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Climate change, water supply and crop production

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Abstract

Changes in environmental components such as atmospheric composition, climate and land use may have major effects on water supply and food production. Hydrological models can be used to investigate the effects of various scenarios at different scales. Two linked hydrological models, SLURP (Semi-distributed Land-use Runoff Processes) and SWAP (Soil-Water-Atmosphere-Plant) were applied to a basin in Turkey. SLURP modelled the entire 17,200 km^2 river basin and SWAP was used to model cotton within a particular irrigation scheme. The outputs from the models include the areal distributions of variables such as soil evaporation and crop transpiration over the basin and crop yield at the field level. The results show that, under a 2 x CO_2 scenario, crop transpiration was reduced almost everywhere in the basin due to generally higher temperatures and lower precipitation. River flows to the sea were also reduced under the 2 x CO_2 scenario as more water was diverted from the river to support crop production, urban and industrial water supplies. At the field scale, crop production was much reduced under the 2 x CO_2 scenario because of an increase in the evaporative demand of the atmosphere.

INTRODUCTION

Adequate food and water are prerequisites for human life. At present, food and water are inadequately distributed over the globe with resulting supply and demand unmatched in many areas. These inequities may be increased in the future if changes occur in atmospheric composition, climate or land use.

An important component of global change is the alteration of the chemical composition of the atmosphere due to human activity. The build-up of carbon dioxide started in the industrial revolution with coal burning and continues today with increasing fossil fuel consumption (IPCC, 1995). Similarly, anthropogenic nitrogen fixation has doubled in the last twenty years as a result of increased fertilizer use, fossil fuel combustion and fixation by leguminous crops (Walker and Steffen, 1999). The atmospheric concentration of methane has increased at a rate of about 1% per year (Glantz and Krenz, 1992) due mainly to wet-paddy rice farming and livestock farming. The direct effects of an increase in carbon dioxide on food production may be positive; raised CO_2 levels increase yields of greenhouse crops (Goudriaan and Unsworth, 1990) as carbon assimilation is increased and transpiration is reduced. Despite the Kyoto Protocol, which agreed on reductions in greenhouse gases by 35 countries, it is certain that atmospheric concentrations of CO_2 will increase for decades (Edmonds, 1999).

Changes in climate have occured since the earth’s formation as a result of permutations of the 105,000, 41,000 and 21,000 year solar obliquity, eccentricity and precession periods (Harrington, 1987). Recent concerns center on the effects of human activity on the climate at a much smaller time scale. Increases in greenhouse gas concentrations are estimated to have caused a 0.5 degree Celcius rise in mean annual global temperature since 1860 (IPCC, 1995). Such changes in temperature are likely to be accompanied by increased atmospheric humidity and precipitation.

Finally, changes in land use have occured over many thousands of years as mankind evolved from hunting to slash and burn agriculture and to large-scale irrigation. The rate of change has increased recently; over half of the world's croplands have been created during the last century (Walker and Steffen, 1999). In the future, the change is likely to be towards less agricultural land, as prime cropland is converted to urban use and as irrigated lands become salinised and useless for crops. The effects of changes in atmospheric gases and climatic change will also have effects on land use. If temperatures rise, migration of natural vegetation can be expected (Harrington, 1987).

