December 1916: Deadly Wartime Weather

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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. Novel insight into the event arises from a detailed reconstruction based on weather forecast models and shows the potential of combining numerical techniques with historical documents. This helps to better understand worst-case weather events in the past and future and their societal impacts.

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 1: The Italian front). 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.[1,2] With an 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 by snow and their bodies, exposed by shrinking glaciers, still provide a touching reminder of that absurd carnage.

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 (Fig. 1), a fact already noticed by contemporaries.[3,4] 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.

However, there was one particular day that tragically entered 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 (see Box 2: Avalanches on the front). The number of human casualties was unprecedented for this kind of natural event. An accurate overall death count is not possible, but estimates of 10 000 by some sources[5] are certainly too high. Official Austri-

***Photo 1:** Trench near Monte Scorluzzo, Stelvio Pass.*

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Box 1: The Italian Front

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 organized 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 a.s.l.), the losses caused by avalanches and exposure were of similar magnitude as those caused by enemy fire.

Box 2: Avalanches on the front

From the beginning of November, there was abundant snowfall along most of the front line.[2,4] 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.

In view of the unlikelihood of attacks by the opposing side, officers often withdrew soldiers from positions endangered by avalanches. Most of the time, however, the higher echelon – 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 on Austro-Hungarian and Italian positions – often expected by those troops in place. The largest single incident took place on the highest mountain of the Dolomites (Mount Marmolada, 3343 m a.s.l.) at Gran Poz (2242 m a.s.l.), where between 270 and 332 men died, some of whom were not recovered until July 1917. Josef Strohmaier, who was stationed there, commented: "every day there were new victims amongst the comrades" and, after being warned that the avalanche was coming, "we wanted to go to the door to escape, [but at this moment] the external wall was smashed by snow and ice. […] My bedfellow only said: 'Kruzifix, now we are gone.'"[2] They – and many more on both sides – could be saved[4,11] and were brought to hospitals like the one in Cortina d'Ampezzo, in which Nicola Ragucci served as a doctor. He commented: "the monster torrent of snow […] overran a two story barrack […] with a company of two hundred men. […] They were all buried by the avalanche, and unfortunately about forty died."[12]

Photo 2: *Field mass on the glacier of Marmolada (25 November 1916) in honor of the new Emperor of Austria, Charles I. Many of these men perished 18 days later under the avalanche of Gran Poz.*

However, direct hits were not the only impact of avalanches. Further casualties were caused by channels of supply that were blocked by the avalanches.[3] In the early morning of 13 December, a large avalanche from the Gatterspitze destroyed parts of a camp close to Lake Obstans. During the evacuation of the soldiers another avalanche hit the cable car, preventing 120 officers and enlisted men from leaving the destroyed camp.[7] Reportedly, both sides tried to trigger avalanches by means of artillery fire. However, the importance of that trigger remains to be studied.

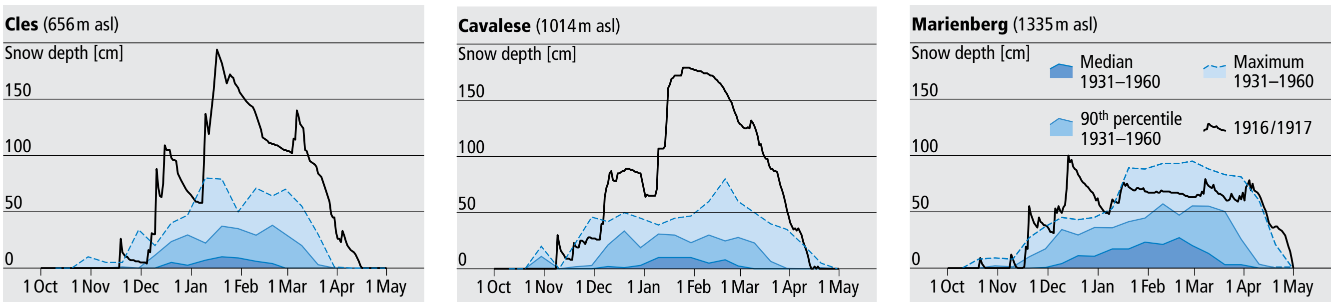


Fig. 1: *Daily snow depth evolution during the winter of 1916/1917 observed at three stations in South Tyrol, compared with the respective statistics of the period 1931–1960.*[10]

Box 3: The avalanche disaster in the newspapers

Der Tiroler

„Der Tiroler" erscheint täglich mit Ausnahme der Sonn- und Feiertage.

