Potential Impacts of a Warming Climate on Water Availability in Snow-Dominated Regions

Article *in* Nature · December 2005

DOI: 10.1038/nature04141 · Source: PubMed

J. C. Adam
Washington State University

REVIEWS

Potential impacts of a warming climate on water availability in snow-dominated regions

T. P. Barnett[1], J. C. Adam[2] & D. P. Lettenmaier[3]

All currently available climate models predict a near-surface warming trend under the influence of rising levels of greenhouse gases in the atmosphere. In addition to the direct effects on climate—for example, on the frequency of heatwaves—this increase in surface temperatures has important consequences for the hydrological cycle, particularly in regions where water supply is currently dominated by melting snow or ice. In a warmer world, less winter precipitation falls as snow and the melting of winter snow occurs earlier in spring. Even without any changes in precipitation intensity, both of these effects lead to a shift in peak river runoff to winter and early spring, away from summer and autumn when demand is highest. Where storage capacities are not sufficient, much of the winter runoff will immediately be lost to the oceans. With more than one-sixth of the Earth's population relying on glaciers and seasonal snow packs for their water supply, the consequences of these hydrological changes for future water availability—predicted with high confidence and already diagnosed in some regions—are likely to be severe.

Water is essential to human sustenance. Well over half of the world's potable water supply is extracted from rivers, either directly or from reservoirs. The discharge of these rivers is sensitive to long-term changes in both precipitation and temperature, particularly in the snowmelt-dominated parts of the world. Changes in the amount of precipitation tend to affect the volume of runoff and particularly the maximum snow accumulation, which usually occurs near the end of the winter at the onset of the melt season. On the other hand, temperature changes mostly affect the timing of runoff. Increasing temperatures lead to earlier runoff in the spring or winter, and reduced flows in summer and autumn—at least in the absence of changes in precipitation.

In general, the direction and (to a lesser extent) the magnitude of surface temperature changes are much more consistent among climate models than are precipitation changes[1]. Near-surface air-temperature predictions from existing global climate models that are forced with anthropogenic increases in atmospheric greenhouse gas concentrations imply a high degree of confidence that future changes to the seasonality in water supply will occur in snowmelt-dominated regions. Even for models with temperature sensitivities near the lower end of the predicted range, impacts on snowmelt-dominated regional water resources are substantial[2]. Indeed, such changes are already obvious in the observational records of key components of the hydrological cycle, such as snow pack in the western USA[3–5]. Taken together, the predictions and observations portend important issues for the water resources of a substantial fraction of the world's population.

It is generally thought that increasing greenhouse gases will cause the global hydrological cycle to intensify[1], with benefits for water availability[1,6], although a possible exacerbation of hydrological extremes may counteract the benefits to some degree. However, in regions where the land surface hydrology is dominated by winter snow accumulation and spring melt, the performance of water management systems such as reservoirs, designed on the basis of the timing of runoff, is much more strongly related to temperature than to precipitation changes. Even though there is relatively little agreement among the global models as to the magnitude (and even direction of) precipitation changes regionally[7–10], there is no indication for a seasonal shift of precipitation to the summer and autumn. The projected changes in temperature therefore strongly imply future changes of seasonal runoff patterns in snowmelt-dominated regions.

The hydrological cycle at the land surface includes the processes of snow/ice accumulation and melting as well as the impact these processes will have on regional changes in evaporative demand. In a warmer climate, snow will melt earlier in the year than it did before and in some places this has already happened[3,11,12]. Taken together, these impacts mean less snow accumulation in the winter and an earlier peak runoff in the spring.

On a global scale, the largest changes in the hydrological cycle due to warming are predicted for the snow-dominated basins of mid- to higher latitudes, because adding or removing snow cover fundamentally changes the snow pack's ability to act as a reservoir for water storage[13]. Studies in various regions of the globe indicate that the stream-flow regime in snowmelt-dominated river basins is most sensitive to wintertime increases in temperature[12,13]. Because of this, and also because there is little certainty in precipitation predictions[7–10], we focus here on the sensitivity of water resources in snowmelt-dominated regimes to temperature.

All models show warming with increasing greenhouse gases, so we can begin to say with some certainty how some critical components of the hydrological cycle will respond in the future.

Global distribution of snowmelt-dominated runoff

We used a spatially distributed macroscale hydrology model[14] to identify the regions of the globe where snowmelt plays a dominant

[1]Climate Research Division, Scripps Institution of Oceanography, La Jolla, California 92093, USA. [2]Department of Civil and Environmental Engineering, [3]Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington 98195-2700, USA.

role in the seasonal patterns of stream-flow. The model was run over all global land areas (excluding Antarctica and Greenland) at a spatial resolution of 0.5° latitude/longitude for a twenty-year (1980–1999) period. We approximated the importance of snow to annual runoff by using the ratio R of the accumulated annual snowfall to annual runoff (Fig. 1, colour scale). This allowed us to determine whether or not runoff for each grid cell is snowmelt-dominated by using the criterion that $R > 0.5$ for these cells.

We compared, for each of the world's major river basins, the simulated annual runoff to the estimated reservoir storage capacity[15,16] in order to determine cases where reservoir storage capacity is adequate to buffer large seasonal stream-flow shifts (and hence exclude basins that, in spite of being snowmelt-dominated, would be insensitive to shifts in runoff timing). Watersheds within the snowmelt-dominated domain that meet these criteria include the Colorado River, the Churchill River and the Grand River (all in North America), and the Angara River (a tributary of the Yenisei River) in Asia. The red outline in Fig. 1 shows the domain where runoff is snowmelt-dominated minus the four basins identified as having large storage capacities relative to runoff. Within this domain, water resources are arguably susceptible to warming-induced shifts in stream-flow seasonality.