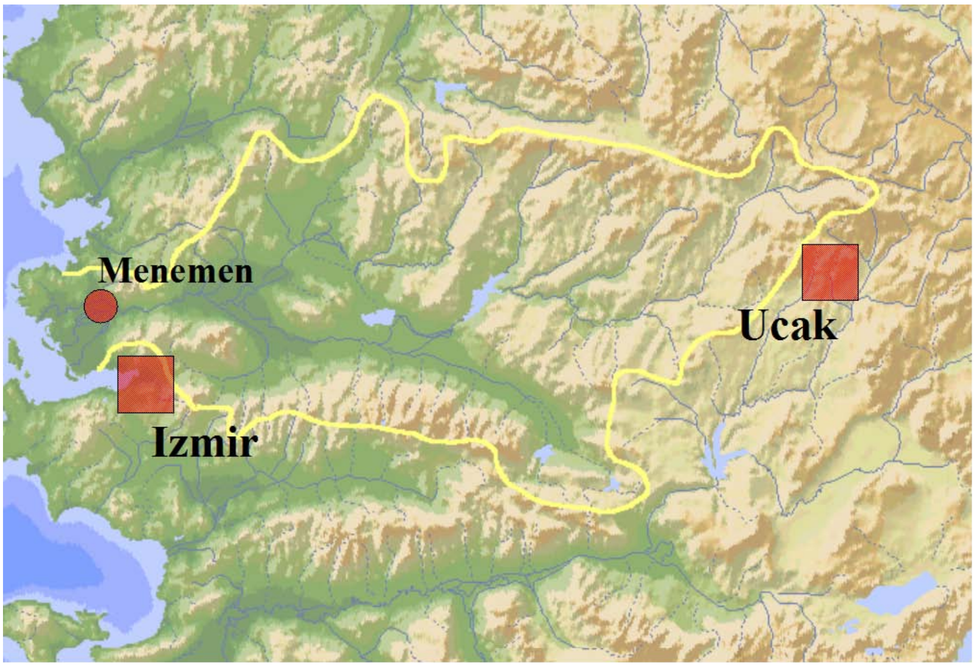

Figure 1. The Gediz Basin, western Turkey.

In this experiment, two linked hydrological models were used to investigate the effects on water availability and on crop production in irrigation schemes within the Gediz River Basin in western Turkey (Figure 1). The Gediz River has a length of about 275 km, drains an area of 17,220 km^2 and flows from east to west into the Aegean Sea just north of Izmir. Precipitation in the basin ranges from over 1000mm/yr in the 2300m high mountains to 500mm near the Aegean coast. Temperatures range from –24°C at high elevations in winter to over 40°C in the interior plains in summer. The natural vegetation of the basin is mainly shrubland, maki (bay, myrtle, scrub oak and juniper trees, amongst others) and coniferous forest with large outcrops of barren limestone mountain. Crop production within the basin includes cotton, cereals, grapes, vegetables and fruits, olives, tobacco and melons. The total irrigated area under large schemes is 125,000 hectares and there are also many smaller schemes.

METHOD

Two linked hydrological models, SLURP (Semi-distributed Land-use based Runoff Processes) (Kite, 2000) and SWAP (Soil-Water-Atmosphere-Plant) (van Dam et al., 1997) were applied at different scales. SLURP modelled the entire 17,200 km^2 river basin and SWAP was used to model cotton and grape crops within the irrigation schemes. The SLURP model simulated the vertical water balance for each of 1369 combinations of sub-basin and land cover for the Gediz Basin and translated the surface and groundwater runoffs down the basin to the Aegean Sea through a series of reservoirs, diversions and irrigation schemes. The SWAP model simulated the detailed soilwater processes for the two main crops and the dominant soil type within the Menemen Left Bank irrigation scheme. The outputs from the models include the areal distributions of variables such as soil evaporation and crop transpiration over the basin, time series such as streamflow at many points in the basin and crop yield at the field level.

The SWAP model is an integrated mechanistic simulation model including submodels on soil water flow, solute transport, soil heat flow, soil evaporation, plant transpiration, irrigation management and crop growth. The water transport module in SWAP is based on the well-known Richards' equation, which is a combination of Darcy's law and the continuity equation, solved by a finite difference solution scheme. Actual soil evaporation and plant transpiration are simulated based on the assumption that there exists a certain potential evapotranspirative demand. This potential demand is reduced according to the available soil water in the top layer or the root zone for, respectively, evaporation and transpiration. Moreover, high solute concentrations can also reduce the amount of transpiration and thus crop growth. The evapotranspirative demand can be defined as a reference evapotranspiration by the user or can be calculated by the program itself, using the Penman-Monteith approach. Crop growth is simulated using a simple crop-growth algorithm based on Doorenbos and Kassam (1979). Finally, irrigation can be prescribed at fixed times, scheduled according to different criteria, or using a combination of both.

SLURP is a continuous simulation semi-distributed hydrological model in which the parameters are related to vegetation type. The SLURP model divides a basin into sub-basins based on topography. Each sub-basin is then further divided into different land covers. For each day of the simulation period the hydrological model carries out a vertical water balance for each element of the matrix of sub-basins and land covers. Each element is simulated by four reservoirs representing canopy interception, snowpack, rapid runoff and slow runoff. Precipitation is intercepted by the vegetation canopy depending on the leaf area index (LAI) for the vegetation type. SLURP computes evaporation and transpiration for each land cover depending on the LAI and on the available soil moisture. Evaporation occurs from soil moisture in the top soil layer and transpiration occurs from deeper soil moisture storage. Excess precipitation either runs off or is infiltrated into the soil from where it either contributes to interflow or percolates to groundwater. Surface runoff, interflow and ground water flows are accumulated from each vegetation type within a sub-basin and the combined runoff is converted to streamflow and routed to the outlet of the basin, taking account of reservoirs, diversions and regulatory structures.