Nummer 286 | Donnerstag, den 14. Dezember 1916. | 35. Jahrgang.

Die Friedenstaube ausgesandt!

Die Mächte des Vierbundes bieten in aller Form die Hand zum Frieden.

Although the series of avalanches in December 1916 was the most disastrous in the collective memory, Austrian daily newspapers did not take much notice. Selected newspapers[13] have been analyzed: three supra-regional ones from the Habsburg Monarchy [the "Arbeiter-Zeitung" (social-democratic), the "Neue Freie Presse" (liberal), and the "Reichspost" (conservative)] and three local Tyrolean newspapers ["Der Tiroler" (Bolzano/Bozen), the "Innsbrucker Nachrichten" (Innsbruck), and the "Tiroler Anzeiger"]. They clarify the reasons for this lack of interest. On the one hand, news on political issues (in particular, possible ceasefire talks after the death of Emperor Franz Joseph I on 21 November 1916) dominated the media. On the other hand, reports on the Italian front in the Dolomite Alps were subject to strict censorship. Whereas long articles were published about the war in Romania, official statements on the southern front between the Austro-Hungarians and Italians were short and meaningless. Only prominent victims of avalanches on the front line, such as the Tyrolean author and journalist Josef Burger, who was buried and killed by an avalanche on 5 December 1916, were mentioned. More fruitful information is available on avalanches in the hinterland. Tyrolean newspapers report the place, date, number of victims, and overall damage of avalanches mostly in the South Tyrolean valleys (Vinschgau and Passeier Valleys), but also in southeastern Switzerland (Tiroler Anzeiger, 15 December 1916, p. 3). An extensive analysis of those reports has not yet been conducted, but will enable us to reconstruct the spatial and temporal distribution of the avalanches and the number of victims in the hinterland. In addition, these newspapers contain interesting descriptions of the weather situation. For example, in the gulf and even in the harbor of Genoa a cyclone brought many ships into distress (Tiroler Anzeiger, 15 December 1916, p. 3). The local newspaper "Der Tiroler" reports on the situation in South Tyrol on 15 December 1916 (p. 3):

"'Even the oldest people,' so to say, cannot remember to have ever experienced such a weather. Southerly winds daily bring snow and rain that cause a tremendous increase of snow in the higher up regions. In the valleys, however, the snow has already been washed away. The heavy, sticky snow has destroyed the telegraph lines in many places."

The interruption of telegraph lines is presumably why many reports on avalanches were published in the newspapers one or two weeks after the event.

an sources give 1 300 deaths and 650 wounded for the period 5–14 December,[6] while later estimates give 2 000 casualties for the avalanches on 12 and 13 December.[7] No Italian estimates seem to exist,[8] but individual accounts suggest that the numbers were similar to those of the Austro-Hungarian side. Dozens of civilians were also killed by the avalanches,[9] which in several cases reached low-altitude settlements that were considered safe. Online resources and even books[5] refer to 13 December 1916, for unknown reasons, as the "White Friday." However, that day was actually a Wednesday.[4] Therefore, we will not use this misleading expression.

Having occurred in the midst of a greater tragedy – the Great War – this event passed almost unnoticed at the time (see Box 3: The avalanche disaster in the newspapers). 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 that can inform us 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. Thus, the tragic event can become instructive.

Photo 3: *Avalanche in Vermiglio, Trentino (1916).*

Reconstructing past weather

Climate reconstructions have become an important tool in climate science. However, impacts on society often arise from a few 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 modeling. The currently available information on the weather 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 be 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, particu-

Box 4: What is a reanalysis?

