CHANGES IN CLIMATE, ATMOSPHERIC COMPOSITION AND LAND-ATMOSPHERE INTERACTIONS ACROSS THE SOUTH ASIAN REGION

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ABSTRACT

The aim of this paper is to review recent advances in our ability to project changes in climate, atmospheric composition and land-atmosphere interactions across the South Asian Region. Firstly we review methodological advances in our ability to project future climate change and its impacts. We review the evolution of climate models towards the new generation of Earth System Models (ESMs), and improvements in process representations in their land components. Here we focus on the Joint UK Land Environment Simulator (JULES), the land surface component of the flagship HadGEM2-ES ESM of the Met Office Hadley Centre, UK. These include advances to account for the effects of atmospheric aerosol-driven changes in the quantity and quality of incoming solar radiation at the surface, and near-surface ozone on terrestrial plant productivity and the land carbon cycle. We then present a brief overview of the Representative Concentration Pathways (RCPs) of climate forcing agents and associated land use and land cover changes from the Intergovernmental Panel on Climate Change fifth assessment report (IPCC AR5). These scenarios are based on future socio-economic storylines, e.g. level of energy intensity, population growth, rate of technological development etc. We present results for the South Asia region from an ensemble of different Earth System Models driven with the RCP2.6, RCP4.5, RCP6.0 and RCP8.5 scenarios, from the Coupled Model Intercomparison Project Phase 5 (CMIP5) activity. These RCPs represent scenarios of increasing global greenhouse gas emissions, and thus global climate change. Spatio – temporal variations in temperature and precipitation across the region from pre-industrial (PI) to 2100 are analysed. We focus on Sri Lanka to explore results in the context of seasonal variations in temperature and precipitation, i.e. the monsoon and inter-monsoon seasons; the ability of climate models to project current seasonal variations in climate, and to quantify future projections in seasonal climate and its uncertainty. Finally we report on the implications of changes in climate and atmospheric composition on ecosystem services: changes in aerosol loading and near-surface ozone, respectively, and future climate change on terrestrial primary productivity over South Asia.

The ensemble of climate models project increases in annual temperature and precipitation across South Asia of 2-6°C and 50-175 mm/yr, respectively, by 2100. The greatest warming is linked to the snow-albedo feedback in snow-dominated regions. Projected increases in annual temperature and precipitation across Sri Lanka are between 0.8 and 2.9°C and 150 and 274 mm/yr, respectively, by the end of the century, the latter mainly between August and November. Increasing atmospheric CO_2 and climate leads to projected increases of between 30 and 70% in Net Primary Production (NPP). However, it is unclear whether this can be translated directly into similar increases in crop yields, due to heat stress and possibly lower CO_2 enhancements in crop yields compared with productivity changes in natural vegetation, and the effect of air pollution on productivity. There remains an urgent need for an integrated study on the impact of atmospheric composition and climate on crops and natural ecosystems over South Asia, including related uncertainties and associated climate-vegetation feedbacks.

INTRODUCTION

Land ecosystems currently moderate global climate change by absorbing over one quarter of the anthropogenic emissions of carbon dioxide (CO_2) on average every year (Le Quéré *et al.*, 2013). This CO_2 'sink' is modulated by climate change and variability (Zeng *et al.*, 2005). Anthropogenic aerosols and tropospheric O_3 are short-lived and also affect atmospheric composition and climate regionally rather than globally, and are particularly relevant for South Asia. For example, a layer of air pollution that covers South Asia during the dry season ("Asian Brown Cloud"), is associated with anthropogenic aerosols from burning of fossil fuels and biomass (Ramanathan *et al.*, 2007). These results in a warmer atmosphere, surface cooling, leading in turn to increased atmospheric stability, decreased surface evaporation and reduced monsoonal strength and rainfall (Ramanathan and Feng, 2009). Although the climate effects have been extensively studied including those on the hydrological cycle (Ramanathan *et al.*, 2005), the net effects of "Asian Brown Cloud" on plant productivity and crop yields have yet to be evaluated.

Mercado *et al.*, (2009) showed how changes in surface irradiance over the global dimming and subsequent brightening period, 1960-2000, associated with changes in anthropogenic scattering aerosols and cloud cover, led to enhanced global plant productivity and carbon storage. Scattering aerosols change both the quantity and quality (diffuse component) of surface irradiance. Diffuse light is able to penetrate further into the canopy than direct light, stimulating production in light-limited understory leaves. Mercado *et al.*, (2009) found this "diffuse radiation fertilization" effect was larger than the negative effect of reduced irradiance on plant productivity globally. However Mercado *et al.*, (2009) also showed local site optima in the relationship between photosynthesis and diffuse light conditions; under heavily polluted or dark cloudy skies, plant productivity will decline as the diffuse effect is insufficient to offset decreased surface irradiance.

Tropospheric O_3 is a global secondary air pollutant, formed as a product of photochemical reactions with precursors: CO, CH_4, Biogenic Volatile Organic Compounds (BVOCs), and NO_x. Over the industrial period anthropogenic emissions of NO_x from fossil fuel burning (e.g. transport and industry) and biomass burning, have led to elevated ambient [O_3] over many regions (Prather *et al.*, 2001), although in some regions, where strong precursor emission controls are put into place, the ozone concentration declines. Ozone impacts plant productivity through effects on stomatal conductance and primary metabolism, causing billions of dollars in lost plant productivity annually (Ainsworth *et al.*, 2012). Present-day monthly O_3 levels exceed 40 ppb during the dry season at 2 monitoring stations in South India, with summer-time [O_3] up to 58 ppb in the Indo-Gangetic plain (Agrawal, 2003). These concentrations are considered damaging to sensitive plant species.

Changes in surface [O_3] affect plant productivity, the carbon cycle, and therefore feedback on climate change (Sitch *et al.*, 2007; Collins *et al.*, 2011; Anav *et al.*, 2012). Sitch *et al.*, (2007) showed how elevated future tropospheric ozone concentrations [O_3] would have detrimental effects on plant productivity, and reduce the efficiency of the terrestrial biosphere to sequester carbon, constituting a large indirect radiative forcing of tropospheric O_3 on climate. Models suggest that surface O_3 is increasing in Asia due to rapid urbanisation across the region (Dentener *et al.*, 2010). Ozone can have significant effects on agricultural regions eventhough they are far removed from industrial sources. Little is known about the interactions between O_3 damage to crops under future climate and atmospheric CO_2 concentrations. Some studies suggest that O_3 damage may counter the productivity increases caused by CO_2 fertilization (Feng and Kobayashi, 2009). However, others suggest that ozone damage is actually reduced under high atmospheric CO_2 as plants reduce stomatal conductance and thus O_3 uptake (Sitch *et al.*, 2007). Increased water stress due to climate change would also cause plants to reduce stomatal

conductance and thus O_3 uptake. However, some studies suggest that under drought conditions, O_3 can act directly on the guard cells, interfering with plant hormonal signalling (ABA), reducing the plants ability to control conductance and thus regulate water losses. Hence O_3 may increase crop vulnerability in a drier climate.

Interactions between climate, chemistry, aerosols and ecosystems have recently been included in the latest generation of climate models, so-named 'Earth System Models' (ESMs) (Collins *et al.,* 2011). Given South Asia comprises 25% of the World's population (~ 1.6 billion people), 15% of global cropland, and agriculture represents 25% of GDP (The Royal Society 2008), this region is therefore highly vulnerable to changes in climate and atmospheric composition and their impacts on ecosystem services.

In this paper we first give an overview of the evolution of ESMs. We then explore changes in climate and atmospheric composition over the South Asia region, and examine impacts on terrestrial primary productivity (Sitch *et al.,* 2007; Mercado *et al.,* 2009; Collins *et al.,* 2010, Anav *et al.,* 2013). This includes an assessment of 18 Earth System Models used for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), for climate projection and changes in terrestrial plant productivity (Anav *et al.,* 2013) over South Asia. Here we define the location of the South Asia as 5°N – 40°N, 60°E – 100°E.

METHODOLOGY

Earth System Models

Over the last two decades models from major climate centres have developed to include process-based representations of the land and ocean carbon cycle. This has enabled fully interactive climate-carbon cycle simulations (e.g. Cox *et al.,* 2000; Friedlingstein *et al.,* 2006). Some climate models also include atmospheric chemistry and aerosols. One example is HadGEM2-ES from the Met Office Hadley Centre (Collins *et al.,* 2011).

