Present and future synoptic circulation patterns associated with cold and snowy spells over Italy

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Abstract. Cold and snowy spells are compound extreme events that have many societal impacts. Insight with the potential of causing high socioeconomic impacts. Gaining insight on their dynamics in climate change scenarios could help adaptationanticipating the need for adaptation efforts. We focus on winter cold and snowy spells over Italy, reconstructing 32 major events in the past 60 years from documentary sources. We show that despite Despite warmer winter temperatures, some very recent cold spells show abundant, have been associated to abundant, and sometimes exceptional snowfallamounts. In order to explain these compound phenomena, we perform ensembles of climate simulations in fixed emission scenarios changing boundary conditions (such sea-surface temperature, SST)and detect analogs of observed events. Our goal is to analyse the dynamical weather patterns associated to these events, and understand whether those patterns would be more or less recurrent in different emission scenarios using an intermediate complexity model (PlaSim). Our results show that the response of extreme cold weather eventsto climate change is not purely thermodynamic nor linked to the global average temperature increase, but crucially depends on the interactions of the atmospheric circulation at mid-latitudes with the thermodynamic feedback from warmer Mediterranean temperatures. This suggests how Mediterranean countries like Italy could observe large snowfall amounts even in warmer climates. suggest no role of SST in these events, as the run characterized by a +4 K SST change does not show any difference compared to the control simulation. Conversely, under RCP-8.5 emissions, the likelihood of analogous synoptic configurations would increase substantially, only in part compensated by the higher air temperature.

1 Introduction

Cold and snowy spells are driven by the mid-latitude atmospheric circulation through the amplification of planetary waves (Tibaldi and Buzzi, 1983; Barnes et al., 2014; Lehmann and Coumou, 2015), while they are sustained by thermodynamic effects occurring at local scales (e.g. presence of snow on the ground, availability of humidity) (Screen, 2017; WMO, 1966). Previous studies on current and future trends in the frequency and intensity of cold and snowy spells are not conclusive because of the disagreement in the definition of these events (Peings et al., 2013; Vavrus et al., 2006). If we consider separately cold spells and snowfalls, a large consensus is found in the literature: when focusing on cold spells events only, the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (Pachauri et al., 2014, Working Group 1, Chapter 4) points as "very likely" a decrease of number of ice days and low temperatures. Indeed, there is also a large consensus that average snowfall and snow-cover are decreasing in the Northern Hemisphere (Liu et al., 2012; Brown and Mote, 2009; Faranda, 2020). These trends have been observed also for Italy in several studies. The decrease in average snowfall on Northern Italy observed in the last decades has been linked to the increase of temperature due to global climate change ~~(Fig. ??)~~ (Asnaghi, 2014; Mercalli and Berro, 2003). Similar conclusions also hold for the Alpine region (Serquet et al., 2011; Nicolet et al., 2016, 2018). For Central and Southern Italy, ~~existing~~ several studies (Diodato, 1995; Mangianti and Beltrano, 1991) also confirm these trends. On a more general basis, the study ~~by~~ of Diodato et al. (2019) shows that the variability of average snowfall over Italy for the past millennium can be connected to the changes in temperature, with periods of abundant average snowfalls corresponding to generally colder periods (e.g. the little Ice Age) and warmer periods yielding ~~to~~ limited snow accumulations. These negative trends on average snowfall are also expected in future warmer climate emission scenarios (Pachauri et al., 2014, Working Group 1, Chapter 4).

In this study, we focus on the dynamics of the compound dynamics of extreme cold and snowy events, for which the response to mean global change might be different than that of the individual variables (temperature and snowfall). Indeed, taking this complementary compound ~~extreme-events point~~ extreme events point of view (Zscheischler et al., 2020), some authors have found ~~that~~ complex interactions between thermodynamic and dynamical processes ~~occur~~ when cold and snowy spells occur (Deser et al., 2017; Overland and Wang, 2010; Strong et al., 2009; Wu and Zhang, 2010; Coumou and Rahmstorf, 2012; Easterling et al., 2000; Marty and Blanchet, 2012). In particular, warmer surface and ~~sea-surface~~ sea surface temperatures can enhance convective snowfall precipitations under specific conditions and over regions with a large availability of moisture, such as the great ~~Lake in~~ Lakes in the US, Japan and Mediterranean countries (Steiger et al., 2009; Murakami et al., 1994). For Japan, Kawase et al. (2016) have shown that the interaction of the Japan Sea polar air mass convergence zone with the topography may enhance extreme snowfalls in future climates via a thermodynamic feedback. Those analyses raise a number of questions: does the anthropogenic forcing affect the frequency and/or intensity of this kind of compound events? Will the large-scale atmospheric dynamics force high impact cold-spell events despite the thermodynamic warming signals? Will local feedbacks (i.e. warm sea-surface temperatures enhancing convective snow precipitations) play a role in increasing cold spells hazards? ~~We~~

