6 Probability density function (based on daily data) for canopy evaporation for each region. Each experiment and CTL is shown (see key in *top left panel*)

Mackenzie, MDB). In regions where the impact is smaller (particularly Amazon and Mississippi) higher rainfall intensities are simulated. Figure 8 shows daily the interception ratio (canopy evaporation divided by precipitation). Since these are based on daily data it is possible for this to exceed 1.0 where precipitation occurs in the evening of day n but the canopy evaporation occurs on day $n + 1$. There are clearly quite large differences in the interception ratio PDFs shown in Fig. 8. Simulation W05l, understandably, stands out in many regions as being quite different from other parameterizations. It is, however, similar to the control simulation over the Mackenzie, Mississippi, Baltic and MDB. Clearly, the PDF of canopy evaporation, and the interception ratio are extremely different depending on the parameterization used and the region examined.

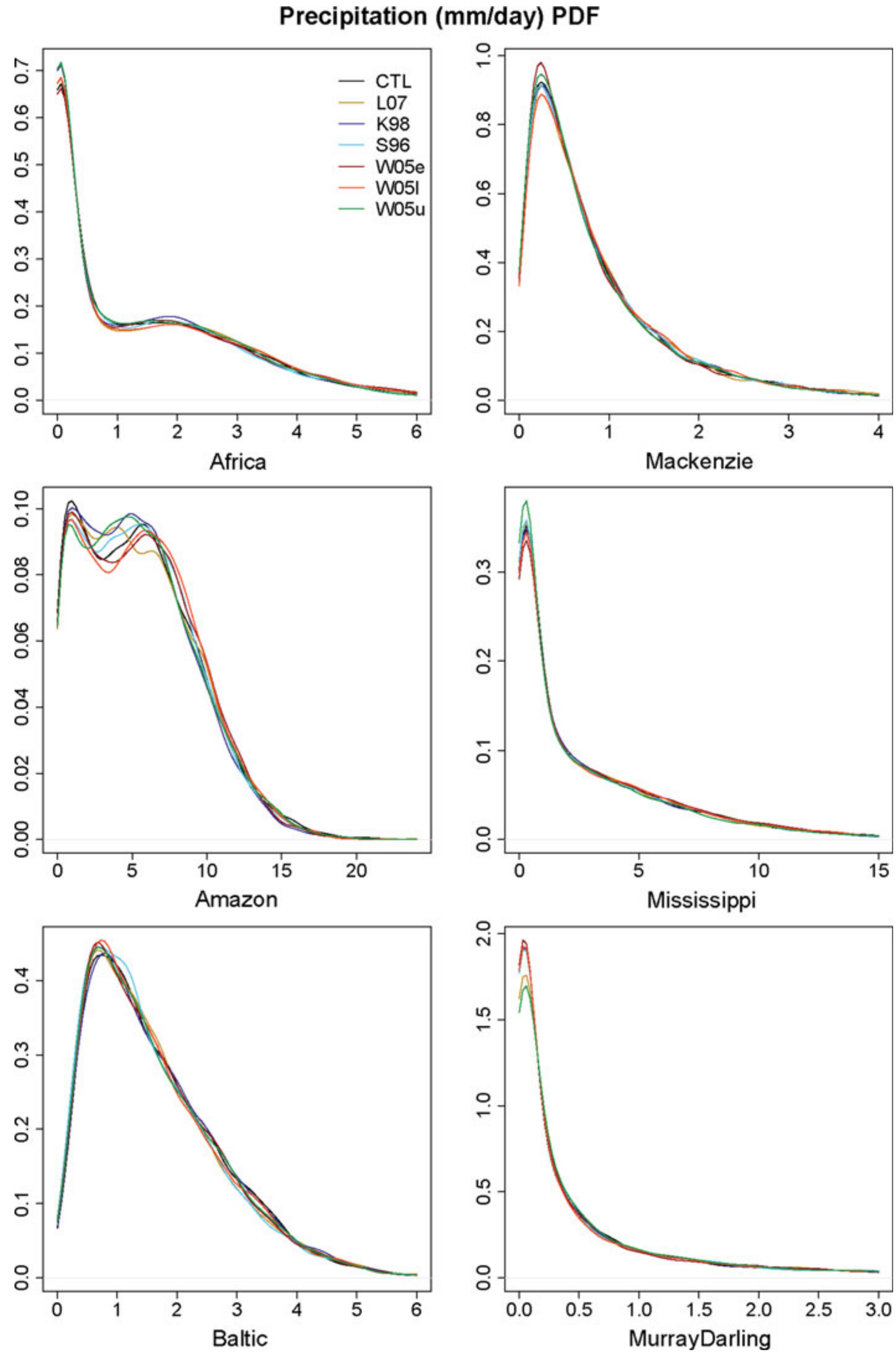


Fig. 7 As Fig. 6 but for precipitation

Figure 7 is also important since it shows that the interception parameterization, even in the extreme W05l case, does not affect the precipitation PDF noticeably. There are changes over the Amazon but these are small changes at lower precipitation amounts. At the higher rates, there is no impact on the probability of rainfall and therefore no impact on rainfall extremes.

The impact of the change in interception parameterization on the canopy transpiration PDF is shown in Fig. 9. The changes are of a similar magnitude (but opposite sign) to the changes in canopy evaporation. For the Amazon there is a clear shift to the left in simulation W05l and a shift to the right for simulation K98—the opposite to canopy evaporation. There are also differences for these two simulations over Africa and the Mississippi.

A climate model is not affected separately by transpiration or canopy evaporation—a climate model is forced from the surface by the total evaporation from the canopy-

