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Impacts of irrigation and anthropogenic aerosols on the water balance, heat fluxes, and surface temperature in a river basin

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[1] Changes in both land cover and the atmosphere have impacted the heat fluxes of south Asia in ways that may have altered the timing and magnitude of the monsoon. Century-long budgets of water and energy in the Krishna Basin (258,948 km^2) in southern India demonstrate that irrigation impacted the sensible heat flux of the land surface (H) as much as or more than did the atmospheric brown cloud (ABC) over 1960–2005. Annual discharge of the Krishna River fell from 226 mm during pre-irrigation land cover (1901–1960) to 64 mm by 1990–2005, when 14–20% of the basin area was irrigated. Over the same period, annual evaporation increased by 166 ± 32 mm (+28%) causing H to decrease by 12.7 ± 2 W m^{-2} (−18%) compared to a decrease of 11.2 ± 1.8 W m^{-2} caused by the atmospheric brown cloud (ABC). The rate of change in H during irrigation expansion (1960–1990) was between −3.4 and −5.0 W m^{-2} per decade (da^{-1}) due to irrigation expansion and −1.8 to −2.3 W m^{-2} da^{-1} due to the ABC. The trend in H caused by irrigation was negligible over 1990–2005 as irrigated area and evaporation stabilized. Previous work using the Parallel Climate Model estimated that the ABC decreased the latent heat flux by 2.4 W m^{-2}; this decrease was more than offset by irrigation, resulting in a net increase in the latent heat flux of 12.9 W m^{-2}. The maximum surface air temperature (Tmax) either decreased or remained the same in areas experiencing irrigation expansion but increased in a majority of unirrigated areas during the post-monsoon season. The results provide observational evidence that irrigation changed both the basin-scale sensible heat flux and surface air temperatures.

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1. Introduction

[2] The fluxes of radiation and heat at the Earth's surface play important roles in climate and regional circulation. Human activities alter radiation and heat fluxes at the surface by adding aerosols and greenhouse gases to the atmosphere and by changing land surface properties. Anthropogenic aerosols, also called the Atmospheric Brown Cloud (ABC) impact the regional energy balance in ways that may have contributed to changes in the timing and strength of the monsoon over south Asia [*Lal et al.*, 1995; *Menon et al.*, 2002; *Meehl and Arblaster*, 2003; *Ramanathan et al.*, 2001, 2005]. The ABC reduces incoming shortwave radiation and land surface temperatures, which weakens the land–ocean thermal gradient. The ABC also heats the upper troposphere and modifies the lapse rate, which increases stability and reduces convection. The ABC also reduces evaporation from the ocean and changes the spatial distribution of sea surface temperature, which may weaken monsoon circulation. The timing of the monsoon has indeed shifted over large areas of central India, with a decrease in July precipitation and increases in precipitation in June and August [*Guhathakurta and Rajeevan*, 2008]. NCEP reanalysis data show evidence of long-term decreases in the strength of monsoon circulation over several regions, including south Asia [*Chase et al.*, 2003]. The ABC is often identified as the primary mechanism driving the observed changes in the monsoon.

[3] Land surface properties, including vegetation and soil moisture, also impact radiation and heat fluxes [*Bonan*, 1997; *Chase et al.*, 2001; *Costa and Foley*, 2000; *Foley et al.*, 2003; *Gibbard et al.*, 2005; *Kleidon et al.*, 2000]. Land surface processes are increasingly seen as critical for modeling climate [*Feddema et al.*, 2005; *Gordon et al.*, 2005],

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including the Indian monsoon [*Krishna Kumar et al.*, 2005]. Irrigation increases the latent heat flux and decreases the sensible heat flux at the surface, thereby reducing surface air temperatures [*Barnston and Schickendanz*, 1984; *Boucher et al.*, 2004; *De Ridder and Galle*, 1998; *Douglas et al.*, 2006; *Kueppers et al.*, 2007; *Ozdogan and Salvucci*, 2004]. Modeling studies suggest that irrigation development may have partially masked the effect of greenhouse gases on surface temperature in India [*Douglas et al.*, 2006]. Statistical analyses suggest that the change in the sensible heat flux and temperature due to irrigation contributed to the observed change in monsoon circulation: increased greenness of the land surface during the pre-monsoon season (March–April–May) correlates with a weakened monsoon and lower precipitation in July [*Lee et al.*, 2008].

[4] Despite its importance for regional atmospheric circulation and climate, the effects of irrigation on the fluxes of water vapor and heat have not been well quantified, particularly at regional scales [*Gordon et al.*, 2005]. Studies of the effect of land cover change on regional heat fluxes have often used land surface models, which mathematically describe the interactions among soil moisture, vegetation, and the water and energy balance [*Douglas et al.*, 2006; *Kueppers et al.*, 2007]. Parameterization of these land surface models is complicated by natural heterogeneity in soil and vegetation, and by lack of data at the spatial and temporal resolutions required by the model. These parameter and input uncertainties can yield both uncertain predictions and ambiguous interpretation of controlling processes [*Franks et al.*, 1997]. Field measurements, including meteorological stations [*Ozdogan and Salvucci*, 2004], Bowen ratio towers [*Drexler et al.*, 2004], or eddy covariance [*Brunel et al.*, 2006] may be used to document changes in temperature and heat fluxes during irrigation development, but the point-wise measurements are not easily scaled to river basins. Satellite methods have been used to map sensible and latent heat fluxes over large areas [*Ahmad et al.*, 2006; *Bastiaanssen et al.*, 1998; *Loukas et al.*, 2005], but cloud-free imagery are often not available during the monsoon season, which complicates estimation of annual heat fluxes. Satellite imagery are also not available prior to the 1970s or 1980s, preventing the construction of multi-decadal budgets of water and energy.

[5] Alternatively, river discharge provides an aggregate measure of the basin water and energy balance. Use of the river basin as the integrator of regional soil–vegetation–atmosphere interactions circumvents the need to parameterize land-surface models with uncertain parameter values and input data, and provides a direct measure of the basin-scale water balance and latent heat flux. This approach builds on a growing interest in hydrology and land surface modeling toward simplification of modeling approaches, with an emphasis on top-down, data-driven analysis [*Klemeš*, 1983; *Sivapalan et al.*, 2003; *Schulz and Beven*, 2003]. In top-down analysis, hypotheses are formulated and tested using observed data at the largest spatial and temporal scales, which then focus further measurements and model development on the most important processes identified at the regional and decadal scales. The emphasis is on the use of observations and data to identify the dominant processes controlling the water or energy balance at large spatial and temporal scales, rather than on precise quantification of the complex and interacting processes governing the transfer of water and energy at the land–atmosphere interface.

[6] This study uses observed rainfall and runoff at an annual time step to quantify the impact of irrigation on the water balance, net radiation, and heat fluxes in a large river basin that experienced rapid irrigation development in the late 20th century. First, a water balance of the basin was constructed over 1901–2005 using observed rainfall, runoff, reservoir storage, and simple assumptions about net annual changes in soil moisture and groundwater. Naturalized evaporation and the impact of irrigation on evaporation were calculated using a regression model of the annual rainfall–runoff relationship. Second, the observed increase in evaporation was compared to the net irrigation requirement estimated from a model of crop water use and a map of irrigated areas. Third, the observed change in evaporation was used to calculate changes in the latent and sensible heat fluxes due to irrigation, and satellite methods were used to quantify the impact of irrigation on albedo and net shortwave radiation. Fourth, the change in the sensible heat flux (H) due to irrigation was compared with the change in net radiation and H due to anthropogenic aerosols. Finally, data from individual meteorological stations were used to document trends in maximum air temperatures in irrigated and unirrigated areas. The main research questions were: How did irrigation expansion change the water balance and heat fluxes of a large river basin? How did the magnitude of those changes compare with changes caused by the ABC? Did maximum air temperatures decrease over the basin during the period of irrigation expansion, and did temperatures decrease more in irrigated areas?

2. Study Area

[7] The Krishna River drains 258,948 km^2 of southern India, making it the fourth largest river basin in India in terms of area and the fifth largest in terms of discharge (Figure 1, see *Biggs et al.* [2007a] for a detailed description). The river originates in the Western Ghats, flows across the Deccan plateau and discharges to the Bay of Bengal. Annual precipitation in the basin averaged 829 ± 124 mm over 1901–2005, and was highest in the Western Ghats and along the eastern coast. Most (84%) of the rain falls during the monsoon from June to October (Figure 2a).

[8] The geology of the basin is dominantly Archaen granite and gneiss of the Dharwar craton, with Deccan basalts in the northwest. Soils formed on the granite and basalt are generally shallow (<1 m) clay loams, gravelly clay, and heavy clay, though soils are generally deeper (>1 m) in valley bottoms [*Biggs et al.*, 2007a]. Aquifers are fractured hard rock with low specific yield (~1%) and low transmissivity [*Naik and Awasthi*, 2003], though the weathered saprolite overlying the fractured granite can have porosity greater than 10 percent [*Dewandel et al.*, 2006]. A typical profile on weathered granite in the central plateau of the Krishna Basin consists of 0.1–0.4 m of soil, 1–3 m of sandy regolith, 10–15 m of laminated saprolite, and 15–20 m of fissured granite with a specified yield of 0.014 [*Dewandel et al.*, 2006]. The water table is generally within the fissured granite layer.

[9] Both rainfed and irrigated crops are grown in the basin. One cropping season (*kharif*) coincides with the monsoon, when most rainfed crops are grown, and the second season (*rabi*) occurs during the post-monsoon (November–March).

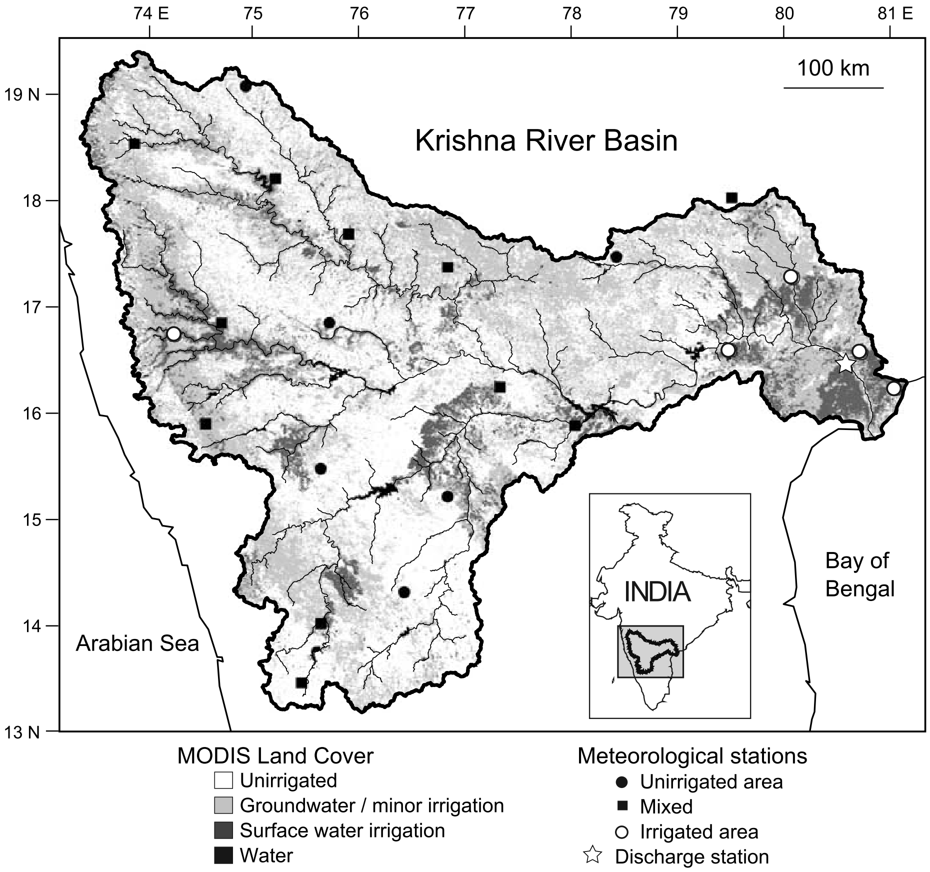

Figure 1. Location map of the Krishna Basin, including irrigated areas, meteorological stations, and the discharge station on the Krishna River at Vijayawada. Modified from *Biggs et al.* [2006].

