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Direct human influence of irrigation on atmospheric water vapour and climate

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Abstract Human activity increases the atmospheric water vapour content in an indirect way through climate feedbacks. We conclude here that human activity also has a direct influence on the water vapour concentration through irrigation. In idealised simulations we estimate a global mean radiative forcing in the range of 0.03 to $+0.1$ Wm^{-2} due to the increase in water vapour from irrigation. However, because the water cycle is embodied in the climate system, irrigation has a more complex influence on climate. We also simulate a change in the temperature vertical profile and a large surface cooling of up to 0.8 K over irrigated land areas. This is of opposite sign than expected from the radiative forcing alone, and this questions the applicability of the radiative forcing concept for such a climatic perturbation. Further, this study shows stronger links than previously recognised between climate change and freshwater scarcity which are environmental issues of paramount importance for the twenty first century.

1 Introduction

The hydrological cycle has an important role in global climate change (e. g. Allen and Ingram 2002; Kaufman et al. 2002). At current concentrations, water vapour is the most important greenhouse gas in the atmosphere and the gas that absorbs most solar radiation (Kiehl and Trenberth 1997). Water vapour is assumed to be responsible for a strong positive climate feedback: an increase in temperature will increase the water vapour pressure at saturation and most likely the average water vapour concentration, strengthening the greenhouse effect (IPCC 2001; Soden et al. 2002). Human activities can influence the water vapour abundance in the atmosphere directly (i.e. not as a climate feedback mechanism) through changes in land use which modify surface properties and evaporation (Pielke et al. 2002), evaporation of water consumed for industrial and domestic use (i.e. from nuclear power plants), emission of water vapour from fossil fuel or biomass combustion at the ground and from aviation, and, most importantly, evaporation induced by irrigation. It is generally considered that anthropogenic sources of water vapour to the troposphere are negligible compared to natural sources from evaporation of water at the surface. Here we reexamine this assumption for the source of water vapour originating from irrigation as irrigation uses over 70% of the world's consumption of freshwater (Döll 2002; Seckler et al. 1998). At present about 70% of the total irrigated area is located in Asia.

The impact of future climate change on freshwater and irrigation demand has led to many studies (Döll 2002). Conversely, by 1959 the possibility that irrigation could impact the climate had already been discussed (de Vries 1959). Regional studies in USA, Israel, India, and China indicate that irrigation may influence surface temperature (Barnston and Schickedanz 1984; de Ridder and Gallée 1998; Jianping et al. 2002; Adegoke et al. 2003), convection and cloud formation (Barnston and Schickedanz 1984; de Ridder and Gallée 1998; Lohar and Pal 1995), rainfall (Barnston and Schickedanz 1984; Lohar and Pal 1995; Segal et al. 1998; Moore and Rojstaczer 2001), and humidity (Barnston and Schickedanz 1984; Lohar and Pal 1995; de Ridder and Gallée 1998; Moore and Rojstaczer 2001; Jianping et al. 2002). These studies are either local or regional in scope and do not give any indication as far as the impact of irrigation on the global climate is concerned. Using a general

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circulation model (GCM) of the atmosphere Milly and Dunne (1994) have investigated the sensitivity of the global water cycle to changes in the water-holding capacity of land. Since evaporation of water used for human activity can be seen as an increase in the water-holding capacity of land, they scaled their results and infer that current levels of water evaporated from human activity would induce an air temperature decrease near the surface of 0.1 K and a global precipitation increase of 8 mm/year over land. In this study we further focus on the global scale to investigate the signature of irrigation on atmospheric water vapour and the climate system.

