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Orographic Precipitation and Climate Change

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1. Introduction

More than half of the accessible freshwater is used directly or indirectly by humankind, and much of this precious resource has its origin in mountainous regions, ultimately in the form of orographic precipitation. In many areas, mountains function as "water towers" for the surrounding regions. Melt from snow cover and glaciers represents an important contribution to runoff in the surrounding areas, especially during seasons when precipitation is sparse or completely absent. Mountain freshwater resources are heavily utilized for agricultural purposes (e.g. irrigation) and for the generation of hydropower, thus being of great socio-economic importance. Yet, heavy orographic precipitation events also represent a potential hazard, as they may lead to floods, avalanches and mudslides that often cause countless loss of life and tremendous damage. The potential consequences of such events may be extreme. For instance, a single catastrophic mudslide event that took place in Venezuela on December 15, 1999, is estimated to have caused more than 20,000 casualties according to re-insurance estimates.

Extreme events are a characteristic property of mountain climates. On geological timescales, heavy precipitation events, floods, water erosion, avalanches and mudslides have contributed towards shaping the landscape and environment. Civilizations in mountainous regions have for a long time adjusted their infrastructure to this challenge (e.g. location of settlements) and have in many regions successfully undertaken measures to protect themselves against natural hazards (e.g. damming of major rivers). In many mountain ranges, a wide range of planning measures is underway to mitigate and adapt to the threat of extreme weather and hydrological conditions (e.g. building codes, dimension of bridges, operation of dams). In general, the planning of such systems is based on the assumption of a stationary climate. However, this principle is likely to become obsolete due to climate change. Indeed, in terms of their socio-economic implications, future changes in the frequency and character of extreme events are likely to be more relevant than the comparatively slow shifts in mean temperature and precipitation.

According to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), there is increasing evidence that the climate system is experiencing pronounced changes. A substantial fraction of the warming observed in the last 50 years is attributed to anthropogenic greenhouse gases (IPCC 2001). The global mean surface temperature has increased by ~0.6°C since the late 19th century, and the 1990s are believed to be the warmest decade of the last millennium in the Northern Hemisphere. In addition to the warming, substantial changes of the hydrological cycle have been detected. In the northern hemisphere, the overall signature is an increase in total precipitation amounts, except for the sub-tropics. In the northern middle and high latitudes, annual land precipitation has increased by 0.5 to 1%/decade during the last 100 years, while over the northern tropics and sub-tropics (0°N to 40°N) there is a tendency for a slight precipitation decrease (New et al. 2001). Where time series are available, changes in annual streamflow are often observed to relate well to changes in total precipitation. Consistent with the observed warming, there has been an increase of the total atmospheric water vapour content.

Climate change scenarios that account for future greenhouse gas and aerosol emissions suggest that the observed warming will accelerate and the hydrological cycle will intensify. Such changes would imply important repercussions for orographic precipitation and mountain climates. However, at present there are major uncertainties in particular regarding the regional patterns of climate change (IPCC 2001). Here, a short overview is presented on the role of climate change on orographic precipitation, including considerations of climate-induced changes in the frequency of extreme weather and hydrological conditions. The paper will cover observations, processes and scenarios and will conclude with a broad outlook.

2. Observations

Monitoring orographic precipitation on seasonal to decadal time scales is a challenging issue for several reasons. Records from conventional rain gauges suffer from systematic measurement biases (Yang et al. 1999) and inhomogeneities due to changes in observation practice and station displacements (Peterson et al. 1998). These errors are particularly large in mountain regions, due to the higher proportion of snowfall and the large spatial variability of precipitation. Monitoring orographic precipitation requires particularly dense networks, which is difficult to achieve considering the technical problems encountered in these remote areas. As a result, analyses of long-term precipitation variations that resolve the prominent topographical imprints are available for a few mountain areas only.

