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Heavy Precipitation Processes in a Warmer Climate

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Abstract. Climate simulations have suggested that a greenhouse-gas induced global warming would also lead to a moistening of the atmosphere and an intensification of the mean hydrological cycle. Here we study possible attendant effects upon the frequency of heavy precipitation events. For this purpose simulations with a regional climate model are conducted, driven by observed and modified lateral boundary conditions and sea-surface temperature distributions. The modifications correspond to a uniform 2K temperature increase and an attendant 15% increase of the specific humidity (unchanged relative humidity). This strategy allows to isolate the effects of an increased atmospheric moisture content from changes in the atmospheric circulation.

The numerical experiments, carried out over Europe and for the fall season, indicate a substantial shift towards more frequent events of strong precipitation. The magnitude of the response increases with the intensity of the event and reaches several 10s of percent for events exceeding 30 mm per day. These results appear to apply to all precipitation events dominated by sea-to-land moisture transport.

Introduction

Simulations undertaken with global climate models (GCMs) suggest that a global-scale climate warming could be associated with a substantial increase in the column-integrated atmospheric moisture content [*DelGenio et al.*, 1991; *Bony et al.*, 1995]. For the extratropics the variations of lower tropospheric moisture were found to be primarily controlled by the temperature dependence of the saturation mixing ratio (described by the Clausius-Clapeyron relation) rather than by changes in the relative humidity. The results suggest an increase of the atmospheric moisture content by about 7% per degree of warming [see also *Mitchell and Ingram,* 1992]. Such a change would influence a variety of climate-related feedbacks and can contribute directly to changes in the regional water cycle and precipitation climate.

Observed variations of the atmospheric moisture content lend support to the general behaviour in the GCM warming experiments: Analyses of satellite data [*Raval and Ramanathan*, 1989; *Bony et al.*, 1995] and in-situ radiosonde measurements [*Gaffen et al.*, 1992] suggest that the thermal variations of the saturation mixing ratio is the dominant contribution for the spatial, seasonal and interannual variations of the atmospheric moisture content. This result applies to middle and high latitudes but not the tropics [*Sun and Oort*, 1995].

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GCM simulations with increased greenhouse gas concentrations also suggest an enhancement of the hydrological cycle [*Kattenberg et al.*, 1996], and they provide some indication of an attendant shift towards more numerous events of heavy precipitation [*Fowler and Hennessy*, 1995; *Gregory and Mitchell*, 1995]. Both effects have been interpreted in terms of the above 'moisture effect' of a global-scale warming. A caveat of these inferences is the limited spatial resolution of the GCMs [*Fowler and Hennessy*, 1995], and moreover the myriad of inter-related physical processes renders difficult the unequivocal attribution to and quantification of the 'moisture effect'.

Here we study the influence of a stipulated increase of the atmospheric moisture content in comparative isolation. Simulations with a regional climate model [*Giorgi et al.*, 1995; *Lüthi et al.*, 1996] are driven by a surrogate climate-change scenario [*Schär et al.*, 1996] of a warmer and moister atmosphere, and the corresponding changes of the hydrological cycle and heavy precipitation is assessed. The simulations are conducted for Europe but the results may also be relevant for other middle and high-latitude regions of the world.

Our study will pay special attention to the coastal areas of Southern Europe and the Alpine mountain range which are particularly often affected by severe precipitation events. These events are associated with the advection of very moist maritime air by a strong south-westerly low-level flow towards the coast and the Alpine topography [e.g. *Buzzi and Tartaglione,* 1995; *Jansa et al.,* 1996], and they are particularly frequent during the fall season. Figure 1 displays a typical example for which the column-integrated moisture content attains values as high as 30mm. It is important to ask whether this common setting of heavy precipitation events is receptive to global-warming related changes in the atmospheric moisture content.

