Modelling future landslide activity based on general circulation models

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Abstract

Currently, global warming due to increasing concentrations of CO_2 and other greenhouse gases is widely accepted. Climate is an important forcing parameter of landslides and, hence, implications of climate change for landslide activity are of high concern for geomorphological research. The present paper offers a method for assessing climate change impacts on landslide frequency based on general circulation models (GCM). GCM results are downscaled with an empirical–statistical technique to derive local precipitation scenarios. These scenarios are used as input to a simple slope hydrological and stability model. The landslide is defined 'active' if simulated groundwater levels exceed a critical level established with the stability model. Recurrence intervals for landslide activity are obtained by applying a Gumbel regression to the simulated annual maximum groundwater levels. Furthermore, it is shown that indirect climate change impacts as well as changing non-climatic parameters can be important for future landslide frequencies too. The use of three different GCM experiments for the assessment of the activity of a small landslide in SE France did not show a consistent picture of future landslide frequencies. This is due to differences between the GCM experiments but might be enhanced by the limited ability of the applied downscaling technique to carry climate change signals. Finally, some possibilities of improving the approach are outlined and the need for better GCM experiments, which provide the basic input of the approach, is addressed. © 1999 Elsevier Science B.V. All rights reserved.

1. Introduction

Global warming due to increasing concentrations of CO_2 and other greenhouse gases is now widely accepted (Hulme, 1996; Houghton et al., 1996). Since climate is an important forcing parameter of many geomorphological processes, it is clear that climate change is of high concern for geomorphological research. In the chapter about mountain environments (Beniston and Douglas, 1996) of the Intergovernmental Panel on Climate Change (IPCC) — publication on climate change impacts is stated (page 199). ''In a future climate in which both the mean and the extremes of precipitation may increase in certain areas, the number of small and large slides would correspondingly rise.'' While this view might be generally acceptable, it does not allow statements

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about either location or magnitude and frequency of future events.

At present, the most plausible projections of a future climate are based on general circulation models (GCMs). Since they are based on fundamental laws of physics, they have the advantage of being able to simulate *new* (new means that no analogs exist) situations like the effects of the human-induced rapidly increasing greenhouse gas concentrations (Trenberth, 1996). However, one major shortcoming is their low horizontal resolution of currently around 250×250 km. With this low resolution, GCMs are not capable of simulating regional aspects of climate (von Storch, 1995) and, furthermore, important orographic features cannot be considered in the model (Beniston, 1994). Approaches to overcome this scale problem could be a postprocessing of the GCM output either with physically based dynamical models or with empirical–statistical downscaling techniques (Arnell, 1995; von Storch, 1995). This offers the chance to assess climate change impacts for small scale geomorphological problems. In the present study, a possible approach to assessing climate change impacts on landslide activity by means of statistical downscaling is presented with some theoretical points of view and illustrated with a case study of a small landslide in South East France.

2. General methodology

In this section, general considerations about linking the various steps of the presented approach from GCMs via downscaling to the impact assessment are outlined. An approach based on GCM simulations is chosen because they produce the physically soundest scenarios of future climate and are recommended in the 'Technical Guidelines for Assessing Climate Change Impacts and Adaptations' of IPCC (Carter et al., 1996) together with subsequent downscaling techniques.

2.1. Identification of relevant climate input

First, it is necessary to define the climatic input parameters which play the dominant role in triggering landslides. Here arises the problem that landslides are a very heterogeneous process group and

hence they show a wide range of triggering mechanisms, even if only climate-related triggers are considered (Gostelow, 1991). However, they can be roughly subdivided into several major groups with precipitation as main triggering factor (Collison, 1996; van Asch, 1996). These are landslides with surficial shear planes (< 1 m), e.g., debris flows, shallow landslides with shear planes at 1–10 m depth and deep seated landslides with shear planes at 10–40 m depth. For these three cases, different hydrologic systems and, hence, climatic input variables have to be considered. They range from yearly, monthly or daily precipitation to short-term intensities in intervals of hours or minutes. Information of this type is necessary to select appropriate climate change scenarios.

2.2. Sensitivity of landslides to climate change

The sensitivity of landslide triggering to climate change compared to other factors like seismicity, material availability, self-stabilization, etc., is important for the usefulness of a climate impact study on landslide activity, and should be tested in a sensitivity analysis. The following simplified example is intended to illustrate the complexity of relevant climatic input as well as the importance of a probable climate change on debris flows. Imagine a situation with debris flows originating in the periglacial belt of the Alps. Three scenarios can be designed considering changes in temperature and precipitation.

(1) Triggering of the debris flow is debris limited. If no debris is available, even the heaviest shower cannot trigger a debris flow. Therefore, a change in precipitation might not be significant for changing the activity of debris flows.

(2) Triggering of the debris flow is precipitation-limited. A change in precipitation might significantly influence the frequency of debris flows.

(3) Special case of 1 (change in debris availability). Debris availability is increasing by means of melting glaciers and permafrost following global warming as outlined in Zimmermann and Haeberli (1992) and Dikau et al. (1996). In this case, increasing temperature alone without additional changes in precipitation could increase the frequency of debris flows.

