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► To cite this version:

Benjamin Einhorn, Nicolas Eckert, Christophe Chaix, Ludovic Ravel, Philip Deline, et al.. Climate change and natural hazards in the Alps.. *Revue de Géographie Alpine / Journal of Alpine Research*, 2015, 103, <https://journals.openedition.org/rga/2878>. 10.4000/rga.2878 . hal-01778184

HAL Id: hal-01778184

<https://sde.hal.science/hal-01778184v1>

Submitted on 8 Oct 2024

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Journal of Alpine Research | Revue de géographie alpine

103-2 | 2015

Impact du changement climatique sur les dynamiques des milieux montagnards

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Observed and potential impacts on physical and socio-economic systems

Benjamin Einhorn, Nicolas Eckert, Christophe Chaix, Ludovic Ravel, Philip Deline, Marie Gardent, Vincent Boudières, Didier Richard, Jean-Marc Vengeon, Gérald Giraud and Philippe Schoeneich



Electronic version

URL: <https://journals.openedition.org/rga/2878>

DOI: 10.4000/rga.2878

ISSN: 1760-7426

This article is a translation of:

Changements climatiques et risques naturels dans les Alpes - URL : <https://journals.openedition.org/rga/2829> [fr]

Publisher:

Association pour la diffusion de la recherche alpine, UGA Éditions/Université Grenoble Alpes

Electronic reference

Benjamin Einhorn, Nicolas Eckert, Christophe Chaix, Ludovic Ravel, Philip Deline, Marie Gardent, Vincent Boudières, Didier Richard, Jean-Marc Vengeon, Gérald Giraud and Philippe Schoeneich, "Climate change and natural hazards in the Alps", *Journal of Alpine Research | Revue de géographie alpine* [Online], 103-2 | 2015, Online since 02 September 2015, connection on 08 December 2022. URL: <http://journals.openedition.org/rga/2878> ; DOI: <https://doi.org/10.4000/rga.2878>

This text was automatically generated on 8 December 2022.



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AUTHOR'S NOTE

Acknowledgments

The PARN thanks the members and partners of its scientific and technical network who contributed to the preparatory work for this review, and the Rhône-Alpes Region for its support of the Alps-Climate-Risks portal initiated in the ClimChAlp project alongside ONERC. The DREAL Rhône-Alpes is also acknowledged for its support of the PARN 'Projects' database, and of the transboundary database on Interreg territorial cooperation projects on natural hazards, developed within the partnership of the RiskNat and RiskNET Alcotra projects. Finally, we thank the two anonymous reviewers, whose suggestions have helped improve the manuscript.

Introduction

- 1 Mountainous territories are particularly concerned by the effects of climate change. Along with observed and potential impacts on a variety of natural hazards combined, increased vulnerabilities in the context of global change occur (Beniston *et al.*, 1996; Boudières *et al.*, 2013).
- 2 In recent years, these rapid changes have drawn attention from and heightened the concerns of populations, scientists and land and natural hazard managers in the Alps. Numerous research and regional cooperation projects have been dedicated to these topics in European, national and regional programmes (Tables 1 and 2).

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

Name/ acronym	Title and regions concerned	Programme period	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 programme 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 Rhône-Alpes and PACA Regions	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	<i>Agence Nationale de la Recherche</i> (The French National Research Agency)	Since 2005	www.agence-nationale-recherche.fr
GICC	<i>Gestion des Impacts du Changement Climatique</i> (Management of 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 (<i>Direction Générale de la Prévention de Risques, DGPR</i>)	Occasional funding	www.developpement-durable.gouv.fr
RGC&U	<i>Réseau Génie Civil et Urbain</i> (Civil Engineering and Urban Network, attached to the ANR in 2005)	1999-2005	www.developpement-durable.gouv.fr/...
IREX	<i>Institut pour la recherche appliquée et l'expérimentation en génie civil</i> (Institute for Applied Research and Experimentation in Civil Engineering)	2015-2020	www.irex.asso.fr
Inter-regional scale			
POIA	<i>Programme Opérationnel Interrégional des Alpes</i> (Inter-regional Operational Programme of the Alps) (follows the previous programme period: 2007-2013)	2014-2020	http://programmes-europeens-2014-2020.regionpaca.fr (pdf)
SDA	<i>Science-Décision-Action pour la prévention des risques naturels</i> (Science-Decision-Action for the prevention of natural risks; sub-programme of the POIA)	2015-2020	www.risknat.org/sda
Regional scale			

<p>CPER</p> <p>Previous: 1989–1993; 1994–1999; 2000–2006; 2007–2013</p>	<p>5 themes are proposed for future contracts <i>Contrats de Projets Etat-Région</i> (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..</p>	<p>2014–2020</p>	<p>www.datar.gouv.fr/contrats-etat-regions</p>
<p>ARC-Environnement Rhône-Alpes (ex Cluster Environnement)</p>	<p>The academic research communities <i>ARC Environnement</i> in Rhône-Alpes aim 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".</p>	<p>Since 2012</p>	<p>www.arc.rhonealpes.fr</p>
<p>LabEx OSUG@2020</p>	<p>Laboratories of Excellence (LabEx), OSUG@2020, <i>Stratégies innovantes pour l'observation et la modélisation des systèmes naturels</i> (Innovative strategies for the observation and modelling of natural systems): project funded by the Future Investments programme launched by the government and implemented by the ANR</p>	<p>2011–2020</p>	<p>www.osug.fr/labex-osug-2020</p>
<p>Sub-regional scale</p>			
<p>PGRN/CG38</p>	<p>Departmental Programme of the <i>Pôle Grenoblois d'études et de recherche pour la prévention des Risques Naturels</i> (PGRN) funded by the General Council of Isere</p>	<p>1989–2010</p>	<p>www.risknat.org/pgrn-cg38</p>

