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Reanalysis sheds light on 1916 avalanche disaster

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One of the worst meteorological disasters in history took place in the southeastern Alps during the infamous winter of 1916/17. Avalanches following a massive snowfall event killed thousands of soldiers as well as civilians. Today's numerical techniques open up new possibilities to study this historical event. Combining historical measurements with reanalyses and dynamical downscaling makes it possible to reconstruct weather even down to local scales and thus to the scale captured by historical documents on weather impacts.

Studying past severe weather events and their impacts can help us to better assess present and future weather hazards. With reference to the heavy snowfall event in December 1916, we demonstrate the potential of combining numerical techniques with historical documents – and of combining the expertise of meteorologists and historians – to achieve a better understanding of severe weather events and their societal impacts (*Brugnara et al.*, 2016). In particular, we show that it is possible to downscale ECMWF's ERA-20C climate reanalysis of the 20th century by means of a high-resolution model to gain insights into the meteorological conditions that led to the disaster.

Sequence of events

A century ago, Europe was in the midst of World War I. On the Italian front, the Austro-Hungarian and Italian armies faced each other on some of the harshest battlefields in history – on the summits of the southeastern Alps (Box A). Here, during a large part of the year, the fighting would cease almost completely as a different war took place: a war against cold, ice, and snow. With average precipitation exceeding 2 m per year in some locations, this part of the Alps is one of the wettest places on the continent. Soldiers were literally buried in snow and their bodies, exposed by shrinking glaciers, still provide a painful reminder of that absurd carnage.

Historical background

A

The Kingdom of Italy declared war on the Austro–Hungarian Empire on 23 May 1915, almost one year into World War I. The border between the two countries was mostly on mountainous terrain, where the Austro-Hungarian army withdrew to solidly organised defensive positions. In fact, there were only minor changes to the front line until October 1917, when German troops joined the Austro-Hungarians to breach the Italian lines (famously known as the Battle of Caporetto). This forced the Italians to retreat more than 100 km into the plain of Veneto to the Piave River. However, the front line did not move between Stelvio and Monte Grappa until the end of the war. Eventually, in 1918, the Austro-Hungarian Empire collapsed and Italy ended up on the victorious side.

The cost in terms of human casualties was enormous. In three and a half years, about 650,000 Italians and 400,000 Austro-Hungarian soldiers were killed. In the high-altitude areas of the front line (in some places exceeding 3000 m), the losses caused by avalanches and exposure were of similar magnitude as those caused by enemy fire. Further casualties were caused by supply channels being blocked by the avalanches.

Field mass on the glacier of Marmolada (25 Nov 1916) in honour of the new Emperor of Austria, Charles I. Many of these men perished 18 days later under the avalanche of Gran Poz. (Photo: Austrian National Library)

Avalanche in Vermiglio, Trentino (1916). (Photo: Austrian National Library)

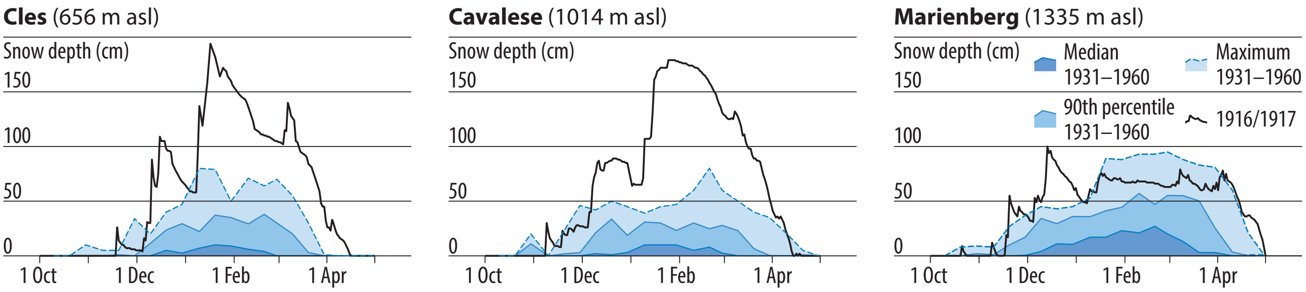


Figure 1 Daily snow depth evolution during the winter of 1916/17 observed at three stations in South Tyrol (see Figure 5 for their locations), compared with the respective statistics for the period 1931–60.