HADGEM2-ES is the "Earth System" configuration of the latest Met Office Hadley Centre GCM. The HADGEM2-ES incorporates the HadGEM2-Atmosphere Ocean (AO) physical coupled AOGCM and various earth system components. The atmospheric model component of HadGEM2-AO runs at N96 horizontal resolution (about 1.875° longitude x 1.25° latitude) with 38 levels in the vertical in the standard configuration and an option for a "high-top" stratosphere resolving version with 60 levels. It also couples together the JULES land-surface model which simulates fluxes and stores of carbon and distribution of 5 plant functional types with the UKCA chemistry and aerosol model which simulates the atmospheric chemistry of reactive trace gases and natural and anthropogenic aerosol species. The land surface also simulates production of mineral dust from regions of bare soil which can deposit onto land and ocean surfaces and acts as a source of iron to marine ecosystems. The ocean component has a variable horizontal resolution from 1 degree at high latitudes to 0.33 degrees near the equator. It includes the diat-HadOCC representation of ocean biogeochemistry which simulates both diatom and non-diatom phytoplankton and zooplankton species. It accounts for carbon uptake by the ocean chemistry and biosphere and also represents emission of DMS to the atmosphere. HadGEM2-ES has been used to perform all of the AR5-CMIP5 centennial climate change experiments. Although this configuration includes a chemistry and aerosol model, this model version still does not consider the impact of ozone on vegetation and the consequent changes in the lower troposphere.

In addition to an increasing number and sophistication of processes explicitly represented in climate models, they are applied at ever finer spatial resolutions taking full advantage in the rapid improvements in computer power. For example, in the 1990s and early 2000s HadCM3 was typically run at a grid resolution of 3.75° longitude and 2.5° latitude (grid resolution ~270 km), whereas now HadGEM2-ES is run at a finer resolution of 1.875° longitude and 1.25° latitude (grid resolution ~ 135 km).

Joint UK Land Environment Simulator (JULES)

The JULES land surface model structure is designed to assess ecosystem response to surface climatology at the large scale (Best *et al.,* 2011, Clark *et al.,* 2011). The model has its origins in being the land surface description in the Hadley Centre family of climate models. JULES has two main components. The first derives land-atmosphere fluxes of water, energy and carbon dioxide, all as a function of surface "weather" and soil moisture status. This is predicted for natural vegetation, and for five potential vegetation types (Plant Functional Types, PFTs) of Broadleaf Trees, Needleleaf Trees, Shrubs and C_3 and C_4 grasses. The second component (called TRIFFID: Top-down Representation of Interactive Foliage and Flora Including Dynamics, Cox, 2001) predicts vegetation growth, both vertically and spatially. The five natural vegetation types compete for space based on the Lotka-Volterra competition equations and a hierarchy of PFT dominance. Additional crop functional types representing the major global crop types have been introduced, and allowed to grow in response to meteorological conditions, biogeochemical pollutants and nutrient constraints. However, in this case, the competition components are switched off and crop is assumed to cover a prescribed "disturbed" region.

To account for potential mitigation of O_3 damage by CO_2-induced stomatal closure a flux-gradient approach is used to modelling O_3 damage (Sitch *et al.,* 2007). Most studies have applied exposure-response functions to determine yield losses, whereas JULES employs a flux-gradient approach, and therefore can quantify the interactive effects of O_3, climate change and atmospheric CO_2 on yield. JULES assumes a suppression of net leaf photosynthesis by ozone that varies proportionally to the ozone flux through stomata above a specified critical ozone deposition flux. As this flux itself depends on the stomatal conductance, which in turn depends upon the net rate of photosynthesis, the model requires a consistent solution for the stomatal conductance, the net photosynthesis and the ozone deposition flux.

JULES accounts for the effects of clouds and aerosols on the land carbon sink through changes in total irradiance, surface temperature and through changes in the diffuse fraction of radiation (Mercado *et al.,* 2009). The model includes a multilayer approach to scale photosynthesis from the leaf to the canopy, and also separates each canopy layer into sunlit and shaded regions. JULES takes into account variations in direct and diffuse radiation on sunlit and shaded canopy photosynthesis. It includes a description of sunfleck penetration through the canopy which separates each layer of the canopy into sunlit and shaded regions. Photosynthesis of sunlit and shaded leaves is calculated separately under the assumption that shaded leaves receive only diffuse light and sunlit leaves receive both diffuse and direct radiation.

JULES diagnoses the hydrological state of the surface and soil given time-varying inputs of temperature, wind speed, humidity, short-wave and long-wave radiation, and precipitation. Within JULES there are four horizontal soil layers, each with an associated temperature and soil moisture content. Water and heat are assumed to move in the vertical direction only. Estimates of surface and subsurface runoff are calculated as the amount of liquid water leaving a grid square on the land and below ground, respectively. Two optional methods are included to represent the heterogeneity for soil moisture, one based upon the TOPMODEL approach (Beven and Kirkby, 1979), and the second on the Probability Distributed Model (PDM) for soil moisture within a catchment described by Moore (1985). When there is snow on the ground, the surface layer has the combined depth and thermal conductivity of the snow layer and the surface soil layer. The surface skin temperature is not allowed to exceed 0°C while snow remains on the ground, and the heat flux used to melt snow is diagnosed as a residual in the surface energy balance. Melt water drains immediately from the snow and is partitioned into soil infiltration and runoff (Essery, 2003). This formulation has been shown to produce estimates of snow cover and depth which are in good agreement with observed measurements.

Recent applications of JULES have demonstrated the highly contrasting effects of different climate forcing agents on ecosystem services (Huntingford *et al.,* 2011), and how vegetation impacts affect climate metrics for ozone precursors (Collins *et al.,* 2011). In addition, application of JULES within the coupled Earth system model has demonstrated that carbon cycle feedbacks are a first-order uncertainty in climate projections (Booth *et al.,* 2011).

IPCC Representative Concentration Pathways (RCPs) and CMIP5

CMIP5 experiments cover two main time periods: near-term (2005-2035) and long-term (2005-2100 and beyond). Long-term experiments are mostly driven by CO_2 concentration, allowing participation of both traditional global climate models and ESMs. There were also some specific ESM experiments targeting carbon cycle feedback quantification. Experiments were divided broadly into 3 categories: model evaluation, climate projections and understanding (Taylor *et al.,* 2011), and further divided into core, Tier 1 and Tier 2 experiments in order of priority. All climate centres conducted the core experiments, and further Tier 1 & 2 experiments based on interest and resource.

Representative Concentration Pathways were developed to provide the necessary and consistent driving variables for climate model application in CMIP5. They were designed to provide plausible scenarios of future socio-economic change, changes in technology, energy use, land use and land cover change, and emissions of climate forcing agents (greenhouse gases and air pollutants) (van Vuuren *et al.,* 2011). They go beyond the previous SRES scenarios as they include scenarios of climate policy, and four RCPs were chosen to span the range of future climate forcing in the literature (van Vuuren *et al.,* 2011). An overview of individual RCPs is given in van Vuuren *et al.,* (2011). RCP2.6, 4.5, 6, 8.5 assumes climate forcing of ~490, ~650, ~850 and ~1370 ppm CO_2 eq. by 2100. RCP8.5 is the most pessimistic scenario and assumes a pathway of rising CO_2 through this century, whereas the other three assume stabilization of climate forcing over the century.

RESULTS AND DISCUSSION

Climate models from IPCC AR4 project a future warming across South Asia (above global average over summer) and an increase in annual rainfall, although most IPCC AR4 models project a decrease in winter months, DJF (Cruz *et al.,* 2007). Results from the ensemble of climate models from CMIP5 used in the IPCC AR5 project increases in annual temperature across South Asia of 2-6°C by 2100 (Fig. 1). As expected the lowest and highest warming were simulated for RCP2.6 and RCP8.5, respectively, with RCP4.5 and RCP6.0 projecting intermediate warming of 3°C and 3.75°C, respectively. The greatest warming is simulated in snow-dominated regions in the northern areas of South Asia (Fig. 2). Enhanced warming is linked to the snow-albedo feedback in these regions; enhanced or earlier snow melt in response to the initial global warming leads to reduced snow extent, and therefore reduced surface albedo (the amount of incoming solar radiation reflected back into space), and thus further warming at the surface.