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				
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.europias.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 (continued): (B) European research and territorial cooperation 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	<i>Risques glaciaires dans les Alpes occidentales</i>	2009-2012	www.glariskalp.eu
	IFP FR-IT	<i>Interreg Forêts de protection - Composante France-Italie</i>	2007-2011	www.interreg-forets-protection.eu

	PERMAdatROC	<i>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</i>	2006-2008	http://www.risknet-alcotra.org/fr/index.cfm/base-donnees-projets/permadataroc.html
	PICRIT	<i>Protection des infrastructures critiques transfrontalières pour la sécurité civile</i>	2012-2013	www.picrit.eu
	PIT EMB - P4H5	<i>Plan Intégré Transfrontalier Espace Mont-Blanc - Volet Éducation à l'environnement</i>	2010-2012	http://pit.espace-mont-blanc.com
	RiskNat	<i>Gestion en sécurité des territoires de montagne transfrontaliers</i>	2009-2012	www.risknat-alcotra.org
	RiskNET	<i>Réseau transfrontalier sur les risques naturels</i>	2013-2015	www.risknet-alcotra.org
	STRADA	<i>Stratégies d'adaptation au changement climatique pour la gestion des risques naturels dans la région frontalière</i>	2010-2013	www.progettostrada.net
FRANCE-SUISSE	HAUT RHÔNE	<i>Le Haut-Rhône et son bassin versant montagneux: pour une gestion intégrée de territoires transfrontaliers</i>	2005-2008	www.institut-montagne.org
	IFP FR-CH	<i>Interreg Forêts de protection - Composante France-Suisse</i>	2007-2011	www.interreg-forets-protection.eu
ESPACE ALPIN	ALP FFIRS	<i>Alpine Forest Fire - warning System</i>	2009-2012	www.alpffirs.eu
	AdaptAlp	<i>Adaptation to Climate Change in the Alpine Space</i>	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): (C) National and regional research projects on climate change and natural hazards in the French Alps

Programme	Project	Title	Duration	Website
National scale				

ANR	MONISNOW	Monitoring Snow in a changing climate	2011-2015	www.agence-nationale-recherche.fr
	MOPERA	<i>Modélisation Probabiliste pour l'Etude du Risque d'Avalanche</i>	2010-2013	www.avalanches.fr/mopera-projet
	Pygmalion	Palaeohydrology and Human Climate Environment Interactions in the Alps	2007-2012	http://edytem.univ-savoie.fr/...
	RIWER 2030	<i>Climat Régionaux et incertitudes, ressources en eau et énergétiques associées de 1960 à 2030</i>	2009-2011	www.lthe.fr/RIWER2030
	SAMCO	<i>Adaptation de la société aux risques en montagne dans un contexte de changement global</i>	2013-2017	www.anr-samco.com
	SCAMPEI	<i>Scénarios Climatiques Adaptés aux zones de Montagne: Phénomènes extrêmes, Enneigement et Incertitudes</i>	2009-2011	www.cnrm.meteo.fr/scampe
	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	<i>Reconstitution de l'activité de glissements de terrain par dendrogéomorphologie</i>	2008-2011	www.fondation-maif.fr/...
	PERMAFROST	<i>Analyse des risques induits par la dégradation du permafrost</i>	2007-2010	
GICC	ADAMONT	<i>Impacts du changement climatique et Adaptation en territoire de Montagne</i>	2015-2017	http://www.gip-ecofor.org/gicc/?q=node/577

	DECLIC	<i>Drôme: Eau, Climat et Impacts liés aux Changements</i>	2010-2012	http://declic.ujf-grenoble.fr
	DRIAS	<i>Donner accès aux scénarios climatiques Régionalisés français pour l'Impact et l'Adaptation de nos Sociétés et environnements</i>	2008-2011	www.drias-climat.fr
	GICC Rhône	<i>Etude des impacts potentiels du changement climatique sur le bassin versant du Rhône en vue de leur gestion</i>	1999-2004	www.gip-ecofor.org/gicc/...
	R²D² 2050	<i>Risque, Ressource en eau et gestion Durable de la Durance en 2050</i>	2010-2013	https://r2d2-2050.cemagref.fr
MEDDE	ECANA	<i>Etude Climatologique de l'Activité Avalancheuse Naturelle</i>	2009-2016	www.avalanches.fr/projet-ecana
	EXPLORE 2070	<i>Eau et changement climatique</i>	2010-2012	www.developpement-durable.gouv.fr/...
IREX / RGC&U	C2ROP	<i>Chutes de Blocs, Risques Rocheux et Ouvrages de Protection</i>	2015-2019	www.c2rop.fr
Inter-regional scale				
POIA	GIRN Alpes	<i>Opération interrégionale "Gestion intégrée des risques naturels dans les Alpes - Expérimentation sur sites pilotes"</i> <i>Essaimage de sites de GIRN dans la nouvelle programmation</i>	2009-2014 2015-2020	www.risknat.org/girn-alpes
Regional scale				
ARC-Environnement	AIC 2012	<i>XXV colloque Association internationale de climatologie</i>	2012	www.arc3-environnement.rhonealpes.fr
	ISSW2013	<i>Organisation de l'International Snow Science Workshop à Grenoble</i>	2013	

