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NATURAL HAZARDS REPORT

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CHAPTER 1

ASSESMENT OF HISTORICAL PROCESSES INVOLVING NATURAL HAZARDS

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1. FLOODS – HISTORICAL PROCESSES REGARDING CLIMATE ISSUES

1.1 Data concerning floods in the Alps

Floods are relatively well observed in both time and space. Monitoring and observation networks are implemented along most of the alpine and peri-alpine rivers. The Alps represent an important part of the big European rivers catchment's area. Indeed, 20% of the Rhône waters and 67% of the Rhine waters originate in the alpine area. Rivers like the Rhône and the Rhine have quite long flow measure chronicles. Furthermore, historic reconstructions (like the one of Pfister in Switzerland) can give an idea of the past activity for the period preceding instrumental records.

1.2 Flood sensitivity and links with climate

The link between climatic parameters and river floods is obscured by many human factors (this is even more perceptible than for torrential events). Land-use changes greatly modify the surface flows and the stream. One can say that today there are no more catchment's areas in the Alps with "natural" flow processes.

The water used for agriculture also represents an important part in the flow balance. Hydraulic works can also have strong influences on river characteristics. Dams radically change the flow patterns, whilst protective buildings and the micro power plants represent "noises" in frequency and intensity analyses.Moreover, "hazard-reducing" measures (dikes, protection forests, etc.) were implemented in the first half of the 20th century, while "hazard-aggrieving" measures (ground waterproofing, concrete banks, etc.) have generally increased in the second half of the 20th century.

The following is the hypothesis generally proposed: in a warmer climate, the situations that could lead to floods would increase (with the postulate that with more energy in the climatic system, the water cycle would be enhanced).

The assumption that precipitation would increase for some part of the year and decrease for other parts of the year is based on the same hypothesis. The hypotheses for floods propose that their evolution should follow the evolution of precipitation. These suppositions do not take into account buffer effects (*e.g.* snow and vegetation cover, dams…) which attenuate the effects of precipitation in large catchment's areas. These buffer effects are far more limited in regards to torrents and their reaction to precipitations (and their evolution) is faster.

1.3 Observed impacts of climate change on floods

Flood intensity: On the world scale, around 70% of rivers flows do not show any significant trends related to climate change. When these trends are significant, they are divided equally between the increase and decrease of flood volume. In France, different studies converge on the fact that there are no significant trends concerning the flood volumes since the mid 20th century. These findings are also valid for Central Europe (Elb and Oder rivers).

Data and study results concerning the other countries of the Alps have not been integrated in the database because they were not available in literature. However, in Southern Germany, the examined runoff time series demonstrate regional increase in floods runoff for some stations in the last 30-40 years; but no significant changes were detected when examining the annual series for 70 to 150 years time series duration.

Flood frequency: An increase in the frequency of « extreme » floods has been observed over the past 20 years in the Alps, compared to the 20th century mean. For example, significant floods hit Switzerland in August 1987, September 1993 and October 2000, the Ticino in 1978, 1987, 1993 and 1994. But this flood increase seems to remain within the natural range of variability. The same kinds of conclusion have been proposed for floods in Central Europe (Oder and Elbe). In France, statistical studies do not show any significant flood frequency increase. In Southern Germany, the KLIWA project stated that the winter floods frequency increased since the 1970s with the exception of Southern Bavaria (*i.e.* North edge of Alps).

Flood intensity/frequency and seasonality: An increase of summer flow for rivers fed by glaciers, due to increased glacier melting, has been observed in the Alps, with favourable impact (on short time scale) on low waters, but no direct impact on floods. In Southern Bavaria, the KLIWA project stated that monthly runoffs during winter time are higher since the 1970s (compared to preceding values, available since 1931).

2. DEBRIS FLOWS AND TORRENTIAL FLOODS – HISTORICAL PROCESSES REGARDING CLIMATIC ISSUES

2.1 Data concerning torrential events

Debris flows and other torrential events are relatively difficult to observe. The same is true of the predisposition, triggering and aggrieving factors of the torrential events. There are insufficiencies in the rain cover network, i.e. a precipitation measure network that is adapted to the torrential phenomenon. With the exception of some experimental basin catchment's areas, the measure stations are rarely located in the close vicinity of the hazard zones and the data have to be extrapolated from distant stations.

