Global warming increases flood risk in mountainous areas

P. Allamano,[1] P. Claps,[1] and F. Laio[1]

Received 19 October 2009; revised 18 November 2009; accepted 23 November 2009; published 24 December 2009.

Citation: Allamano, P., P. Claps, and F. Laio (2009), Global warming increases flood risk in mountainous areas, *Geophys. Res. Lett.*, *36*, L24404, doi:10.1029/2009GL041395.

[1] The paper aims at assessing the impact of global warming on flood risk in mountainous regions, providing measurable evidence of possible hydrologic changes due to temperature increase. It shows that large floods in mountain basins are now more frequent than in the past and that they may become even more frequent under global warming. The morpho-climatic model used for prediction is very simple and does not require calibration, which makes it suitable for application in scarcely gauged mountainous areas of the world.

[2] Mountainous regions account for one fourth of the Earth land surface and are inhabited by 800 millions of people. The major rivers of the world originate from these areas. In mountainous regions temperature determines the state of precipitation (liquid or solid) and in turn significantly affects runoff formation. For instance, the seasonality of streamflow in mountainous basins has been found to be extremely sensitive to global warming [*Diaz et al.*, 2003; *Barnett et al.*, 2005; *Bates et al.*, 2008; *Marty*, 2008]. While the concern about the increase of flood risk in these areas is rapidly raising [*Olsen et al.*, 1998; *Palmer and Ralsanen*, 2002], in the scientific literature there is still a lack of consensus about the effects of temperature variations on floods [*Mudelsee et al.*, 2003; *Birsan et al.*, 2005; *Koutsoyiannis et al.*, 2009]. The purpose of this study is to investigate the effects of temperature and precipitation variations on the flood frequency distribution in mountainous basins, without intervening in the dispute between climate change supporters and opponents [*Bates et al.*, 2008; *Koutsoyiannis et al.*, 2009; G. Blöschl and A. Montanari, Climate change impacts: Throwing the dice?, submitted to *Hydrological Processes*, 2009].

[3] Analyzing peak discharge time-series recorded in 27 gauging stations in the Swiss Alps we find a significant increase of flood peaks during the last century. We interpret this increase through a simple model as the effect of recorded increases of temperature and precipitation in the same period. The model also predicts, under the hypothesis of a 2°C temperature increase and of 10% increase in the precipitation intensity [*Klein Tank and Können*, 2003; *Schmidli and Frei*, 2005; *Bates et al.*, 2008], that the 100-year flood discharge will reduce its return period to about 20 years (becoming five times more frequent), with possible relevant consequences on high elevation ecosystems and anthroposystems.

[4] The Swiss alpine region is one of the most intensely monitored mountainous areas in the world. Temporal variations in temperature and precipitation regimes in this region are widely documented in the literature [*Klein Tank and Können*, 2003; *Birsan et al.*, 2005; *Schmidli and Frei*, 2005]. Our aim is to understand if small variations in time of temperature and precipitation may have had an effect on the flood frequency distribution in mountain basins that is compatible with the observed variations.

[5] The links between climatic fluctuations and temporal variation in flood frequency are the object of investigation by numerous authors [*Panagoulia and Dimou*, 1997; *Olsen et al.*, 1998; *Milly et al.*, 2002]. The majority of the literature studies, however, addresses the problem from a site-specific point of view, whereas the literature appears to be scarce of studies that examine the problem at the regional scale. A different type of approach is one that evaluates the effects of climatic change on the evolution of flood frequency by coupling high-resolution regional climate models with hydrologic models [*Prudhomme et al.*, 2002; *Bronstert*, 2003]. The use of this approach, however, becomes rather questionable in mountainous regions, where topography is very poorly resolved even by regional climate models, and the scarcity of data may seriously compromise the representativeness of hydrological models [*Hostetler*, 1994; *Xu*, 1999].