In this paper, we focus specifically over Italy: recent cold and snowy spells in this country have caused several casualties in the population, strongly affected ground and air transportation and caused disruptions in services (meteogiornale.it, last access: 26/07/2020; ansa.it, last access: 26/07/2020). Our strategy to tackle these questions is to analyse ~~ensemble~~ simulations produced in a Global Circulation Model (GCM) under different emission scenarios. We first validate the cold and snowy spells produced in a simplified GCM of intermediate complexity, i.e. the Planet Simulator (PlaSim) (Fraedrich et al., 2005a, b) against those detected in ~~the reanalysis~~ a reanalysis dataset. Then we analyse dynamic analogues of cold and snowy spell ~~ensembles under different emission~~ events under different climate change scenarios. This work is structured as follows: in Section ~~2~~ 2.1, we present sources and ~~data-sets~~ datasets used for the detection of compound cold and snow events over Italy. Simulation results obtained with Plasim GCM are presented in Section 3. We discuss our findings and give an outlook for future studies in Section 4.

2 ~~Methods~~Cold-spells definition and detection of analogues

2.1 Sources and data-set

Our study is based on the ~~simulations of cold and snowy spells produced with PlaSim~~detection of synoptic meteorological configurations likely linked to cold spells over Italy in PlaSim, considering a control run based on present-day climate, a run involving increased SST to evaluate the thermodynamic role of the ocean, and a high CO_2 emission scenario at the steady state. In order to ~~assess the capability of this model in reproducing the dynamics of~~ do so, we will proceed with the following steps:

1. identify large scale, high impact winter cold spells over Italy;
2. describe the dynamic and thermodynamic conditions associated to such cold spells;
3. detect cold spell analogues in a historical climate dataset;
4. detect cold spell analogues in PlaSim runs, and evaluate if climate change can significantly modify their frequency;
5. characterize the PlaSim cold spell analogues in analogy to point 2, to assess the potential of the considered dynamic configuration in producing relevant winter phenomena in a sensibly warmer climate.

In order to identify relevant cold spells over Italy, we ~~have first constructed a dataset of large scale high impacts cold andsnowy spells occurring over Italyduring winter season. For the detection, we combine both professional and~~ consider documented events that have produced at least a record low temperature and/or a record snowfall amount (or snow at locations where snowfall has never been previously reported) at one or more locations in Italy. We combine official sources and ~~non-professional weather-climate websites~~ both professional and avocational websites dedicated to weather and climate, where collections of weather ~~events are availableand~~ event reports are available, and we counter-check their validity with station data and trusted documentary sources (Bailey, 1994; Payne and Payne, 2004).

Our documentary sources ~~are local informal networks~~include local networks, newspapers and periodicals (see ~~Appendix for details);~~ Section 2.2); news and commercial meteorological websites [ansa.it; meteo net; meteolanguedoc.com; 3bmeteo.com; meteociel.fr; meteogiornale.it~~, etc.~~]; ~~temperatures~~ temperature and hydrological records [evalmet.it, Servizio Idrografico e Mareografico Nazionale]. ~~At national scale, we will use the National Centers for Environmental Prediction (NCEPv2) Reanalysis datasets to analyze the meteorological fields observed during the detected events and compare them to those obtained in control runs of Plasim (see Section 3). We give a flavour of the type of events detected by presenting~~