A notable example is the region of the European Alps, where data from present-day high-resolution networks (Frei and Schär 1998) and sparser homogenized long-term records (Schmutz et al. 2003) can be used for the reconstruction of precipitation variability and trends back to the beginning of the 20th century (Fig. 1; Schmidli et al. 2000; 2001): During the winter season, mean precipitation has increased, particularly in the north-western parts of the Alps, whilst a decreasing trend was detected for the southern and eastern parts of the ridge during autumn. These observed trends are statistically significant and amount to 30% per 100 years. Their spatial distribution shows a relation to some of the topographic characteristics of the region. Trends during spring and summer are smaller and barely significant. Some of these observed changes are in qualitative agreement with climate change scenarios (see below), however, the extent to which these changes are related to anthropogenic climate change is unknown.

The identification of trends in heavy precipitation is confronted with even more obstacles. Firstly, it is difficult to recover high-quality station records with daily resolution over sufficiently extended periods. Secondly, there are fundamental limitations in our ability to distinguish between systematic trends and merely random occurrence in records of rare extremes. The ability to identify trends in extreme events can be described by the "detection probability" (Frei and Schär 2001). The detection probability decreases with increasing rareness of events and becomes negligible for events with a return period of several years or more, even if the change corresponds to a doubling of the event frequency. It follows that care must be exercised when inferring the absence of a trend from the absence of statistical significance, and trend analysis should preferably focus on more frequent moderate intensity (rather than rare

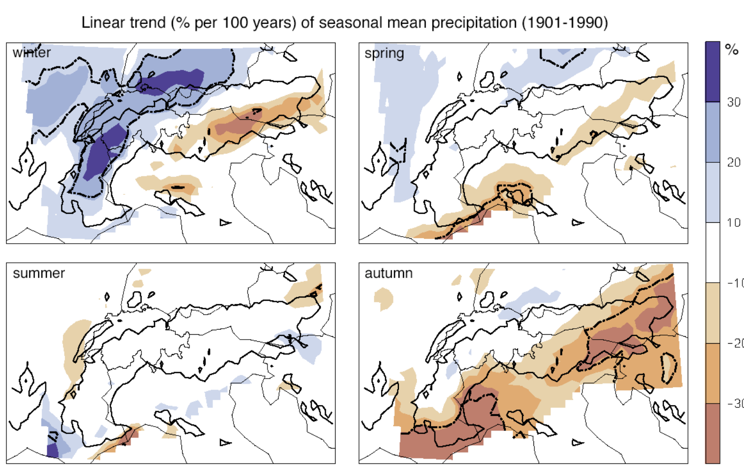

Figure 1: Alpine precipitation trends stratified according to season (Schmidli et al. 2002). Colors: Trend magnitude in % change per 100 years; Bold contours: 850 m topographic contour; Thick dash-dotted contours: Statistical significance at the 10% level.

extreme) events.

In the Swiss portion of the Alpine region, the frequency of intense daily precipitation events (days exceeding the 30-day return period threshold) has increased in winter and autumn by 20–80% during the 20th century (Frei and Schär 2001). In autumn, the increase in precipitation intensity is accompanied by a decrease in rainday frequency and these trends mutually compensate to yield no trend in mean precipitation. A similar compensation was found for the Italian part of the Alps (Brunetti et al. 2001). Recent climate change scenarios for the Alps predict changes of intense precipitation with similar seasonal characteristics (e.g. Durman et al. 2001).

Long-term trends in the components of the water cycle have been reported for several other mountain regions of the world. For Scandinavia, analyses of homogenised precipitation series indicate that mean precipitation has increased in coastal Norway, Sweden and Denmark (Hanssen-Bauer and Forland 2000; Schmith 2000). In winter, the 20th century increase amounts to 15-20%, and is related to particularly wet conditions since ~1980. During the same period, the atmospheric circulation regime of the North Atlantic (the so-called North Atlantic Oscillation, NAO, see e.g. Wanner et al. 2001) was in a prolonged phase of strong westerlies (i.e. high NAO-index states), characteristic of enhanced transport of warm and moist airmasses towards the European continent. Some fraction of the observed precipitation trend in Scandinavia is therefore related to the recent NAO anomalies (Hurrell 1995). However, attempts to quantify this contribution were not successful in explaining the full magnitude of the observed precipitation trend (Hanssen-Bauer and Forland 2000; Schmith 2000).