	—	<i>Influence du climat sur le déclenchement des éboulements rocheux</i>	2013	
	—	<i>Archives climatiques de la dernière période interglaciaire en Rhône-Alpes, et nouvelles méthodologies pour la reconstruction des paléo-températures</i>	2015	
	PERMARISK	<i>Contribution à l'amélioration de la gestion de risques émergents associés à la dégradation du permafrost de montagne</i>	2015	
CPER PACA	RHYTMME	<i>Risques HYdrométéorologiques en Territoires de Montagnes et MEditerranéens</i>	2008-2013	http://rhytmme.irstea.fr
Régions RA, LR, MP	CLIMFOUREL	<i>Adaptation des systèmes fourragers et d'élevage péri-méditerranéens aux changements et aléas climatiques, un projet tri-régional Rhône-Alpes, Languedoc-Roussillon, Midi-Pyrénées</i>	2008-2010	http://climfourrel.agropolis.fr
Sub-regional scale				
LabEX ITEM	CrHistAl	<i>Crues Historiques dans les Alpes</i>	2012-2013	http://www.labexitem.fr/wp-content/uploads/2012/04/Projet-CrHistAl.pdf
LabEx OSUG@2020	MONISNOW Alpes	<i>Monitoring Snow in a changing climate - Alps</i>	2012	www.osug.fr/labex-osug-2020/...
	—	<i>Structure des précipitations orographiques en région Méditerranéenne: Mécanismes et Prévision</i>	2012	www.osug.fr/labex-osug-2020/...

	—	<i>Impacts environnementaux du retrait glaciaire dans le Massif du Mont Blanc: quantification des processus contemporains et perspectives d'évolutions futures</i>	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/pgnr-cg38

- 3 Continuing on from 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, relying on knowledge capitalisation portals (Table 3). It also presents an overview of current observation services (Table 4).

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

Knowledge capitalisation tools	Website
<i>Alpes-Climat-Risques</i> web-portal for the project ClimChAlp (Prudent-Richard <i>et al.</i> , 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
<i>Base Projets</i> : 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 4: Observation and monitoring systems providing data on climate change, the physical environment and natural hazards in the French Alps.

Observation services and databases	Missions and subjects of study	Data type	Supporting organisations and data producers*
Climatic observations			

<p>Météo-France http:// www.meteofrance.com/</p>	<p>Public service missions of information dissemination on meteorology and climate. Publish, in particular, annual and seasonal climatic balance assessments.</p>	<p>Observational data (<i>in situ</i>, radar, satellite), climatology, forecast data and models, and climate forecasts</p>	<p>Météo-France</p>
<p>Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region (HISTALP) www.zamg.ac.at/histalp/</p>	<p>Long-term climate parameters covering the European Alps</p>	<p>Homogenised monthly temperature, precipitation, atmospheric pressure, sunshine duration and nebulosity data</p>	<p>ZAMG (Austria)</p>
<p>Alpine environment</p>			
<p><i>Les GLACIers, un Observatoire du CLIMat</i> (GLACIOCLIM) www-lgge.ujf-grenoble.fr/ServiceObs/</p>	<p>Environment Research Observatory on the theme 'Continental Surfaces and Interfaces' on glaciers and climate studies</p>	<p>Glacier mass balances</p>	<p>LGGE, Irstea</p>
<p><i>Réseau de mesure du permafrost et des processus liés au gel</i> (PermaFRANCE)</p>	<p>Observational and monitoring network on French mountain permafrost, freezing-related phenomena and associated periglacial processes</p>	<p>See Bodin <i>et al.</i>, 2015 (this volume)</p>	<p>PACTE, EDYTEM</p>
<p>Natural hazards</p>			
<p><i>Enquête permanente sur les avalanches</i> (EPA) www.avalanches.fr/epa_observation-actuelle</p>	<p>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)</p>	<p>Database of events observed for each site (dates, altitudes, deposit, characteristics, forecast 3 days before, forecast 4 hours before, causes, victims, damage or places affected)</p>	<p>Irstea, ONF-RTM, MEDDE</p>

<p><i>Observatoire des Risques Naturels en Montagne du service de Restauration des Terrains en Montagne (BD RTM Evénements)</i> http://rtm-onf.ifn.fr</p>	<p>Database on events of avalanche, flood, debris flow, gullyng, rockfall, landslide, subsidence and compaction by withdrawal</p>	<p>Information on more than 30,000 events and more than 19,000 works of protection against natural hazards (grouped into 2,400 protective devices)</p>	<p>ONF-RTM, IFN, MEDDE, French Ministry of Agriculture</p>
<p><i>Observatoire Multidisciplinaire des Instabilités de Versants (OMIV)</i> http://omiv.osug.fr/</p>	<p>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).</p>	<p>Development of a permanent multidisciplinary instrumentation on each site, to characterise: i) the kinematics of movement and deformation (geodesy, inclinometers, extensometers, aerial and satellite imagery), ii) the seismic behaviour of the slip (fragile damage via microseisms and responses to regional earthquakes), iii) the hydraulic responses to meteorological forcing.</p>	<p>ISTerre, Géoazur, EMMAH, IPGS-EOST, Chrono-Environnement</p>
<p><i>Surveillance Séchilienne</i> www.versant-sechilienne.developpement-durable.gouv.fr/</p>	<p>Operational system for the monitoring of the <i>Ruines de Séchilienn'</i> unstable slope (Isere)</p>	<p>Teletransmission of monitoring data: extensometry, GPS positioning, movement velocity</p>	<p>MEDDE, CEREMA</p>
<p><i>Banque Nationale de Données pour l'Hydrométrie et l'Hydrologie (Banque HYDRO)</i> www.hydro.eaufrance.fr</p>	<p>Hydrological database of state services administered and managed by the <i>Service Central d'Hydrométéorologie et d'Appui à la Prévision des Inondations</i> (Central Service of Hydrometeorology and Support for Flood Forecasting)</p>	<p>Water height measurements at various time steps from 3,500 measuring stations (including 2,400 in service) located on French rivers and access to station metadata</p>	<p>MEDDE, (SCHAPI, DREAL, SPC, etc.), EDF, Irstea, development companies</p>

<i>Service de Prévision des Crues des Alpes du Nord</i> (“ <i>Information sur la vigilance crues</i> ”) 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)
(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			

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

Climate changes and observed physical impacts

Measured climate change

- 5 Climate warming in the Alpine range is well documented (Table 5) from varied sources (occasional series, reanalysis, results from simulations 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 temperature and its effects on directly related phenomena, such as snowfall or evapotranspiration.

