August 2005 intense rainfall event in Switzerland: Not necessarily an analog for strong convective events in a greenhouse climate

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[1] The intense convective storms that affected the Swiss Alps in late August 2005 resulted in what has been referred to as the "floods of the century" (i.e., the past 100 years). While exceptional in terms of their intensity, the 2005 storms do not appear to be anchored within any long-term trends; there are no more intense storms today than a century ago. Despite uncertainties related to regional climate simulations of precipitation in complex terrain, projections for a "greenhouse climate" by 2100 suggest that extreme rainfall events may undergo a seasonal shift, with a rise in the number of episodes in the spring and autumn. Paradoxically, associated impacts may be reduced because the buffering effects of snowfall on runoff may be greater in future springs and autumns than during current summers, implying the 2005 floods are not necessarily an analog for such events by the end of the 21st century.
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1. Introduction

[2] The very severe flooding event that parts of the Alpine region and Switzerland in particular experienced on August 21–22, 2005 has been one of the most catastrophic in the last 100 years, in view of the loss of life and the damage to infrastructure, communication routes and agriculture (estimated according to the national press at between 1–2 billion Euros). Floods severely damaged historic buildings in Bern and Lucerne, and numerous mountain communities like Engelberg were also affected by landslides, damaging road and rail communications and disrupting power supply.

[3] The extreme precipitation that occurred on August 21–22 followed a prolonged warm spell and was associated with strong moisture convergence into the Alpine region, triggering intense convection in the northern Swiss Alps. The map in Figure 1 presents the regions severely affected by the floods and the locations of the climate observing stations analyzed in this study.

[4] This paper puts the 2005 event in a historical perspective, to assess to what extent the term "flood of the century" is warranted. An analysis of heavy precipitation at 6 selected sites has been conducted to detect possible trends in rainfall extremes during the 20th century. In addition, the paper addresses the issue of whether extreme precipitation may increase in a future climate forced by enhanced concentrations of atmospheric greenhouse gases.

2. Data

[5] The Swiss climate observing system operated by the Swiss weather service consists of a dense network of recording stations with homogenized data in digital form since 1901 for many locations. The 6 sites are located within the region that was most severely affected by the 2005 floods, at the foot of the northern Alpine forelands or just within the Alps themselves. It would have been preferable to use data at higher temporal resolution to investigate extreme rainfall events, because daily rainfall totals often mask the true intensity of a short-lived, heavy downpour event. However, long-term high-frequency records are not available prior to 1978 and, in addition, the climate model data used here also only makes use of daily totals.

[6] Four regional climate models (RCMs) have been used to investigate precipitation in the regions affected by the 2005 floods, both to test their skill in reproducing current events and to provide an insight into changes in a "greenhouse climate" by 2100. The 4 RMCs include the Danish Meteorological Institute HIRHAM model, RCAO of the Swedish Rossby Center, a version of RegCM used at the International Center for Theoretical Physics (ICTP) in Trieste, and CHRM developed at ETH-Zurich.

[7] These 4 particular models have been selected to assess the relative performances of two RCMs designed for Nordic regions, and two focusing more on central and southern European regions. The RCMs have been applied to current (1961–1990) and future European climates (2071–2100) in the context of a major EU project (PRUDENCE) [*Christensen et al.*, 2002] that was completed end 2004. The future climate simulations are based on the IPCC SRES A2 and B2 scenarios [*Nakicenovic et al.*, 2000], with initial and boundary conditions generated by the UK Hadley Center HadCM3 and HadAM3H models [*Johns et al.*, 2003].

[8] *Déqué et al.* [2005] and *Christensen and Christensen* [2006] report on model performances and inter-model variability when using identical driving GCM data applied to a common region, a theme that will be briefly revisited in this paper. In addition, the RCMs have shown some skill in simulating certain extremes, such as in the context of the 2003 European heat wave for the HIRHAM [*Beniston*, 2004] and CHRM [*Schär et al.*, 2004] models, and a range of other extremes that affect Europe [*Beniston et al.*, 2006].