Meteorological observations provide information on the real atmosphere, but are temporally and spatially incomplete. Numerical weather prediction models provide a physically consistent and complete depiction of the atmosphere, but do not always agree with reality. By constantly correcting a model simulation toward the observations, reanalyses combine the advantages of both data sources. The corrections are not only applied at the observation locations, but the entire model state is corrected in a consistent way. Therefore, reanalyses are physically consistent, spatially complete, and encompass many variables (e.g., radiation) for which observations are not always available. However, they are not actual observations.

For the 1916 case, air pressure observations are used to correct the model state. Thus, the model is forced to generate realistic weather systems (with wind fields, temperature, moisture transport, etc.) so that they are consistent with the observed spatiotemporal air pressure variations.

***Photo 4:** Swiss soldiers perform ski jumps near the Umbrail Pass, close to the tricountry point between Switzerland, Austria-Hungary, and Italy (close to the first Italian line and within the range of fire of the Austro-Hungarian and Italian artillery).*

larly near the front line, and caused the loss of weather registers.[14]

In recent years, numerical techniques have been developed that allow detailed, quantitative weather reconstructions. These so-called reanalyses (see Box 4: What is a reanalysis?), which combine weather observations with a numerical weather prediction model, are standard data sets in atmospheric science. Until recently, they were restricted to reconstructions of past decades for which abundant observations from weather balloons are available. However, recent approaches require fewer observations. Air pressure at a few dozen locations already suffices to construct a complete three-dimensional picture of the atmosphere every six hours. This allows an extension of global data sets back to the start of the national meteorological networks in the 19th century. Today, several global data products[15,16] can reproduce the meteorological situation in December 1916 (Fig. 2). However, they have a coarse spatial resolution that is insufficient for analyzing a regional event in a complex topography such as that of the Alps. A further step is dynamical downscaling (see Box 5: Dynamical downscaling) of the reanalysis, which is similar to operations by meteorologists to provide more accurate weather forecasts on a regional scale.

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

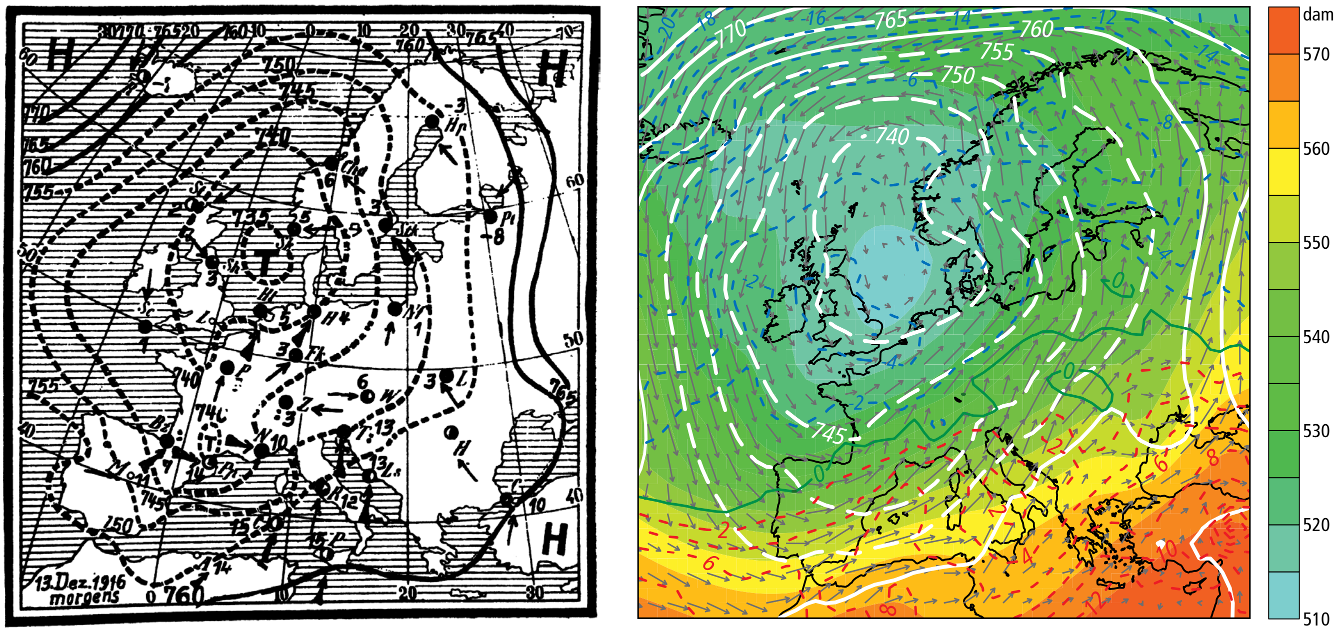
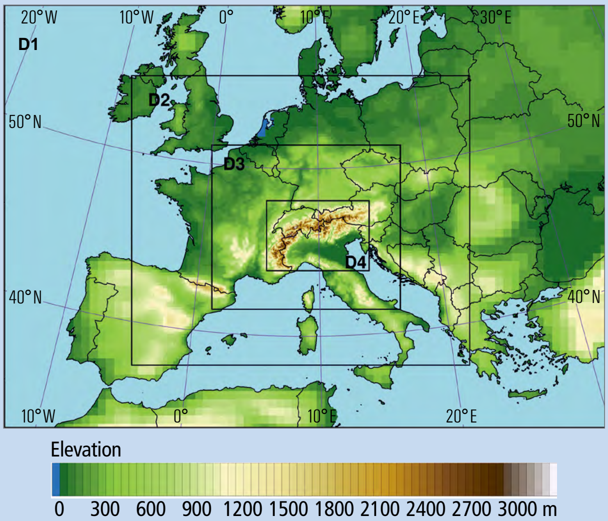