In general, the snowmelt-dominated regions occupy parts of the globe that are at latitudes greater than ~45° (North and South), with some exceptions. (1) Mountainous regions (except those nearest the Equator) are generally snowmelt-dominated (the inset of Fig. 1 shows the regions of the world that are topographically complex according to a criterion based on average slope[17]). (2) Some regions poleward of 45° North that are warmed by oceans do not experience enough snowfall to be snowmelt-dominated (for example, parts of Europe and the coastal regions of the USA Pacific Northwest and British Columbia). (3) Cold dry regions that experience little wintertime precipitation also do not receive enough snowfall to be snowmelt-dominated (for example, northeastern China).

The domain of influence within the red line of Fig. 1 is almost certainly underestimated, because the criterion we used is applied on a grid cell by grid cell basis, and does not account for areas where water availability is predominantly influenced by snowmelt that is generated upstream. Therefore, we extended the domain of influence into sub-basins where the annual runoff originating in the snowmelt-dominated cells accounts for at least 50% of the runoff for the entire sub-basin (black lines in Fig. 1). These regions include parts of northern China, northwestern India, areas south of the Hindu Kush, sub-basins downstream of the southern Andes, north-central USA, and some coastal areas of western North America and Europe. According to a year 2000 population map[18], approximately one-sixth of the world's population lives within this combined snowmelt-dominated, low-reservoir-storage domain. The population affected by warming-induced shifts in water availability is most probably greater than this estimate because we do not account for populations that derive their water resources from outside the basins in which they dwell. Note that the combined region in Fig. 1 encompasses much of the industrialized world, accounting for roughly one-quarter of the global gross domestic product.

Evapotranspiration in a warming climate

Our discussion so far has focused on the direct effects of warming on stream-flow seasonality in snowmelt-dominated regions. Warming-induced changes to evapotranspiration may also affect regional water availability. Unfortunately, there is little agreement on the direction and magnitude of historical, let alone one predicted, evapotranspiration trends. Observations from various countries in the Northern Hemisphere show that pan evaporation has been steadily decreasing for the past fifty years, contrary to the expectation that warming would cause increased evaporation[19–22]. Two proposals exist to explain this paradox.

First, decreasing pan evaporation trends may be indicative of increasing actual (as opposed to potential) evapotranspiration in moisture-limited regions because increased land surface evaporation alters the humidity regime surrounding the pan, causing the air over the pan to be cooler and more humid[23–26]. Second, consistent declines of pan evaporation, diurnal temperature range, and global solar irradiance suggest that actual evapotranspiration is also declining because of increased cloudiness and concentrations of atmospheric aerosols that systematically reduce surface energy availability for evaporation[19,27–29]. Changes in wind speed or in the attenuation of wind at the surface due to changes in vegetation at observing sites

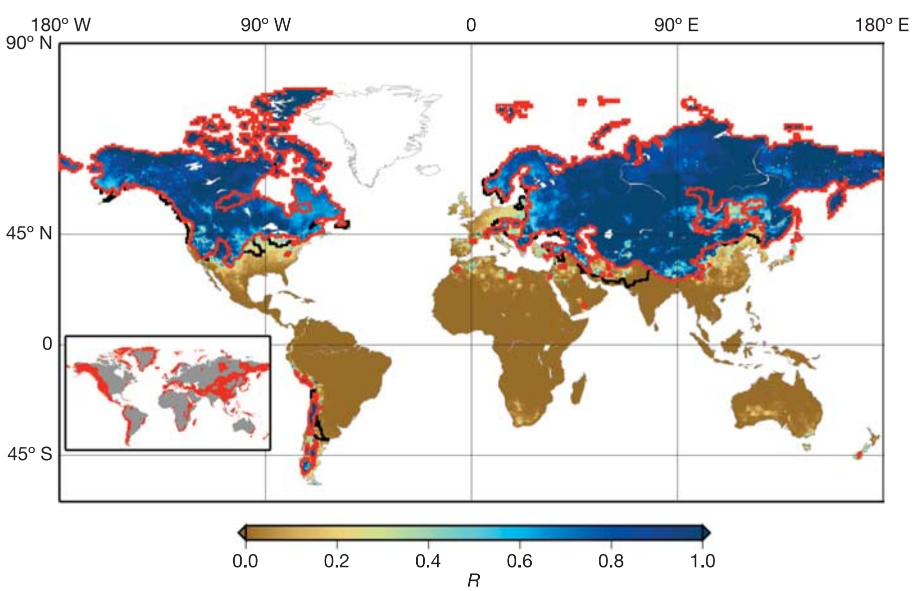

Figure 1 | Accumulated annual snowfall divided by annual runoff over the global land regions. The value of this dimensionless ratio lies between 0 and 1 and is given by the colour scale, R. The red lines indicate the regions where streamflow is snowmelt-dominated, and where there is not adequate reservoir storage capacity to buffer shifts in the seasonal hydrograph. The black lines indicate additional areas where water availability is predominantly influenced by snowmelt generated upstream (but runoff generated within these areas is not snowmelt-dominated). The inset shows regions of the globe that have complex topography using the criterion of ref. 17.

may also play some role in apparent downward trends in pan evaporation data[30].

