Climate Change and Natural Hazards in the Alps:
Observed and potential impacts on physical and socio-economic systems

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Abstract

Under the effects of climate change, alpine mountainous regions register fast and well-perceptible evolutions that are causing a growing attention of people, scientists and managers. For better coping with hazards and vulnerabilities specific to these territories, the current national and European public policies in the alpine countries now prescribe adapting natural hazards prevention to climate change. This paper proposes a review of recent advances in knowledge on perceived, measured and projected changes in i) climate patterns, ii) cryosphere, hydrosystems and geomorphological dynamics on alpine slopes, iii) natural hazards evolution and induced risks at the scale of the French Alps. We give a brief overview of new results achieved in research, cooperation and capitalization projects on these thematic fields during the programmatic period 2007-2013, that are made available on databases, thematic knowledge platforms and observatories developed by different scientific and technical operators in the larger framework of the European alpine arc. We illustrate this renewed synthesis by published examples of hydro-gravitational hazards activity chronicles, along with climate patterns identified as “predictors”.

Keywords

Natural hazards, observation, projection, adaptation

Introduction

Mountainous territories are particularly concerned by the effects of climate change. Along with observed and potential impacts on a variety of natural hazards combine, increased vulnerabilities in the context of global change occur (Beniston *et al*., 1996; Boudières *et al*., 2013).

In recent years, these rapid changes draw attention and heightened concerns from the populations, scientists and land and natural hazards managers in the Alps. Numerous research and regional cooperation projects have been dedicated on these topics in European, national and regional programs (Tabs. 1 and 2).

Name/ acronym	Title and concerned regions	Programming periods	Website
International scale			
BELMONT FORUM	Call for Proposals on "Mountains as Sentinels of Change" of the Belmont Forum Collaborative Research Action	Launched in 2015	http://igfagcr.org/cra-2015-mountains-as-sentinels-of-change
WCRP	World Climate Research Programme of the World Meteorological Organization	Created in 1980	www.wcrp-climate.org
European scale			
ALCOTRA	France-Italy transboundary cooperation Programme (previous programming periods: 1989–1999 ; 2000–2006 ; 2007–2013)	2014–2020	www.interreg-alcotra.org
ESPACE ALPIN	Alpine space transnational cooperation Programme, launched in 2000, concerns the seven countries of the Alps and covers both Regions Rhône-Alpes and PACA	Idem since 2000	www.alpine-space.eu
FRANCE-SUISSE	France-Switzerland transboundary cooperation Programme	Idem	www.interreg-francesuisse.org
MED	Covers the coastal and Mediterranean regions of nine member states of the European Union.	Idem	www.programmemed.eu
PCRD	The EU Framework Programme for Research and Innovation (Horizon 2020, or FP8) Main European instrument for Development Research and Innovation.	Since 1984	www.horizon2020.gouv.fr
CORDEX	European branch of the international CORDEX initiative, sponsored by the World Climate Research Program (WRCP)	Since 2009	www.euro-cordex.net (for Europe)
COST	European Cooperation in the field of scientific and technical research. Programme funded by the European Commission, Directorate General for Research, via the Framework Programme	Idem	www.cost.eu
National scale			
ANR	Agence Nationale de la Recherche (The French National Research Agency)	Since 2005	www.agence-nationale-recherche.fr
GICC	Gestion des Impacts du Changement Climatique ('Management and Impacts of Climate Change' federating research programme)	Since 1999	www.gip-ecofor.org/gicc
MEDDE	Projects and actions financed notably by the Directorate General of Risk Prevention ('Direction Générale de la Prévention de Risques', DGPR)	Punctual funding	www.developpement-durable.gouv.fr
RGC&U	Réseau Génie Civil et Urbain (Civil Engineering and Urban Network, attached to the ANR in 2005)	1999-2005	www.developpement-durable.gouv.fr/...
IREX	Institut pour la recherche appliquée et l'expérimentation en génie civil ('Institute for applied research and experimentation in civil engineering')	2015-2020	www.irex.asso.fr
Interregional scale			
POIA	Programme Opérationnel Interrégional des Alpes ('Interregional Operational Programme of the Alps') (follows the previous programming period: 2007-2013)	2014-2020	http://programmes-europeens-2014-2020.regionpaca.fr (pdf)
SDA	Science-Décision-Action pour la prévention des risques naturels (sub-programme of the POIA)	2015-2020	www.risknat.org/sda
Regional scale			
CPER Previous : 1989–1993 ; 1994-1999 ; 2000–2006 ; 2007–2013	5 themes are proposed to contracting for future 'Contrats de Projets Etat-Région' ('State-Region Project Contracts', 2014-2020) : i) higher education, research and innovation; ii) the territorial coverage of high-speed broadband and development of uses of digital technology; iii) innovation, promising niches and the factory of the future; iv) multimodal mobility; v) environmental and energy transition..	2014–2020	www.datar.gouv.fr/contrats-etat-regions
ARC-Environnement Rhône-Alpes (ex Cluster Environnement)	The academic research communities 'ARC Environment' in Rhône-Alpes aims to help the region to "maintain the basic balance, but fragile, sustainable development based on the area of research and innovation, particularly active in the environmental engineering and the study of health-environment relationships themes.	Since 2012	www.arc.rhonealpes.fr
LabEx OSUG@2020	Laboratories of Excellence (LabEx), « OSUG@2020, Stratégies innovantes pour l'observation et la modélisation des systèmes naturels » ('Innovative strategies for the observation and modeling of natural systems'): project funded by the Future Investments program launched by the government and implemented by the ANR	2011-2020	www.osug.fr/labex-osug-2020
Subregional scale			
PGRN/CG38	Departmental Programme of the 'Pôle Grenoblois d'études et de recherche pour la prévention des Risques Naturels' (PGRN) funded by the General Council of Isere	1989-2010	www.risknat.org/pgrn-cg38

Table 1: Main international, European and national programmes on climate change and natural hazards interesting the French Alps.

Programme	Project	Title	Duration	Website
European scale				
FP5	GLACIORISK	Survey and prevention of extreme glaciological hazards in European mountainous regions	2001-2003	http://glaciorisk.grenoble.cemagref.fr
	PRUDENCE	Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects	2001-2004	http://prudence.dmi.dk/
	STARDEX	Statistical and Regional dynamical Downscaling of Extremes for European regions	2002-2005	www.cru.uea.ac.uk/projects/stardex
FP6	ENSEMBLES	Ensemble-based Predictions of Climate Changes and their Impacts	2004-2009	www.ensembles-eu.org
FP7	ACQWA	Assessing Climate Impacts on the Quantity and quality of WAter	2008-2013	www.acqwa.ch
	ConHaz	Costs of Natural Hazards	2010-2012	http://conhaz.org
	EURO4M	European Reanalysis And Observations For Monitoring	2010-2014	www.euro4m.eu
	EUROPIAS	European Provision Of Regional Impacts Assessments on Seasonal and Decadal Timescales	2012-2015	www.euporias.eu
	SafeLand	Living with landslide risk in Europe: Assessment, effects of global change, and risk management strategies	2009-2013	www.safeland-fp7.eu
WRCP	EURO-CCORDEX	European Coordinated Regional Climate Downscaling Experiment - European Domain	2009	www.euro-cordex.net
CIRCLE Mountain	ARNICA	Assessment of Risks on transportation Networks resulting from slope Instability and Climate change in the Alps	2010-2013	www.circlemontagne.fr
	Changing RISKS	Changing pattern of landslide risks as response to global changes in mountain areas	2010-2013	www.circlemontagne.fr
COST	FloodFreq	European Procedures for Flood Frequency Estimation	2010-2014	www.cost-floodfreq.eu
	HOME	Advances in homogenisation methods of climate series	2007-2012	www.homogenisation.org

Table 2: (A) Examples of European Research and Development projects on climate change and natural hazards in the Alps.

