Heavy Alpine snowfall in January 2019 connected to atmospheric blocking

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Introduction

Atmospheric blocking often triggers anomalous weather patterns in mid-latitudes. Blocking is characterised by a quasi-stationary high-pressure system and reversal of the westerly flow near its southern edge, which can persist for several weeks and lead to extreme weather events (Rex, 1950; Tibaldi and Molteni, 1990; Pelly and Hoskins, 2003). In summer, atmospheric blocking over Europe is associated with heatwaves, while in winter, it is linked to cold weather extremes associated with the equatorward advection of cold air masses from the polar region (Tyrlis and Hoskins, 2008; Sillmann et al., 2011). Regions on the edge of the block can also be affected by hydrological extremes due to the deflection of the storm track or moisture advection downstream of the blocking high (Barnes et al., 2013; Sousa et al., 2017).

European weather and climate are strongly affected by the Euro-Atlantic blocking regimes, which modulate tropospheric moisture transport (Pasquier et al., 2019). The topography of the Alpine mountain range, located in Central Europe, acts as a barrier for meridional moisture fluxes by inducing precipitation via orographic lifting. Two distinct precipitation patterns are observed depending on the moisture sources (Sodemann and Zubler, 2009). In winter, the northern Alpine slope and Central Europe are affected mainly by moisture advected from the North Atlantic. In contrast, precipitation at the southern Alpine slope is associated with moisture transport from the Mediterranean. Typically, a northwesterly flow resulting from a blocking ridge over the eastern North Atlantic produces heavy snowfalls in the Alps (Burroughs, 2000).

Previous studies have highlighted the important role of troposphere–stratosphere interactions for winter surface weather (Thompson and Wallace, 1998; Baldwin and Dunkerton, 2001; Karpechko et al., 2018). Several other studies linked winter tropospheric blocking to polar stratospheric variability, suggesting that blocking may alter the vertical propagation of planetary waves and trigger sudden stratospheric warmings (SSWs) (Martius et al., 2009). SSWs are dramatic events characterised by a breakdown of the westerly stratospheric circulation and a reversal to easterlies, with associated rapid warming of the polar stratosphere. Martius et al. (2009) reported that SSWs are often preceded by tropospheric blocking and that its location over the Atlantic or Pacific can affect the type of SSW, involving either vortex displacement or vortex splitting. Blocking can also follow an SSW, such as blocking over Greenland during a negative phase of the North Atlantic Oscillation (e.g. Domeisen et al., 2020). A two-way connection of these phenomena is possible: the stratospheric circulation perturbed by an SSW, itself initially forced by blocking, can further influence the persistence of that blocking (Woollings and Hoskins, 2008). Both phenomena are associated with cold air outbreaks in Eurasia (Kolstad et al., 2010; King et al., 2019).

In January 2019, the Northern Hemisphere extratropics featured two remarkable atmospheric phenomena: a major SSW (2 January) and persistent North Atlantic Heavy Alpine snowfall in January 2019 connected to atmospheric blocking

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Figure 1. Mean snow depth for January 2019 in the Austrian Alpine region based on SNOWGRID data. Indicated are four selected stations: 1, Seefeld in Tyrol; 2, Hochfilzen in Tyrol; 3, Abtenau in Salzburg; and 4, Bad Aussee in Styria.
Heavy Alpine snowfall connected to atmospheric blocking. At the same time, a persistent northwesterly to northerly flow set in over the Alpine region, and significant snow accumulation took place in the Northern Alps. The January snowfall amount broke the 100-year snow records at some stations (Radlherr et al., 2019). Zentralanstalt für Meteorologie und Geodynamik (ZAMG) – the national meteorological service of Austria – issued the highest alert (red level) for fresh snow three times in a row (4–6 January, 8–10 January, 13–15 January).

Such extreme snowfall is a natural hazard that often causes direct and indirect damages, with severe socio-economic consequences posing risks to human lives, transport and infrastructure. An improved understanding of the event’s evolution and underlying processes responsible for the extreme precipitation is crucial for both enhancing its predictability and disaster risk assessment.

