Development of a method for predicting the impact of climatic change on slope stability.

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ABSTRACT

A major effect of man-induced climate change could be a higher frequency of extreme rainfall events in Europe. Consequently, the frequency of landslides could increase, affecting erosion and deposition regimes of upland areas. Assessment of this effect on a landslide scale is difficult, due to regional variations in magnitude of climate change across Europe as well as different landslide triggering mechanisms. A potential method for predicting climate change impact on landsliding is to link conceptual slope hydrology/stability models to climate scenarios obtained through downscaling General Circulation Models (GCM). First results and problems encountered are discussed for a selected test site in South East France.

1. CLIMATE CHANGE AND LANDSLIDING

Recent predictions of climate change as a consequence of increased greenhouse gas production suggest that Europe will experience a higher frequency of extreme rainfall events (Cubasch et al., 1995). This could cause an increase in landslide activity, resulting in an increase in natural hazards. However, the spatial pattern of landslide (re)activation is likely to be complex as different areas in Europe will experience variable changes in the magnitude and frequency of precipitation. Moreover different types of landslides will respond either to changes in the long term climate (monthly or yearly rainfall) or short term weather (daily or weekly rainfall).

A potential method for predicting the consequences of climatic change is to link conceptual slope hydrology / stability models to climate scenarios produced by General Circulation Models (GCMs). GCMs are successful in simulating the large-scale state of the atmosphere. However, their low horizontal resolution (about 200x200 km) inhibits their direct use for climate impact studies on the local scale, such as landslide studies. Several alternatives to improve regional performance of the models are discussed in literature (von Storch, 1995; Beniston, 1994; Cubasch et al., 1996). One is to develop GCMs with a higher spatial resolution, but this alternative does not seem feasible in the near future because computing time and memory requirements for high resolution GCMs are very high.

Downscaling techniques, which derive regional meteorological features from synoptic large-scale atmospheric structures like air pressure, are a less expensive alternative. In the present study, an attempt is made to apply one such downscaling technique to the Barcelonnette basin (SE France). The obtained regional precipitation scenarios are used as input to a combined slope hydrology/stability model to obtain future scenarios for the temporal frequency of movement of a landslide in this region.

2. DOWNSCALING PROCEDURE

An empirical-statistical downscaling approach developed by von Storch et al. (1993) is applied in this study. The procedure is as follows (after Heyen et al. in press):

1. A large-scale parameter G has to be identified which controls a local parameter L.
2. A statistical relationship between L and G has to be found.
3. The relationship must be validated with an appropriate method.
4. If the relationship is confirmed, G from GCM-experiments can be applied to estimate L.

The statistical regression model relies on three assumptions. First, the large scale parameter is simulated well by GCMs. Second, most of the regional climatic variation is determined by large-scale atmospheric conditions. Third, the relationship is stationary under climate change. Patterns and time series of both large scale atmospheric conditions and small scale meteorological data are used to establish empirically a linear regression model. This model is based on empirical orthogonal functions (EOFs, also known as Principal Component Analysis) and a canonical correlation analysis (CCA). Details are given in von Storch et al. (1993) and Heyen et al. (in press). Since the relationship is purely statistical, a further physical interpretation of the results is necessary. Based on the statistical regression model, local climate change is calculated from large-scale conditions derived from GCM-experiments. The technique was used for example by von Storch et al. (1993) and Gyalistras et al. (1994).

3. APPLICATION OF STATISTICAL DOWNSCALING TO THE BARCELONNETTE BASIN (SE FRANCE)

The Barcelonnette basin, SE France (figure 1), suffers from diffused landsliding due to widespread outcropping of 'Terres Noires' black marls, which are very soft and erodible (Antoine et al., 1995). For the station Barcelonnette Le Verger (1150 masl) time series of daily precipitation from 1928 to 1994 were obtained from Meteo-France, as well as daily maximum and minimum temperature from 1956 onwards. The homogeneity of the Barcelonnette time series may be affected by multiple changes in the location of the gauge, and one change of instrumentation. This was tested by calculating the ratio between this series and one from a rain gauge in Jausiers (6 km E of Barcelonnette). The Jausiers gauge has been operative since 1961 without any change in location or instrumentation. This analysis did not reveal obvious inhomogeneities in the precipitation record of the period concerned.