As shown in Fig. 1, we may expect several impacts by irrigation on climate. Evaporation of irrigation water may lead to additional water vapour in the atmosphere resulting to additional greenhouse effect and absorption of solar radiation. Evaporation of irrigation water is also accompanied by a cooling of the surface (known as evaporative cooling). The additional water vapour injected into the atmosphere will eventually condense, which will release latent heat in the atmosphere. Therefore irrigation also has a direct effect on the temperature profile by cooling the surface and heating the atmosphere, but these two opposite effects may occur in different regions. The change in the water vapour profile may also directly affect convection and subsequent precipitation. If the additional water vapour from irrigation triggers convection and precipitation which would not have occurred otherwise, the consequence may be a local decrease rather than an increase in atmospheric water vapour. The direct (from evaporation/condensation) and indirect (through interaction with radiation) changes in the temperature profile may also influence the saturated mixing ratio of water vapour, convection, cloud formation, precipitation, radiative effect of greenhouse gases, and the (natural) evaporation of water in irrigated and adjacent non-irrigated regions. Since it is rather straightforward to estimate the evaporative cooling at the surface due to irrigation (see next section), we focus on the atmospheric response to irrigation through a range of experiments which are described in Sect. 3.

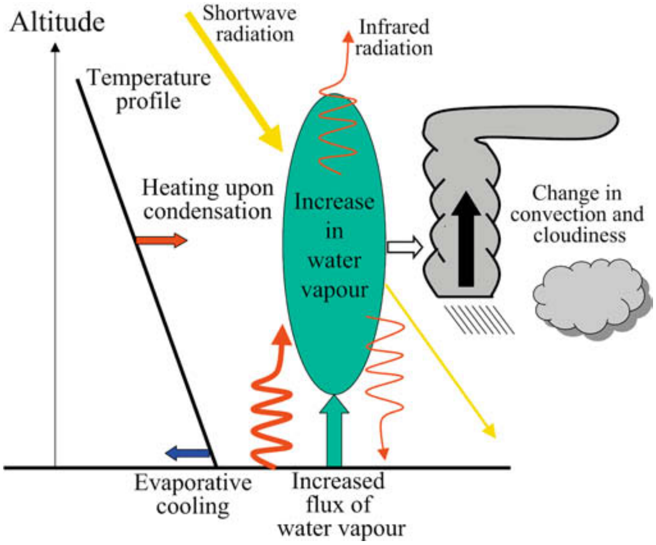

Fig. 1 Schematic of the atmospheric properties and processes potentially induced by irrigation

2 Irrigation data

Evapotranspiration from irrigation is defined as the difference between the potential evapotranspiration from crops and the evapotranspiration that would occur without irrigation. In order to generate a geographical distribution of evapotranspiration from irrigation we have combined two irrigation datasets. The annual net evapotranspiration from irrigation on a country basis is taken from Seckler et al. (1998). This is combined with the geographical distribution of areas equipped for irrigation based on data at resolution of 0.5° × 0.5° (Döll and Siebert 2000). Based on Seckler et al. (1998) the annual net evapotranspiration of water from irrigation is 1006 km^3/year. This quantity refers to irrigation requirements of year 1990. Seckler et al. (1998) also estimated the total irrigation withdrawal (water extracted for irrigation purposes) at 2353 km^3/year. In comparison Döll and Siebert (2002) estimated 1092 and 2452 km^3/year for the evapotranspiration from irrigation and total irrigation withdrawal, respectively, for the year 1995. These values are slightly larger than those of the Seckler et al. (1998) data, which could be due to a difference in baseline years. This is supported by the fact that Seckler et al. (1998) estimated a significant increase in the irrigation requirements from 1990 to 2025. However, these estimates are about half the estimate of 2050 km^3/year given by Shiklomanov and Markova (1987, pp 77, quoted by Milly and Dunne 1994). Since Döll and Siebert (2002) found a reasonable agreement when comparing their estimates with independent irrigation data, we argue here that a value of 1000–1100 km^3/year might be more representative on the global scale. The annual cycle of evapotranspiration from irrigated areas is determined by climatological data on the growing season and precipitation. The geographical distribution of the evaporation rate is shown in Fig. 2. Large evaporation rates from irrigation are evident over South Asia, the United States of America and parts of Europe.