Rainfed crops include lentils, sorghum, millet, groundnut, and oilseeds. Net cultivated area (A_c), which includes both rainfed and irrigated crops, expanded from 125,000 km^2 (48% of total basin area, A_t) in 1900 to 149,000 km^2 (58%) in 1950, but was relatively stable (54–59% of A_t) from 1950 to 1990 (Figure 3, based on *Ramankutty and Foley* [1998]).

[10] The development of irrigation in the basin may be divided into three periods: pre-irrigation (1901–1959), irrigation expansion (1960–1990) and steady-state (1990–2005). Irrigation has been practiced for centuries near small reservoirs and around hand-dug wells. Large-scale canal irrigation began with the construction of an anicut across the Krishna River at its delta in the 1850s, but the 1960s marked the beginning of the construction of large reservoirs and irrigation canals on the Deccan plateau. For simplicity, the period prior to 1960 is referred to as the pre-irrigation period. Starting in the 1960s, several large reservoirs and irrigation projects were constructed. By the year 2000, the basin had 26 large reservoirs (gross storage greater than 150 million m^3) with a total storage capacity of 43 km^3 (166 mm), or 73% of the annual pre-irrigation runoff (Figure 4b). The basin also has thousands of small reservoirs, but their contribution to total storage capacity has not quantified. The thirteen largest reservoirs in the basin accounted for 37.5 km^3, or 87% of the total gross storage capacity. Irrigated area expanded rapidly from ~18,000 in 1960 to ~34,000 km^2 in 1990 (Figure 1, Figure 3). Gross reservoir storage capacity reached its maximum and total irrigated area was stable after 1990, defining a "steady state" period. The term steady state is used to emphasize that increases in irrigated area in one part of the basin, such as expansion of groundwater irrigation, were approximately balanced by decreases in other areas, including decreases in the area irrigated by surface water (Figure 3). This situation is also referred to as "basin-closure", when most available water resources in a river basin have been appropriated for human use [*Keller et al.*, 1998].

[11] The area irrigated in 2002 was mapped using the Moderate Resolution Imaging Spectroradiometer (MODIS) [*Biggs et al.*, 2006]. Irrigated crops include rice, cotton, and chili in the eastern part of the basin, and sugarcane and rice are grown at the base of the Western Ghats. Irrigation expansion has typically involved replacement of unirrigated crops with rice and sugarcane, rather than expansion onto uncultivated land. Total irrigated area was estimated at between 32,520 km^2 (13% of A_t) and 53,580 km^2 (21% of A_t) depending on the irrigated fraction used for each MODIS class. More than half of the irrigated area is defined as "minor irrigation" (command area less than 0.2 km^2), which is a heterogeneous mosaic of rainfed crops and small plots irrigated by groundwater or small reservoirs.

3. Methods

[12] The equations used to quantify the budgets of water and radiation and the fluxes of heat are presented in sections 3.1 to 3.4. The data used in the budgets is detailed in section 3.5, and the temperature analysis is described in section 3.6.

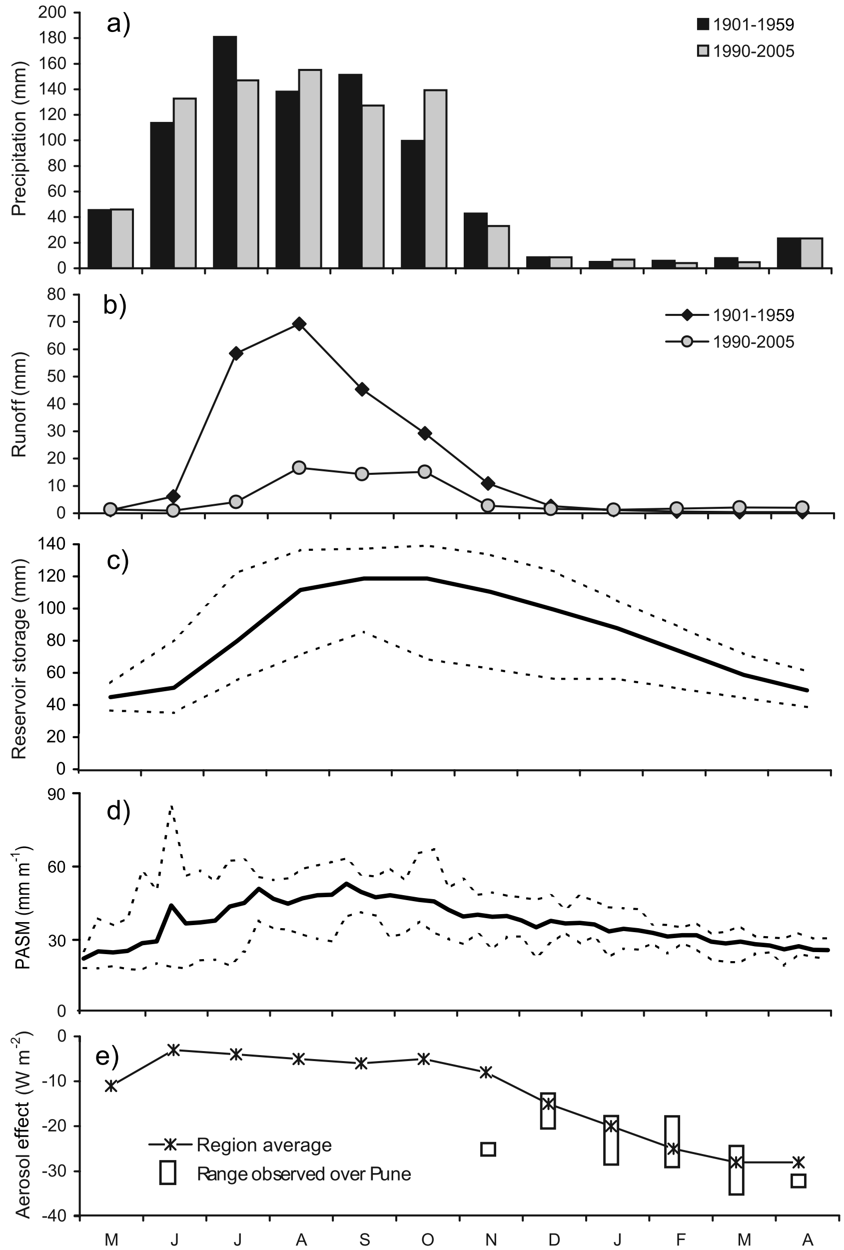

Figure 2. (a) Monthly average rainfall, (b) runoff, (c) and reservoir storage (1990–2005) in the Krishna Basin, and (d) plant available soil moisture measured at an unirrigated site (20.1°N, 74.1°E) over 1988–1995, including the mean (dark line) and maxima and minima (dashed lines) derived from *Robock et al.* [2000] and (e) aerosol effects on incoming shortwave radiation at the ground surface, including the regional average (0–30°N and 60°–100°E) during 1995–1999 [*Ramanathan et al.*, 2005], and the range observed at Pune (18.5°N, 73.9°E) in 2001 and 2002 [*Pandithurai et al.*, 2004].

3.1. Basin Water Balance

[13] Annual evaporation (E) and the latent heat flux (λE) were calculated from the basin water balance:

$$E = P - Q \pm \Delta V \pm \Delta S \pm \Delta GW \quad (1)$$

where P is precipitation, Q is runoff observed at the basin outlet, and ΔV, ΔS, and ΔGW are the net annual changes in reservoir storage, soil moisture, and groundwater storage (mm y^{-1}). The water balance was calculated for a May–April water year since runoff, reservoir levels and soil moisture reach their annual minima at the end of the dry season in April and May (Figures 2a–2d).

[14] Three components of the water balance (P, Q and V) were obtained from existing data sets (Table A1). The two remaining terms (ΔS and ΔGW) were difficult to determine with existing data, so simple models were used to estimate them (Table 1). Plant-available soil moisture in the upper 60 cm measured at an unirrigated location 80 km north of the Krishna Basin (20.1°N and 74.1°E [*Robock et al.*, 2000]) returned to a low baseline (18–25 mm m^{-1}) by 1 May of each year over 1988–1997, with a net annual change in soil moisture of −6.1 to +6.3 mm (Figure 2d).

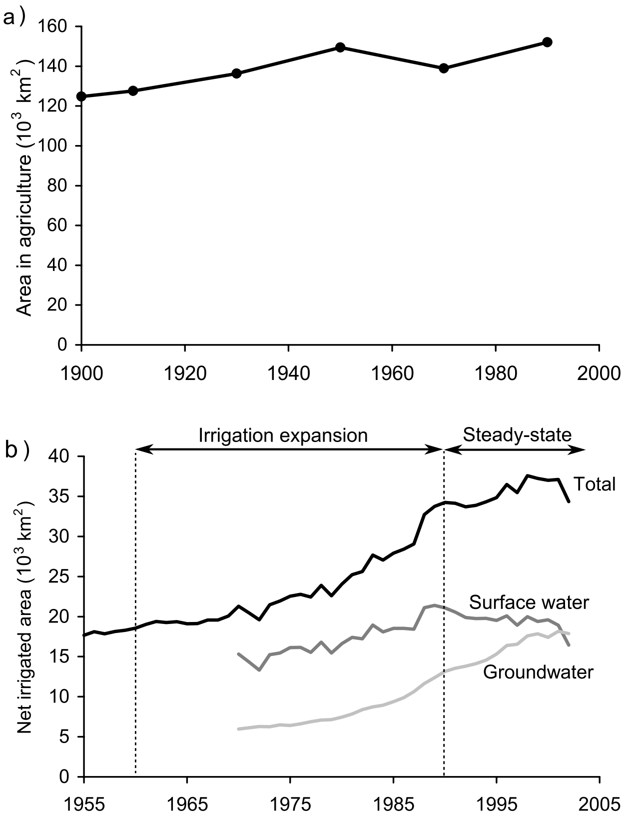

Figure 3. (a) Total cultivated area in the Krishna Basin, 1900–1990, based on data from *Ramankutty and Foley* [1998]. (b) Net irrigated area in the Krishna Basin, 1955–2002. The data were compiled from various sources [*Government of Andhra Pradesh*, 2006; *Government of Karnataka*, 2001; *Government of Maharashtra*, 2004].

