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Earth System Dynamics Discussions

The influence of vegetation on the ITCZ and South Asian Monsoon in HadCM3

M. P. McCarthy[1], J. Sanjay[2], B. B. B. Booth[1], K. Krishna Kumar[2], and R. A. Betts[1]

[1]Met Office, Hadley Centre, Fitzroy Road, Exeter, EX1 2NY, UK
[2]Indian Institute of Tropical Meteorology, Pashan, Pune, 411008, India

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Correspondence to: M. P. McCarthy (mark.mccarthy@metoffice.gov.uk)

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Abstract

The role of extra-tropical vegetation on the large-scale tropical circulation is examined in the version 3 Hadley Centre Climate Model (HadCM3). Alternative representations of present day vegetation from observations and a dynamic vegetation model were used as the land-cover component for a number of HadCM3 experiments under a nominal present day climate state, and are shown to induce perturbations to the simulated global dynamics. This results in a shift in the location of the Inter Tropical Convergence Zone (ITCZ) and changes in the South Asian monsoon circulation. This has a significant impact on the Indian land precipitation compared to the standard configuration of HadCM3. This large-scale forcing is consistent with documented mechanisms relating to temperature and snow perturbations in the Northern Hemisphere extra-tropics. This analysis demonstrates that uncertainties in the representation of present day vegetation cover can result in significant perturbations to the simulated climate.

The role of the Northern Hemisphere extra-tropics is further demonstrated with a fourth representation of vegetation cover produced by imposing simulated changes in Northern Hemisphere extra-tropical vegetation from the end of the 21st century on the present day climate. This experiment shows that through similar processes extra-tropical vegetation changes in the future contribute to a strengthening of the South Asian monsoon in this model, with a particular influence on the monsoon onset. These findings provide renewed motivation to give careful consideration to the role of global scale vegetation feedbacks when looking at climate change and its impact on the tropics and South Asian monsoon in the latest generation of Earth System models.

1 Introduction

An important aspect of climate research is to identify potential feedbacks and assess if such feedbacks could produce large and undesired responses to perturbations resulting from human activities (Denman et al., 2007). A significant driver of the climate

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research effort has focused on incorporation and quantification of the complex climate atmosphere-ocean-biosphere interactions within climate model frameworks. One particular area which has received greater attention in the past decade has been the representation of the land surface; motivated by the recognition of the potential for dramatic reductions in future carbon uptake into land carbon stores (Cox et al., 2000; Friedlingstein et al., 2006). While the focus of this model development has been largely aimed at improved modelling of land-atmosphere carbon exchange, this development has also lead to more sophisticated representations of the land surface characteristics within climate models. A number of models now dynamically model vegetation distributions (e.g. Cox, 2001; Levis et al., 2004; Gallimore et al., 2005; Jones et al., 2011) where the fraction of tree and grass species is a function of the local climate state. Previously, climate models needed to prescribe vegetation coverage. The strength of this new approach is that future changes in vegetation extent can now be represented explicitly. For example Cox et al. (2000) demonstrated the potential for large scale Amazonian forest loss due to changes in projected rainfall, promoting continued research into both the resilience and response of tropical forests to climate change (Malhi et al., 2009).

In this study we examine climate and vegetation in experiments performed using the Hadley Centre global atmosphere-ocean climate model, HadCM3, coupled to a dynamic global vegetation models (DGVM). The analysis was initially motivated by observing a significant decline in precipitation over India during the South Asian Monsoon in an ensemble of simulations of the carbon-cycle version of HadCM3 (below and Booth et al., 2011) when compared with an ensemble of the standard HadCM3 configuration without the carbon cycle. Previous studies using different versions of this model for shorter time periods had indicated that the land use and land cover change did not significantly affect climate at the regional and local scales (e.g. Lawrence and Slingo, 2004; Osborne et al., 2004; Crucifix et al., 2005). Using the atmospheric component of this model, Lawrence and Slingo (2004) found little difference in climate simulations that use annual mean vegetation characteristics compared with those that use a prescribed seasonal cycle. Osborne et al. (2004) used a similar version and assessed the