Ohmura and Wild[28] discuss some complications that impede our understanding of global trends in evapotranspiration. In snowmelt-dominated regions, though, these uncertainties are arguably of reduced importance, because changes in the timing of snowmelt runoff induce a negative feedback on changes in evapotranspiration. Earlier melt results in increased soil moisture (and so also the water available for evapotranspiration) earlier in the season, a time when potential evaporation (dominated by net radiation) is low. Later in the year, when potential evaporation is higher, the shift in snowmelt timing reduces soil moisture, and hence evaporative resistance is increased, again reducing the effect of evaporation changes. Therefore, although changes in evapotranspiration are critical to runoff production in most hydrological regimes, their effect (and hence the effects of the above-noted uncertainties) are attenuated in the snowmelt-dominated regions of the globe.

Impacts on regional water supplies

We examine three case studies from different parts of the world that are in the snowmelt-dominated domain. These case studies were selected to help provide an appreciation for the magnitude of the potential regional water problems that may be associated with shifts in the seasonality of runoff associated with climate change.

Western USA. The Accelerated Climate Prediction Initiative (ACPI)[2] demonstration project was launched in 2000 to investigate the impacts of greenhouse warming on water supplies in the western United States[31]. The methods and detailed results are included in 16 papers in a special volume of the journal *Climatic Change*[2]. The most obvious signature of climate change in the simulations generated by this project was a general warming over the western USA: a warming that by the middle of the 21st century was projected to be 0.8–1.7 °C greater than present values. This warming is projected to be accompanied by little or no change in precipitation according to the climate change scenarios generated for the project by the NCAR-DOE Parallel Climate Model[2]. In the western USA, much of the annual precipitation falls as snow in the mountains during the winter, and then melts during the spring and summer: that is, it is within the red lines shown in Fig. 1.

The most significant impact of a general warming was found to be a large reduction in mountain snow pack and a substantial shift in stream-flow seasonality, so that by 2050, the spring stream-flow maximum will come about one month earlier in the year. There is not enough reservoir storage capacity over most of the West to handle this shift in maximum runoff and so most of the ‘early water’ will be passed on to the oceans. These hydrological changes have considerable impacts on water availability and are discussed in the literature[2]. For example, in the Columbia River system, less winter snowfall and earlier melting will force residents and industries to face, by 2050 or before, a choice of water releases for summer and autumn hydroelectric power or spring and summer releases for salmon runs. The ACPI research shows that, with the predicted climate change, the river cannot be managed to accommodate both, unless we are ready to accept substantial (10–20%) reductions of hydropower generation or serious harm to the federally protected salmon population of the region (Fig. 2)[32].

The Rhine River in Europe. Climate-change simulations project a warming in the Rhine River basin of 1.0–2.4 °C over present values by the middle of the century[1]. Hydrological simulations suggest that this warming will shift the Rhine River basin from a combined rainfall and snowmelt regime to a more rainfall-dominated regime, resulting in an increase in winter discharge, a decrease in summer discharge, increases in the frequency and height of peak flows, and longer and more frequent periods of low flow during the summer[33]. Socio-economic implications include: a reduction in water availability for industry, agriculture and domestic use during the season of peak demand (which is further stressed by an increase in summertime demand due to higher temperatures); an increase in the number of low-flow days during which ships cannot be fully loaded on major transport routes (causing an increase in transportation costs); a decrease in the level of flood protection (given no additional implementation of flood defence measures); a decrease in annual hydropower generation in some parts of the basin; and a loss in revenue due to a shortened ski season[33].

Canadian prairies. Climate studies for the Canadian prairies generally agree that a doubling of atmospheric CO_2 will result in an increase in surface air temperature (possibly as much as 8 °C during winter), a decrease in snow pack, an earlier snowmelt, and a decrease in summer soil moisture[34]. These effects and a longer period of low flows during summer and autumn could lead to an increase in the frequency and severity of droughts[35]. Historically, nearly 50% of the water use over the Canadian prairies has been for agriculture through irrigation, and this demand has been met primarily with surface water, unlike the prairies of the USA, which rely also on groundwater[34,36]. For this reason and because stream-flows are limited and extremely variable from year to year, agriculture in the Canadian prairies is very sensitive to drought[34,36]. Although global climate models do not predict great changes in precipitation for Canada, an earlier spring runoff peak will probably cause agriculture in the Canadian prairies to become more at risk in a warming climate[37]. Furthermore, increased water demand for irrigation will also lead to heightened competition with other water needs, including stream-flow requirements to maintain aquatic habitat, and the needs of water users downstream of the Alberta–Saskatchewan border (under a 1969 agreement, Alberta must allow 50% of stream-flow to pass downstream of the border)[36].

Summary of regional impacts. The studies summarized above show that current demands for water in many parts of the world will not be met under plausible future climate conditions, much less the demands of a larger population and a larger economy.

The physics behind this statement is temperature-driven, not precipitation-driven, and this makes the conclusions robust because all current models predict a warmer future world. The other key factor affecting water availability is the lack of enough reservoir storage to manage a shift in the seasonal cycle of runoff. Current information about the climate-related water challenges facing much of the world, although by no means perfect, is sufficiently robust that major future problem areas can now be defined. The matter takes on a greater urgency because the model-predicted signals are already being observed.