In this paper, we investigate the synoptic conditions that prevailed during European winter (December–January) 2018/2019 and how they led to the episode of extreme snow accumulation across the Northern Alpine region during January 2019.

Data

Data from ERA5 (Hersbach et al., 2020), the fifth-generation reanalysis of the European Centre for Medium-Range Weather Forecasts (ECMWF), are used as a basis for this study. In the impact analysis, we use station data and snow cover model data provided by ZAMG. The spatial distribution of accumulated snow is estimated using the snow cover model SNOWGRID, which is driven with gridded meteorological data from ZAMG’s nowcasting system INCA (Integrated Nowcasting through Comprehensive Analysis) (Olefs et al., 2013). The model is based on a radiation model and simulates the temporal development of snow height and snow water equivalent for Austria in 15-min time steps.

In addition, we use snow measurements from selected meteorological stations provided by ZAMG (Schöner et al., 2019) to highlight the extreme snowfall in January 2019. Four stations located in the northern part of the Alpine range and representative of the western and eastern regions of the Austrian Alps are selected in our study. The selected stations are: Seefeld, Tyrol (1182m above mean sea level (amsl), 47°32′ N, 11°17′ E); Hochfilzen, Tyrol (962m amsl, 47°46′ N, 12°61′ E); Abtenau, Salzburg (709m amsl, 47°58′ N, 13°34′ E) and Bad Aussee, Styria (667m amsl, 47°61′ N, 13°78′ E).

For discussion of the prediction of the event, we use short- and medium-range forecasts from the ECMWF high-resolution forecast (HRES) and ensemble forecast (ENS) provided four times a day, and extended-range forecast provided twice per week (ECMWF, 2021). The forecasts were based on the ECMWF Integrated Forecasting System (IFS) cycle 46r1.

Methods

In this study, we focus on the Euro-Atlantic region (45°–72°5′ N, 30°W–45°E), which covers the area of the North Atlantic block-
Heavy Alpine snowfall connected to atmospheric blocking and the affected part over Europe. We calculate daily anomalies of geopotential height (GPH) and temperature with respect to the climatological daily-mean from 1981 to 2010. To identify blocking, we compute blocking indices based on 500hPa GPH gradients. We follow the three-step algorithm described by Brunner and Steiner (2017) and Brunner (2018). At the first step, the algorithm identifies instantaneous blocking (IB) if the meridional 500hPa GPH gradient is reversed within the region from 35 to 80°N. Then, extended IB events are selected if the meridional GPH gradient reversal spans at least 15° in longitude, i.e. only large systems are considered. Finally, blocking is identified when extended IB occurs within a region of 10° in longitude and 5° in latitude for at least five consecutive days, defined as blocking (B). This approach identifies persistent and stationary upper-level high-pressure systems.

Heavy snowfall events in the Austrian Alps

From 30 December 2018 to 15 January 2019, a sequence of heavy snowfall events affected the entire Austrian side of the northern Alps. Highest-level avalanche warnings were issued in Salzburg, Styria (e.g. LWD Steiermark, 2020), Upper Austria and Lower Austria, and in some parts of Tyrol and Vorarlberg (Radlherr et al., 2019). Infrastructure and traffic were significantly affected. As the event evolved, many roads were blocked and 86 500 people were left without a transport connection. Although the entire Austrian Alpine region (46–49°N, 9–17°E) was affected by the snowfall, the amounts of snow were different from region to region. Radlherr et al. (2019) explained the complexity of the situation as a result of several frontal systems from the north leading to varying snowfall levels during the 17 day episode resulting in high snow loads and related impacts. Figure 1 shows the affected region with the four selected stations (Seefeld, Hochfilzen, Abtenau and Bad Aussee) marked on the map. In January 2019, the mean snow depth in the Austrian Alps ranged from 1m to more than 4m. Three peaks of fresh snow
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measurements (4–6 January, 8–10 January, 13–15 January) were recorded during the 17 day snowfall event (Figure 2).