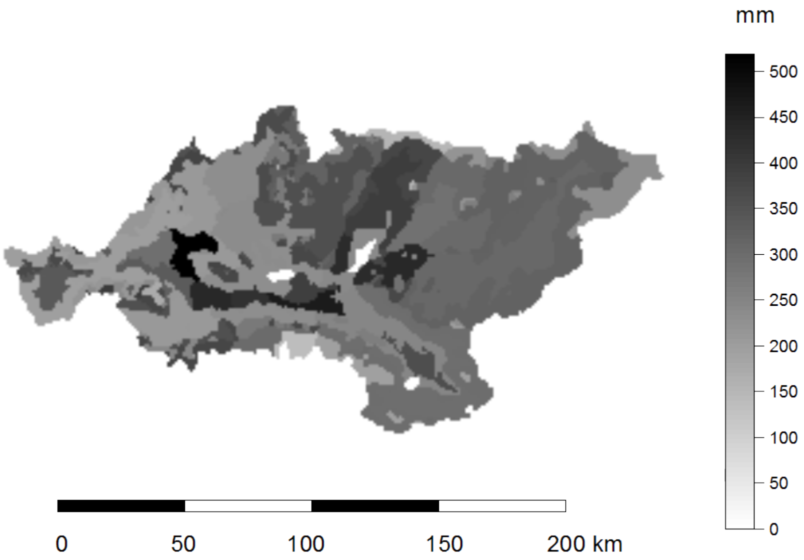

Figure 2. Areal distribution of actual annual crop transpiration for 1992 for the 17,200 km^2 Gediz Basin.

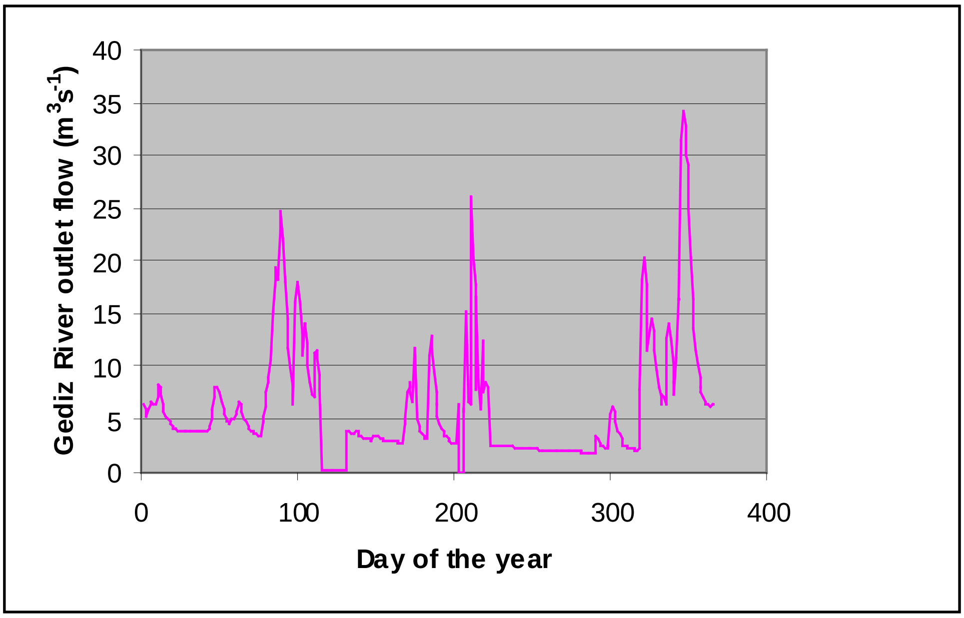

Figure 3. Hydrograph of the outflow from the Gediz River to the Aegean Sea, 1992.

RESULTS

The two models were first used to simulate the daily hydrology and water resources of the basin, irrigation schemes and fields for 13 recent years including both wet years and a major drought and including the actual operations of the various dams, diversions and irrigation management functions. Figure 2 shows the distribution of 1992 total annual transpiration computed by the model and Figure 3 shows the simulated flow of the Gediz River to the Aegean Sea during 1992. Figure 4 shows annual potential transpiration, actual transpiration and crop yield for a cotton field in 1992 as simulated by SWAP.