[6] In this paper we propose to reproduce the essential mechanisms that connect climatic variability to flood frequency by means of a simple morpho-climatic probabilistic model that aims to generalize the classical site-specific flood frequency approach. Note that we are not interested in investigating the actual magnitude of the floods corresponding to a given return period, but rather the rate of change of the flood itself in the presence of climate change. The model is conceived to describe the dominant components of flood runoff in basins subjected to a seasonal transition of the freezing elevation $ZT(t)$. In the model, the freezing elevation is related to the temperature regime $T(t)$ (i.e., the curve of seasonal variations of average temperature) according to a standard lapse rate of temperature. As exemplified in Figure 1, for a given watershed, the areas above $ZT(t)$ are determined according to the basin hypsometric curve. The extension of the area above the freezing elevation becomes a basin-characteristic factor of mitigation of peak flow, because of the occurrence of precipitation as snow above $ZT(t)$. Given the structure of the precipitation process, flow mitigation hence depends on the seasonality of temperature and on the distribution of elevation within the basin, that concur in determining the portion of the watershed that receives liquid precipitation, called contributing area, Ac (Figure 1, left).

[7] Considering flood runoff directly proportional to the amount of liquid precipitation, the probability distribution of specific annual discharge extremes is obtained in close

[1]Dipartimento di Idraulica, Trasporti ed Infrastrutture Civili, Politecnico di Torino, Turin, Italy.

0094-8276/09/2009GL041395$05.00

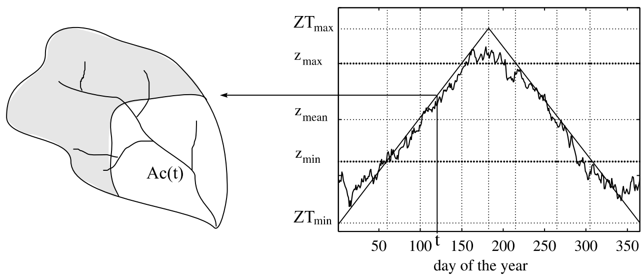


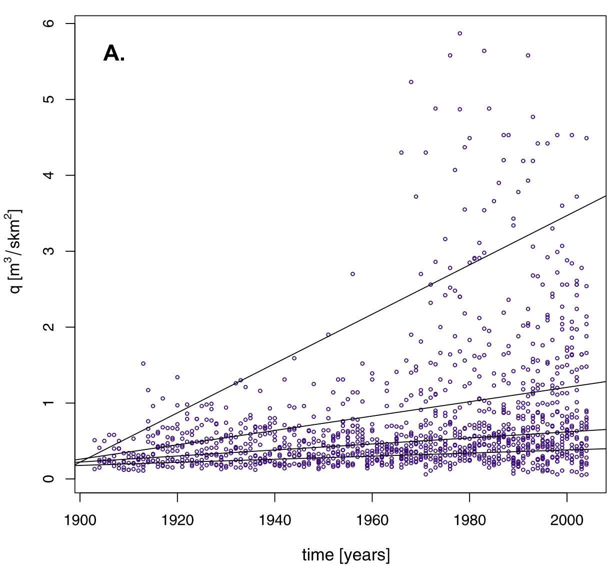
Figure 1. (left) Schematic representation of basin partitioning by the freezing level elevation *ZT*(*t*). The contributing portion of the basin is indicated with the acronym *Ac*. (right) Shown is the corresponding freezing level regime curve. The regime curve is bounded by $ZT_{\max}$ and $ZT_{\min}$. Elevations $z_{\max}$, z_{mean} and $z_{\min}$ represent the maximum, mean and minimum elevations of the catchment.

analytical form, assuming that precipitation follows a Poisson distribution of storm arrivals in time with rate λ, and that the depth *h* of each storm follows an exponential distribution with mean α. The parameters of the resulting probabilistic model are the freezing-curve boundaries, $ZT_{\max}$ and $ZT_{\min}$, and the parameters of the precipitation model. Details on the analytical derivation of the flood frequency curves are provided by *Allamano et al.* [2009]. Time-dependent parameter values can be used when flood response to long-term fluctuations of temperature and precipitation are investigated.