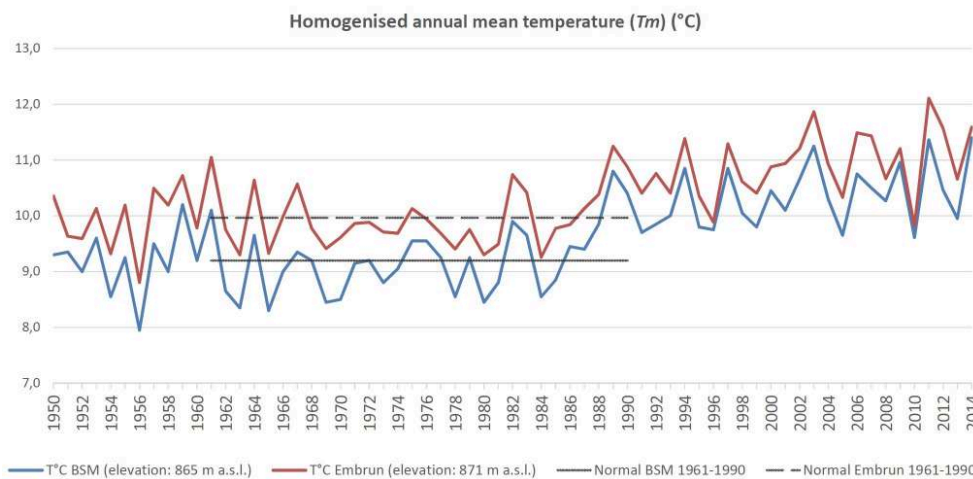
Table 5: Results from (A) reconstitution and (B) observation of the plurisecular temperature evolution in the Alps

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 and much faster warming than, for example, the one rebuilt for the medieval warm period.	Corona <i>et al.</i> (2010)

<p>(B) The long series of homogenised temperatures covering the Alps (HISTALP) show a uniform warming of 2 °C between the late nineteenth and early twenty-first century (Auer <i>et al.</i> 2007), which has accelerated since 1970, including at high altitude. In fact, the end of the 1980s was marked everywhere by significant warming. The average height of the 0 °C isotherm rose by 400 m compared with the beginning of the 1980s (Böhm <i>et al.</i>, 2010).</p>	<p>Auer <i>et al.</i> (2007) (see ref. in Böhm <i>et al.</i> (2010)); Böhm <i>et al.</i> (2010)</p>
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- 6 In the French Alps, located at the intersection of several climatic influences, the increase in temperatures after 1980 has affected 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 domains¹.

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



- 7 Monthly long series in the 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 increased over recent 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 the Northern Alps climate arises, this phenomenon having already occurred along the Rhône Valley and in the Midi-Pyrénées (Climfouré project).
- 8 SAFRAN reanalysis² over the 1958-2002 period (Durand *et al.*, 2009a) shows a temperature increase especially marked at medium altitudes (1500-2000 m, > +0.3 °C/decade) which significantly decreases above 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 ice temperature profiles increased by 0.14 °C/decade during the twentieth century (Gilbert and Vincent, 2013).
- 9 Rainfall in the Alps has a much more heterogeneous pattern of change at regional and seasonal scales (Table 6).

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

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 south-eastern part, in relation to a decrease in cloud cover and a drying trend.	Auer <i>et al.</i> (2007) (see ref. in Böhm <i>et al.</i> , 2010)
(B) Daily rainfall data of over 5,000 stations covering the Alps over 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 emphasise the asymmetry of the frequency distribution of daily precipitation between the regions north of the Alps, where rainy days (> 1 mm) are more common, and their southern flank, where they are less frequent but more intense on average.	Isotta <i>et al.</i> (2014)

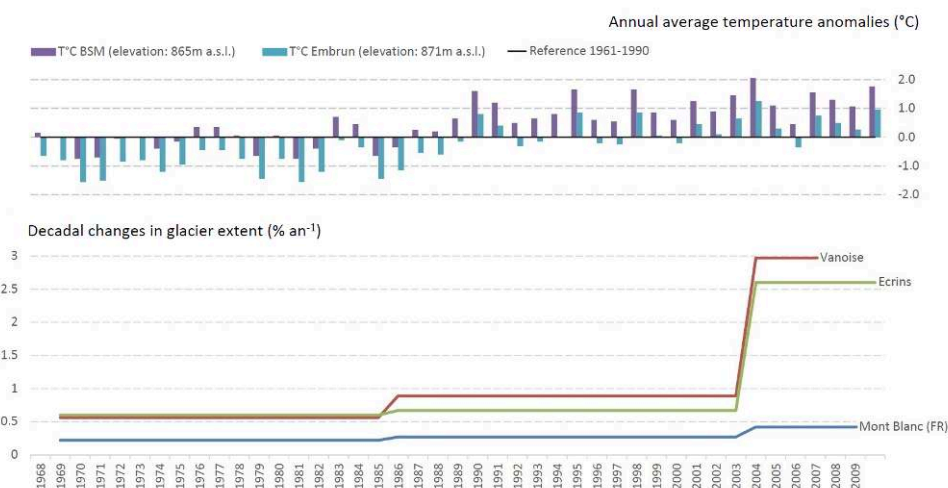
- 10 In the French Alps, the average annual rainfall observed and simulated by SAFRAN and the Météo-France homogenised climate series show no statistically significant trends (Durand *et al.*, 2009a), apart from a decrease in winter precipitation in the internal Alps (Haute Maurienne, Queyras), which reached 30 % between the 1961-1990 and 1981-2010 climate periods³.
- 11 It is difficult to conclude regarding extreme precipitation 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 rainfall in the southeast of France⁴.