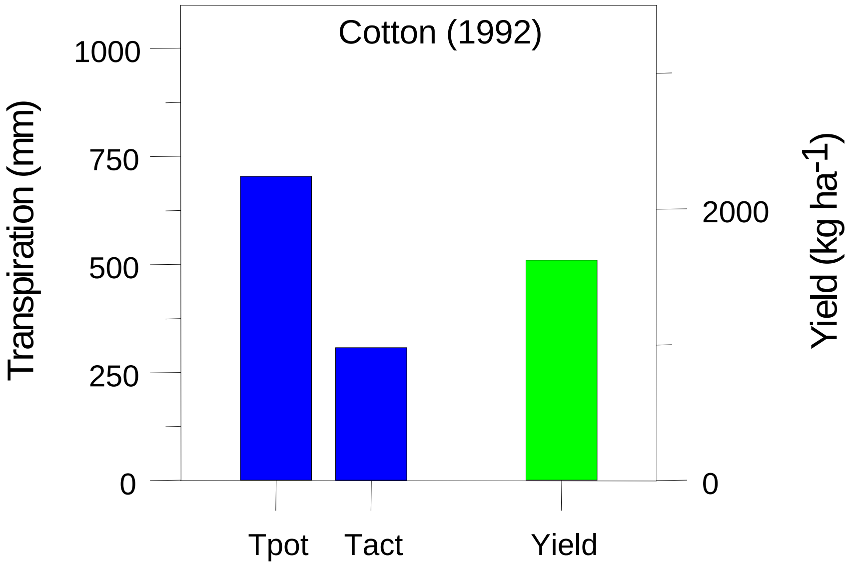

Figure 4. Annual potential transpiration, actual transpiration and crop yield for a cotton field in 1992.

Second, atmospheric data from the UK Meteorological Office's general circulation model for a 2 x CO_2 scenario were used as inputs to both hydrological models to investigate the effects of a possible climate change scenario on water supply and on food production. The results of the model runs for the base case scenario (present-day) and the 2 x CO_2 scenario were compared using three parameters; annual crop transpiration across the entire basin, river discharges to the Aegean Sea and crop yields for the two dominant crops. Crop transpiration is often regarded as an indicator of productivity for irrigated agriculture and river flows to the sea may be regarded, from a purely agricultural viewpoint, as unused water. The models show (Figure 5) that crop transpiration for 1992 (a dry year) was reduced almost everywhere in the basin due to generally higher temperatures and lower precipitation under the 2 x CO_2 scenario. The only exceptions are high mountain areas where the higher temperatures allowed higher transpiration from an adequate rainfall regime.

River flows to the sea were also reduced under the 2 x CO_2 scenario (Figure 6) as more water was diverted from the river to support food production, urban and industrial water supplies.

The model outputs also showed (Figure 7) that, at the field scale, crop production was much reduced under the 2 x CO_2 scenario because of an increase in the evaporative demand of the atmosphere.

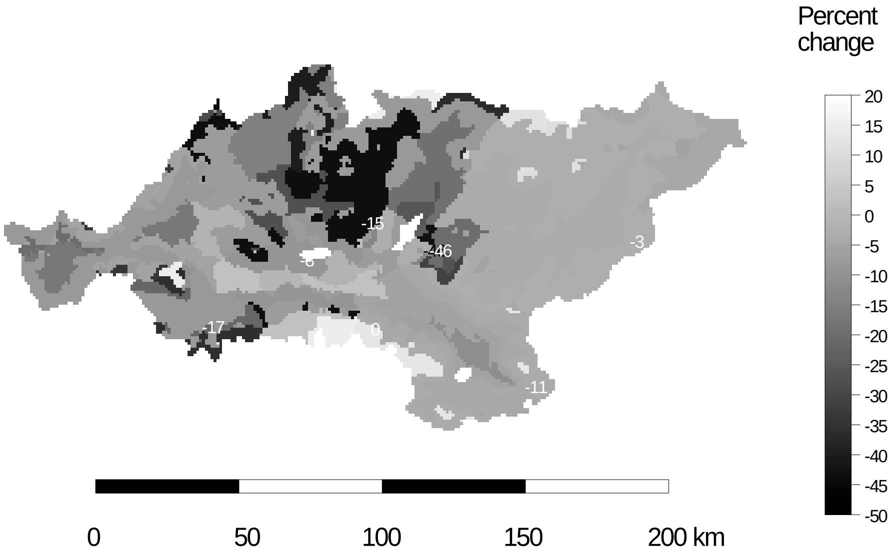

Figure 5. The change in areal distribution of actual annual crop transpiration (%) between a 2 x CO_2 climate and the base case.