These changes were sufficiently small compared to annual precipitation and runoff that ΔS in unirrigated areas was considered to be zero. The transition of an area from unirrigated to irrigated may increase the amount of residual soil moisture left after the end of the *rabi* crop in April. An upper-bound estimate of ΔS due to irrigation expansion in a given year is:

$$\Delta S = \frac{\Delta A_{irr} W z}{A_t} \quad (2)$$

where ΔA_{irr} is the net change in irrigated area over a given year (km^2 y^{-1}), A_t is total basin area (km^2), W is the available water holding capacity of the soil (mm m^{-1}), and z is the depth of soil (m). This model assumes that soil moisture was at the wilting point each May in unirrigated areas, and was at field capacity each May in irrigated areas. These assumptions maximize the estimate of soil moisture change during irrigation expansion.

[15] The annual net change in groundwater storage (ΔGW) was estimated as:

$$\Delta GW = \frac{bn\left(\Delta h_{gw} A_{gw} + \Delta h_{sw} A_{sw}\right)}{A_t} \quad (3)$$

where Δh_{gw} and Δh_{sw} are the average annual net change in the groundwater table in areas irrigated by groundwater and surface water, n is aquifer porosity, b is for units conversion (1000 mm m^{-1}) and A_{gw} and A_{sw} are the areas irrigated by groundwater and surface water. This model neglects lateral flow in groundwater, which is likely small because of the low transmissivity of the fractured hard-rock aquifers [*Maréchal et al.*, 2006].

[16] A regression model was used to estimate the runoff depth for pre-irrigation land cover, called the "naturalized runoff":

$$Q_n = \beta o + \beta_1 P \pm \varepsilon \quad (4)$$

where Q_n is naturalized runoff (mm y^{-1}), β_o, and β_1 are regression parameters, and ε is the error term. Equation (4) was calibrated to observed rainfall and runoff over 1901–1959 (Figure 5) and then used to estimate Q_n over 1960–2005. The difference between naturalized and observed runoff, plus or minus changes in storage, gives the annual evaporation due to irrigation:

$$Eirr = \beta o + \beta_1 P - Q \pm \Delta V \pm \Delta S \pm \Delta GW \pm \varepsilon \quad (5)$$

The change in evaporation due to irrigation is the net result of several land surface processes, including the reduction of albedo and subsequent increase in net radiation, differences in the physiology of irrigated and unirrigated crops, evaporation from reservoirs, and increases in soil moisture. The relationship between precipitation and naturalized runoff from unirrigated areas (equation (4)) is assumed to be constant over 1901–2005. This assumption could be violated if changes in radiation or land use other than irrigation altered evapotranspiration and runoff from unirrigated areas. A distributed hydrologic model of the Krishna Basin [*Bouwer et al.*, 2006] suggested that climate variability caused small changes in runoff (−6% to +15%) compared to the change due to irrigation. A general circulation model (PCM) over India [*Ramanathan et al.*, 2005] provides estimates of the change in the latent heat flux of unirrigated areas due to the ABC and GHGs, and these estimates are compared with the observed change in the water balance. While conversion of land cover from natural vegetation to unirrigated cultivation can alter the rainfall-runoff relationship, net cultivated area in the Krishna Basin, including irrigated and unirrigated areas (A_c), expanded during 1901–1950 (Figure 3a) when the rainfall–runoff relationship was relatively stable (Figure 5), and the total cropped area did not change from 1950–1990.

3.2. Irrigation Requirement Model

[17] The net irrigation requirement (I_{net}) is amount of irrigation water needed for optimal crop growth. It is the difference between the evapotranspiration needed for optimal growth and the amount supplied by rainfall that infiltrates into the soil. It does not include requirements for leaching of salts or maintenance of flooded conditions for rice, since this water recharges groundwater and remains in the basin. I_{net} was calculated using the CROPWAT model [*Döll and Siebert*, 2002; *Smith*, 1992] and a land cover map of the Krishna Basin [*Biggs et al.*, 2006] in order to test the hypothesis that the E_{irr} calculated from the basin water balance could be accounted for by the additional water demand from irrigated crops:

$$I_{net} = \frac{1}{A_t} \sum_{i=1}^{m} \sum_{j=1}^{12} f_i A_i I_{ij} \quad (6)$$

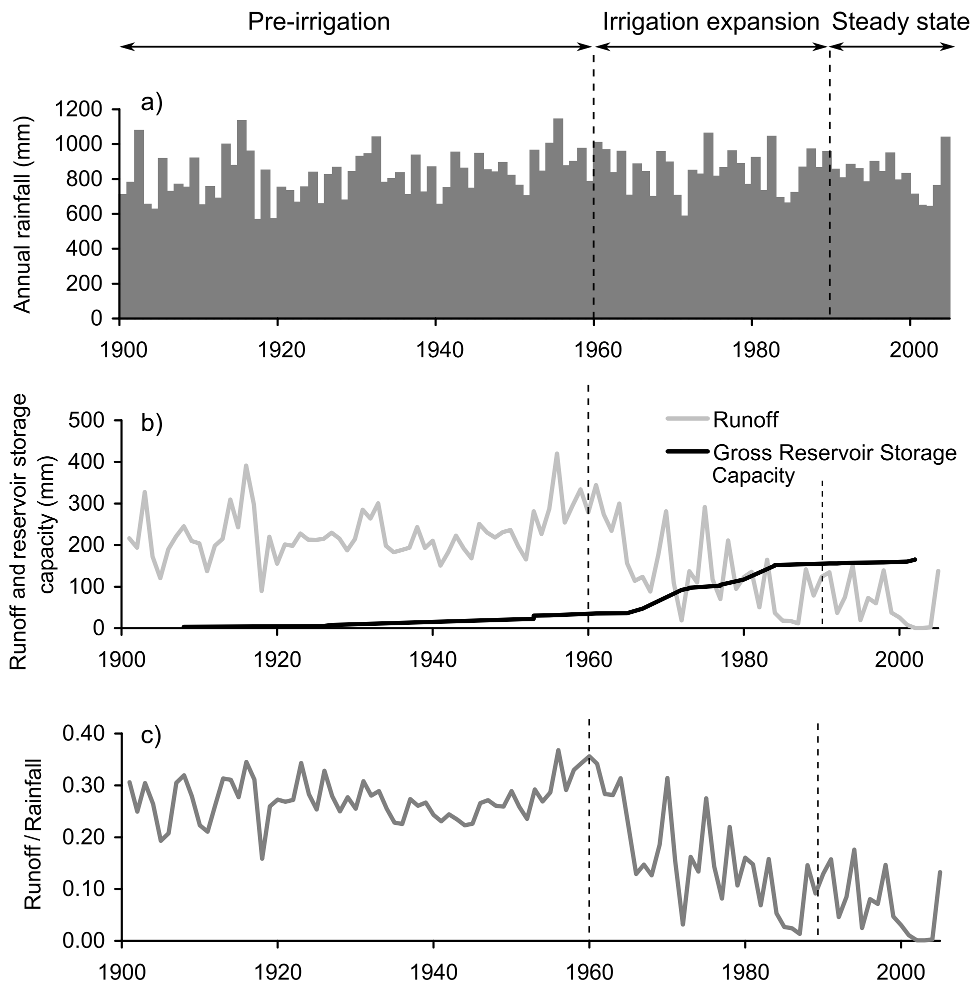

Figure 4. Time series of (a) annual rainfall (P), (b) annual runoff (Q, grey line), gross reservoir storage capacity (black line), and (c) the annual runoff coefficient in the Krishna Basin, 1901–2005.

where f_i is the irrigated fraction for a given land cover class i, A_i is the area of the basin in land cover class i, m is the number of land cover classes, and I_{ij} is the net irrigation requirement for irrigated areas in class i in month j (mm y^{-1}), which is the difference between potential evapotranspiration and effective rainfall:

$$I_{ij} = K_j E_{pj} - P_j(1 - c) \quad (7)$$

Table 1. Model Parameters Treated as Random Variables for the Water and Energy Balance (Equations (2)–(4)), and Crop and Runoff Coefficients Used to Model the Irrigation Requirement (Equations (6)–(7))

Normal Distribution	μ	σ
ε (mm y^{-1})	0	31
Uniform Distribution	Min	Max
W (mm m^{-1})	130	200
z (m)	0.5	1.5
Δh_{sw} (m y^{-1})	0.1	1.0
Δh_{gw} (m y^{-1})	−2.0	−0.1
n (unitless)	0.02	
K_{ini}	Min	Max
Rice	0.95	1.05
Sugarcane	0.40	0.75
Other (cotton, chili)	0.28	0.35
K_{mid}		
Rice	1.35	1.57
Sugarcane	1.25	1.57
Other (cotton, chili)	0.96	1.20
c	0.51	0.72

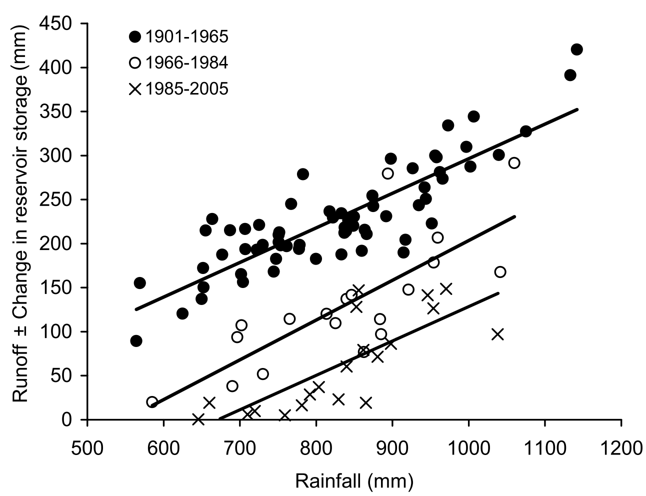

Figure 5. Rainfall and runoff in the Krishna Basin, grouped by three periods. Each point indicates total rainfall and runoff for one water-year (May to April).

where K_j is the crop coefficient in month j, E_{pj} is potential evapotranspiration in month j, c is the runoff and interception coefficient on irrigated plots, and P is precipitation in month j. The data used to parameterize equations (6) and (7) are described in section 3.6, Appendix Table 1, and the range of parameter values are listed in Table 1.