In some regions, the amount of fresh snow was unusually large, e.g. 3.71m of accumulated snow over 17 days at Seefeld, which statistically occurs only every 50 or 100 years (Radlherr et al., 2019). The largest reported accumulation of fresh snow over this period was 5.21m at Hochfilzen. To provide a historical perspective, we show long-term snow measurement series for the four selected stations (Figure 3). Analysis of maximum 17-day snowfall periods for each winter reveals that the 2018/2019 event was exceptionally large with record amounts of fresh snow accumulation in Seefeld, Hochfilzen, Abtenau and Bad Aussee, where fresh snow measurements are available since 1981, 2001, 1981 and 1971, respectively. The measurements of maximum snow depth at Seefeld (available since 1948), Hochfilzen (since 2001), Abtenau (since 1963) and Bad Aussee (since 1957) (Figure 3) are the highest or second highest on record.

Synoptic evolution

From early December, synoptic conditions in the Euro-Atlantic region were characterised by persistent blocking centred over Eurasia, extending over Scandinavia and the North Atlantic. Figure 4 shows the evolution of the 500hPa GPH anomalies and mean sea-level pressure from 15 December 2018 to 15 January 2019. An upper-level ridge associated with blocking over Scandinavia and the North Atlantic persisted from 10 to 21 December 2018 (Figure 4a). On 25 December, a ridge emerged over the eastern North Atlantic and northwestern Europe with the maximum GPH anomaly centred at 60°N and 10°W (Figure 4c). After that, the ridge evolved into an omega-shaped blocking high with low-pressure systems upstream and downstream of the blocking ridge over eastern Canada and Scandinavia, respectively (Figures 4c–e). The slightly retrograding omega block over the North Atlantic remained well established for the next 3 weeks until its dissipation on 15 January (Figure 4f). The near-surface circulation pattern resembled the mid-tropospheric ridge-trough configuration (Figures 4a–f). On 2 January, the two low-pressure systems associated with the upper-level troughs to the west and east of the blocking ridge deepened and increased their spatial extent (Figure 4d). In the region to the east of the blocking high, the amplifying trough reached southern Europe.

The temporal evolution of blocking in December 2018 and January 2019 is illustrated in a Hovmöller diagram (Figure 5) indicating IB (light grey) and extended IB (grey) and final persistent blocking (black) (as defined in Methods). During this period, there were mainly three blocking processes consistent with the evolution of the 500hPa GPH anomalies shown in Figure 4. The first two blocking patterns occurred in December 2018 (from 10 to 17 December between 0°E and 60°E and from 10 to 22 December between 60°W and 0°W) and
correspond to the upper-level ridge over Scandinavia and the North Atlantic shown in Figure 4. The third block emerged during the first two weeks of January 2019 and extended over the eastern North Atlantic and western Europe (centred between 30°W and 0°W).

Figure 6 shows the evolution of the 250hPa wind, which is the approximate altitude of the jet stream core. Figures 4 and 6 show that the jet stream configuration is aligned with the high-pressure system over the North Atlantic and evolves within the zone of strong GPH gradients. The jet stream was initially split into northern and southern branches by the anticyclonic flow associated with blocking over Scandinavia, as indicated in Figure 6(a). Then, the configuration changed (Figure 6b), and the jet stream displaced poleward over the eastern North Atlantic, forming a ridge (Figures 6(c–f)).

Figures 4(c) and 6(c) show that the tropospheric flow configuration established a northerly wind regime over Central Europe on 25 December. The occurrence of heavy snowfall during this period suggests the availability of above-normal amounts of moisture. To understand why the snowfall was so extensive, we analyse horizontal water vapour transport represented as vertically integrated water vapour flux in Figure 7. During the 17-day snowfall event, a relatively large amount of moisture (100–300kgm⁻²s⁻¹) was transported from the North Atlantic towards the Alps. Also, Sodemann and Zubler (2009) and Froidevaux and Martius (2016) found the Atlantic source dominant for the moisture delivery to the Alps in the winter season. Figures 6 and 7 suggest that the jet stream position and intensity modulated the water vapour flux. Thus, the blocking played a central role in the advection of cold and moist air from the North Atlantic to the Alps, setting the stage for the heavy snowfall event.