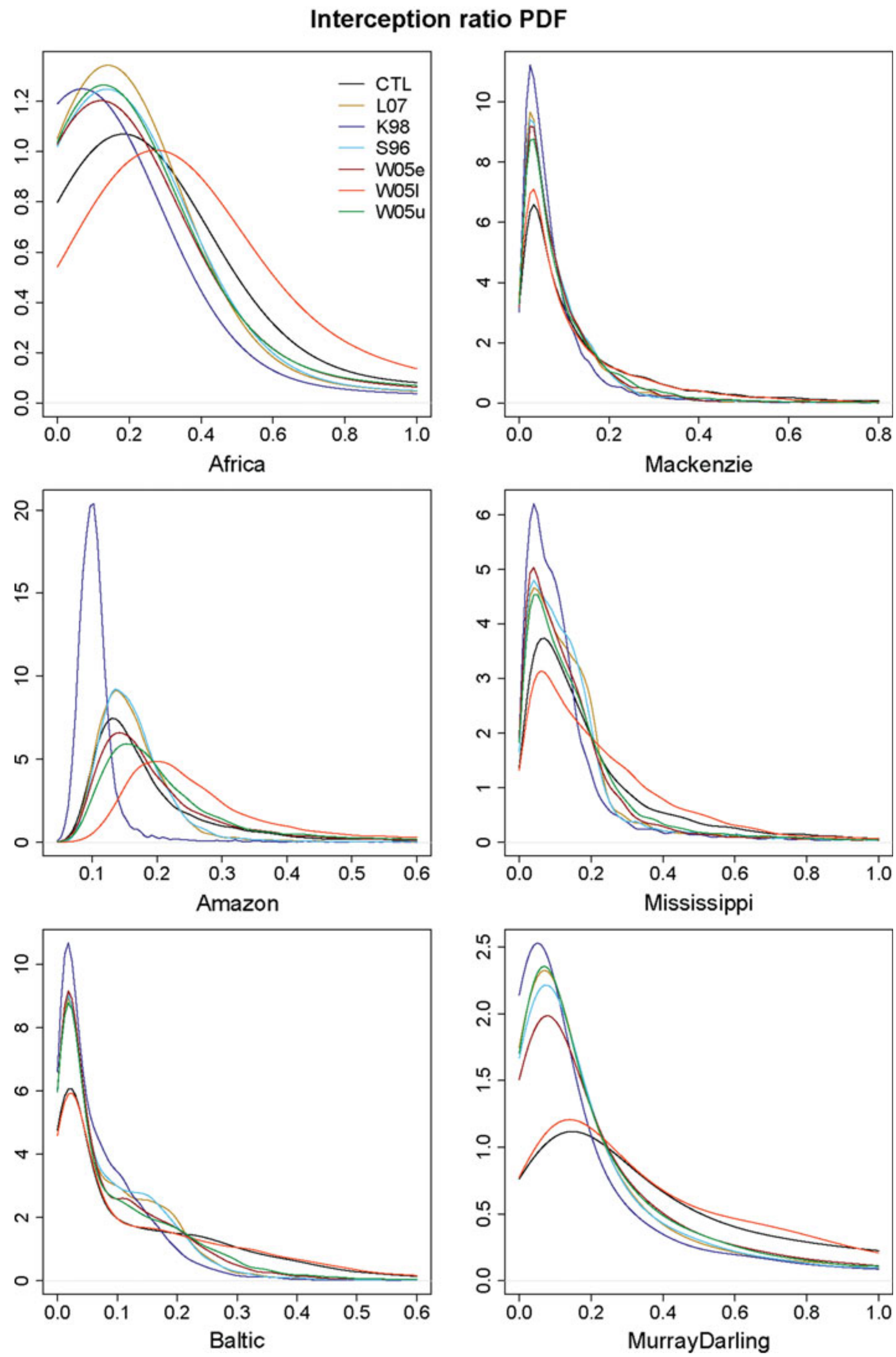


Fig. 8 As Fig. 6 but for the interception ratio (interception divided by precipitation)

soil system. While changes in the partitioning of rainfall between the rapidly recycled intercepted rainfall and the more slowly evaporated soil moisture can be important, the signal has to be systematic to affect the atmosphere of the climate model. There are changes in total evaporation over the six regions that are on a scale of those of canopy evaporation and transpiration—that is, the method used for interception parameterization affects the regional seasonal climatology of total evaporation. The scale of the impact, however, is not enormous. Table 3 shows the control simulation climatology for total evaporation. The largest changes in each region are 0.1–0.15 mm day^{-1}—or about 5% of the control climatology (Table 3). Figure 10 shows that the differences in some simulations in the PDFs for transpiration and canopy evaporation disappear in the total evaporation PDFs. Thus, in terms of the total flux of water to the atmosphere in the coupled climate model, while there are impacts from parameterization choice on