3.3. Basin Energy Balance and Heat Fluxes

[18] Net radiation (R_n) is calculated as:

$$R_n = R_{no} - R_{nABC} + R_{nALB} \quad (8)$$

where R_{no} is annual net radiation without the effects of the atmospheric brown cloud (ABC) or irrigation, and R_{nABC} is the change in net radiation caused by the ABC, which was calculated as:

$$R_{nABC} = \sum_{j=1}^{12} (1 - \alpha_j) F_{SWABCj} \quad (9)$$

where F_{SWABCj} is the change in incoming shortwave radiation caused by the ABC, and α_j is the basin-average albedo in month j. F_{SWABCj} in a given month was assumed constant over the study area. The change in R_n due to changes in the albedo of the land surface during irrigation development (R_{nALB}) was calculated as:

$$R_{nALB} = \frac{A_{irr}}{A_{irr2002}} (\alpha_{2002} - \alpha_n) F_{SW} \quad (10)$$

where $A_{irr2002}$ is the irrigated area at steady-state (2002), A_{irr} is the irrigated area in a given year, α_{2002} and α_n are the albedo in 2002 and prior to irrigation development, and F_{SW} is incoming shortwave radiation.

[19] The latent heat flux is calculated directly from the basin water balance as λE, and the additional latent heat flux due to irrigation is λE_{irr}. The sensible heat flux (H) is the difference between net radiation and the latent heat flux. The change in H due to irrigation is $-\lambda E_{irr}$. The change in H due to the ABC is calculated in two ways. First, an upper bound is calculated by assuming that the ABC has a minimal effect on the latent heat flux ($H_{ABC} = R_{nABC}$). Second, H_{ABC} is estimated as a constant fraction of R_{nABC} ($H_{ABC} = \gamma R_{nABC}$). This fraction ($\gamma$) is calculated as $\gamma = 1 - \lambda E_{ATM}/R_{nABC}$, where λE_{ATM} is the change in the latent heat flux due to both the ABC and GHGs from unirrigated areas calculated using the Parallel Climate Model (PCM) [*Ramanathan et al.*, 2005]. GHGs offset some of the decrease in the latent heat flux caused by the ABC, so the value of γ is likely an overestimate of the fraction of R_{nABC} partitioned into H. Excluding GHGs from the estimates of the changes in R_n and H was done in order to focus the analysis on the ABC and irrigation, and to maximize the estimate of the effect of the ABC on the sensible heat flux.

3.4. Uncertainty Analysis

[20] The uncertainty in E_{irr} and H_{irr} due to the regression model error (ε) and uncertainty in the storage terms (ΔS and ΔGW) was assessed using Monte Carlo simulation. All terms in the water balance model were linear, so the variance of E_{irr} could be calculated directly using the method of moments, but determination of uncertainty in the trends in H_{irr} required error propagation. Each parameter in the models of ΔS and ΔGW was assigned a uniform probability distribution (Table 1). The error term (ε) from the regression model had a normal distribution. Estimates of E_{irr} and H_{irr} were calculated using parameter values sampled from the probability distributions with 5000 replications. The trend in H_{irr} was determined with linear regression for the period of rapid irrigation expansion (1960–1990) and the period with stable irrigated area (1990–2005) for each of the 5000 model runs. The trend over 1960–1990 was sensitive to the rapid change in E_{irr} and H_{irr} over 1960–1965, so the trends were also calculated for 1965–1990. The error term of the regression model (ε, equation (4)) was not autocorrelated with a one year lag ($p > 0.1$), so it was sampled as an independent random variable for the Monte Carlo simulations.

3.5. Data Sources

[21] The data used for the water and energy balance are summarized in Table A1. Precipitation data (P) was obtained from the Indian Institute of Tropical Meteorology (IITM, http://www.tropmet.res.in/, access date 7 May 2007), which reports mean monthly precipitation in meteorological subdivisions of India. The boundary of the Krishna Basin was overlain on a map of the IITM subdivisions to calculate the area-weighted precipitation. Runoff (Q) in the Krishna River measured at the basin outlet at Vijayawada (Figure 1) was obtained from the RivDis database [*Vörösmarty et al.*, 1998] and India's Central Water Commission. Gross water storage (V) in the thirteen largest reservoirs, which account for 87% of the gross storage capacity of large reservoirs in the basin, was obtained from State Irrigation Departments.

[22] The probability distributions of the model parameters used to calculate ΔS and ΔGW are listed in Table 1. The available water holding capacity (W) of soils in the Krishna Basin ranged from 150 to 200 mm m^{-1} on 1:5,000,000 scale soil maps [*Food and Agriculture Organization*, 1995]. The average soil depth (z) was between 0.5 to 1.5 m on 1:500,000 scale soil maps [*Challa et al.*, 1996; *Government of India*, 1999; *Sehgal et al.*, 1996]. The annual change in the water table in groundwater irrigated areas (Δh_{gw}) was a maximum of -2 m y^{-1} in southern India [*Singh and Singh*, 2002]. In the Musi River basin (11,000 km^2), a sub-basin of the Krishna with extensive groundwater irrigation, groundwater levels declined by 0.1 to 0.4 m y^{-1} over 1989–2004 [*Massuel et al.*, 2007], so a range of -2.0 to -0.1 m y^{-1} was used for Δh_{gw}. The water table rose at a rate of between +0.1 and +1.0 m y^{-1} in surface irrigation projects of India, and at +0.32 m y^{-1} in the Nagarjuna Sagar command area in the eastern part of the Krishna Basin [*Singh and Singh*, 2002]. The range observed in India (+0.1 to +1.0 m y^{-1}) and a uniform probability distribution is used for Δh_{sw}. While Δh_{sw} likely decreases with time in any given irrigated area, the Δh_{sw} for the water balance is the basin average, which includes multiple irrigated areas in various stages of development. Porosity (n) was set to 0.02, which is an upper estimate for hard rock aquifers of the area [*Maréchal et al.*, 2006]. Time series of the area irrigated by groundwater (A_{gw}) and surface water (A_{sw}) were taken from a compilation of government statistics books [*Government of Andhra Pradesh*, 2006; *Government of Karnataka*, 2001; *Government*

of Maharashtra, 2004]. Total irrigated area (A_{irr} in equations (2) and (10)) is the sum of A_{gw} and A_{sw}.

[23] A map of land cover in 2002 [*Biggs et al.*, 2006] was used to determine the area of the basin in each land cover class (A_i) and the irrigated fraction for each class (f_i). The irrigated fraction included all areas that were irrigated in one or more seasons in 2002. The map had nine classes and two estimates of f_i, one derived from agricultural census data and the other from ground surveys. The Krishna Delta was excluded from the calculation of I_{net}, since its command area was developed before 1960. Potential evapotranspiration from irrigated crops (E_{pj}) was calculated using the Penman–Monteith equation and temperature, wind speed and vapor pressure interpolated from the 22 meteorological stations. The bulk surface resistance was set to the default values for the reference grass (r_s = 70 s m^{-1}) and the aerodynamic resistance was computed for the reference grass height of 12 cm. Net radiation for the irrigation requirement model was the mean over all available years (1985–1994) from NASA's Surface Radiation Budget (SRB) version 2 [*Gupta et al.*, 1999], which is in 1-degree resolution grids. Shortwave radiation from the SRB showed good agreement with pyranometer measurements at two locations in the basin (RMSE 11–15 W m^{-2}) [*Biggs et al.*, 2007b]. The runoff coefficient in irrigated areas (c in equation (7)) was taken from *Kang et al.* [2006] for irrigated rice. A gridded precipitation data set with 0.5 degree resolution [*Mitchell and Jones*, 2005] was used to obtain values of P_j over 1990–2002 for the irrigation requirement model (I_{net}). The gridded data were used instead of the IITM data for the calculation of I_{net} because the gridded data had a higher spatial resolution that captured strong spatial gradients around the Western Ghats. Precipitation data from the IITM was used for the basin water balance instead of the gridded data because the IITM data included 2003–2005 and predicted pre-irrigation runoff (1901–1959) as accurately as did the gridded data set [*Biggs et al.*, 2007a].

[24] A range of crop coefficients (K_j) was compiled from the literature for each of three major irrigated crops: rice, sugarcane, and cotton/chili (Table 1, Table A1). The crop coefficients for cotton/chili were taken from the range observed for well-watered pulses and oilseeds [*Biggs et al.*, 2008]. Monthly crop coefficients were scaled to the observed NDVI for each MODIS class [*Biggs et al.*, 2006], with the minimum NDVI corresponding to the initial growth stage (K_{ini}) and the maximum NDVI to the mid-season growth stage (K_{mid}). Minimum and maximum values of I_{net} were calculated using minimum or maximum values of K_j, c, and f_i.

[25] The change in incoming shortwave radiation due to the ABC (F_{SWABC}) was quantified for 1930 to 1998 over South Asia and the Northern Indian Ocean (0° to 30°N and 60° to 100°E) by *Ramanathan et al.* [2005]. F_{SWABC} was measured during 1995–1998 using a combination of satellite, aircraft, and surface observations during the Indian Ocean experiment, and F_{SWABC} during the wet season was estimated using an aerosol assimilation model [*Ramanathan et al.*, 2001]. The emission history of SO_2 and black carbon over India was used to quantify F_{SWABC} over 1930–1994. F_{SWABC} was assumed to be zero prior to 1930. After 1998, F_{SWABC} was estimated both as the mean over 1996–1998 and as an extrapolation of the linear trend over 1990–1998. The regional average F_{SWABC} was compared to measurements of F_{SWABC} taken in the city of Pune (18° 32′N 73°51′E) during the dry seasons of 2001 and 2002 [*Pandithurai et al.*, 2004].

[26] Albedo was calculated from the MODIS Filled Land Surface Albedo Product [*Moody et al.*, 2005]. Blue-sky albedo was calculated from white and black-sky albedo weighted by the fraction of diffuse to total radiation from the SRB. Two albedo maps were prepared: one for 2002 and the other for pre-irrigation land cover. The pre-irrigation albedo map was prepared by setting all pixels with an irrigated fraction greater than 20% in the land cover map [*Biggs et al.*, 2006] to the mean albedo of pixels classified as rangeland or unirrigated agriculture in a 30-cell (15 × 15 km) window. Net radiation with minimal influence from the ABC or irrigation (R_{no}) was calculated using the mean net radiation from the SRB and the values of R_{nABC} and R_{nALB} over 1985–1994.

3.6. Maximum Air Temperature

[27] The monthly mean of the daily maximum air temperature (*T*max) was measured at 22 meteorological stations maintained by the Indian Meteorological Department (IMD). The fraction of the land surface that was irrigated in a 5x5 km window around each station (f) was determined using the land cover map of 2002 [*Biggs et al.*, 2006]. The stations were classified as being in areas that were irrigated ($f \geq 0.25$, N = 5), mixed ($0.05 < f < 0.25$, N = 11) or unirrigated ($f \leq 0.05$, N = 6). Two stations in the Krishna Delta, where irrigation developed prior to 1960, were excluded from the trend analysis, leaving three stations in irrigated areas. The temperature anomalies were calculated as the difference between *T*max and the mean over 1952–1970. The trends in *T*max and their statistical significance were determined using Sen's slope and the Mann–Kendall trend test.