The precipitation data provided by the meteorological stations also have limits when trying to assess the link between torrential events and climatic parameters. Indeed, the significant precipitation gradient on the mountainous relief makes the data from permanent measure stations located at the piedmont or valley floor unusable. For example, during the August 2005 floods in the Belledonne massif (France), 278 mm of rain was been recorded in 48 hours at the La Pra refuge (2100 m a.s.l) whilst only 32 mm was recorded at the Versoud automatic station (220 m a.s.l).

To correctly assess the meteorological situations associated with the triggering of torrential events in a particular location, it would be necessary to have measure stations in these locations or at least to have a network representing the massif with a good altitudinal distribution.

The implementation of automatic flow monitoring station is not really possible as these installations would most likely be carried away during each torrential flood. Even direct observation during the events is difficult as it is hard to correctly estimate torrent flow during a flood. However it is easier to evaluate the carried materials volume, especially coarse debris (*e.g.* those exceeding 1 meter in diameter). Automatic monitoring systems exist in Switzerland but they are used to give the alert and cannot provide instrumental data that could be used for studying the events.

The torrents have a very punctual observation. In France, these observations are realised on the field by the RTM service (Special Office for the Restoration of Mountain Soils) in the Alps and the Pyrénées. These specific studies of some torrential catchment areas usually provide long event chronicles but with the difficulties mentioned above, especially the concerning volume estimation.

This does not mean that no data exists for torrents and associated natural phenomena, but the data are too heterogeneous or too rarely synthesised at the regional scale to propose a complete analysis of the evolution of torrential events.

2.2 Debris flow sensitivity to climate

Fluctuations in precipitation amount can have an influence on torrential events. Debris flows are triggered above all by violent water release on areas where materials are available that will potentially be carried away by the rush of water. The threshold values for the triggering of debris flows can be very different from one massif to another, and even between two hazard areas within the same massif. This violent release of water can be characterised as follows:

- Spring / beginning summer thunderstorms (May, June and July) with very confined and short (1 to 4 hours duration) events but at a period when the mountainous catchment’s areas are still moist from the recent snow melting.
- Generalised autumn events (end August, September, October) when the water is falling on drier ground, but with much intensity, longer duration (6 to 18 hours) and wider area. The autumn events show more intensity due to their origin, the Mediterranean Sea is warmer during this period of the year.

At Ritigraben (Wallis, Switzerland), it has bee observed that the precipitation events that can lead to debris flows have increased during the last three decades. However, the precipitation data available are at the daily scale while for a more precise assessment, hourly precipitation data would be required. Indeed, hourly precipitation intensity is an important parameter, and for a given daily precipitation value, the hourly precipitation distribution can vary greatly.

If the heavy precipitation occurrence is a decisive factor in the triggering of debris flows, the material availability is another. These two parameters are the main debris flow factors that could be influenced by new climatic conditions. In some rare cases, glacial events with liquid water release (glacial lake outburst flooding, glacial water pocket, and even sérac falls) can also trigger debris flows with significant volumes.

Many hypotheses propose links between permafrost degradation and an increase in debris flows intensity and frequency. The degradation of frozen grounds concerns the periglacial area[1] in its entirety. Permafrost thawing diminishes the cohesion inside already unstable or metastable structures and could potentially increase the future material availability for debris flows. Glacier retreat also exposes large amount of freshly exposed materials presenting very low cohesion.

All these phenomena that could lead to debris flows are potentially influenced by climate change, through changes in the freezing/defreezing cycles, changes in the heavy precipitation seasonality and frequency, changes in glaciers patterns and through changes in the available materials for debris flows triggering.

Debris flows and mud flows are phenomena characterised by very significant spatial and time variability. This significant variability leads to difficulties in assessing the impact of climate change on these natural events.

2.3 Observed impacts of climate change on debris flows

Debris flow intensity / frequency: Despite the important number of hypotheses proposing an increase in debris flow intensity with climate change, no trends have been observed or modelled. The available studies mention a decrease in the occurrence of debris flows. Thus, the debris flow frequency in the Swiss Wallis seems to be the lowest for the last 300 years and a significant decrease in the number of debris flows has also been observed since the mid 1970s in the Écrins and Dévoluy massifs (France).

