Modelling the hydrological cycle in assessments of climate change

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Climate change caused by increasing atmospheric concentrations of greenhouse gases may have important effects on water circulation and availability and thus on agriculture, forestry and river flow, with significant economic consequences. A variety of models are being used to evaluate hydrological effects, but their hydrological responses to global warming are often inconsistent. Improved understanding of basic hydrological processes is needed if we are to assess the impact of future climate change.

THE current political debate concerning the necessary steps to limit greenhouse gas emissions depends crucially on the possible consequences of taking no action. Two questions arise: what will be the resulting climate change, and what will be the impact of that change. To address these questions, two Intergovernmental Panel on Climate Change (IPCC) working groups were established. The first (Working Group I) was assigned the task of identifying changes in climate resulting from increased concentrations of greenhouse gases. The second (Working Group II) was required to assess the environmental and socioeconomic consequences of climate change. Reports were issued by both groups in 1990[1,2], updates have recently been released, and it is intended that efforts should continue at least until the next century.

The hydrological cycle is central to both groups' concerns. Water vapour and cloud feedbacks currently provide the predominant positive amplifications of the direct CO_2-induced warming in general circulation models (GCMs)[1], increasing the direct CO_2 warming by 2–3 times. Changes in water availability directly affect agriculture, forestry, river flow and many different human activities, with important economic consequences. Clearly, our ability to determine the impacts of current greenhouse gas emissions depends heavily on our understanding of the hydrological cycle.

Models are important both for projecting the likely climate change and for assessing the environmental and socioeconomic response. Studies such as those reviewed by IPCC Working Group II and organized by the United States Environmental Protection Agency[3] (EPA) have used a combination of climate and impact models. Climate change estimates from GCMs (generally temperature and precipitation) are used as the input to physical process models to produce estimates for quantities such as agricultural yields, forest biomass or river flow, and the resulting output is often used to evaluate the financial consequence. The predictions of these studies are alarming, with crop production estimated to decrease by some 30% and forest biomass by 40% in the United States[3]. But the results depend crucially on the hydrological cycles embedded in the different models; the issue of confounded hydrology is the focus of this review. We show that uncertainties in hydrological processes and inconsistencies in both climate and impact models limit our confidence in current assessments, and we suggest a future course of cooperative action.

A comparative study

For this review, we have chosen representative versions of several different types of models, all of which have contributed to climate impact assessments[2-4]. For climate change we use the Goddard Institute for Space Studies (GISS) GCM[5], for agricultural impact the CERES maize and wheat models[6,7], for forest response the FORENA forest dynamics model[8] and for water availability the Palmer drought severity index (PDSI) hydrological model[9]. Hydrologies were evaluated for both the current climate and a 4.5 °C temperature increase, for 15 different sites in the United States (Fig. 1). This temperature change is at the upper end of the projection for warming caused by CO_2 doubling, and clearly illustrates the differences between models. In the following tables results are shown from all 15 sites for the GCM, maize and PDSI models. Both the wheat model and forestry model could function at only eight sites with the prescribed warming; at the other seven, nothing could grow. Nevertheless, a comparison using the eight sites for which all models ran showed the overall characteristics reported here. Note that the GCM produces all elements of its hydrological cycle interactively, whereas the impact models are forced with specified precipitation and temperature (observed values are used for the current climate).

Although each of the models purports to represent the hydrological cycle with physically based parameterizations, the ground hydrological schemes that are used differ considerably from one another. Table 1 gives a summary of the various parameterizations and timescales involved. Differences arise in every category; for example, different formulae are used to calculate potential evapotranspiration (PET), which is the maximum evaporation possible under given atmospheric conditions. The actual evaporation may or may not be a function of ground wetness or leaf area index, depending on the model. In some cases runoff is calculated as a direct function of precipitation, whereas in others it is calculated only when the soil is completely saturated. Given such differences, it would be no surprise if the models' responses to climate change varied considerably.