For other types and settings of mass movements, other facts might be important, e.g.,

- changing landuse, human-induced or due to climate change,
- vegetation succesion due to climate change,
- changing weathering regime due to climate change,
- changing slope geometry due to landsliding or other processes, and
- self-stabilization (event-resistance) or increasing instability following the concept of Crozier (1986) where a slope can gain or lose strength due to occurence of landslide events.

While the first three points are also related to climate, the latter two are dependent mainly on the geomorphological process system. They can, however, play an important role in changing the overall susceptibility of a slope to climatic factors (Crozier, 1986).

2.3. Techniques to obtain local climate change scenarios

After identifying relevant climate parameters, one has to deal with the question of how to obtain them. Can the required information be derived succesfully from GCM simulations by means of downscaling, in suitable quality, and is it realistically simulated?

Several downscaling techniques are described in the literature. They range from simple empirical–statistical relationships between large-scale atmospheric variables and local target climatic parameters (e.g., von Storch et al., 1993; Lettenmaier, 1995; Zorita et al., 1995) to physically based regional climate models which are nested within GCMs (e.g., Giorgi et al., 1994; Frey-Buness et al., 1995).

In an earlier paper (Buma and Dehn, 1998), it was shown that statistical downscaling techniques are potentially suitable for modelling of landslide activity. All of these techniques rely on homogeneous long time series of the target parameter on the local scale and one or several atmospheric variables like sea level pressure or geopotential heights on the large-scale. A major limitation is the assumption that the relationships obtained under present conditions will also hold true under a changing climate.

2.4. Linking climate change data and impact model

The long pathway from greenhouse gas emission scenarios to climate change impact studies is shown in Fig. 1. Emission scenarios published by the IPCC (Houghton et al., 1992) are based on assumptions about global demographic and economic growth and energy supplies. Using these scenarios GCMs simulate future climates on the large-scale, which can be used to derive local climate scenarios with techniques mentioned before. As already indicated, scenarios of other than climatic factors should be included in the approach to complete the assessment of future changes. However, since this is not always an easy or trivial task, the direct effect of climate change on the landslide process can be assessed as a partial approach to the problem. In all cases it is important to quote all underlying scenarios, models and assumptions included in the approach to make it as transparent as possible (Arnell, 1995).

2.5. Sources of uncertainty

Uncertainty increases within and between every link of the approach, as shown in Fig. 1. This uncertainty depends on:

1. quality of GCM simulations, regarding the predictor variables for downscaling (uncertainty of emission scenario included herein);
2. quality of downscaled scenarios, due to inhomogeneities in observed data and shortcomings of the technique applied;
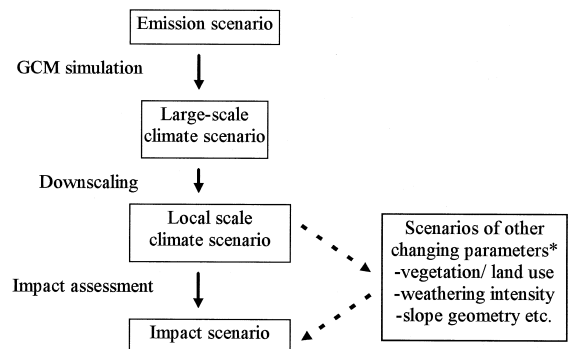

Fig. 1. Chain of scenarios and modelling steps leading to local climate change impact scenarios. Solid arrows are obligatory, dashed arrows are supplementary. *Refer to explanation in text.

3. quality and resolutions of the impact model(s), which are often strong simplifications of reality; and
4. errors in input data, e.g., underestimation of precipitation falling as snow due to wind effects.

GCM uncertainty might be assessed by using different GCMs and by using Monte Carlo experiments with one GCM starting with different initial conditions (Cubasch et al., 1994) and thus seizing some model-independent background noise which is traced into local scenarios. Uncertainty due to downscaling techniques might be assessed, e.g., by using different downscaling techniques or by varying parameterizations of the downscaling models. Likewise, uncertainties of impact models can be estimated by varying input parameters, taking into account, e.g., sampling errors.