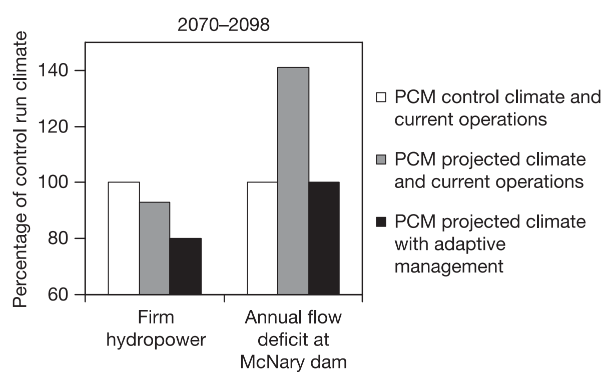

Figure 2 | Trade-off between firm hydropower and stream-flow requirements. The effect of Parallel Climate Model (PCM) climate change projections for the period of 2070 to 2098 on Columbia River Basin reservoir system reliabilities, as compared to the PCM control climate and operations scenario. Implementing adaptive management reduces the annual environmental flow deficit at McNary Dam in southeastern Washington, USA (benefiting salmon), but decreases firm (reliable) hydropower. Figure created by A. Hamlet using results from ref. 32.

Will changes in precipitation patterns offset the problems associated with warming? The most likely answer is 'no'. If less rain falls over a region, water availability will decrease. If more rain falls and the reservoir storage capacity is much less than the annual runoff, then the water will be lost downstream (to the ocean in many cases)—particularly in regions, like the western USA, where precipitation is mainly in winter and the effective storage capacity of winter snow pack will be lost. The changes in precipitation required to ameliorate the problem would have to come through a shift in the seasonal cycle of rainfall towards the dry season, a feature that is not usually exhibited by anthropogenically forced climate models.

Two examples of impacts on glaciers. The results for the regional water resources case studies discussed above and the simple physics behind them seem likely to be qualitatively reproduced in virtually all regions where snowmelt is important to local water availability[6] and where annual runoff exceeds storage capabilities. Our results in the western USA suggest that even more serious problems may occur in regions that depend heavily on glacial meltwater for their main dry-season water supply. This is because, once the glaciers have melted in a warmer world, there will be no replacement for the water they now provide, in contrast to the present snow-pack-dependent water supply that is renewed seasonally. In this case, the natural storage of fossil water in the glaciers has even more importance than seasonal storage in just the snow pack. It is well documented that glaciers are in retreat over most (but not all) of the world[1,38,39], so the threat here seems both real and immediate—a situation also well documented in the world's press over the past several years.

Himalaya–Hindu Kush region. Perhaps the most critical region in which vanishing glaciers will negatively affect water supply in the next few decades will be China and parts of Asia, including India (together forming the Himalaya–Hindu Kush (HKH) region), because of the region's huge population (about 50–60% of the world's population). The ice mass over this mountainous region is the third-largest on earth, after the Arctic/Greenland and Antarctic regions. The hydrological cycle of the region is complicated by the Asian monsoon, but there is little doubt that melting glaciers provide a key source of water for the region in the summer months: as much as 70% of the summer flow in the Ganges and 50–60% of the flow in other major rivers[40,41,42]. In China, 23% of the population lives in the western regions, where glacial melt provides the principal dry season water source[43].

There is little doubt that the glaciers of the HKH region are melting and that the melting is accompanied by a long-term increase of near-surface air temperature (ref. 44 and Figs 2.9 and 2.10 in ref. 1), the same level of warming we saw impacting the western USA. After 25 years of study, the China Glacier Inventory was recently released[45]. It showed substantial melting of virtually all glaciers, with one of the most marked retreats in the last 13 years (750 m) of the glacier that acts as one of the major sources of the Yangtze River, the largest river in China. In total, it is estimated that the entire HKH ice mass has decreased in the last two decades. Furthermore, the rate of melting seems to be accelerating[46].

The few analytical studies that exist for the region suggest both a regression of the maximum spring stream-flow period in the annual cycle by about 30 days (ref. 47) and an increase in glacier melt runoff by 33–38% (ref. 48). These numbers seem consistent with what is being observed and bear striking similarities to the stream-flow results from the western USA. The huge inconsistency, however, occurs in the impacts on local water supplies. In the western USA, model-predicted impacts are already being seen in the hydrological cycle. The models suggest that the impacts will appear as a long-term trend in snow amount and runoff. But in the HKH region, there may (for the next several decades) appear to be normal, even increased, amounts of available melt water to satisfy dry season needs. The shortage, when it comes, will likely arrive much more abruptly in time; with water systems going from plenty to want in perhaps a few decades or less.

It appears that some areas of the most populated region on Earth are likely to 'run out of water' during the dry season if the current warming and glacial melting trends continue for several more decades. This may be enough time for long-term planning to see just how the region can cope with this problem. Unfortunately, the situation here is that when the glaciers melt and their fossil water is used or lost, their contribution to the water supply of the region will cease.

South American Andes. A large fraction of the population living west of the South American Andes relies on the glacial melt from those mountains to feed the area's rivers to supply water and hydropower. Without the glacier-supplied river water, the people and economies of the region would have to undergo tremendous adjustments[49,50]. The physics governing the Andean glaciers are more complicated than simple temperature forcing. Depending on the latitude and on which side of the Andes we consider, the glaciers' mass balance can be controlled by different factors[51,52]. Although air temperature changes are still important in most areas, other processes (such as moisture flux and precipitation) dominate in some regions. This makes the prediction of what might happen in the Andes much more difficult. Although all greenhouse models predict warming air temperatures, they can disagree on predicted changes in rainfall, moisture flux, and so on.