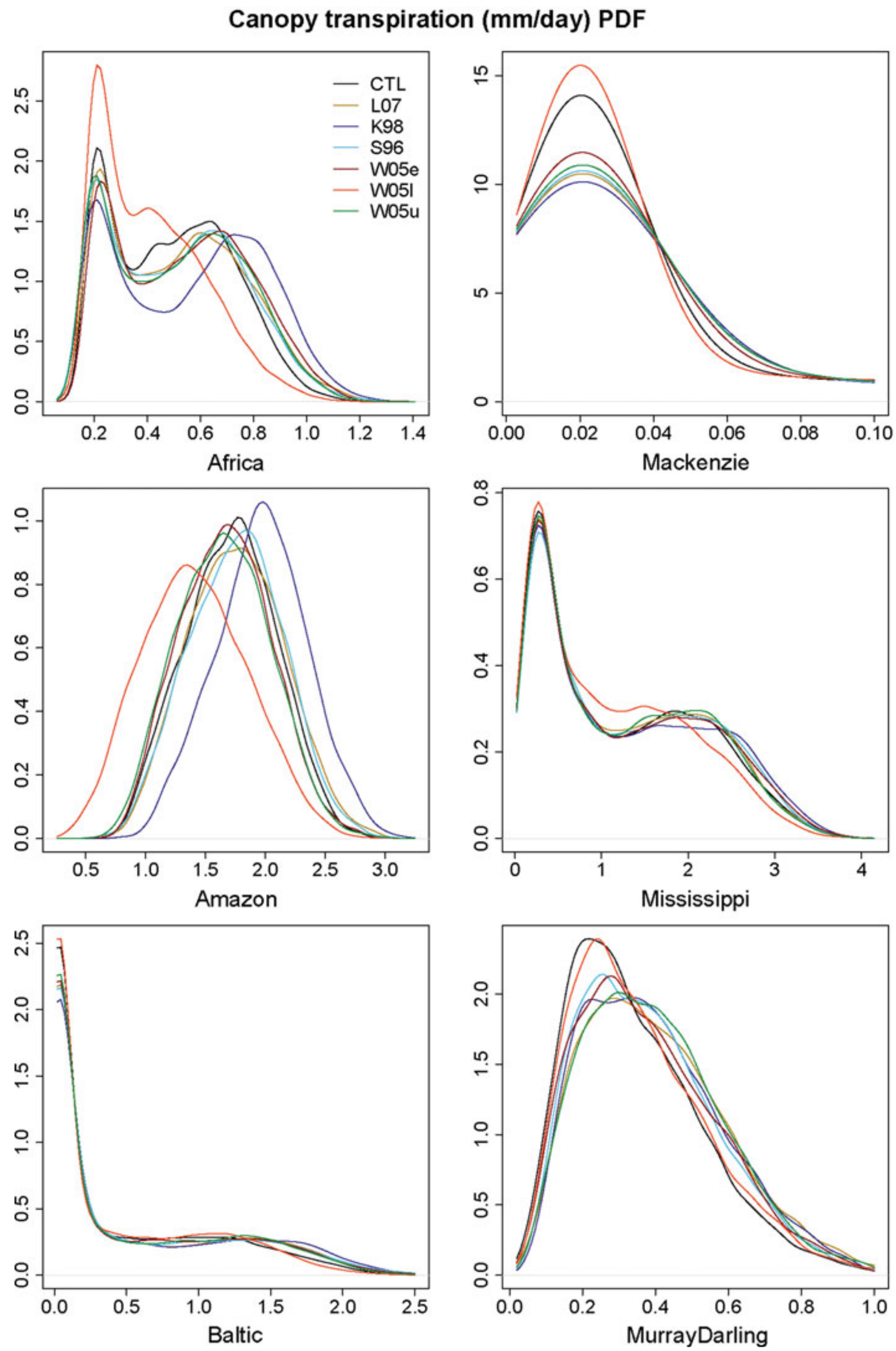


Fig. 9 As Fig. 6 but for transpiration

transpiration and canopy evaporation, these largely cancel each other, and once combined with soil evaporation the scale of the change is largely within 5%.

The impact of canopy evaporation was generally negligible on other variables analyzed. This includes surface temperature where the impact of canopy interception parameterization was within ~0.1°C on the seasonal mean (not shown). There is also no noteworthy impact on the PDF of maximum (or minimum) temperatures, including no impacts at the tails of the distributions, suggesting that the choice of canopy interception parameterization, even in the W05l case, does not affect the probability of extreme temperature.

6 Discussion

The impacts of the seven interception parameterizations were first assessed on the JJA climatology of several

Table 3 Difference in the mean seasonal climatology from the control simulation (CTL) for the six regions discussed in the text