***Fig. 2:** (left) Hand-drawn synoptic map of Europe for the morning of 13 Dec 1916, with black lines indicating sea level pressure (mmHg).[17] Note that the map is based on asynchronous observations spread over a few hours. (right) Synoptic map at 0600 UTC 13 Dec 1916 from the European Centre for Medium-Range Weather Forecasts (ECMWF) 20th Century Reanalysis (ERA-20C). White contours indicate sea level pressure (mmHg for comparison), colored contours (green for zero, red for positive values, and blue for negative values) and vectors indicate temperature (°C) and wind at the isobaric level of 850 hPa (vector length is proportional to wind speed), respectively. Filled contours indicate geopotential height at 500 hPa (dam).*

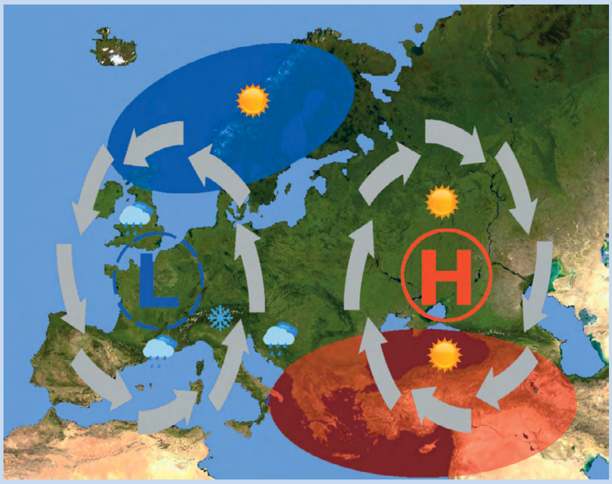
Box 5: Dynamical downscaling

Reanalyses are the product of atmospheric models that cover the entire globe, known as general circulation models. Their spatial resolution is usually limited to 100–200 km, representing the Alps as a 1 km high plateau. Therefore, many parameters reconstructed by reanalysis, such as precipitation, have limited use over the Alps. A solution for this problem is to ingest the reanalysis fields into a high-resolution 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 used four nested simulations with the Advanced Research version of the Weather Research and Forecasting (WRF) Model (ARW), version 3.7.1[18] (with resolutions of 54, 18, 6, and 2 km).