[8] We exemplify our approach on a sample of annual maxima of peak discharge collected at 27 Swiss discharge gauging stations. Specific discharge values (i.e., divided by catchment area) are shown in Figure 2a versus their year of occurrence, together with the outcomes of a linear quantile regression analysis [*Koenker and Bassett*, 1978]. The result is an apparent increase in the number of large floods in recent years, in particular as regards the 0.95 sample quantile (the data are assumed to be independent when analyzing the significance of the relation). Determining whether these variations are symptoms of increasing trends or just long-term cycles due to the presence of long-term persistence [*Koutsoyiannis and Montanari*, 2007] is out of the scope of this paper. However, we computed the lag-1 autocorrelation coefficient on all series, obtaining a very low average value (<0.1), which goes in the direction of confuting the hypothesis of long-term persistence.

[9] In addition, one may argue that the trend in flood values could be influenced by local situations as, for example, the progressive activation/dismissal of gauging stations for basins with anomalous morpho-climatic features (with respect to the sample average). We account for these possible distortions by performing multiple linear quantile regressions between specific peak discharge and a number of morpho-climatic descriptors, such as watershed mean elevation, catchment area, the growth-rate *a* and exponent *n* of the areal depth-duration-frequency curves, obtaining significant relations in all the coefficients at a 5% level. After removal of the above dependencies, however, we still find a significant relation between specific discharge and time. In this case, trend coefficients are smaller than those of Figure 2a, but remain positive and statistically significant for all quantiles (see Figure 2b, grey-shaded column).

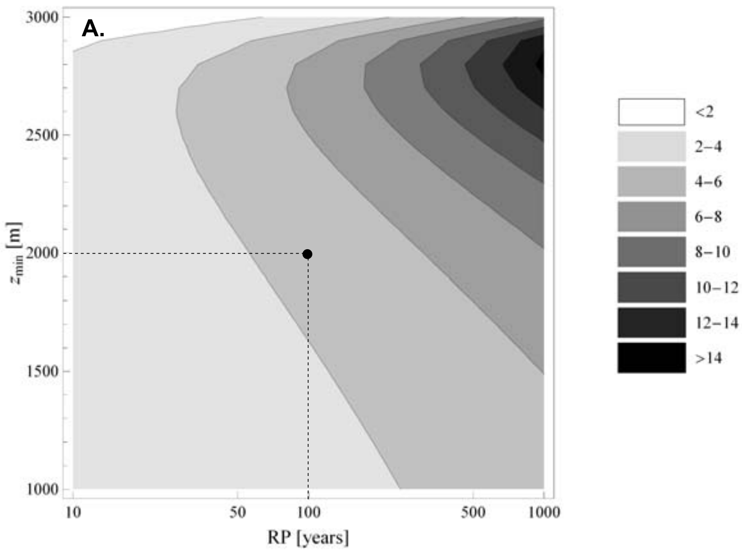
[10] Trend coefficients for flood quantiles are then reproduced by using the morpho-climatic model. Flood quantiles variations over time are obtained by imposing a temporal trend to temperature *T*(*t*) and to the precipitation intensity α. Different scenarios, inspired by literature studies referred to the Swiss territory [*Beniston et al.*, 1997; *Klein Tank and Können*, 2003; *Schmidli and Frei*, 2005], have been considered. Model performances are presented hereafter for two of these scenarios: (1) a temperature increase of 2°C in 100 years, resulting in a rigid upward shift of the temperature seasonal curve *T*(*t*) (that we call the ΔT scenario) and



B. Outcomes of quantile regression compared with model results. The underlined coefficients are not-significant at a 5% level.

		Regressions	Model	
		t	ΔT	ΔT + Δα
Quantiles	**0.95**	0.266 σ = 0.085	0.096	0.20
	0.75	0.144 σ = 0.048	0.074	0.15
	0.50	0.096 σ = 0.025	0.062	0.11
	0.25	<u>0.039</u> σ = 0.026	0.051	0.09

Figure 2. (a) Annual maxima of specific discharge for 27 Swiss watersheds versus their year of occurrence. The lines represent statistically significant (at a 5% level) temporal trends obtained by linear quantile regressions (the 0.25, 0.5, 0.75 and 0.95 quantiles are reported). (b) Outcomes of multiple quantile regressions, with standard error (σ), compared with model results in terms of flood quantiles increase in 100 years.