In the North American Rocky Mountains, an increase of mean precipitation was found from September through December and this was accompanied by an increase in annual stream flow (Lettenmaier et al. 1994). More than half of the 20th century increases in mean annual precipitation is due to more frequent heavy precipitation in the upper 10 percentiles of the distribution (Karl and Knight 1998). At the same time, the frequency of convective cloud types was found to have increased over the last 40-50 years (Sun et al. 2001). However, the observed increase in heavy precipitation events is not accompanied by an upward trend in peak stream flow in the Rockies (unlike in the rest of the country). This might be explained by the observed decrease in the extent of spring-time snow cover, which compensates for the precipitation increase (Groisman et al. 2001). Long-term trends in mean precipitation, showing strong regional variations, were also reported from Alaska (Stafford et al. 2000).

For the tropics, observations demonstrate that the prime mode of variability is associated with El Niño (e.g. Dai et al. 1997). This phenomenon yields variability on time-scales of a few years, which is likely to dominate the system for some time into the future. Nevertheless, long-term trends are also reported for some tropical land areas, especially the latitude band 0-20°N, where mean annual land precipitation decreased during the second half of the 20th century (see New et al. 2001).

3. Processes and feedbacks

On the global scale, the term "climate change" is often equated with the term "climate warming". However, the energy cycle of the climate system is intrinsically linked with the hydrological cycle. To a first approximation, it would indeed be more appropriate to equate "climate change" with "climate moistening", as in terms of energy the moistening is more relevant than the warming. One of the primary drivers behind the associated intensification of the hydrological cycle is the Clausius-Clapeyron relationship, which represents the dependency of the saturation vapor pressure upon temperature. In quantitative terms, the ability of air to hold water vapor increases by ~6% per degree Kelvin. There are strong indications – from physical arguments, climate observations and climate models (see e.g. DelGenio et al. 1991; Allen and Ingram 2002) – that the relative humidity of the atmosphere will in the long-term and large-scale mean not change much in a future climate (with the possible exception of tropical regions). The Clausius-Clapeyron relation thus implies that the total moisture content of the atmosphere must increase by ~6% per degree warming.

The simplest picture of the intensified hydrological cycle in a warmer world is thus one of a percent-wise intensification, where the atmospheric moisture content, evapotranspiration and precipitation increase simultaneously at a rate comparable to the aforementioned ~6%/K. However, such a scenario is not likely to come true. Rather, GCM scenarios of greenhouse gas-induced warming suggest that, although the atmospheric moisture content will increase by ~6%/K, precipitation and evapotranspiration will increase at a slower rate of 1-3%/K (IPCC 2001). This peculiar behavior is due to the large-scale balances between atmospheric and terrestrial radiation, evaporative cooling and condensational heating (Boer et al. 1993; Hartmann 1994; Trenberth 1999), but the underlying processes are still not fully understood. As a result, we are facing a climate in which the intensification of the global mean hydrological cycle is substantially weaker than the increase of the atmospheric water content. The unequal increase of these critical factors implies an increase in the mean atmospheric residence time of water molecules (Trenberth 1999). This will likely be accompanied by changes in the intensity of rainfall events and shifts in the geographical distribution of climate zones. In addition, the increase of the atmospheric moisture content implies important changes in the radiation balance, as water vapor is the most important greenhouse gas of our atmosphere.

The expected increase of global mean precipitation by 1-3%/K alone would probably be of comparatively minor concern. This increase may however be amplified in certain regions and over complex topography:

- First, the increase in precipitation will not occur uniformly but changes will be associated with specific geographical patterns and will vary with seasons. More specifically, the mid and high latitudes are expected to experience a higher relative increase in total precipitation in particular during winter, while there is evidence that some sub-tropical and semi-arid regions might experience an increased risk of summer droughts (e.g. Weatherald and Manabe 1995). These may arise where the local increase in evapotranspiration exceeds the increase in precipitation.
- Second, the frequency of heavy precipitation events is not directly linked to mean precipitation amounts. Frequency changes at the extreme tails of the distribution can take on large magnitudes even if mean changes are small (Frei et al. 1998). Also, several climate model scenarios suggest that the frequency

of heavy precipitation events may increase irrespective of a decrease in mean precipitation amounts (e.g. Durman et al. 2001; Semenov and Bengtsson 2002). Recent observations have revealed such trends, for instance in the Alps, where total autumn precipitation has changed little or has even decreased, but intense precipitation events have increased (Frei and Schär 2001; Schmidli et al. 2002).