Modelling Set-up

The modelling strategy adopts a methodology using surrogate climate-change scenarios for experiments with a limited-area climate model [*Schär et al.*, 1996]. In a first step a control simulation (referred to as CTRL) is conducted of the present-day climate by driving the model at its lateral boundaries with the observed weather evolution (perfect boundary conditions). In the second step a sensitivity experiment is conducted with the initial and boundary fields of the first realisation modified by an uniform temperature increase of 2K. Also, consonant with inference from observations and GCM experiments, the boundary condition for relative humidity is left unchanged and this results in a domain-averaged 15% increase of the atmospheric moisture content. The thermodynamic modification is dynamically compatible with the imposed flow and the synoptic-scale flow patterns are only mildly altered by changes in diabatic processes [*Schär et al.*, 1996]. The second simulation (re-

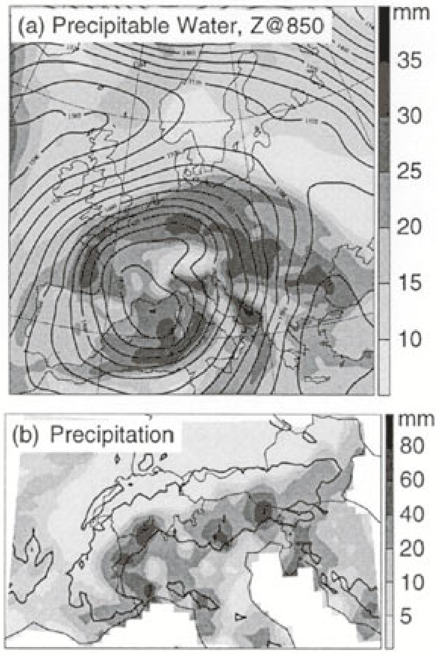

Figure 1. Typical heavy precipitation event in the southern Alpine region (October 5, 1992), associated with strong moisture advection from the Mediterranean. (a) precipitable water (in mm, shaded) and 850 hPa geopotential (20 gpm contour interval). (b) Precipitation analyses for the same day in the Alpine region [*Frei and Schär,* 1998].

ferred to as WARM) serves as a surrogate for a warmer and moister climate. It allows to separate the 'moisture effect' from other large-scale components of climate change, such as variations of the storm tracks.

The regional climate model utilized is the hydrostatic mesoscale weather forecasting model developed at the German Weather Service [*Majewski*, 1991; *Lüthi et al.*, 1996]. It is operated with a horizontal resolution of 56 km for a domain covering Europe and the North Atlantic. The model parameterizations include Kessler-type microphysics and a mass-flux scheme for moist convection. Lateral boundary fields are derived from the ECMWF-analyses. For the selected model domain and for synoptically active seasons (fall through spring) the simulated circulation has shown to be essentially deterministically controlled by the lateral boundary forcing [*Lüthi et al.*, 1996; *Schär et al.*, 1996].

Results will be presented of month-long simulations for an ensemble of five October months (1987, -88, -89, -90, -92), representative for the fall-time climatic conditions over Central Europe. Several events of heavy precipitation systems comparable to that of Fig. 1 are comprised in the simulated periods.

Response of the Mean Water Cycle

The ensemble mean fields of evapotranspiration and precipitation for CTRL (Fig. 2a,b) exhibit pronounced contrasts between oceanic surfaces, coastal areas and the continental interior. There is a surplus of evaporation over pre-