In spite of this complexity, melting of the glaciers is well documented for the Andes[53,54]. In Peru alone, the glacier-covered area has been reduced by 25% in the last three decades (as reported at the Conference on Mass Balance of Andes Glaciers, Huaraz, Peru, 6–9 July 2004; http://www.inrena.gob.pe/serusu/serusu_ppoint.htm). At current rates, some of the glaciers may disappear in a few decades, if not sooner. The high-frequency surges and retreats and the uneven spatial distribution of the general glacier retreat makes understanding and predicting the behaviour of glaciers in this area uncertain.

The melting started some decades ago. The International Panel for Climate Change (IPCC) shows a long-term trend in increasing air temperature in the region (ref. 38 and Figs 2.9 and 2.10 in ref. 1). Higher-resolution, more-detailed analysis of many stations in the region show a similar temperature increase, one that seems to be increasing[55,56]. Consider the case of Quelccaya in the Andes (Fig. 3). When the summit core was originally drilled in 1976, it contained clear annual cycles in its layering that extended back in time for approximately 1,500 years (ref. 38). When it was re-drilled in 1991, the annual layers in the upper 20 m of the core had been obliterated by percolation of meltwater. Together, these two results show that melting at the summit had occurred, a condition that had not previously occurred in the last 1,500 years. The probability seems high that the current glacier melting in the Andes will continue, just as it will in Asia (and other regions of the world). It is fossil water that has been lost and will not be replaced anytime soon, especially not in the context of anthropogenically induced greenhouse warming. The results and projections suggest that current dry-season water resources will be heavily depleted once the glaciers have disappeared.

Some uncertainties in estimating impacts. All of the future climate predictions have uncertainties. We touch on only a few of the more important ones below, with the goal of seeing whether they might overcome the warming signal and make the conclusions above moot. We do not, however, attempt here a complete discussion of all the uncertainties that attend climate models.

In some cases, the uncertainties have to do with the models' inability to reproduce today's climate, casting doubt on future climate predictions. Predictions using regional, high-spatial-resolution models, of the type needed for regional water studies, are only now starting to come into their own in the greenhouse arena, but they carry a whole set of problems in addition to those associated with the coupled atmosphere–ocean general circulation models (CGCMs). For instance, they often have different physics from the CGCMs—there are scale-dependence issues, and new levels of parameterizations are required. However, such regional models will be required for good quantitative estimates of potential future water problems. Such high-resolution, regional hydrological studies have not yet been undertaken for either the HKH region or South America.

One of the greatest uncertainties in future prediction has to do with how the models are forced. Stated more directly, what are the implications of omitting forcings that we strongly suspect (or know) are important but cannot yet reliably be included in the model physics? Of these, the most important is thought to be the incomplete inclusion of aerosols and their impacts, especially on clouds. Excellent discussions of the current state of the aerosol problem may be found in refs 57 and 58, and ref. 59 shows the sensitivity of climate model predictions to uncertainties in indirect aerosol forcing.

The key question for this paper is: Can the aerosol/cloud problem overwhelm the direct greenhouse-gas-induced temperature forcing that affects the regional hydrological cycle, giving net cooling as opposed to warming? We consider below some of these uncertainties qualitatively to see how they might impact the results discussed above.

Aerosols and clouds. Aerosols are thought to cool the planet's surface through increased scattering and cloud cover and re-radiation of solar energy to space. The representation of clouds in CGCMs carries a large uncertainty all by itself, but the joint interaction of clouds and aerosols represents one of the major challenges to climate modellers today. Virtually all climate models have some representation of direct aerosol effects (that is, reflectivity of the particles) in them, but none have yet fully included the indirect effects (for example, the effect of aerosols on cloud distributions via their role as cloud condensation nuclei, or other effects discussed below). A preliminary study[60] suggests that indirect aerosol impacts on clouds are important but, even given the uncertainty in estimating these impacts, this mechanism is not strong enough to counter greenhouse warming effects.

Recent observational studies[58,60] show that locally, over India, the total aerosol effect (direct plus indirect) has been associated with a surface cooling of 0.3 °C over the last three decades. This is close to the warming expected from greenhouse gases. However, the aerosols are observed to be associated with warming in the lower to middle troposphere—the regions inhabited by the glacier fields. In this case the aerosols may be enhancing the direct temperature forcing by contributing to the melting of the higher glaciers of the HKH region.

Snowfall amounts. Aerosols are found to alter cloud physics in a manner that reduces precipitation downstream from the pollution source[61,62]. This also reduces the snow particle rime growth, resulting in lower snow water equivalent, a result obtained from direct field measurements[62–64]. Properly represented aerosols in climate models will apparently also work together with increasing temperature to reduce snow/ice in regions where heavy air pollution exists (for example, China, the western USA and Europe).

