



## CLIMATE CHANGE AND THE HYDROLOGICAL CYCLE

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**ABSTRACT:** The threat of climate change has increased interest in climate research, which focuses on observing, understanding and modelling the five interconnected components that comprise the climate system: atmosphere, oceans, land surface, cryosphere, and biosphere. Feedbacks at a variety of spatial and temporal scales shape the system's overall behaviour, and the hydrological cycle plays a critical role in this respect, via two important feedback processes that involve water vapour and clouds. Climate modelling improves understanding of climate processes and characteristics, and several approaches are available, from simple models to general circulation models (GCM). GCMs offer the most realistic simulations of the global and continental climate, but cannot provide the most important climatic variables to regional-scale hydrological modelling. Therefore, many research groups have begun to use regional circulation models to downscale the coarse-resolution information generated by GCMs; they then apply these driving-fields to hydrological models. Downscaling improves the representation of climatic behaviour, but does not allow for feedback between models. Simple models may offer an alternative for certain hydrological applications.

### 1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) warned, in 2001, that the global climate is changing, largely because of human activities (Mitchell *et al.* 2001). The recognition that climate change could pose a serious threat to the sustainability of our current way of life has led to increasing interest in *climate system* research. Hydrotechnical engineers can contribute greatly to this growing field of study, since they are well-suited to examine the strong connections between the climate system and the hydrological cycle. However, engineers first require a greater understanding of the feedbacks between these two systems. This understanding is crucial, because changes in the climate will trigger long-term, and potentially extensive, changes in the hydrological cycle, with significant impacts on society and on the environment (Arnell *et al.* 2001).

Following the approach of the IPCC (Harvey *et al.* 1997), this paper considers the climate system as composed of five separate components: atmosphere, oceans, cryosphere, land surface, and biosphere. Each component receives a fairly thorough discussion, which focuses on its climatically important characteristics and processes, and the discussion of the atmospheric component explains the basis of anthropogenic climate change. After each component is described individually, a discussion of feedbacks explains the importance of both connections between climate system components, and spatial and temporal scale in determining system behaviour. Two examples of important feedbacks in the climate system are given – both form integral parts of the global hydrological cycle.

In addition to explaining the basis of general circulation model (GCM) use with hydrological applications, an alternative approach is provided, which promotes the use of simple but comprehensive, rather than complex but climate-only models. Such an approach cannot provide high resolution results for hydrological studies, but it includes the social, economic, and environmental context of climate change, which is beyond the capabilities of GCMs.

## 2. CLIMATE SYSTEM COMPONENTS AND FEEDBACKS

Our understanding of the climate system is based on long term observations and modelling work. Climate monitoring provides an observational record of the past and current state of the climate, including mean state and variability. Such information is necessary if we are to understand climate change and its causes, track the results of climate change adaptation and mitigation efforts, and improve and validate climate models. Modelling serves a very different purpose. It allows us to test and improve our understanding of the physical processes that drive the climate system, to identify the feedbacks that operate within and between climate system components, and to predict future changes in regional and global climate (Hartmann 1999).

In climate system research, the atmosphere and the oceans have generally received the most attention from the climate modelling community, which has focused primarily on simulating the processes within and between these two parts of the overall system. While initial work on general circulation models (GCM) considered the atmosphere and oceans separately, resulting in the creation of individual Atmospheric GCMs (AGCMs) and Ocean GCMs (OGCMs), the focus has shifted over the past decade or so to *coupling* the two through the mass, heat, and momentum exchanges, or *flows*, between them. In such coupled models, there is also a growing recognition that the cryosphere, the land surface, and the biosphere play crucial roles in the climate system through feedbacks to the atmosphere and the oceans (Baede *et al.* 2001). This section examines the individual components of the climate system and then describes two of the most important climate feedbacks from a hydrological point of view.

### 2.1. The Atmosphere

One of the two fluid components of the climate system, the atmosphere is characterized by organized circulation, chaotic motions, and random turbulence, and forms the most variable and rapidly changing part of the climate system (Baede *et al.* 2001). The atmosphere has characteristics that vary with height, from sea level to an altitude of roughly 100 km. These changes in physical properties result in a height-based division of the atmosphere into four parts, two of which are relevant to climate change: the *troposphere*, (from sea level to 10-15 km in altitude), and the *stratosphere* (from the top of the troposphere, to about 50 km altitude) (Salby 1992).