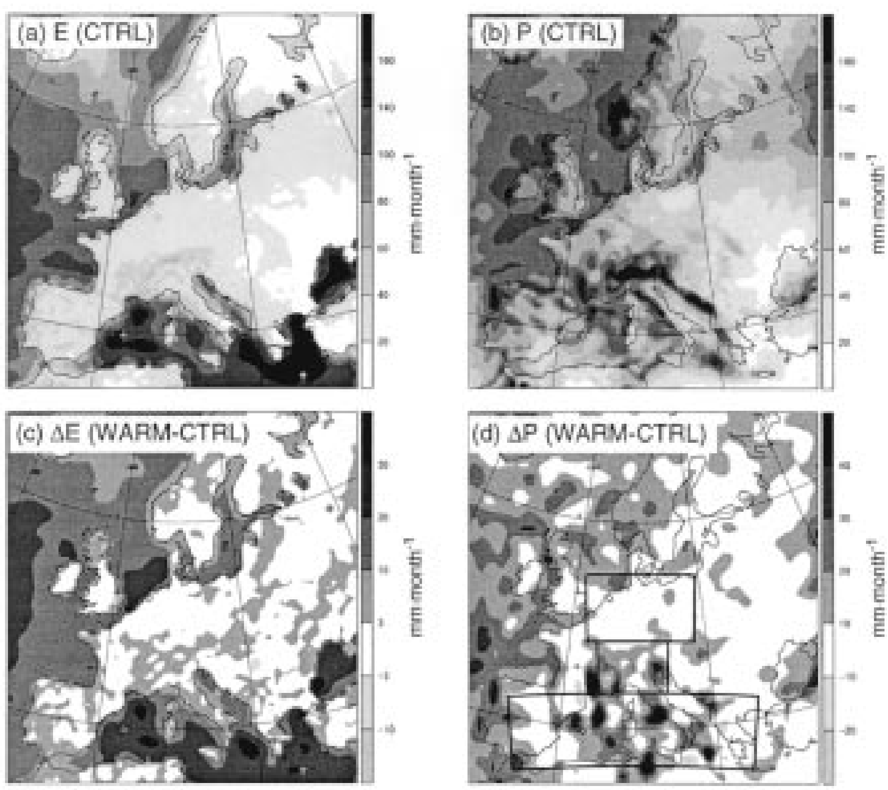

Figure 2. Distribution of evapotranspiration (a) and precipitation (b) of the CTRL simulation with the regional climate model (mean of 5 October months). Panels (c) and (d) depict the effects of a warmer (by 2 K) and moister atmosphere (differences between the WARM and the CTRL simulations).

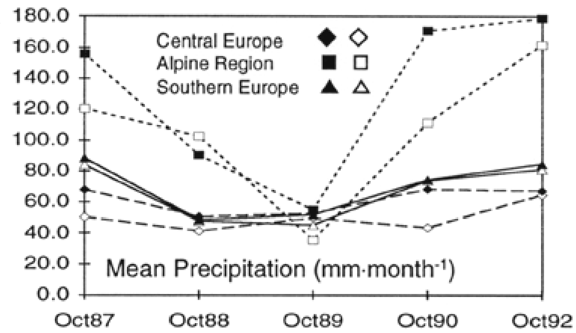

Figure 3. Comparison of simulated (CTRL, full symbols) and observed (empty symbols) mean precipitation amounts (in mm per month) for 3 subdomains (see Fig. 2d) and the individual members of the October ensemble.

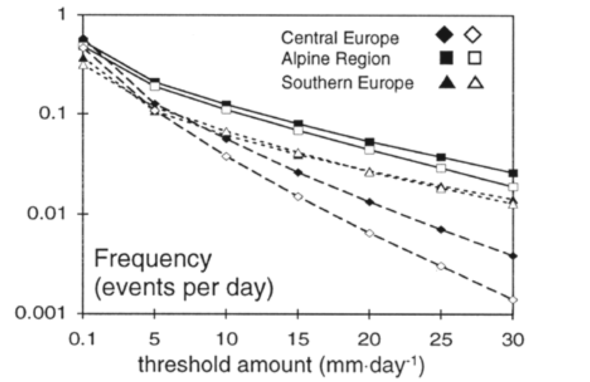

Figure 4. Frequency of precipitation events exceeding some threshold of the daily total (subdomains of Fig. 2d). Results pertain to the CTRL simulations (full symbols) and the observed daily precipitation of the same months (light symbols).

cipitation over the ocean whilst the inverse applies over land. Also Southern Europe and the Alps experience particularly wet conditions. The precipitation pattern over land is in good agreement with an objective analysis from a network of 1350 rain-gauge stations. In particular, the characteristic variations between individual months of the ensemble are well reproduced (Fig. 3). In the average over the terrestrial portion of the domain there is a wet bias of 13%.

With the idealized warm climate scenario (WARM) the simulated mean evaporation and precipitation show spatial variations very similar to that of the CTRL, but there is a significant overall increase. The enhancement of evaporation from the ocean amounts to 14% (Fig.2c). This can be interpreted in terms of changes in the turbulent transfer through the atmospheric boundary layer over the ocean, which is in turn induced by the increased vertical gradient in the mean specific humidity. Over land the evaporation increase is somewhat lower (11%).

Averaged over the model domain the ensemble-mean precipitation increases by between 12 and 15% for individual months of the ensemble. The increase is most evident for areas that already experience wet conditions in the CTRL simulation, i.e. the ocean, Southern Europe and the Alpine region (Fig.2d). For the Mediterranean subdomain (see frame in Fig. 2d), the relative increase (17%) is larger than for the Alpine region (12%) and Central Europe (9%), however the limited sample size and the magnitude of the case-to-case variations militate against identifying statistically significant regional variations for this relative increase.

Together the changes in precipitation and evaporation imply an enhancement of the mean regional water cycle, and the magnitude of the percentage increase is of the same order as the increase in specific humidity.