Fate was not on the side of those men as the winter of 1916/17 turned out to be one of the snowiest of the century. Between November 1916 and January 1917, a rain gauge located on today's Italy–Slovenia border measured 1432 mm of precipitation, about 80% of the local mean annual total. After a dry February, an additional 560 mm fell between March and April 1917. Figure 1 shows the snow depth evolution during that winter at three sites. At two of them maximum snow depth reached more than twice the maximum value found at any time during the 1931–1960 period.

Reports by contemporaries suggest that, for most of the mountainous front line between Stelvio and Mount Krn, the shovel was the most important tool for soldiers and civilians alike. Avalanches came down almost daily, causing new casualties again and again. On the front line, tunnels were dug in the snow to reach the foremost positions.

However, there was one particular day that tragically entered the history books: 13 December 1916. On this day, following a week of abundant snowfall, advection of a warm and humid air mass from the Mediterranean brought intense precipitation and a rise of snow level, causing countless avalanches across the region. The number of human casualties was unprecedented for this kind of natural event. An accurate overall death toll is impossible to provide, but estimates of 10,000 by some sources are certainly too high. Official Austrian sources speak of 1,300 deaths and 650 wounded for the period 5–14 December, while later estimates give 2,000 casualties for the avalanches on 12 and 13 December. No Italian estimates seem to exist, but individual accounts suggest that the numbers were similar to those on the Austro-Hungarian side. Dozens of civilians were also killed by the avalanches, which in several cases reached low-altitude settlements that were considered safe.

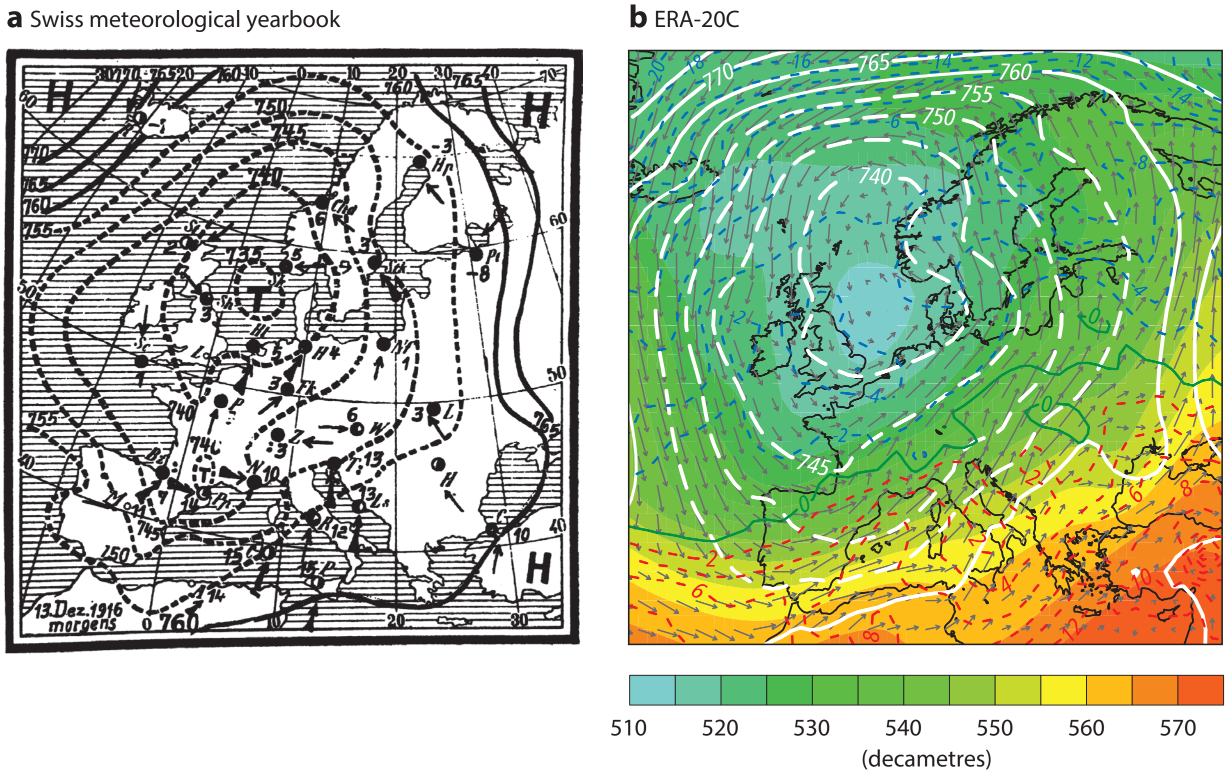
In view of the unlikelihood of attacks by the opposing side, officers often demanded the withdrawal of soldiers from positions endangered by avalanches. Most of the time, however, the higher echelons, based in warm offices in the valleys, demanded that the troops hold their positions. In the early hours on 13 December 1916 and later in the day, large avalanches plunged down onto Austro-Hungarian and Italian positions. The largest single incident took place on the highest mountain of the Dolomites (Mount Marmolada, 3343 m) at Gran Poz (2242 m), where between 270 and 332 men died.