The troposphere contains the majority of the earth's weather, and is fundamentally driven by surface heating, which results in "the convective overturning of air [that] characterizes the region" (Salby 1992: 57). The atmospheric circulation in the troposphere depends on imbalances between radiative heating at low- and high-latitudes. This uneven heating leads to a distribution of mass that "drives a meridional overturning of air, with rising motion at low latitudes and sinking motion at high latitudes" (*ibid.*: 67). The atmosphere also circulates latitudinally, because of the Earth's rotation, so that at middle and high latitudes, the general thermal structure approximately parallels the latitudinal circles. The majority of the longitudinal (*meridional*) heat distribution is based on asymmetries in the instantaneous circulation, which leads to heat exchange between the tropics and the poles. At low latitudes, planetary rotation plays a smaller role; instead, the geographical distribution of atmospheric heating determines atmospheric circulation via latent heating and the resulting *Walker* (east-west overturning) and *Hadley* (north-south overturning) circulations. As a consequence of the atmospheric general circulation, temperatures at fixed altitudes in the troposphere decrease poleward from the equator, where they are at a maximum. Furthermore, pressure is only 10% of its surface value at an altitude of 10 km, while temperature falls almost linearly at a *lapse rate* of 6 K km<sup>-1</sup> to roughly 220 K (-53°C) at the same altitude. The stratosphere differs significantly from the troposphere because of weak vertical motions and strong radiative processes

(*ibid.*). Although generally neglected in the past, the IPCC reports that stratospheric effects “can have a detectable and perhaps significant influence on tropospheric climate” (Stocker *et al.* 2001: 433).

The climate varies naturally, but the current changes in the climate system result from anthropogenic emissions of *greenhouse gases* to the atmosphere (Mitchell *et al.* 2001). As a whole, the atmosphere consists primarily of nitrogen and oxygen (78% and 21% by volume, respectively), while argon (0.93%), water vapour, carbon dioxide, ozone, and several other gases make up the remaining 1% of the atmospheric volume (Baede *et al.* 2001; Salby 1992). Nitrogen, oxygen, and argon are not greenhouse gases; however, *trace* gases like carbon dioxide (CO<sub>2</sub>), methane, nitrous oxide, and others are, and therefore both absorb and emit infrared radiation, making them an important part of the Earth’s energy balance. Furthermore, water vapour and ozone, although not directly emitted like the other trace gases, are also highly important, natural greenhouse gases with concentrations that vary according to atmospheric feedbacks. These greenhouse gases allow solar radiation to pass through the atmosphere freely but capture the infrared radiation emitted by the Earth, thereby performing a critical service to all life on Earth – without them the planet would be roughly 33°C cooler, with an average temperature of -18°C rather than a comfortable 15°C (Baede *et al.* 2001).

So the problem is not the greenhouse effect, *per se*. Instead, the current change in climate results from an *enhanced greenhouse effect* (Baede *et al.* 2001), caused by an increase in the atmospheric concentration of anthropogenic trace gases. Increases in *greenhouse gases*, and particularly in CO<sub>2</sub>, enhance absorption and emission of infrared radiation and lead to an increase in the opacity of the atmosphere. Since the Earth emits longwave radiation essentially like a *blackbody radiator*, and an increase in opacity shifts the height at which radiation is emitted to space toward higher, colder altitudes, this decrease in emitting-temperature leads to a reduction in the outgoing longwave radiation, and a consequent increase in global surface temperature (Stocker *et al.* 2001). Overall, the imbalance between incoming and outgoing radiation, called a *radiative forcing*, is very small, at 4 W m<sup>-2</sup> of forcing for a doubling of CO<sub>2</sub>. Without any further feedbacks, this forcing would result in a surface-troposphere temperature increase of roughly 1.2°C (Baede *et al.* 2001). However, the increase in global surface temperatures triggers a series of feedbacks within and between different climate system components, which result in a temperature increase of between 1.5°C and 4.5°C (Stocker *et al.* 2001). These feedbacks relate the atmosphere to all of the other climate components.

## 2.2. The Oceans

As the second of the two fluid components of the climate system, the oceans are more stable than the atmosphere. Oceanic circulation depends on both winds and density contrasts caused by thermal and salinity gradients, and occurs more slowly than the atmospheric circulation (Baede *et al.* 2001). Basically, water in tropical regions stores a great deal of heat from the warm, tropical atmosphere, which ocean currents then transport towards the poles. At higher latitudes, the transported water cools, warming the cooler atmosphere there – this kind of circulation reduces the pole-to-equator temperature gradient. The strongest currents generally take the form of *Western Boundary Currents*, such as the Gulf Stream, Kuroshio, Agulhas Current, and others, which transport much of the heat and fresh water in the climate system. They are mainly wind-driven, with typical widths of 50 km (Stocker *et al.* 2001).