3. Case study: Barcelonnette Basin, French Alps

3.1. Landslide setting

Fig. 2 shows the location of the Boisivre landslide in high alpine topography. Caris and van Asch (1991) have investigated this small landslide in detail. The following information is extracted from their findings. The slope is covered with pine forest. The landslide is developed in Jurassic marls called 'Terres Noires'. The landslide is about 175 m long and has an average depth of 7 m. It consists of a shallow colluvium layer (average thickness 1.5 m) overlying the in situ Terres Noires. The slip surface is located in the marls. Hydrological tests showed that infiltrating precipitation is temporarily stored in dead-end cracks in the permeable colluvium layer. A stability analysis showed that a continuous groundwater level in the weathered marls of at least 3 m over the slip surface (i.e., about 4 m below ground surface) is required to trigger movement of the landslide. Caris and van Asch (1991) concluded that such a critical hydrological condition can only occur if the presence of water in the cracks of the colluvium layer lasts long enough to maintain percolation into the weathered marls. This in turn requires relatively long periods with neglegible evapotranspiration. Based on these findings, monthly precipitation in the winter
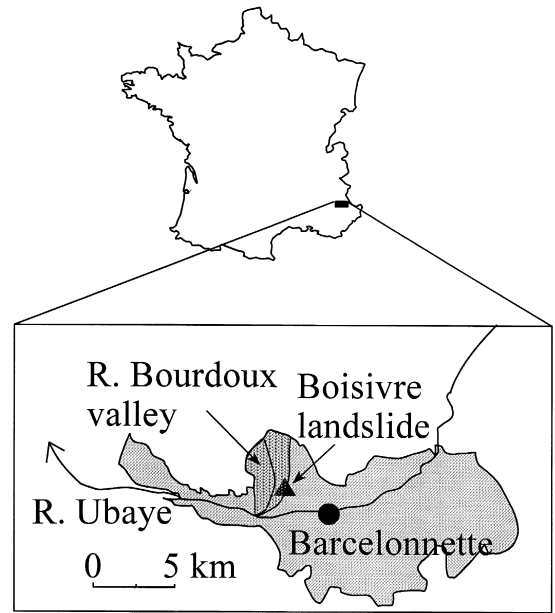

Fig. 2. Location of the Boisivre landslide, SE France. The grey-coloured Barcelonnette Basin (altitude 1100 m) is surrounded by mountain peaks reaching 3000 m.

months (October through April) is suspected to be the main climatological trigger of this landslide.

3.2. Applied downscaling technique

The downscaling technique is based on the assumption that the North Atlantic mean sea level pressure field (SLP) explains a significant proportion of Barcelonnette precipitation. Monthly precipitation and temperature data were obtained from Météo-france. Seven linear regression models relating fields of monthly SLP anomalies and corresponding monthly Barcelonnette precipitation are computed for October through April for the period 1928–1994 by using empirical orthogonal functions (EOFs also known as principal component analysis) and a canonical correlation analysis (CCA) as presented by von Storch et al. (1993) and Heyen et al. (1996). Power transformations of the monthly precipitation series were carried out to obtain normally distributed series for the regression. The CCA patterns for February and April precipitation are shown in Fig. 3. Properties of the seven regression models are shown in Table 1. Since the technique is purely statistical, a
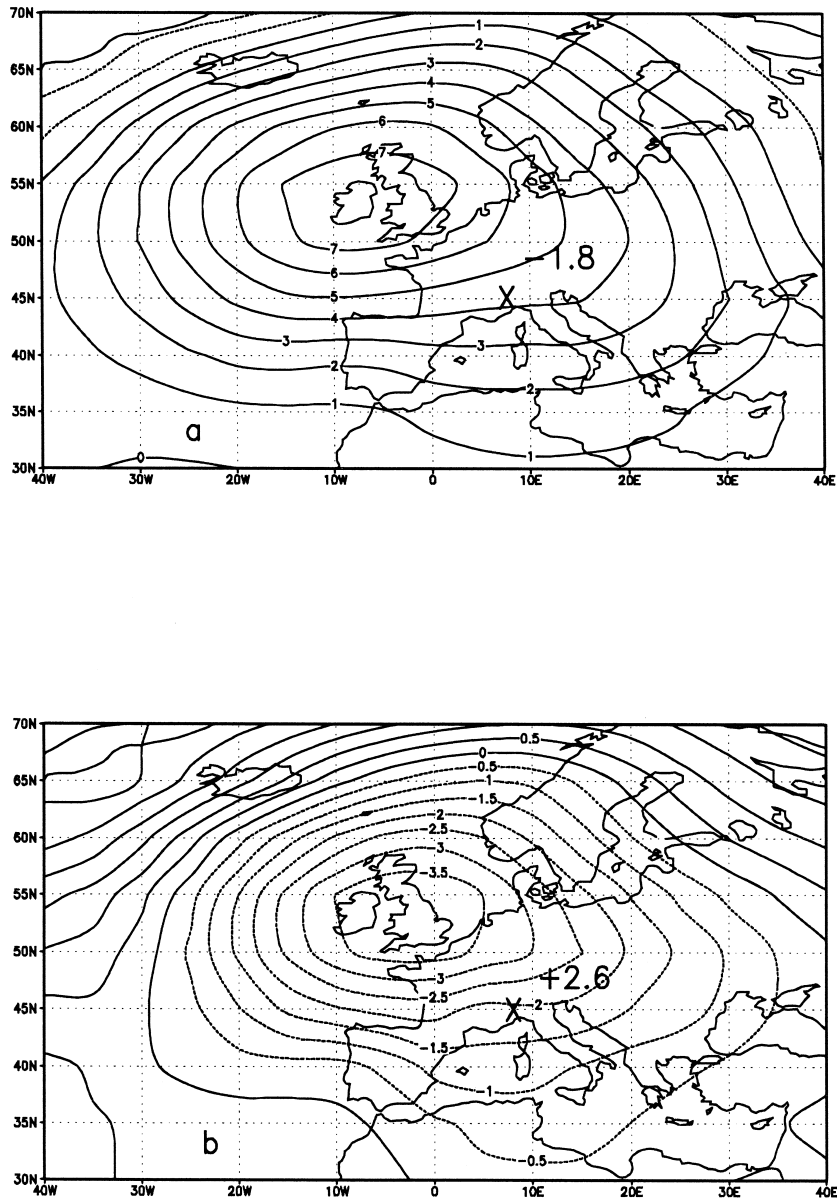
Fig. 3. Canonical correlation patterns of observed SLP field and simultaneous Barcelonnette precipitation in February (a) and April (b). The typical precipitation anomaly at Barcelonnette is negative in February and positive in April (see cross in figures) which is associated with a high pressure and low pressure anomaly, respectively, above Ireland and Great Britain.