We find aspects and uncertainties in this estimate which are worth mentioning here. First, the estimate of evapotranspiration from irrigation stems solely from the crop. Accounting for evaporation of water due to irrigation (e.g. from the soil, channels, and dams) could increase the estimate. Part of the large difference in the evapotranspiration from irrigation and total irrigation withdrawal is probably due to evaporation of water, however, runoff is likely to dominate. Molden (1997), Postel (1999), and Kite and Droogers (2000) indicate that accounting for evaporation of irrigated water from soil would increase the total evapotranspiration rate of water vapour from irrigation by a factor of approximately 1.3. Because of lack of data on the geographical distribution of irrigation techniques, this effect is not accounted for here. Second, the estimate of net evapotranspiration of crops from irrigation can be too high for certain years due to water scarcity.

This evaporation flux of irrigation water can be converted into a globally averaged cooling rate of the surface of 0.15 Wm^{-2}. The surface cooling rate can be as large as 30 Wm^{-2} in irrigated areas. Conversely a globally averaged release of latent heat in the atmosphere of 0.15 Wm^{-2} can be expected.

3 Methods

We present five different methods of increasing complexity to estimate the impact of irrigation on the atmospheric water vapour content and the radiation field. The first four estimates should be viewed as sensitivity tests aimed at providing an order of magnitude

Fig. 2 Spatial distribution of the water vapour flux from irrigation (kg m^{-2} year^{-1}). *White* is for non-irrigated areas

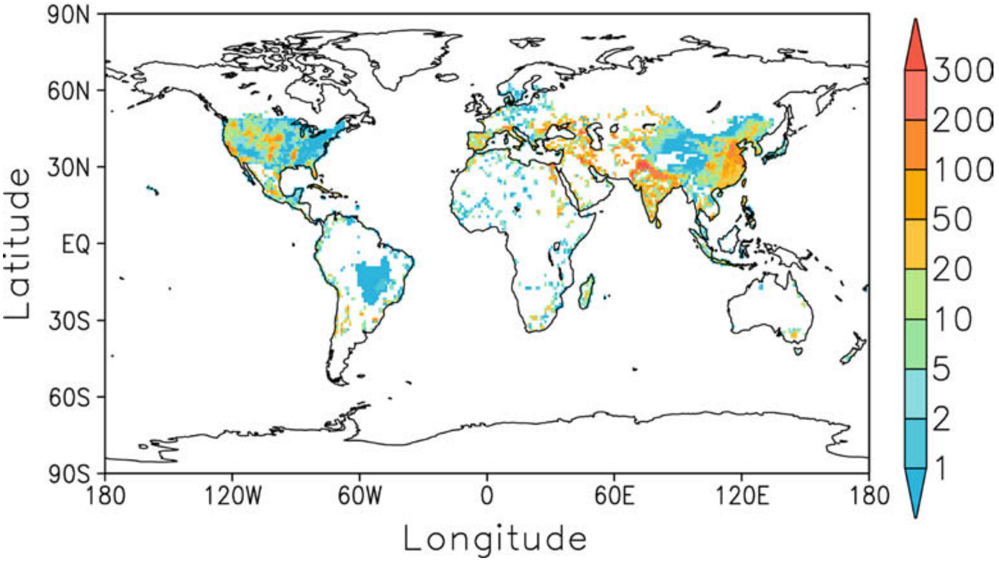

Table 1 Increase in the water vapour tropospheric column and radiative forcings due to increase in water vapour from irrigation as inferred from four idealised experiments (1–4) and the CONTROL and IRRIG simulations (5)

Estimate number	Short description of method	Increase in water vapour column	Shortwave radiative forcing (Wm^{-2})	Longwave radiative forcing (Wm^{-2})	Net radiative forcing (Wm^{-2})
1	Global uniform column increase in tropospheric water vapour by 0.18%	0.18%	0.004	0.024	0.028
2	Column increase in tropospheric water vapour in proportion to irrigation evaporation flux	0.18%	0.013	0.079	0.092
3	Water vapour treated as a tracer and soluble as sulfate aerosols	0.13%	0.008	0.091	0.099
4	Water vapour treated as a “more soluble” tracer than in experiment 3	0.12%	0.006	0.068	0.074
5	Water vapour increase modelled using the LMDZT climate model (IRRIG-CONTROL)	0.14%	0.004	0.026	0.030