The oceans consist of two vertical layers, the *surface mixed layer*, and the *ocean interior*. The mixed layer is generally more buoyant than water in the ocean interior, being warmer and less salty, and a thermocline, lying at 100 m to 1000 m depth, normally separates the layers. Subduction and convection form the basis of exchanges between the surface and interior. Subductive processes work as follows. In sufficient quantities, turbulent energy can increase the depth of the mixed layer through entrainment of deeper water. However, upwelling at the base of the mixed layer, from *Ekman pumping*, can cause the deepened mixed layer to cool quickly, leading to a shallowing of the mixed layer. When this occurs, water that passes the deepest point of the mixed-layer is transferred to the ocean interior and is *subducted*. Larger horizontal gradients in the mixed layer depth lead to larger subduction rates, meaning that “variations in mixed layer depth are of primary importance in setting the structure of the interior of the ocean” (Stocker *et al.* 2001: 436).

Convection plays a large role in determining the overall circulation of the oceans, and generally depends on seasonal differences in water temperature. At high latitudes during the winter, surface water loses its buoyancy and becomes denser than the water below. The result is mixing of the surface layer with the ocean interior at highly variable mixing depths, which reach their maximum at the end of the cooling season. During the summer, the ocean surface warms, creating a shallow mixed layer that isolates the newly formed deep water from the atmosphere, which currents and mesoscale eddies (at a scale of 50 to 100 km) then transfer into the abyssal ocean. Overall, deep convective mixing “constitutes a very efficient vertical transfer process” (Stocker *et al.* 2001: 436). For example, the Labrador Sea, a major site of open ocean deep convection, replenishes the deep waters of the Atlantic, Pacific, and Indian Oceans. Related to deep convective mixing, *shelf convection* occurs near continents, and is likely the source of the densest bottom water, Antarctic Bottom Water (AABW), which circulates through all three major oceans. Deep water heating, via *diapycnal mixing* across density surfaces in the ocean interior, allows the cold water to rise through the thermocline, slowly returning it to the ocean surface (*ibid.*).

### 2.3. The Cryosphere

The cryosphere consists of all the snow and ice in the climate system, and “includes the ice sheets of Greenland and Antarctica, continental glaciers and snow fields, sea ice, and permafrost” (Baede *et al.* 2001: 88). It has several characteristics that are important to the climate system, including its high reflectivity of solar radiation (*albedo*), low thermal conductivity, and high thermal inertia, and its storage of large quantities of fresh water (*ibid.*).

On the land, snow cover changes the Earth’s albedo and surface roughness, and influences water transfer between snow and soil. Permafrost may affect the climate by releasing greenhouse gases as it thaws, and vegetation changes may influence the radiation balance and surface hydrology as the active layer above permafrost thickens. Land ice also takes the form of glaciers and ice sheets, both of which are formed by the burial and densification of snow. Glaciers come in many shapes and sizes; when they become “continental scale masses of fresh water ice”, they are called ice sheets, which exist either entirely on land or have areas that are afloat (Stocker *et al.* 2001: 448).

Sea ice is impossible to describe without including climate system feedbacks. It serves several purposes in the climate system, moderating the heat exchange between the ocean and atmosphere, transporting fresh water in the ocean, and modifying the surface albedo. Sea ice at higher latitudes influences the extent of visible ocean surface and affects the albedo. Furthermore, ice thickness and open leads (gaps) determine heat releases to the atmosphere and subsequent temperature increases. Finally, sea ice formation can alter oceanic deep water production through the process of *brine rejection* – brine affects surface water density. Because denser water sinks, changes to this process could have “an influence on the water mass structure that stretches far beyond the area of sea ice” (Stocker *et al.* 2001: 446).

### 2.4. The Land Surface

According to Baede *et al.* (2001), land surface characteristics of relevance to the global climate include vegetation cover and soil properties, land surface texture, and the amount of dust, which affects atmospheric radiative processes when wind-borne. Vegetation cover and soil qualities influence the transfer of solar energy from the ground to the atmosphere, as infrared radiation or as latent (evapotranspiration) heat – soil moisture content influences surface temperatures strongly through the energy used in evaporating water. Land surface texture, or roughness, affects atmospheric dynamics through its influence on winds (Baede *et al.* 2001); mountains can also have large effects on the climate at regional and continental scales (Wang *et al.* 2004), or even global scales (Stocker *et al.* 2001).

Climate modellers and hydrological engineers view the land surface fundamentally differently. This difference in focus has a simple root: hydrological engineers interact more directly with society than do climate modellers, working to mitigate water related hazards (floods, droughts, and landslides), and to improve “agriculture and food production, human health, municipal and industrial supply, and environmental quality” (Entekhabi *et al.* 1999: 2043). They also tend to work on hydrological issues at much smaller *spatial* – catchment or municipality, rather than ocean, continent or globe – and *temporal* –

hours, days, years, rather than seasons, decades, centuries – scales, and require much more location-specific data than modellers do.