further procedure is useful to show the physical plausibility of the technique. With respect to the 10 moistest and 10 driest Octobers of the observed record, high-frequency fluctuations of daily SLP, filtered through a 2.5- to 6-day filter, give indica-

tions of cyclonic storm activity. The difference between the resulting two fields (not shown) indicates a higher storm activity in the Bay of Biscay for the moist Octobers, thus, supporting the plausibility of the downscaling approach.

Table 1

Properties of the seven regression models applied in the study. The values are shown for observed and estimated precipitation series in Barcelonnette of the period 1928–1994

	October	November	December	January	February	March	April
Correlation	0.61	0.59	0.56	0.56	0.72	0.52	0.58
Explained variance	0.37	0.35	0.31	0.29	0.52	0.23	0.34

3.3. Local climate change scenarios

In order to obtain various local winter precipitation scenarios for Barcelonnette, and to include also the effect of tropospheric sulphate aerosols on climate change impact, SLP simulated by three different GCMs were used for downscaling. All three GCMs are based on the emission scenario IS92a of the IPCC (Houghton et al., 1992). The fourth generation European Centre/Hamburg Model coupled to an ocean circulation model with isopycnal grids (ECHAM4/OPYC3) from the Max-Planck-Institut für Meteorologie Hamburg was forced with greenhouse gases only. The second generation Hadley Centre Coupled Model (HadCM2) was forced with greenhouse gases only (HCGG) and alternatively with greenhouse gases and sulphate aerosols (HCGS). Some characteristics of the experiments are given in Table 2.

A comparison of isobar maps of observed and GCM-simulated long-term monthly mean winter SLP (December–February) is shown in Fig. 4. It can be seen, based on this simple comparison, that the three applied GCMs are quite successful in simulating large-scale patterns of SLP and hence can be used for downscaling with some confidence. However, more sophisticated tests would be necessary to eval-uate the GCMs concerning mean patterns and variability in detail.

Monthly precipitation was derived from SLP fields as described above. Fig. 5 shows precipitation derived from downscaling the three GCMs. Monthly mean precipitation of three periods of each GCM is presented in Table 3. A consequence of the limited amount of explained precipitation variance by SLP, is an accordingly reduced variability of the downscaled precipitation series (Buma and Dehn, 1998). In order to preserve the variability of the observed series, the estimated precipitation was combined with the residual values of the regression. These can be viewed as a noise component, statistically independent of the large-scale climate. In the formula:

$$R_{total} = R_{CCA} + R_{residual} \qquad (1)$$

with R_{total} = observed precipitation, R_{CCA} = precipitation explained by CCA and $R_{residual}$ = residuals of CCA.

If this operation is carried out on the estimated series of the regression fitting period, the (trivial) result is the observed series. For the climate scenarios, R_{CCA} is obtained by downscaling the GCM scenarios while $R_{residual}$ remains unchanged. In this way, the problem of limited correlation between predictor and predictand variables may be tackled.