	Africa	Amazon	MDB	Baltic	Mississippi	Mackenzie
Canopy interception (mm day^{-1})						
DJF	0.01	0.97	0.13	0.00	0.07	0.00
MAM	0.16	0.93	0.07	0.19	0.28	0.04
JJA	0.37	0.38	0.08	0.49	0.62	0.23
SON	0.25	0.85	0.11	0.13	0.18	0.04
Precipitation (mm day^{-1})						
DJF	0.02	6.98	1.21	1.41	2.08	0.68
MAM	0.94	6.99	0.80	1.54	3.35	0.82
JJA	2.75	1.83	0.95	1.91	3.97	1.07
SON	2.00	6.13	0.61	1.81	2.28	1.02
Total evaporation (mm day^{-1})						
DJF	0.31	3.14	1.12	0.28	0.94	0.09
MAM	0.79	2.98	0.79	1.26	2.75	0.61
JJA	2.20	2.32	0.71	2.23	3.73	1.28
SON	1.78	2.52	0.88	0.69	1.91	0.35
Transpiration (mm day^{-1})						
DJF	0.29	1.83	0.39	0.00	0.24	0.00
MAM	0.34	1.79	0.33	0.33	1.22	0.04
JJA	0.64	1.80	0.23	1.28	2.29	0.40
SON	0.69	1.44	0.45	0.20	1.01	0.04
Net radiation (W m^{-2})						
DJF	71.92	120.03	152.06	−17.18	41.04	−12.21
MAM	103.62	118.27	73.27	71.76	120.79	48.66
JJA	125.54	114.18	41.47	110.09	160.20	97.23
SON	105.26	124.66	119.86	10.76	74.54	−0.95
Maximum temperature (°C)						
DJF	34.62	32.04	41.56	1.49	13.31	−7.32
MAM	40.43	32.10	30.85	11.03	25.00	4.16
JJA	37.84	33.30	21.32	24.21	37.36	22.18
SON	37.29	35.79	34.07	13.15	25.65	7.06
Minimum temperature (°C)						
DJF	8.19	19.28	11.91	−22.85	−15.04	−45.05
MAM	13.86	18.83	4.92	−10.73	−1.84	−28.08
JJA	18.66	16.52	−0.65	3.93	11.85	−0.11
SON	14.54	19.57	4.36	−5.91	−1.23	−17.89

important variables. Interception parameterization changes did not affect the simulation of atmospheric variables statistically significantly over more land grid points than would be expected by chance (Table 1) in any season, even for the artificially high W05l case. Figures 4 and 5 suggest some sub-continental scale areas are affected (North America for maximum JJA temperature and western North America for precipitation). The rainfall changes are related to a change in total evaporation in this region (Fig. 3) but it is more likely that the change in JJA rainfall causes the increase in the total evaporation. In summary, there is little evidence that the scale of impact of the seven different interception parameterizations affects the climatology of air temperature, rainfall or any other atmospheric quantity. It is of course possible that impacts occur on the timing of rainfall, rainfall extremes, temperature maxima, etc. that cannot be identified in the daily mean. For example, changes in the interception could cause changes in the sub-daily timing of evaporation that then leads to impacts on the evolution of the boundary layer, convection and the timing of rainfall and we cannot exclude this possibility.