For climate modellers, the important processes and characteristics of the land surface are those that act at large scales to influence the global climate, and particularly the atmosphere and oceans, through latent and sensible heat transfers in the atmosphere (Stocker *et al.* 2001); snow, ice, or vegetation-cover albedo effects; and water transfers from the continents into the cryosphere or the oceans. Some land-surface schemes now include river routing, improving runoff-modelling from large ( $10^5$  km<sup>2</sup> or greater) drainage basins (McAvaney *et al.* 2001). However, the climate modelling community has begun to improve its representation of land surface processes, realizing that accurate modelling of atmosphere-land surface feedbacks is critical for realistic simulation of continental climate and hydrology (Stocker *et al.* 2001).

Hydrological engineers are interested in precipitation, evaporation, water storage and runoff, which affect soil moisture, groundwater resources, river flows, and lake levels (Arnell *et al.* 2001), and are affected in turn by soil structure, soil chemistry, vegetation, climate and topography (Entekhabi *et al.* 1999). All of these hydrological processes and characteristics play a role in water resources management issues such as “irrigation and drainage, hydropower, flood control, water supply, and inland navigation” (Varis *et al.* 2004: 333). On a large scale, “precipitation drives the continental hydrology, and influences the salinity of the ocean” (Stocker *et al.* 2001: 431). It is, however, highly variable in both space and time: stratiform precipitation, with a spatial resolution of up to and beyond 100 km, dominates in the extra-tropics except over the continents in summer, whereas convective precipitation, with a horizontal scale of only a few kilometres, dominates in the tropics (*ibid.*). Evaporation occurs from open water, shallow groundwater, and water stored on vegetation, and depends on available energy, the moisture content of the air, and air movement; as surface temperatures increase, the level of potential evaporation tends to rise as well, because warmer air holds more water. Water storage in soil influences the rate of actual evaporation and the rate of runoff, and depends on soil properties (Arnell *et al.* 2001). Finally, runoff occurs when precipitation is greater than the sum of the evapotranspiration and water storage in a catchment. Interestingly, with the exception of water storage in aquifers and ice, all of these important hydrological processes involve feedbacks from one component of the climate system to another.

## 2.5. The Biosphere

The biosphere includes both terrestrial and oceanic life. Terrestrial life plays an important role in the global carbon cycle, the hydrological cycle, and the surface albedo, all of which involve feedbacks between different climate system components. Oceanic life helps to moderate atmospheric CO<sub>2</sub> concentrations. In terms of the carbon cycle, apparent enhancements of photosynthetic versus respiration rates in the last several decades imply that the global carbon cycle could strongly influence the future concentrations of atmospheric carbon dioxide, and thus reduce both the rate and extent of global warming (Stocker *et al.* 2001). However, temperature increases associated with higher atmospheric CO<sub>2</sub> concentrations may also enhance microbial decomposition of soil matter, resulting in releases of CO<sub>2</sub> (Falkowski *et al.* 2000) – views are mixed on this subject (Melillo *et al.* 2003).

On time scales of millennia, the oceans determine atmospheric CO<sub>2</sub> concentrations through two fundamental processes: the *solubility pump* and the *biological pump* (Falkowski *et al.* 2000). Oceanic convection transfers surface water containing dissolved CO<sub>2</sub> into the deep ocean, providing an effective, long-term means of carbon storage in the ocean interior; however, CO<sub>2</sub> is most soluble in cold, saline water, so the solubility pump may become less effective as surface temperatures rise. The biological pump may provide an alternative. Phytoplankton use carbon dioxide for photosynthesis, which lowers the partial pressure of CO<sub>2</sub> in the upper ocean and promotes its absorption from the atmosphere. Furthermore, certain species of phytoplankton and zooplankton form dense calcium carbonate shells. When they die, their shells ‘rain’ down into the deeper water – this *carbonate pump* therefore also results in CO<sub>2</sub> transfer to the ocean interior (*ibid.*).

In terms of the hydrological cycle, increasing atmospheric CO<sub>2</sub> concentrations allow vegetation to maintain the same photosynthetic rate at a lower evapotranspiration rate (Stocker *et al.*, 2001), which may result in a decrease in transpiration. However, CO<sub>2</sub>-fertilization causes plants to grow faster and larger, and may

counteract CO<sub>2</sub>-driven increases in vegetation's water use efficiency (Arnell *et al.* 2001). Unfortunately, the effects of increasing carbon dioxide on terrestrial vegetation are therefore difficult to predict.

Finally, terrestrial vegetation can influence local albedo strongly, potentially affecting not only regional, but even global climate. For example, many hope that increased forest cover at high latitudes will help to sequester CO<sub>2</sub>, thereby reducing its atmospheric concentration; however, since forests are generally darker than open land, the resulting lower surface albedo may cause boreal and cool-temperate forests to warm the climate. Overall, vegetation effects on climate are simply not straightforward, since boreal forests tend to warm the environment through decreased albedo, while tropical forests generally cool and moisten the local climate through evapotranspiration (Betts 2000).