The regression model for downscaling :
The hydrological model requires monthly precipitation totals as meteorological input. The downscaling technique provides a linear regression model for the winter season. It is supposed that North Atlantic air-pressure controls a great part of monthly winter precipitation in Barcelonnette, and only to a lesser degree summer precipitation. Sea-level pressure (SLP) was chosen as large-scale atmospheric variable G. Monthly mean SLP from the National Meteorological Center NMC-dataset interpolated to a 5°x5° grid box from 70°N/40°W to 30°N/40°E was utilized. The local parameter L consists of monthly precipitation sums from

1928-1994. Normalized anomalies of this series are used in the analysis. Using EOFs and the CCA (von Storch et al., 1993; Heyen et al., 1996) the regression model for local precipitation was constructed for the period 1928-1994. Figure 2 shows the resulting CCA-pattern. The validation was carried out with cross-validation (Michaelson, 1987).

Downscaling results :
Cross-validation for downscaling monthly precipitation totals showed a CCA-correlation between SLP and local precipitation of 0.58. The correlation between observed and estimated time series is 0.56 with an explained variance of 0.31. This relatively low explained variance of the regression results in a lowered variability of the estimated series. To apply this series to landslide modeling it was necessary to inflate the variance to obtain the observed variability. Precipitation in Barcelonnette 1928-1994 as observed and as derived from observed SLP are shown in figure 3.

A test for the physical plausibility of the relationship found was carried out exemplarily for January 1954-1994 with a composite analysis. The January CCA-coefficients are divided into two groups with standard deviation $\sigma > 1.0$ (1966, 1969, 1970, 1977, 1979) and $\sigma < -1.0$ (1957, 1964, 1973, 1983, 1989, 1991). The hypothesis is, that the years with $\sigma > 1.0$ have above average and the years with $\sigma < -1.0$ below average storm activity. To make this visible, daily SLP was filtered with a band filter to keep only the frequencies between 2.5 and 6 days, which is the typical time range of mid latitude cyclonic storm tracks. Monthly variance anomalies averaged for the above mentioned years are shown in figure 4. Positive values indicate above average while negative values indicate below average storm activity. It is clearly shown that for the years having CCA-coefficients with $\sigma > 1.0$ there is above average strom activity in the area of Barcelonnette and vice versa, indicating that the statistical relationship is physically plausible.

4. SCENARIO FOR FUTURE CLIMATE CHANGE

The regression model was applied to SLP simulated in a coupled atmosphere-ocean GCM (ECHAM4/OPYC3) of the Deutsches Klimarechenzentrum (DKRZ), Hamburg. The horizontal resolution of this T42 model is approximately 250x250 km. The experiment was integrated for GCM-years 100-230 with observed greenhouse gas concentrations from 1860-1990. Subsequent model years 231-339 were forced with emission scenario IS92a from IPCC (Houghton et al. 1992) (Roeckner, personal communication). From this GCM-run years 1860-1970 have been taken as control run, while years 1971-2099 are considered as climate change scenario. The application of the regression models for winter time precipitation resulted in the time series shown in figure 5. Monthly mean temperature was derived directly from the GCM. The average value of four grid points closest to Barcelonnette was taken as scenario. However, a correction had to be made to account for the elevation of Barcelonnette (1150 masl), which certainly is not represented in the GCM grid points. This was done by simply calculating the difference between observed Barcelonnette temperature (1956-1994) and GCM-temperature for the four gridpoints. This difference was subsequently subtracted from the GCM-scenario temperatures. An assumption inherent to this adjustment is that temperature change in mountainous Barcelonnette is identical to that in the (sea level) GCM-points.

5. THE RIOU BOURDOUX LANDSLIDE

The Riou Bourdoux landslide is situated 4 km NW of Barcelonnette on a 200 m long slope covered with pine trees (figure 1). Details about the geological and hydrological characteristics of the landslide can be found in Caris & Van Asch (1991). The lithology can be schematised as follows: a permeable colluvium top layer (thickness 1.5-2 m), underlain by a less permeable weathered marl layer (thickness 5-6 m), underlain by bedrock of unweathered marls, assumed impermeable. Since the slide surface is located at the bedrock contact, groundwater height above bedrock is considered important to slope stability.

Preferential flow takes place in the colluvium layer, and probably as well in the weathered marl layer through shrinkage cracks, macropores and landslide cracks. Because the landslide does not react to short-duration, high-intensity rainstorms it is thought that matric groundwater levels, rather than quickly responding preferential groundwater flow, determine the stability of the slope. Based on low measured percolation velocities in the weathered marl layer, Caris and Van Asch (1991) supposed that these matric groundwater levels are more sensitive to long-term than to short-term precipitation.