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influence of vegetation in the tropics by comparing the results of integrations with and without tropical vegetation. Their results indicated that in the tropics vegetation produced variability in surface fluxes and their coupling to precipitation. However Osborne et al. (2004) found significant regional variations in the feedback of vegetation on the local precipitation. For example, the state of the land surface of India had a relatively small influence on the monsoon climate, whereas the climate of China was found to be sensitive to the presence of vegetation cover. Crucifix et al. (2005) analysed the impact of vegetation variability on climate simulated with an atmosphere-slab ocean version of the Hadley Centre climate model coupled to a dynamic global vegetation model. Their results suggested that the impact of inter-annual vegetation variability on boundary layer potential temperature and relative humidity were small, implying that precipitation persistence was not strongly modified by vegetation dynamics in this model. This simulated weak coupling between vegetation and climate variability was attributed to a greater intrinsic variability in this model, overriding the effects of vegetation on the variability of surface fluxes. However they pointed out that the weak coupling strength between surface fluxes and precipitation in this model (Koster et al., 2004) might have also contributed to the weak vegetation-climate coupling. In this study we revisit the impact of vegetation on climate in HadCM3 and utilise a number of HadCM3 simulations to identify potential teleconnections linking large-scale vegetation changes to impacts on the tropical large-scale circulation and monsoon.

2 HadCM3 model and data

2.1 Model description

This study compares the results from transient climate simulations of the Hadley Centre Climate Model (HadCM3, Pope et al., 2000; Gordon et al., 2000). This is an ocean-atmosphere general circulation model (GCM). The atmospheric component of HadCM3 is a hydrostatic grid-point model with a regular grid of 3.75° longitude by 2.5° latitude,

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approximately comparable to a T42 spectral resolution (Pope et al., 2000). In this study we utilize a version of HadCM3 incorporating both carbon cycle and dynamic vegetation components first documented in Cox et al. (2000). In contrast to the standard HadCM3 configuration this model uses version 2 of the Met Office surface exchange scheme (MOSES2, Essery et al., 2001) with a tiled representation of sub-grid scale heterogeneity and is coupled to the Top-down Representation of Interactive Foliage and Flora Including Dynamics (TRIFFID) dynamic global vegetation model (DGVM, Cox, 2001). This allows both biogeophysical (photosynthesis) and biogeochemical (carbon cycle) feedbacks between the terrestrial biosphere and the atmosphere. The model also includes an interactive sulphur cycle component (Jones et al., 2001) within the standard HadCM3 resolution. The model configuration was the unperturbed member of an ensemble of 17 parameter-perturbation experiments that were individually flux corrected for sea surface temperature and salinity, which minimised the regional temperature biases produced by this model across the ensemble. For the purposes of this analysis the flux adjustment means that climatological sea surface temperature differences between the model experiments are constrained to be small. The basis experiment (Booth and Jones, 2011) was run for two periods historical (1860–1989) and a future business as usual scenario (1989–2100) based on the A1B SRES scenario (Nakićenović et al., 2000) using non-CO_2 forcings as described by Johns et al. (2003).

2.2 Vegetation description

The standard vegetation distribution used in HadCM3 is derived from the global land use data of (Wilson and Henderson-Sellers, 1985, hereafter WHS), but the MOSES2 configuration uses data derived from the International Geosphere-Biosphere Programme (IGBP) DISCover land-cover dataset (Loveland et al., 2000). This dataset uses information from the Advanced Very High Resolution Radiometer (AVHRR) data to define 14 land-cover classes at 1 km resolution (Hansen et al., 2000). The mapping between these classes and assumed fractions of the MOSES2 surface types are given in Essery et al. (2003). TRIFFID simulates the carbon uptake of, and competition

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between, five plant functional types (PFTs): broadleaf tree, needleleaf tree, C3 grass, C4 grass, and shrubs. Stomatal conductance and photosynthesis are calculated via a coupled leaf-level model, with leaf area index estimated from a percentage of the whole-plant carbon balance. Net primary productivity (NPP) is the difference between the simulated photosynthesis and dark respiration, with photosynthesis coupled to transpiration. NPP increases with CO_2 and also responds to temperature, photosynthetically active radiation (PAR), humidity, and soil moisture stress (Cox, 2001). The TRIFFID model therefore provides an alternative representation of global vegetation cover. WHS is the standard vegetation ancillary for HadCM3, so we will use WHS as our basis for comparison. We do not make any comment on the quality or biases in these datasets, instead they are used in experiments to demonstrate the sensitivity of HadCM3 atmospheric dynamics to these alternative representations of present day vegetation cover.