## 2.6. Feedback Processes

Issues of connectivity and scale are critical in feedback relationships. Clearly, although climate system feedbacks exist both within particular system components and between them, the descriptions of climate system components above focussed, where possible, on the processes and characteristics relevant to *individual parts* of the overall system. In explaining the components separately, the aim was twofold: first, to improve understanding of the climatically-important elements of each system component; and second, to demonstrate how climate behaviour arises from, and depends on, links between components. The Earth system functions as a whole, not as separate parts. Feedbacks between components are critical to understanding climatic behaviour, because the system is *complex*. According to Rind (1999: 105), “a complex system is literally one in which there are multiple interactions between many different components” – a description that matches the climate system perfectly. However, despite its complexity, the climate is not entirely unpredictable (Baede *et al.* 2001), and typically exhibits linear behaviour to small changes in *external* forcings. In the highly improbable circumstances that climate forcings exceed certain *thresholds* (Weaver and Zwiers 2000), the climate system undergoes dramatic reorganizations (Stocker *et al.* 2001). Overall, then, connectivity issues form the basis of understanding and predicting the response of the climate system to anthropogenic forcings,

Feedbacks can connect small to large scales, as described in the examples below. However, spatial and temporal scales are generally important for a different reason: they determine which feedbacks to include in climate *models*, and which to neglect. Essentially, the feedbacks included in a model depend on the model's purpose. For example, in modelling global-mean temperature, the accuracy of regional precipitation predictions is unimportant, since GCMs that cannot predict regional climate already simulate surface air temperature “particularly well... with nearly all models closely matching the observed magnitude of variance and exhibiting a correlation >0.95 with the observations” (McAvaney *et al.* 2001: 482); however, if the flooding of a small catchment is of interest, local rainfall predictions are clearly critical. This section therefore describes feedbacks that are important at global versus regional scales – a discussion more useful to hydrological engineers than one dealing with differences in temporal feedback scales between months and millennia. It turns out that two of the most important feedbacks at any scale relate directly to the hydrological cycle: the water vapour feedback, and the cloud feedback.

Water vapour is the strongest greenhouse gas (Baede *et al.* 2001): its associated feedback approximately doubles the climate warming from what it would be with fixed atmospheric levels (Stocker *et al.* 2001). At present, the amount of water vapour in the atmosphere can certainly increase, as the majority of the troposphere is highly undersaturated with respect to water (Hartmann 1999). The feedback functions as follows. Water vapour enters the atmosphere through evaporation from either the land surface or from the oceans, and the lateral transport of water through the atmosphere supplies the necessary moisture for precipitation and runoff. Once in the atmosphere, increases in the “abundance and vertical distribution of water vapour [cause very strong interactions] with convection and cloudiness, thereby influencing the albedo of the planet as well as the infrared opacity of the atmosphere” (*ibid.*: 77). In general, large spatial scales apply to water vapour feedbacks, because of the large-scale atmospheric circulations that influence the horizontal water vapour concentrations (Hartmann 1999) – for example, “less than 20% of the precipitation that falls comes from evaporation within a distance of about 1000 km” (Trenberth 1999: 331). However, along with exchanges of energy, moisture transfers between soil, vegetation, snow, and the overlying atmosphere determine a large part of regional climate (Entekhabi *et al.* 1999). Overall, the water

vapour feedback, as just one part of the hydrological cycle, involves interaction between the atmosphere, oceans, land surface, and biosphere.

Clouds and water vapour are directly connected: clouds serve as both sources and sinks for water vapour, while water vapour provides the foundation for cloud formation (Stephens 2005). Like water vapour, clouds have strong effects on the climate system; unlike water vapour, the cloud response to climate change “remains a dominant source of uncertainty” in climate modelling and prediction (Stocker *et al.* 2001: 427). Indeed, at present there is not even a theoretical basis for predicting the sign of cloud-cover feedback (Hartmann 1999). Overall, the difficulty with the cloud feedback is its complexity: while the large-scale atmospheric processes determine the formation and evolution of clouds, short temporal and spatial scales control important radiative and latent heating processes that feed back to the global scale (Stephens 2005). For example, buoyancy, moisture and condensation interact on scales of millimetres to tens of kilometres to determine the behaviour of critical convective processes (Stocker *et al.* 2001). Latitude and altitude also play a role: at low latitudes, clouds warm the surface by increasing *infrared* radiation absorption and reducing *longwave* emissions to space, but also cool the surface by directly reflecting *solar* radiation to space; at high latitudes, they seem to operate in the opposite fashion. To confuse the issue further, high, cold clouds warm the atmosphere, while low clouds cool the atmosphere, especially at high latitudes. And yet, in spite of this complexity, it is important that the cloud feedback is understood, because cloud feedbacks “are likely to control the bulk precipitation efficiency and associated responses of the planet’s hydrological cycle to climate radiative forcings” (Stephens 2005: 269). Cloud process modelling at various scales has provided considerable insight into the cloud feedback (Stocker *et al.* 2001) – climate modelling is the subject of the next section.