4. Results

4.1. Basin-Scale Water Balance

[28] The annual runoff at Vijayawada decreased from an average of 226 ± 59 mm in 1901–1959 to 64 ± 56 mm by 1990–2005, despite no statistically significant trend in annual precipitation (Table 2, Figures 4a, 4b). Runoff was nearly zero (<2 mm) during a drought from 2002 to 2004, and the runoff ratio (Q:P) decreased from 0.15–0.35 in the pre-irrigation period to 0–0.15 in 1990–2005 (Figure 4c). Annual evaporation (E) increased by an average of 166 mm, or 28% of the average over 1901–1959. The volume of water in the thirteen largest reservoirs increased to a maximum of 34 km^3 in 1991 (Figure 6) and fell to between 9 and 13 km^3 at the end of every *rabi* season, with small interannual changes in storage.

[29] Runoff correlated linearly with precipitation over 1901–1959 (Figure 5). The values of the regression parameters for predicting naturalized flow (equation (4)) were determined from this linear relationship as $\beta_o = -90$ mm y^{-1} and $\beta_1 = 0.383$ ($R^2 = 0.72$, $\varepsilon = 31$ mm y^{-1}). The intercept of the rainfall–runoff relationship changed starting in the 1960s following the construction of several large reservoirs. By 1985–2005, a given annual precipitation depth yielded ~170 mm less annual runoff than the same precipitation depth in 1901–1959. Annual evaporation due to irrigation

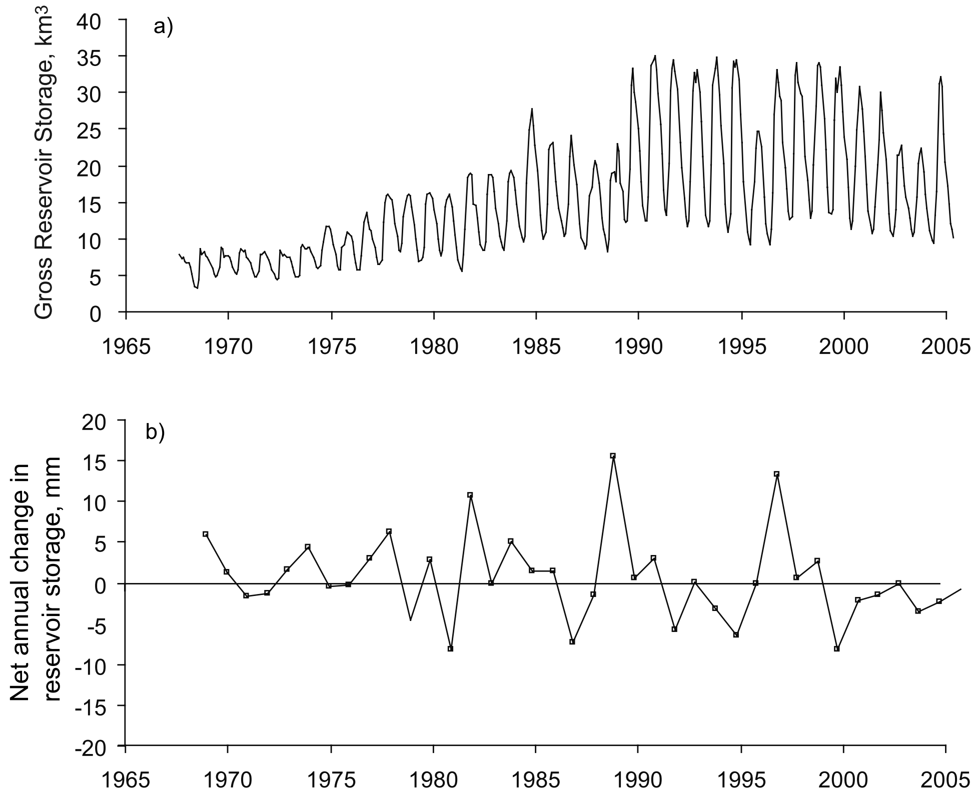

Figure 6. (a) Gross reservoir water storage and (b) net change in gross reservoir storage in the Krishna Basin from May to April, 1967–2005.

(E_{irr}) increased from zero in 1901–1959 to 163 ± 85 mm during 1990–2005 (Table 2, Figure 7). E_{irr} was within the range of the net irrigation requirement (I_{net}, Figure 7), suggesting that irrigation alone was sufficient to cause the observed reduction in runoff.

[30] The increase in evaporation due to irrigation (E_{irr}, +163 mm y^{-1}) was more than an order of magnitude larger than the largest change in storage (Table 3). The error term in the estimation of naturalized runoff (ε) had a 95% confidence interval of ± 52 mm. This 95% confidence interval was 32% of E_{irr} during 1990–2005 and was the largest source of uncertainty in the estimation of E_{irr}. The net change in reservoir storage from May to April (ΔV) ranged from a minimum of −8 mm in 2000–01 to a maximum of +14 mm in 1997–1998 (Figure 6b), suggesting that nearly all live storage was used each year. The changes in reservoir storage were measured and did not contribute to the uncertainty in E_{irr}. The maximum total change in dry season soil moisture from pre-irrigation to steady-state irrigated area was 1.8–3.6 km^3 (7–14 mm) with a range of −2.1 to +2.8 mm y^{-1} for individual years. The net annual change in soil moisture was zero over 1990–2005 when irrigated area did not have a significant trend (Table 3). The net annual change in groundwater storage ranged from −5.3 mm y^{-1} to +0.6 mm y^{-1}, which was small compared to E_{irr}.

[31] The Parallel Climate Model estimates that the ABC and GHGs combined decreased the latent heat flux from unirrigated areas by 2.4 W m^{-2} [*Ramanathan et al.*, 2005]. This is equivalent to a decrease in evaporation (E_{ATM}) of −31 mm y^{-1}. Runoff would increase by an equivalent amount assuming no net change in soil or groundwater storage. The sum of the atmospheric and irrigation effects on evaporation and the latent heat flux is constrained by the observed water budget, so including E_{ATM} in equation (5) to account for the reduced evaporation from unirrigated areas increases the estimate of E_{irr} from 163 to 194 mm y^{-1}. In order to simplify the analysis and provide a conservative estimate of the effect of irrigation, the results presented for the water balance and latent heat flux neglect the combined

Table 2. Basin-Scale Water and Energy Balance of the Krishna Basin, in Pre-irrigation (1901–1959) and Steady-State (1990–2005) Time Periods[a]

	1901–1959	1990–2005	Change	% Change
	WATER BALANCE (*mm* y^{-1})			
P	822 ± 131	826 ± 108	+4	+0.5%
Q	226 ± 59	64 ± 56	−162	−72%
E	596 ± 87	762 ± 70	+166	+28%
E_{irr}	0 ± 31	163 ± 85	+163	–
	ENERGY BALANCE (*W* m^{-2})			
R_n	123.5 ± 9.0	113.3 ± 3	−10.2	−8.6%
R_{nABC}	−0.2 ± 0.6	−11.4 ± 2.7	−11.2	–
R_{nALB}	–	+1.0 ± 0.03	+1.0	–
λE	46.4 ± 6.7	59.3 ± 5.4	+12.9	+28%
λE_{irr}	0.0 ± 2.3	12.7 ± 2.4	+12.7	–
H	77.2 ± 6.8	53.8 ± 5	−23.4	−30%
H_{irr}	0.0 ± 2.0	−12.7 ± 2	−12.7	–
H_{ABC}				
γ = 0.8	−0.1 ± 0.5	−9.1 ± 1.5	−9.0	–
γ = 1.0	−0.2 ± 0.6	−11.4 ± 1.8	−11.2	–

[a]The values of net radiation and the sensible heat flux do not include changes in greenhouse gas forcing of longwave radiation.

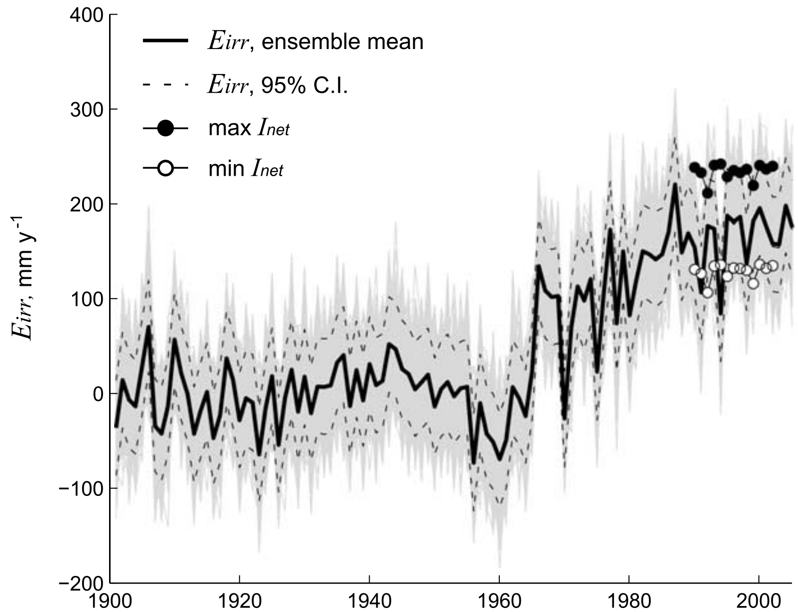

Figure 7. Time series of evaporation from irrigation as estimated from the basin water balance (E_{irr}) in the Krishna Basin over 1901–2005. The light grey lines are 1000 individual model simulations of equation (7), and the dashed lines indicate 95% confidence intervals of the 5000 model runs. The net irrigation requirement for two different sets of model parameters (I_{net1} and I_{net2}) is presented for 1990–2002 (equation (7)). E_{irr} does not include the effect of GHGs or the ABC on changes in runoff from unirrigated areas.

impact of GHGs and the ABC on runoff from unirrigated areas.

4.2. Basin-Scale Energy Balance and Heat Fluxes

[32] The mean monthly change in shortwave radiation at the surface due to the ABC (F_{SWABC}) over the South Asian region (0° to 30°N and 60° to 100°E) during 1995–1999 ranged from a minimum of -3 W m^{-2} during the monsoon to -28 W m^{-2} at the end of the dry season (Figure 2e) [*Ramanathan et al.*, 2005]. The regional mean matched measurements made over Pune in the north-western corner of the Krishna Basin (Figure 2e), so the regional mean aerosol effect was taken as the best available estimate of F_{SWABCj} over the Krishna Basin. Annual R_{nABC} averaged 11.4 W m^{-2} over 1990–2005 (Table 2).

[33] Albedo was lowest over forest and continuously irrigated areas and highest over rangelands and rainfed agriculture (Figure 8). The basin average albedo prior to irrigation (α_n) was 0.170, compared with 0.164 in 2002 (-3.5%). The difference between α_n and the basin-average in 2002 (α_{2002}) was largest in the late monsoon and post-monsoon season (September–December, Figure 9). The change in net radiation due to albedo (R_{nALB}) was +1.0 W m^{-2} (+0.8%). Over 1985–1994, the mean R_n from the SRB was 117.1 ± 8.9 W m^{-2}, R_{nABC} was -7.3 ± 1.3 W m^{-2}, and R_{nALB} was +0.6, giving R_{no} of 123.7 ± 9.0 W m^{-2}.