Box 6: East Atlantic/West Russia pattern

Certain patterns in the atmospheric circulation are more frequent than others and can become stationary for days or even weeks. In these conditions, it is more likely that extreme events (such as heat waves, cold spells, and strong precipitation) will happen. The pattern that has the largest potential for extreme winter precipitation in the southern Alps is the negative phase of the so-called East Atlantic/West Russia pattern. It is represented by a vast high pressure ridge over western Russia, opposed by a low pressure area over western Europe. This means that the warm and humid air over the western Mediterranean is pushed toward the Alps, where it gets lifted and cooled, causing the water vapor to condense and fall on a small area between the Alpine foothills and the watershed.



December 1916 reloaded

Contemporary meteorologists analyzed the synoptic configuration on 13 December 1916 and their hand-drawn maps can be found in meteorological bulletins and yearbooks (Fig. 2, left). These show a cyclone centered between Scotland and Denmark and a secondary low pressure system over southern France. Figure 2 (right) shows the situation as depicted by ERA-20C [a 100-yr reanalysis generated as part of the European Union-funded European Reanalysis of Global Climate Observations (ERA-CLIM) project[16]].

Although most of the large avalanches occurred on 13 December, this was a consequence of 9 days of relentless precipitation.[4] Reanalyses can help us understand the natural factors that caused this extreme, high-impact event. Atmospheric circulation (Fig. 3) was held in the shape of a blocking configuration known as the East Atlantic/West Russia pattern, one of the leading modes of variability in the Eurasian sector[19] (see Box 6: East Atlantic/West Russia pattern). This configuration usually brings wet spells to the southern Alps[20] and higher-than-normal temperatures in the eastern Mediterranean[21] (instrumental air temperature records from Greece indicate that December 1916 was the warmest December in the last 120 years[22]; see also Fig. 3). The consequences include positive water temperature anomalies in the Mediterranean, which is a main source of water vapor for the southern Alps and cause of extreme events.[23]

By downscaling ERA-20C to 2-km resolution (see Box 5: Dynamical downscaling), 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), with large spatial variations typical of a complex topography (Fig. 4a). This precipitation added critical weight to a snow pack that had already increased by up to 2.5 m over the previous days (Fig. 4b). Moreover, the rise in temperature brought rain up to 2000 m a.s.l., making the snowpack heavier. The combination of intense precipitation and high temperature raised Wörthersee, Carinthia's largest lake, to its maximum observed lake level.[24] 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.[5] 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), are in good agreement with the simulated values (although there can be large deviations locally, especially for single days; see Fig. 4a). 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