2.3 Experiment description

The experiments TRIF1 and TRIF2 are two versions of the unperturbed member of the HadCM3 ensemble described above and in Booth and Jones (2011) and Booth et al. (2011), initialised in 1859 and free running experiments with the TRIFFID DGVM. These experiments are used as basis experiments for a number of additional thirty year time-slice experiments initialised from TRIF1 and TRIF2 at model date of December 1959. The experiments are summarized in Table 1. TRIF3 has a fixed vegetation distribution, but that distribution is provided by the TRIFFID model in TRIF1 run to the year 2100 with CO_2 emissions and other forcings from the A1b scenario (Nakićenović et al., 2000). WHS1 and IGBP1 are initialised from TRIF1 with different observationally based vegetation estimates, and do not include leaf phenology. WHS2 and IGBP2 are initialised from TRIF2 and do include leaf phenology. It was found that the leaf phenology had minimal impact on the processes under consideration here, consistent with Lawrence and Slingo (2004), so the TRIF1 and 2, WHS1 and 2, and IGBP1 and 2 are considered together to provide 60 years of simulation for each vegetation description

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and will be referred to as TRIF, WHS, and IGBP respectively. In the case of TRIF3 the vegetation distribution from TRIF1 (Booth and Jones, 2011) at the year 2100 for land areas north of 20° N in response to an imposed forcing (Nakićenović et al., 2000) is used. Large perturbations to the tropical rainforests in response to climate change occur under the future simulation, but in this study we are interested in sensitivity to Northern Hemisphere extra-tropical vegetation changes so we only perturb the Northern Hemisphere.

Differences between the present day vegetation estimates from WHS, IGBP, and TRIFF1-3 are shown in Fig. 1. Compared to WHS the IGBP has reduced shrub and needleleaf trees over the northern mid-latitudes, less vegetation over the arid subtropics and fewer trees in the tropical forest regions. IGBP does have more deciduous broadleaf tree cover in the mid-latitudes. TRIFFID generally has higher total vegetation except over the desert regions of North Africa and central Asia, but the extent of evergreen needleleaf is greatly diminished over the Eurasian continent replaced with shrub and grass. The TRIF3 vegetation shows expansion of the northern mid-latitude tree line and a shift from grass to shrub over other parts of the northern continents.

3 Climate response to vegetation distribution

3.1 Global response

The zonal mean perturbations to temperature, precipitation, and 200 hPa winds resulting from changes to vegetation cover are presented in Fig. 2 as a gauge of the thermal, hydrological, and dynamical impacts of the vegetation change respectively. Compared to the climate associated with WHS both IGBP (solid line in Fig. 2) and TRIF (dashed line in Fig. 2) experiments show a cooling of the Northern Hemisphere sub tropics and mid-latitudes. At higher latitudes (60° N) the TRIF experiment shows a net warming, regional analysis shown in Fig. 3 shows a warming over Canada, but cooling over the Eurasian continent at high latitudes. There is a southward shift in the Inter-Tropical

Convergence Zone (ITCZ) evidenced by the precipitation changes in the middle panels of Fig. 2 and the 200 hPa wind speeds show a dynamical response particularly through a strengthening of the subtropical jets. The difference between TRIF3 and TRIF1 show essentially a similar but opposite pattern, suggesting that the simulated vegetation changes in this case work to offset the differences between the observed and simulated present day vegetation.