[34] The latent heat flux (λE) of the Krishna Basin increased from 46.4 ± 7 W m^{-2} in the pre-irrigation period to 59.3 ± 5 W m^{-2} during 1990–2005 (+12.9 W m^{-2}, Table 2, Figure 10). The sensible heat flux ($H = R_n - \lambda E$) decreased by a total of -23.4 W m^{-2}. Assuming that the ABC changed only H and had minimal impact on the latent heat flux ($\gamma = 1, H_{ABC} = R_{nABC}$), the ABC reduced H by 11.4 ± 1.8 W m^{-2} and irrigation reduced H by 12.7 ± 2.0 W m^{-2} (Table 2, Figure 11). The PCM output suggests that a reduction in incoming solar radiation of 11.4 W m^{-2} decreased the latent heat flux over the Krishna Basin by approximately 2.4 W m^{-2}, giving a value of γ of ~0.8. Assuming γ of 0.8, the ABC reduced H by 9.0 ± 1.5 W m^{-2} in 1990–2005 compared to 1901–1959. The trend in H due to irrigation during the period of irrigation expansion was larger than the trend in H caused by the ABC (Table 4). Over the steady-state period (1990–2005), there was no statistically significant trend in H due to irrigation, while the trend in H_{ABC} was between -2.7 ± 0.3 and -5.5 ± 0.4 W m^{-2} da^{-1}.

4.3. Temperature Change and Irrigation

[35] The seasonal mean of the maximum daily air temperature (Tmax) increased over 1952–1997 at all but one meteorological station located in unirrigated areas but decreased or had no trend in irrigated areas during the post-monsoon season (Table 5). The trends differed most

Table 3. Sources of Uncertainty in the Estimation of E_{irr}, 1990–2005, in mm y^{-1}[a]

				Percent of E_{irr}	
	Mean	Q5	Q95	Q5	Q95
ΔS	0.0	−1.0	+2.1	−0.6%	+1.3%
ΔGW	−1.1	−2.3	−0.4	−1.4%	+0.2%
ε	0	−52	+52	−32%	+32%

[a]Q5 and Q95 indicate the 5th and 95th percentiles of each variable from the 5000 simulations. ε is the error term in the rainfall–runoff relationship used to predict naturalized flow (equations (4) and (5)).

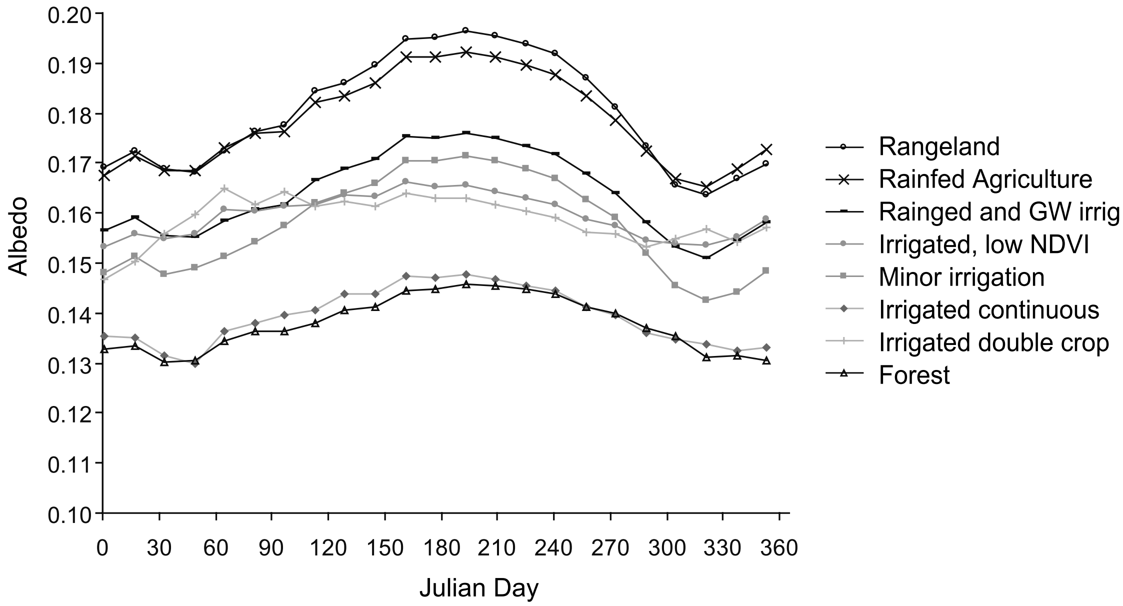

Figure 8. Albedo by land cover type, as measured by the MODIS albedo product, 2002.

among land cover types in MAM, when most (5 of 6) stations in unirrigated areas showed a positive trend ($p < 0.05$), while 2 of 3 stations in irrigated areas had a negative trend. *T*max increased or did not change during the monsoon (JJA and SON) for all stations in all land cover types.

[36] The mean *T*max anomaly at stations located in unirrigated areas increased by 0.26°C per decade in MAM ($p < 0.01$), compared with no change in the mean anomaly at stations located in irrigated areas (Figure 12, Table 6). The trend in the mean anomaly at stations in irrigated areas (Figure 12) was not statistically significant in MAM because of the large interannual variability at one station that did not have a trend. *T*max decreased in irrigated areas in DJF by 0.19°C da^{-1} and increased slightly (0.07°C da^{-1}) in unirrigated areas. *T*max showed a large decrease at one station in an irrigated area in DJF (−1.4°C), which resulted in a statistically significant trend in the mean anomaly of the three stations in irrigated areas. During 1990–1997, the mean *T*max anomaly was 1.5°C and 1.0°C higher in unirrigated areas compared to irrigated areas in MAM and DJF, respectively.

5. Discussion

[37] The budgets of water, radiation and heat of the Krishna Basin (258,948 km^2) provide evidence that irrigation had a large effect on the sensible heat flux (H) over a region that accounts for 10% of the total land surface of India. The changes in H caused by irrigation expansion were similar in magnitude to the changes caused by the ABC (Figure 11, Table 2). A downward approach [*Sivapalan et al.*, 2003; *Schulz and Beven*, 2003] was used to identify the dominant processes changing the annual water and energy balance. A linear relationship between precipitation and pre-irrigation runoff allowed the use of a simple regression model to quantify the effect of irrigation on evaporation and heat fluxes, which circumvented the need to parameterize a complex model of land–atmosphere interactions.

5.1. Water Balance and Heat Fluxes in India

[38] The change in evaporation and latent heat flux in the Krishna Basin during 1901–2005 was determined directly from the observed water balance, and the estimates of those changes did not depend on a model of land–atmosphere interactions. Attributing the change in evaporation to irrigation alone assumed that the rainfall–runoff relationship for unirrigated areas remained the same throughout the study period. The PCM suggested that atmospheric phenomena (the ABC and GHG) decreased the latent heat flux, and therefore increased runoff, from unirrigated areas. The sum of the irrigation and atmospheric effects on evaporation and runoff must add to the change observed in the water balance. Including any increase in runoff from unirrigated areas in the water balance would increase the estimate of the effect of irrigation on the basin water balance. In this study, the assumptions were designed to give a conservative estimate of the impact of irrigation on evaporation and the basin heat fluxes, while maximizing the estimate of the effect

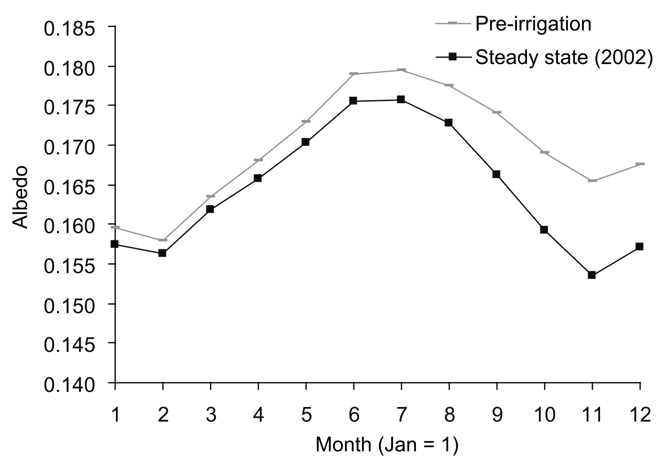

Figure 9. Albedo for pre-irrigation and irrigated conditions, 2002.

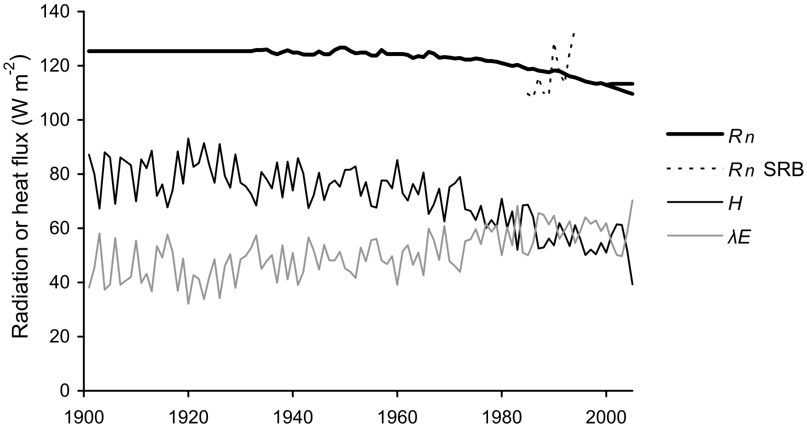

Figure 10. Time series of net radiation and heat fluxes in the Krishna Basin, 1901–2005, including the effects of the ABC and irrigation. The two different R_n lines indicate estimates for 1999–2005 based on the average of the late 1990s and extrapolation of the linear trend over 1990–1998. R_n *SRB* is radiation from NASA's Surface Radiation Budget. GHG forcing and interannual variability in R_n due to sources other than aerosols are not included in the calculation of R_n or *H*.

of the ABC. Future modeling studies may narrow the range of estimates; the simple, data-driven approach taken here identified the large role of irrigation in the basin water balance and heat fluxes, and suggested that the irrigation effect is comparable to or larger than the atmospheric effect on the sensible heat flux.

[39] The changes in evaporation (+28%) and the sensible heat flux due to irrigation (-12.7 W m^{-2}) observed in the Krishna Basin were larger than changes estimated using a land surface model over all of India [*Douglas et al.*, 2006], where irrigation increased annual evaporation by 17% and reduced *H* by 9 W m^{-2}. The larger irrigation effect in the Krishna Basin was due to a combination of the irrigated fraction, which is 0.13–0.21 in the Krishna Basin compared to 0.14 in India, and to the drier climate in the Krishna Basin. The Krishna Basin has lower average rainfall (826 mm) compared with the average over India (1090 mm) [*Parthasarathy et al.*, 1994], which increases the irrigation requirement. The water balance method used here could be extended to other basins of India, though the method depends on the availability of long time-series of rainfall and runoff to establish the pre-irrigation evaporation and latent heat flux.