Programme	Project	Title	Duration	Website
European scale				
ALCOTRA	FLORA	Flood estimation and forecast in complex orographic areas for risk mitigation in the Alpine Space	2009-2012	www.risknet-alcotra.org (info)
	GlaRiskAlp	Risques glaciaires dans les Alpes occidentales	2009-2012	www.glariskalp.eu
	IFP FR-IT	Interreg Forêts de protection – Composante France-Italie	2007-2011	www.interreg-forets-protection.eu
	PERMAdataROC	Elaboration d'une base de données et expérimentation de méthodes de mesure des mouvements gravitaires et des régimes thermiques des parois rocheuses à permafrost en haute montagne	2006-2008	www.risknet-alcotra.org (info)
	PICRIT	Protection des infrastructures critiques transfrontalières pour la sécurité civile	2012-2013	www.picrit.eu
	PIT EMB - P4H5	Plan Intégré Transfrontalier Espace Mont-Blanc – Volet Éducation à l'environnement	2010-2012	http://pit.espace-mont-blanc.com
	RiskNat	Gestion en sécurité des territoires de montagne transfrontaliers	2009-2012	www.risknat-alcotra.org
	RiskNET	Réseau transfrontalier sur les risques naturels	2013-2015	www.risknet-alcotra.org
	STRADA	Stratégies d'adaptation au changement climatique pour la gestion des risques naturels dans la région frontalière	2010-2013	www.progettostrada.net
FRANCE-SUISSE	HAUT RHÔNE	Le Haut-Rhône et son bassin versant montagneux : pour une gestion intégrée de territoires transfrontaliers	2005-2008	www.institut-montagne.org
	IFP FR-CH	Interreg Forêts de protection – Composante France-Suisse	2007-2011	www.interreg-forets-protection.eu
ESPACE ALPIN	ALP FFIRS	Alpine Forest Fire _warning System	2009-2012	www.alpffirs.eu
	AdaptAlp	Adaptation to Climate Change in the Alpine Space	2008-2011	www.adaptalp.org
	C3-Alps	Capitalising climate change knowledge for adaptation in the alpine space	2012-2014	www.c3alps.eu
	ClimChAlp	Climate change, impacts and adaptation strategies in the Alpine Space	2006-2008	Web site no more available
	CLSIP	Climate Change Adaptation by Spatial Planning in the Alpine Space	2008-2011	www.clisp.eu
	MANFRED	Management strategies to adapt Alpine Space forests to climate change risk	2009-2012	www.manfredproject.eu
	PARAmount	Improved accessibility: reliability and security of alpine transport infrastructure related to mountainous hazards in a changing climate	2009-2012	www.paramount-project.eu
	PermaNET	Permafrost long-term monitoring network	2008-2011	www.permanet-alpinespace.eu
	START_it_up	State-of-the-Art in Risk Management Technology: Implementation and Trial for Usability in Engineering Practice and Policy	2013-2014	http://startit-up.eu
	WikiAlps	A wiki for capitalising on spatial-development projects	2013-2014	www.wikialps-project.eu

Table 2 (continued): (B) European research and territorial cooperation projects on climate change and natural hazards in the Alps.

Programme	Project	Title	Duration	Website
National scale				
ANR	MONISNOW	Monitoring Snow in a changing climate	2011-2015	www.agence-nationale-recherche.fr
	MOPERA	Modélisation Probabiliste pour l'Etude du Risque d'Avalanche	2010-2013	www.avalanches.fr/mopera-projet
	Pygmalion	Paleohydrology and Human Climate Environment Interactions in the Alps	2007-2012	http://edytem.univ-savoie.fr/...
	RIWER 2030	Climat Régionaux et incertitudes, ressources en eau et énergétiques associées de 1960 à 2030	2009-2011	www.lthe.fr/RIWER2030
	SAMCO	Adaptation de la société aux risques en montagne dans un contexte de changement global	2013-2017	www.anr-samco.com
	SCAMPEI	Scénarios Climatiques Adaptés aux zones de Montagne : Phénomènes extrêmes, Enneigement et Incertitudes	2009-2011	www.cnrm.meteo.fr/scampei
	SLAMS	Séchilienne Land movement : Multidisciplinary Studies from Hazard assessment to associated risk and consequences	2010-2013	http://isterre.fr/recherche/...
	VIP-Mont-Blanc	Rates of the processes controlling the morphologic and environmental changes in the Mont-Blanc massif	2014-2019	http://vip-montblanc.osug.fr/
Fondation MAIF	DENDROGLISS	Reconstitution de l'activité de glissements de terrain par dendrogéomorphologie	2008-2011	www.fondation-maif.fr/...
	PERMAFROST	Analyse des risques induits par la dégradation du permafrost	2007-2010	
GICC	ADAMONT	Impacts du changement climatique et Adaptation en territoire de Montagne	2015-2017	www.gip-ecofor.org/gicc/...
	DECLIC	Drôme : Eau, Climat et Impacts liés aux Changements	2010-2012	http://declic.ujf-grenoble.fr
	DRIAS	Donner accès aux scenarios climatiques Régionalisés français pour l'Impact et l'Adaptation de nos Sociétés et environnements	2008-2011	www.drias-climat.fr
	GICC Rhône	Etude des impacts potentiels du changement climatique sur le bassin versant du Rhône en vue de leur gestion	1999-2004	www.gip-ecofor.org/gicc/...
	R²D² 2050	Risque, Ressource en eau et gestion Durable de la Durance en 2050	2010-2013	https://r2d2-2050.cemagref.fr
MEDDE	ECANA	Etude Climatologique de l'Activité Avalancheuse Naturelle	2009-2016	www.avalanches.fr/projet-ecana
	EXPLORE 2070	Eau et changement climatique	2010-2012	www.developpement-durable.gouv.fr/...
IREX / RGC&U	C2ROP	Chutes de Blocs, Risques Rocheux et Ouvrages de Protection	2015-2019	www.c2rop.fr
Interregional scale				
POIA	GIRN Alpes	Opération interrégionale « Gestion intégrée des risques naturels dans les Alpes – Expérimentation sur sites pilotes »	2009-2014	www.risknat.org/girn-alpes
		Essaimage de sites de GIRN dans la nouvelle programmation	2015-2020	
Regional scale				
ARC-Environnement	AIC 2012	XXV colloque Association internationale de climatologie	2012	www.arc3-environnement.rhonealpes.fr
	ISSW2013	Organisation de l'International Snow Science Workshop à Grenoble	2013	
	—	Influence du climat sur le déclenchement des éboulements rocheux	2013	
	—	Archives climatiques de la dernière période interglaciaire en Rhône-Alpes, et nouvelles méthodologies pour la reconstruction des paléo-températures	2015	
	PERMARISK	Contribution à l'amélioration de la gestion de risques émergents associés à la dégradation du permafrost de montagne	2015	
CPER PACA	RHYTMME	Risques HYdrométéorologiques en Territoires de Montagnes et MEditerranéens	2008-2013	http://rhytmme.irstea.fr
Régions RA, LR, MP	CLIMFOUREL	Adaptation des systèmes fourragers et d'élevage péri-méditerranéens aux changements et aléas climatiques, un projet tri-régional Rhône-Alpes, Languedoc-Roussillon, Midi-Pyrénées	2008-2010	http://climfourel.agropolis.fr
Subregional scale				
LabEX ITEM	CrHistAl	Crues Historiques dans les Alpes	2012-2013	www.labexitem.fr/...
LabEx OSUG@2020	MONISNOW Alpes	Monitoring Snow in a changing climate - Alps	2012	www.osug.fr/labex-osug-2020/...
	—	Structure des précipitations orographiques en région Méditerranéenne : Mécanismes et Prévision	2012	www.osug.fr/labex-osug-2020/...
	—	Impacts environnementaux du retrait glaciaire dans le Massif du Mont Blanc : quantification des processus contemporains et perspectives d'évolutions futures	2014	www.osug.fr/labex-osug-2020/...
PGRN/CG38	Several projects	Some projects on climate change from over 200 projects on natural hazards	1989-2010	www.risknat.org/pgrn-cg38

Table 2 (continued): (C) National and regional research projects on climate change and natural hazards in the French Alps.

In continuity with previous syntheses (Prudent-Richard *et al.*, 2008 ; Richard *et al.*, 2010 ; Einhorn and Peisser, 2011), this paper presents the main results of recent work on these themes in the French Alps, bearing on knowledge capitalization portals (Tab. 3). It also presents an overview of existing observation services (Tab. 4).

Outil de capitalisation des connaissances	Site internet
'Alpes-Climat-Risques' web-portal from the project ClimChAlp (Prudent-Richard *et al.*, 2008): bibliographical knowledge base (350 references) and newsletter on climate change and its effects on alpine physical systems and natural hazards.	www.risknat.org/alpes-climat-risques
'Base Projets': database on the results of research projects on alpine natural hazards.	www.risknat.org/baseprojets
Database of the RiskNET project on Franco-Italian-Swiss Interreg cooperation projects on natural hazards in the ALCOTRA territory.	www.risknet-alcotra.org

Table 3: Tools giving access to full references (projects, publications) of the results discussed in the text.