Having occurred in the midst of a greater tragedy – the Great War – this event passed almost unnoticed at the time, all the more as news from the front underwent censorship. Nevertheless, it represents one of the worst weather-related disasters in European history in terms of loss of human life. It is the kind of event from which we can learn about worst-case present and future extremes. With its well-documented impact, what is required is a detailed, quantitative understanding of the responsible atmospheric processes. Such an understanding may enable us to learn lessons from this tragic event.

Reconstructing past weather

Climate reconstructions have become an important tool in climate science. However, impacts on society often arise from distinct weather events whose relation to climate is not always straightforward. In these instances, weather reconstructions are required. For decades, past weather has been reconstructed by historians, often very precisely, but on a local scale and in a descriptive way. These weather reconstructions cannot be used for applications such as risk modelling. The currently available information on the weather in the Alps in December 1916 is primarily based on qualitative descriptions from diaries, memoirs, and anecdotes passed down through generations. Some quantitative information can be recovered from weather stations of national weather services and used to reconstruct such extreme events. However, these observations are usually limited to the bottom of valleys, where most of the population lives, and give little information on the peaks and slopes, where the event took place. In addition, the war disrupted many weather stations, particularly near the front line, and caused the loss of weather registers.

In recent years, numerical techniques have been developed that enable not only climate reconstructions, but also weather reconstructions. It has been demonstrated that useful global reanalyses can be obtained from assimilating only surface data. Knowledge of air pressure at just a few dozen locations suffices to construct a complete three-dimensional picture of the atmosphere every six hours. This enables an extension of global data sets back to the early days of national meteorological networks in the


a Swiss meteorological yearbook

b ERA-20C

Figure 2 Panel (a) shows a hand-drawn synoptic map of Europe for the morning of 13 December 1916, with contours indicating sea level pressure (mmHg), published in the Swiss meteorological yearbook of 1916. Note that the map is based on asynchronous observations spread over a few hours. Panel (b) shows a synoptic map for 0600 UTC 13 December 1916 from the ECMWF 20th century reanalysis ERA-20C. White contours indicate sea level pressure (mmHg for comparison); coloured contours indicate temperature (°C; green for zero, red for positive values, and blue for negative values); and vectors indicate wind at the isobaric level of 850 hPa (vector length is proportional to wind speed). The shading indicates geopotential height at 500 hPa.