for the irrigation effect. The fifth estimate relies on climate simulations made with the Laboratoire de Météorologie Dynamique (LMD) General Circulation Model (GCM), also known as LMDZ (e.g. Zhou and Li 2002). LMDZ is a grid-point model which builds upon the former LMD5 and LMD6 models (e.g. Le Treut et al. 1998). The present resolution is 3.75° in longitude, 2.5° in latitude with 19 vertical layers of hybrid sigma-pressure coordinates. Atmospheric transport is computed with a finite volume transport scheme for large-scale advection (van Leer 1977; Hourdin and Armangaud 1999), a scheme for turbulent mixing in the boundary layer, and a mass flux scheme for convection (Tiedtke 1989). The surface model is a bucket model. The calculation of the surface temperature is incorporated in the boundary layer and based on the surface energy balance equation. The holding capacity of the surface is fixed at 150 mm of water, and all the water above this value is lost as runoff.

The estimated evaporation rate of water from irrigation (1006 km^3/year) represents 0.18% of the natural evaporation rate in the LMDZ climate model. In the first estimate, the water vapour content in the troposphere has therefore been increased uniformly by 0.18% up to the tropopause, i.e. in the same proportion as the estimated increase in evaporation rate. Because of the strong reduction in water vapour content with altitude, this places most of the additional water vapour in the lower part of the atmosphere but also modifies water vapour in the upper troposphere where it is more effective in producing a greenhouse effect. In the second estimate, the increase in tropospheric water vapour content varies spatially and temporally in proportion to the ratio of the irrigation to natural evaporation fluxes. This increase is scaled so that the global increase in water vapour content remains the same at 0.18%. This second estimate places more of the additional water vapour in dry and hot regions where the greenhouse effect is larger. It does not change much the vertical distribution of the additional water vapour. In the third and fourth estimates, water vapour evaporated from irrigation is treated as a passive tracer in the LMDZT climate model. It is emitted based on the mentioned spatial and temporal source distribution, transported, and removed by wet deposition following our scheme for soluble species (Boucher et al. 2002; Boucher and Pham 2002). We apply the same parameters for wet scavenging as for soluble sulfate aerosols in the third estimate while we scavenge water vapour even more efficiently in the fourth estimate with an in-cloud uptake of 100%.

Finally, we have generated a fifth estimate by performing numerical climate experiments with our atmospheric general circulation model. Two ensembles of five 5-year long simulations were performed with the same set of initial conditions and prescribed sea surface temperatures (SSTs). The first ensemble performed with the standard model version serves as a control experiment (CONTROL). In the second ensemble of simulations (IRRIG) we prescribed an artificial source of water vapour equal to the irrigation flux described already. The corresponding evaporative cooling is also entered into the surface energy budget in IRRIG. The natural evaporation rate and the land surface temperature therefore adjust themselves in the model in order to maintain the surface energy balance. However, energy is not conserved at the global scale because of the assumption of fixed SSTs. Note finally that in IRRIG the irrigation flux is prescribed independently from the meteorological conditions. We examine the differences between the 25-year averages of the CONTROL and IRRIG simulations. Tests of statistical significance are done from the sets of 5-year averages using Student's *t*-tests.

Off-line radiative transfer schemes for longwave and solar radiation (Myhre and Stordal 2001) have been used to calculate the radiative forcing (RF) for the water vapour changes of all five estimates. These radiative schemes are more accurate than the radiative schemes of the GCM itself, which is the reason why they have been preferred here.