The evaluation of events considered as «extreme» when they occurred (this is especially true concerning the Ritigraben torrent in Switzerland in 1987 and 1993) has been moderated by recent publications. Early analyses which interpretated these events as the first signs of climate change incidence have been attenuated because further investigations on the site showed that such intense events occurred with the same frequency in the past.

Debris flow seasonality: Debris flows mainly occur during summer time, generally between June and October. A seasonal shift has been observed at Ritigraben where the debris flow season shifted from June/July/August to August/September. The authors interpret this seasonal

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[1] Area where freezing/defreezing and snow cover alternation play a predominant role

change as a consequence of the temperature increase at high altitude and of permafrost degradation (to be confirmed).

Debris flow localisation: An altitude increase has been observed in the triggering area of debris flows for some massifs, such as the Ecrins (France), where their altitude rose by more than 100 m between 1952 and 2000. The triggering areas located under 1800m a.s.l. have remained inactive since 1976. But no variations have been observed above 2200 m a.s.l. The temperature increase and the decrease in freezing days are supposed to explain these altitudinal shifts. Another study at the Mont Rose, also mentioning a spatial shift proposes glacier retreat as an explanation.

Nevertheless today, no changes in debris flow activity directly caused by changes in the available materials volume in these areas have been detected. However, regarding the limited number of studied sites, and the fact that studies do not focus on the material availability, this does not mean that no changes have yet occurred.

3. AVALANCHES– HISTORICAL PROCESSES REGARDING CLIMATE ISSUES

3.1 Data concerning avalanches in the Alps

Past avalanche activity reconstructions are realised by using historical documents reporting damages to buildings and inhabitants, some of these chronicles date back to the 16th century. However this kind of analysis cannot be used to assess the evolution of natural events because only catastrophic events, which led to damages, are reported and detailed. Some dendrochronology and lichenometry techniques have also been used to characterise past avalanche activity in a very precise location. These techniques are still being developed and many limits still exist; the limited number of available studies hinders a critical view of the method used. Some problems concerning the time calibration can also be found.

Furthermore, even if avalanche activity can be reconstructed for a precise location using these techniques, the link with climatic parameters is not easy to discern. Even if it is possible to assess the link scientifically, the researcher must extrapolate data from meteorological stations often located quite far from the observation site.

Avalanche observation is compiled in avalanche atlases, data bases which are often maintained by the forest services or their equivalent in the alpine arc. This observation work is done from identified avalanche locations on maps.

The technicians observe the events and describe the characteristics using a data form; all these data forms represent a data base describing the avalanche activity for the monitored avalanche area.

Some cooperation networks with ski resorts provide information about avalanche activity in the ski resort area or in its vicinity. The data analysis is not able to propose a clear evolution of the avalanche hazard and even less to provide links between avalanches and climatic parameters.

3.2 Avalanche data in France

The « Enquête Permanente sur les Avalanches » (EPA) started around 1900 in Savoy and has been carried out systematically on the French mountain ranges since 1965, leading to a data base which now includes over 70 000 events. For a long period, this monitoring was dependent on the initiative and good will of the ONF (National Office of Forestry) personnel and particularly the RTM services.

Since 2002, the « Ministère de l'Écologie et du Développement Durable » (today MEDAD) has been willing give an official frame for this action (following one recommendation of the back analysis commission set up after the catastrophic avalanche of Montroc in 1999). A protocol has been developed so that the information is homogenous for all the sites: the observation is always conducted from the same location, indications on the map help the observer to estimate the event's magnitude and the periods without avalanche activity are also detailed not to be considered as period without observation. All theses recommendations are detailed in an instruction book.

The Snow-Meteorological Network was implemented in the 1980s through cooperation with Météo-France. This network provides daily information on avalanche activity in ski resort areas and their vicinity during the tourism period. These data are not exhaustive in terms of area covered or in terms of time covered. They are of very poor quality when the meteorological conditions do not enable the personnel to make direct observations (*e.g.* because of fog).

Despite the importance of the data collected and its compilation within a homogeneous data base, it does not represent a systematic and instrumental chronicle of avalanche activity. The information is limited to certain areas and even to particular periods of time.