Climate Projections for South Asia

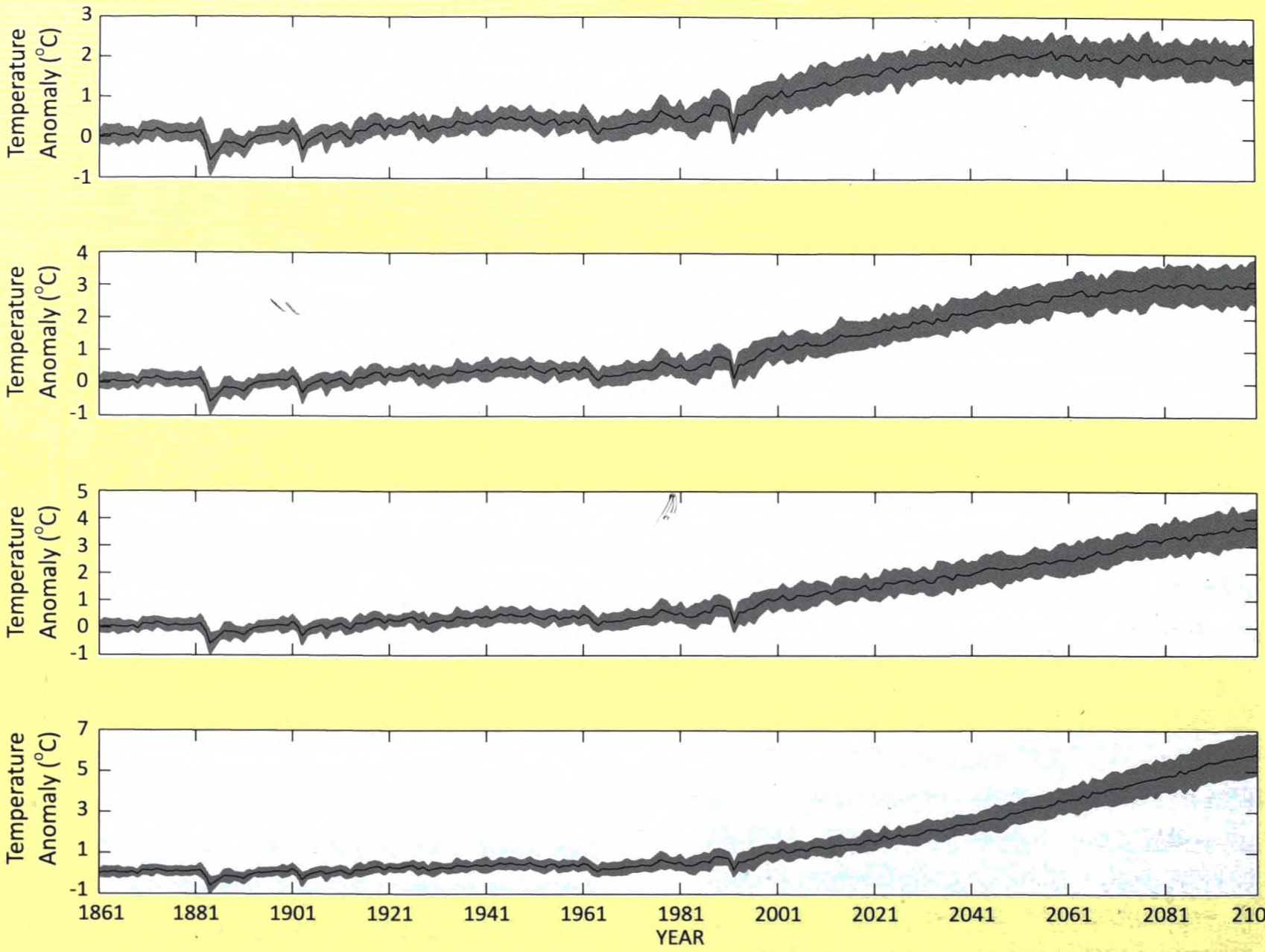


Fig. 1. Change in temperature (°C) over South Asia between 1861 and 2100 for 4 RCP scenarios. The solid line is the ensemble mean, and grey shading is the range of climate model projections.

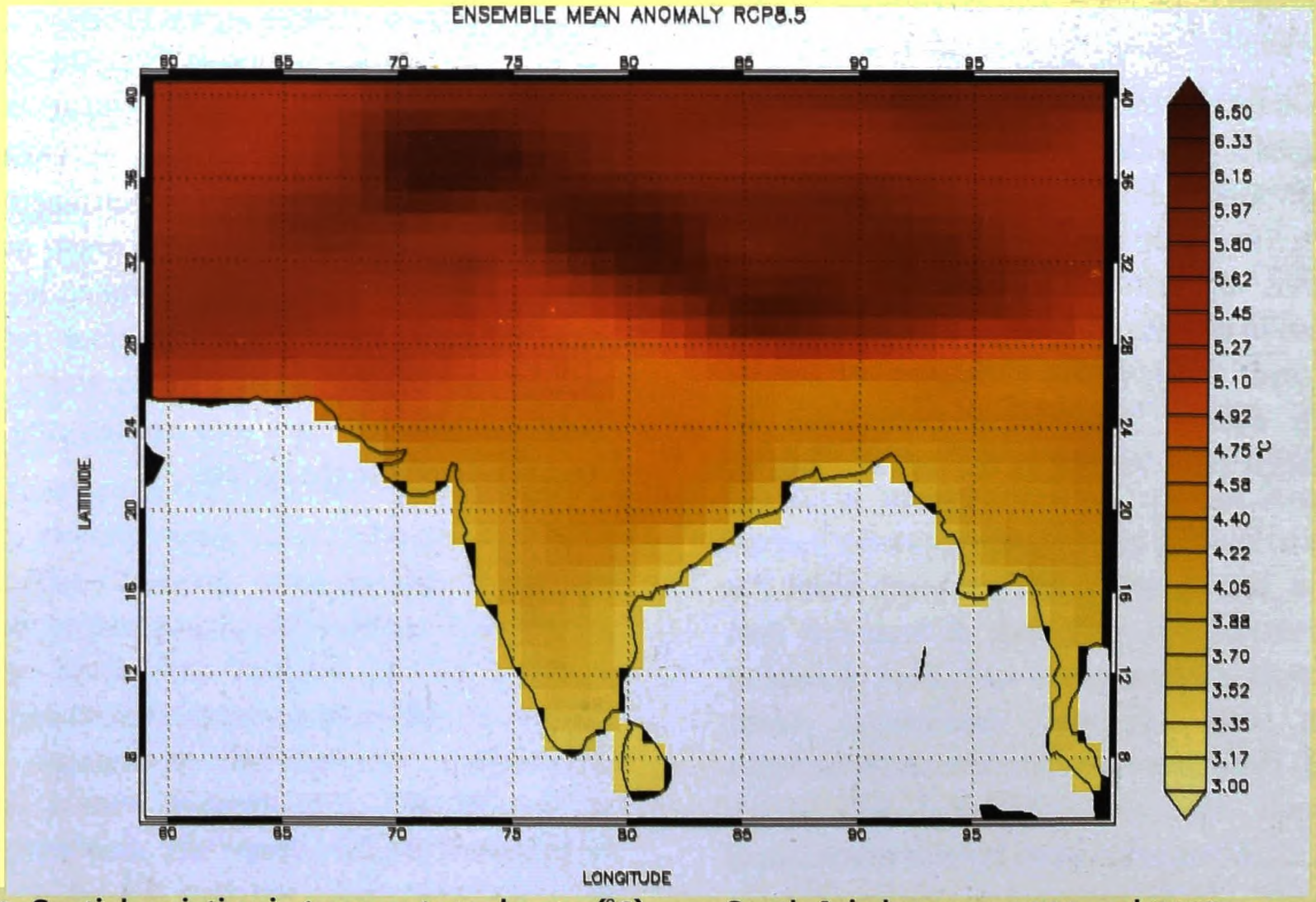
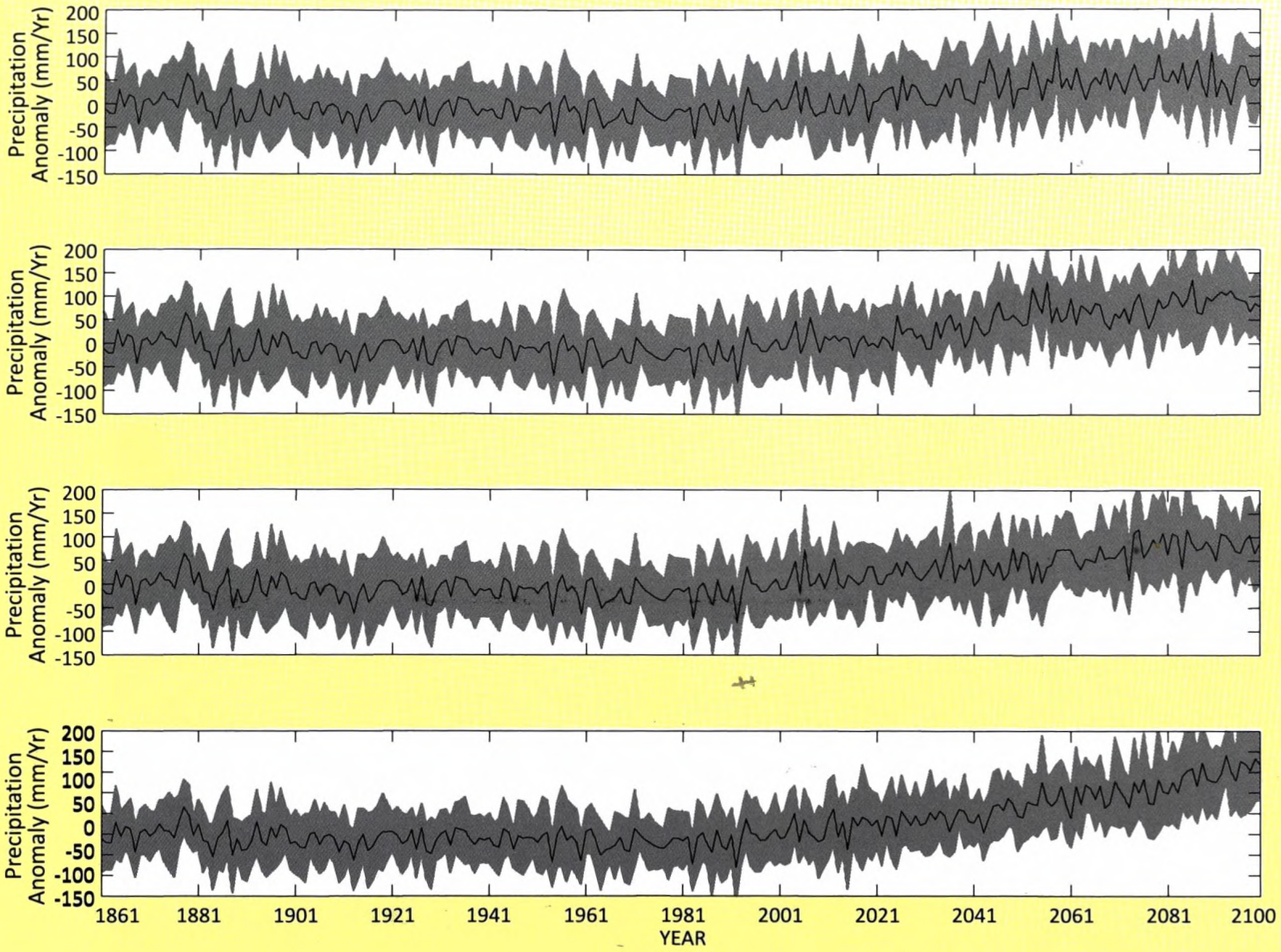