Before we proceed with a more in-depth description of the effects of each cold spell at the country level, we provide a general picture of the typical event through a local analysis ~~for two cities : Bologna ,~~ focused on the cities of Bologna and Campobasso. The former stands at the Southern edge of the Po Valley, at the foot of the North-Eastern Appenninic range; the latter is located in the Po valley on the Northern border of the Apennines and Campobasso, located on the Adriatic Apennines (Fig. ??). Southern Appennini, at about 45 km from the closest Adriatic and 85 km from the closest Tyrrhenian coast. Due to their positions, both cities are exposed to snowfall in case of cold spells characterized by either cold air flowing directly from the East, or by Mediterranean cyclogenesis. In the latter case, Arctic air reaches the Mediterranean Sea through the Rhone Valley — often after the formation of a cyclone leeward to the Alps — and hits the Eastern Italian coasts as Sirroco and Bora winds, as the pressure minimum moves South. In both cases, snowfall on the two cities can be enhanced by the interaction of the Easterly low level winds drawing moisture from the Adriatic with Appenninic range, due to orographic effects. Data for Bologna are taken by provided by the local Regional Environment Protection Agency [https://www.arpae.it/documenti.asp?parolachiave=sim_annali&cerca=si&idlivello=64] and books (Randi and Ghiselli, 2013) by Randi and Ghiselli (2013), while those used for Campobasso by [Servizio Idrografico e Mareografico di Pescara, ; https://www.regione.a Figure 1 shows the amount of snowfall, the minimum temperature near the surface and the duration of each cold spell that are recorded in Campobasso and in Bologna between 1954 and 2018 from hydrological archives [www.arpae.it/documenti.asp]. Since these data are issued from documentary sources, they cannot be used to perform statistical inference of the general behavior of cold and snowy spells over these regions. Qualitatively, they indicate

Given the heterogeneous and, in some cases, unofficial origin of the considered data, we only aim at drawing a qualitative picture. Overall, our analysis indicates that extreme snowfalls have occurred in recent yearsand even with warmer , despite warming temperatures (Fig. 1a). For example, 50 cm to 60 cm snow height was measured in the bordering side of the coasts in Puglia and Marche during the January 2016 event, and a similar amount is was recorded in the hill of Campobasso Campobasso area. The snowfall amounts do not seem to yield decreasing trends, although it can be argued that the duration of the events slightly decreases and their temperatures slightly increase. In another study performed using reanalysis and observational data, Faranda (2020) performed yearly block maxima analyses of snowfalls over Europe, showing that contrasting trends appear for extreme snowfalls over Italian regions.

2.2 Model

In this paper we use The Planet Simulator model (Fraedrich et al., 2005a, b). PlaSim is a climate model of intermediate complexity developed by the University of Hamburg and released open source (see https://www.mi.uni-hamburg.de/en/arbeitsgruppen/theor PlaSim has been applied to a variety of problems including climate response theory (Lucarini et al., 2014), storm tracks (Fraedrich et al., 2005b), climatic tipping points (Boschi et al., 2013; Lucarini et al., 2010a), to analyse the global energy and entropy budget (Fraedrich and Lunkeit, 2008; Lucarini et al., 2010b), to simulate extreme European heatwaves (Ragone et al., 2018) , and to analyse the late Permian climate (Roscher et al., 2011). The horizontal resolution used in this study is about 300 km (T42, $\sim 2.8\,^\circ \times 2.8\,^\circ$) with ten vertical, non-equidistant levels. The dynamical core for the atmosphere is adopted from Portable University Model of the Atmosphere (PUMA). The model includes a full set of parameterization of physical processes such as those relevant for describing radiative transfer, clouds formation, and turbulent transport across the boundary layer. The horizontal heat transport in the ocean can be prescribed or parameterized by horizontal diffusion. The parametrization by the horizontal diffusion has a simplified representation of the large scale oceanic heat transport and then it ameliorates the realism of the resulting climate. The atmospheric dynamical processes are modelled using the primitive equations formulated for vorticity, divergence, temperature, and the logarithm of surface pressure. The governing equations are solved using a spectral transform method. In the vertical, five non-equally spaced sigma (pressure divided by surface pressure) levels are used. The model is forced by diurnal and annual cycles.