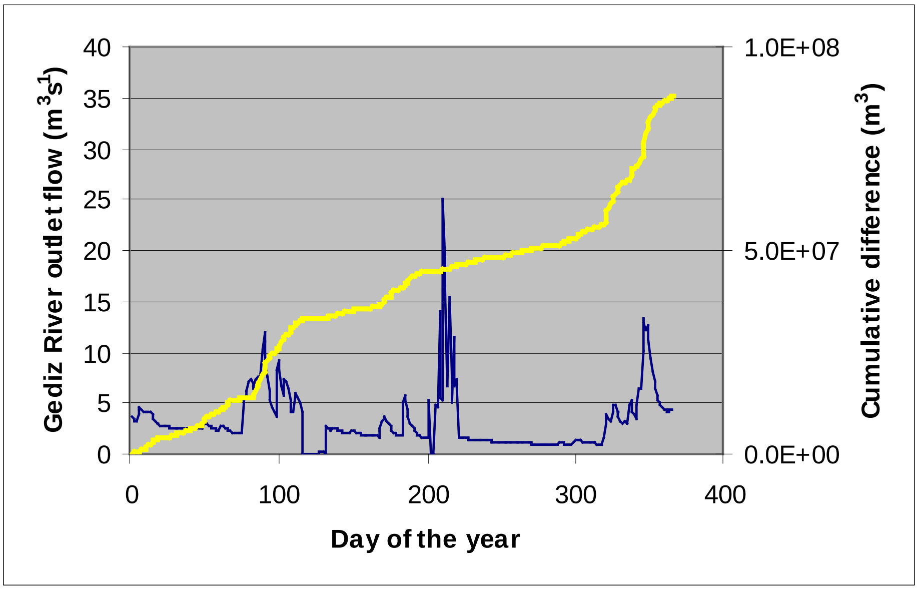

Figure 6. Gediz River outflows to the Aegean Sea, m^3/s, under a 2 x CO_2 scenario (black) and the cumulative difference (white) between the 2 x CO_2 scenario and the base case.

CONCLUSIONS

Two models have been used at different scales to investigate the effects of a 2 x CO_2 scenario on water availability and crop productivity within the Gediz Basin in western Turkey. The results show that the effects of such a scenario would be serious for water supply and crop production. Annual cotton production was reduced by more than 10% and annual water flow at the outlet of the Gediz River was reduced by more than 100 million cubic metres. The SLURP and SWAP models have been shown to be useful in determining the relationships between changes in the environment and changes in water supply and crop production. Both models use public-domain datasets generally available on the internet and are suitable for application in many parts of the world to investigate similar scenarios.

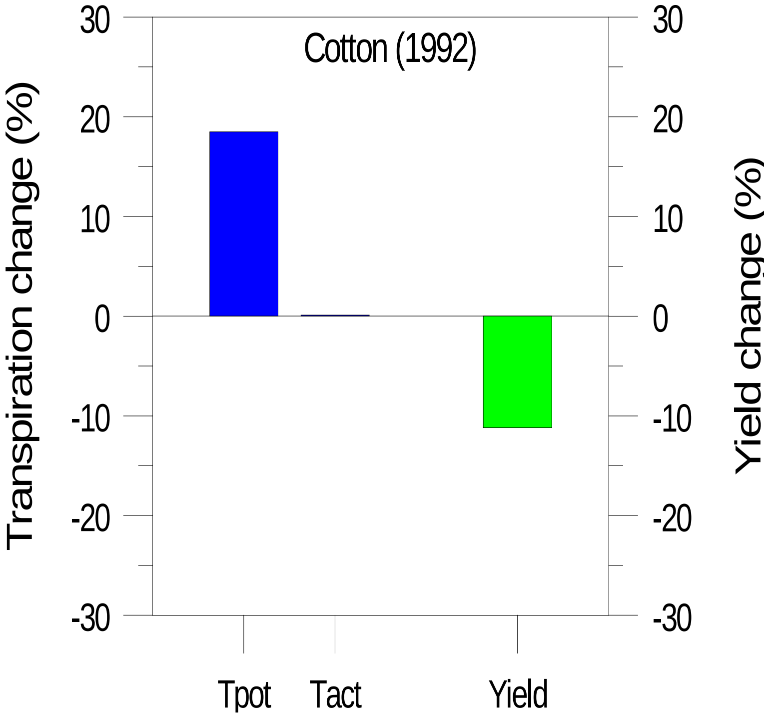

Figure 7. Changes in annual potential crop transpiration, actual crop transpiration and crop yield for a cotton field between a 2 x CO_2 scenario and the base case.

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