Observed impacts on the Alpine cryosphere

- 12 Under the effect of climate change, the Alpine environment is undergoing 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 and the altitudinal position of snow cover and the equilibrium-line altitude (LEA) of glaciers. These factors mainly control the hydrological regime, vegetation dynamics and, to a lesser extent because of the complexity of systems, *s.l.* erosion processes in watersheds.
- 13 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 shown a sharp decline at low and medium altitude since the late 1980s, while it has increased at high altitude (2700 m).
- 14 Glaciers are the most visible markers of previous 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; Table 2). Their surface area in late 2000 (275 km²) was almost 20 % less than in 1985 to 1986 (340 km²) and 26 % less than in the years 1967 to 1971 (370 km²; Gardent *et al.*, 2014), in response to the strong warming mentioned above (Fig. 2). Yet, the most direct measurement of climate control on glacier dynamics is provided by the mass balance. There are only data for some glaciers, especially those monitored by the observatory GLACIOCLIM (Table 4; Vincent, 2002). For example, seasonal variations in the Sarennes glacier since 1949 quantify accurately the evolution of winter snowfall and summer temperatures at high altitude (Thibert *et al.*, 2013).

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)



- 15 Satellite imagery documents spatial changes in a more continuous way. 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, with a concomitant increase in 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 on the recent evolution of Alpine glaciers, despite the variability due to the local topographical context (Cossart, 2013).
- 16 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).

Observed impacts on natural hazards

- 17 Research projects (Table 2) and long-term observation programmes (Table 4) have provided significant results on the evolution of natural hazard activity over recent decades.

Alpine floods

- 18 The analyses conducted across homogenous hydro-climatic regions in the AdaptAlp project⁵ 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 volume of their floods and an evolution of their seasonality, with an earlier and longer snowmelt period (Bard *et al.*, 2012).

Snow avalanches

- 19 Methodological progress achieved in the MOPERA and ECANA projects has improved knowledge of fluctuations in avalanche activity and its climate control (Eckert *et al.*, 2010a & b; 2013). A relative minimum in runout-altitudes can 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, while the rise during 1980-2005 is the period of increased warming. The influence of the cold, snowy winters recorded since 1998 is clear (Fig. 3C).
- 20 This overall scheme conceals different trends depending on the altitude (Lavigne *et al.*, 2015). At low altitude (<2000 m), the reduction in 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 floods and debris flows

- 21 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

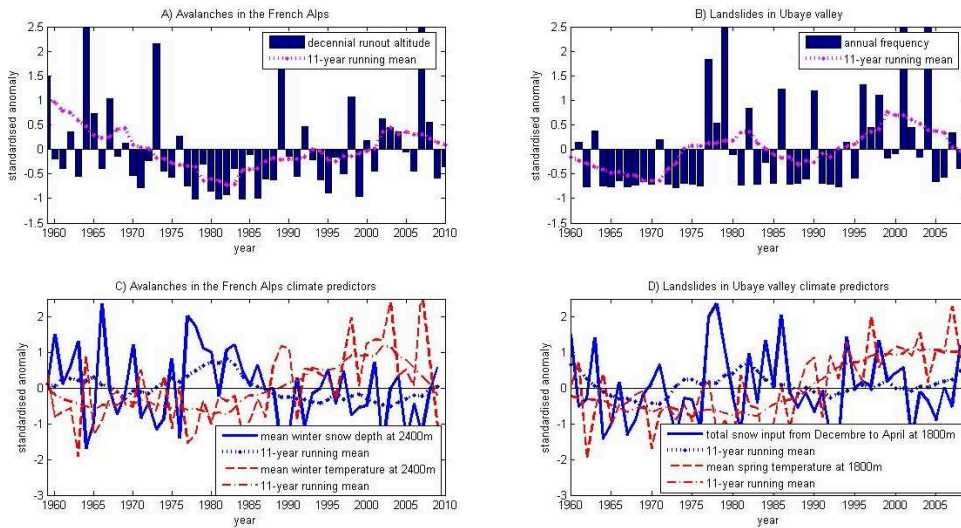
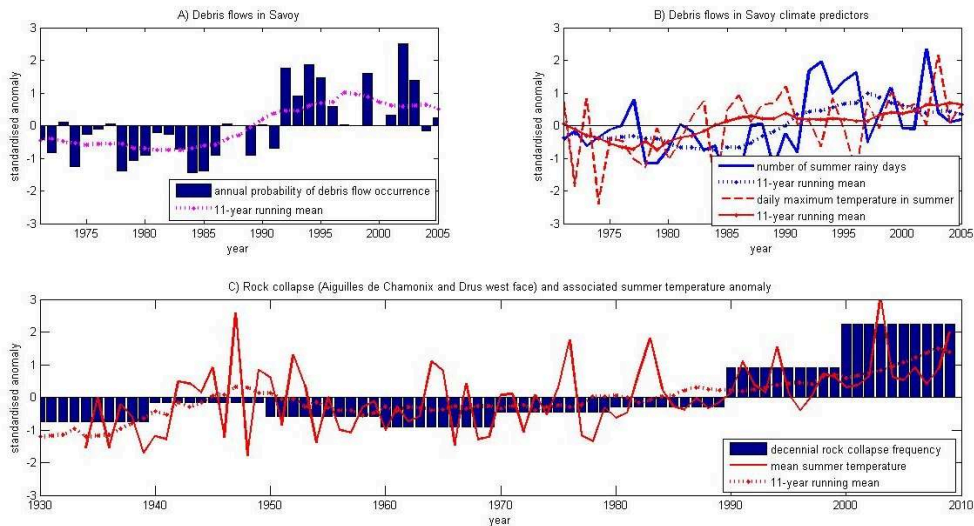


Figure 4: Response of two hazards to recent changes in summer meteorological factors. (A) Annual frequency of debris flows in Savoy (B) and identified predictors (Jomelli *et al.*, in press). (C) Number of rockfalls in the Aiguilles de Chamonix and the Drus and associated temperature anomaly (Ravel and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



22 Reconstructions of flood chronicles also document the activity of the torrential processes over longer timescales (Table 7).