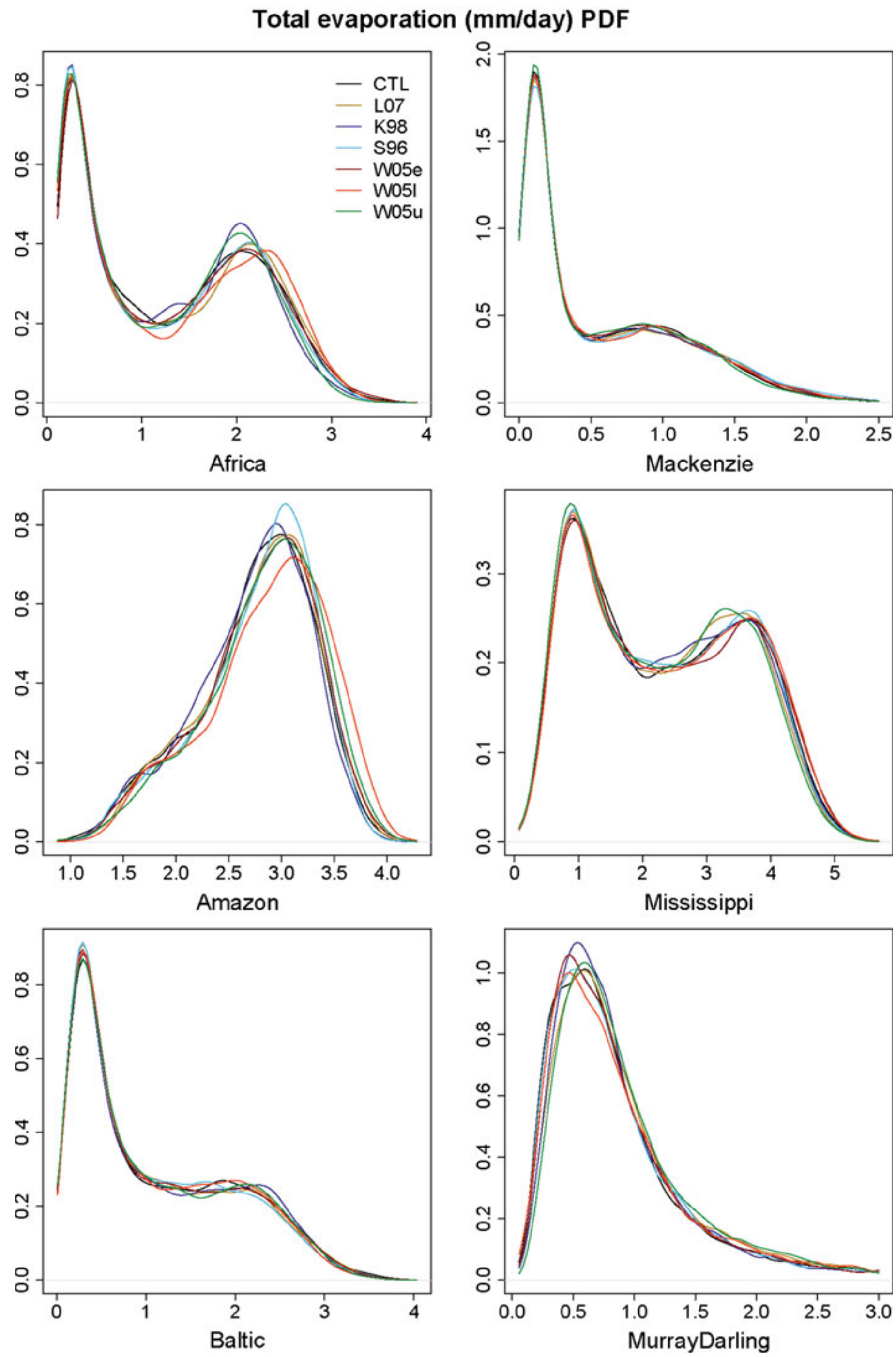
In contrast to atmospheric variables, Figs. 1 and 2 show that the interception parameterization has a major impact on the canopy water balance in the climate model. Large changes in JJA canopy evaporation are simulated (Fig. 1) with opposing changes in JJA transpiration. There is no doubt, based on our experiments, that interception parameterization has a large, widespread and seasonally significant impact on the canopy water balance. However, the impacts on canopy evaporation are the opposite sign of the impacts on transpiration and these tend to cancel each other out to some degree. Thus the changes in the total evaporation (Fig. 2) are smaller and less widespread and do not appear to provide a strong enough signal to affect the atmosphere at large spatial scales and on time scales greater than 1 day.

We would conclude from this part of the study that interception parameterization is important to the surface hydroclimatology but the differences between the various interception parameterizations tested in this paper generate too small a signal to affect the atmosphere significantly in our model. This is true even for the very high interception W05l case. This is a *climatological* result where there is negligible impact on the surface climatology of the model despite significant changes in components of the model (transpiration and canopy evaporation).

We also explored the impact of interception parameterization on the PDFs of key variables. It is possible that while the average climatology is not affected by interception parameterization, an important change in the probability of extremes might occur. We could not show, for any region, a strong impact of interception parameterization on precipitation (Fig. 7). The upper tails of each set of distributions are very similar and neither low rainfall events (the known systematic bias in some climate models towards drizzle, Sun et al. 2006) nor the higher intensity rainfall events were affected by the interception parameterization. We were also unable to show significant differences in the PDFs of maximum temperature, including in the tails of the PDF. We remind the reader that PDFs do not incorporate measures of the *timing* of rainfall extremes and we cannot exclude the possibility that interception affects the sub-daily timing of rainfall.

The PDFs of total evaporation (Fig. 10) do show some differences caused by the changes in the interception

Fig. 10 As Fig. 6 but for total evaporation



parameterization, but the differences are too small to affect the atmosphere, including in the very high interception W05l case.