### 3. MODELS OF THE CLIMATE SYSTEM

At least three main categories of climate models exist, with their classification based on both model resolution and purpose. *Simple models* have low temporal and spatial resolution, and produce zonally- or globally-averaged results for temperature, but not for other variables such as rainfall; however, they are computationally fast and their behaviour is easy to understand (Harvey *et al.* 1997). *Earth System Models of Intermediate Complexity* (EMIC) sit in the middle of the climate model range, being simpler and lower resolution than GCMs, and therefore running much faster. However, they are also much more comprehensive than simple models, and explicitly couple components of the Earth system (Claussen *et al.* 2002). Finally, *General Circulation Models*, or *Global Climate Models* (GCM), calculate “the full three-dimensional character of the climate comprising at least the global atmosphere and the oceans. The solution of a series of equations that describe the movement of energy, momentum, and various tracers... and the conservation of mass is therefore required” (McGuffie and Henderson-Sellers 1997: 48). Of the three model types, GCMs provide the most realistic and complete representation of climate.

Current coupled GCMs join atmospheric and oceanic components with generally simple sea-ice and land-surface process models (McAvaney *et al.* 2001). These models run, with typical time-steps of 30 minutes, at variable resolutions on a three-dimensional grid: AGCMs typically employ horizontal resolutions of roughly 250 km and 10 to 30 vertical levels, while typical OGCMs have horizontal resolutions of 125 to 250 km, and vertical resolutions of 200 to 400 m (Baede *et al.* 2001). Overall, GCMs produce credible simulations of annual mean climate and seasonal cycles that are useful even at the sub-continental scale, but their resolution is insufficient to provide regional predictions of climate change, mostly because of poor simulation of land-surface processes. They therefore cannot simulate regional rainfall, much less extreme events: “extreme precipitation is difficult to reproduce, especially for the intensities and patterns of heavy rainfall which are heavily affected by the local scale” (McAvaney *et al.* 2001: 508). Indeed, with grid resolutions generally greater than 200 km, models cannot even resolve many precipitation-related processes, which must therefore be parameterized (Stocker *et al.* 2001).

GCM results are extremely hard to evaluate because of model complexity, which places severe limits on analyzing and understanding the models’ processes, interactions, and uncertainties (McAvaney *et al.* 2001). Simulations require so much computational power and time that only limited numbers of multi-decadal experiments can be performed (Claussen *et al.* 2002), and model intercomparison projects have

trouble obtaining the necessary broad participation (Stephens 2005). However, such intercomparisons are crucial, because there is no 'best' model, making combinations of results from many coupled models necessary for accurate prediction of climate change effects (McAvaney *et al.* 2001).

#### 4. LINKING CLIMATE AND HYDROLOGICAL MODELS

Although climate change will certainly affect the hydrological cycle, its results will not be distributed uniformly over the globe. Because of the potentially drastic consequences for societies and ecosystems of water scarcity or overabundance, an increasing number of researchers have attempted to determine the results of climate change in specific regions, or for certain river basins. In general, they have used at least four approaches to assessing climate change impacts on catchments and river basins, including "(1) estimates obtained by applying arbitrary changes in climate input to hydrological models, (2) spatial analogue techniques, (3) temporal analogue techniques, and (4) the use of results from GCMs, either directly or by downscaling to the appropriate catchment scale" (Arora and Boer 2001: 3335).

Of the four options, GCM-derived results present the best choice for hydrological model inputs, although the application of a GCM to regional or smaller scales presents certain difficulties, the most obvious of which lies in the incompatibilities between model scales. The variables provided by GCM simulations rarely match those required by hydrological applications – GCMs can provide, for example, mean river flow, mean and seasonal groundwater recharge, and mean seasonal (monthly) variation in river flow, but they cannot directly give flow-duration curves of river flow, run-sums for reservoirs, mean annual flood, and so on (see Varis *et al.* 2004: 333 for further details). Unfortunately, even the direct use of GCM data is problematic, as it often gives "inaccurate hydrological simulations due to the different temporal and spatial scales used in GCMs and hydrological models" (*ibid.*: 333).