The annual average hydrological cycles for the current climate from the models are presented in Table 2*a*, together with observations from various sources[10-14]. Averaging the cycles annually and over diverse geographical regions removes some of the discrepancies between the models; it also allows us to illustrate succinctly the basic conclusions, which are not altered by this procedure. The observations of precipitation and runoff are relatively well constrained by measuring gauges; evaporation is a calculated quantity, which can be checked to ensure hydrological balance with precipitation and runoff (for the long-term annual average this is probably realistic). Soil moisture values are the result of water budget analyses[13]; although this procedure can produce realistic results when compared with *in situ* observations[15], it depends on the accuracy of all the other observations and the PET formulation.

PET is a hypothetical variable, indicative of the maximum amount of evaporation possible in a given circumstance. In most formulations it can be constrained by pan evaporation measurements[14] over a completely wet surface, But the aerodynamic formulations that are used in GCMs calculate PET above

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TABLE 1 Hydrological processes in climate and impact models

	Parameter	GISS GCM	CERES Wheat, maize	FORENA	Palmer drought severity index
Precipitation	P				
Method		Calculated	Input	Input	Input
Time interval		Hour	Daily observed	Long-term monthly observed	Monthly observed
Runoff	R	f(SM, P)	f(Soil type, SM, P)	SM > soil water capacity	SM > soil water capacity
Infiltration		$P-R-E$	$P-R$	P until SM > soil water capacity	P until SM > soil water capacity
Potential evaporation	PET	Aerodynamic[5]	Priestley–Taylor[27]	Thornthwaite[28]	Thornthwaite[28]
Total evaporation	E	f(PET, ground wetness)	f(PET, LAI, time)	f(PET, ground wetness)	PET (SM > 0)
Drainage	D	none	SM > soil water capacity, bottom layer	none	none
Soil moisture	SM	$P-E-R$	$P-E-R-D$	$P-E-R$	$P-E-R$
Area of calculation		10^5–10^6 km^2	Single plant*	10^2–10^3 m^2*	10^4–10^5 km^2†

All parameters used in the table are given in column 2, except LAI (leaf area index).
* Assumes uniform stand.
† By state, as used here.

partially wet surfaces over large geographical areas and produce significantly higher values (Table 2*a*), as the partially wet surfaces have higher temperatures than water in a pan.

The current climate values are similar for many quantities. The GCM has perhaps too high a ratio of evaporation to runoff, and the FORENA model has too much soil moisture (which is strongly dependent on the soil type used), but overall the basic hydrological variables are reasonably close to the observed values (which are only approximate in any case). It is likely that all the models are calibrated to the current climate in their development mode, given the observed precipitation which thus must be balanced by evaporation, runoff and soil moisture storage. Not surprisingly, the greatest discrepancies are found in the soil moisture (which is the least well-observed quantity) and potential evapotranspiration (which is calculated differently in the different models); the larger value listed for the GCM is the aerodynamic PET used to calculate the model's evaporation[4], whereas the smaller number is a diagnostic calculation of the Penman PET[16].

We now consider how the different models respond to a 4.5 °C warming. The impact models were re-run with temperatures warmed uniformly by this amount, and no change in precipitation from current climate values (to simplify the analysis); the GCM changes are produced by warming the sea surface temperatures by 4.5 °C everywhere, which results in little change in the annual average precipitation. Note that in contrast with the customary procedure, we are not using the GCM-generated changes in the impact models but are forcing all the models with a specified warming to illustrate their hydrological sensitivity.

The annual results are shown in Table 2*b*, with the number in parentheses representing the percentage change from the control run. Large disparities are evident: the PDSI indicates a 35% decrease in soil moisture, whereas the maize model shows a slight increase; the PDSI predicts a 46% decrease in runoff, and the forestry model a 24% decrease, in contrast to the much smaller changes in the agricultural models (owing to their lack of soil moisture change). The GCM results, produced by warming the sea surface temperatures by 4.5 °C everywhere, are often intermediate in magnitude.