3.3 Avalanche sensitivity and links with the climate

No complete model exists today to assess the predisposition, the triggering and the flow of avalanches, but some partial models have been developed. In France, software have been developed by Météo-France to estimate the snow cover (including wind transport and metamorphosis) and its stability on a slope and by the Cemagref to calculate the avalanche flow and limits of propagation.

Avalanche characteristics (stopping distance, volume in movement, etc.) depend not only of the quantity of available snow pack, but also of the snow, conditioning different types of avalanches. Fresh snow avalanches (aerosol) are almost independent of the local topography during their propagation, contrary to wet-snow or snow-slab avalanches that are extremely sensitive to relief details. Vegetation cover also plays a role for the triggering of slab avalanches. Nevertheless, all avalanches are linked to the existence of snow and a possible reduction in snow cover (both in height and duration) or the elevation of the snow/rain limit will have direct consequences on avalanche activity. However, the mean climatic trends which are based on the most efficient climate model currently available are not sufficient to predict the future evolution of avalanche activity.

Indeed, an avalanche often results from the combination of an extreme meteorological situation (massive snow falls, intense melting) and of an already significant existing snow cover. It is therefore necessary to know the evolution of such extreme meteorological situations to be able to assess the evolution of avalanche activity.

But the understanding and integration of extreme meteorological events into the climatic model is still in process. Furthermore, trends for each altitude have to be characterised since avalanches often concern a wide range of altitudes. Thus it is very important to identify the trends for the triggering area, for the flow area and for the stopping area.

All these factors are obstacles to providing a direct link between avalanche activity and climatic parameters on one hand and between avalanche activity and snow cover on the other.

Even with good snow cover observations showing clear trends for its evolution and the existence of good modelling of snow cover evolution in a warmer climate, this information would not be sufficient to assess potential avalanche activity evolution. Some hypotheses can be proposed but they encounter the limits mentioned above.

Some publications have also studied the possible link between avalanche activity and large scale climatic circulations such as the North Atlantic Oscillation, but no links have been found.

Considering the land use changes and the avalanche protection policy, it is very likely that any change in forest cover, or the implementation of active and passive protection measures would have a far greater impact than the one potentially produced by climate change. Similarly to floods, avalanches are highly monitored (in the critical area) and many prevention/protection measures exist. All theses measures represent “noise” in the signal of the natural event itself, making its interpretation more difficult.

Avalanches are chiefly governed by short-term meteorological situations (periods of a few days), while climatic studies are more concerned with long-term trends and mean values. Furthermore, the data samples for avalanches are not prolonged enough to observe a statistically significant evolution of the natural event. Indeed, contrary to floods, avalanches are very punctual events, both in terms of time and space. The data are not available every year and for every avalanche location.

The data deficit is a crucial problem for the question of avalanche evolution. Methods aiming to account for these insufficiencies (using automatic monitoring with seismic captors or satellite data for example) are currently under development or test.

3.4 Observed impacts of climate change on avalanches

The climate does not seem to have evolved enough yet to really have consequences on the avalanche activity. Indeed, no trends have been observed considering the frequency, the intensity, the seasonality or the localisation of the avalanche in the Alps.

The catastrophic avalanche situations, such as the one that hit the Alps in 1999, are the consequences of extreme snow falls. Such situations are encountered around once each ten years and no changes concerning this kind of situations have been detected so far.

4. MASS MOVEMENTS– HISTORICAL PROCESSES REGARDING CLIMATIC ISSUES

4.1 Data concerning mass movements

There are many data base in the Alps that inventory mass movement. In France, there are two main databases. One is the BDMvt, held by the BRGM (Office for geologic and mining risks). In this data base, the mass movement (landslides, rock falls, mudflows, etc.) characteristics are recorded. For each movement data form, the precise location (both geographic and administrative data), the date, the volume, the width and the possible damages are detailed. However, all the parameters that could lead to these movements (geologic, precipitation, chemical, etc.) are not recorded. The second database is the RTM service data base, that is filled by the observations of forestry agents working on estate, communal or State lands.

In these data base, only the events leading to damages are generally recorded, contrary to systematic instrumental inventory (*e.g.* seismic monitoring data network). These data base are strongly influenced by the vulnerability evolution and thus need to be used with high caution in order to evaluate the natural event evolution.

These precise kinds of information are only available for experimental sites (“observatories”), monitored by laboratories or observatories. These sites have a good time cover but are limited geographically. An extrapolation based on these data for wider territories is not really possible as each movement is strongly conditioned by local parameters.