Manabe *et al.* (2004), Wood *et al.* (2005), and Arora and Boer (2001) describe applications of GCMs to hydrological modelling. Manabe *et al.* (2004) attempt to determine the effects of quadrupled atmospheric CO<sub>2</sub> concentrations on river discharge and soil moisture, using a relatively coarse-resolution coupled GCM and a hydrological 'bucket' model, in which a bucket represents the moisture-holding capacity of each continental grid box. They find that water-rich areas will receive more water, and water-poor areas will lose more water under climate change, and discuss their results in terms of climatic processes and feedbacks, rather than comparing them with observations. Wood *et al.* (2005) compare forecasts of streamflow and other seasonal hydrological variables obtained from climate models versus forecasts formed via resampling of climate observations, and obtain variable results: "while climate model forecasts presently suffer from a general lack of skill, there may be locations, times of year, and conditions (e.g. during El Nino or La Nina) for which they improve hydrological forecasts..." (*ibid.*: 15). Arora and Boer (2001) analyze the hydrology of 23 major river basins as atmospheric CO<sub>2</sub> concentrations increase by 1% year<sup>-1</sup> from the present until 2100. They determine the effects of climate change on basin-wide averaged mean annual precipitation, evapotranspiration, and discharge, monthly streamflow at the river mouths, and changes in extreme flow events; however, because of differences in mean annual precipitation between model simulations and observations, "the values of mean annual discharge from the control simulation do not always compare well with observations" (*ibid.*: 3338) – note that the simulated mean annual runoff was within 20% of the observed estimates for only 4 of the 23 river basins (Varis *et al.* 2004).

Downscaling provides an alternative to the problems posed by using GCMs to drive hydrological models directly. Although a variety of techniques exist, including statistical-empirical, dynamical, and statistical-dynamical methods (Varis *et al.* 2004), this paper describes *dynamical downscaling*, because of its close connection to GCMs and climate modelling. Dynamical downscaling involves the use of a fine-resolution model, called a *Regional Circulation Model* (RCM), to provide driving-fields of climatic variables to hydrological models. Most RCMs are applied at a spatial resolution of 30 to 100 km to a grid-box side; however, some research groups have run multi-year simulations at a resolution of between 10 and 20 km. Since most RCMs simulate regions of the Earth, rather than the whole globe, they require input at their lateral boundaries from either GCMs or observational data (Wang *et al.* 2004). They certainly offer advantages over coarser models in predicting regional climate, such as temperature biases of only about



2°C, and precipitation biases of about 50% of observations, for models with 50 km horizontal resolutions that are driven by climate observations. However, RCMs also have drawbacks, including high computational cost, sensitivity to errors in the driving GCM, and a lack of feedback from RCM to GCM, since RCMs are usually 'one-way nested' in GCMs (*ibid.*). Furthermore, when driving-fields from RCM climate simulations form the input to hydrological models, the same feedback issues arise, especially if GCMs drive RCMs, and RCMs drive hydrological models in turn, with no feedbacks from any finer- to coarser-resolution models.

Overall, RCMs provide better forcings for hydrological models than GCMs do. Kim (2005) investigates the effects of climate change on extreme events in the Western United States, using a 36-km resolution RCM forced by a single GCM simulation. He describes the changes in hydrological variables associated with an increase in atmospheric CO<sub>2</sub>, and finds overall that climate change will increase extreme events in the region, both in terms of the number of wet days and the mean intensity of the events, and that the changes will occur most strongly in mountainous regions. Kleinn *et al.* (2005) simulate streamflows in the Rhine basin, using a set of two RCMs that were driven by weather observations, coupled to a fine-resolution (1 km grid-size) hydrological model. Their modelling configuration includes a coarse resolution RCM (56 km grid-size) and its nested fine-resolution RCM (14 km grid-size), "a distributed hydrological runoff model, and a downscaling interface for the one-way coupling of the two models" (*ibid.*: 2). They find that, although the finer model captures regional precipitation patterns better than its coarser counterpart, there are no appreciable differences in the simulated hydrological outputs, probably because of the aggregation of precipitation in the hydrological model. Finally, Andreasson *et al.* (2004) simulate the results of climate change on six river-basins in Sweden, using two GCMs to provide climatic driving-fields for two RCMs, which drive a hydrological model in turn. They explain that changes in large-scale circulation patterns between the two GCMs play a large role in determining the outputs of the hydrological models, and conclude that regional impact studies must use more than one global model. They also provide a list of expected changes in local climate in Sweden, including increased runoff in the north and decreased runoff in the south of the country, and changes in seasonal behaviour.

## 5. MODELLING FEEDBACKS

The modelling approaches discussed up to this point offer complex representations of the climate system, and can resolve sub-continental (GCMs), and even regional (RCMs), variations in climate with a fair level of accuracy. Furthermore, despite difficulties in predicting certain highly-local climate characteristics like precipitation, there is good reason to believe that improvements both in model resolution and in the representation of physical processes will lead to better models, better agreement with climate observations, and ultimately more reliable predictions. However, climate models currently cannot provide the kind of fine detail necessary for hydrological modelling at the catchment scale, and computational requirements mean that very few studies can be run and for very short simulated periods; the results of simulations can also be very hard to evaluate because of the complexity of these high-resolution models. On top of all these problems, GCMs ignore connections between the climate system and the socio-economic system, which share important feedbacks – after all, anthropogenic emissions are responsible for the current changes in global climate.