[40] The effect of irrigation on the latent heat flux in the Krishna Basin (+12.7 W m^{-2}) was larger than estimates in other basins such as the Colorado and the Mekong, where irrigation increased the latent heat flux by 1.2 and 1.3 W m^{-2} respectively [*Haddeland et al.*, 2006]. The smaller irrigation effect in these two basins was because of the low total irrigation requirement (15 and 17 mm) compared with the Krishna Basin (163 mm). In the Colorado River Basin, irrigation was limited by low pre-irrigation runoff (40 mm y^{-1}) compared with the Krishna Basin (226 mm y^{-1}), while high precipitation in the Mekong (>1500 mm y^{-1})

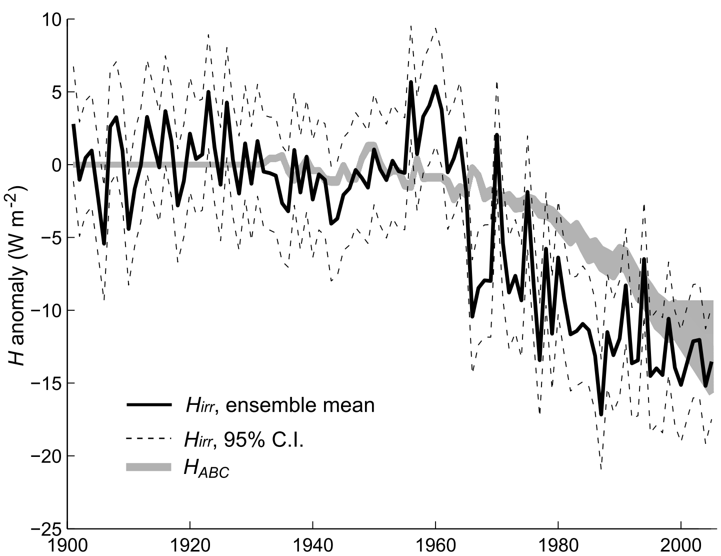

Figure 11. Time series of changes in the sensible heat flux of the Krishna Basin due to irrigation (H_{irr}) and anthropogenic aerosols (H_{ABC}). The range of H_{ABC} includes maximum (γ = 1) and minimum (γ = 0.8) values for the fraction of the reduction in net radiation (R_{nABC}) that is partitioned into sensible heat.

Table 4. Rate of Change in the Sensible Heat Flux due to Irrigation Development (H_{irr}) and Anthropogenic Aerosols (H_{ABC}) Over 1960–1990, 1965–1990 and 1990–2005, in W m^{-2} da^{-1}[a]

		Anthropogenic Aerosols (H_{ABC})	
	Irrigation (H_{irr})	min (γ = 0.8)	max (γ = 1.0)
1960–1990	−5.0 ± 0.5	−1.8 ± 0.2	−2.3 ± 0.3
1965–1990	−3.4 ± 0.6	−2.1 ± 0.2	−2.7 ± 0.3
1990–2005	n.s.	−2.7 ± 0.3	−5.5 ± 0.4

[a]The mean and standard deviation of the slopes for H_{irr} were calculated from the 5000 Monte Carlo simulations. n.s. indicates not significant (p > 0.05).

resulted in a low irrigation requirement. The large pre-irrigation runoff in the Krishna Basin was due to high rainfall rates and large runoff coefficients in the Western Ghats, which cover 9% of the basin area but produce more than 50% of the runoff [*Biggs et al.*, 2007a]. Irrigated area expanded most on the semi-arid plateau of the basin, which has a high irrigation requirement. The net impact of irrigation on heat fluxes was particularly large in the Krishna Basin because of this spatial combination of a mountain range with high pre-irrigation runoff adjacent to an agricultural plateau that has a sub-humid to semi-arid climate and large irrigation requirements.

[41] The albedo of cropland in the Krishna Basin (0.13–0.17) was similar to values measured for global cropland using MODIS [*Myhre et al.*, 2005]. Irrigation decreased albedo and increased net radiation in the Krishna Basin (+1.0 W m^{-2}), though albedo was quantified for only one year (2002), did not include changes in unirrigated areas. Inclusion of additional years of satellite data may revise this estimate of albedo change throughout the basin. The increase in net radiation due to decreased albedo was small compared a potential increase in albedo and decrease in net radiation of −2 to −6 W m^{-2} due to conversion of potential vegetation (forest, shrubs, grassland) to croplands over southern India [*Myhre et al.*, 2005]. Total cropped area was stable in the Krishna Basin from 1950–2005 (Figure 3), so most of the increase in albedo from conversion of potential vegetation to crops likely happened prior to 1900, though continued degradation may have further increased albedo [*Tripathy et al.*, 1996]. The change in net radiation due to the lower albedo of irrigated areas accounted for a relatively small portion (6%) of the total increase in the latent heat flux observed in the water balance. This suggests that much of the change in evaporation was caused by the differences in the physiology of irrigated versus unirrigated crops, evaporation from open water bodies, and, most importantly, changes in soil moisture. Evaporation from rainfed crops in the Krishna Basin is strongly limited by soil moisture availability, particularly during the post-monsoon season [*Biggs et al.*, 2008]. Alleviation of this soil moisture stress can increase evapotranspiration from crops several fold.

5.2. Heat Fluxes and Surface Temperature

[42] Trends in the mean maximum daily air temperature (*T*max) differed between irrigated and unirrigated areas, but only in the post-monsoon season. During the monsoon (JJA and SON), anomalies in *T*max were presumably dominated by interannual variability in precipitation and evaporation. Evaporation measured using thermal satellite imagery in the eastern Krishna Basin was similar in unirrigated and irrigated areas during the monsoon but was lower in unirrigated areas in the post-monsoon because of soil moisture limitation [*Bouwer et al.*, 2007]. Similar results were found by a modeling study of irrigated areas in California [*Kueppers et al.*, 2007], and in observed air temperatures in northern India [*Roy et al.*, 2007], where irrigation had the clearest effect on temperature in drier seasons.

[43] The trends in *T*max observed at the meteorological stations must be interpreted with caution and may not be due only to a change in the sensible heat flux. Changes in specific humidity and other land use changes around the stations, including urbanization, could also affect temperature [*Pielke et al.*, 2007]. The Krishna Basin results suggest that land surface properties such as irrigation need to be accounted for in interpreting temperature trends in India [*Roy et al.*, 2007], regardless of whether the changes were caused by a reduced sensible heat flux or increased humidity. There were also relatively few stations in irrigated areas, and these stations were typically located on compounds surrounded by a heterogeneous mix of irrigated and unirrigated areas (personal observation). Stations located in "pure" irrigated or unirrigated areas might be expected to show a larger temperature signal [*Ozdogan and Salvucci*, 2004], but such observations were not available in the Krishna Basin. The timing and spatial distribution of irrigation around the stations is also not known, complicating the interpretation of the temperature trends in the context of the basin-scale sensible heat flux.

[44] Several studies have documented decreases in air temperature due to irrigation development, though most have used regional averages instead of individual station measurements. Average air temperatures in the Indo-Gangetic plain of northern India decreased by 0.37°C over 1958–1997, which *Singh and Sontakke* [2002] attributed to irrigation. A climate model suggested that local daytime

Table 5. Number of Stations With Statistically Significant (p < 0.05) Negative (−), Significant Positive (+) or Non-significant (ns) Trends in Maximum air Temperature Over 1952–1997 for Stations Located in Unirrigated (N = 6), Mixed, (N = 11) or Irrigated Areas (N = 3)

	Unirr	Mix	Irr
		Post-monsoon	
DJF			
−	1	1	1
ns	2	3	2
+	3	7	0
		MAM	
−	0	1	2
ns	1	4	1
+	5	6	0
		Monsoon	
JJA			
−	0	0	0
ns	3	8	3
+	3	3	0
SON			
−	0	0	0
ns	2	2	3
+	4	9	0

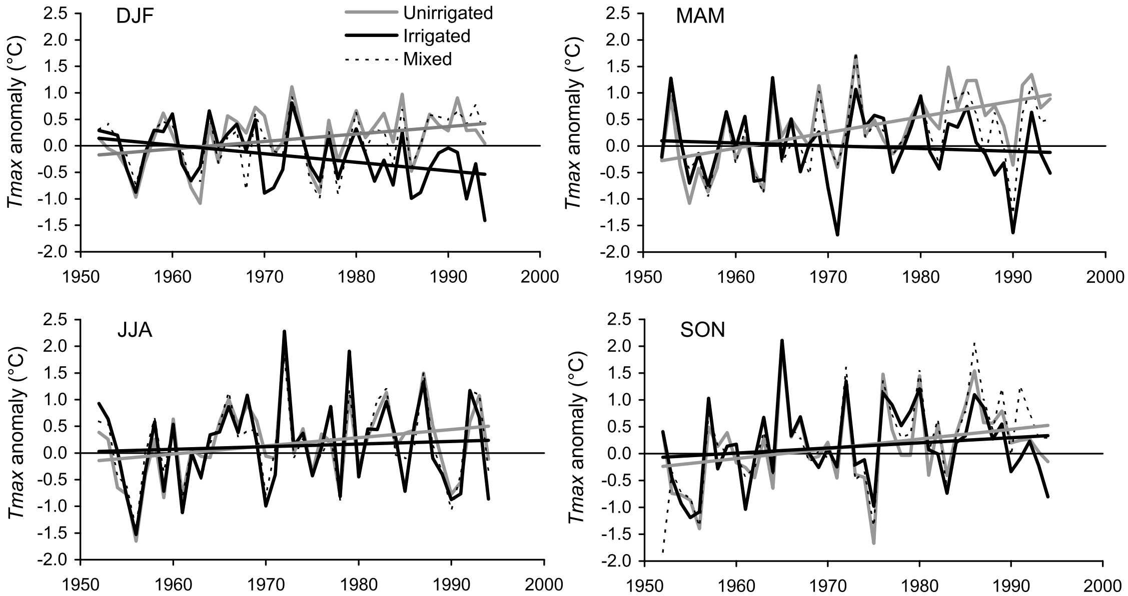

Figure 12. Time series of the mean anomaly in maximum air temperature (*T*max) at stations located in irrigated, unirrigated, and mixed areas of the Krishna Basin by season, 1952–1997.

temperatures decreased by 3–4°C in irrigated areas in northern India, though regionally averaged meteorological records showed negative but not statistically significant trends in temperature [*Roy et al.*, 2007]. The coupled model suggested that irrigation had roughly twice the cooling effect of aerosols, though temporal fluctuations in aerosols complicated quantitative comparison. Gridded climate data show decreased maximum air temperature in the Indo-Gangetic plain of 0.2°C over 1950–2000 [*Bonfils and Lobell*, 2007], though the relative effects of aerosols and irrigation were not explicitly separated.