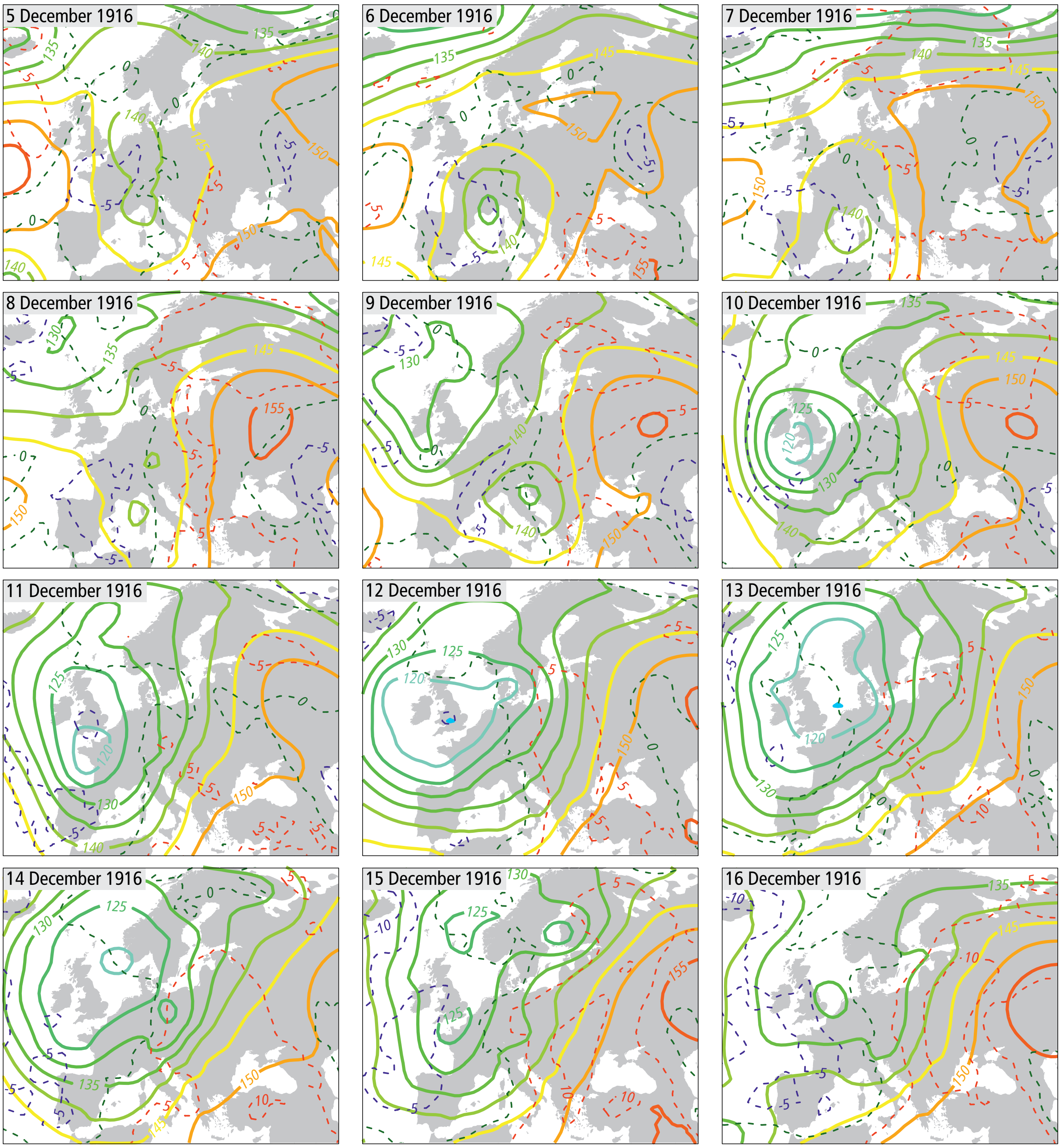


Fig. 3: *850 hPa geopotential height (thick contours; dam) and 850 hPa temperature anomaly with respect to the reference period 1961–90 (dashed contours; °C) at 0000 UTC for each day from 5 to 16 Dec 1916 (ERA-20C).*

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

An instrument with great potential

Reanalyses are currently available as continuous, 6-hourly data sets going back to the 1850s. Tests have been conducted for the years 1815–17 (encompassing the "year without a summer" that followed the Tambora eruption[27]) and there is even the potential to employ them for the 18th century in central Europe. However, they rely on pressure observations, which have traditionally been undervalued and hence have often not been digitized. This task must now be undertaken. 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.

Reanalyses are not always able to correctly reproduce real atmospheric circulation, particularly on a local scale. Therefore, they cannot be taken for truth. Rather, they represent a physically consistent, possible truth, which becomes meaningful when