Snow/ice melt rates. A common aerosol found in the atmosphere over many regions of the earth is black carbon. This substance absorbs sunlight. It is scrubbed from the atmosphere by precipitation and, because it is ubiquitous, is likely to end up in the snow and ice fields of the planet. There it could decrease the surface albedo, causing the snow/ice to absorb solar energy more readily and thereby melt sooner. Measurements of black carbon amounts and its budgets are only now being made. By whatever means, darkening the surface of a snow/ice field will enhance melt rates. Again, it seems that proper inclusion of aerosols in global climate models will increase early melting of snow packs and, especially, glaciers and sea ice[65].

The bottom line here is that other important, but poorly represented, atmospheric physical and chemical processes seem unlikely to neutralize or reverse greenhouse warming. This is true even if we take the lower end of the estimated warming by the IPCC (1.4 °C) to be the net thermal forcing on the snow/glacier packs. Our ACPI study[2] showed that such an increase, coupled with inadequate containment, is all it takes to invoke the water storage problems noted above.

Overview of expected regional water impacts

In this review, we suggest that the simplest of changes associated with global warming (a modest increase in near-surface air temperature) will be responsible for alterations of the hydrological cycle in snowmelt-dominated regions via seasonal shifts in stream-flow. Without adequate water storage capacity, these changes will lead to regional water shortages. The model-predicted changes are already being seen in the observed data. If maintained at current levels, these changes will lead to a serious reduction in dry-season water availability in many regions of the Earth within the next few decades.

The physical principles found to apply in snowmelt-dominated regions (for example, the western USA) are one of the probable causes of the observed early snowmelt and, more importantly, deglaciation that is now occurring in most mountainous regions of the world. The serious situations developing in the HKH region and South America have been briefly presented. It is clear that both regions, as well as others not mentioned, are headed for a water-supply crisis. Better water management techniques can help, but cannot solve the problem without significant changes to agriculture, industry and lifestyle. Detailed studies of the future impact of global warming on water resources in these regions are long overdue.

a 1978

b 2002

Figure 3 | Changes in the Qori Kalis Glacier, Quelccaya Ice Cap, Peru, between 1978 (a) and 2002 (b). Glacier retreat during this time was 1,100 m (L. Thompson, personal communication). Photographs courtesy of L. Thompson.

We have discussed briefly here some of the major uncertainties in the models, in particular the impacts of aerosols and clouds, as well as their suspected impacts on the aspects of the hydrological cycle having to do with snow and ice. In all the cases considered, current scientific evidence suggests that these processes, which are currently either not included, or are marginally included, in IPCC scenario runs, will act to increase the impact of mere temperature increase on the snow and ice fields of the planet.

Time is running out for nations in the sensitive areas we have evaluated, particularly those whose water supplies are dependent on mid-latitude glaciers, to understand just what the future might hold for them. How much they can do is uncertain given the several decades of warming that will occur as a result of past actions, even if greenhouse emissions were halted at today's levels[66], but perhaps the initiation of strategic planning will be motivated by the prospect (and what is rapidly becoming the reality) of diminished water supplies.