Radiocarbon dating methods enable the scientists to re-construct the temporal distribution of landslides for various locations in Europe during the Holocene. Some dendromorphology methods are also used to reconstruct the past rock fall activity by studying the impacts done by rock falls on trees. This kind of process is still under development and many limits still exist: the rock falling can impact only one tree, several trees or not at all. As it is impossible to determine, the scientists take the postulate that "each impact corresponds to a rock fall event". The impacts can make scars or "traumatisms" in the resin duct, but these signs are not easy to study.

Furthermore, the correlation test with climatic parameter are based on measures from very far meteorological stations (from some km to dozen of km). The limits are numerous and the proposed results have to be carefully considered.

4.2 Mass movements / Shallow landslides– historical processes regarding climatic issues

4.2.1 Shallow landslides sensitivity and links with the climate

Intense precipitation increase could lead to shallow landslides increase. The increasing number of landslides in the "Romandie" and Ticino canton (Switzerland) seems to be linked with the precipitation increases observed for two decades on these territories. The shallow landslides can also be impacted indirectly by climate change, trough the impacts on glaciers, permafrosts or forest fires. The glacier retreat and the permafrost degradation would lead to large area of slopes in unstable conditions (especially because of the cohesion loss due to the melting of ice particles in theses slopes). These voluminous material amounts could potentially become debris flows at high altitudes; this is even truer for the very steep slopes.

With a temperature increase, some hypotheses are also proposed concerning a possible re-colonisation of scree slopes because of longer vegetative period. The re-vegetation would enhance the slope cohesion. This stabilisation as a result of vegetation cover could also be limited by the appearance of acidifying species (such as Ericaceae s.l. on grassland) limiting the growing of plants with a wider roots system. The vegetation conditions can also be very harsh at high altitude and the re-vegetation in this case will be quite slow.

After forest fire event, the ground looses a great part of its protection that was previously provided by the vegetation cover. Furthermore, the fact they are very small particles (such as ash and coal) can play the rule of lubricant and would favour the surface erosion. All these conditions are aggrieving the aggressive effects of intense precipitation and could lead to more superficial mudflows. The forest fire multiplication (plausible in a climate change context) is a supplementary aggrieving factor for shallow landslide increase. This type of aggrieving circumstances has been observed after the forest fire in the Chamatte massif, the 6th of July 1982 (Alpes-de-Haute-Provence, France). The 18th of July, a thunderstorm occurred and reactivated slopes (considered as non active) leading to mudflows on the Angle village. However these ground conditions degradation is only temporary and after some years, the vegetation recolonises these slopes and provides again its protection effect. Similar features can also be observed after heavy storms, when wide parts of the forest cover are destroyed.

4.2.2 Observed impacts of climate change on shallow landslides

No observed direct impacts of climate change on shallow landslides are currently available in the referenced literature. However, indirect impacts via forest fires and storms might are often mentioned or locally observed, but the observations are limited both in terms of time series and geographical extent. Thus, despite the lack of significant trend, these indirect impacts have to be considered as potential emerging risks.

4.3 Mass movements / Deep landslides– historical processes regarding climatic issues

4.3.1 Deep landslides sensitivity and links with the climate

Deep landslides often occur on “dormant” landslides (e.g. Val Pola 1987). The assessment of such old inactive features as well as of slow creeping slopes is possible with geomorphological studies, but the forecasting of their reactivation is difficult to assess.

The annual precipitations and even pluri-annual means are proposed by different scientists as the key-parameter for the deep landslides, trough the influence of deep infiltrating waters and underground waters. Thus, any marked change in the precipitation pattern may have consequences on the deep landslide activity. Particular case: the slopes with stability controlled by foot erosion would be more sensitive to surface water runoffs linked with intense precipitation.

On the very long term, a dendrochonologic study has highlighted a link between climate and landslides activity in the Fribourg Pre-Alps (*e.g.* Hohberg and Falli-Hölli sites) where warm periods led to deep landslide activity increase in the Flysch area under 1500m a.s.l. This re-activation seems to be linked with the 0°C isotherm position. But these links between warm periods and deep landslides activity increase can not be extrapolated for the Alps.