Fig. 2. Spatial variation in temperature change (°C) over South Asia between 1861 and 2100 across the ensemble climate model mean for RCP 8.5

Climate models project an ensemble mean increase in annual precipitation across South Asia of between 50 and 175 mm/ yr, by 2100 (Fig. 3). Nevertheless there is a large model spread (denoted by the grey shaded area in Fig. 3), of *ca.* ±75 mm/yr for all RCP scenarios, implying a possible near-zero change in the three less severe scenarios RCP2.5, RCP4.5 and RCP6.0. Models project large spatial variations in precipitation changes over South Asia, with increases projected over Bangladesh and the eastern Himalayas, southern India and Sri Lanka (Fig. 4.)



Fg. 3. Change in precipitation (mm/year) over South Asia between 1861 and 2100 for 4 RCP scenarios. The solid line is the ensemble mean, and grey shading is the range of climate model projections.

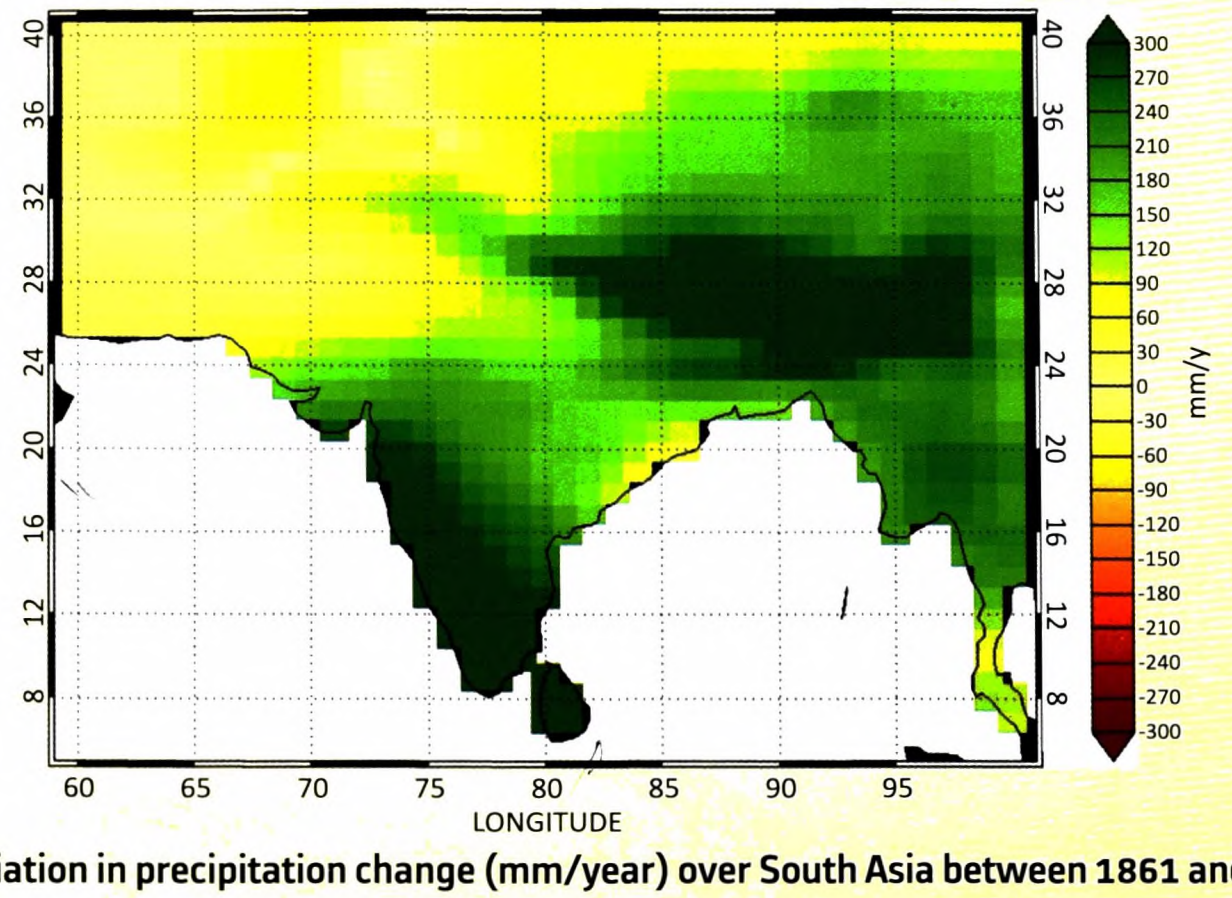


Fig. 4. Spatial variation in precipitation change (mm/year) over South Asia between 1861 and 2100 across the ensemble climate model mean for RCP 8.5

Models project increases in annual temperature and precipitation across Sri Lanka of between 0.8 and 2.9°C and 150 and 274 mm/yr, respectively, by the end of the century (Fig. 5). Models are able to reproduce the observed annual cycle in temperature and project uniform increases in temperature across the cycle. Climate models are able to reproduce present-day precipitation during both the summertime S-W monsoon and wintertime N-E monsoon seasons, however, over predict precipitation during the intermonsoon season, possibly linked to uncertainties in resolving local convective rainfall during this period.