4 Results

Results are summarized in Table 1. The RF increases by a factor of three from 0.03 (estimate 1) to 0.09 Wm^{-2} (estimate 2) if the additional water vapour is introduced in irrigated regions which are hotter and drier than average. It therefore matters a lot where the additional water vapour from irrigation is placed in the atmosphere, which gives a rationale for performing the tracer simulations of estimates 3 and 4. These two simulations indicate a RF of 0.1 and 0.07 Wm^{-2} with increases in the total water vapour tropospheric columns of 0.13 and 0.12%, respectively. In all these calculations the longwave forcing strongly dominates the shortwave forcing by a factor larger than 5 (Table 1). Overall these results suggest that irrigation can represent an important mechanism of climate change.

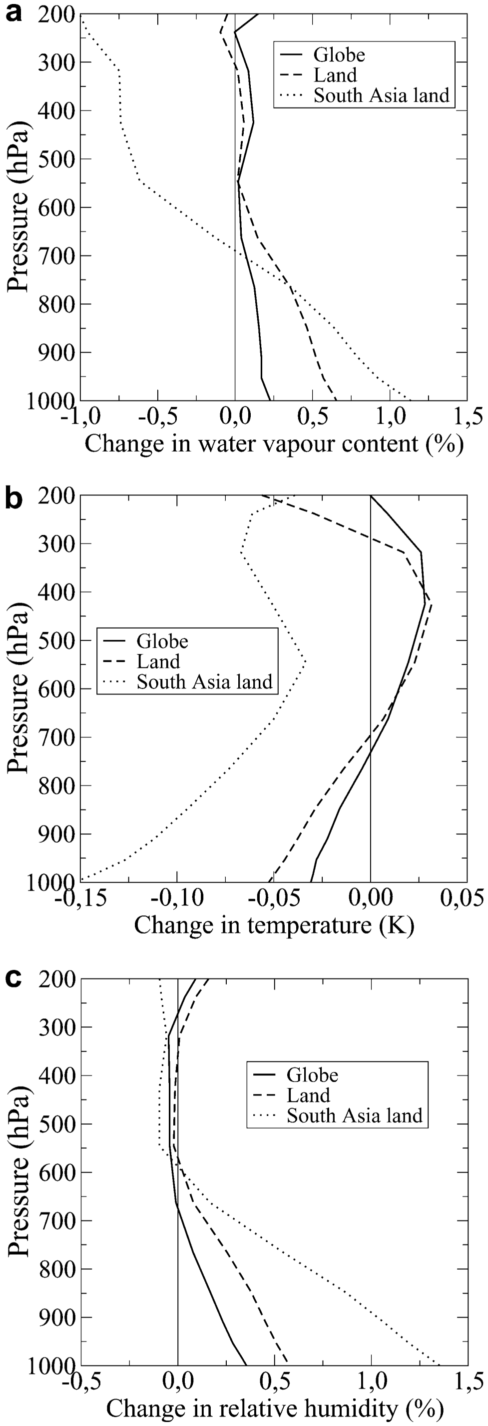

Fig. 3 a Change in the vertical profile of water vapour content (expressed in % change of water vapour content in kg kg^{-1}), **b** change in temperature (expressed as a difference in temperature in K), and **c** change in RH (expressed as a difference in RH in %) between the CONTROL and IRRIG experiments. For each plot we show the global average (*solid line*), the global land average (*dashed line*), and the land average over a South Asian box (40°E–130°E, 0°N–45°N, *dotted line*)

Estimates 1–4 all assume that water vapour from irrigation does not feedback on the water cycle, which, as discussed in the introduction, may not be the case. Moreover the fact that the concentration of water vapour cannot exceed saturation in the atmosphere is a strong constraint. It is therefore useful to consider, at least qualitatively, the various effects of irrigation on the atmosphere as done in the fifth estimate. The IRRIG simulation shows an overall, but non-uniform, increase in water vapour, which translates into a RF of 0.03 Wm^{-2} . This is significantly lower than the RFs computed from the idealised simulations 2–4 (see Table 1), which suggests the presence of feedback mechanisms in the IRRIG simulations. In this case the global increase in the water vapour tropospheric column is 0.14%. We observe a global increase in the water vapour content which is largest close to the surface (Fig. 3a) and almost no change above 600 hPa. Averaged over land the increase is larger at about 0.5–0.6% close to the surface. If we further restrict the land average over the South Asian region (40°E–130°E, 0°N–45°N) where the irrigation is largest, the model simulates an even larger increase in water vapour in the boundary layer and a decrease higher up, suggesting changes in the vertical transport of water vapour. These changes in the water vapour content are statistically significant at the 90% level at the near-surface, up to 900 hPa, and up to 800 hPa for the global, land, and South Asian land averages, respectively. The model also shows a