4.3.2 Observed impacts of climate change on deep landslides

No observed impacts of climate change on deep landslides are currently available in the referenced literature.

4.4 Mass movements / Rock fall – historical processes regarding climatic issues

4.4.1 Rock fall sensitivity and links with the climate

Positive correlations between rock falls and the days with freezing/defreezing have been highlighted. But the link with precipitation has not been established. In France, a study on 46 rock falls in the Chartreuse and Vercors massifs has shown no correlation between rock falls activity and precipitation; but a correlation has been shown for the day with freezing/defreezing cycles. This link is valid for small to medium scale rock fall. For very large events (millions of cubic meters, e.g. Randa 1991), the importance of climatic factors becomes negligible in comparison geological patterns.

During the 2003 summer, many rock falls have been observed in mountainous area. This rock fall activity increase could be the consequence of permafrost degradation induced by very high summer temperature. The permafrost thaw depth reached values 10 to 50 cm deeper than the mean for the precedent 20 years. It is interesting to note that these instabilities occurred between June and August, *i.e.* not when the thawing phenomenon was at its deepest point but when the heat flow in the superficial layer was at its maximum. Many studies propose the hypothesis of a link between permafrost degradation and rock fall activity. This permafrost degradation may have consequences on the intensity, the frequency, the seasonality and the localisation of the natural event.

After the immediate response of the superficial permafrost layer to increased temperature, the lower limit of permafrost may rise in altitude and several instabilities may develop at high altitude where there are usually no freezing/defreezing actions. The penetration of freezing front in previously thawed materials may lead to important constraints trough the ice formation in cracks.

The forest and vegetation cover disappearing following forest fires would have potential consequences for the rock falls triggering and the rock stopping distance (forest protection effect): a forest fires multiplication (likely to happen in a climate change context) may be an aggrieving factor for the rock falls evolution. These negative consequences have been observed after the fire at Argentière-la-Bessée in 2003 (Hautes Alpes, France) and at the Néron, also in 2003 (Isère, France).

4.4.2 Observed impacts of climate change on rock falls

Rock fall intensity: A study using dendromorphology technique in the Swiss Pre-Alps did not show any intensity evolution for the rock fall activity in the studied area in the last decades.

Rock fall frequency: The rock falls frequency seems to have increased in the Swiss pre-Alps. Many rock falls events have been observed during the 2003 summer. But because of observation lacks, it is hard to determine if the rock falls during this scorching summer was higher than during a “normal” summer. A statistical study proposed that the occurrence probability of rock falls events is 2.5 higher for the days with freezing/defreezing effects than for the days without theses influences (evaluation for the Chartreuse and Vercors massif, France).

Rock fall localisation: During the 2003 heat wave, numerous rock falls have been observed in the north face in the alpine mountains. This increase frequency may be explained by more important permafrost surface in the north faces. A study on the Monte Rosa (Swiss Wallis) observed an altitudinal rise of the triggering area. This spatial shift has been explained (as for the debris flows) by glacier retreat.

5. GLACIAL HAZARDS – HISTORICAL PROCESSES REGARDING CLIMATIC ISSUES

The following parts are mainly based on the comment of C. Vincent from the Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE, Université Joseph Fourier, Grenoble), information collected in the GLACIORISK project and experience.

5.1 Data concerning glacial hazards

The last catastrophe due to a glacier in the Alps occurred in 1965, in Switzerland. The terminal part of the Allallin glacier tongue broke off and devastated the Mattmark dam building site (Swiss Wallis). As few glacier catastrophes occurred during the second half of the 20th century, the attention given to this hazard has decreased.

However, some potentially dangerous situations have existed in the Alps during the last few years, such as the pro-glacial Arsine lake (Hautes Alpes, France), the supra-glacial lake on the Rochemelon glacier (Savoie, France) or the Laggo Effimero on the Belvedere glacier (Piemonte, Italy).

The GLACIORISK program (2001-2003) aimed to propose a homogeneous data base concerning glacial hazards in Europe. This data base provides data forms for 166 alpine glaciers considered as "hazardous" and located in France, Switzerland, Austria and Italy.

The glaciers characteristics (length, altitude, type, surface, slope, orientation and localisation) are detailed as well as known glacial events that occurred in the past. But all the glacial events are not reported and the data quality is not homogeneous for all the events; some have been provided by technical services observers, other are quite old and based on various historical documents. Therefore, this data base, a unique piece regarding glacial hazards, does not allow glacial hazards evolution assessment.