Table 2

Main features of the three GCMs used in present study. GHG = greenhouse gases

| Feature	ECHAM4/OPYC3	HCGG	HCGS
Simulated period	1860–2099	1861–2099	1861–2099
Radiative forcing	1860–1990 = observed	1861–1990 = observed	1861–1990 = observed
	1991–2099 = IS92a	1991–2099 = IS92a	1991–2099 = IS92a
Tropospheric gases	GHG only	GHG only	GHG + sulphate aerosol
Horizontal resolution	T42, 2.8° × 2.8°	2.5° × 3.75° (lat. × long.)	2.5° × 3.75° (lat. × long.)
Reference	Roeckner et al., 1996	Johns et al., 1997	Johns et al., 1997
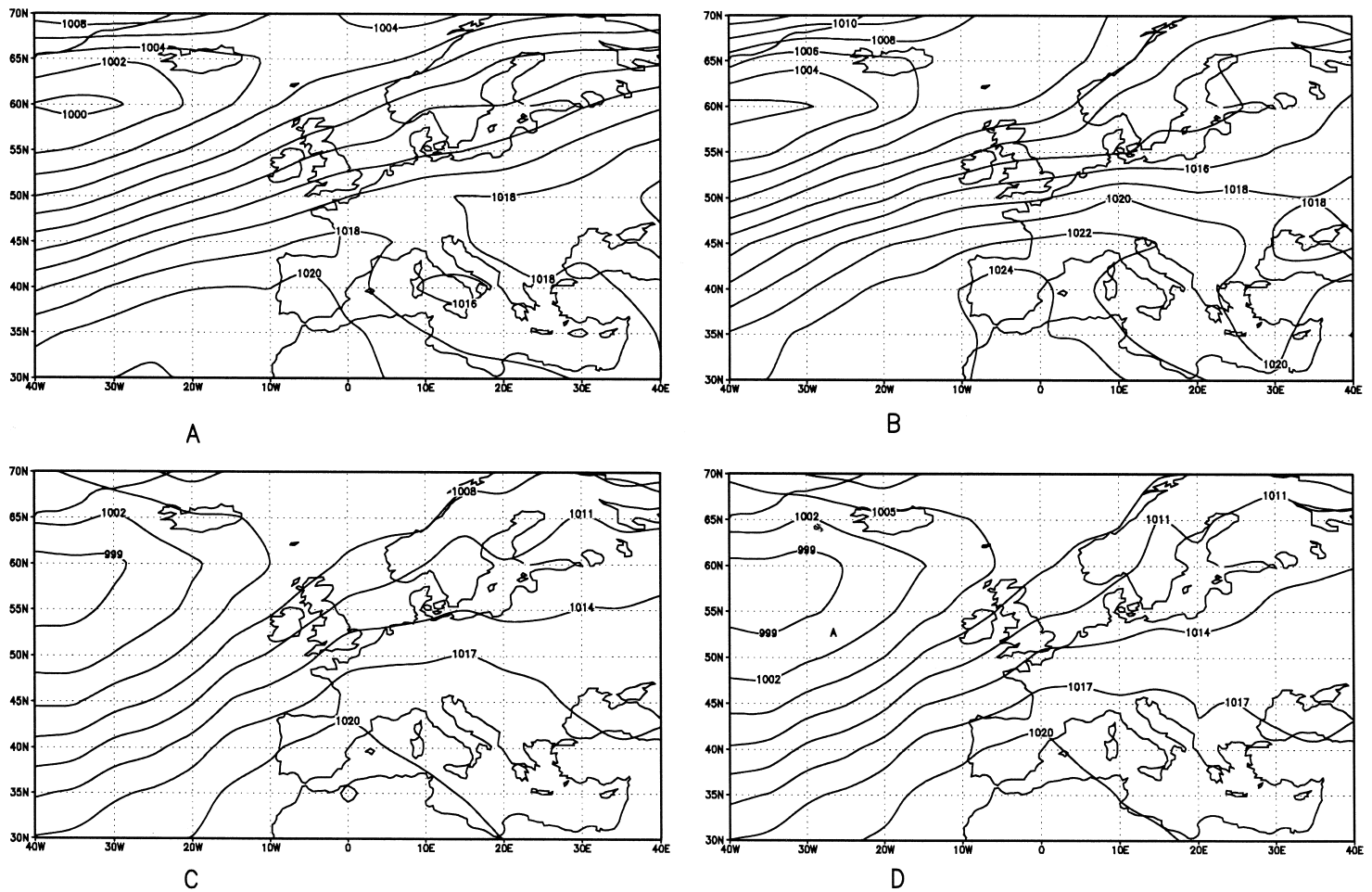
Fig. 4. Long-term monthly mean sea level pressure (hPa) in winter (DJF) 1960–1989 from analysed observations (A), ECHAM4/OPYC3 (B), HCGG (C) and HCGS (D).
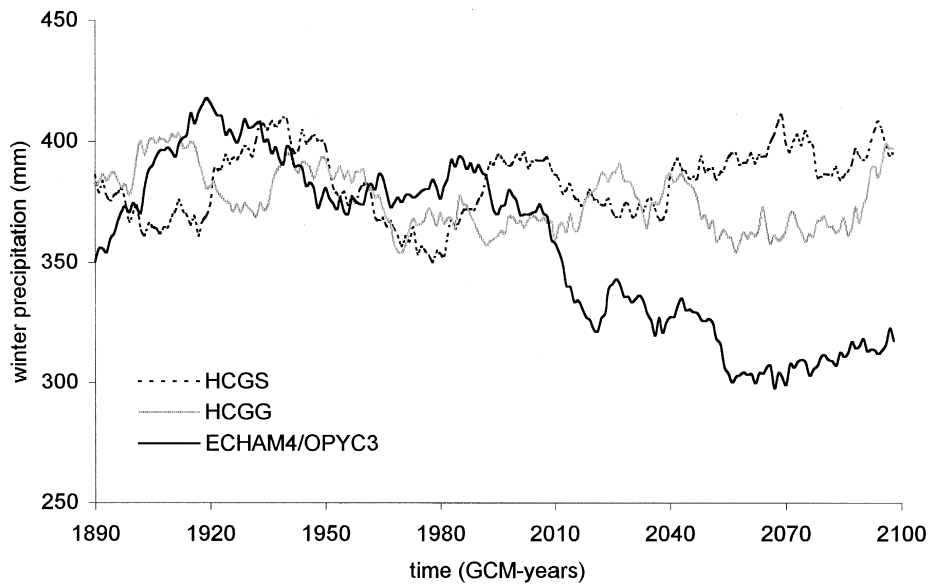
Fig. 5. Barcelonnette winter precipitation scenarios (October–April) obtained with downscaling mean monthly sea level pressure of three different GCM experiments (30-year moving averages).