19th century. Two ECMWF reanalyses now cover the entire 20th century, namely ERA-20C (*Poli et al.*, 2016; *Poli et al.*, 2014) and the recently finished CERA-20C, the first coupled reanalysis of the full 20th century (*Laloyaux et al.*, 2016; *Laloyaux et al.*, 2017). They were generated as part of the European Union-funded projects ERA-CLIM and ERA-CLIM2 (European Reanalysis of Global Climate Observations). In addition to surface pressure, ERA-20C and CERA-20C also use marine winds.

All available reanalyses reproduce the meteorological situation in December 1916 well. As an example, Figure 2 shows the fields from the ERA-20C reanalysis together with a synoptic map produced at the time. However, the global reanalyses have a coarse spatial resolution that is insufficient for analysing a regional event in a complex topography such as that of the Alps. Their spatial resolution is usually as low as 100–200 km, which means that the Alps are represented as a plateau about 1 km high. Particularly for variables such as precipitation or snow accumulation, which are strongly related to topography, reanalyses have limited use over the Alps. A further step is dynamical downscaling of the reanalysis, which is similar to operations by meteorologists to provide weather forecasts on a regional scale.

In dynamical downscaling, the reanalysis fields are ingested into a high-resolution weather forecast model that covers a small region. This process can be repeated several times with progressively higher resolutions for smaller areas. To reconstruct the weather in December 1916, we started form ERA-20C and then used four nested simulations with the Advanced Research dynamical solver (ARW) of the Weather Research and Forecasting (WRF) Model, version 3.7.1. Figure 3 shows the four domains used, with resolutions of 54, 18, 6, and 2 km, respectively. The result is an hourly reconstruction of local weather, including snow accumulation. This means that the reconstruction is now at the same scale as the historical descriptions.

These numerical techniques do not replace but complement the work of historians. Whereas reanalyses provide a dynamical interpretation for documented weather phenomena, historical documents provide impacts of the reanalysed weather systems. This encourages interdisciplinary collaboration, as demonstrated by the December 1916 case.

December 1916 reloaded

Contemporary meteorologists analysed the synoptic configuration on 13 December 1916 and their hand-drawn maps can be found in meteorological bulletins and yearbooks (Figure 2a). These show a cyclone centred