Glacial water pockets are up to now impossible to observe and despite some attempts using teledetection, there are no data for this class of glacial hazard. Glacial lakes and séracs falls are observed punctually by research institutes (e.g. the French LGGE or the Swiss VAW - Versuchsanstalt für Wasserbau, hydrologie und glaziologie-) in experimental sites (which can also correspond to hazardous areas threatening human stakes).

These punctual observations enable scientists to develop models (especially a serac falls prevision model with a precision of 1-2 weeks range) and trends for some specific sites but general trends cannot really be proposed.

5.2 Glacial hazards / Glacial Lake Outburst Flooding – historical processes regarding climatic issues

5.2.1 "Glacial Lake Outburst Flooding" sensitivity and links with the climate

There are different types of glacial lakes, notably supra-glacial lakes, located on the glacier surface and pro-glacial lakes, located at the glacier front. The climatic conditions and glacier dynamics (indirectly and not exclusively influenced by climatic conditions and a potential temperature increase) explain these lake formations.

Pro-glacial lake occurrence is closely linked to glacier retreat. When the glacier retreats, moraines can become dams, thus creating pro-glacial lakes. These dams are often constituted with unstable materials and very low cohesion (some of these moraines can also be partially frozen). The over-digging ice free basin following the glacier retreat can be filled with liquid precipitation and the water released during the glacier and snow cover melting, eventually becoming a pro-glacial lake.

Pro-glacial lakes can also appear behind glacial rock bolts, *e.g.* at the Rhône glacier (Swiss Wallis). If the dikes bursting leading to floods are a threat, this is far less plausible for the lakes behind a rock bolt.

Supra-glacial lakes can also be the consequence of the glacier dynamic, as supposed at the Belvedere glacier in 2002. This lake is thought to be the consequence of the strong advance of this glacier since 2000[2]. The climatic conditions can also lead to the formation and extension of the supra-glacial lakes. This kind of lake needs further study to better understand the conditions that led to their creation as well as the method of safely draining the lake (uncertainties during the Rochemelon Lake draining concerning the ice channel behaviour during the operation).

Séracs falls in glacial lakes can also create waves (as the 50 cm wave observed at the Arsine pro-glacial lakes, 14th of September, 1996). These waves can potentially cause a dike to burst.

5.2.2 Observed impacts of climate change on "Glacial Lake Outburst Flooding"

No observed impacts of climate change on Glacial Lakes Outburst Flooding are currently available in the referenced literature.

5.3 Glacial hazards / Glacial water pocket – historical processes regarding climatic issues

5.3.1 Glacial water pocket sensitivity and links with the climate

The formation and the bursting of glacial water pockets (both intra-glacial and sub-glacial pockets) remain unknown processes. Liquid water flows inside glaciers are also quite unknown today. In the Mont Blanc massif, some water release and their consequences have been observed at the Trient glacier, at the Mer de Glace and at the Tête Rousse glacier (1995).

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[2] Even if glacier retreat is general, some particular glaciers can be advancing.

All these observations of liquid water release cannot yet be linked with clearly identified causes : they could be the consequence of accelerated melting of some part of the glacier, of the bursting of small glacial water pockets, of the flow of precipitation falling on the glacier or also of unknown intra-glacial liquid water flows.

5.3.2 Observed impacts of climate change on glacial water pocket

Considering the lack of knowledge mentioned above, the observation of glacial water pockets evolution is impossible to assess.

5.4 Glacial hazards / Sérac falls – historical processes regarding climatic issues

5.4.1 Sérac fall sensitivity and links with the climate

Sérac falls are quite a frequent phenomenon for glaciers and constitute a part of their natural ablation process. The link with climatic conditions is mainly indirect because the sérac falls are influenced by the glacier movements and dynamic, themselves influenced by climatic parameters. A glacier with a strong dynamic experiences frequent sérac falls.

A mean temperature increase would lead to an ablation increase and an accumulation decrease (unless the precipitation increase hypothesis for high altitude is confirmed and strong enough to counterbalance the effect of temperature). This would result in a negative mass balance and the glacier flow should decrease, as well as the sérac flows. This evolution should be experienced in the long term and the evolution of sérac falls for the next 20-30 is quite uncertain.