Furthermore, because no significant correlation between monthly SLP and precipitation was found for the months May through September, summer precipitation was kept unchanged in the scenarios.

Mean monthly temperature is characterised by less spatial variability than monthly precipitation. Furthermore, simulation of temperature in GCMs is more reliable on the regional scale than precipitation.

Therefore, regional scenarios of mean monthly temperature are not obtained by downscaling but by interpolation between the four closest GCM grid points. Temperature in the decade 2090–2099 in comparison to 1980–1989 increases between +3.8°C, +3.6°C and +3.7°C in January and +8.0°C, +6.0°C and +3.6°C in July for ECHAM4/OPYC3, HCGG and HCGS, respec-

Table 3
Downscaled mean monthly precipitation (mm) for different periods of the GCM experiments

	October	November	December	January	February	March	April
ECHAM4							
1960–1989	68.2	71.1	48.2	60.6	35.6	48.1	56.8
2020–2049	50.8	60.8	45.7	37.2	43.7	42.6	46.2
2070–2099	40.5	58.7	37.1	48.3	54.3	40.1	41.6
HCGG							
1960–1989	74.2	69.0	47.1	39.5	41.4	45.1	48.5
2020–2049	62.0	56.9	50.9	49.5	47.2	50.2	51.4
2070–2099	57.4	51.7	38.7	49.5	70.7	58.5	68.5
HCGS							
1960–1989	66.3	74.6	49.3	46.8	42.6	40.2	53.1
2020–2049	80.4	56.7	49.1	51.6	39.1	52.9	59.3
2070–2099	66.5	53.1	49.3	61.0	40.5	54.9	63.7

tively. In July, the reducing effect of sulphate aerosols for greenhouse warming is clearly visible.

3.4. The impact model

The precipitation scenarios were used in a simple slope model. A hydrological tank model using effective monthly precipitation and an empirical drainage parameter simulates groundwater levels in the slope. The output groundwater series are checked for occurrences of monthly groundwater levels higher than the critical level described in Section 3.1.

Fig. 6 displays the tank model. The tank represents the whole landslide and has the same dimensions. The water level in the tank is determined by 'what comes in', i.e., effective precipitation, 'what goes out' and its porosity. The model value for the porosity is based on pF curves of soil samples taken from various depths in the slope (Kruse and Terlien, 1990). The discharge coefficient for 'what goes out' was optimized.

Effective precipitation was obtained by calculating potential evapotranspiration according to Thornthwaite (1948), relating this to actual evapotranspiration using a soil water balance model (Thornthwaite and Mather, 1957) and subtracting the actual amount from gross precipitation. The effect of snow was roughly incorporated by storing any precipitation occurring in months with a mean air temperature $< 0°C$ in a 'waiting room'. The contents of this waiting room are released into the hydrological model once mean air temperature rises above 0°C.

In the absence of reliable groundwater data, the slope model was roughly calibrated against dendrochronological datings obtained for the period 1956–1980 (van Asch and van Steijn, 1991), so that periods (years) with supercritical groundwater levels coincided with eccentricities in the tree rings.

Because the focus is on the derivation and application of consistent precipitation and temperature scenarios, a detailed assessment of uncertainty sources brought in by the slope model is beyond the
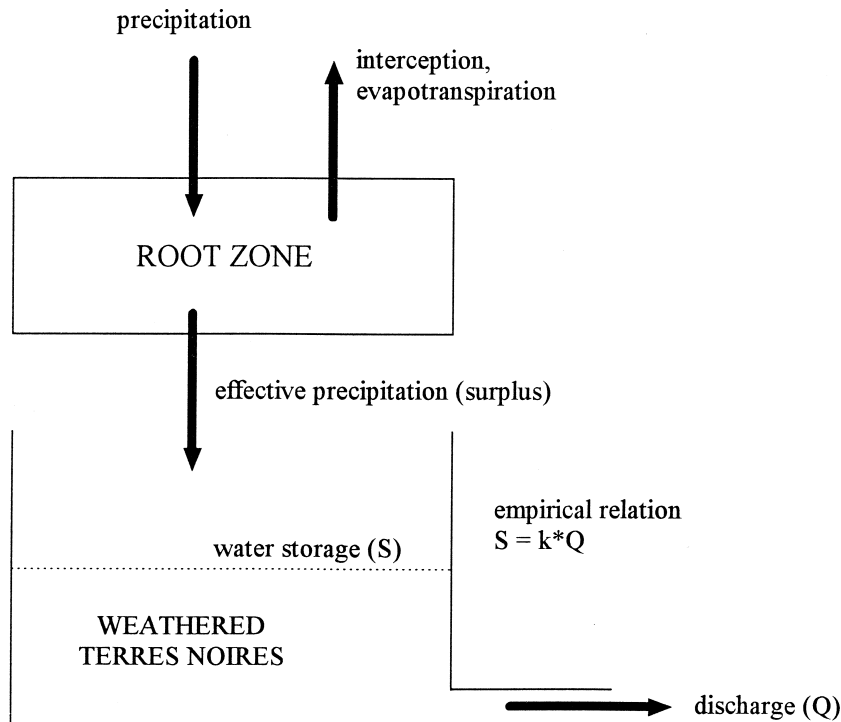