Table 7: Examples of reconstructions of previous torrential flood activity

Project	Main results	Reference
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Pygmalion (ANR)	Reconstructions of flood chronicles suggest that flood frequency over a centennial-to-millennial timescale increases during cold periods over the whole French Alps, probably owing to an intensification of westerly flow and greater 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 <i>et al.</i> (2012) and references therein
DENDROGLISS, ACQWA, PGRN	Some dendrogeomorphological reconstructions of torrential flood activity are available in the French Alps. For example, in the case of Torrent Manival (Isere), 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 also demonstrates 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 <i>et al.</i> (2011)

Landslides

- 23 An extensive dendrogeomorphological survey in the Ubaye valley (DENDROGLISS project) estimated a regional frequency of superficial landslides (Fig. 3B; Lopez Saez *et al.*, 2013). The phases of activation, longer since the end of the 1970s, seem directly linked to marked winter snow accumulations and positive temperature anomalies (Fig. 3D), while Malet *et al.* (2007) concluded there was no 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 more or less proven sensitivity to hydro-climatic forcing (Table 8).

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

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 4,000 years ago, possibly related to climate forcing.	Zerathe <i>et al.</i> (2013)

SLAMS (ANR)	In the case of the Séchilienne deep-seated unstable slope, the displacement time series measured by the monitoring system since 1985 shows no apparent connection with the evolution of temperature or precipitation parameters. However, intra-annual seasonal variations are synchronous with precipitation. Wavelet analysis showed that the slope destabilisation is rather linked to effective rainfall than to raw precipitation (rainfall + snowfall), thus involving a groundwater process. Due to the progressive degradation of its mechanical properties, this unstable slope has become, in recent years, more sensitive and reactive to short-term events, while seasonal variations are less pronounced.	Vallet <i>et al.</i> (2013)
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Rockfalls

- 24 Below the periglacial belt, no tangible impact on rockfalls has been 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

- 25 A growing body of research reinforces the empirical link between the rapid changes observed in the cryosphere and the resurgence of high mountain destabilisation phenomena (Raveland, 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 m³) and warming since the early 20th century (Figure 4C; Raveland and Deline, 2011).
- 26 No trend has been firmly established for glacial hazards because, apart from the low volume serac falls, they occur relatively rarely. Nonetheless, the observed changes in geometry and the thermal regime of glaciers are likely to alter the conditions of formation of this type of hazard. Research is being conducted to inventory at-risk glaciers, including tracking the evolution of large seracs over time and detecting the presence of interglacial water pockets, whose sudden drainage can trigger debris flows with catastrophic consequences (Gilbert *et al.*, 2012; Vincent *et al.*, 2012). Furthermore, the risks of instabilities that may arise in recently deglaciated margins are being assessed (Gardent, 2014): sudden outburst of juxta-, supra- and pro-glacial lakes (Vincent *et al.*, 2010), increased storage of sediments available for torrents, cascading processes that can lead to devastating phenomena.

Table 9: Examples of recent work on glacial hazards

Project	Main results	Reference
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RiskNat, GlaRiskAlp and ACQWA	The outburst of glacial water pockets 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 <i>et al.</i> (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 tests on four pilot sites (inventory of processes, and their possible combinations, quantification of volumes involved, characterisation of the stability of materials). On four pilot sites: data acquisition and testing of methods on ice dynamics, serac falls and the formation conditions of glacial water pockets (Taconnaz, Grandes Jorasses, Tête Rousse, and Argentière glaciers).	Gardent (2014)

- 27 Climate change, its impact on the Alpine environment and on natural hazards observed in the French Alps thus reveals climatic control mechanisms exercised by some parameters (thermal, *a minima*) on formation conditions for certain types of hazard. Without supporting an excessive catastrophism, these findings nevertheless encourage a certain degree of vigilance towards the future development of phenomena whose “climate sensitivity” has been proven.

Future impacts on physical systems

The Alpine climate in the coming decades

- 28 Numerous projects have proposed climate projections for the whole Alpine area, which have then been used as inputs for transverse or targeted impact studies (Table 10). For the French Alps, there is a relative consensus 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.
- 29 Regarding precipitation on the other hand, there is a near-absence of a predictable trend in the cumulative precipitation at various timescales, except for a slight deficit precipitation in autumn (Rousselot *et al.*, 2012), and perhaps in summer (Aladdin model of Météo-France/CNRM, DRIAS project) for the end of the century. Although an increase in intensity and/or frequency of extreme precipitation is projected on a global scale (IPCC, 2012), its magnitude remains uncertain in the French Alps, particularly for convective rainfall.
- 30 According to the results of the SCAMPEI and ECANA projects, the reduction in 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 1800-2100 m should remain relatively preserved by 2050, with small decreases varying according to the economic scenario and slope aspect considered, this critical altitude should then rise to 2400 m for the most optimistic scenario, and even higher for other scenarios. These quantitative variations will be accompanied by qualitative changes, for example the gradual appearance of a wet snowpack at the heart of winter at high altitude (Castebrunet *et al.*, 2014).