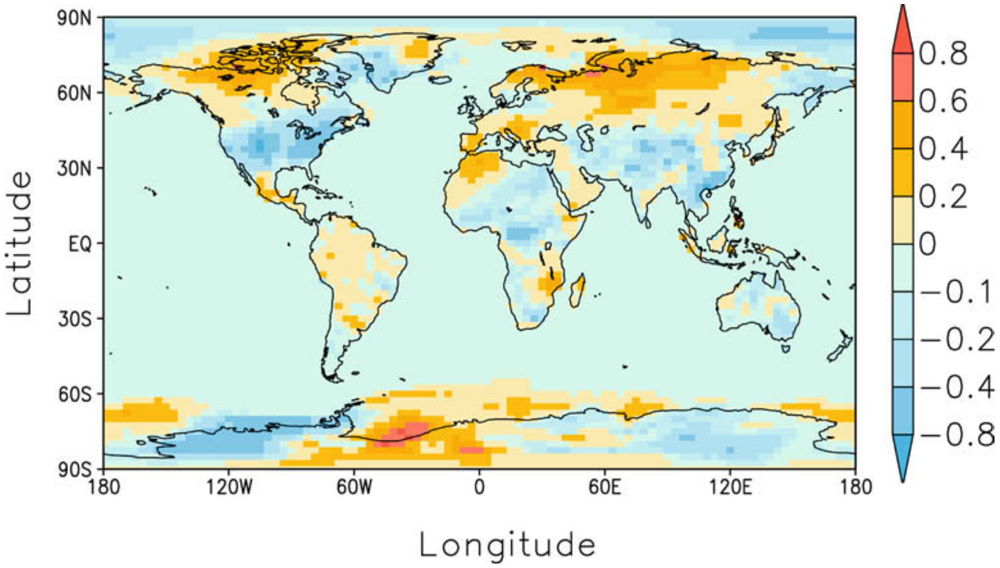

Fig. 4 Change in surface temperature (K) between the CONTROL and IRRIG experiments

significant cooling above irrigated continental regions of up to 0.8 K (Fig. 4) which spreads vertically over some regions (Fig. 3b). On a global average the lapse rate is decreased with a cooling of the lower layers of 0.03 K and a warming of upper layers of similar magnitude. Averaged over land and South Asian land, the cooling at the near-surface is 0.05 and 0.15 K, respectively. Over South Asian land, the cooling at the surface is not compensated by a warming higher up, suggesting that condensation of water vapour emitted from irrigation partly takes place in adjacent regions. Again the changes are significant in the lower levels (up to 900 hPa for the South Asian land average) but not higher up. As expected the combined increase in the water vapour content and decrease in air temperature in the lower troposphere result in a large (absolute) increase in relative humidity (RH). In Fig. 3c the change in RH extends to the 600–700 hPa pressure level. It is 0.3% close to the surface at the global scale and reaches 1.3% over South Asian land. Over South Asia the changes are statistically significant to the 90% level up to 750 hPa. As a whole these results highlight irrigation as a key climate forcing mechanism among others to understand the inhomogeneous (i.e. regional) pattern of observed temperature changes (IPCC 2001).

