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Multitemporal glacier inventory of the French Alps from the late 1960s to the late 2000s

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ABSTRACT

The most recent and complete French glacier inventory was previously the Vivian database, dating from the end of the 1960s but incorporated in the World Glacier Inventory database at the end of the 1990s. Because of the important changes in glacier extent over recent decades an update of the inventory of glaciers of the French Alps was made in a digital vector format (with the associated database) for several dates covering the last 40 years. Such a multitemporal glacier inventory matches a key demand of the Global Terrestrial Network for Glaciers and the Global Land Ice Measurements from Space initiative (GLIMS). Topographical maps, aerial photographs and satellite images were used to map the extent of glaciers using both manual and automatic methods; and the database was generated considering the design of the GLIMS database. Glaciers in the French Alps covered 369 km^2 in 1967/71, 340 km^2 in 1985/86, 300 km^2 in 2003, and 275 km^2 in 2006/09. This represents a decrease in surface area of about 25% over the entire study period. Acceleration in glacier shrinkage during the study period was revealed, probably linked to the increase in average air temperature in the 20th century, which has been particularly pronounced since the 1970s. The behaviour of glaciers of the French Alps is in agreement with that of glaciers observed by other studies across the European Alps. We also report the distribution of the morpho-topographic variables (aspect, elevation, etc.) of glaciers of the French Alps for the period 2006/09, and analyse changes of these variables in the last four decades.

1. Introduction

As in most mountain ranges worldwide (e.g. Berthier et al., 2010; Rabatel et al., 2013a; Vincent et al., 2013), the Alps have seen general glacier shrinkage over the last decades (Abermann et al., 2009; Paul et al., 2011; Thibert et al., 2013). In this context, the accurate quantification of glacier changes is needed to better understand relationships with climate changes; and the glacier area survey is necessary to estimate at regional/global scales the ice volume, through area/volume relationships, and therefore the impacts of glacier changes on water resources or on sea level (Huss et al., 2010; Kaser et al., 2010; Bahr and Radić, 2012). Since the mid-1970s, international inventories like the World Glacier Inventory (WGI), services like the World Glacier Monitoring Service (WGMS), initiatives like GLIMS (Global Land Ice Measurements from Space), and projects like GlobGlacier have been established to address the question of glacier changes in mountainous areas by gathering measured data worldwide.

An inventory of the glacierized areas of the Alps was made by Paul et al. (2011) in the framework of GlobGlacier; it used automated techniques to identify glacier outlines on Landsat TM images acquired in 2003, with manual corrections. Previously, glacier inventories in the Alps had only been conducted at country or regional scales (Table 1). For the French Alps, two inventories were made by Mougin (1925) using topographical maps dating from the mid-19th century, and Vivian (1975) at the end of the 1960s based on topographical maps and aerial photographs; few subsequent updates were conducted at local scale for different dates (Table 1). The Vivian database was not originally in digital vector format; it was incorporated in the WGI database at the end of the 1990s as a table, and is available in digital format where each glacier or group of glacierets is represented as a single point. The lack of cartographic representation of the outlines of the glaciers and the fragmentation of glaciers since the 1970s make it difficult to compare the WGI database with the other local datasets. In addition, the exact date when the data for each glacier were collected is missing.

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Table 1
References of existing glacier inventories concerning the Alps.