Fig. 6. Schematic representation of the EPL tank model used for hydrological modelling of Boisivre landslide. *S* is water storage defined by water height above the bottom and the porosity of the weathered Terres Noires. *k* is an empirical discharge coefficient and *Q* is discharge.

scope of the present paper. Such an assessment is, however, crucial if practical applications are considered.

Probable indirect climate change impacts or nonclimatic factors, which could also influence the future activity of Boisivre landslide but are not considered explicitly in the present paper, are:

· vegetation (forest) succesion due to climate change which could alter the slope hydrology by changing evapotranspiration;
· faster weathering of marls due to increasing temperature and changing soil properties; and
· undercutting of the landslide body by Riou Bourdoux during an extreme flood event, since the lower end of Boisivre landslide is only 20 m away from the floodplain.

3.5. Estimating future landslide activity

The Boisivre landslide is defined as being 'active' in years when the maximum monthly groundwater level exceeds the critical level. Recurrence intervals

of landslide activity were calculated for five 30-year periods of the climate scenarios: 1870–1899, 1910–1939, 1960–1989, 2020–2049 and 2070–2099. Of these, the former three are used as control periods, for which the calculated intervals should resemble that obtained with observed data. Residual winter precipitation, as well as summer precipitation series are consequently taken from 1960–1989 to complete *all* the 30-year scenarios. This is the only period fully covered by observations.

For each period, a monthly groundwater series was calculated with the slope model. The annual maximum of simulated monthly groundwater levels obeys the Gumbel distribution (Gumbel, 1958) closely in all model runs, which means that it can be related to its ranking in the 30-year series and, hence, to its recurrence time. Thus, the recurrence interval of this entity equaling (or exceeding) the critical level could be calculated. The recurrence intervals are shown in Fig. 7.

For the control period, the ECHAM4/OPYC3 scenario produces recurrence intervals matching that obtained with the observed 1960–1989 data, while a dry bias is present when using HCGG, and to a
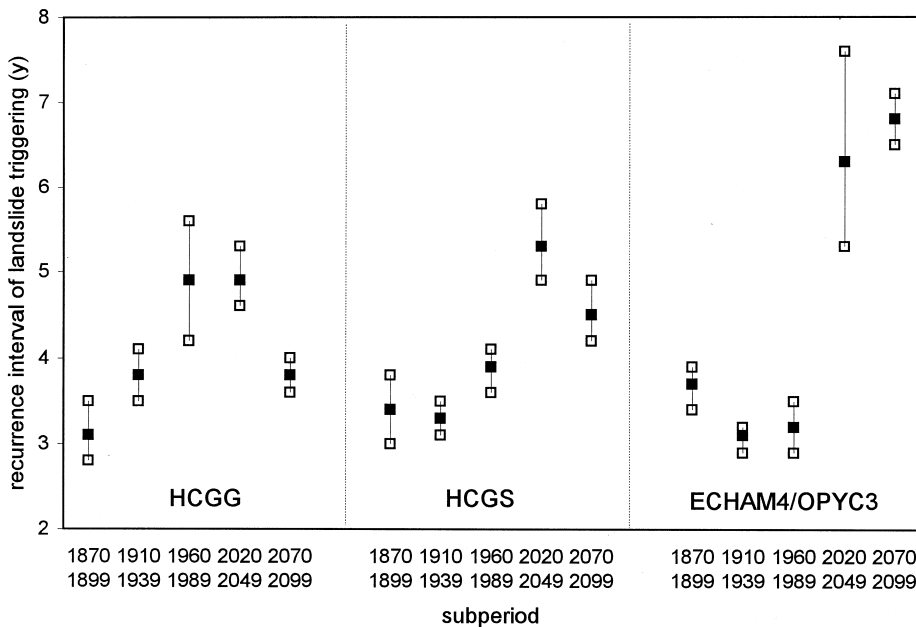

Fig. 7. Recurrence intervals of supercritical groundwater conditions based on a Gumbel regression for five subperiods of the three GCM experiments. The open dots indicate the 95% confidence intervals of the Gumbel regression. Years with supercritical groundwater conditions are defined as years with landslide activity.

lesser extent HCGS. The scenarios based on ECHAM4/OPYC3 and to a lesser extent HCGS show significant decreases in landslide activity in 2020–2049 and 2070–2099 compared to the reference and control periods. In HCGG, the maximum change in the perturbed climate (2020–2049) is as large as the bias in the control period 1960–1989, and is therefore not significant. Note that although the overall HCGG scenario is dryer than HCGS in 2020–2049 (see Fig. 5), simulated landslide activity is higher in the former scenario. Because February is the only month for which HCGG is considerably wetter, precipitation in this month is apparently important.