Observation services and databases	Missions and objects of study	Data types	Carrying organisms and data producers*
Observations climatiques			
Météo-France http://www.meteofrance.com/	Public service missions of information dissemination on meteorology and climate. Publish in particular annual and seasonal climatic balance assessments.	Observational data (*in situ*, radar, satellite), climatology, forecast data and models, and climate forecast	Météo-France
Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region (HISTALP) www.zamg.ac.at/histalp/	Climate parameters long series covering the European Alps	Homogenized monthly temperature, precipitations, atmospheric pressure, sunshine duration and nebulosity data	ZAMG (Autriche)
Alpine environment			
Les GLACIers, un Observatoire du CLIMat (GLACIOCLIM) www-lgge.ujf-grenoble.fr/ServiceObs/	Environment Research Observatory on the theme 'Continental Surfaces and Interfaces' on glaciers and climate studies	Glacier mass balances	LGGE, Irstea
Réseau de mesure du permafrost et des processus liés au gel (PermaFRANCE)	Observational and monitoring network on French mountain permafrost, freezing-related phenomena and associated periglacial processes	See Bodin *et al.*, 2015 (this volume)	PACTE, EDYTEM
Natural hazards			
Enquête permanente sur les avalanches (EPA) www.avalanches.fr/epa_lobservation-actuelle	Regular avalanche observation in France providing access to an inventory, as complete as possible, of avalanche events that took place on the sites observed during the winter season (4000 paths to date)	Base de données des événements observés pour chaque site (dates, altitudes, dépôt, caractéristiques, météo 3 jours, précédents, météo 4h, précédentes, causes, victimes, dégâts ou lieux atteints)	Irstea, ONF-RTM, MEDDE
Observatoire des Risques Naturels en Montagne du service de Restauration des Terrains en Montagne (BD RTM Evénements) http://rtm-onf.ifn.fr	Database on events of avalanche, flood, debris flow, gullying, rockfall, landslide, subsidence and compaction by withdrawal	Information on more than 30 000 events and more than 19 000 works of protection against natural hazards (grouped into 2,400 protective devices)	ONF-RTM, IFN, MEDDE, Ministère de l'Agriculture
Observatoire Multidisciplinaire des Instabilités de Versants (OMIV) http://omiv.osug.fr/	Study of landslide dynamics (damage, triggering, and propagation) and the effect of external forcing (climate, earthquakes) on four sites representative of the mechanisms observed in the French Alps (soft rock / dense, slow or fast movements).	Development of a permanent multidisciplinary instrumentation on each site, to characterize: i) the kinematics of movement and deformation (geodesy, inclinometers, extensometers, aerial and satellite imagery), ii) the seismic behavior of the slip (fragile damage via microseisms and responses to regional earthquakes), iii) the hydraulic responses to meteorological forcing.	ISTerre, Géoazur, EMMAH, IPGS-EOST, Chrono-Environnement
Surveillance Séchilienne www.versant-sechilienne.developpement-durable.gouv.fr/	Operational system for the monitoring of the 'Ruines de Séchilienne' unstable slope (Isere)	Teletransmission of monitoring data: extensometry, GPS positioning, movement velocity…	MEDDE, CEREMA
Banque Nationale de Données pour l'Hydrométrie et l'Hydrologie (Banque HYDRO) www.hydro.eaufrance.fr	Hydrological database of state services administered and managed by the 'Service Central d'Hydrométéorologie et d'Appui à la Prévision des Inondations' ('Central Service of Hydrometeorology and Support to Flood Forecasting')	Water height measurements at various time steps from 3500 measuring stations (including 2 400 in service) located on the French rivers and access to station metadata	MEDDE, (SCHAPI, DREAL, SPC, etc.), EDF, Irstea, compagnies d'aménagement
Service de Prévision des Crues des Alpes du Nord (« Information sur la vigilance crues ») www.vigicrues.gouv.fr	Regulatory mission of monitoring, forecasting and transmission of information on floods	Data measuring stations water heights and discharge of major metropolitan rivers (stored in the 'Banque HYDRO' database)	MEDDE, SPC Alpes du Nord (DDT38)
Base de Données sur les Incendies de Forêt en France (BDIFF) http://bdiff.ifn.fr/	Collects all the data related to forest fires in France since 1992	Declarative data complementarily collected by different local services (departmental or regional)	MAAPRAT, MIOMCTI, DGPAAT, IGN

Notes:
* Acronyms: see websites

Table 4: Observation and monitoring systems providing data on climate change, physical environment and natural hazards in the French Alps.

On these bases, the present contribution reviews observed and projected changes in: i) climate patterns, ii) cryosphere, hydrosystems and slope morphodynamics, iii) natural hazards, and iv) induced risks on human installations and activities in the French Alps. It is illustrated by chronicles of hydro-gravitational processes activity, along with time series of climate pattern identified as their most significant predictors. In addition to the resources and to the references inventoried, and to allow deepening this review, other papers of the volume focusing on certain topics handled in this paper are reported.

1. Climate changes and observed physical impacts

1.1 Measured climate change

The warming of the climate in the Alpine range is well documented (Tab. 5) from varied sources (punctual series, reanalysis, results from simulation of the past, etc.) with different spatial and altitudinal resolution, and covering various periods, whose use requires homogeneous databases. Robust findings focus on the general rise in temperatures and its effects on directly related phenomena, such as snowfall or evapotranspiration.

Results	References
(A) According to a regional dendroclimatological reconstitution in the Alps, the last decade of the twentieth century was the warmest period in the last millennium, with more warming and much faster than, for example, the one rebuilt for the warm period medieval.	Corona *et al*., (2010)
(B) The long series of homogenized temperatures covering the Alps (HISTALP) show a uniform warming of 2 °C between the late nineteenth and early twenty-first century (Auer *et al*. 2007), which has accelerated since 1970, including at high altitude. Everywhere, indeed, the end of 1980s marked in significant warming. The average height of the isotherm 0 °C so rose of 400 m with compared with the beginning of 1980s (Böhm *et al*., 2010).	Auer *et al*. (2007) (see ref. in Böhm *et al*., (2010)) ; Böhm *et al*., (2010)

Table 5: Results from (A) reconstitution and (B) observation of the plurisecular temperature evolution in the Alps.

In the French Alps, located at the intersection of several climatic influences, the warming of temperatures after 1980 affects all stations, with slight contrasts between the Northern and Southern part (Fig. 1). The warming of +1.8 and +2.1 °C on annual average in the Northern Alps and in the 'Prealps' since 1950 is faster than that observed in the Southern Alps (+1.5 to + 1.7 °C), with intermediate values in transitional areas between these two climatic domains[1].

[1] Source: analysis of homogenized temperature data of Météo-France by MDP/OsCC. For Northern Alps, OsCC provides annual and seasonal climate assessments (www.mdp73.fr).

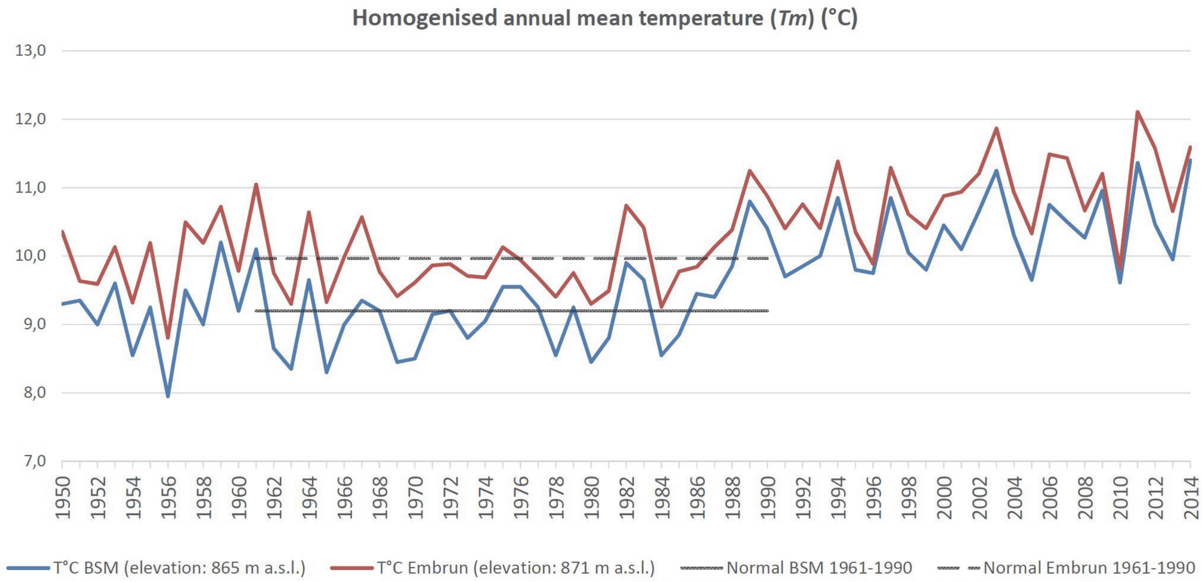

Figure 1: Homogenised annual mean temperature from 1950 to 2014 at Bourg-Saint-Maurice (BSM) and Embrun and normal values over the reference period 1961-1990. Data: Météo-France; Processing: MDP-OsCC/PARN.