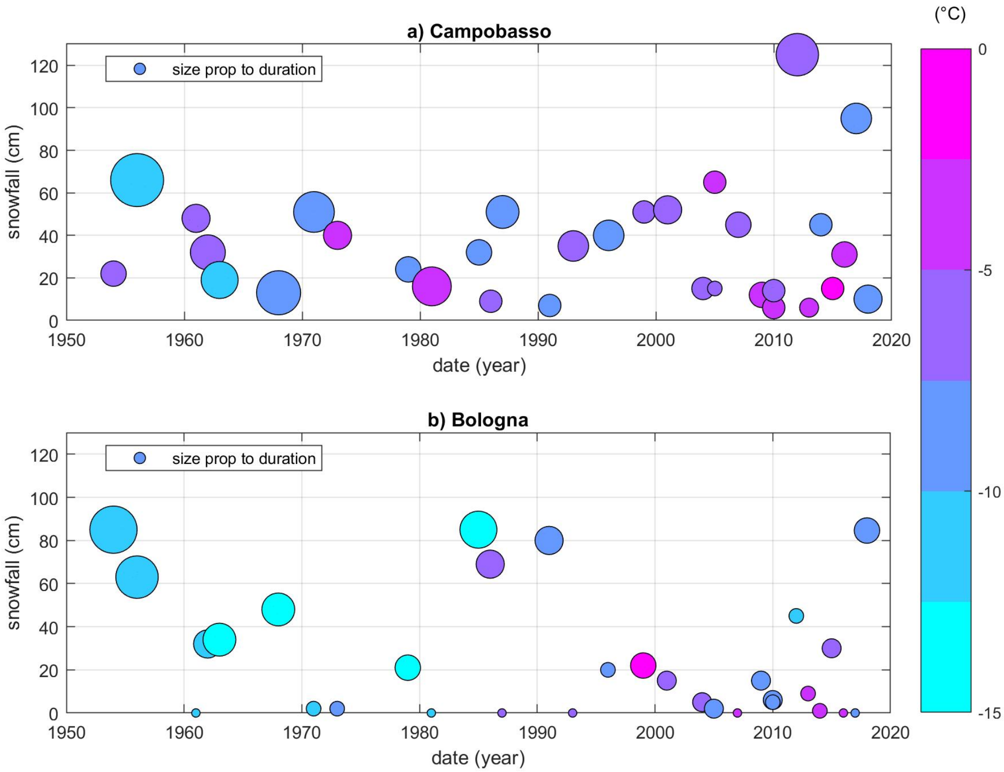

Figure 1. **Cold spells from documentary sources.** Data recorded in a) Campobasso (686 m of altitude); b) Bologna (54 m of altitude). Each ball represents one cold spell event. The size is proportional to the number of snowfall days. The y-axis shows the snowfall measured during each event. The color shows the minimum near surface temperature recorded during the event (see Sources and data-set).

Most of the events detected in the documentary sources include snowfalls that occur near coastal areas or on low lands. In PlaSim, snowfall accumulates for ground temperatures equal or less than zero, if surface energy balance prevents melting. If snow melts according to the energy budget, surface temperature is kept to freezing point until snow is melted completely. Snow cover significantly changes the surface properties like albedo and heat capacity amplifying cooling by a strong positive feedback. On the other hand, the transition from snow to snow-free strongly enhances warming trends. Thus, zero degree can be seen as a threshold were warming and cooling trends may be significantly intensified by a snow cover feedback.

2.2 Description of detected Events

The observational data often come as snow height values (in m), whereas models and reanalysis provide more reliable data on snowfall and then compute snow depth in $\mathrm{kgm^{-2}}$. Since the conversion between these two quantities imply the use of a density which depends on the nature of the snow, there is no direct equivalence between observational data and model simulations. However, PlaSim assumes only a single value for the density involved in this conversion (330 $\mathrm{kgm^{-3}}$) (Kiehl et al., 1996).

Finally, in order to analyse the atmospheric stability during snowfalls events, we will use the PlaSim convective precipitation rate P_c mm/dayof each cloud layer, defined by

$$P_c = \frac{c_p \Delta p}{L g \rho_{\mathrm{H_2O}}} \frac{(\Delta T)^{cl}}{2\Delta t}$$

where Δp is the pressure thickness of the layer and ρ_{H_2O} is the density of water. $(\Delta\mathrm{T})^{cl}$ is temperature tendency and 2Δt is the leap frog time step of the model. L is either the latent heat of vaporization or the latent heat of sublimation depending on the temperature, c_p is the specific heat for moist air at constant pressure and g is the acceleration of gravity.

2.3 Experimental set up: the simulation ensemble

The three simulations that we show in this study are performed with T42 resolution, 500 years long, with a mixed layer ocean. To get reasonable response and present-day climate one needs to add an oceanic heat transport in the mixed layer model (slab ocean, without motion), this can be done in several ways: for our set up we tuned horizontal diffusion (h_{diff}) to have a reasonable global mean SST and a realistic response of SST and ice to the forcing ($h_{\mathrm{diff}} = 4 \cdot 10^4$).