- Third, orographic precipitation is likely to increase at a similar rate as the atmospheric moisture content (~6%/K), rather than at the rate of the global mean precipitation increase (1-3%/K). This particular characteristic of orographic precipitation is due to the fact that mountains effectively extract a fraction of the atmospheric moisture flux, which increases at a similar rate as the atmospheric water content. Again, there are indications for this kind of behavior. For instance, Figure 1 shows the most pronounced trends in Alpine precipitation (of either sign) in the immediate vicinity of the topography.

Our analysis suggests that the anticipated intensification of the hydrological cycle may be particularly effective in the mid and high latitudes, in relation to heavy precipitation events, and in mountainous regions. With regard to runoff and flooding in mountainous regions, the increase in the frequency and intensity of extreme precipitation events is of concern, as this factor works in the same direction as the anticipated increase in the fraction of liquid precipitation at the expense of snowfall. These hydrological factors are discussed in other chapters of this book.

The above argumentation is in its core a thermodynamic one and therefore applies at best to the large-scale mean and not necessarily to individual mountain ranges. Indeed, there is broad evidence that interannual variations of orographic precipitation are largely controlled by planetary and synoptic-scale atmospheric circulation anomalies (e.g. Massacand et al. 1998). Hence, a thermodynamic argument alone is insufficient to derive realistic and spatially specific climate change scenarios.

4. Scenarios

The overall changes in the hydrological cycle will be highly complex and will involve a number of factors, such as changes in storm track dynamics, soil moisture conditions, and cloud formation processes. The complexity of these interactions calls for a detailed numerical assessment using general circulation models (GCMs). Most GCM studies of increased greenhouse gas scenarios show a pronounced increase in the frequency and intensity of heavy precipitation events. For instance, for equilibrium doubling of carbon dioxide, Hennessy et al. (1997) find that, for a specified return period of 1 year (corresponding to an event size that is exceeded once every year) there is an increase in precipitation intensity of 10 to 25% in Europe, North America, Australia and India. McGuffie et al. (1999) confirm this conclusion when comparing the results from five different GCMs. From an ensemble of transient GCM experiments, Kharin and Zwiers (2000) compute the change in the 20-year return period of daily rainfall for the next 100 years. They find an increase in precipitation intensity almost everywhere on the globe, with the relative change in precipitation extremes exceeding that in mean precipitation. Semenov and Bengtsson

(2002) find increases in mean precipitation intensity, even in regions where mean annual precipitation decreases. Using a probabilistic analysis of 19 GCM simulations, Palmer and Räisänen (2002) estimate that the probability of total winter precipitation exceeding two standard deviations above normal will increase by a factor of five over parts of the UK during the next 100 years. They find similar increases in probability for the Asian monsoon region, with potentially serious implications for flooding in Bangladesh.

The aforementioned studies serve to demonstrate the high sensitivity of precipitation to global warming scenarios. Currently, however, most coupled atmosphere-ocean models have a horizontal resolution of ~300 km, and this is insufficient to properly resolve even major mountain ranges. As a result, coupled atmosphere-ocean GCMs drastically underestimate the intensity of extreme precipitation events in mountainous region. In response to this model limitation, a wide range of downscaling methodologies has been developed. These include both statistical approaches (which are calibrated with observational data from the past) and numerical approaches (which are more closely based on physical laws). Succinct reviews of these methodologies can be found in Giorgi and Mearns (1991) and Wilby and Wigley (1997).

Numerical downscaling procedures typically employ a sequence of nested models, ranging from a low-resolution GCM to a high-resolution impact model. In the example illustrated in Figure 2, two regional climate models (RCMs) are utilized to bridge the scale-gap between the low-resolution GCM and a high-resolution runoff model covering the Rhine basin upstream of Cologne (Kleinn et al. 2002). At each step in the chain, models are forced at their lateral boundaries (and in terms of their sea-surface temperatures) by the results of larger-scale models that are one step up in the spatial hierarchy. With increasing model resolution, the weather evolution and the hydrological cycle are simulated with increasing spatial detail and accuracy.