1. The International Panel for Climate Change (IPCC) *Climate Change 2001: The Scientific Basis* (eds Houghton, J. T. *et al.*) (Cambridge Univ. Press, Cambridge, UK, 2001).
2. Barnett, T. P. & Pennell, W. (eds) Impact of global warming on Western US water supplies. *Clim. Change* **62** (Spec. Vol.) (2004).
3. Mote, P. W., Hamlet, A. F., Clark, M. P. & Lettenmaier, D. P. Declining mountain snow pack in western North America. *Bull. Am. Met. Soc.* **86,** 39–49 (2005).
4. Dettinger, M. D., Cayan, D. R., Meyer, M. K. & Jeton, A. E. Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900–2099. *Clim. Change* **62,** 283–317 (2004).
5. Hamlet, A. F., Mote, P. W., Clark, M. P. & Lettenmaier, D. P. Effects of temperature and precipitation variability on snow pack trends in the western U.S. *J. Clim.* (in the press).
6. Douville, H. *et al.* Sensitivity of the hydrological cycle in increasing amounts of greenhouse gases and aerosols. *Clim. Dyn.* **20,** 45–68 (2002).
7. Giorgi, F., Whetton, P. H. & Jones, R. G. Emerging patterns of simulated regional climatic changes for the 21st century due to anthropogenic forcings. *Geophys. Res. Lett.* **28,** 3317–3321 (2001).
8. Giorgi, F. & Bi, X. Regional changes in surface climate interannual variability for the 21st century from ensembles of global model simulations. *Geophys. Res. Lett.* **32,** L13701, doi:10.1029/2005GL023002 (2005).
9. Ruiz-Barradas, A. & Nigam, S. IPCC's 20th century climate simulations: Varied representations of North American hydroclimate variability. *J. Clim.* (submitted).
10. Dai, A. Precipitation characteristics of eighteen coupled models. *J. Clim.* (submitted).
11. Cayan, D. R., Kammerdiener, S. A., Dettinger, M. D., Caprio, J. M. & Peterson, D. H. Changes in the onset of Spring in the Western United States. *Bull. Am. Met. Soc.* **82,** 399–415 (2001).
12. Stewart, I., Cayan, D. C. & Dettinger, M. D. Changes in snowmelt runoff timing in Western North America under a 'business as usual' climate change scenario. *Clim. Change* **62,** 217–232 (2004).
13. Nijssen, B., O'Donnell, G. M., Hamlet, A. F. & Lettenmaier, D. P. Hydrologic vulnerability of global rivers to climate change. *Clim. Change* **50,** 143–175 (2001).
14. Liang, X., Lettenmaier, D. P., Wood, E. F. & Burges, S. J. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *J. Geophys. Res.* **99**(D17), 14415–14428 (1994).
15. Vörösmarty, C. J. K. *et al.* The storage and aging of continental runoff in large reservoir systems of the world. *Ambio* **26,** 210–219 (1997).
16. Vörösmarty, C. J. *et al.* Anthropogenic sediment retention: Major global impact from registered river impoundments. *Glob. Planet. Change* **39,** 169–190 (2003).
17. Adam, J. C., Clark, E. A., Lettenmaier, D. P. & Wood, E. F. Correction of global precipitation products for orographic effects. *J. Clim.* (in the press).
18. Center for International Earth Science Information Network (CIESIN). *Socioeconomic Data and Applications Center (SEDAC): Gridded Population of the World, Version 3* (Columbia University and Centro Internacional de Agricultura Tropical, Palisades, New York, 2004); available at ⟨http://beta.sedac.ciesin.columbia.edu/gpw⟩.
19. Peterson, T. C., Golubev, V. S. & Groisman, P. V. Evaporation losing its strength. *Nature* **377,** 687–688 (1995).
20. Chattopadhyay, N. & Hulme, M. Evaporation and potential evapotranspiration in India under conditions of recent and future climate change. *Agricult. Forest Meteorol.* **87,** 55–73 (1997).
21. Thomas, A. Spatial and temporal characteristics of potential evapotranspiration trends over China. *Int. J. Clim.* **20,** 381–396 (2000).
22. Golubev, V. S. *et al.* Evaporation changes over the contiguous United States and the former USSR: a reassessment. *Geophys. Res. Lett.* **28**(13), 2665–2668 (2001).
23. Brutsaert, W. & Parlange, M. Hydrologic cycle explains the evaporation paradox. *Nature* **396,** 30 (1998).
24. Lawrimore, J. H. & Peterson, T. C. Pan evaporation trends in dry and humid regions of the United States. *J. Hydrometeorol.* **1,** 543–546 (2000).
25. Hobbins, M. T. & Ramirez, J. A. Trends in pan evaporation and actual evapotranspiration across the conterminous U.S.: paradoxical or complementary? *Geophys. Res. Lett.* **31,** doi: 10.1029/2004GL019846 (2004).
26. Walter, M. T., Wilks, D. S., Parlange, J.-Y. & Schneider, R. L. Increasing evapotranspiration from the conterminous United States. *J. Hydrometeorol.* **5,** 405–408 (2004).
27. Roderick, M. L. & Farquhar, G. D. The cause of decreased pan evaporation over the past 50 years. *Science* **298,** 1410–1411 (2002).
28. Ohmura, A. & Wild, M. Is the hydrological cycle accelerating? *Science* **298,** 1345–1346 (2002).
29. Wild, M., Ohmura, A. & Gilgen, H. On the consistency of trends in radiation and temperature records and implications for the global hydrological cycle. *Geophys. Res. Lett.* **31,** doi: 10.1029/2003GL019188 (2004).
30. International Panel for Climate Change. *Climate Change 2001: Impacts, Adaptation and Vulnerability* (eds McCarthy, J. J. *et al.*) (Cambridge Univ. Press, Cambridge, UK, 2001).
31. Barnett, T. P. *et al.* The effects of climate change on water resources in the West: Introduction and overview. *Clim. Change* **62,** 1–11 (2004).
32. Payne, J. T., Wood, A. W., Hamlet, A. F., Palmer, R. N. & Lettenmaier, D. P. Mitigating effects of climate change on the water resources of the Columbia River Basin. *Clim. Change* **62,** 233–256 (2004).
33. Middelkoop, H. *et al.* Impact of climate change on hydrological regimes and water resources management in the Rhine basin. *Clim. Change* **49,** 105–128 (2001).
34. Gan, T. Y. Reducing vulnerability of water resources of Canadian prairies to potential droughts and possible climatic warming. *Wat. Res. Manag.* **14,** 111–135 (2000).
35. Burn, D. Hydrologic effects of climatic change in west-central Canada. *J. Hydrol.* **160,** 53–70 (1994).
36. de Loë, R., Kreutzwiser, R. & Moraru, L. Adaptation options for the near term: climate change and the Canadian water sector. *Glob. Environ. Change* **11,** 231–245 (2001).
37. Schwindler, D. W. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. *Can. J. Fish. Aquat. Sci.* **58,** 18–29 (2001).
38. Thompson, L. G. *et al.* Tropical glacier and ice core evidence of climate change on annual to millennial time scales. *Clim. Change* **59,** 137–155 (2003).
39. Combes, S., Prentice, M. L., Hansen, L. & Rosentrater, L. *Going, Going, Gone! Climate Change and Global Glacier Decline* 1–6 (World Wildlife Fund Climate Change Programme, WWF Germany, Berlin, 2004).
40. Singh, P. & Bengtsson, L. Hydrological sensitivity of a large Himalayan basin to climate change. *Hydrol. Process.* **18,** 2363–2385 (2004).
41. Singh, P., Jain, S. K. & Kumar, N. Estimation of snow and glacier-melt contribution to the Chenab River, Western Himalaya. *Mount. Res. Develop.* **17**(1), 49–56 (1997).
42. Singh, P. & Jain, S. K. Snow and glacier melt in the Satluj River at Bhakdra Dam in the western Himalayan region. *Hydrol. Sci. J.* **47,** 93–106 (2002).
43. Gao, Q. & Shi, S. Water resources in the arid zone of northwest China. *J. Desert Res.* **12**(4), 1–12 (1992).
44. Hou, S. *et al.* Climatological significance of an ice core net-accumulation record at Mt. Qomolangma. *Chin. Sci. Bull.* **45,** 256–261 (2000).
45. Chinese Academy of Sciences. *China Glacier Inventory* (World Data Center for Glaciology and Geocryology, Lanzhou Institute of Glaciology and Geocryology, Lanzhou, 2004); available from NSIDC User Services (nsidc@nsidc.org).
46. Meier, M. & Dyurgerov, M. Deciphering complex changes in snow and ice. *Science* **297,** 350–351 (2002).
47. Singh, P. Effect of warmer climate on the depletion of snow covered area in the Satluj basin in the western Himalayan region. *Hydrol. Sci. J.* **48,** 413–425 (2003).
48. Singh, P. & Kumar, N. Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan river. *J. Hydrol.* **193,** 316–350 (1997).
49. Liniger, H., Weingarten, R. & Grosjean, M. *Mountains of the World: Water Towers for the 21st Century* 1–24 (Mountain Agenda, Center for Development and Environment, Institute of Geography, University of Bern, Bern, 1998).
50. Mark, B. G. & Seltzer, G. O. Tropical glacier melt water contribution to stream discharge: a case study in the Cordillera Blanca, Peru. *J. Glaciol.* **49,** 271–281 (2003).
51. Kaser, G., Georges, C., Juen, I. & Moelg, T. in *Global Change and Mountain Regions: A State of Knowledge Overview* (eds Huber, U. M., Bugmann, H. K. M. & Reasoner, M. A.) 185–196 (Springer, New York, 2005).
52. Mark, B. G. & Seltzer, G. O. Evaluation of recent glacier recession in the Cordillera Blanca, Peru (AD 1962–1999): spatial distribution of mass loss and climatic forcing. *Quat. Sci. Rev.* (in the press).
53. Francou, B., Vuille, M., Wagnon, P., Mendoza, J. & Sicart, J. E Tropical climate change recorded by a glacier in the central Andes during the last decades of the 20th century: Chacaltaya, Bolivia. *J. Geophys. Res.* **108,** D54154, doi:10.1029/2002JD002959 (2003).