Monthly long series in Northern Alps over the period 1885-2007 (Dumas, 2013) show that warming on an annual scale occurred without much amplification until 1960. Then the rate of warming has increased over the past decades to exceed +4.0 °C/100 years (especially in spring and summer). This value is consistent with the rate of +0.4 °C/decade in the Northern Alps since 1950, higher than in the rest of France, especially for the maximum temperatures (Gibelin *et al*., 2014). The issue of 'Mediterraneanisation' of Northern Alps climate arises, this phenomenon having already occurred along the Rhône Valley and in Midi-Pyrénées (Climfourel project).
SAFRAN reanalysis[2] over the 1958-2002 period (Durand *et al*., 2009a) show a temperature increase especially marked at medium altitudes (1500-2000 m, > +0.3 °C/decade) which significantly reduces beyond 3000 m a.s.l.. At very high altitude (> 4000 m a.s.l.), in the Mont Blanc, the air temperature reconstituted by inversion of the ice temperature profiles increased by 0.14 ° C / decade during the twentieth century (Gilbert and Vincent, 2013).

Rainfall in the Alps have a much more heterogeneous pattern of change at regional and seasonal scales (Tab. 6).

Results	**References**
(A) At the scale of the Alpine range and during the 20th century, precipitation has increased by 9% in the northwest of the chain, where cloud cover also increased, while falls were even (-9%) in its southeastern part, in relation with a decrease in cloud cover and a drying trend.	Auer *et al*. (2007) (voir réf. dans Böhm *et al*., 2010)
(B) Daily rainfall data of over 5,000 stations covering the Alps on the 1971 to 2008 period were interpolated in a high-resolution grid (5 km) more finely integrating the complex influence of topography and reducing traditional biases of interpolation. The studied indices emphasize the asymmetry of the frequency distribution of daily precipitation between the regions north of the Alps, where rainy days (> 1mm) are more common, and their southern flank, where they are less frequent but more intense on average.	Isotta *et al*. (2014)

Table 6: Results of (A) reconstitution (HISTALP) and (B) observation on of the plurisecular evolution of precipitation and nebulosity in the Alpine region.

[2] Mesoscale analysis system of near surface atmospheric variables: www.drias-climat.fr/accompagnement/section/137

In the French Alps, the average annual rainfall observed and simulated by SAFRAN, and Météo-France homogenized climate series, show no statistically significant trends (Durand *et al*. 2009a), apart a decrease in winter precipitation in the internal Alps (Haute Maurienne, Queyras), which reached 30% between 1961-1990 and 1981-2010 climate periods[3].
On extreme precipitation, it is difficult to conclude for the Alps. While a tendency to increase, variable by region was reported for Europe, with a median reduction of 21% of the return period of extreme events (van den Besselaar *et al*., 2013), Météo-France data do not indicate any increase in extreme rains in the Southeast of France[4].

1.2 Observed impacts on alpine cryosphere

Under the effect of climate change, the Alpine environment records fast and obvious changes: less snow, receding glaciers, permafrost degradation, species rise in altitude and latitude, warming of lakes and rivers, etc. The impacts reported in the mountains result primarily from the effects of temperature increase, which largely controls the alternating freeze/thaw, the rain/snow ratio or the altitudinal position of snow cover and the equilibrium-line altitude (LEA) of glaciers. These factors largely control the hydrological regime, vegetation dynamics and, to a lesser extent because of the complexity of systems, *s.l.* erosion processes in watersheds.

Snow-cover at 1800 m in the French Alps showed a strong spatial variability from the late 1950s to the mid-1980s, after which it became less variable from one massif to another, with decreased mean values and a reduced amplitude of extreme values (Durand *et al*., 2009b). The thickness of snow in early winter has showed a sharp decline at low and medium altitude from the late 1980s, while it increased at high altitude (2700 m).

Glaciers are the most visible marker of past warming and its recent acceleration. A multisource cartographic reconstitution of glacial extent in the French Alps has assessed its diachronic evolution in recent decades (GlaRiskAlp project; Tab. 2). Their surface in late 2000 (275 km²) fell by nearly 20% from 1985 to 1986 (340 km²) and by 26% from the years 1967 to 1971 (370 km²; Gardent *et al*., 2014), in response to strong warming above-mentioned (Fig. 2). Yet, the most direct measure of climate control on glacier dynamics is provided by the mass balance. Data exist only for some glaciers, especially those monitored by the observatory GLACIOCLIM (Table 4; Vincent, 2002). For example, seasonal variations in Sarennes glacier since 1949 quantify accurately the evolution of winter snowfall and summer temperatures at high altitude (Thibert *et al*., 2013).

[3] Cf. Note 1.
[4] http://pluiesextremes.meteo.fr/

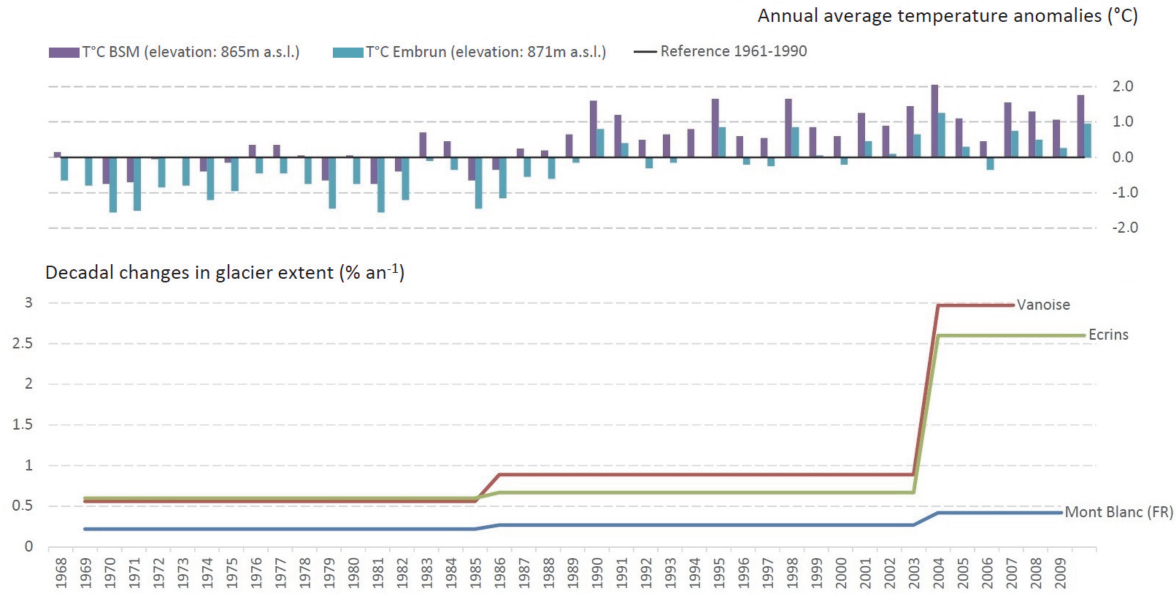

Figure 2: (A) Annual average temperature anomalies in Bourg-Saint-Maurice and Embrun over the period 1967-2010 compared to the 1961-1990 normal (see Fig. 1). (B) Estimation of decadal changes in glacial extent in the main massifs of the French Alps for different periods from 1967/71 to 2006/09, expressed in % per year (Gardent *et al.*, 2014).

Satellite imagery documents changes in a more continuous way spatially. Data on 43 glaciers in the French Alps show an increase in the average altitude of the equilibrium-line altitude (ELA) by about 170 m over the period 1984-2010, a concomitant increase of summer cumulative positive degree days by about 150 days at 3000 m a.s.l., while winter precipitation remained stable (Rabatel *et al.*, 2013). These results underline the preponderant influence of temperature increase in the recent evolution of alpine glaciers, despite the variability due to the local topographical context (Cossart, 2013).

Finally, the establishment of long-term observation networks (PermaNET project; PermaFRANCE network) marks an advance in the knowledge and monitoring of the distribution of permafrost, its thermal evolution and the processes associated with its degradation (see Bodin *et al.*, this volume).

1.3 Observed impacts on natural hazards

Research projects (Tab. 2) and long-term observation programs (Tab. 4) have delivered significant results on the evolution of natural hazards activity over recent decades.