B. Return period ratio sensitivity

	+0°C	+1°C	+2°C	+3°C	+4°C	+5°C
α	1.0	1.8	3.0	4.6	6.7	9.2
1.05 α	1.3	2.3	3.8	5.7	8.1	11.0
1.10 α	1.7	2.9	4.6	6.8	9.6	12.9
1.15 α	2.1	3.5	5.5	8.1	11.2	14.9
1.20 α	2.5	4.2	6.5	9.4	12.9	17.0
1.25 α	3.0	5.0	7.6	10.9	14.7	19.1

Figure 3. (a) The graph relates the return period ratio to the undisturbed return period *RP* (x-axis) and to the elevation of the basin outlet (y-axis) (under the hypothesis of $\Delta T = 2$°C and $\Delta\alpha = 10\%$, corresponding to the grey-shaded cell in Figure 3b). (b) Return period ratio sensitivity to different increases of temperature and rainfall intensity, for $RP = 100$ years and $z_{\min} = 2000$ m (black dot in Figure 3a).

(2) a 10% increase of the precipitation parameter α, simultaneous with the temperature increase (identified as the $\Delta T + \Delta\alpha$ scenario). Model results, shown in the last two columns of Figure 2b, are obtained taking as model parameters the average characteristics of the sample of basins (i.e., minimum elevation $z_{\min} = 650$ m a.s.l, maximum elevation $z_{\max} = 3200$ m a.s.l., mean elevation $z_{mean} = 1900$ m a.s.l., $\alpha = 25$ mm/d; $\lambda = 20$ yr^{-1}; lapse rate = 6.5°C/km). The resulting trend coefficients are compared with those obtained from regressions and reported in Figure 2b.

[11] When temperature and precipitation increase are combined together ($\Delta T + \Delta\alpha$ scenario), the increase of flood quantiles obtained from the regressions and from the model appear rather similar (i.e., the coefficients in the last column are comparable with those reported in the grey-shaded column). In fact, the increase in flood quantiles obtained with the model (with the exception of the 0.25 quantile) is found to fall within one standard error (σ in Figure 2b) distance from the regression-based trend coefficient. When the temperature change alone is applied (ΔT scenario), the time-discharge dependence is captured only partially. Therefore, both precipitation and temperature seem to be responsible for the discharge temporal trend, even though none of the two, considered separately, is able to explain the behavior completely. This example proves that the model can be useful in investigating the mechanisms behind changes in the flood frequency at high-elevation basins. In this sense, the agreement between regression and model based flood temporal changes represents a validation of the hypotheses on which the model is based, which is especially striking because results are obtained without any calibration. Model parameters, in fact, are fixed to literature values and kept constant all over the region.

[12] Based on the above premises, an application of the model to a wide range of basin morphologies (i.e., with different elevation characteristics) is desirable. This is performed by applying the model to hypothetical basins having different elevation features but subjected to the same meteorological forcings and trends. The results are shown in Figure 3a, in which the combined effect of temperature and precipitation variation (according to the $\Delta T + \Delta\alpha$ scenario) are shown in terms of changes in the return period. For a given flood event with peak discharge Q, the graph reports on the x-axis the "undisturbed" return period $RP = \frac{1}{1-P_Q(Q)}$, being $1 - P_Q(Q)$ the probability of exceedance of Q under undisturbed temperature and precipitation conditions. The elevation of the basin outlet is on the y-axis. In each point of the plane the intensity of the grey-shade is proportional to the "return period ratio", defined as the ratio of *RP* to the "altered" return period $RP' = \frac{1}{1-P'_Q(Q)}$, being $1 - P'_Q(Q)$ the exceedance probability of Q under modified $T + \Delta T$ and $\alpha + \Delta\alpha$ conditions. As anticipated, it is found that extreme floods under global warming will tend to become more frequent in time. In fact, the return period ratio is always greater than 1. As expected, the ratio is found to increase for increasing undisturbed return periods and for increasing elevations, at least until an upper bound is reached (in correspondence of basins with outlets between 2500 and 3000 m). For example, the 100-year flood discharge estimated today in a watershed having the outlet at 2000 m will have, under a 2°C temperature and a +10% precipitation increase, a return period ratio equal to 4.6, that means that the same discharge value under altered conditions will be, on average, a 20-year flood (i.e., will become five time more frequent). For very high elevations the grey bands bend to the right, meaning that the return period ratio increases more slowly. This is due to the lesser influence of the temperature increase on very high watersheds, which are almost exempt from the effects of small shifts of the temperature regime (i.e., in the order of magnitude of the one considered in this