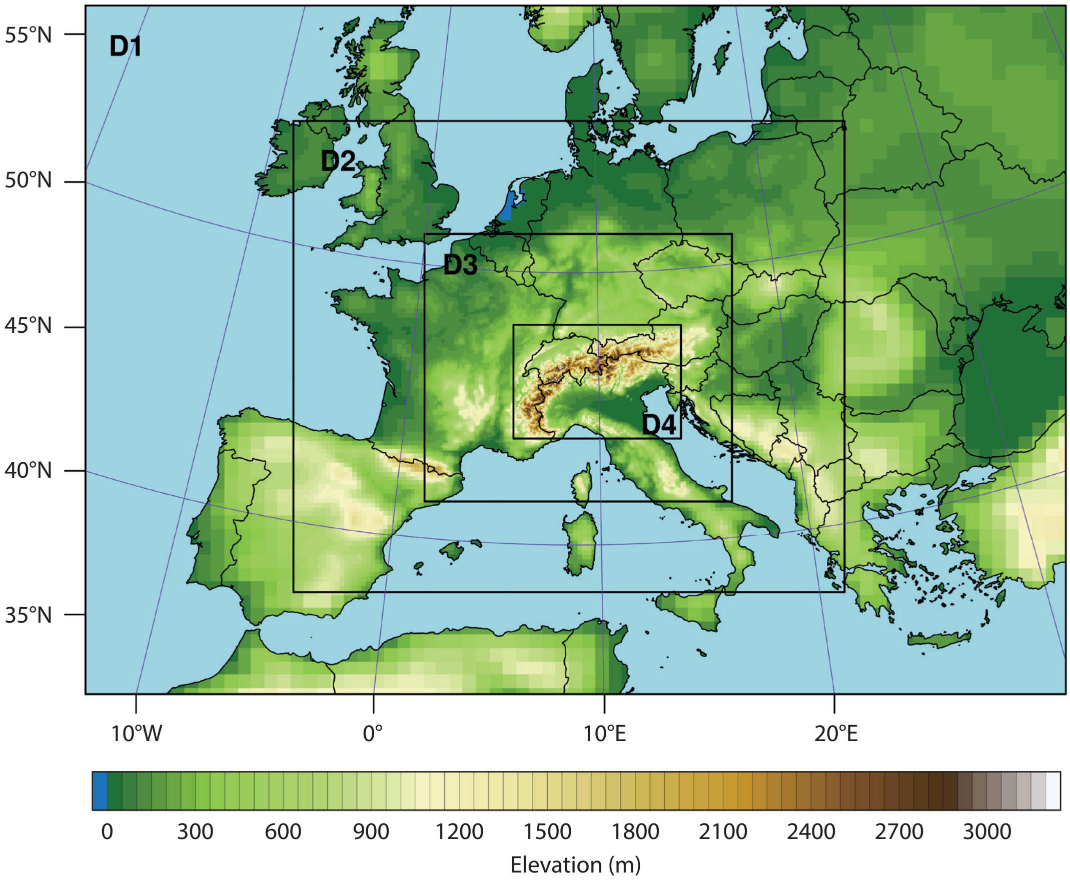


Figure 3 Nested domains at different resolutions (horizontal grid spacing of 54, 18, 6, and 2 km) used for the dynamical downscaling of ERA-20C with the WRF model.

between Scotland and Denmark and a secondary low pressure system over southern France. Figure 2b shows the situation as depicted by ERA-20C. The reanalysis reproduces the hand-drawn map well but provides much additional information. For instance, ERA-20C exhibits higher than normal temperatures over most of the Mediterranean Sea (dashed coloured lines, see also Figure 4).

In order to better understand the event, we must start one or two weeks earlier. Although most of the large avalanches occurred on 13 December, this was a consequence of nine days of relentless precipitation. Reanalyses can help us understand the natural factors that caused this extreme, high-impact event. Atmospheric circulation (Figure 4) was held in the shape of a blocking configuration resembling the negative mode of the so-called East Atlantic–West Russia pattern, one of the leading modes of variability in the Eurasian sector and a mode that is relevant for extremes (*Casanueva et al.*, 2014). It is characterised by a vast high-pressure ridge over western Russia, next to a low pressure area over western Europe. This means that warm and humid air over the western Mediterranean is pushed toward the Alps, where it is lifted and cooled, causing intense precipitation in a small area between the Alpine foothills and the watershed. This configuration therefore usually brings wet spells to the southern Alps and higher-than-normal temperatures in the eastern Mediterranean. In fact, instrumental air temperature records from Greece indicate that December 1916 was the warmest December in the last 120 years. The consequences include positive water temperature anomalies in the Mediterranean, which are a main source of water vapour for the southern Alps.

By downscaling ERA-20C to a grid spacing of 2 km, we find precipitation amounts on 13 December that locally exceed 200 mm in the Julian Alps, in agreement with the local maximum daily amounts observed in December 1916, although the exact date of these maxima is unavailable. The downscaling also produces large spatial variations typical of a complex topography (Figure 5a). An animation of wind and precipitation in the innermost domain as well as an animation of snow accumulation from 6 to 16 December can be found here: *www.geography.unibe.ch/december1916*. The precipitation on 13 December added critical weight to a snow pack that had already increased by up to 2.5 m over the previous days (Figure 5b). On Bernina Pass (2323 m) in Switzerland, snow height was 3.70 m on 12 December and then increased to 5 m.

In addition to the precipitation amount, temperature was a critical factor. The rise in temperature brought rain up to 2000 m, making the snowpack heavier. Below 2000 m, particularly in the southern and eastern part of the affected region, this was a 'rain-on-snow' event, a type of event that is known to trigger avalanches. The combination of intense precipitation and melting snow raised Wörthersee, Carinthia's largest lake, to its maximum observed water level. On the front line, a major Italian offensive had to be delayed, because the troops deployed on the low-lying karst plateau were "drowning in mud", as General Luigi Cadorna reported. The postponement lasted five months and enabled the struggling Austro-Hungarians to transfer critical reinforcements from the eastern front.