There is considerable evidence from both paleoclimate and modelling studies that Northern Hemisphere cooling for example during glacial periods, results in a southward shift in the ITCZ. Broccoli et al. (2006) and Kang et al. (2008) conducted idealised model studies imposing anomalous cooling to the Northern Hemisphere and warming of the south. These simulations resulted in a shift of the ITCZ toward the warmer hemisphere. While the increased poleward eddy energy flux from the tropics induces a shift in the ITCZ, Kang et al. (2008, 2009) go on to demonstrate the importance and complicating influence of cloud and water vapour feedbacks, and the sensitivity of the tropical response to the parametrisation of entrainment within convective plumes. The results presented in Fig. 2 are broadly consistent with these previous studies although the maximum cooling is further south, and over land in these simulations compared to the idealised experiments of Kang et al. (2008) and include a marked cooling of the subtropics. The simulations presented here provide further evidence that the representation of vegetation distribution within HadCM3 can produce sufficiently large perturbations to the surface climate to induce changes to the global hydrological cycle and large scale dynamics, particularly in the tropics.

3.2 Regional response

The regional pattern of change for boreal winter and summer are shown in Fig. 3 for the case of TRIF-WHS, which shows the largest impact. Temperature perturbations are concentrated over much of the Eurasian continent. In contrast the precipitation and upper level wind anomalies tend to be larger over the oceans and reflect the shift in the ITCZ and modifications to the subtropical jet. During summer there is also a marked weakening of the tropical easterly Jet over Africa and reductions in precipitation over the Indian sub-continent. This summer rainfall deficit over India during the summer monsoon is the largest impact of the vegetation changes to land precipitation, and the weakening of the Tropical Easterly jet further indicates a perturbation to the dynamical South Asian monsoon system rather than through local vegetation feedbacks over India itself.

One possible mechanism through which the vegetation is inducing these changes in the mid and high latitudes is through snow feedbacks. Figure 3 shows that through the boreal winter and spring the TRIF experiments have greater snow cover over the Eurasian continent. Conversely northern Canada is warmer with less snow in the TRIF experiments, possibly a result of increased needle leaf tree cover in this region shown in Fig. 1.

3.3 The South Asia Monsoon

Changes in precipitation and dynamical indices of the South Asian monsoon are shown in Fig. 4. All India precipitation is determined from land only model gridcells over India. The Indian Monsoon Index of Wang et al. (2001, hereafter W01) compares 850 hPa zonal wind speeds in a region bounded by 5° N to 15° N, and 40° E to 80° E with those from 20° N to 30° N, and 60° E to 90° E while the index of Goswami et al. (1999, hereafter G99) assesses the 850 hPa – 200 hPa meridional wind shear in the domain 10° N to 30° N, and 70° E to 110° E. The dynamical index of Webster and Yang (1992, hereafter WY99) is determined as the zonal wind shear from 850 hPa – 200 hPa in the region 0° N to 20° N, and 40° E to 110° E. The greatest impact on precipitation is seen during the monsoon onset in June where IGBP and TRIFFID vegetation both induce significant reductions to the strength of the low level jet and all India rain. A precipitation anomaly then persists through the rest of the monsoon season. The W01 index also shows greatest difference during the months of June and September, indicating that the low level circulation is affected primarily during the onset and decay phases of the monsoon although an increase in the W01 during July and August is seen in the

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TRIF experiment. The G99 index has only a marginal change during summer. There is however further indication of a reduction in G99 for the IGBP and TRIF experiments compared to WHS for the month of June, and the summer weakening of the upper level easterly jet can be seen in Fig. 3. The WY99 index is similar in all experiments during the months of July and August, but deviations in April to June and September to November are again suggestive of a dynamical response to the vegetation changes during the pre-monsoon, monsoon onset and post-monsoon periods.