Although these models do not all have hydrological cycle changes as their primary output, such changes affect the key results that the models were designed to produce. For example, if the maize model were to experience the runoff and soil moisture deficits associated with the PDSI or forestry models, it would probably show greater reductions in maize yields. As the PDSI was designed for agricultural assessments[17], such discrepancies are not to be taken lightly.

The differences in response are associated to a high degree with the governing parameterizations or assumptions embedded in each model (Table 1). For example, the Thornthwaite PET incurs a higher percentage increase than does the Priestley-Taylor indicating that a greater percentage increase in evaporation is possible (and does in fact occur) with the Thornthwaite formulation. The PDSI and the GCM have very different evaporation efficiencies, with the PDSI converting increased atmospheric demand to evaporation at ~90% efficiency, whereas the GCM has ~20% efficiency, owing primarily to differences in the empirical and aerodynamic PET formulations[4].

The models also contain very different assumptions. The agricultural models have extremely low values of soil moisture loss except during their explicit growing season. Thus, during

FIG. 1 Stations used in the comparison of model output.

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TABLE 2 Annual hydrological cycle and change predicted for 4.5 °C warming

(*a*) Annual hydrological cycle for the current climate

Source	Precipitation (mm per day)	Evaporation (mm per day)	Runoff (mm per day)	Soil moisture (mm)	Potential evaporation (mm per day)
Observations	2.30	1.55	0.70	78.2	3.16
GCM	2.55	2.07	0.49	98.0	10.4/21.7
PDSI	2.30	1.67	0.64	113.0	2.32
Maize	2.30	1.56	0.77	130.0	3.77
Wheat	2.69	1.80	0.91	151.3	3.85
Forest	2.92	2.13	0.89	293.6	2.28

(*b*) Change in annual hydrologic cycle with a 4.5 °C warming

Source	Temperature (°C)	Precipitation (mm per day)	Evaporation (mm per day)	Runoff (mm per day)	Soil moisture (mm)	Potential evaporation (mm per day)
GCM	4.43	0.003	−0.01 (1%)	−0.07 (14%)	−4.1 (4%)	2 (17%)/10 (48%)
PDSI	4.50	0	0.29 (18%)	−0.30 (46%)	−39.9 (35%)	0.86 (37%)
Maize	4.50	0	0.02 (2%)	−0.03 (3%)	0.7 (0.5%)	0.61 (16%)
Wheat	4.50	0	0.02 (2%)	−0.08 (9%)	−3.3 (2%)	0.94 (24%)
Forest	4.50	0	0.27 (13%)	−0.21 (24%)	−32.3 (11%)	0.89 (39%)

Results from the wheat and forest models come from eight sites; all other results are from the full 15 sites.

July when temperatures are warmest, the 4.5 °C increase provides little additional evaporation in the wheat model despite a soil moisture increase, in contrast to the response in the other models (Fig. 2). This is because wheat is not growing, and roots are not present to extract water from lower soil layers. These results imply that if forests and wheat fields were to be located in the same region, large horizontal gradients in soil moisture would exist under equilibrium conditions. The forestry model assumes that at the beginning of the year (January) soil moisture is returned to saturation conditions both in the current climate and in changed climates, a hypothesis which is far from certain with large climate alterations. When the model was re-run without this assumption, larger soil moisture deficits occurred in some regions, with results closer to the PDSI values.

Future directions

This comparative study raises many questions and suggests much-needed improvements. Primarily, we must increase our understanding of the hydrological cycle; different formulations are possible in models because of the lack of general consensus on the physical processes and their parameterizations. In particular, we need to know how to model many of the processes depicted in Table 1. Can runoff and infiltration be calculated accurately from models that have relatively coarse vertical and horizontal resolution? Does small-scale heterogeneity overwhelm averaged values of surface parameters, used in these models by necessity, and how do we model sub-grid-scale soil moisture (or precipitation)? What is the proper formulation for PET? How accurate is the crop model's low estimate of soil moisture loss for high temperature in the non-growing season? Can large horizontal gradients in soil moisture exist between a forested and agricultural landscape for long periods of time, as implied by these results (Fig. 2)? Is drainage through a permeable bottom layer necessary for accurate representation of surface hydrology (as shown in Table 1, it is included only in the crop models)?