Alpine floods

The analyses conducted across homogenous hydro-climatic regions in the AdaptAlp project[5] suggest that the trends affecting alpine rivers depend on their hydrological regime. Only snowmelt and glacial regime rivers are experiencing an increase in the intensity and the volume of their floods and an evolution of their seasonality, with an earlier and longer snowmelt period (Bard *et al.*, 2012).

[5] The analyzed data series covering 177 alpine stations are available from the international database of the Global Runoff Data Center (GRDC) www.bafg.de/GRDC

Snow avalanche

Methodological progresses achieved in MOPERA and ECANA projects have improved the knowledge of fluctuations in avalanche activity and its climate control (Eckert *et al*., 2010a & b; 2013). A relative minimum in runout-altitudes could be identified around 1980, followed by a sharp rise in elevation (Fig. 3A). The decrease over the period 1960-1980 corresponds to colder and snowy winters, and the rise in 1980-2005 years is the period of increased warming. The influence of the cold, snowy winters recorded since 1998 is clear (Fig. 3C).
This overall scheme conceals different trends depending on the altitude (Lavigne *et al*., 2015). At low altitude (<2000 m), the reduction of activity (number of avalanches) since 1980 has been drastic, while it has recently increased at high altitude, perhaps in connection with the possible increase in climate variability during winter.

Torrential flood and debris flow

The statistical analysis of more than 500 events listed since 1970 in the RTM database (Table 4; ARNICA project) showed the essential role played by climate variables at the regional level in the probability of debris flow occurrence. In some sectors, the increased frequency of debris flows since the late 1980s (Fig 4A. Jomelli *et al*., in press) may be an effect of summer warming, which leads to more convective effects and therefore more summer thunderstorms (Fig. 4B). In other areas, the control of the temporality of debris flows by sediment supply seems to outweigh its control by the climate (Garitte *et al*., 2007).

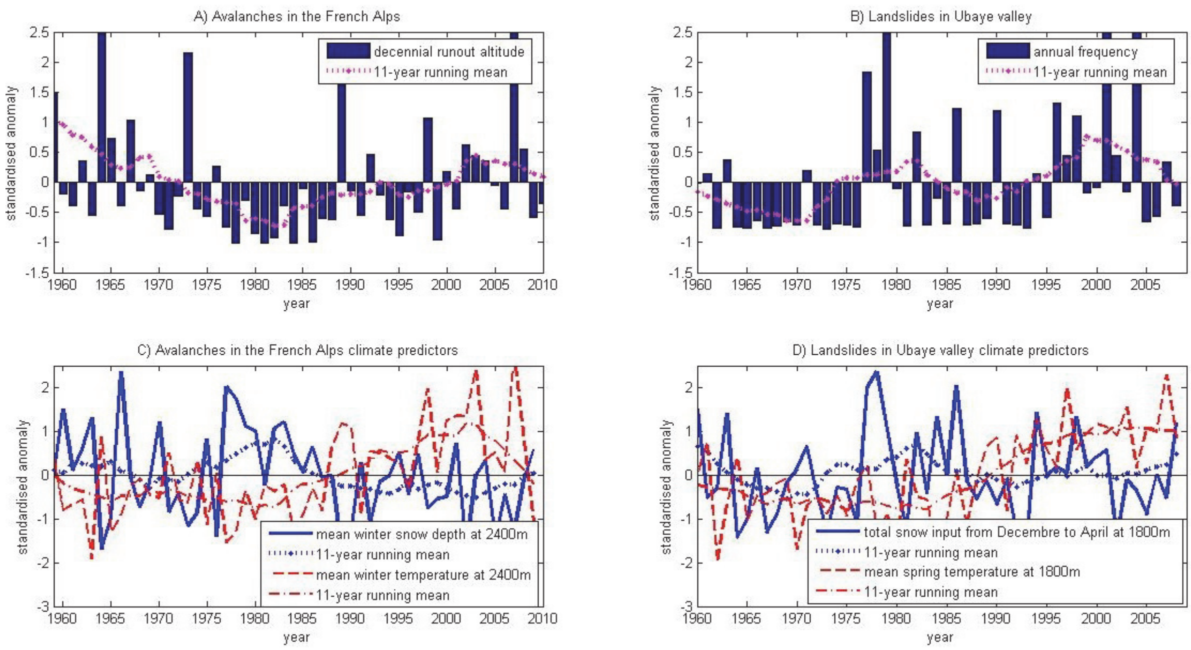

Figure 3: Response of two hazards to recent changes in winter snow and weather factors. (A) Decennial runout-altitude of snow-avalanches in the French Alps and (C) identified predictors (Eckert *et al*., 2013). (B) Annual frequency of landslides in Ubaye and (D) identified predictors (Lopez Saez *et al*., 2013). Anomalies were calculated with respect to the considered period of study.

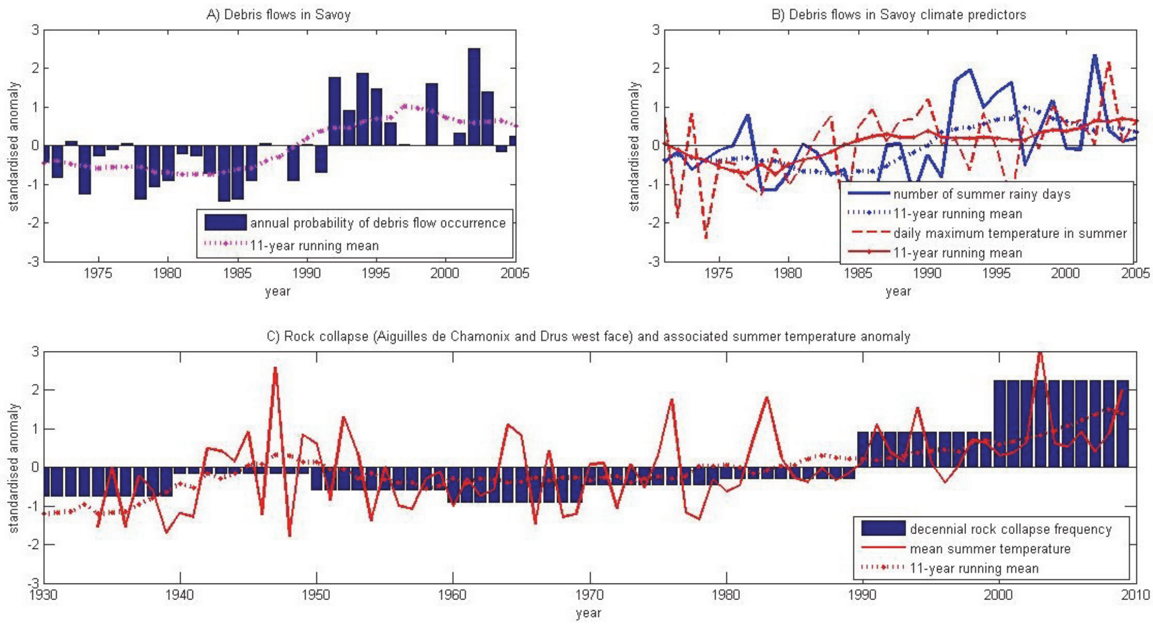

Figure 4: Response of two hazards to recent changes in summer meteorological factors. (A) Annual frequency of debris flow in Savoy (B) and identified predictors (Jomelli *et al*., in press). (C) Number of rockfalls in the Aiguilles de Chamonix and the Drus and associated temperature anomaly (Ravanel and Deline, 2011). Anomalies were calculated with respect to the considered period of study.

Reconstructions of flood chronicles also document the activity of the torrential processes on longer timescales (Tab. 7).

Projects	Main results	Reference
Pygmalion (ANR)	Reconstructions of flood chronicles suggest that flood frequency over a centennial-to-millennial time-scale increases during cold periods over the whole French Alps, probably owing to an intensification of westerly flow and a more important cyclonic activity. In addition, there is a differentiated regional evolution of torrential activity according to predominant forcing factors: flood intensity also increases during cold periods in the Southern Alps in apparent connection with negative phases of the North Atlantic Oscillation while in the Northern Alps intensity also increases during warmer periods.	Wilhelm *et al*. (2012) and references
DENDROGLISS, ACQWA, PGRN	Some dendrogeomorphological reconstructions of torrential floods activity are available in the French Alps. For example, in the case of Torrent Manival (Isère), where this method has identified 13 debris flow events during the period 1931-2008, results show that the temporal distribution of debris flows has not changed significantly since the early 20th century. This study shows, on the other hand, that analysis of the spatial distribution of stressed trees can help identify secondary channels of debris flows as well as potential breakout locations.	Lopez Saez *et al*. (2011)

Table 7: Examples of reconstruction of torrential floods past activity.