Discussions of extra-tropical forcing of the South Asian monsoon have been ongoing for more than one hundred years (Blandford, 1884), with particular interest paid to the role of Eurasian and Himalayan winter snow cover in modifying the subsequent summer monsoon, (e.g. Peings and Douville, 2010, and references therein). The potential for vegetation to induce such impacts has also been documented in studies of the Last Glacial Maximum (Crucifix and Hewitt, 2005) with somewhat more extreme vegetation changes than are considered here. Furthermore the importance of the boreal forests has been highlighted within a number of studies (e.g. Bonan et al., 1992; Douville and Royer, 1996), but a more recent study by Peings and Douville (2010) questions the robustness of the snow-monsoon link, particularly due to apparent complicating influence of El Niño and Southern Oscillation variability (Fasullo, 2004). However a recent study by Turner and Slingo (2011) demonstrate the teleconnection does exist within the HadCM3 model by using idealised snow forcing experiments. They demonstrate the importance of the Himalayas and Tibetan Plateau in reducing meridional tropospheric temperature gradients largely through snow albedo feedbacks resulting in a weakening of the early monsoon. Compared to WHS the IGBP and TRIF experiments both have significant cold anomalies during winter and Spring through much of Eurasia, the middle East, and the Tibetan Plateau. The U200 anomalies in Fig. 3 for DJF and MAM also show a strengthening of the subtropical jet during DJF and MAM that is a potential pre-cursor to a weak monsoon (Yang et al., 2004).

The difference between TRIF3 and TRIF1 (dashed line in Fig. 4) show a similar pattern but in the opposite sense. The simulated change in extra-tropical vegetation

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by the TRIFFID DGVM for the 21st century is therefore expected to have a positive impact on the strength of the South Asian monsoon in that simulation, through similar processes to those that contribute to the large-scale tropical climate perturbations discussed above. The greatest potential impact on the simulated land precipitation occurring during the monsoon onset. Within the transient climate change scenario these vegetation feedbacks would interact with other land surface (e.g. snow albedo) and atmospheric climate feedbacks.

4 Conclusions

In this paper we have demonstrated a sensitivity of HadCM3 tropical climate to extra-tropical vegetation changes resulting from the use of broadly similar, but different, land use datasets. The resulting dynamical response and impact on the South Asian summer monsoon in particular are consistent with numerous previous studies in both the HadCM3 model and other GCMs resulting from changes in midlatitude temperatures and snow albedo feedbacks affecting in particular the onset of the summer South Asian Monsoon. This study does not offer any new insights into these teleconnection processes specifically, but rather serves to demonstrate how the representation of vegetation, and uncertainties associated with correctly doing so, can have significant implications for the representation of tropical climates in this model. Feddema et al. (2005) presented a similar argument based on an analysis of the impact of land cover change on the NCAR-DOE PCM. HadCM3 has previously been noted for having a relatively weak surface-atmosphere coupling in a comparison of 12 GCMs (Koster et al., 2004), yet still large-scale dynamical responses can result from uncertainty in vegetation classifications.

With the emergence and continued development of earth system models to explore both 21st century climate change, and reconstruct paleo-climates, due consideration should be made for the potentially important role that extra-tropical vegetation feedbacks might have on tropical climate change and its uncertainty. Idealised experiments

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such as those of Kang et al. (2008) and Turner and Slingo (2011) identify the dynamical mechanisms for key feedbacks in individual GCMs, but the representation of these teleconnections may not be consistent across different climate models (Peings and Douville, 2010). In order to compare the outcomes of different climate models it is desirable to use common land use classification, as adopted by Hurtt et al. (2011), but alternative estimates of current and future land use and vegetation properties are desirable for exploring the wider importance of the terrestrial biosphere in GCMs, not just for regional detail of surface-atmosphere interaction but also for its contribution to large-scale atmospheric teleconnections.

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Table 1. Summary of the HadCM3 experiments.

Name	Vegetation cover	Leaf Phenology	TRIFFID
TRIF1	TRIF1	Yes	Yes
TRIF2	TRIF2	Yes	Yes
TRIF3	TRIF1 at 2100	Yes	No
WHS1	WHS	No	No
WHS2	WHS	Yes	No
IGBP1	IGBP	No	No
IGBP2	IGBP	Yes	No