Connection to the stratosphere

In January 2019, a major SSW occurred in the Arctic stratosphere (Rao et al., 2020). To characterise the SSW, we analyse the temporal evolution of the 10hPa zonal-mean zonal wind (U) at 60°N and the 10hPa meridional zonal-mean temperature difference (ΔT) between 60°N and 85°N for December 2018 to January 2019 (Figure 8a). There was a significant deceleration of U from 22 December and finally a wind reversal (from 30 to −10m⁻¹s⁻¹) on 2 January. This process was accompanied by a rapid increase in stratospheric temperature starting on 25 December and lasting during January (Figure 8b). The easterly regime persisted for 21 days until 23 January 2019. This is classified as a major SSW (see, e.g. Charlton and Polvani, 2007; Butler et al., 2017).

The January 2019 SSW was of a mixed type, i.e. the polar vortex was first displaced, and then it split. Figures 9(a–c) show the polar vortex evolution from 25 December to 15 January. The vortex displaced in the last week of December and split into two vortices on 2 January, with one lobe residing over eastern Canada and another over Eurasia. The vortex split co-occurred with the North Atlantic blocking (Figure 4) and coincided with a peak of upward propagating eddy heat flux from the troposphere to the stratosphere (Rao et al., 2019; Butler et al., 2016; Lee and Butler, 2020), suggesting that the blocking pattern may have helped split the vortex. This association is further supported by the analysis of the evolution of GPH anomalies for a vertical cross-section of the North-Atlantic blocking region (50–60°N and 30°W–0°W) in Figure 10(a), which shows coherent GPH anomalies throughout the entire atmospheric column from 25 December to 12 January. This suggests a dynamic coupling between the troposphere and the stratosphere.

Figure 10(b) gives a more detailed insight by resolving the longitudinal structure of the GPH anomalies for 4 January. It illustrates coupling in the region of the block (30°W–10°E) and on the western (50–80°W) and eastern (10–60°E) side of the block, where the vortex lobes resided. Additionally, Figure 10(b) reveals the almost barotropic structure of the block from the troposphere to the stratosphere over the North Atlantic region.

The event was classified as non-downward propagating (i.e. with less probable tropospheric impact) (Rao et al., 2020). However, it is plausible that once split, the ‘daughter’ vortices could have enhanced the tropospheric troughs on either side of the blocking for a few days from 2–6 January when coupling was observed.

Our analysis is consistent with Martius et al. (2009), which revealed a strong link between tropospheric blocking and major SSWs since the stratospheric flow can be disturbed by vertically propagating Rossby waves emitted from the blocking regions.

Prediction of the event

On 27 December, the ECMWF ensemble forecast (ENS) predicted a low-pressure anomaly centred over the North Atlantic...
for the week of 7–13 January (day 12 to 18 in the forecast, Figure 11). The forecast from 31 December had changed to an anticyclonic anomaly over the same area and a cyclonic anomaly over northeastern Europe, bringing cold air towards Austria. This change agrees with the increased signal for precipitation over Austria for 4–6 January that appeared in the forecasts from 28–30 December (Figure 12). This setup left Central Europe and the Alpine region exposed to a northwesterly to northerly flow, part of a meandering frontal zone (Figures 4d,e). It separated maritime subtropical air mass in the west from maritime polar air mass in the east, setting the stage for the 17-day extreme snowfall event (30 December 2018 to 15 January 2019) in the Northern Alps (see the section Synoptic evolution).

On 29 December 2018, ECMWF HRES and ENS predicted the first of the three precipitation peaks (4–6 January 2019) in the Northern Alps as being extreme (Figure 11). The pattern of the blocking high over the eastern North Atlantic stayed remarkably persistent in the period of 7–13 January 2019 when the second and third precipitation peaks occurred.