The impact of canopy interception parameterization is clear and significant on the canopy water balance. Large changes in the PDFs of canopy evaporation, the interception ratio and canopy transpiration were shown. There are fundamental differences in the PDFs of transpiration over Africa, the Mackenzie Basin, and the Amazon. Simulation W05l is commonly (and unsurprisingly) anomalous, although is sometimes closely matched (Mackenzie, MDB) by CTL. W05l and CTL tend to give lower transpiration rates compared to the other simulations; directly related to their higher interception (Fig. 6). This is most clearly visible in the interception ratio PDFs (Fig. 8) where W05l and CTL are quite similar for many regions. However, while the interception, interception ratio and transpiration PDFs for W05l and CRL appear anomalous compared to the other simulations this cannot be compared to representative observations at spatial scales used by climate models. Further, despite the large differences visible in Figs. 6, 8 and 9, the total evaporation (Fig. 10) does not show similarly large differences. Again, compensations have occurred, even on the daily timescale of the PDFs, such that the overall impact of the interception parameterization changes is negligible.

There are several important caveats relating to our work. First, we explored seven interception parameterizations, most are currently in use in climate models. This is a reasonable sample but it is conceivable that we have not tested a reasonable method that would have performed very differently. Second, CSIRO Mk3L is a relatively coarse-resolution model and it is possible that interception, and changes in total evaporation, require a fine spatial scale to perturb atmospheric processes (e.g. convection, cloud processes and radiation) and it is the changes in these processes that then affect larger-scale dynamics and atmospheric physics. Our use of a coarse resolution model may mask these processes and therefore hide any large-scale signal. This could be resolved via the repeat of our experiments with several climate models running at relatively high resolution. An example of exploring the sensitivity of the atmosphere to interception parameterization was provided by Wang et al. (2008) who found that incorporating sub-grid variability of precipitation and canopy water storage increased rainfall, a result that contrasts with Hahmann (2003) who found that it decreased rainfall. These examples, combined with our results, highlight the model dependency of the impact of interception in climate models. This dependency is common in land surface perturbation experiments in part due to differences in the coupling strength between the land and the atmosphere (Koster et al. 2004). Further exploration across multiple climate models of coupling strength and how it explains the diversity of model predictions of the impact of a land-based anomaly is essential if we are to fully resolve the role of interception (and many other terrestrial processes) in coupled climate models.

7 Conclusions

Using a coupled climate model, we have explored the impact of seven different interception parameterizations using 30-year simulations for each experiment. The various interception parameterizations have a large and spatially statistically significant impact on canopy interception and transpiration. However, the impact on interception is of the opposite sign and approximately a similar magnitude to the impact on transpiration. Thus there is a (partial) canceling out of these two changes and total evaporation (the variable that forces the lowest layer of the atmosphere in the climate model) is not affected to the same degree.

We explored the impact of canopy interception on the PDFs of *daily* quantities. The various interception parameterizations led to some remarkably different PDFs for canopy evaporation and transpiration but large-scale results these two variables had compensating effects such that the PDFs of total evaporation were very similar. We could not analyze whether the impact of interception affected the timing of atmospheric variables at sub-daily timescales.

We conclude that our results reaffirm that the parameterization of interception is important to the modeling of interception and transpiration. However, across the seven interception methods used here, the scale of the impact of the differences between the methods were too small to affect the climatology of the climate model, including in an extreme canopy interception example. This was true for the zonal average, the seasonal global climatology and the PDFs of daily atmospheric quantities. Most surprising, the different interception parameterizations did not affect the probability of extreme temperatures or extreme rainfall. This paper does *not* show or attempt to imply that interception is not important; clearly it affects the surface hydrometeorology. Rather we show that the various methods tested in this paper lead to statistically identical results in large-scale atmospheric quantities. This leads to a conclusion that differences in how various climate models simulate temperature, temperature extremes, rainfall and rainfall extremes are not likely linked to how interception is parameterized, if one of the schemes tested in this paper is used.

Acknowledgments We wish to thank Dr D Wang for providing the code for their interception schemes as well as two dedicated anonymous reviewers who greatly improved this paper. A. J. Pitman acknowledges support by the Australian Research Council (LP0774996).

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