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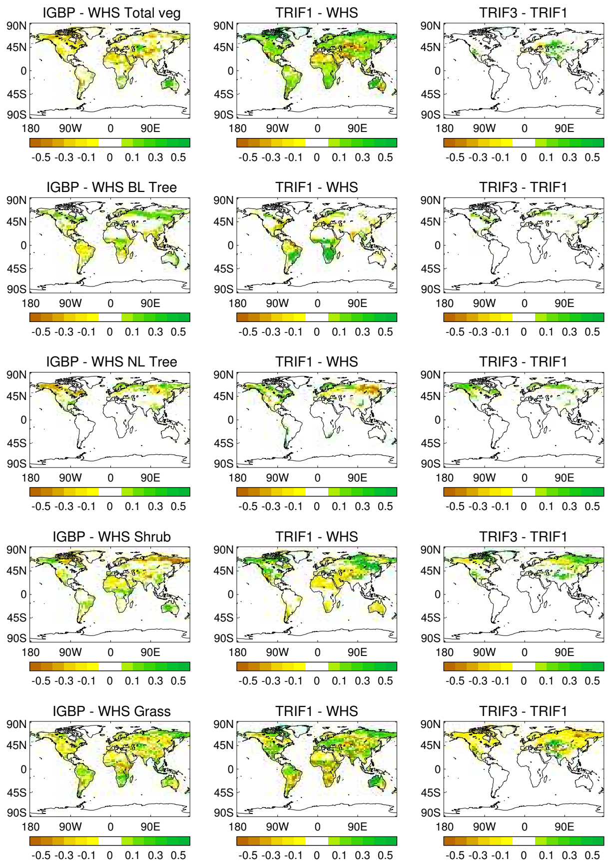

Fig. 1. Difference in vegetation cover (as a fraction of each model grid cell) compared to WHS1 of (left panels) IGBP1 and (middle panels) TRIF1 and between (right panels) TRIF3 and TRIF1. Each row represents the difference in (top to bottom panels) total vegetation, (BL) broadleaf trees, (NL) needleleaf trees, shrub, and grass.

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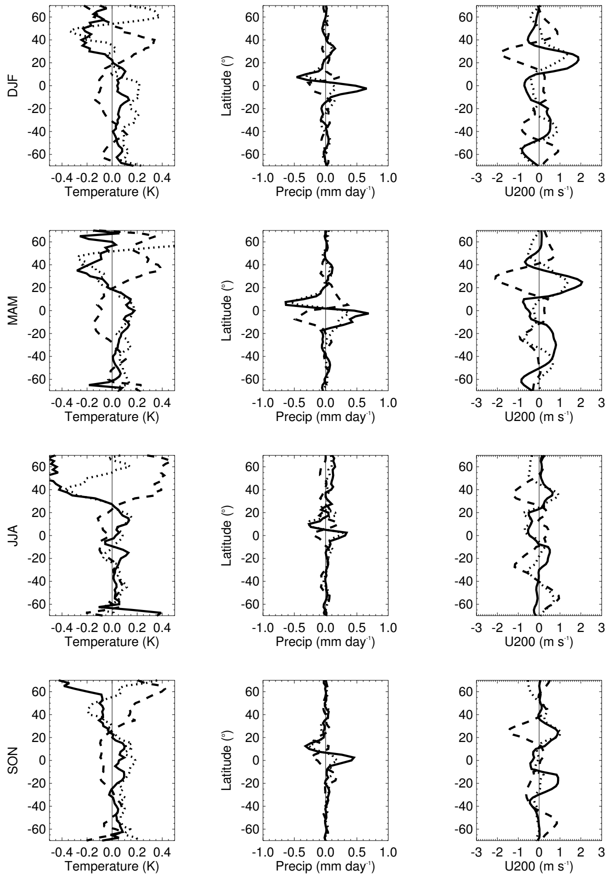

Fig. 2. Climate impact of imposed vegetation for (left panels) temperature, (middle panels) precipitation, and (right panels) 200 hPa zonal wind. The zonal mean differences between (solid) IGBP-WHS, (dot) TRIF-WHS, and (dash) TRIF3-TRIF1 are shown.