6. THE HYDROLOGICAL MODEL

Following the hydrological concept outlined above, groundwater levels were simulated with a hydrological model named Gw-Fluct. The model was calibrated on a monthly base. Dendrochronological datings (Van Asch & Van Steijn, 1991) were used to identify periods of increased landslide activity. A critical groundwater level was back-calculated with the simplified Janbu stability model using soil strength parameters. Simulated groundwater levels should be higher than the critical level in the periods identified by the datings.

Gw-Fluct is very simple, in fact it is an advanced reservoir model (figure 6). Two reservoirs were defined, representing the two upper layers in the landslide. Downslope groundwater discharge and downward percolation are calculated with Darcy's law. Preferential flow is regarded as sink term, assuming it leaves the system within one timestep. For the period 1956-1980, the model reproduces dated periods of landsliding reasonably well, although the preferential flow parameters are a source of large uncertainties (Van Asch & Buma, 1996).
To obtain suitable model input, first a conversion from gross to effective precipitation was made using models of Thornthwaite (1948) and Thornthwaite & Mather (1957).

7. LINKED DOWNSCALING AND SLOPE STABILITY MODELING OF THE RIOU BOURDOUX LANDSLIDE

The hydrological model was run deterministically with downscaled precipitation data derived from observed North-Atlantic SLP. Missing values in the observed Barcelonnette series were substituted with values from Jausiers. Figure 7 shows results for the period 1956-1994. Agreement with the calibrated groundwater levels is reasonable for Gw-Fluct except between 1976 and 1980. Periods that are badly downscaled are strongly reflected. This shows the sensitivity of the model to precipitation input. On the other hand it illustrates that the remainder of the period is downscaled quite well while the graphs are close.

8. SCENARIOS FOR FUTURE CLIMATE CHANGE

A stochastic approach was adopted for linked modeling of future activity of the landslide. The procedure was as follows:
Statistical characteristics (mean, skewness and standard deviation) of populations of precipitation and temperature values of a given period or situation, were determined. Using these characteristics and a random generator, 1024-year series of monthly precipitation and temperature were made. These series, representing the meteorological conditions of the situation, were put into the hydrological model. Subsequently the occurrences of supracritical groundwater levels in 1024 years are counted to obtain a landslide recurrence interval ρ for landsliding conditions. Finally, ρ values of various periods or scenarios were compared. Since temperature influences effective precipitation, a change in this variable should also be taken into account.

The following situations were compared (code in brackets):

- 1964-1994 (OBS1), using observed precipitation and temperature. The problem arose that the observed series is incomplete.
- 1964-1994 (OBS2a), using observed temperature, and precipitation derived from downscaling observed sea level pressures.
- 1964-1994 (OBS2b) is identical to OBS2a, but excluding periods for which the observed series contains missing values. Thus a better comparison with OBS1 can be made.
- Precipitation and temperature scenarios derived from downscaling GCM-simulations. Those indicated with "CON" represent the GCM control period, while those indicated with "S" are scenarios.
    A. 1899-1929 (CON1)
    B. 1934-1964 (CON2)
    C. 1964-1994 (CON3)
    D. 2020-2050 (S1)
    E. 2069-2099 (S2)

Since it is not yet possible to downscale precipitation successfully for Barcelonnette in the summer months, summer precipitation (April-September) was generated from the observed series. For CON1, summer precipitation of 1934-1964 was used. For S1 and S2, summer precipitation of the longest possible period (1928-1994) was used to minimize short-term bias. For each OBS-situation, the obtained ρ values should match. ρ for this period should also approximate the results of the deterministic Gw-Fluct run using observed Barcelonnette precipitation, with which four critical years were simulated between 1964 and 1994. Thus the deterministic ρ is 7.5 years.

9. RESULTS

Table 1 shows results of the stochastic Gw-Fluct simulations.
An increase in landslide recurrence interval ρ is predicted, implying that the landslide becomes inactive. Most of the variance in ρ could be explained by the sum of median and standard deviation of precipitation (87%). This suggests that the number of wet months in a given period is more important than the mean precipitation per month.

Discussion and conclusions: to be discussed on the workshop

REFERENCES

Antoine, P., Giraud, A., Meunier, M. & vand Asch, Th.W.J. (1995): Geological and geotechnical properties of the 'Terres Noires' in southeastern France: Weathering, erosion, solid transport and instability. Engineering Geology 40, 223-234.