3. Results

[9] In order to determine how exceptional the August 2005 heavy precipitation event was in Switzerland, it is necessary to investigate the chronology of such events

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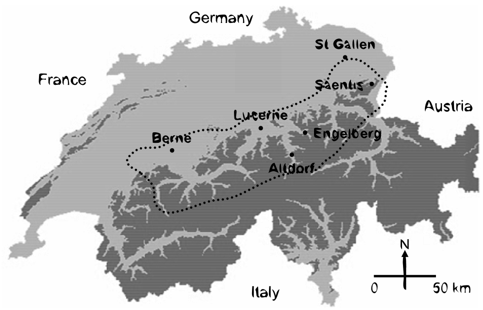

Figure 1. Map of Switzerland showing the regions affected by the August 2005 floods and the location of the climate observing sites used in this study. Dotted region: areas severely affected by floods; dark gray shading: altitudes >1,200 m above sea level.

during the course of the 20th century. While there are many pathways by which precipitation can lead to floods and landslides in the Alps, such as brief but intense rainfall or moderate but continuous precipitation over a period of several days, the focus in this paper will be on major single events that occur in a 24-hour period. To this effect, the 99% quantile of rainfall has been used to define a threshold of extreme daily precipitation, which for the 6 selected sites ranges from 40 to 60 mm/day; the chosen quantile is computed by ranking the levels of precipitation, including days with no precipitation, and taking the value that corresponds to the 1% of days within the heaviest precipitation category. Such rainfall levels have the potential for generating floods and geomorphologic hazards in the mountains.

[10] At all the sites investigated in the Alpine foreland region, the highest rainfall totals occur generally from June–September, with August being the peak month in most locations. The enhanced summer rainfall arises from a combination of warm ground surfaces and moisture convergence into the Alpine region (enhanced by topographic effects) that triggers occasional intense convection. Table 1 lists the distribution of heavy precipitation from June–September at the 6 investigated sites; close to half the events exceeding the 99% quantile (all seasons) at the selected stations occur in summer and 20% in August alone, closely followed by July (16%). It is thus not surprising that the catastrophic 2005 events in Switzerland also took place in August.

[11] Figure 2 shows the anomalies of August precipitation totals since 1931, based on the 1961–1990 reference period at Altdorf (450 m above sea level), St Gallen (780 m), and Engelberg (1,035 m). The 2005 event is clearly out of the range of long-term interannual variability at Altdorf and Engelberg. Both these stations, located within the center of strongest convective activity in August 2005 event, have clearly established record rainfall amounts; the August totals

Table 1. Frequency of Monthly Extreme Precipitation Events (As % of Annual Totals) Beyond the 99% Quantile at the Six Observation Sites During the Reference Period 1961–1990

J	F	M	A	M	J	J	A	S	O	N	D
2	1	3	4	11	12	16	20	12	9	6	4

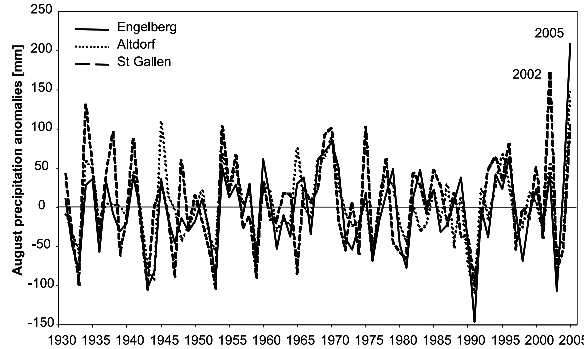

Figure 2. Anomalies of observed mean precipitation at Engelberg, Altdorf and St Gallen from 1931–2005.

exhibit an excess of 15% over the previous record at Altdorf and 33% at Engelberg. St Gallen, on the other hand, is located just outside the region of most intense rainfall and 2005 represents a strong but not exceptional event; there are several episodes in the past with higher precipitation, such as August 2002. The 2002 floods were associated with a major disturbance that affected a far wider area than just the Swiss Alps and resulted in some of central Europe's most catastrophic floods in eastern Switzerland, Austria, the Czech Republic and the Elbe River basin in Germany. The series illustrated in Figure 2, as for the other stations (not shown here), do not exhibit any significant trends, partially because of the as-yet rare nature of such extremes, as pointed out by *Frei and Schär* [2000]. Statistical analyses of links between mean and extreme seasonal precipitation return very low r^2 values that suggest no significant trends (i.e., high seasonal precipitation is not related to extreme precipitation levels). Table 2 breaks the data down into 15-year periods to demonstrate that while some decades have recorded fewer extreme rainfall events (e.g., the 1940s and 1950s), there is no marked increase in threshold exceedance in the most recent part of the record, nor is there any particular clustering of high precipitation in any 15-year period. Indeed, the number of events is remarkably similar between the first and the last 30 years of the record. It is thus difficult to establish any cause-to-effect relationship between observed warming and catastrophic precipitation in the Alps on the basis of the available data.