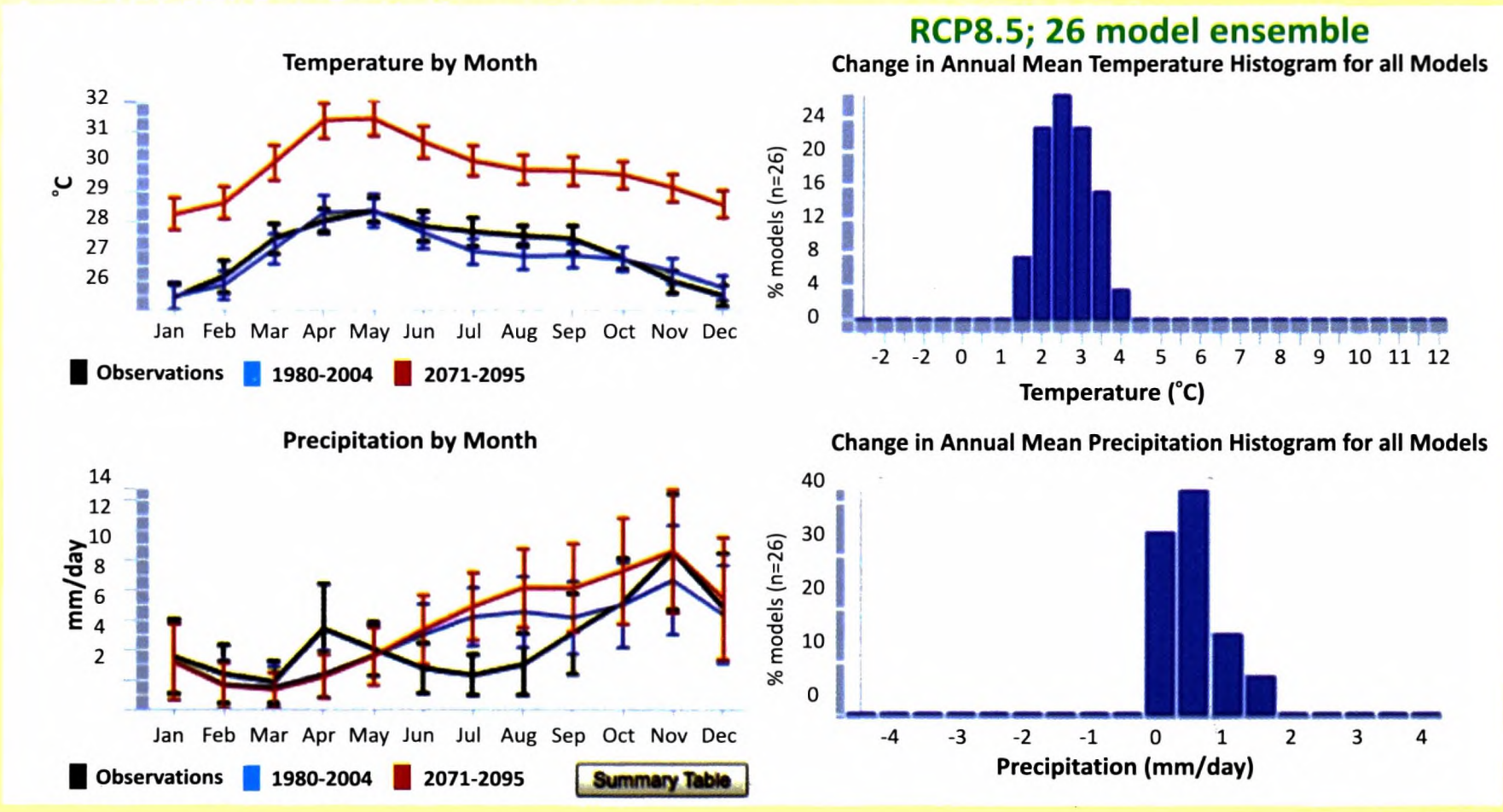


Fig. 5. Seasonal variation in temperature(°C) and precipitation (mm/ day) over Sri Lanka for RCP8.5. Observations and climate model projections for the present day are in black and blue, respectively. Climate model projections for the end of the century are in red. The right-hand panels show the annual mean histogram for all climate models for temperature (top panel) and precipitation (bottom panel). These maps were created using the USGS CMIP5 global climate change viewer (http://regclim.coas.oregonstate.edu/visualization/gccv/cmip5-global-climate-change-viewer/index.html)

Changes in Net Primary Production across South Asia

The ESMs from CMIP5 project an ensemble mean future increases in annual Net Primary Productivity (NPP) of between 100 g C m^{-2} yr^{-1} and 225 gC m^{-2} yr^{-1} across the four RCPs by 2100 (Fig. 6). This represents a substantial increase of 30-75%. Integrated over the whole region NPP is simulated to positively respond to the combined changes in climate and atmospheric composition. All models include a strong fertilization effect of plant productivity in response to increasing atmospheric CO_2 content, and will simulate increases in Water Use Efficiency (WUE) in dry environments, as less water is needed to maintain the same productivity, all else being equal (Friedlingstein *et al.,* 2006, Sitch *et al.,* 2008). However, NPP changes vary markedly in both sign and magnitude across the region, with the greatest increases simulated in the east of the region, with moderate increases across India and Sri Lanka (Fig. 7). Decreases in NPP are simulated in western South Asia. These spatial variations are likely driven by the patterns of precipitation change over the region in combination with warming. In western South Asia results appear to suggest that reductions in precipitation combined with elevated temperatures lead to further water limitation, i.e. reduced water supply and enhanced rates of evapotranspiration, in spite of any increases in WUE with elevated atmospheric CO_2. Also it must be emphasized the large variation across ESMs in projected future changes in NPP across the region (Figs. 6, 7 & 8).