Landslide

An extensive dendrogeomorphological survey in the Ubaye valley (DENDROGLISS project) allowed estimating a regional frequency of superficial landslides (Fig. 3B; Lopez Saez *et al*., 2013). The phases of activation, more important since the end of the 1970s, seem directly linked to strong winter snow accumulations and to positive temperature anomalies (Fig. 3D), while Malet *et al*. (2007) concluded to the absence of correlation between rainfall amounts and landslides in the same area. No trend was detected for deep landslides (for which the data remain scarce), despite their sensitivity more or less proved to hydro-climatic forcing (Tab. 8).

Project	Main results	Reference
CEREGE (supported by PACA Region)	For many large landslides in the Alpes Maritimes department, surface exposure dating using the cosmogenic nuclides method shows synchronous triggering phases about 4000 years ago, possibly related to climate forcing.	Zerathe *et al*. (2013)
SLAMS (ANR)	In the case of Séchilienne deep-seated unstable slope, displacement time series measured by the monitoring system since 1985 show no apparent connection with the evolution of temperature or precipitation parameters. However, seasonal intra-annual variations are synchronous to precipitation. Wavelet analysis showed that the slope destabilization is rather linked to effective rainfall than to raw precipitation (rainfall + snowfall), involving then groundwater process. Due to the progressive degradation of its mechanical properties, this unstable slope become, since a few years, more sensitive and reactive to short-term events, while seasonal variations are less pronounced.	Vallet *et al*. (2013)

Table 8: Examples of reconstruction and observation on large slope instabilities.

Rockfall

Bellow the periglacial belt, no tangible impact on rockfalls is demonstrated to date, despite an apparent increase in their impact on mountain roads reported in the Isère, Savoie and Haute-Savoie departments (Einhorn and Peisser, 2011; Wurtz, personal communication).

Glacial and periglacial hazards

A growing body of research reinforces the empirical link between the rapid changes observed in the cryosphere and the resurgence of high mountain destabilization phenomena (Ravanel, 2009), particularly in glacial and periglacial areas (Bodin *et al*., this volume). Thus, the reconstructions in permafrost areas in the Mont Blanc massif show a correlation between the decadal frequency of rockfalls (> 100 m^3) and the warming since the early 20th century (Figure 4C;. Ravanel and Deline 2011).

No trend has been firmly established for glacial hazards because, apart from the low volume seracs falls, they occur relatively rarely. The observed changes in geometry and the thermal regime of glaciers are nonetheless likely to alter the conditions of formation of this type of hazard. Research is being conducted to inventory at risk glaciers, including track over time of large seracs evolution and detection of the presence of interglacial water pockets, whose brutal drain can trigger debris flows of catastrophic consequences (Gilbert *et al*. 2012; Vincent *et al*., 2012). Furthermore one aims at assessing the risks of instabilities that may arise in recently deglaciated margins (Gardent, 2014): brutal outburst of juxta-, supra- and pro-glacial lakes (Vincent *et al*., 2010), increased stock of sediments available for torrents, cascading process that can lead to devastating phenomena.

Projects	Main results	Reference
RiskNat, GlaRiskAlp and ACQWA	The outburst of glacial water pocket is one of the dangers with the most catastrophic potential consequences in the Alps (St-Gervais Disaster in July 1892). The research initiated following the crisis related to the detection of a water pocket in the Tête Rousse glacier (Haute-Savoie) showed the possible influence of the thermal regime of the glacier on the formation of the water pocket.	Gilbert *et al*. (2012)

GlaRiskAlp	• Inventory of current and former extensions of glaciers at the regional scale of the Western Alps and geomorphological mapping of deglaciated sectors since the end of the Little Ice Age. • Development of a typology of glacial hazards. • Development of a methodology for evaluating the susceptibility to hazards of glaciated and recently deglaciated areas, and test on four pilot sites (inventory of processes, and their possible combinations, quantification of volumes involved, characterization of the stability of materials). • On four pilot sites: data acquisition and test of methods on the ice dynamics, serac falls and the forming conditions of glacial water pockets (Taconnaz, Grandes Jorasses, Tête Rousse, and Argentière glaciers).	Gardent (2014)

Table 9: Example of recent work on glacial hazards.

Climate change, its impact on the Alpine environment and on natural hazards observed in the French Alps thus show the existence of climatic control mechanisms exercised by some parameters (thermal, *a minima*) on forming conditions for certain types of hazards. Without supporting an excessive catastrophism, these findings nevertheless invite to a certain degree of vigilance towards future development of phenomena whose "climate sensitivity" is proven true.

2. Future impacts on physical systems

2.1 The alpine climate in the coming decades

Numerous projects proposed climate projections for the whole Alpine space, then used as inputs for transverse or targeted impact studies (Tab. 10). For the French Alps, a relative consensus exists on the extent of future warming: + 1.5 °C in the middle of the 21st century and +2 to + 4 °C at the end of the century compared to the reference period 1960 -1990, with spatial and/or seasonal variations.

Regarding precipitation on the other hand, we note a quasi-absence of predictable trend in the cumulative precipitation at various timescales, except a slight deficit precipitation in autumn (Rousselot *et al*., on 2012), and maybe in summer (model Aladdin of Météo-France/CNRM, DRIAS project) for the end of the century. If an increase in intensity and/or in frequency of extreme precipitation is projected on a global scale (IPCC, 2012), its magnitude remains uncertain across the French Alps, in particular concerning convective rainfalls.

According to the results of SCAMPEI and ECANA projects, the reduction of the currently observed average snowfall will continue in the 21st century in all the French Alps, because of the change in rain-snow ratio related to current warming. If the areas located above 1800-2100m should remain relatively preserved by 2050 with low decreases varying according to the economic scenario and slope aspect considered, this critical altitude should then rise to 2400m for the most optimistic scenario, and even more for other scenarios. These quantitative variations will come along with qualitative changes, for example with the gradual appearance of a wet snowpack at the hearth of winter at high altitude (Castebrunet *et al*. 2014).