[12] In order to address the issue of whether extreme rainfall events may increase in a warmer climate resulting from anthropogenic greenhouse-gas forcing by the end of the 21st century, it is first necessary to evaluate the capability of the 4 RCMs in simulating the 1961–1990 precipitation characteristics in the study region. While it

Table 2. Frequency of Occurrence of Precipitation Events Beyond the 99% Quantile for 15-Year Intervals Between 1901 and 2005

	Altdorf	Bern	Saentis	% events 1901–2005
1901–1915	15	4	11	15.2
1916–1930	13	5	9	13.7
1931–1945	12	3	11	13.2
1946–1960	8	4	6	9.1
1961–1975	12	7	12	15.7
1976–1990	15	10	9	17.3
1991–2005	14	5	12	15.7

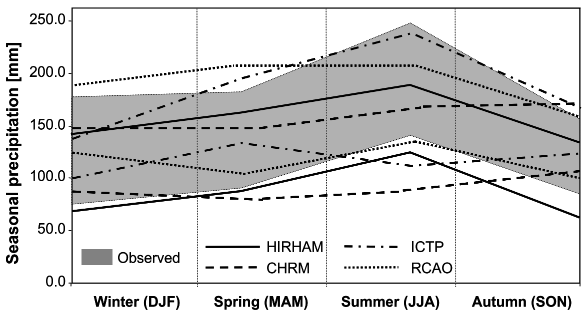

Figure 3. Comparisons of observed and simulated mean seasonal precipitation at the 6 observation sites. For purposes of clarity, only the minimum-to-maximum range of precipitation across all stations is shown, rather than the curves for each individual site.

is of notoriety that climate models have greater difficulty in simulating precipitation than temperature, particularly in regions of complex terrain and because of often inadequate convective parameterizations within coarse model grids, several in-depth analyses have been conducted to establish the strengths and weaknesses of precipitation simulations with the RCMs, *inter alia* by *Christensen and Christensen* [2003] and *Schmidli and Frei* [2005].

[13] Figure 3 compares the simulations of seasonal precipitation at the grid points closest to the 6 sites and observations for the reference 1961–1990 climate. Only the range of precipitation for all sites is shown, rather than the seasonal rainfall at each individual site, for the sake of clarity. The amplitude between low and high precipitation is a striking example of the influence of topography, since the altitudes of the 6 sites range from 450 m above sea level at Altdorf to 2,500 m at Säntis. While there are clearly differences between the model results when the lower and upper range of RCM seasonal precipitation are superimposed upon the observed range, the simulated seasonal totals remain remarkably close to the observations. In addition, 3 of the models identify well the summer rainfall peak.

[14] Bearing in mind the inevitable discrepancies between models at coarse resolution and observations, the RCMs nevertheless show some skill in the simulation of precipitation, sufficiently so to justify further simulations aimed at identifying possible changes in rainfall extremes in the future. The "greenhouse" climate is based on the IPCC "A2" scenario, which assumes high emissions throughout the 21st century leading to a strong climatic response by 2100.

4. Discussion

[15] All models applied to the A2 scenario climate for the period 2071–2100 show a marked shift of the seasonality of mean precipitation compared to 1961–1990 (Figure 4). The 4 models agree on increases in winter and spring precipitation, and reductions in summer and autumn. The principal cause of the change in seasonal patterns is related to the strong summer warming and drying in the Mediterranean zone that would also affect the Alps and regions to the north, and the enhanced winter precipitation that a milder climate is expected to bring to the region. As a result of the shifts in mean precipitation, the frequency of extreme events also changes in seasonality compared to current climate. Table 3 lists the exceedance of precipitation beyond the 99% quantile for the observed data at the 6 sites, and for both the control and scenario simulations. While the "nordic RCMs" underestimate heavy precipitation and ICTP and CHRM overestimate such events, the models mirror fairly well the current seasonal pattern of extremes despite the coarse grids used and the complexity of the Alpine terrain. For the scenario climate, the RCMs project the largest changes in spring and autumn with large increases in intense precipitation. Summer rainfall extremes are projected to decline and, in the RCAO and HIRHAM models, autumn events are more frequent than summer extremes.