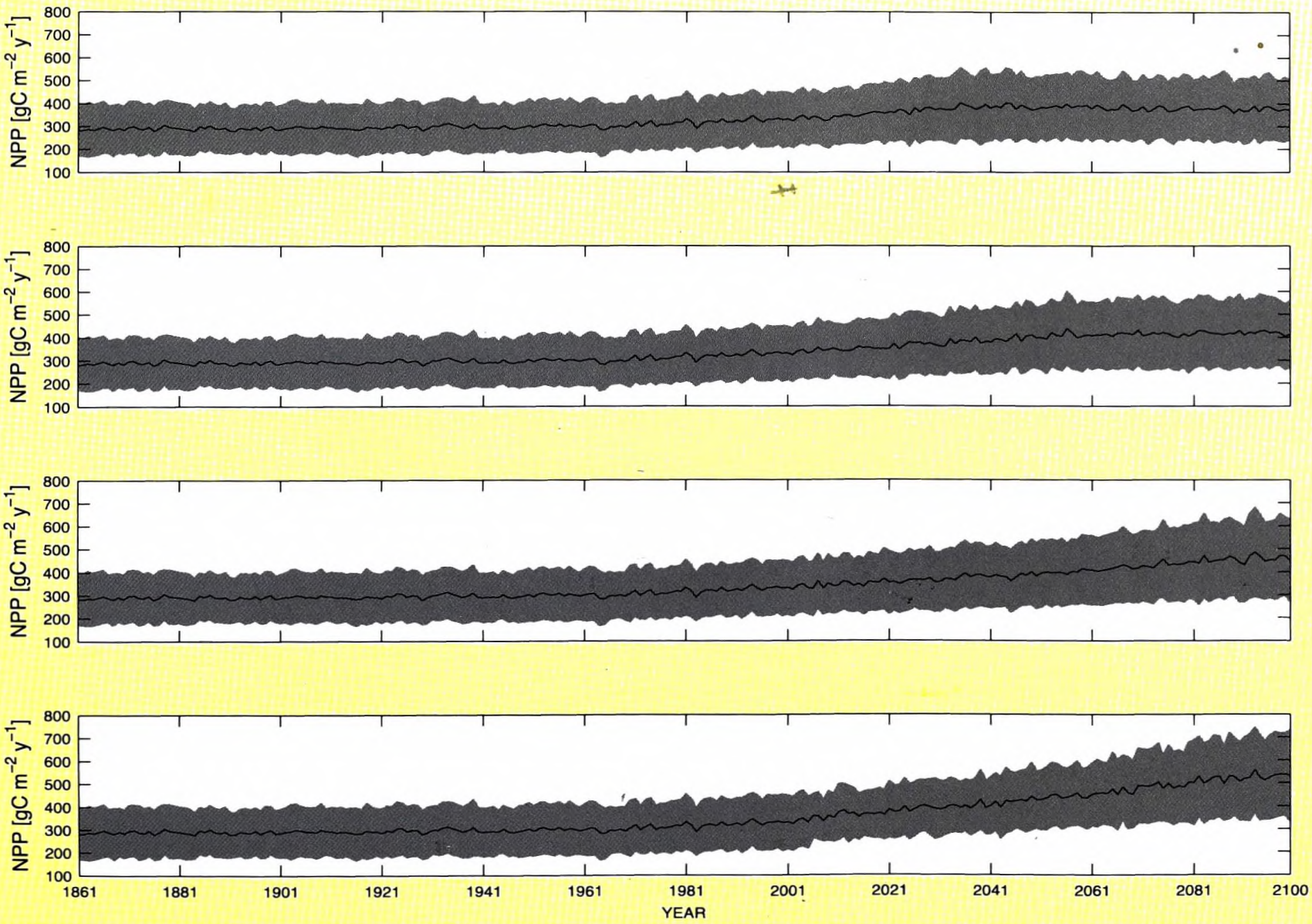


Fig. 6. Change in Net Primary Production (gC m^{-2} Yr^{-1}) over South Asia between 1861 and 2100 for 4 RCP scenarios. The solid line is the ensemble mean, and grey shading is the range of climate model projections.

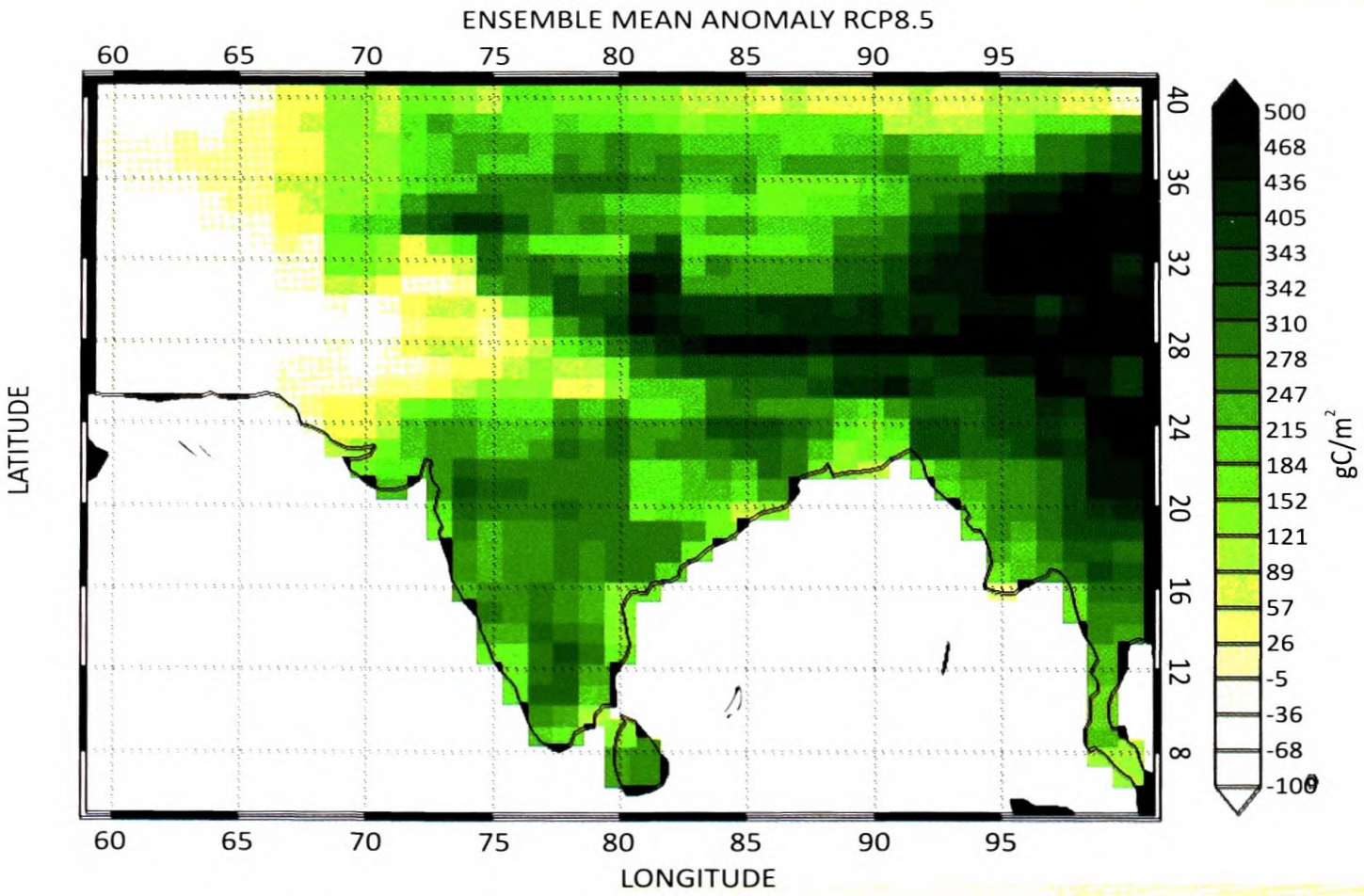


Fig. 7. Future increases in NPP (gC m^{-2} Yr^{-1}) across South Asia by 2100 across the ensemble climate model mean for RCP 8.5.

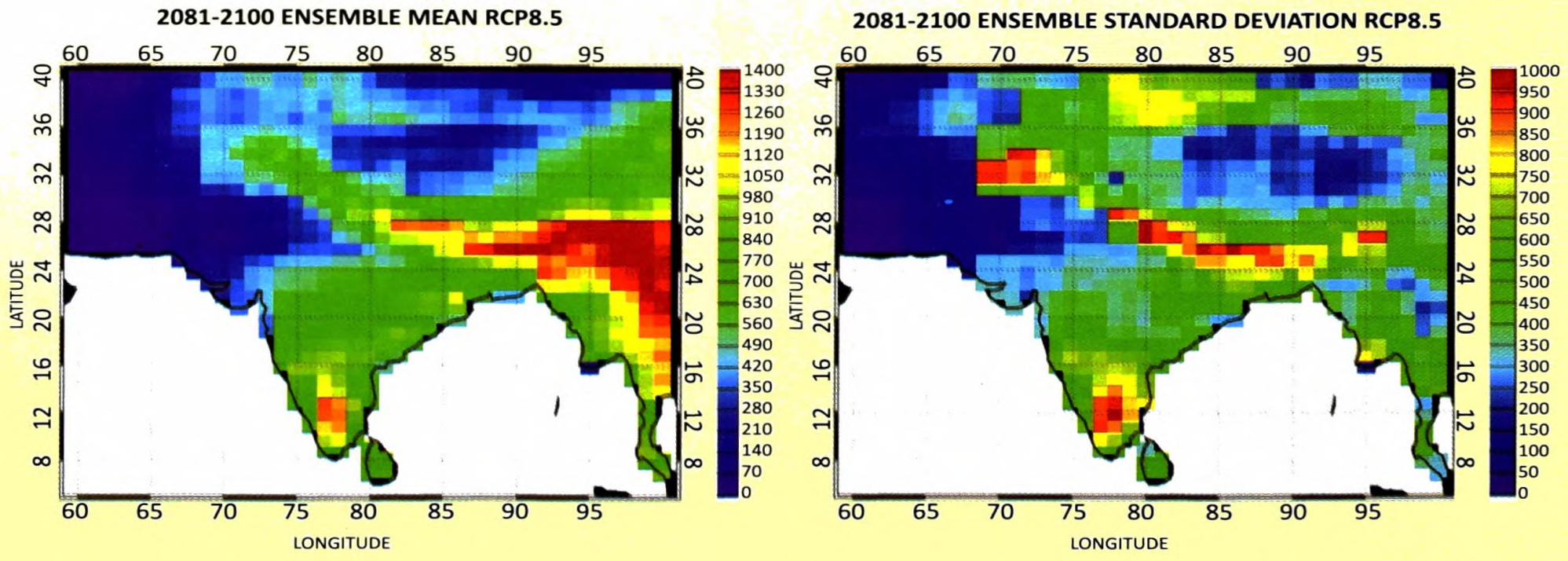


Fig. 8. Spatial variation in NPP in 2100 (g C m^{-2} Yr^{-1}) across South Asia for RCP8.5.
Left panel: ensemble climate model mean. Right Panel: the ensemble mean standard deviation.