Project | Types of models and scenarios used | Main results	Website
Europe	
ENSEMBLES (FP6) | Multimodel regional climate projections over Europe and the Alps (maximum spatial resolution of 25 km) for the 21st century (2070-2099) based on the A1B SRES (Special Report on Emission Scenario) scenario for greenhouse gas (GHG) emission from IPCC. | For the Alpine region, models agree on an increase in the intensity of extreme events in all seasons and in most regions, with the exception of summer events in the southern regions, the largest increase (up + 30%) being simulated in the autumn and in the north of the Alpine range (Rajczack *et al*., 2013).	www.ensembles-eu.org
EURO-CORDEX (WRCP) | Multimodel high resolution (12.5 km) regional climate projections over Europe and the Alps, providing better a representation of physical processes and intense precipitation, based on global climate simulations from CMIP5 and on new scenarios for GHG concentration established within the fifth IPCC assessment report (*Representative Concentration Pathways*, RCPs), for three time periods: 2021–2050 and 2071–2100 vs 1971–2000. | Compared to previous results of the ENSEMBLES project, new simulations (Jacob *et al*., 2014) indicate: (i) A warming, with regional differences, in the range of 1–4.5 °C (RCP4.5) and of 2.5–5.5 °C (RCP8.5). (ii) A reduced northwards shift of Mediterranean drying evolution (in the Alps, with a decrease in extended dry spells, but an increasing number of all dry spells). (iii) A reduction in the frequency of weak-intensity rainfall (<10 mm/day), but an increase in high intensity events (> 30 mm/day).	www.euro-cordex.net
France	
Driasles futurs du climat | Fine scale climate projections over France for the 21st century. The DRIAS portal integrates including regionalized simulations from the SCAMPEI project (see below) and two new ensembles of simulations from the IPSL2014 and CNRM2014 experiences, made from the new RCP scenarios.	www.drias-climat.fr
Alpine space	
ClimChAlp | Regional climate simulations over the Alpine Space with three regional climate models (RegCM, REMO, HIRHAM and COSMO-CLM) using different SRES scenarios SRES (A1B, A2, B1 and B2) from IPCC for two temporal horizons (2001-2100 et 2070-2100). | Results show: (i) An increase in the monthly average temperature up to 5 K in August. Even with scenario B2 an increase in summer temperature up to 3.8 K and an increase to 2 K in winter are calculated. Summer and autumn temperatures are expected to rise more than winter and spring temperatures. (ii) A decrease in rainfall of up to 30% in summer, but in winter an increase of about 20% (40% in some areas).	www.climchalp.org (non maintenu)
EEA, 2009 (European Environment Agency) | Regional climate simulations over the Alpine range for 2071-2100 time horizon, based on IPCC A1B SRES scenario. | Compared to the 1970-2000 reference period, these simulations indicate: (i) A temperature rise of 3.9 °C up until the end of the 21st century, particularly elevated in the high mountains (> 1 500 m), with a 4.2 °C increase, comparatively low until 2050 (1.4 °C), then much faster in the second half of the 21st century. (ii) A slight decrease in precipitation up until the end of the century, ranging between –1 % and –11 % depending on model and region, with the strongest decrease in the south-western Alps, and very different trends depending on season. The greatest changes are projected in summer, with a –25 % decrease north-east of the Alps and up to –41 % in the south-western part up to the end of the 21st century, while most regions would experience increased precipitation in the spring and winter.	www.eea.europa.eu
AdaptAlp | Multimodel regional climate simulations over the Alpine Space for "near future" (2021-2050) and "distant future" (2071-2100) compared to the period 1971-2000, based on the IPCC SRES A1B scenario. | These projections indicate: (i) An increase in mean annual air temperature of 1.5 °C to 2.25 °C in the near future (higher in winter than in summer) and 3.5 ° C to 4, 75 ° C in the distant future (on the contrary higher in summer than in winter). (ii) A slight increase (+ 5%) of annual rainfall in the winter in the northern parts of the Alps and a slight summer decrease (-5%) in Mediterranean areas in 2050, while at the end of the century they show an increase of 15% in winter (+25% in the Central Alps) and a decrease of -15% in summer (-25% in Mediterranean areas). (iii) An increase in meteorological drought disposition in summer.	www.adaptalp.org
CLISP | Regional climate simulations over the Alpine Space based on IPCC SRES A1B and B1 scenarios for two future 20-year periods (2011-2030 and 2031-2050) compared to the reference period 1961-1990. | A warming of average temperatures is projected in all seasons after 2030, stronger in summer (between 1.3 °C and 3 °C by 2050). In continuity with trends observed in the past, the central part of the Alps would warm faster than piedmont regions. Projected maximum temperature shows almost the same trend like average temperature (indicating that temperature extremes will become more frequent in the future), as the minimum temperatures. The later, however, have even stronger trends in winter, which would imply a further reduction in the number of frost days and thus snow cover and glaciers (which are particularly sensitive to increases in minimum temperatures). Regarding precipitation, the clearest trend can be observed for summer, where a majority of scenarios shows a trend to a slight decrease of precipitation of up to –55 mm.	www.clisp.eu
ACQWA (FP7) | Regional climate simulations over the Alpine realm. | The main conclusions are: (i) An overall warming of up to 2 °C by 2050, greater above 1500 m altitude in autumn. (ii) An increase in precipitation in winter but rather a decrease in spring and summer, but probably a strong spatial variability, with increases north of the Alps in spring, summer and fall, and decreases in the southern and western parts. (iii) A decrease in snow depth in winter and spring. (iv) Higher frequencies of extreme precipitation event occurrences are projected, as well as more separate wet periods within events, with shorter durations but higher intensity. | An overview of projected changes for the twenty-first century in water cycle and natural hazards in the Alpine range is available in Gobiet et al. (2013).	www.acqwa.ch
Note: See also regional climate simulations across the Alpine Space from MANFED and ALP FFIRS projects (cf. Tab. 2B).	www.manfredproject.eu www.alpffirs.eu
French Alps	
SCAMPEI (ANR)|Climate projections for near future (2021-2050) and distant future (2071-2100) based on SRES scenarios (A1B, A2 and B1) from IPCC, combining high-resolution simulations (12 km) with three regional climate models and statistical adaptation of fine analyzes (8km) to reflect the best of topographic complexity. | For the French Alps, the results of SCAMPEI simulations are consistent with regional projections across Europe and the Alps. In particular, an increase in thermal extreme is expected in the Prealps (Rome *et al*., 2013).	www.cnrm.meteo.fr/scampei

Table 10: Examples of projects and works proposing climatic and/or impact projections for various study areas including the French Alps (titles and websites of the projects appear in Tabs. 2A, 2B and 2C).

2.2 Future impacts on alpine environments

The absence of past situation similar to the projected climate makes it even more difficult to predict the effects on the activity of natural hazards (Schoeneich and de Jong, 2008). We summarize here the most substantiated results achieved so far on the future dynamics of hydro-gravitational hazards.

Continuation of the glacial withdrawal and the degradation of the permafrost

The forcing of more or less sophisticated glaciological models with future climate scenarios suggests the acceleration of glacial retreat in the Alps during the next decades. According to the warming (2-5 °C in 2100) and the spatial scale considered, the reduction of volume and/or surface would be 20-35 % compared with 2000, until a quasi-total disappearance of glaciers (Zemp *et al.*, 2006 ; Salzmann *et al*., 2012).

For the French Alps, Le Meur *et al*. (2007) project the total disappearance of the Saint Sorlin glacier (Grandes Rousses Massif) to 2070, and Vincent *et al*. (2014) show that the withdrawal of the Mer de Glace (Mont-Blanc Massif) will continue even in the current climate. Some glacial hazards will disappear because of changes in glacier configuration, while others previously mentioned will appear. Permafrost degradation should result in an increase in the frequency or volume of rockfalls and in an acceleration of rock glaciers creep, even their detachment (see Bodin *et al*., this volume).

Snow avalanche

The expected evolution in snowpack will increase the proportion of wet snow avalanches compared to dry snow avalanches, which seems to begin to be detected in observational series (Pielmeier *et al*., 2013). The induced changes (runout distance, impact pressure) however do not have univocal s implication in term of risks. Nevertheless, the expected evolution of snow in the French Alps suggests an overall decline of 20-30% in avalanche activity for the 21st century, particularly strong at low altitude. During cold and very snowy even episodes, possible large-scale avalanches may nevertheless still occur. At high altitude, there will most probably be no fast decrease in activity as long as the snowpack will remain substantial; stronger extreme snowfall predicted by certain climate models and the highest variability already observed in winter temperatures may even lead to a higher frequency of wet snow avalanches in the middle of winter (Castebrunet *et al*., 2014).

Torrential flood and debris flow

Weather conditions favourable to the triggering of landslides and debris flows should become more frequent in the Alps for most of seasons except in July and August, although the frequency of intense rainfalls (> 30 mm/day) may increase in some regions (ARNICA project). Whatever the climate model used as input, a significant increase in the occurrence of debris flow probability in the north and the south of the Alps is expected for 2050 and 2100 (Jomelli *et al*., 2009), although these approaches do not take into account sediment transfer in catchments.

Alpine flood

Projections for the future development of Alpine floods in intensity, frequency and seasonality have to integrate a multitude of complex and multi-scale effects related to increased temperature, the change in rainfall patterns, or changes in land cover. Projects have produced impact simulations using several types of indicators of future flood disposition at different time step (Tab. 11), with sometimes contradictory results according to the studied areas or to climate models and scenarios used, e.g. for changes in summer extreme rainfall.

Project / reference*	Main results	Study area and time horizon
AdaptAlp	• Near future: a relative stagnation of the 5-day precipitation maxima per season for most of regions or seasons, but possible increase in the northern sectors in spring and autumn • Distant future: reduced heavy precipitation events during summer in most regions (up to –30%). For the winter, simulations indicate more intense heavy precipitation events (up to +20%) in all sectors (Nilson *et al*., 2012).	Alpine arc Near future: 2021-2050 Distant future: 2071-2100
CLISP	Projections at the scale of the Alpine Space based on a conceptual model linking change in flood return periods with the extent of the contributing area in Alpine catchments indicate that centennial flood discharges would increase more in high altitude basins, and more in the Western Alps than in the Eastern Alps. The most affected catchments would be in the Swiss and Italian Alps, where more catchments tend to turn from nival to pluvial regimes (EURAC, 2011 and references therein).	Alpine arc
Agence de l'eau RMC (2012)	Projections considered strong over the south-eastern part of France are: a decrease in summer and autumn river discharges (-20 to -50%), a change in the regime of snow-influenced rivers (earlier melting peak one to two months), more severe and longer low flow, a decrease in the water equivalent of snow at 1200 m a.s.l. from 2030. This projection is more robust for 2080, with a sharp decline in south of the Alps (near disappearance of the snow in spring at 1200 m), lower summer and autumn discharges in non-Mediterranean tributaries of the Rhone (-20 to -50% in 2050) and a sharp decline in summer discharge of the Isere and Durance rivers (up 75% in June-July 2050). Projections considered more uncertain are the following: increased discharges in winter; rather decreased modules but uncertainties depending on seasonal contrasts; stable or increased winter discharge of the Rhone; decrease in the water equivalent of snow northeast of the Alps (with considerable uncertainty about the magnitude of this decline); uncertainties about the water equivalent of snow at high altitudes (stable or declining in the northern Alps, significantly down south); stable or increased winter discharges of non-Mediterranean tributaries of the Rhone; higher winter discharges of the Isere and the Durance; uncertainties about the evolution of winter discharges of Mediterranean rivers; uncertain decrease in groundwater recharge (which could be more pronounced in the Alps and Corsica). The authors conclude that, in general, despite the projected general decline in average discharges in the 21st century, high discharge values and flood amplitude and frequency are not expected to decrease and may even worsen, which would affect the design of structures, with stronger contrasts to manage.	Rhône-Mediterranean and Corsica (RMC) catchments
EXPLORE 2070	The findings of the EXPLORE 2070 project on decadal flood discharges indicate a possible increase in the intensity of floods in the Cévennes, and, on the contrary, a possible decrease in decadal flood discharges in high relief areas (Alps, Pyrenees, Jura) in 2046-2065 horizon. The authors emphasize that developments on flood remain highly dependent on the climate downscaling method chosen, and it should remain cautious about the significance of simulated evolution.	France

Table 11: Examples of future alpine flood projections (projects: cf. Tab. 2). For the Alpine space, see also projections of the ACQWA project and those published by EEA (2009). In the basin of the Durance, see R²D² and RIWER2030 projects.