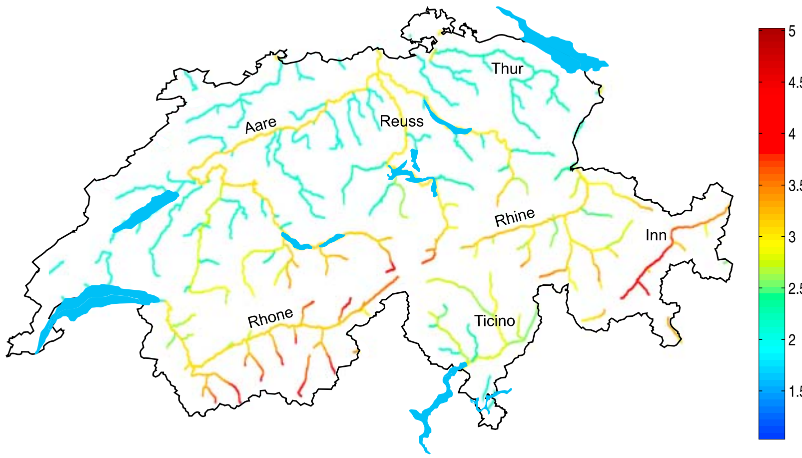


Figure 4. Variability of the return period ratio (referred to the 100-years undisturbed flood, under the hypothesis of $\Delta T = 2°C$ and $\Delta\alpha = 10\%$) along the Swiss river network. The names of the main rivers are indicated on the map.

study), because they remain almost always above the freezing level. A complete analysis of the return period ratio sensitivity to different hypotheses of increase of temperature and rainfall intensity is presented in Figure 3b, where the values refer to the case of $RP = 100$ years and $z_{\min} = 2000$ m.

[13] Diagrams like those shown in Figure 3 entail the possibility to use the model to represent also in space the increase of flood risk under varied climatic conditions. A spatial application to the Swiss territory is shown in Figure 4, where the return period ratio is computed for real basins (with their own hypsometry, and average climatic parameters) and mapped along the river network in correspondence of an undisturbed *RP* of 100 years. In the map, each section of the river network is colored according to the return period ratio computed for the basin having the outlet in that point. For example, the points with return period ratio close to five are indicated in red. It can be observed that the basins that are most exposed to the flood frequency increase are in the Southern part of Switzerland, where the elevations are typically higher. Moving northwards, the return period ratios are found to drop to values between 2 and 3. Another interesting outcome of the analysis is represented by the variability of the return period ratios in the Northern part of the country, for example along the Aare river or, analogously, along the Reuss river. In both cases, in fact, moving downstream the return period ratios are found to assume higher values along the main river than along the tributary network. This happens because the mean elevations of the catchments drained by the tributary streams (of the Aare or Reuss rivers) are lower than the mean elevation of the main basin, making the latter more exposed to flood risk increase than its tributaries.

[14] Downstream areas are often densely populated. On these areas the increase in flood frequency can have dramatic effects in terms of expected damage to civil infrastructures and loss of human lives. Results analogous to those shown in Figure 4 could be easily obtained also in regions with scarce data availability, thanks to the ease of use and parsimony of the model, which is suitable to produce these scenarios using only a digital elevation model and basic precipitation data. Still, the model-based conclusions are inevitably conditioned by the model assumptions. In this specific case, assumptions are introduced about the rainfall model; it is assumed that the flood runoff is directly proportional to the liquid precipitation, and that the related proportionality coefficient is not changing in a changing climate; relevant changes in time of the climatic forcing (temperature and precipitation) are finally hypothesized. Also in this respect, we believe the adoption of a parsimonious model represents a relevant added-value, with respect to the existing methods, to analyse the vulnerability of mountain areas to climate change.