Another possible source of hydrological inconsistencies arises from the different scale sizes used by the models. There are obvious difficulties associated with going from the large scale of the GCM grid boxes (hundreds of kilometres) to the small scales of the physical processes (hundreds of metres), or even down to the level of a single plant (Table 1). Various approaches are being tested, including the interpolation of grid box averages to the smaller scales, the use of empirical relationships between the large and small scales for the current climate, and the embedding of finer-resolution grids within the GCM at particular locations. Although all of these techniques are subject to error, they should be evaluated so as to provide a range of potential forcings.

Other translation problems exist. Because of the difficulties in modelling current precipitation using GCMs, the ratio of the GCM's new-climate to present-climate precipitation is often used to estimate precipitation change, but this approach does not allow for changes in precipitation frequency. It is hoped that improvements in aspects of GCMs such as their physical representation of the land surface[18] and convection[19] will ultimately eliminate the need for this.

The versions of these models that we have compared are those used in the EPA study on the impact of climate change in the United States[20,21]. Most of the models were not originally intended for the purpose of climate-change assessment, and although new versions are being developed, it is necessary to guarantee that we establish a suite of models with consistent hydrological representations and assumptions if they are to be used together.

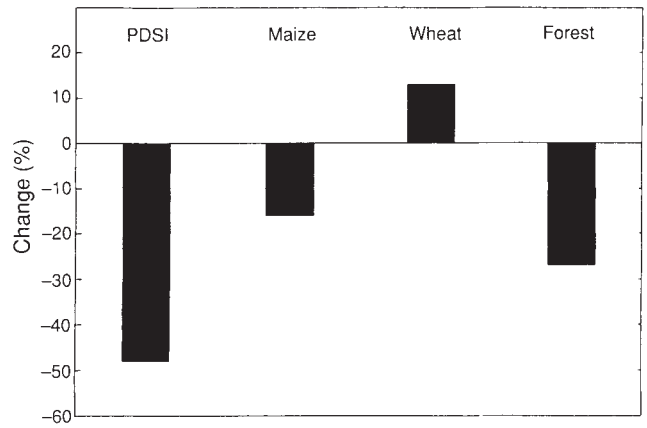

FIG. 2 Soil moisture changes during July caused by 4.5 °C temperature increase in the various impact models.

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The temperature and precipitation forecasts of GCMs are strongly affected by the soil moisture changes, which are directly associated with aspects of their ground hydrology schemes (for example control-run values of soil moisture[22], or run-off over frozen ground[23]); can it really be sensible to use GCM predictions in models that then calculate a very different soil moisture response?

The need to understand hydrological processes better has motivated the Global Energy and Water Cycle Experiment (GEWEX)[24], a component of the World Climate Research Program, which has as an initial goal the observation and modelling of the Mississippi River basin beginning in 1993. In the United States, the interagency Committee on Earth and Environmental Sciences (CEES) has identified the hydrological cycle in general as the highest scientific priority for global change research. Intensive field studies, of the nature of FIFE[25], HAPEX and others[26], will be necessary for a wide variety of terrains in order to answer these basic questions.

To engender consistent and appropriate models, we must foster a community of modellers, concerned both with climate changes and with impacts (IPCC Working Groups I and II). Early communication between these two groups has consisted of the development of 'wish lists' of GCM variables needed for impact studies. The results discussed here reveal some of the weaknesses of this approach, and emphasise that the next stage of communication must concern processes. Interactions are also necessary between modellers in the impact community; with models ostensibly operating for the same site, how much heterogeneity in response is plausible? The climate change and climate impact communities must together use whatever new understanding of hydrological processes arises from present or future programme if we are to improve our assessments of the impact of climate change. □

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