Location		Year	Bibliographic references	Type of document	Delineation technique
Alps	Alps	1970s	Haeberli et al., 1989; Zemp et al., 2006		-
	Alps	2003	Paul et al., 2011	Landsat images	A + M
Switzerland	Switzerland	1850	Maisch et al., 1999	Field investigations + old documents	M
	Switzerland	1973	Müller et al., 1976; revised in 1999 by Maisch et al., 1999	Ortho.	M
	Switzerland	1998/99	Paul et al., 2004b	Landsat images	A + M
	Bernese and Valais Alps	1985	Kääb et al., 2002	Landsat images	A + M
Austria	Austria	1969	Patzelt, 1978; Patzelt, 1980; Gross, 1987	Ortho.	M
	Austria	1998	Lambrecht and Kuhn, 2007; Kuhn et al., 2009	Ortho.	M
	Otztal Alps	2006	Abermann et al., 2009	LIDAR + Ortho.	A + M
	Tyrol	1992	Paul, 2002	Landsat images	A + M
Italy	Italy	1925	Porro, 1925	Topographical maps	M
	Italy	1957/58	CNR-CGI, 1961	Field investigations	M
	Italy	1989	Biancotti and Motta, 2000; Ajassa and Brancucci, 1993	Ortho.	M
	Lombardy	1991 (1988/91)	Servizio Glaciologico Lombardo, 1992; Gallucio and Catasat, 1992; Diolaiuti et al., 2012	Information missing	Information missing
	Lombardy	1999 (1997/99)	Regione Lombardia, 2004; Citterio et al., 2007; Diolaiuti et al., 2012	Information missing	Information missing
	Lombardy	2003	Regione Lombardia, 2007; Diolaiuti et al., 2012a; Scotti, 2012	Ortho.	M
	Lombardy	2007	Scotti, 2012	Ortho.	M
	Adamello	1983, 1999, 2003	Maragno et al., 2009	Ortho. + DGPS	
	Dosdè Piazzi glaciers (Lombardy)	1954, 1981, 1999, 2003	Diolaiuti et al., 2011	Ortho. + DGPS	M
	Ortles-Cevedale group (Lombardy)	1987, 2009	Carturan et al., 2013	Landsat images	A + M
	South Tyrol	2006	Knoll and Kerschner, 2009	LIDAR + Ortho	A + M
	Pièmont	2001-06	CNR-IRPI	Ortho.	M
	Aosta Valley	1975	Diolaiuti et al., 2012b	Ortho.	M
	Aosta Valley	1999, 2005	Diolaiuti et al., 2012a	Ortho. + GPS	M
France	France	1895	Mougin, 1925	Old maps	M
	Occidental Alps	1967/71	Vivian, 1975	Field investigations, Ortho.	M
	Hte Maurienne	LIA to 2003 (13 dates)	Jobard, 2005	Old maps, Ortho., sat. im.	M
	Belledonne	1926 to 2006 (13 dates)	Deroin and Condom, 2007	Ortho., sat. im.	M
	Ecrins	1967/71	Edouard, 1978	Ortho., maps	M
	Vénéon Valley (Ecrins)	LIA to 2003	Le Roy, 2006	Ortho.	M
	Gyronde Valley	LIA to 2002	Cossard, 2005	Field investigations, Ortho.	M

Concerning the type of document: Ortho. = orthophotographs; sat. im. = satellite images. Delineation technique: A = automatic; M = manual.

The recent glacier shrinkage largely justifies updating the extent of glacier cover in the French Alps, while creating repeat inventories at a time scale of a few decades is also a key demand of the Global Terrestrial Network for Glaciers (GTN-G). It is also worth emphasizing that the current work is made within the framework of the GLIMS Regional Centre #33 (French Alps) and the French observatory of glaciers: GLACIOCLIM which manages the glaciological measurements conducted on the French glaciers.

We first describe the data (topographical maps, aerial photographs and satellite images) and methods (including uncertainties quantification) used to map the glacier extent. Then, we present the results for 1967/71, 1985/86, 2003, and 2006/09, the changes the glaciers have undergone in the last four decades, and their relationship with topographical variables are presented. Finally, we discuss the timing and patterns of glacier changes, and compare our results with other Alpine regions.

2. Study region and datasets

2.1. Study area

In the French Alps (35,000 km^2), glaciers cover less than 1% of this region. They are located in eight main mountain massifs (Fig. 1 and Table I in Supplementary Materials) and distributed in the Rhône, Isère, and Durance watersheds.

The climate of the French Alps is temperate, with a mean annual air temperature (MAAT) decreasing from SW to NE: for the Ecrins massif at 1800 m (all the elevations in the present work are given above sea level, and the acronym a.s.l. is not specified), MAAT was 4.2 °C during the period 1958–2002, and 3.5 °C for the Mont-Blanc massif. For precipitation, annual amount is decreasing from north to south with a mean annual precipitation at 1800 m for the Mont-Blanc massif of 1827 mm yr^{-1}, and 944 mm yr^{-1} for the Ubaye massif (Durand et al., 2009).

2.2. Characteristics of the data sources

To be optimal for a glacier inventory, the used documents need to be dated, to cover the entire region of interest and to be integrated in a geographic information system (GIS) for mapping and database management. In addition, aerial photographs and satellite images need to be acquired at the end of the annual ablation period to minimize the impact of residual snow cover (potentially hiding the glacier outline). Ideally, images should also have minimal shadowing. In France, most geographic data are collected by the IGN (*Institut national de l'information géographique et forestière*), and since 2010 most of the data became freely available to French research institutes. Satellite data from Landsat platforms since 1972 are also freely available through the USGS EROS Data Centre.