[15] **Acknowledgments.** The work was funded by the Italian Ministry of Education (grant 2007HBTS85). Comments from A. Montanari and G. Di Baldassarre are gratefully acknowledged.

References

Allamano, P., P. Claps, and F. Laio (2009), An analytical model of the effects of catchment elevation on the flood frequency distribution, *Water Resour. Res.*, *45*, W01402, doi:10.1029/2007WR006658.

Barnett, T., J. Adam, and D. Lettenmaier (2005), Potential impacts of a warming climate on water availability in snow-dominated regions, *Nature*, *438*, 303–309, doi:10.1038/nature04141.

Bates, B., Z. Kundzewicz, S. Wu, and J. Palutikof (Eds.) (2008), Observed and projected changes in climate as they relate to water, in *Climate Change and Water*, *IPCC Tech. Pap. VI*, pp. 13–31, Intergov. Panel on Clim. Change Secr., Geneva, Switzerland.

Beniston, M., H. Diaz, and R. Bradley (1997), Climatic change at high elevation sites: An overview, *Clim. Change*, *36*, 233–251.

Birsan, M., P. Molnar, P. Burlando, and M. Pfaundler (2005), Streamflow trends in Switzerland, *J. Hydrol.*, *314*, 312–329.

Bronstert, A. (2003), Floods and climate change: Interactions and impacts, *Risk Anal.*, *23*, 545–557.

Diaz, H., J. Eischeid, C. Duncan, and R. Bradley (2003), Variability of freezing levels, melting season indicators, and snow cover for selected high-elevation and continental regions in the last 50 years, *Clim. Change*, *59*, 33–52.

Hostetler, S. (1994), Hydrologic and atmpospheric models: The (continuing) problem of discordant scales, *Clim. Change*, *27*, 345–350.

Klein Tank, A., and G. Können (2003), Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99, *J. Clim.*, *16*, 3665–3680.

Koenker, R., and G. Bassett (1978), Regression quantiles, *Econometrica*, *46*(1), 33–50.

Koutsoyiannis, D., and A. Montanari (2007), Statistical analysis of hydroclimatic time series: Uncertainty and insights, *Water Resour. Res.*, *43*, W05429, doi:10.1029/2006WR005592.

Koutsoyiannis, D., A. Montanari, H. Lins, and T. Cohn (2009), Discussion of: The implications of projected climate change for freshwater resources and their management, *Hydrol. Sci. J. Sci. Hydrol.*, *54*, 394–405.

Marty, C. (2008), Regime shift of snow days in Switzerland, *Geophys. Res. Lett.*, *35*, L12501, doi:10.1029/2008GL033998.

Milly, P., R. Wetherald, K. Dunne, and T. Delworth (2002), Increasing risk of great floods in a changing climate, *Nature*, *415*, 514–517.
Mudelsee, M., M. Börngen, G. Tetzlaff, and U. Grünewald (2003), No upward trends in the occurrence of extreme floods in central Europe, *Nature*, *425*, 166–169.
Olsen, R., J. Lambert, and Y. Haimes (1998), Risk of extreme events under nonstationary conditions, *Risk Anal.*, *18*, 497–510.
Palmer, T., and J. Ralsanen (2002), Quantifying the risk of extreme seasonal precipitation events in a changing climate, *Nature*, *415*, 512–514.
Panagoulia, D., and G. Dimou (1997), Sensitivity of flood events to global climate change, *J. Hydrol.*, *191*, 208–222.
Prudhomme, C., N. Reynard, and S. Crooks (2002), Downscaling of global climate models for flood frequency analysis: Where are we now?, *Hydrol. Processes*, *16*, 1137–1150.
Schmidli, J., and C. Frei (2005), Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th century, *J. Climatol.*, *25*, 753–771.
Xu, C. (1999), Climate change and hydrologic models: A review of existing gaps and recent research developments, *Water Resour. Manage.*, *13*, 369–382.

P. Allamano, P. Claps, and F. Laio, Dipartimento di Idraulica, Trasporti ed Infrastrutture Civili, Politecnico di Torino, Corso Duca degli Abruzzi 24, I-10129 Torino, Italy. (paola.allamano@polito.it)