Response of the Precipitation Intensity

The response in precipitation intensity is assessed by considering the simulated daily rainfall totals at gridpoints grouped in sub-areas of the model domain. The frequency distributions for the ensemble of the CTRL integrations (Fig.4) compare well with those derived from an objective analysis of observed daily precipitation. The slight tendency to overestimate the occurrence of moderate to high precipitation events is associated with the overall wet bias. Nevertheless the model successfully reproduces the characteristic variations of the distribution between the sub-areas.

The simulated warming has a significant impact upon the intensity distribution of the precipitation events (Fig.5). For light-intensity events the effect is marginal, and the frequency of rainy days (>0.1mm per day) remains almost unchanged. However the effect progressively increases with precipitation intensity, and is most pronounced for strong events. Occurrences exceeding 30mm per day are more frequent by more than 20% for all three subdomains. Indeed it is the change in the frequency of high-intensity events that is the major contributor to the simulated increase in the mean precipitation. A progressively increased response towards the upper part of the intensity spectrum is also found for other subdomains - both over land and sea.

The response evident in the frequency distributions is not necessarily the result of a process that is sensitive to precipitation intensity. A similar effect can be obtained with a uniform relative shift of the intensity of each precipitation event [see also *Fowler and Hennessy,* 1995]. The modulation of the frequency distribution associated with such a shift by 15% is indicated in Fig. 5 (dashed lines). It reproduces the strong effects at high intensities and can explain some of the

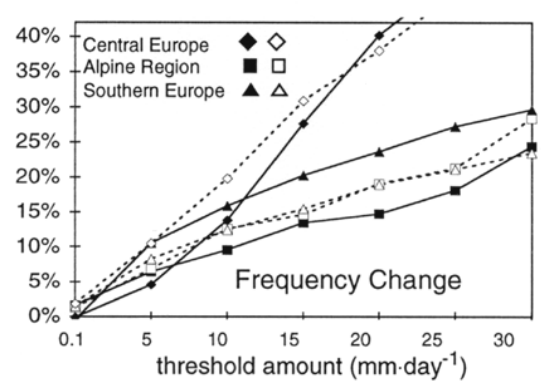

Figure 5. Relative change of the frequency of precipitation events from the CTRL to the WARM simulation (full lines, subdomains of Fig. 2c). Dashed lines depict the changes from an uniform increase by 15% of each daily precipitation in the CTRL simulation.

regional variations of the simulated response.

The results suggest that the stipulated increase in the atmospheric moisture content has marginally affected the spatial extent of the simulated precipitation systems but resulted in a change of their intensity leading to substantial reductions in the return period of strong events.

Further Remarks

In summary the regional climate simulations indicate an intensification of the regional hydrological cycle, and suggest a strong sensitivity of the return period of heavy precipitation events to the atmosphere's temperature and moisture transport capacity. A warming of 2K leads to an increased frequency of heavy precipitation events (>30 mm/day) by more than 20%.

Comparable effects can be expected for other regions in mid-latitudes and for other months provided the ocean-land moisture transport by synoptic systems is a dominant factor in the regional water cycle. However the results may not be applicable for the summer season over central Europe, where the local interplay between soil hydrology and convection appears to be an essential factor of the water cycle [*Schär et al.*, 1998].

The results suggest that the relative changes in the hydrological cycle are approximately controlled by the Clausius-Clapeyron relationship. Although the simulated response is stronger over maritime areas, the present sample of integrations does not allow to detect statistically sound conclusions for regional variations. Nevertheless from the nature of the mechanism it can be expected that the results are particularly relevant for coastal areas and other regions where low-level moisture advection is a key to the occurrence of strong precipitation. The coasts of Southern Europe and the Alpine region may be particularly receptive to the 'moisture effect'.

Previous global [e.g. *Gregory and Mitchell,* 1995; *Fowler and Hennessy,* 1995] and regional [*Jones et al.*, 1997] climate simulations of the effects of increased greenhouse gas concentrations have already indicated a tendency towards more frequent occurrence of strong precipitation events. Observations over the continental United States also show that the fraction of precipitation originating from high-intensity events has increased during this century [*Karl et al.*, 1995]. The present results suggest that the physical mechanism for such a signal may relate primarily to changes in the atmospheric moisture content. Such a mechanism would imply increasingly larger effects at higher precipitation intensity. The magnitude of the response from the 'moisture effect' is noteworthy and the signal could compensate or enhance other effects such as those related to changes in the storm tracks or the large-scale atmospheric stratification. Clearly, a reduction in the return period by several 10s of percent could have major societal, ecological and economic repercussions.

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