It is interesting to note that for the ECHAM4/OPYC3 case, 75% of the decrease in 2070–2099 is accounted for by the $+8°$ temperature rise, and only 25% by the precipitation decrease which amounts to about 67 mm in the winter season. This was found by running the slope model with perturbed temperature and unchanged precipitation series, and vice versa. The cause seems to be again that in ECHAM4/OPYC3 February becomes wetter despite a generally decreasing trend. This supports the approach of assessing both precipitation and temperature changes for landslide activity.

4. Discussion

The impact of climate change on simulated landslide frequencies based on three GCM experiments presents quite different scenarios. This is a general problem, i.e., it does not pertain to specific regions. The precipitation scenarios range from a significant, monotonous decrease in the ECHAM4/OPYC3 scenario to a noisier pattern in HCGG and HCGS and can be regarded as uncertainty of the various GCM experiments.

Fig. 5 shows 30-year moving averages of Barcelonnette precipitation, downscaled from the three GCM-simulations. Trends are generally overshadowed by large interdecadal fluctuations. Interdecadal variability is a natural element of climate and is simulated by GCMs with reasonable confidence (Roeckner et al., 1996; Johns et al., 1997). It may not be very meaningful to define arbitrary sub-

periods for impact modelling, as is done in the present study. A better strategy would therefore be to carry out the described modelling procedure on moving windows of 30 years within each climate scenario, going from 1860–1889 to 2070–2099.

As already outlined in Section 3.5, residual winter precipitation and summer precipitation series of the 1960–1989 period are combined with each R_{CCA} scenario from each GCM. However, treating them correctly as unknown, a stochastic method of combination with R_{CCA} would be the conceptually better choice. Therefore, alternative 30-year series were produced for HCGS only by randomly sampling values from the pool of 1928–1994 observations of both variables. $R_{residual}$, R_{CCA} and R_{summer} are statistically independent and not autocorrelated. The procedure was repeated 100 times, for which the mean recurrence interval was calculated, as well as the range covering 95% of the recurrence interval values. For HGCS (1960–1989 and 2070–2099), mean values decrease by 5% and 9% respectively, compared with the standard results. The 95% ranges are somewhat wider than the 95% confidence band calculated from the Gumbel regression. This difference could also be due to the fact that the former is a nonparametric estimate based on 100 cases only while the latter is a parametric estimate. Therefore, the two are not strictly comparable.

The implicit assumption that the proportion of Barcelonnette precipitation explained by SLP carries the entire climate change signal, might be wrong. The unexplained proportion, which in our case is quite important, could also contain signals which are not extracted by the linear regression with CCA. This could be tested by applying other downscaling techniques.

The sensitivity of the recurrence intervals to downscaling uncertainties was tested by establishing the regression for two alternative fitting periods 1928–1964 and 1965–1994 instead of 1928–1994. The recurrence intervals for HGCS, 1960–1989 and 2070–2099, were then calculated based on these new downscaled scenarios. For 1960–1989, no change is seen, but for 2070–2099, changes amount to -11% and $+7\%$ (fitting periods 1928–1964 and 1965–1994, respectively). This may be due to small differences in the empirical regression models resulting from information missing in the shorter fitting peri-

ods. This illustrates the importance of long climato-logical time series for statistical downscaling.

Furthermore, it must be realised that the statistical relationship between SLP and precipitation, established for 1928–1994, may become invalid in future climates which lie outside the range of climate situations covered by this period.

Finally, there are several sources of uncertainty associated with the impact model and input data, as already outlined in Section 3.4. The instantaneous release of accumulated snow once temperature rises above zero causes a large amount of infiltration into the slope, in turn generating a higher groundwater level than would be the case if this amount were to infiltrate gradually during several months. Indeed, almost all supercritical groundwater levels are simulated during early spring. This might explain the relatively large contribution of temperature rise to the decreasing landslide activity, as well as the relatively large importance of February precipitation suggested by the results. It also shows the importance of adequately modelling snow processes in Alpine landslide studies.

5. Conclusions

Several conclusions can be drawn from this study:

1. The approach of linking GCMs and a slope stability model via a downscaling technique to derive landslide frequencies is feasible.
2. Some components of uncertainty of the approach were quantitatively assessed.
3. Quantification of all sources of uncertainty is required to derive impact assessments with an acceptable degree of confidence.
4. No consistent picture of future landslide activity based on three different GCM experiments could be obtained. We must wait for improved GCMs but should work on optimizing the approach in the meantime.

Acknowledgements

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