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 Tables 2A, 2B and 2C)

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) 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 <i>et al.</i> , 2013).	www.ensembles-eu.org
EURO-CORDEX (WRCP) Multimodel high resolution (12.5 km) regional climate projections over Europe and the Alps, providing a better 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 (<i>Representative Concentration Pathways</i> , RCPs), for three time periods: 2021–2050 and 2071–2100 vs. 1971–2000. Compared to previous results of the ENSEMBLES project, new simulations (Jacob <i>et al.</i> , 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 northward 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	
Drias ^{les futurs du climat} Fine-scale climate projections over France for the 21st century. The DRIAS portal includes regionalised simulations from the SCAMPEI project (see below) and two new groups of simulations from the IPSL2014 and CNRM2014 experiences, made from the new RCP scenarios.	www.drias-climat.fr
Alpine Space	

<p>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 and 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).</p>	<p>www.climchalp.org (not maintained)</p>
<p>EEA, 2009 (European Environment Agency) Regional climate simulations over the Alpine range for the 2071-2100 time horizon, based on the 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 the model and region, with the strongest decrease in the south-western Alps, and very different trends depending on the 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 will experience increased precipitation in the spring and winter.</p>	<p>www.eea.europa.eu</p>
<p>AdaptAlp Multimodel regional climate simulations over the Alpine Space for the “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.</p>	<p>www.adaptalp.org</p>

<p>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 will warm faster than piedmont regions. Projected maximum temperatures shows almost the same trend as average temperatures (indicating that temperature extremes will become more frequent in the future), and minimum temperatures. The latter, 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 the majority of scenarios show a trend of a slight decrease in precipitation of up to -55 mm.</p>	<p>www.clisp.eu</p>
<p>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 1,500 m in 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 autumn, 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 the water cycle and natural hazards in the Alpine range is available in Gobiet <i>et al.</i> (2013).</p>	<p>www.acqwa.ch</p>
<p>Note: See also regional climate simulations across the Alpine Space from MANFED and ALP FFIRS projects (cf. Table 2B).</p>	<p>www.manfredproject.eu www.alpffirs.eu</p>
<p>French Alps</p>	
<p>SCAMPEI (ANR) Climate projections for the 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 analyses (8 km) 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 extremes is expected in the Prealps (Rome <i>et al.</i>, 2013).</p>	<p>www.cnrm.meteo.fr/scampe</p>

Future impacts on Alpine environments

- 31 The absence of a 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 summarise here the most substantiated results achieved so far on the future dynamics of hydro-gravitational hazards.

Continuation of glacial withdrawal and the degradation of the permafrost

- 32 The forcing of more or less sophisticated glaciological models with future climate scenarios suggests an 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 in volume and/or surface area would be 20-35 % compared with 2000, until an almost total disappearance of glaciers (Zemp *et al.*, 2006 ; Salzmann *et al.*, 2012).
- 33 For the French Alps, Le Meur *et al.* (2007) project the total disappearance of the Saint Sorlin glacier (Grandes Rousses Massif) in 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 glacier creep, or even their detachment (see Bodin *et al.*, this volume).

Snow avalanches

- 34 The expected evolution in the snowpack will increase the proportion of wet snow avalanches compared to dry snow avalanches, which seems to be beginning to be detected in observational series (Pielmeier *et al.*, 2013). However, the induced changes (runout distance, impact pressure) do not have univocal implications in terms of risk. 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 marked at low altitude. During cold and very snowy episodes, large-scale avalanches may still occur. At high altitude, there will most probably be no rapid decrease in activity as long as the snowpack remains substantial; greater extreme snowfall predicted by certain climate models and the widest 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 floods and debris flows

- 35 Weather conditions that favour the triggering of landslides and debris flows should become more frequent in the Alps for most seasons except in July and August, although the frequency of intense rainfall (> 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 floods

- 36 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 indicator of future flood disposition at different time steps (Table 11), with sometimes contradictory results according to the studied areas or to the climate models and scenarios used, e.g. for changes in summer extreme rainfall.

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

Project / reference*	Main results	Study area and time horizon
AdaptAlp	<p>Near future: a relative stagnation of the 5-day precipitation maxima per season for most regions and seasons, but a possible increase in the northern sectors in spring and autumn</p> <p>Distant future: reduced heavy precipitation events during summer in most regions (up to -30 %). For winter, simulations indicate more intense heavy precipitation events (up to +20 %) in all sectors (Nilson <i>et al.</i>, 2012).</p>	<p>Alpine arc</p> <p>Near future: 2021-2050</p> <p>Distant future: 2071-2100</p>
CLISP	<p>Projections at the scale of the Alpine Space based on a conceptual model linking changes in flood return periods with the extent of the contributing area in Alpine catchments indicate that centennial flood discharges will 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).</p>	<p>Alpine arc</p>

<p>Agence de l'eau RMC (2012)</p>	<p>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 (melting peak one to two months earlier), 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 the south of the Alps (near the 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 the summer discharge of the Isere and Durance rivers (up to 75 % in June-July 2050).</p> <p>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 lower in the 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).</p> <p>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.</p>	<p>Rhône-Mediterranean and Corsica (RMC) catchments</p>
<p>EXPLORE 2070</p>	<p>The findings of the EXPLORE 2070 project on decadal flood discharges indicate a possible increase in the intensity of floods in the Cevennes and, on the contrary, a possible decrease in decadal flood discharges in high relief areas (Alps, Pyrenees, Jura) in the 2046-2065 horizon. The authors emphasise that flood developments remain highly dependent on the climate downscaling method chosen, and one should remain cautious about the significance of simulated evolutions.</p>	<p>France</p>

Socio-economic impacts

- 37 Observed and potential impacts on society can be considered by crossing observed and expected changes in hazards with exposed elements, mainly people, buildings, infrastructure and economic activities.
- 38 It is thus necessary to take into account the concomitant evolution in material, structural and functional vulnerabilities specific to mountainous territories in the larger context of global change. These include all the interactions resulting from the complex interplay between climate-induced changes, socio-economic changes and

politico-institutional changes (Boudières *et al.*, 2013). Thus, 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 citizens) aspects need to be considered at the same time.