Environmental effects on crop yields

It is unclear whether these simulated changes in NPP for natural vegetation can be used to infer future changes in crop yields (Doherty *et al.,* 2010). There is some evidence to suggest that crop yields in low latitude will decrease with warming. Some crops may suffer heat stress irrespective of whether plants are grown in ambient or elevated CO_2 (Wheeler *et al.,* 1996). In addition, Long *et al.,* (2006) suggests that theoretical increases in carbon uptake are higher than observations for some crops suggest, and also that these increases are not translated into proportional increases in crop yields, i.e. implicating changing carbon allocation patterns with CO_2.

The effect of aerosol on NPP

Surface irradiance decreased by 10Wm^{-2} between 1970 and 2004 at Indian stations (Ramanathan *et al.,* 2005), and Aerosol Optical Depth (AOD) from satellite and surface data suggest increases in anthropogenic aerosols since the mid-1990s over South Asia (CCSP 2009). Fig. 9 shows the simulated effects of changes in aerosols and clouds on plant productivity over South Asia in 1999. Although increases in diffuse fraction are simulated to enhance productivity, this is more than offset by the negative effect of reductions in incoming radiation on plant productivity. Future projections of Aerosol Optical Depth (AOD) are highly uncertain for the South Asia region. Model results project changes in AODs of -36.0%, and 48.6% by 2030 compared to 2000, for the IIASA-MFR ("Maximum Feasible Reduction") and IIASA-CLE ("Current Legislation"), respectively (Kloster *et al.,* 2008).

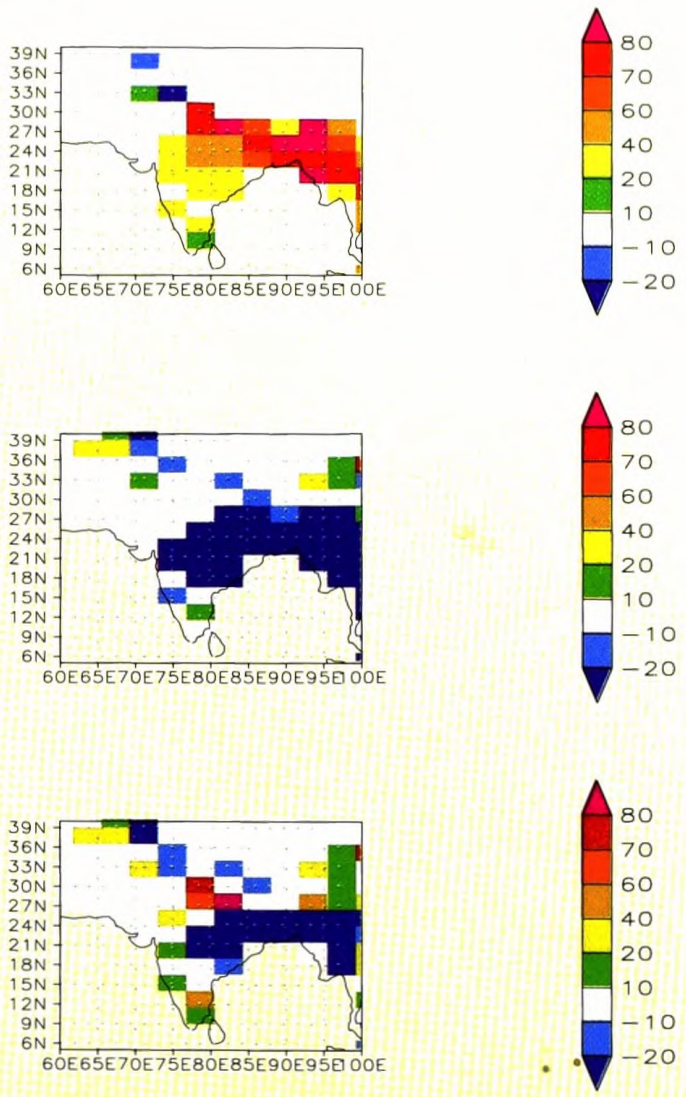


Fig. 9. Contribution of changes in the quantity (SW) and quality (diffuse fraction, Rd) of incoming solar radiation to changes in Gross Primary Productivity in 1999. Top panel: contribution of diffuse fraction, Middle Panel: contribution of changes in total incoming solar radiation, bottom panel: net effect of changes in incoming solar radiation (Rd + SW) on GPP in 1999 (Mercado *et al.,* 2009)

The effect of ozone pollution on NPP

Evidence suggests adverse effects of surface [O_3] above 40 ppb on plant productivity and crop yields in sensitive plant species (Ashmore, 2005). Present-day monthly O_3 levels exceed 40 ppb during the dry season at two monitoring stations in South India (Van Dingenen *et al.,* 2009), with summer-time [O_3] up to 58 ppb in the Indo-Gangetic plane (Agrawal, 2003). This is a particular concern as pulses grown during the dry

season provide an important source of protein for a large vegetarian population (The Royal Society, 2008). Fig. 10 shows the satellite-derived observed seasonal variations in column ozone concentration over South Asia. For the present day model-based estimates (Van Dingenen *et al.,* 2009, The Royal Society, 2008) suggest O_3 related reductions in crop yield of between 6-19% across India. This compares with experimental evidence from specific locations in South Asia of crop yield losses due to current O_3 levels of between 10% and 47% (The Royal Society, 2008, Wahid. *et al.,* 1995 a, Wahid *et al.,* 1995 b).

Sitch *et al.,* (2007) projects large regional reductions in plant productivity by 2100 in response to future elevated ozone concentrations associated with the pessimistic SRES A2 scenario (Fig. 11). Over the period 2000 to 2030 simulated changes in surface [O_3] range between -5.9 ppb, +7.2 ppb and + 11.8 ppb for the IIASA-MFR, IIASA-CLE, and SRES-A2 scenarios, respectively (Dentener, *et al.,* 2006); the latter associated with large increases in Asian NO_x emissions. South Asia has the highest projected relative crop yield loss from 2000 to 2030 of around on average 7% (Van Dingenen *et al.,* 2009, The Royal Society, 2008), with wheat particularly affected with losses of 10.7%, 16.7% and 26.3% across India, Bangladesh and Pakistan, respectively (Van Dingenen *et al.,* 2009, The Royal Society, 2008).

However there are significant uncertainties associated with such projections. Applying two different exposure indicators (AOT40, M7) the effect of present-day [O_3] on wheat yield loss across India ranges between 13.2 and 27.6%. Critically these indicators do not account for plant physiological response to ambient atmospheric conditions. Also Van Dingenen *et al.,* 2009 did not consider feedback between climate change and O_3 and physiological effects of elevated CO_2 on plant O_3 uptake - very important in times of drought (Löw *et al.,* 2006). As CO_2 increases, leaf stomata will not need to open as widely to allow sufficient CO_2 to enter for photosynthesis. Ozone dry deposition will decrease, resulting in higher O_3 levels in the atmosphere. For example, Sanderson *et al.,* (2007) projected surface O_3 levels over parts of Europe, Asia and the Americas to increase by 4–8 ppb with a doubling of CO_2. Also, emissions of reactive hydrocarbons by vegetation will also have an effect on the future O_3 levels.