[16] In terms of the potential for floods, landslides and damages, it should be stated that heavy precipitation is a necessary but not always sufficient condition for strong impacts. The response of hydrological systems to high precipitation levels is a function of the prior history of precipitation, evaporation rates, the permeability of soils and, a factor unique to mountain regions, the buffering effect of the altitude at which snow falls during an event. The more elevated the freezing level, the greater the potential for strong runoff since there is a larger surface area capable of capturing rain waters and channeling these into river catchments [*Stoffel et al.*, 2005]. The potential increase in water volume that can run off the Bernese Alps (the region particularly affected by the August 2005 floods) is about 15% when the freezing level rises from 2,500 to 3,000 m, for example, and is close to 25% if the snowline is located at 3,500 m, because of the additional surface area that intercepts rain water. The same quantity of precipitation can thus lead to a very different hydrological response according to the level at which snow falls during an intense precipitation event; without the buffering effect of snow, a heavy downpour can become a catastrophic event.

[17] Table 4 shows the freezing level for the 10 heaviest daily precipitation totals recorded at Engelberg; the altitudes at which snow falls during these events spans a range of 1,000 m, from less than 3,000 m above sea level to close to 4,000 m. The combination of precipitation totals and the freezing level determines the potential for impacts; the critical threshold above which snow fall no longer sufficiently buffers the effects of heavy rainfall on runoff amounts is about 3,400 m. In the right-hand columns, the results of the 10 most extreme precipitation events in the Engelberg area in the scenario climate (using the HIRHAM model) highlight the seasonal shift in mean and extreme

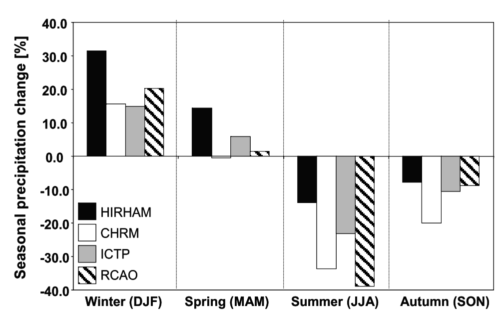

Figure 4. Change in average seasonal precipitation for the control and scenario climates as simulated by the 4 RCMs.

Table 3. Observed and Simulated Number of Extreme Precipitation Events from 1961–1990 (CTRL), Simulations for 2071–2100 (A2 Scenario), and Differences Between A2 and Control Climates, for the 6 Observation Sites and for the Four Models Used in This Study[a]

	Winter	Spring	Summer	Autumn	Annual
Observed 1961–1990	7 (5.3%)	17 (13.0%)	82 (62.6%)	25 (19.1%)	131 (100%)
HIRHAM 1961–1990	18 (22.8%)	9 (11.4%)	36 (45.6%)	16 (20.3%)	79 (100%)
CHRM 1961–1990	34 (21.9%)	19 (12.3%)	57 (36.8%)	45 (29%)	155 (100%)
ICTP 1961–1990	31 (17.8%)	18 (10.3%)	70 (40.2%)	55 (31.6%)	174 (100%)
RCAO 1961–1990	10 (10.1%)	16 (16.2%)	40 (40.4%)	30 (33.3%)	99 (100%)
HIRHAM 2071–2100	11 (10%)	27 (24.5%)	34 (30.9%)	38 (34.5%)	110 (100%)
% difference A2-CTRL	−38.9	+200.0	−5.6	+137.5	+39.2
CHRM 2071–2100	41 (19.4%)	46 (21.8%)	64 (30.3%)	60 (28.4%)	211 (100%)
% difference A2-CTRL	+190.0	+206.3	−53.3	+109.3	+36.1
ICTP 2071–2100	32 (14.0%)	55 (24.1%)	79 (34.6%)	62 (27.2%)	228 (100%)
% difference A2-CTRL	+3.2%	+205.6%	+12.9%	+2.7%	+31.0%
RCAO 2071–2100	29 (15.9%)	49 (26.9%)	14 (7.7%)	90 (49.5%)	182 (100%)
% difference A2-CTRL	+190.0	+206.3	−65.0	+172.7	+83.8