Contemporary meteorological observations that were not used in the reanalysis, in particular temperature, precipitation (mostly in Switzerland), and snow depth (in Austria-Hungary), digitised within the ERA-CLIM2 project, are in good agreement with the simulated values although there can be large deviations locally, especially for single days (see Figure 5a). However, taken alone they would draw a rather incomplete picture of the event, because very few daily observations are available for the most affected areas. Taken together, the downscaled reanalysis and the observations provide a detailed, comprehensive view and allow a physically meaningful interpretation. Now that the main

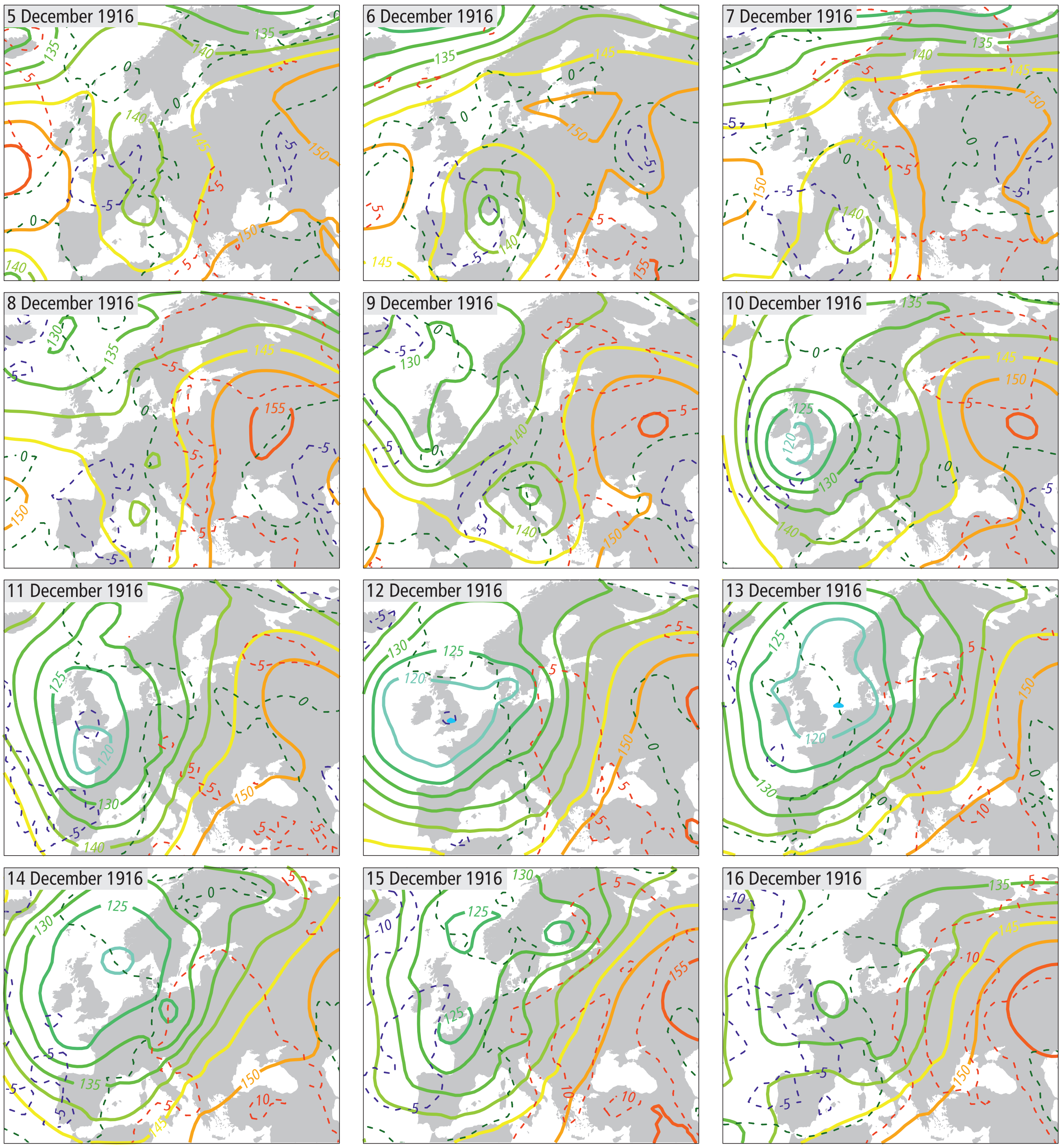


Figure 4 850 hPa geopotential height (solid contours; in decametres) and 850 hPa temperature anomaly with respect to the reference period 1961–90 (dashed contours; in °C) at 0000 UTC for each day from 5 to 16 December 1916 (ERA-20C).