Beniston, M. (1994): Climate scenarios for mountain regions: an overview of possible approaches. In: Beniston, M. (ed. 1994): Mountain environments in changing climates. Routledge, London and New York, 136-152

Braam, R.R., Weiss, E.E.J. & Burrough, P.A. (1987): Spatial and temporal analysis of mass movement using dendrochronology. Catena 14, 573-584.

Caris, J. and Van Asch, Th.W.J., 1991, "Geophysical,geotechnical and hydrological investigations of a small landslide in the French Alps." Engineering Geology 31, 249-276.

Cubasch,U., Hasselmann, K., Höck, H., Maier-Reimer, E., Mikolajewicz, U., Santer, B.D. & Sausen, R. (1992): Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model. Climate Dynamics 8, 55-69

Cubasch, U., Waszkewitz, J., Hegerl, G.C. & Perlwitz, J. (1995): Regional climate changes as simulated in time-slice experiments. Climatic Change, 2-4, 273-304

Cubasch, U., von Storch, H., Waszkewitz, J. & Zorita, E. (1996): Estimates of Climate Change in Southern Europe using Different Downscaling Techniques. MPI-Report 183

Gyalistras, D., von Storch, H., Fischlin, A. & Beniston, M. (1994): Linking GCM-simulated climatic changes to ecosystem models: case studies of statistical downscaling in the Alps. Climate Research 4, 167-189

Heyen, H., Zorita, E. & von Storch, H. (1996): Statistical downscaling of monthly mean North Atlantic air-pressure to sea level anomalies in the Baltic Sea (Tellus A, in press)

Houghton, J.T., Callander, B.A. & Varney, S.K. (Eds. 1992): Climate change 1992. The supplementary report to the IPCC scientific assessment. Cambridge University Press

Michaelson, J. (1987): Cross-validation in statistical climate forecast models. J. Climate Appl. Meteor. 26, 1589-1600

Thornthwaite, C.W., 1948. An approach towards a regional classification of climate. Geographical Review, 38, 55-94.

Thornthwaite, C.W. and Mather, J.R, 1957. "Instructions and tables for computing potential evapotranspiration and the water balance. Drexel Institute of Technology, laboratory of Climatology", Publications in Climatology, Centerton, New Jersey Vol 10(3):185 - 309.

van Asch, Th.W.J. & Buma, J.T. (1996): Modeling groundwater fluctuations and the frequency of movement of a landslide in the Terres Noires region of Barcelonnette (France). Earth Surface Processes and Landforms, in press.{PRIVE }

von Storch, H. (1995): Inconsistencies at the interface of climate impact studies and global climate research. Meteorologische Zeitschr., N.F. 4, 72-80

von Storch, H., Zorita, E. & Cubasch, U. (1993): Downscaling of climate change estimates to regional scales: an application to Iberian rainfall in winter time. Journal of Climate 6, 1161-1171

Zorita, E., Hughes, J.P., Lettenmaier, D.P. & von Storch, H. (1995): Stochastic characterization of regional circulation patterns for climate model diagnosis and estimation of local precipitation. Journal of Climate 8, 1023-1042

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Table 1. Modelled scenarios for future activity of the Riou Bourdoux landslide.

model scenario	mean winter P (mm)	median winter P (mm)	σ of winter P	mean summer P (mm)	median summer P (mm)	σ of summer P	mean ρ (years)
OBS1	345.3	334.0	94.3	353.6	367.4	92.5	85
OBS2a	355.5	360.0	138.4	353.6	367.4	92.5	18
OBS2b	345.3	355.8	138.8	353.6	367.4	92.5	22
CON1	382.3	395.6	126.8	340.8	325.8	86.0	20
CON2	368.9	371.6	129.2	340.8	325.8	86.0	57
CON3	364.7	361.7	87.9	353.6	367.4	92.5	37
S1	292.6	281.3	124.5	355.8	345.2	88.0	10^3
S2	279.6	263.9	123.4	355.8	345.2	88.0	$5 \cdot 10^3$

FIGURE CAPTIONS

Figure 1 : The Barcelonnette Basin
Figure 2 : CCA pattern
Figure 3 : Precipitation in Barcelonnette 1928-1994 as observed and as downscaled from observed SLP.
Figure 4 : Variance anomalies downscaled precipitation
Figure 5 : Decreasing winter precipitation for Barcelonnette, downscaled from GCM-predictions of SLP.
Figure 6 : Groundwater levels simulated with Gw-Fluct using observed and downscaled precipitation as input.