The quality of climate change scenarios critically depends upon the quality of both the global model component (which must accurately describe the large-scale climatology) and that of the downscaling procedure (which must adequately represent smaller-scale processes). In particular, downscaling cannot correct for systematic errors in the large-scale forcing. The quality of a downscaling procedure can be assessed by testing – under current climatic conditions – its ability to represent the mean climate, the frequency of rare events, natural interannual variations, as well as specific meteorological processes (e.g. Christensen et al. 1996; Frei et al. 2003; Vidale et al. 2003; Wild et al. 2001; respectively).

The credibility of a specific scenario depends upon a wide range of factors, among them the geographical region and season under consideration, and the GCM and RCM under use. Recent studies confirm that increasing the computational resolution does indeed improve the representation of the hydrological cycle, in particular in mountainous regions (e.g. Jones et al. 1995; Leung and Ghan 1999; Durman et al. 2001; Giorgi et al. 2001). Despite this progress, current models entail substantial uncertainties. For instance, difficulties exist concerning the simulation of large-scale quasi-stationary atmospheric circulation patterns, the terrestrial hydrological cycle in semi-arid regions, and convective precipitation processes. In addition, some aspects of the climate system are not predictable, as the atmosphere is an inherently chaotic dynamical system (Palmer 2000). Climate change scenarios (from numerical as well as statistical approaches) should thus be used in a process/sensitivity study mode, rather than be taken literally as predictions. In particular, the term "scenario" is defined as a consistent evolution of a system into the future, but *without* specified probability. Thus, future research in this area should aim towards the construction of probabilistic climate change scenarios, a task that will require the quantification of all relevant uncertainties.

5. Outlook

While there is ample evidence to reject the assumption of a stationary precipitation climate, current climate models can at most simulate the general direction of mean precipitation changes, and it appears unrealistic at present to make quantitative statements about the geographical distribution of climate changes in specific mountainous regions. For actual planning purposes relating to flood protection, agriculture and water resource infrastructure, the prime implication of climate change is thus to increase the uncertainty. This uncertainty – in concert with the growing population pressure, changes in land-use and settlement structure, and per-capita increases in freshwater use – implies that the role of mountains as a freshwater source will become more critical and more difficult to assess.

A better understanding of climate and climate variability, the underlying atmospheric and hydrological processes and their interaction with topography is thus urgently needed. A specific list of key topics is discussed in the recent IPCC report (IPCC 2001). Regarding climate and climate change in mountainous regions, there is a particular need to better understand diurnal mountain circulations, land-surface processes, orographic precipitation processes, and their interactions. The investigation

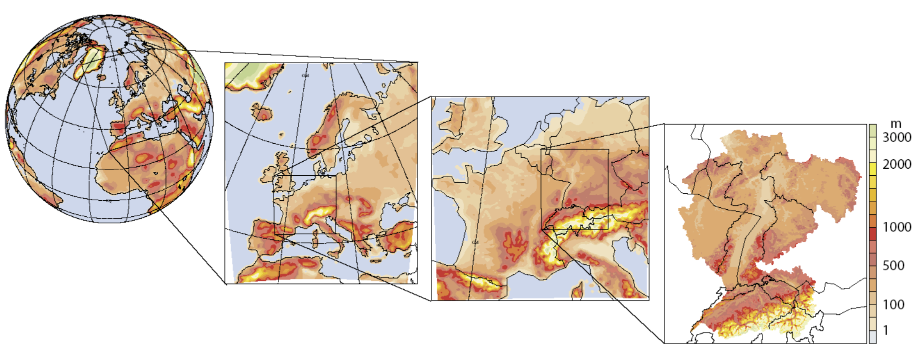

Figure 2: An example of a downscaling model chain used for the assessment of climate-change impacts upon the runoff of the river Rhine (Kleinn et al. 2002). The downscaling chain includes a coupled atmosphere/ocean GCM with a horizontal resolution of ~300 km, an atmosphere-only GCM with a resolution of ~120 km, two regional climate models with resolutions of 56 and 14 km, respectively, and a hydrological runoff model with a resolution of 1 km. The panels show the topography [m] for the different model components.

of these issues is coordinated under the umbrella of large international cooperations such as the World Climate Research Program (WCRP), the Climate Variability and Predictability (CLIVAR) and the Global Energy and Water Cycle (GEWEX) programs of the World Meteorological Organisation (WMO) and the International Council of Scientific Unions (ICSU).