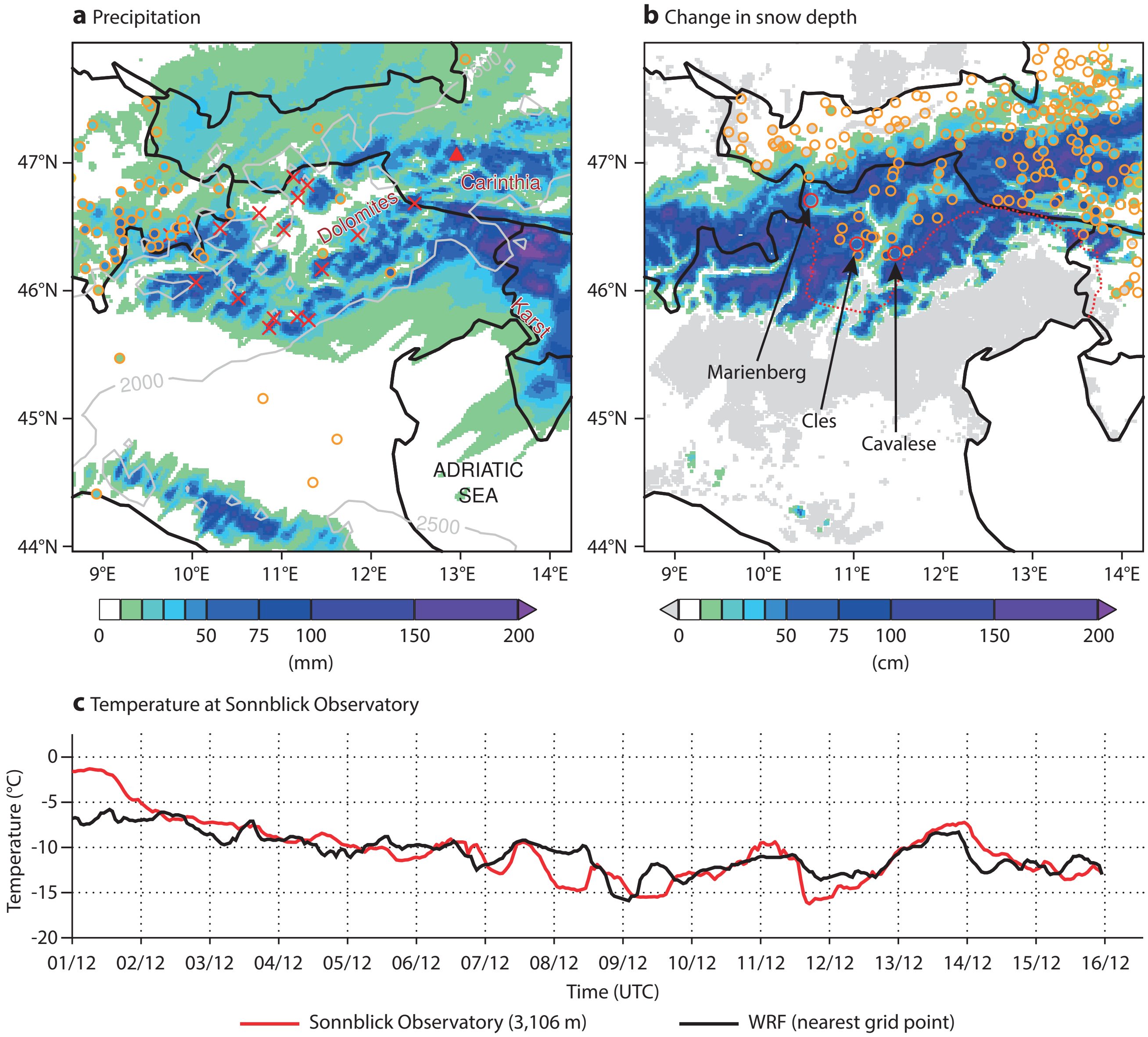


Figure 5 Results from the dynamical downscaling of ERA-20C. Panel (a) shows total precipitation (shading) on 13 December 1916 (defined as the 24 hours until 0700 UTC on 14 December 1916) and mean freezing level (grey contours; in m). Circles represent the location of observations obtained from public datasets and digitised by the authors and red crosses show the locations of documented major avalanches on 13 December 1916. Panel (b) shows the change in snow depth between 5 and 13 December 1916 (at 0700 UTC) with circles representing observations from the network of the Austro-Hungarian hydrographic office (red circles show the locations of the stations referred to in Figure 1). The military front line in 1916 is also shown (red dotted line). Panel (c) shows hourly air temperature between 1 and 15 December 1916 observed at Sonnblick Observatory (the highest staffed weather station in the world at that time) compared with the simulation (temperature at station altitude was extrapolated from the two closest model levels). The position of Sonnblick Observatory is marked in (a) by the red triangle.

ingredients of the weather situation (persistent blocking, possible influence of warm eastern Mediterranean Sea, moisture transport, and temperature increase) and of the societal vulnerability are identified, the behaviour of these factors in a future climate or a future society can be studied.

An instrument with great potential

Several long, historical reanalyses have been produced that provide global, three-dimensional, 6-hourly atmospheric data sets. ERA-20C and CERA-20C cover the 20th century. The Twentieth Century Reanalysis (20CR, *Compo et al.*, 2011) Versions 2 and 2c go even further back, to 1871 and 1851, respectively. Tests have been conducted for the years 1815–17 (encompassing the 'year without a summer' that followed the Tambora eruption) and there is even the potential to employ them for the 18th century in central Europe, where the station network was already relatively dense. Ensemble-based reanalyses, such as CERA-20C, provide additional information in the form of ensemble spread.

However, the reanalyses rely on pressure observations, which have traditionally been undervalued and hence have not yet been digitised in many cases. In fact, reanalyses demonstrate how almost forgotten historical observations can once again become valuable, requiring scientists to go back to the archives – work that is best performed jointly by climatologists and historians. Consequently, large efforts were devoted within the ERA-CLIM and ERA-CLIM2 projects to rescue historical observations, which will be assimilated in future reanalyses. Reanalysis efforts are therefore not just large undertakings that exploit the available data and models to produce a huge data set. They must also prepare the ground for future reanalysis efforts by means of data rescue and further development of coupling methods, bias correction methods, and the like.

It is important also to note that reanalyses are not always able to correctly reproduce real atmospheric circulation, particularly on a local scale. Therefore, they cannot be regarded as the truth. Rather, they represent a physically consistent, possible truth, which becomes meaningful when analysed together with documentary information on the real-world weather.

The results for December 1916 suggest that reliable high-resolution reconstructions can be achieved with only sparse surface data. Combined with detailed historical analyses, they allow insight into an event that is not only historically relevant but still very much present today. Such analyses result in precious information for numerous applications including the attribution of weather events to climate change or other causes, impact analysis, risk assessment, and societal resilience, responses and perception.

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