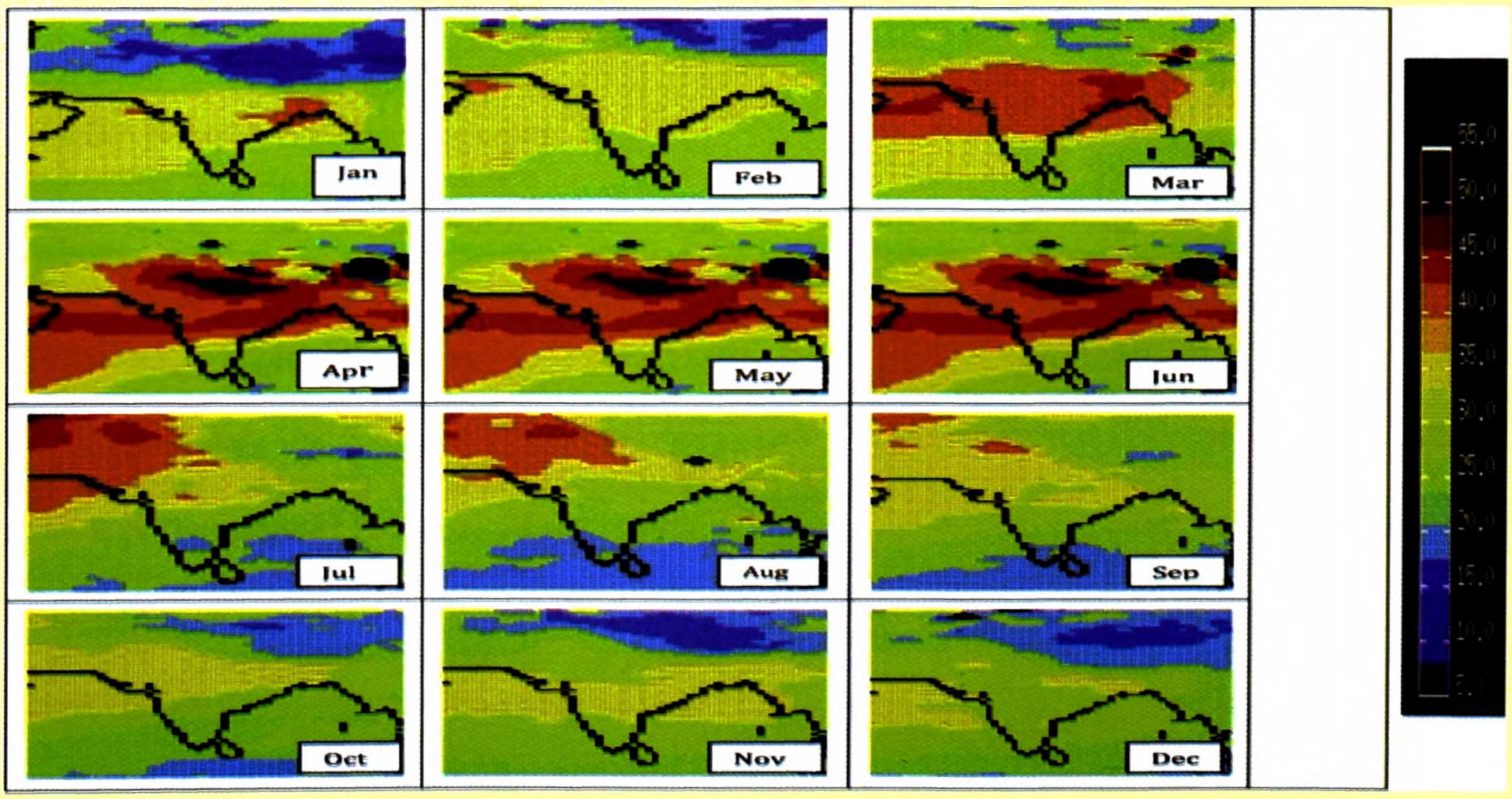


Fig. 10. Seasonal variations in satellite derived Column tropospheric Ozone (Dobson units) over South Asia.

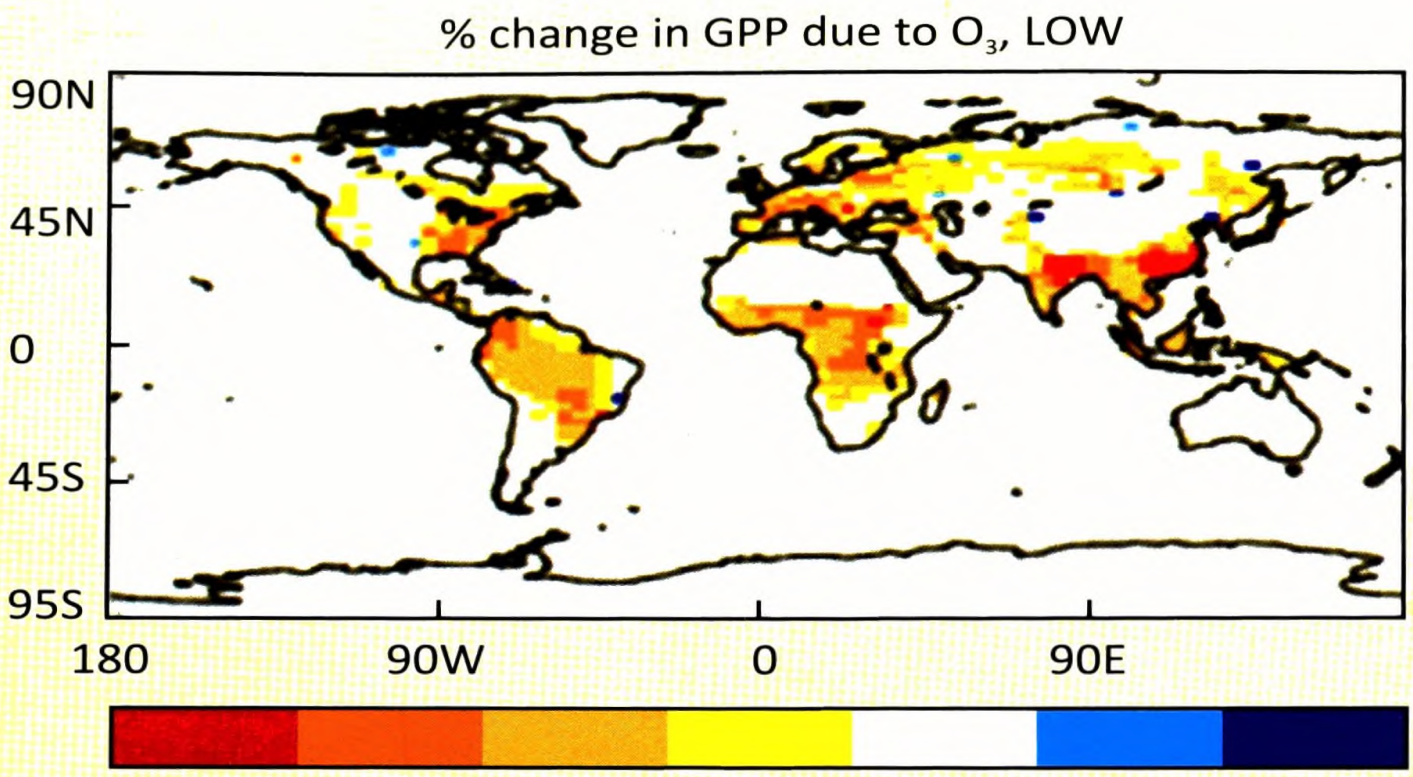


Fig. 11. Simulated reduction in Gross primary productivity (%) over South Asia by 2100 assuming lower plant ozone sensitivity to ozone parameterization. JULES was run using future ozone fields generated from the STOCHEM chemistry transport model driven with the pessimistic SRES A2 scenario.

CONCLUSION

Projected increases in annual temperature and precipitation across South Asia of 2-6°C and 50-175 mm/yr, respectively, by 2100. The greatest warming linked to snow-albedo feedback in snow-dominated regions. Projected increases in annual temperature and precipitation across Sri Lanka of 0.8 – 2.9°C and 150 - 274 mm/yr, respectively, the latter mainly during Aug-Nov. Increasing atmospheric CO_2 and climate leads to projected increases of 30-70% in Net Primary Production. However it is unclear whether this can be translated directly into similar increases in crop yields, due to heat stress and lower CO_2 fertilization in crops and the effect of air pollution on productivity. Two important recent papers in the journal Nature (Sitch *et al.,* 2007, Mercado *et al.,* 2009) have highlighted the intricate coupling of atmospheric composition and land biogeochemistry that goes well beyond the existing paradigm of direct climate-carbon cycle feedbacks. In addition there is an acute need for good observational constraints, coupled with ensemble approaches, to tell us what the direct CO_2 and ozone (O_3) effects on crop yields are likely to be. A high O_3 and CO_2 World could present a significant challenge for biotechnology (Ainsworth *et al.,* 2008). Estimating potential changes in future global food production is a critical element of climate impact assessments. However, O_3 impacts are rarely included in crop simulation models and few impact assessments on crop production have adequately considered O_3. There remains an urgent need for an integrated study on the impact of atmospheric composition and climate on crops and natural ecosystems over South Asia, including related uncertainties and associated feedbacks.

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