3. Socio-economic impacts

We can consider observed and potential impacts on society by crossing observed and expected changes in hazards with exposed elements, mainly people, buildings, infrastructure and economic activities.

It is thus necessary to consider the concomitant evolutions in material, structural and functional vulnerabilities specific to mountainous territories in the larger context of global change. The latter understood as all the interactions resulting from the complex interplay between climate-induced changes, socio-economic changes and politico-institutional changes (Boudières *et al*., 2013). We shall consequently consider at the same time the aspects of both social and economic (cost of damage, disruption of activities, etc.), financial (robustness of insurance and reinsurance systems), regulatory and legal (responsibility of decision-makers and the citizens).

With the aim of an assessment of potential risks, for example within the framework of a prospective approach as that of territorial vulnerability studies in adaptation plans, managers have to find relevant indicators allowing appreciating the evolutions of the territory in term of “trajectories of vulnerability” (Magnan *et al*., 2012).

3.1 Observed impacts

The evolution damage on the built heritage caused by natural hazards in mountain remains poorly documented, although data exist (insurances), and the possible influence of climate change cannot be discerned using existing indicators (e.g. arrested natural disaster). However, various sources mention possible impacts on linear infrastructure.

At high elevation, mountain practitioners and professionals report an increase of the dangerousness of certain routes linked to the fast withdrawal of glacier and permafrost.

Practitioners and mountain professionals report an increase in the danger of some high altitude routes, linked to rapid glacier retreat and permafrost degradation, which generate a gradual change in mountaineers practices to adapt to new conditions, including seasonal (Weiss, 2011; oral Investigations « *Alpinisme et changement climatique* »[6] ; Debate « *Coup de chaud sur l'alpinisme !* »[7])). Furthermore, the number and the overall cost of maintenance work on damaged trails in protected areas such as the Parc des Ecrins increase (Claude Dautrey, personal communication).

Questioning are emerging today as for the known destabilization phenomena of tourist infrastructures (refuges, equipment of ski lifts, etc.) in high mountain in context of permafrost and glacial withdrawal (Piccardi, 2014; Duvillard *et al.*, this volume, and references)[8].

In more anthropized spaces, at lower elevations, the impacts higher concern problems of mobility and accessibility in the alpine valleys: risks of cuts of the road and railroad junctures. In particular, the cross-border and transnational ways represent critical infrastructures, considered as strategic by communities mountain dwellers and the regional, national and European authorities (cf. PICRIT project, Tab. 2B). Access to ski resorts is also a strong economic stake. In several Alpine ‘departments’, services in charge of roads testify to an apparent increase in interventions related to the rising incidence of hydro-gravitational hazards and the need for them, in a context of budget restrictions, to rank the hazards and prioritize safety work. Note that, in all these examples of impacts on the straight roads and trails, the changing needs of intervention can also be related to an increased level of user requirements in terms of "permanence" of the service.

If the physical impacts of avalanches on the main roads of the Southern French Alps are also increasing (Leone *et al*., 2014), the respective part of climatic and anthropogenic factors is not established, either. However, the episodes of isolation caused by avalanche cycles seem well and truly to multiply there, such as in the Clarée or Upper Guil in 2008, 2012 and 2015.

[6] Videos available at http://www.pierresquiroulent.fr/)

[7] Projection-debate organized by P. Bourdeau, Grenoble, November 14, 2014.

[8] http://www.fondazionemontagnasicura.org/fr/news/la-gestion-des-voies-dacces-aux-refuges-dhaute-montagne-suite-aux-changements-climatiques-rencontre-en-transfrontalier

3.2 Other potential and/or predictable future impacts

Due to the increased population and infrastructure in Alpine valleys, repetition of extreme historical events such as the devastating floods in June 1957 or the water pocket outburst of Tête Rousse glacier in 1892 (Vincent *et al*., 2012) inevitably would have considerable destructive impacts, regardless of climate change. However, these risks are not similar, because of changing runoff conditions by protection works, water projects and catchment changes induced by global warming and its consequences (e.g. glacial retreat).

Given the existing projections, some yet costly protective structures might be undersized towards possibly not envisaged or underestimated strong magnitude events. In addition, protection forests could suffer a potential proliferation of disturbances related to extreme events (IFP and MANFRED projects; Tab. 2B).

Scenario based approaches seem convenient in a context of uncertainty strengthened by the impacts of climate change, but also to open the range of possibilities regarding adaptive or alternative responses for decision-makers. Some European and national projects are devoted to the development scenarios of the impact of global, climatic, environmental or societal changes on the future evolution of hazards and risks in Europe as on a local scale (Tab. 12).

Projet	Principaux résultats	Référence
CLISP (Alpine Space)	A modeling of potential impacts of rockfalls related to permafrost degradation was performed at the scale of the Alpine Space, in terms of reducing the accessibility of the valleys. This analysis shows that many roads could be interrupted by the trajectories of potential rockfall. The assessment of impacts on road traffic in terms of an extension of time of travel and population affected (the product is used as an indicator of the magnitude of these impacts) indicates that the economic consequences of these impacts could be significant. The costs of protection and restoration of the road network could therefore increase significantly.	EURAC (2011)
SafeLand (FP7)	In Safeland project, dedicated to landslides, a specific methodology was developed to combine susceptibility propagation models integrating climate scenarios with prospective data on the evolution of elements at risk (roads, buildings and population) to assess their exposure to the level of hazard considered. The exploratory results on the Barcelonnette basin (Ubaye) project a decrease in the number of kilometers impacted along the road network exposed to low to medium risks, while the number of kilometers of roads impacted by strong to very strong fluctuations would rather tend to increase.	Baills *et al.* (2012)

Table 12: Examples of work crossing climate projections of impacts on vulnerabilities related to road access.

In the post Fukushima context, at the request of public authorities, scenario based approaches are also used in the risk analyzes made by classified facilities managers to reflect the possible couplings between natural hazards and dangers of anthropogenic origin, to anticipate crisis and emergency situations that could cause such “coupled” or “cascading” risk (Boudières *et al*., 2012).

Conclusion and perspectives

Recent results presented in this review come to strengthen the diagnosis of the nature and magnitude of climate change impacts in the Alps (Prudent-Richard *et al*., 2008; Richard *et al*., 2010). New elements of spatial differentiation allow sketching a regionalized approach of observed developments and proven and projected impacts in the French Alps.

Progress achieved on these issues rest in particular on a significant contribution of the French research in geosciences. The analysis of potential risks, which will depend as much on the evolution of vulnerabilities as on the changes in hazards, requires an increased contribution of human and social sciences on these questions (geography, economics, sociology, political science, history and legal approaches of the risk), and especially an increased coupling between the various disciplinary fields. Despite this progress, many uncertainties remain in the characterization of observed changes and future changes projection. The society's ability to anticipate and adapt is also uncertain, if not illusory. It is nevertheless necessary to continue to fund applied and territory-focused but also more "fundamental" research for reducing these uncertainties. In this regard, the absolute necessity of maintaining observatories over the long term must be reaffirmed. In parallel, it seems important to strive for integrating preventive action and publicly restoring these margins of uncertainty, to establish more transparent and more accepted management practices.

In the perspective of taking into account mountainous natural hazards in an integrated and sustainable way, this synthesis also opens a questioning about the capacity of monitoring and anticipating changes in the adaptation strategies of Alpine territories. These issues lead in turn to question the responses given by public and private actors facing the challenges offered by these environmental and societal changes.

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