- 39 In order to assess potential risks, for example within the framework of a prospective approach such as that of territorial vulnerability studies in adaptation plans, managers have to find relevant indicators to identify the evolution of the territory in terms of “trajectories of vulnerability” (Magnan *et al.*, 2012).

Observed impacts

- 40 The evolution of damage to the built heritage caused by natural hazards in mountains remains poorly documented, although some data exist (insurances), and the possible influence of climate change cannot be discerned using current indicators (e.g. arrested natural disaster). However, various sources mention possible impacts on linear infrastructure.
- 41 Practitioners and mountain professionals report an increase in the danger of some high altitude routes, linked to rapid glacier retreat and permafrost degradation, which are generating a gradual change in mountaineer 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 amount and overall cost of maintenance work on damaged trails in protected areas such as the Parc des Ecrins are increasing (Claude Dautrey, personal communication).
- 42 Questions are now emerging about the known destabilisation phenomena of tourist infrastructures (refuges, equipment of ski lifts, etc.) in high mountains in the context of permafrost and glacial withdrawal (Piccardi, 2014; Duvillard *et al.*, this volume, and references therein)⁸.
- 43 In more anthropised spaces, at lower elevations, the impacts largely concern problems of mobility and accessibility in the Alpine valleys: risk of roads and railways being blocked. In particular, the cross-border and transnational routes represent critical infrastructures, considered strategic by mountain communities and regional, national and European authorities (cf. the PICRIT project, Table 2B). Access to ski resorts is also an important economic issue. In several Alpine ‘departments’, the road maintenance services testify to an apparent increase in interventions related to the rising incidence of hydro-gravitational hazards and their need, in the context of budget restrictions, to rank the hazards and prioritise safety work. Note that, in all these examples of impacts on roads and trails, the changing needs for intervention can also be related to an increased level of user requirements in terms of the availability of the service.
- 44 Although the physical impacts of avalanches on the main roads of the Southern French Alps are also increasing (Leone *et al.*, 2014), the respective part played by climatic and anthropogenic factors has not been established. However, the episodes of isolation caused by avalanche cycles certainly seem to be growing there, such as in the Clarée or Upper Guil in 2008, 2012 and 2015.

Other potential and/or predictable future impacts

- 45 Due to the increased population and infrastructure in Alpine valleys, the repetition of extreme historical events, such as the devastating floods in June 1957 or the water pocket outburst of the Tête Rousse glacier in 1892 (Vincent *et al.*, 2012), would inevitably 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).
- 46 Given the existing projections, some costly protective structures might be undersized in relation to unenvisaged or underestimated events of strong magnitude. In addition, protection forests could suffer a potential proliferation of disturbances related to extreme events (IFP and MANFRED projects; Table 2B).
- 47 Scenario-based approaches seem convenient in a context of uncertainty strengthened by the impacts of climate change, and also to widen the range of options 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, like on a local scale (Table 12).

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

Project	Main results	Reference
CLISP (Alpine Space)	A modelling 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 rockfalls. 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 the 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 kilometres impacted along the road network exposed to low to medium risks, while the number of kilometres of roads impacted by strong to very strong fluctuations would rather tend to increase.	Baills <i>et al.</i> (2012)

- 48 In the post-Fukushima context, at the request of public authorities, scenario-based approaches are also used in the risk analyses made by managers of classified facilities to identify the possible links between natural hazards and dangers of anthropogenic

origin, and to anticipate crisis and emergency situations that could cause such “coupled” or “cascading” risks (Boudières *et al.*, 2012).

Conclusion and perspectives

- 49 Recent results presented in this review 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 enable a regionalised approach of observed developments and proven and projected impacts in the French Alps.
- 50 Progress achieved on these issues particularly relies on the significant contribution of 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 a greater contribution of human and social sciences on these questions (geography, economics, sociology, political science, history and the legal aspect of the risk), and especially an increased combination of the various disciplinary fields. Despite this progress, many uncertainties remain in the characterisation of observed and projected future changes. 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 to reduce 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 to integrate preventive action and publicly restore these margins of uncertainty, to establish more transparent and more accepted management practices.
- 51 In the perspective of taking into account mountainous natural hazards in an integrated and sustainable way, this synthesis also opens up a discussion 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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NOTES

1. Source: analysis of homogenised temperature data of Météo-France by MDP/OsCC. For the Northern Alps, OsCC provides annual and seasonal climate assessments (www.mdp73.fr).
2. Mesoscale analysis system of near surface atmospheric variables: www.drias-climat.fr/accompagnement/section/137
3. Cf. Note 1.
4. <http://pluiesextremes.meteo.fr/>
5. The analysed data series covering 177 alpine stations is available from the international database of the Global Runoff Data Center (GRDC) www.bafg.de/GRDC
6. Videos available at <http://www.pierresquiroulent.fr/>
7. Projection-debate organised 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>

ABSTRACTS

Under the effects of climate change, Alpine mountainous regions are undergoing fast and well-perceptible evolutions, which are attracting the growing attention of people, scientists and managers. To cope better with the hazards and vulnerabilities specific to these territories, the current national and European public policies in the Alpine countries now prescribe adapting natural hazard prevention to climate change. This paper provides a review of recent advances in knowledge on the perceived, measured and projected changes in i) climate patterns, ii) the cryosphere, hydrosystems and geomorphological dynamics on Alpine slopes, and iii) natural hazard evolution and induced risks at the scale of the French Alps. We give a brief overview of

new results achieved by research, cooperation and capitalisation projects in these thematic fields during the programme period 2007-2013, which are 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 hazard activity chronicles, along with climate patterns identified as “predictors”.

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Keywords: natural hazards, observation, projection, adaptation

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