Discussion and conclusions

In this study, we have identified several factors that contributed to the heavy Alpine snowfall of January 2019. The main characteristics of this event are summarised as follows:

- ZAMG evaluated the 17-day snowfall from 30 December to 15 January 2019 as exceptional in some regions of the Austrian Alps. At several stations, like Hochfilzen and Seefeld in Tyrol, and Abtenau in Salzburg, the total fresh snow amounts measured over 17 days broke 100-year records.
- The snowfall was associated with a northwesterly to northerly flow, which transported water vapour from the North Atlantic toward the Alps. The

Figure 8. (a) Zonal-mean zonal wind at 60°N (dark blue line) and zonal-mean temperature difference between 85°N and 60°N (red line) at 10hPa. (b) Vertical profile of area-weighted zonal mean (60–90°N) temperature anomalies for December 2018 to January 2019.

Figure 9. Polar vortex evolution at 50hPa geopotential height on three selected dates in winter 2018/2019. Panels show (a) vortex prior to before splitting, (b) vortex split and (c) further split with the two smaller vortices displaced apart.
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The atmospheric blocking high over the eastern North Atlantic and a low-pressure system over Eastern Europe. Due to the orographic effect of the mountains, large amounts of snow accumulated on the northern side of the Alps.

- A major SSW occurred in early January 2019. During the SSW, the polar vortex was displaced southward over the North Atlantic region and split into two vortices, with one lobe residing over eastern Canada and another over northwestern Siberia. During these events, the geopotential height anomalies were coupled between the lower troposphere and stratosphere over the North-Atlantic region, where the blocking was located. The reported couplings suggest a possible connection between the evolution of the block and the stratospheric polar vortex split. Blocking may have helped split the vortex due to enhanced upward wave propagation, and subsequent displacement of the daughter vortices could have enhanced the tropospheric troughs on either side of the blocking.
- The accurate location and persistence of the blocking high were only predicted after the stratospheric polar vortex split occurred. It is an open question whether this was just due to reduced lead time or due to improved predictability of the model after assimilating details of the polar vortex split and subsequent SSW once they had been observed. At the regional level, the total amount of snowfall was not precisely resolved, making the forecast of local hazards and impacts (e.g. avalanche risk, snow load) challenging.

The results of this study highlight the importance of further investigation of the connection between winter blocking events and SSWs, which may offer the potential for improved predictions of winter weather. Particularly, investigating the evolution of the zonal asymmetry of the vortex in relation to surface weather may prove helpful in this respect. Future changes in the frequency and intensity of heavy snowfall events remain uncertain. The variability of the amount of snow in the Alps is critically dependent on the Euro-Atlantic flow regimes. According to Scherrer et al. (2004), European blocking regimes explain half of the Alpine snow variability. Given that the European Alps are exposed to the Atlantic and Mediterranean climatic regimes, heavy precipitation, associated with intensified moisture fluxes from these regions, as the result of increasing sea surface temperatures cannot be ruled out. A better understanding of the changes in blocking under a warming climate is therefore fundamental to assess changes in heavy snowfall episodes.

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Figure 11. Weekly-mean ECMWF analysis and ENS forecast sea level pressure anomalies relative to the past 20-year model climate for 7 January 2019 to 13 January 2019. Eight forecasts are shown for that week (bottom right to top middle panel), showing how well the anomalies were predicted compared with the analysis. Shaded areas are significant at 10% level, contours at 1% level. The areas where the ensemble forecast is not significantly different from the ensemble climatology are blank.

Figure 12. Evolution of ECMWF ENS and HRES forecasts of 72-hour area mean precipitation (4–6 January 2019) for the Northern Alps (47–48°N; 10–15°E). The blue box-and-whiskers indicate the 1st, 10th, 25th, 75th, 90th and 99th percentile, black dots the ensemble median, red dots the HRES forecast, and red box-and-whisker the model climate. The green cross corresponds to the mean precipitation for Austria according to ECMWF high-density observations (HDOBS).
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