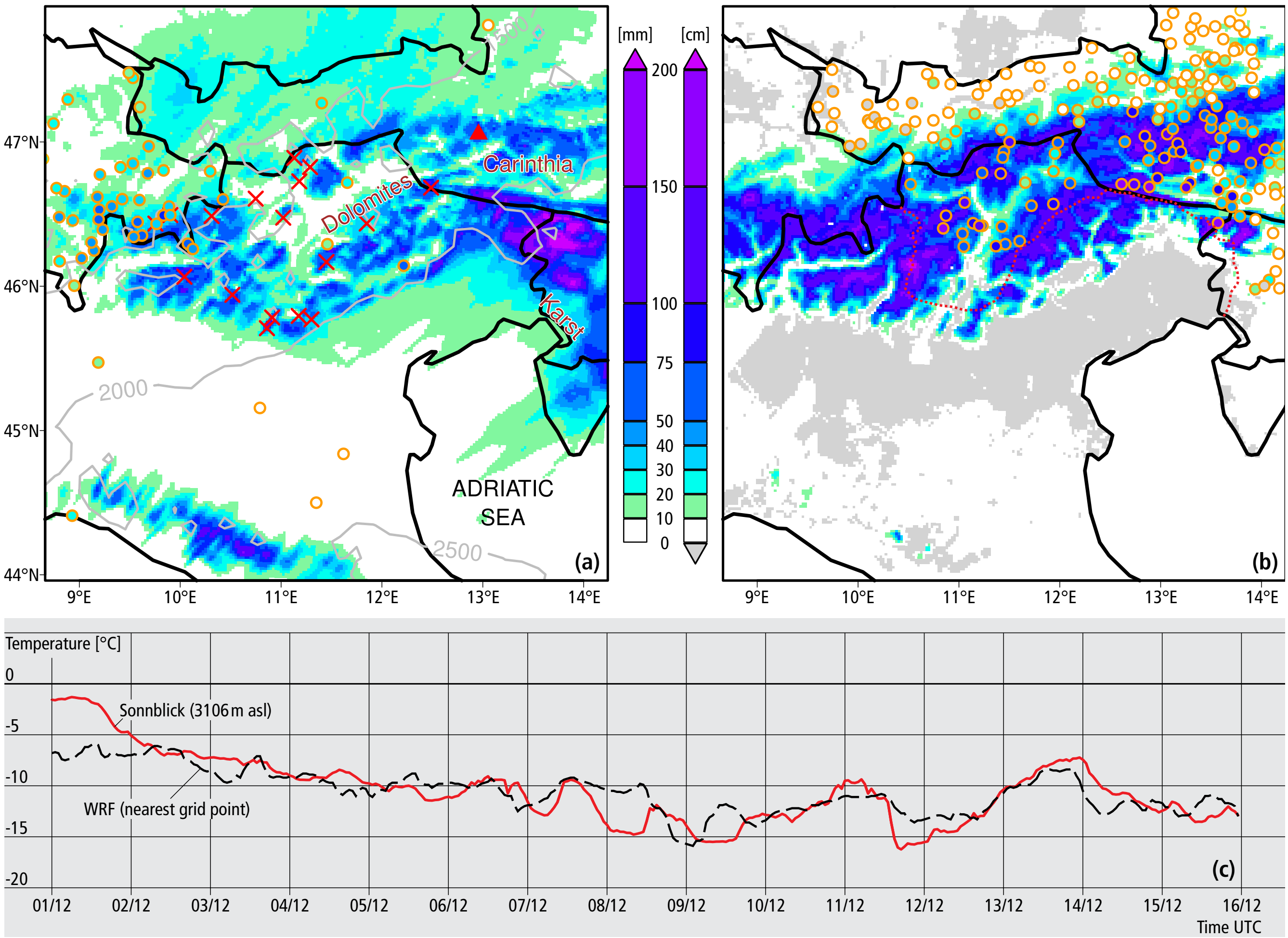


***Fig. 4:** Results from the dynamical downscaling of ERA-20C. (a) Total precipitation on 13 Dec 1916 (defined as the 24 hours until 0700 UTC 14 Dec 1916) with mean freezing level (m) indicated by the gray lines. Circles represent observations obtained from public datasets[25] or digitized by the authors and red crosses locate documented major avalanches on 13 Dec 1916. (b) Change in snow depth between 5 and 13 Dec 1916 (at 0700 UTC) with circles representing observations from the network of the Austro-Hungarian hydrographic office[26]. The military front line in 1916 is also shown (red dotted line). (c) Hourly air temperature between 1 and 15 Dec 1916 observed at Sonnblick Observatory (the highest manned 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.*

analyzed together with documentary information on the real-world weather.

The results for December 1916 suggest that reliable high-resolution reconstructions can be achieved even with 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 that include attribution; impact analysis; risk assessment; and societal resilience, responses, and perception.

***Photo 5:** Howitzer aiming at Val Rimbianco, Three Peaks, Dolomites.*

***Photo 6:** Remnants of a trench at Monte Piana.*

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