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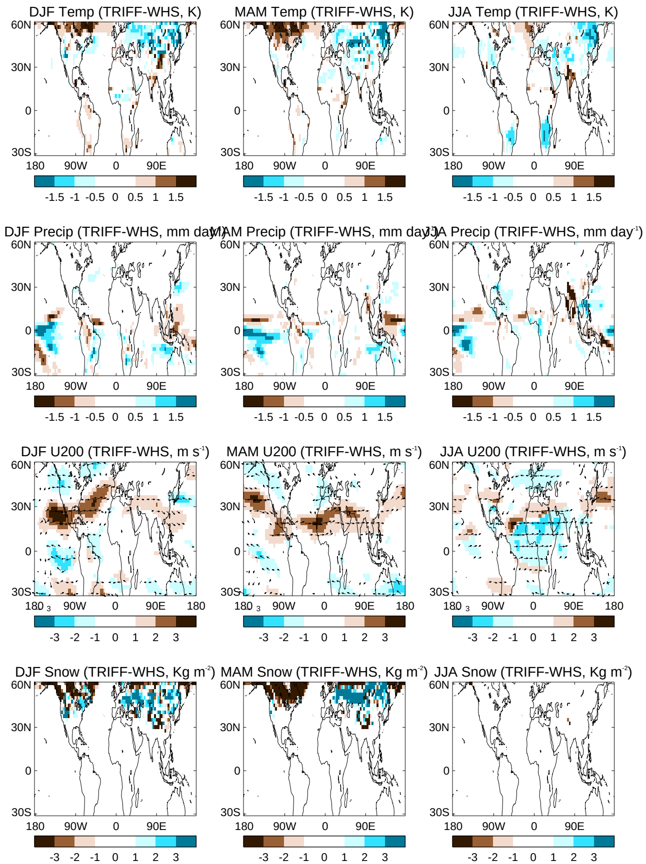

Fig. 3. Regional differences between TRIF and WHS for (upper panels) temperature, (middle panels) precipitation, 200 hPa zonal wind, (lower panels) snow cover for boreal (left panels) winter DJF, (middle panels) spring MAM and (right panels) summer JJA. The wind vector anomalies are also included in the U200 plots.

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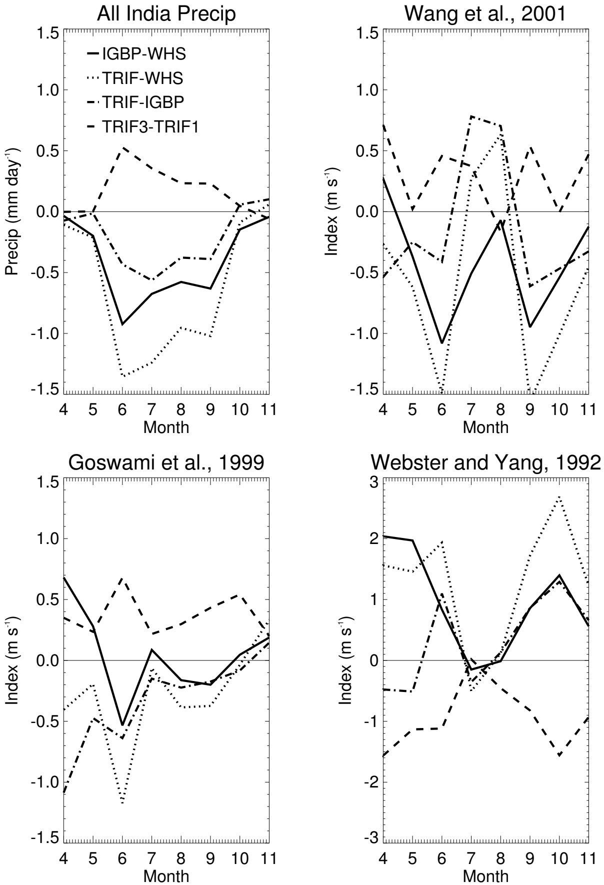

Fig. 4. Differences in the seasonal cycle of (top left panel) all India precipitation, (top right panel) Indian monsoon index of W01, and (bottom-left panel) the dynamical index of G99, and (bottom-right panel) the dynamical index of WY99. Differences are presented as (solid) IGBP – WHS, (dotted) TRIF – WHS, (dash-dot) TRIF-IGBP, and (dash) TRIF3-TRIF1.

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