It is, however, important to realize that weather, climate and hydrology of many mountain ranges are poorly understood, even under current climatic conditions. It is the authors' opinion that in such circumstances climate change assessments are of limited use. Establishing the current climatology, assessing its natural seasonal and interannual variations, understanding the underlying key processes on short (meteorological and hydrological) time scales, and pinpointing the vulnerability of settlements and infrastructure under current climatic conditions are preconditions for climate change assessments. Improving the understanding of these issues is also of practical benefit for weather and hydrological forecasting on daily to seasonal time scales. Key aspects of this avenue are:

Observations: Although considerable progress has been made in the collation of long-term data and the establishment of global surface-climate analyses (e.g. Dai et al. 1997; Huffman et al. 1997; New et al. 2001), the picture of the Earth's mountain climates offered by these analyses is still very limited. The available station data is mostly confined to dedicated WMO stations, and current analyses can rarely provide the spatial resolution that is necessary for many applications. Therefore, there is an urgent need to improve the accessibility of existing observational data for the scientific community by relaxing restrictions on data exchange (see also Hulme 1994). Considering emerging tendencies of network optimization, there is also a need to preserve the quality of existing networks with regard to spatial resolution and temporal homogeneity (e.g. Karl et al. 1995).

Assimilated Data: For remote mountain areas, better use of existing data will only marginally improve the situation, due to the sparse coverage with climate stations. One way to overcome the irrecoverable lack of data in these cases is the use of model-aided data from atmospheric data assimilation and reanalysis systems (Kalnay et al. 1996; Gibson et al. 1997; Rabier et al. 2000). Such systems are able to assimilate meteorological data from a wide range of sources – among them conventional radiosonde and surface station data, satellite information and data from commercial aircrafts – and exploit numerical models to estimate poorly observed variables (such as precipitation) in remote areas. In many large-scale mountainous river catchments, such data – in conjunction with existing runoff data and satellite information on snow cover extent – is the only hope to better understand the natural interannual and inter-decadal variations of the atmospheric water cycle and the hydrological response.

Numerical Weather Prediction: Twenty or thirty years ago, numerical weather prediction in mountainous regions required a tremendous effort that appeared only feasible in industrialized countries. With the advent of high-resolution atmospheric prediction models (e.g. Simmons and Hollingsworth 2002), it has become feasible to utilize global forecasting products even at remote locations and in regions where data is sparse. Furthermore, with the decreasing price of high-speed computers and the increasing speed of Internet connections, it has become feasible to run purpose-designed high-resolution limited-area forecasting systems at comparatively small costs. The use of such procedures appears particularly promising as regards quantitative precipitation forecasting in mountainous regions. Such applications allow a direct coupling with hydrological runoff and water resource assessment models. In addition, there are promising prospects regarding the prediction of extreme events (e.g. Bougeault et al. 2001), which enables the implementation of short-term warning systems.

Seasonal Forecasting: For many tropical mountain ranges, the future climate will continue to be dominated by El Niño type natural variability (although global warming may impact ENSO frequency and intensity). Such variability is to some extent predictable with lead times of 3 to 6 months (e.g. Stockdale et al. 1998), thus providing important information for the management of water resources over seasonal time scales. In the extratropics, however, the predictability of seasonal variability related to El Niño is much poorer, and it remains to be seen whether seasonal forecasting is of much practical applicability in these areas.

Climate Change Scenarios: A better understanding of the above issues will also help to improve methodologies for constructing climate change scenarios. As almost all mountain ranges are characterized by highly complex topography, it is not feasible to directly rely upon output from coupled atmosphere/ocean GCMs, but rather some downscaling procedure must be applied. Today, RCMs are considered the only foreseeable downscaling tool that is able to adequately represent the inherent non-linearities of regional climates. When applied in mountainous regions, the high spatial resolution of RCMs is of particular advantage. Statistical downscaling methods may also serve their purpose and these are much simpler and cheaper to apply. In the medium term, methodologies will be needed that provide probabilistic climate predictions (rather than scenarios of unknown probability).

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