54. Mark, B.G. & Seltzer, G.O. in *Global Change and Mountain Regions: A State Of Knowledge Overview* (eds Huber, U. M., Bugmann, H. K. M. & Reasoner, M. A.) 205–214 (Springer, New York, 2005).
55. Vuille, M. & Bradley, R. S. Mean annual temperature trends and their vertical structure in the tropical Andes. *Geophys. Res. Lett.* **27,** 3885–3888 (2000).
56. Vuille, M., Bradley, R. S., Werner, M. & Keimig, F. 20th century climate change in the tropical Andes: observations and model results. *Clim. Change* **59**(1–2), 75–99 (2003).
57. Kaufman, Y. J., Didier, T. & Olivier, B. A satellite view of aerosols in the climate system. *Nature* **419,** 215–223 (2002).
58. Ramanthan, V., Crutzen, P. J., Kiehl, J. T. & Rosenfeld, D. Aerosols, climate, and the hydrological cycle. *Science* **294,** 2119–2124 (2001).
59. Kiehl, J. T., Schneider, T. L., Rasch, P. J. & Barth, M. C. Radiative forcing due to sulfate aerosols from simulations with the National Center for Atmospheric Research Community Climate Model, Version 3. *J. Geophys. Res.* **105,** 1441–1457 (2000).
60. Krishnan, R. & Ramanathan, V. Evidence of surface cooling from absorbing aerosols. *Geophys. Res. Lett.* **29,** 54–56 (2002).
61. Rosenfeld, D. TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. *Geophys. Res. Lett.* **26,** 3105–3108 (1999).
62. Rosenfeld, D. Suppression of rain and snow by urban air pollution. *Science* **287,** 1793–1796 (2000).
63. Borys, R. D., Lowenthal, D. H., Cohn, S. A. & Brown, W. O. J. Mountaintop and radar measurements of anthropogenic aerosol effects on snow growth and snowfall rate. *Geophys. Res. Lett.* **30(** 10), 45-1–45-4 (2003).
64. Givati, A. & Rosenfeld, D. Quantifying precipitation suppression due to air pollution. *J. Appl. Met.* **43,** 1038–1056 (2004).
65. Hansen, J. & Nazarenko, L. Soot climate forcing via snow and ice albedos. *Proc. Natl Acad. Sci. USA* **101,** 423–428 (2004).
66. Hansen, J. *et al.* Earth's energy imbalance: Confirmation and implications. *Science* **308,** 1431–1435 (2005).

Acknowledgements This work is a contribution from IDAG, the International Detection and Attribution Group jointly supported by NOAA and DOE. The gross domestic product data set was developed by the Center for International Earth Science Information Network (CIESIN) at Columbia University, New York, with funding from the National Aeronautics and Space Administration. This manuscript was improved considerably through the suggestions of D. Pierce and A. Gershunov.

Author Information Reprints and permissions information is available at npg.nature.com/reprintsandpermissions. The authors declare no competing financial interests. Correspondence should be addressed to T.P.B. (timdotbarnett@ucsd.edu) or D.P.L. (dennisl@u.washington.edu).