Therefore, another option is the use of more comprehensive, but less complex models. Simple models offer a means of improving our understanding of the feedbacks that connect the climate with the carbon cycle, the energy sector, economics, population, government, and social welfare. These models sacrifice resolution for completeness, and so cannot provide useful inputs to catchment-scale hydrological projects, or include the number of physical processes present in GCMs; however, high-resolution models currently cannot provide reliable regional information either, as demonstrated above. Furthermore, simple models supply a context for climate change, which global models driven by emissions scenarios cannot offer; they run very quickly on simple computers, making multiple simulations and an assessment of model sensitivities possible; and they improve our understanding of the feedbacks between the socio-economic and climate systems.

Both Nordhaus and Boyer (2000) and Fiddaman (2002) have developed simple climate-economy models, called DICE and FREE, respectively; such models attempt to include a broad range of relevant disciplines in the modelling process, and to provide information suitable for policy development. Our current work builds on DICE (Nordhaus and Boyer, 2000) and FREE (Fiddaman 2002), improving the representation of physical processes by developing more complex models of the climate system and the carbon cycle. We use a methodology called *System Dynamics* that can both deal with long time delays, multiple feedback processes, and other elements of dynamic complexity (Sterman 2000); and also combine the very different research fields of engineering and the natural sciences, political science, and economics. Overall, our research will contribute to an understanding of climate change, add to number of approaches available for climate change modelling, introduce system dynamics with its *explicit* feedback processes to the earth-system modelling community, and link scientific and socio-economic disciplines.

## 6. CONCLUSIONS

The *atmosphere* and the *oceans* have generally been the focus of climate modelling in the past; however, the other components of the climate system, *cryosphere*, *biosphere*, and the *land surface*, have received increasing amounts of attention lately, as their role in determining not only local, but global, climate has become clearer. As the concentrations of anthropogenic emissions, especially carbon dioxide, in the atmosphere rise, radiative forcings enhance the natural greenhouse effect and lead to warmer surface temperatures. Increases in surface temperatures trigger a series of feedbacks that result in temperature increases of between 1.5°C and 4.5°C – the most important feedbacks are tied to the hydrological cycle: the water vapour- and the cloud-feedback. The oceans transport heat from low latitudes to colder, mid- and high-latitudes, moderate climate variability, and provide the majority of the water in the climate system. The cryosphere has climatically important characteristics such as high albedo, low thermal conductivity, and high thermal inertia, and sea ice is particularly important to climate properties at high latitudes. The land surface affects albedo, evapotranspiration, and atmospheric dynamics via vegetation cover, soil properties, and land surface texture. Finally, the biosphere is involved in the global carbon cycle, the hydrological cycle, and the surface albedo.

The Earth system functions as a whole. Feedbacks within and between individual climate system components largely determine its overall behaviour, and so an appreciation of both complexity and the nature of feedback processes is critical to an understanding of the climate. Spatial and temporal scales also play an important role in the climate system by tying together small- and large-scale, and short- and long-term, processes; however, a model's purpose also determines the relevant connections and feedback scales to include for best results. The water vapour feedback and the cloud feedback serve as examples of the interconnectedness of the climate system and of the importance of scale in understanding system behaviour. Both feedbacks relate directly to the global hydrological cycle.

General circulation models couple atmospheric and oceanic components with simple sea-ice and land surface models. The resulting coupled GCMs produce credible simulations of continental to sub-continental scale, but cannot resolve regional and local climate or particularly variable behaviour accurately. When used with high-resolution hydrological models, GCM results can provide driving-fields for regional circulation models, which seem to improve the reliability of hydrological predictions, or can be applied directly to hydrological models. Generally, however, incompatibilities between model scales present difficulties in obtaining accurate predictions of climate change impacts on river-basin or catchment hydrology. Furthermore, model 'nesting' from GCM to RCM to hydrological model leads to high computational costs, a lack of feedback relationships from finer- to coarser-resolution models, and sensitivity to errors in driving-fields.

Another option is the use of simple rather than complex models. Such models cannot provide the fine detail necessary for studies of small catchments, and most cannot even simulate variables such as rainfall. However, simple models can include the vital feedbacks that connect human activities to the global climate, and can therefore present important processes as feedbacks to other processes, rather than resorting to driving-fields. They also allow multiple simulations in a short time, easy comprehension of model behaviour, and simple sensitivity analysis. In essence, when choosing between the use of

GCMs and simple models, one must decide whether to sacrifice resolution for completeness, or whether to sacrifice completeness for resolution. Since anthropogenic effects form one of the largest uncertainties facing climate prediction efforts, it makes sense to include them in our models. Hydrological engineers deal with climatic variables, but social need and general well-being form the overall context of their work.

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