In some extreme cases, it is the whole terminal part of the glacier tongue that can break off from the glacier and fall downstream. This kind of phenomenon occurred, for example in 1949 at the Tour glacier (Haute-Savoie France) and in 1965 at the Allalin glacier. Hanging glaciers can effectively break off from their anchorage site if the “freezing conditions” at their base is no more garantied. The switch from a “cold” glacier thermal mode (the glacier sticks to the bed rock because of the low ice temperature) to a “temperate” glacier thermal mode (many liquid flows can lubricate the glacier at its interface with the bed rock) would thus be the main consequence of climate change affecting hanging glaciers and their stability. This is even more worrying because a warming of the cold glacier located at high altitude has been highlighted in the Alps. Some “hazardous” sites have been identified; Dôme du Goûter et Taconnaz (Haute Savoie, France where sérac falls on a voluminous snow cover lead to avalanches), Grandes Jorasses (Aoste, Italy) or Randa/Weisshorn (Swiss Wallis).

5.4.2 Observed impacts of climate change on sérac falls

Sérac fall localisation: A study done at the Monte Rosa (Swiss Wallis) has shown that more new sérac fall triggering zones have developed at higher altitude than were present before. This report is the only source mentioning a spatial shift of the sérac fall triggering zones and it is premature to draw general conclusions.

6. STORMS – HISTORICAL PROCESSES REGARDING CLIMATIC ISSUES

6.1 Data concering the storms

In France, there is no exhaustive inventory for the storms for the last centuries, the wind measures networks have been implemented only in the beginning of the 20th century. It is possible to use air pressure data, available since the end of the 18th century for thirty stations, to extrapolate the storm activity (this method seems to be very efficient). The exceptional events leading to important damages (and also kept in mind by the populations) are generally well documented. But these extreme and punctual events alone are not sufficient for a storm evolution assessment.

6.2 Storm sensitivity and links with climate

When the winds are stronger than 89km/h (corresponding to the 10 degree on the Beaufort scale), they are considered as “storm”. Most of the storm hitting Europe form over Atlantic, between 35 and 70° latitude. These storms occur mainly during winter and autumn in Europe (especially between November and February). The winds are the direct consequences of pressure differences. The climate and global warming influence on storm activity remains unknown. The storm creation is closely linked to the barocline instability (which is preponderant in the depression formation). But the link between the North Atlantic Oscillation and the storm is blurred.

It is quite premature to propose a storm evolution assessment regarding the available knowledge and modelling.

6.3 Observed impacts of climate change on tempests

Tempest intensity (France): There is no significant trend for the intensity tempest evolution in France between 1950 and 2000.

Tempest frequency: There has been a slight tempest frequency increase over the North Atlantic during the 20th century, but the intensities events remained unchanged. In France, around 15 tempests are recorded in France each year. The interannual variability of the tempests is very important, for example, 25 events in 1962 against 7 in 1968. One on ten is usually considered as “strong” (*i.e.* at least 20% of the departmental stations record an instantaneous maximum wind above 100km/h), the frequency of such events is around 1.4 event/year over the last 50 years. There has been a slight decrease of the tempest number over the last 50 years in France, but this trend between 1950 and 2000 is not significant.

List of Acronyms

- **BRGM:** Bureau des Risques Géologiques et Miniers (Office for geologic and mining risks, France)
- **EPA:** Enquête Permanente sur les Avalanches (Permanent avalanche monitoring, France)
- **GLACIORISK:** Survey of extreme glaciological hazards in European mountainous regions
- **KLIWA:** Klimaveränderung und Konsequenzen für die Wasserwirtschaft (Climate change and consequences for water management, Germany)
- **LGGE:** Laboratoire de Glaciologie et de Géophysique de l'Environnement (Laboratory of glaciology and environmental geophysics, France)
- **MEDAD:** Ministère de l'Écologie, du Développement et de l'Aménagement durables (Ministry for ecology, sustainable development and landplaning, France)
- **ONF:** Office National des Forêts (National office for forest, France)
- **RTM:** Restauration des Terrains de Montagne (Mountain soils rehabilitation service, France)
- **VAW:** Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (Research institute for hydrology and glaciology, Switzerland)

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