As already mentioned there is a strong constraint from the fact that the water vapour mixing ratio can only marginally exceed saturation in the atmosphere. To further test any non-linearity which may result from this effect we made a one-year simulation (labelled as IRRIG × 10) where the prescribed irrigation flux of water vapour to the atmosphere was multiplied by a factor of 10. The results are qualitatively consistent with IRRIG experiments with a large increase in precipitable water above and around India where the irrigation flux is large. The region of large increase in precipitable water is surrounded by a region of decrease which encompasses parts of China where the irrigation flux is also large. The increase in precipitable water in IRRIG × 10 is about 10 times larger over and around India when compared to the IRRIG simulation, but is about the same on global average. This demonstrates that the additional emission of water vapour in dry, hot regions translates into a proportional increase in precipitable water at the regional scale, which is somehow compensated by a decrease in precipitable water in other regions through some feedback mechanisms which may be related to convection.

5 Discussion of the radiative forcing concept

We simulate a positive RF and a surface cooling due to irrigation. The complexity of the effects that irrigation has on climate therefore questions the applicability of the RF concept which assumes that RF and surface temperature change are of the same sign (IPCC 2001). Radiative forcing should also be estimated with holding the surface and troposphere fixed (in particular the temperature and water vapour profiles). This is clearly not possible for irrigation which impacts directly these profiles in several ways as has been discussed. Some other mechanisms of climate change have been suggested recently for which the concept of RF may not be appropriate. Absorbing aerosols tend to heat the atmosphere and cool the surface, thereby stabilizing the atmosphere and increasing the saturation water vapour pressure at the cloud level (Ackerman et al. 2000; Hansen et al. 1997). Such a forcing mechanism could exhibit a larger climate sensitivity because of a reduction in low-level, reflective clouds. There is also some controversy whether the second aerosol indirect effect (an increase in cloud liquid water content and cloud cover induced by a reduced precipitation efficiency) should be considered as a forcing or a feedback (IPCC 2001; Rotstayn and Penner 2001). Unlike the other forcing mechanisms which can be estimated instantaneously in a model, the second aerosol indirect effect requires to integrate in time cloud processes such as precipitation. Pielke et al. (2002) showed that land-use changes impact both regional and global climate and suggested the need to develop a new metric of climate change that would stem from changes in the individual terms of the surface energy budget at the regional scale. While it is out of the scope of this study to propose or assess a new metric of climate change, it should be recognised that evaporation of irrigated water impacts directly (through thermodynamics) and indirectly (through radiation) the temperature and humidity profiles, which challenges the RF concept.

6 Conclusions

We have combined data of evapotranspiration from irrigation on a country basis with data of irrigated areas. This dataset has been implemented in a GCM to estimate the global impact of irrigation on the water vapour distribution and temperature changes. Due to the complex and important role of water in the climate system we have performed some sensitivity tests to understand and illustrate the potential impact of irrigation on the global atmosphere. We predict a regional surface cooling and changes in the vertical temperature profile and estimate a radiative forcing in the range of 0.03 to 0.1 Wm^{-2} due to the additional atmospheric water vapour for the year 1990. It also appears that this climate forcing mechanism challenges the concept of radiative forcing. Unlike other climate forcing mechanisms increase in water vapour from irrigation may result in a negative climate sensitivity because of the effect of evaporative cooling at the surface.

Gaffen and Ross (1999) discussed reasons for the increase in humidity over the United States. They ruled out emissions of water vapour from fossil fuel combustion as the cause for the observed trends in near-surface specific and relative humidity but considered emissions of water vapour from irrigation as one of the possible causes. IPCC (1999) indicates a radiative forcing of water vapour from aviation that is at least an order of magnitude smaller than we have found from irrigation. Industrial and domestic water use is significantly smaller than for irrigation (Döll 2002; Seckler et al. 1998). Irrigation and vegetation changes seem therefore clearly to be dominating factors of direct anthropogenic influence on the atmospheric water vapour content. Moreover it is expected that water withdrawal for irrigation could increase considerably in the future.

Irrigation is also accompanied by a change in vegetation not considered here, thus modifying the surface albedo, the surface roughness, and the surface energy budget. It is important that the couplings between the biosphere, the surface hydrological cycle, and the atmosphere be now fully considered. The on-going development of Earth System Models (ESM), along with appropriate in-situ and satellite observations, appear to be a very promising approach for studying the impact of irrigation on the climate system.

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