[a]Figures in parentheses give the % of annual total.

rainfall in the future. Under current climate, the most intense events all occur during the summer months, with an average freezing level at 3,500 m. In the scenario climate, on the other hand, the freezing level associated with heavy rainfall is, on average, 500 m lower. This apparent paradox is linked to the fact that extreme precipitation is simulated to occur more during the spring and autumn than in the summer, as seen from the dates of the events: 9 out of the 10 strongest episodes occur during the summer under current climate, but only 4 out of the future 10 most intense events. Even in a warmer climate by 2100, spring and autumn temperatures remain on average 4–7°C lower than current summer temperatures, such that the impacts of intense rainfall could well be mitigated by the lower elevations of the 0°C isotherm, at least within the mountains themselves. However, even though summer events are projected to decrease in the future, they will still be fairly frequent and could trigger even more severe impacts than today because of the higher freezing levels associated with future summers. All models suggest an overall annual increase in extreme rainfall events between the control and scenario simulations, from +30% (ICTP) to 80%(RCAO).

5. Conclusions

[18] This paper has focused upon a limited set of climate statistics related to the ‘‘flood of the century’’ that affected the northern slopes of the Swiss Alps in August 2005. The conclusions from the analyses of long time-series does not point to any discernible cause-to-effect relationship between ‘‘global warming’’ and the 2005 event, since the frequency and intensity of such extremes do not exhibit any clear trend over the past century. The type of storm and the impacts that it generated cannot necessarily be used as an analog for the future in a greenhouse climate, because RCM simulations suggest that mean and extreme precipitation may experience strong seasonal shifts, moving away from the summer months to the winter and spring. As a result, there may be stronger buffering effects of snow that falls in the mountains during these events, because intense precipitation is projected to increase in seasons that, even in a warmer climate, remain colder than current summers. The impacts of strong rainfall events may thus be on average less extreme than they are today, except when they occur in summer.

[19] These results are based upon a limited set of RCM simulations, and it is known that precipitation is often poorly simulated, particularly in regions of complex topography. Because of the general agreement between the 4 models, however, the implications of the present findings can be of value for strategic planning aimed at reducing the risks of heavy rain, floods, and other geomorphologic processes in mountain regions. Further work on this topic will draw upon the emerging results from multi-model, multi-ensembles climate simulations from

Table 4. Freezing Level Altitude for the 10 Most Extreme Events Exceeding the 99% Quantile Observed at Engelberg from 1961–1990 and Simulated for 2071–2100 (by the HIRHAM Model[a]

Engleberg			HIRHAM Model Simulation		
Year/Month	Maximum Daily Rainfall, mm	Freezing Level Altitude, m	Year/Month	Maximum Daily Rainfall, mm	Freezing Level Altitude, m
2005-08	*111*	*3350*	**2098-09**	**108**	**4160**
1978-08	*94*	*3560*	2077-03	103	3110
1954-08	*90*	*3590*	**2085-09**	**98**	**3520**
1984-08	86	3360	2090-03	90	2240
1939-08	*85*	*3950*	**2078-06**	**89**	**3450**
1960-09	81	3790	2078-03	88	2510
1973-06	*80*	*3950*	**2088-06**	**86**	**3560**
2005-08	*79*	*3310*	2097-03	85	2540
1954-07	72	2960	2091-04	82	2480
1977-07	71	3190	2084-10	81	2550

[a]Italicized figures highlight the observed flood events, and bold figure represent the potential for flooding in the scenario climate.

the current EU-ENSEMBLES project [*Hewitt and Griggs*, 2004], as a means of reducing the uncertainties related to RCM simulations of extreme precipitation.

[20] **Acknowledgment.** This work has been undertaken partly in the context of the Swiss NCCR-Climate project and the EU-ENSEMBLES project.

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