[45] Both irrigation and the ABC reduced the sensible heat flux (total change −23.4 W m^{-2}). This might be expected to reduce surface air temperatures [*Haddeland et al.*, 2006], but maximum mean temperatures increased in at least one season in both irrigated and unirrigated areas (Table 5). Decreasing incoming shortwave radiation with simultaneous increases in temperature have also been observed for all of India [*Padma Kumari et al.*, 2007] and globally [*Romanou et al.*, 2007; *Liepert et al.*, 2004], which is attributable to greenhouse gas (GHG) forcing of long-wave radiation but may be partly due to changes in specific humidity [*Pielke et al.*, 2007]. GHG forcing of longwave radiation measured from either the top of the tropopause (+2.6 W m^{-2}) or at the land surface (∼+0.4 W m^{-2}) is smaller than both the aerosol effect and irrigation-related changes in H, though surface forcing "should not be used to compare forcing agents" [*Forster et al.*, 2007]. Results from the PCM suggest that the ABC has masked as much as half of the increase in temperature because of GHGs [*Ramanathan et al.*, 2005], though the net trend in temperature over India was still positive. GHGs increase longwave radiation throughout the year, while the effects of aerosols and irrigation fluctuate with atmospheric conditions, soil moisture, and irrigation scheduling. This was reflected in the seasonal trends: maximum temperature increased in both irrigated and unirrigated areas during the monsoon, when evaporation from both land cover types was similar and ABC effects were smallest (Figure 2e). In the post-monsoon season, the temperature increase in unirrigated areas and decrease in irrigated areas suggests that land cover change masked the effect of GHGs on maximum surface temperature. Changes in water vapor and GHG forcing may also have been caused by irrigation development, which could be important for basin-scale heat fluxes and surface temperature.

5.3. Irrigation Expansion and Trends in Heat Fluxes

[46] Irrigation expansion resulted in a temporary trend in H over 1960–1990 that masked the warming experienced in unirrigated areas. This masking was likely temporary because the trend in H depended on rapid expansion of irrigated area and increasing diversion of surface water. By 1990–2005, nearly all surface flow had been appropriated and 78% of runoff was being evaporated from irrigated areas. The increase in groundwater irrigation in the 1990s was accompanied by a decrease in surface irrigated area, suggesting that much of the water pumped from aquifers for irrigation resulted in streamflow depletion. Many ground-

Table 6. Trends in the Mean Anomaly of Maximum Temperature and Precipitation by Season for Meteorological Stations in Unirrigated (N = 6) or Irrigated Areas (N = 3) Over 1952–1997 (°C da^{-1})[a]

	Unirr	Irr
	Post-monsoon	
DJF	+0.07**	−0.19**
MAM	+0.26**	−0.03 (ns)
	Monsoon	
JJA	+0.17 **	+0.06 (ns)
SON	+0.14**	+0.05 (ns)

**$p < 0.01$.

[a]The trend values are the Sen's slope, and the statistical significance is from the Mann–Kendall test.

Table A1. Variables Used to Calculate the Water and Energy Balance With Descriptions and Data Sources[a]

Variable	Description	Units	Source
P	Precipitation	mm y^{-1}	Indian Institute of Tropical Meteorology
Q	Runoff at Vijayawada	mm y^{-1}	RivDis Database (1901–1960, 1965–1979) and Central Water Commission (1961–1964 and 1980–2005).
V	Reservoir storage	mm	State Irrigation Departments
E	Evaporation	mm y^{-1}	Equation (1)
Q_n	Naturalized runoff prior to irrigation	mm y^{-1}	Equation (4)
E_{irr}	Evaporation from irrigated areas	mm y^{-1}	Equation (5)
E_{ATM}	Change in evaporation from unirrigated areas due to the ABC and GHGs	mm y^{-1}	*Ramanathan et al.* [2005]
ΔGW	Net change in groundwater storage due to irrigation	mm y^{-1}	Equation (3)
n	Aquifer porosity	unitless	*Marechal et al.* [2006]
Δh_{gw}	Change in groundwater level, groundwater irrigated areas	m y^{-1}	*Singh and Singh* [2002], *Marechal et al.* [2006], *Massuel et al.* [2007]
Δh_{sw}	Change in groundwater level, surface water irrigated areas	m y^{-1}	*Singh and Singh* [2002]
A_{gw}	Basin-wide area irrigated by groundwater	km^2	*Various*[b]
A_{sw}	Basin-wide area irrigated by surface water	km^2	*Various*[b]
ΔS	Net change in soil moisture storage from changes in irrigated area	mm y^{-1}	Equation (2)
A_{irr}	Total irrigated area in a given year	km^2 y^{-1}	$A_{gw} + A_{sw}$
W	Available water holding capacity	mm m^{-1}	*Food and Agriculture Organization* [1995]
z	Soil depth	m	*Challa et al.* [1996]; *Government of India* [1999]; *Sehgal et al.* [1996].
I_{net}	Net irrigation requirement	mm y^{-1}	Equation (6)
A_i	Area of MODIS class i	km^2	*Biggs et al.* [2006]
f_i	Irrigated fraction for MODIS class i	unitless	*Biggs et al.* [2006]
c	Runoff coefficient in irrigated plots	unitless	*Kang et al.* [2006]
E_{pj}	Potential evapotranspiration of reference crop in month j	mm	Penman–Monteith equation
P_j	Gridded precipitation in month j	mm	*Mitchell and Jones* [2005]
K_j	Crop coefficient in month j	unitless	
	Rice		*Mohan and Arumugam* [1994] *Tyagi et al.* [2000];
	Sugarcane		*Inman-Barber and McGlinchey* [2003]
	Other crops (cotton, chili, oilseeds, pulses)		*Biggs et al.* [2008]
R_n	Net radiation	W m^{-2}	Equation (8) (1901–2005) and Surface Radiation Budget v2 (1985–1994)
R_{no}	Net radiation with no ABC or irrigation	W m^{-2}	Equation (8)
R_{nABC}	Change in R_n due to the ABC, 1930–1999	W m^{-2}	Equation (9)
R_{nALB}	Change in R_n due to albedo of irrigated areas	W m^{-2}	Equation (10)
F_{SW}	Incoming shortwave radiation at the surface	W m^{-2}	Surface Radiation Budget v2
F_{SWABC}	Change in F_{SW} due to the ABC, 1930–1999	W m^{-2}	*Ramanathan et al.* [2005]
H	Sensible heat flux	W m^{-2}	R_n-λE
H_{irr}	Change in H due to irrigation	W m^{-2}	$-\lambda E_{irr}$
H_{ABC}	Change in H due to the ABC	W m^{-2}	γR_{nABC}
γ	Fraction of R_{nABC} partitioned into H		min = $1-\lambda E_{ATM}/R_{nABC}$, max = 1
α_{2002}	Albedo in the year 2002	unitless	MODIS Albedo Product
α_n	Albedo of the land surface prior to irrigation	unitless	MODIS Albedo Product

[a]ABC is the abbreviation for the Atmospheric Brown Cloud, and SRB is for the Surface Radiation Budget, version 2 [*Gupta et al.*, 1999].
[b]*Government of Andhra Pradesh* [2006], *Government of Maharashtra* [2004] and *Government of Karnataka* [2001].

water irrigated areas are located directly downstream from small reservoirs, which are used to capture surface runoff and enhance aquifer recharge. The stabilization of irrigated area and evaporation over 1990–2005 suggest that further expansion of irrigated area and continued increases in evaporation are unlikely without large inter-basin transfers of water. Inter-basin transfers have been proposed at the national scale in a massive Interlinking of Rivers project [*Gupta and Deshpande*, 2004]. If implemented, the project could allow continued expansion of irrigation in India, which would generate continued impacts on H and surface temperatures.

[47] The stabilization of irrigated area in the basin may result in increased sensitivity of surface temperatures to the ABC and GHGs in the coming decades. Some evidence for this is found in the Krishna Delta, where irrigation was established in the 1850s. Unlike stations in other irrigated areas, maximum temperatures increased at one of two stations during the post-monsoon in the Delta over 1952–1997 ($p < 0.05$), suggesting that active expansion of irrigation is necessary to change the surface heat flux in ways that counteract the effect of greenhouse gases. A similar conclusion was reached for irrigation in California, where stabilization or reduction of irrigated area is expected to result in increased temperatures because of GHGs [*Bonfils and Lobell*, 2007].

5.4. Heat Fluxes and Regional Circulation

[48] One motivation for studying the heat flux and surface temperature of India is the important role that land–ocean temperature gradients have on regional circulation and the monsoon. Several studies have pointed to the potential effects of anthropogenic aerosols on convection and thermal gradients [*Menon et al.*, 2002; *Meehl and Arblaster*, 2003; *Ramanathan et al.*, 2005]. While aerosols are important in driving regional energy fluxes and changing monsoon circulation patterns, the Krishna Basin water and energy balance suggests that irrigation had a similar or

larger impact on the sensible heat flux at the land surface over the late 20th century, and may have contributed to the observed changes in timing and magnitude of the monsoon. Statistical analyses suggest that early monsoon precipitation (July) is lower when vegetation growth is strong in the preceding March–April–May (MAM), as measured by the normalized difference vegetation index (NDVI) [*Lee et al.*, 2008]. NDVI in MAM correlates with irrigated area, suggesting that irrigation expansion had a role in changing the temporal and spatial distribution of rainfall over India. The effect of aerosols on atmospheric circulation differs from the effect of irrigation in that aerosols also heat the upper troposphere, which increases atmospheric stability [*Menon et al.*, 2002]. Aerosols also reduce evaporation over the ocean and change the spatial distribution of sea surface temperatures, which also affect monsoon circulation [*Ramanathan et al.*, 2005]. The propagation of the change in the water and energy budget at the surface through the troposphere, the impact of irrigation on greenhouse gas forcing due to enhanced atmospheric water vapor, and the net effect on atmospheric circulation remain unknown.

6. Conclusion

[49] Basin-scale hydrology, radiation, heat fluxes, and surface temperature interact with land cover change in complex ways. This study used observations of the annual water balance and surface temperature to document the impact of irrigation on the heat fluxes and surface temperature of a large region that has experienced rapid irrigation development. The downward, data-driven approach gave results that are comparable with modeling studies, which also find that irrigation has decreased the sensible heat flux and surface air temperatures as much as, or more than, the atmospheric brown cloud over India. The decrease in the latent heat flux of the land surface predicted for unirrigated land cover by the Parallel Climate Model ($\sim$2.4 W m^{-2}) [*Ramanathan et al.*, 2005] was more than compensated for by increased evaporation from irrigated areas, resulting in a net increase in the latent heat flux of +12.9 W m^{-2}. More detailed modeling of the water and energy balance [*Liang et al.*, 1994; *Haddeland et al.*, 2006] utilizing maps of the aerosol effect on shortwave radiation [*Sarkar et al.*, 2006] would help further refine estimates of the timing, magnitude, and spatial distribution of the impacts of aerosols and irrigation on surface heat fluxes. Models of the heat flux and regional circulation of India and other areas with extensive irrigation development should include the effects of irrigation, and could usefully incorporate observations of river flow to constrain model estimates.

Appendix A

[50] Table A1.

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