The first simulation is the control run (CTRL) with radiative forcing levels relative to nowadays values: CO_2 concentration is set to a value of 360 ppmv, which is representative of the CO_2 concentration in 2000. The second simulation is based on one of the four Representative Concentration Pathways (RCPs) developed for the climate modeling community as a basis for long-term and near-term modeling experiments (Van Vuuren et al., 2011) (Fig. **??**), the baseline emission scenarios (RCP-8.5) (Riahi et al., 2011). While this scenario consist of increasing greenhouse forcing from 2005 to 2100, in this study the CO_2 concentration is instantaneously set to 1370 ppm (corresponding to a radiative forcing of 8.5 W/m^2) and kept constant afterwards. Our choice of using such a forcing is motivated by the fact that the RCP-8.5 is representative of the high range of non-climate policy scenarios and corresponds to a high greenhouse gas emissions pathway compared to the scenario literature (Fisher et al., 2007; Pachauri et al., 2014). The third simulation is the same as control run except adding a uniform +4 K to the sea surface temperature (4K-SST) globally (Giorgetta et al., 2012). One of the reason for choosing such extreme boundary conditions is the faster warming of the Mediterranean sea compared with the other oceans (Vautard et al., 2014) expected to lead to $\sim +3.5$K SST at the end of the 21st century (Adloff et al., 2015).

Our idea is to explore two scenarios where the radiative heat is affecting mostly the atmosphere (RCP 8.5) and where the heat is mostly stored in the ocean (4K SST) and investigate which differences in the dynamics of cold and snowy spells appear.

In order to assess the proximity of cold spells obtained in simulations to those detected from documentary sources, we will use a methodology of analogues of atmospheric circulation (Yiou et al., 2013) to find the simulation days whose SLP fields over the large Eurasia domain minimize the Euclidean distance from the averaged cold spells detected on NCEP reanalysis. To keep the same statistical sample as that of observations, we select 32 best analogues from simulations.

3 Results

2.1 Atmospheric mechanisms of observed events

In order to track the evolution of a cold spell, we chose a set of variables capable to follow dynamics, thermodynamics and physics of these extreme events. We use sea-level pressure (SLP) (Faranda et al., 2017; Faranda, 2020) (Fig. **??**a) to track cyclonic structures, temperature at 850 hPa (T850) (Fig. **??**b) to track cold air advection without surface disturbances (Grazzini, 2013), geopotential height at 500 hPa (Z500) (Jézéquel et al., 2018) (Fig. **??**c) to follow the large scale circulation associated to cold spell dynamics, , and snow depth (Fig. **??**d) as precipitation variable. Although cold spells cover an area containing Italian borders, the large scale dynamics needs to be tracked on a much larger region including Eurasia 70–22.5N,10W–70E. First, we stress that the average of the four variables over the 32 cold spells shown in figure **??** is similar to a single specific episode. The main characteristics of a cold spell associated with the SLP is the placement of a low pressure over the Mediterranean sea and two high pressure patterns over the Iberian Peninsula and Russia, causing strong cooling over Western/Northern Europe (Fig. **??**a). Temperature at 850 hPa, shows the incursion of cold air coming from Scandinavia and parts of Siberia that extends into South-West Europe (Fig. **??**b). This corresponds to an increase of the Z500 (here expressed in decametres, dam) troughs all over Southern Europe (Fig. **??**c). Over the region where this cold air is advected (Fig. **??**a) snowfall is observed (Fig. **??**d). The snow depth anomaly in this day increases snow cover all over Southern Europe including Italy at low altitude (Fig. **??**b).

2.1 Model assessment for cold and snowy events

The first step is to ensure that the PlaSim model is capable of representing realistic cold and snowy spells. In order to compare the simulated cold spells to those identified in the documentary sources, for each simulation, the 32 best analogues of the NCEP events are selected. We show the average of the sea-level pressure (SLP) (Fig. **??**a,b,c), temperature at 850 hPa (T850) (Fig. **??**d,e,f), geopotential height at 500 hPa (Z500) (Jézéquel et al., 2018) (Fig. **??**g,h,i) and snow depth (Fig. **??**j,k,l) fields for the 32 events identified in the three simulations and visually compare them to those extracted from NCEP (Figure **??**). For all runs we find similar pattern of the evolution of a cold spell in the same set of variables (SLP, T850, Z500, snow depth) as NCEP dataset. the SLP pattern for the control run (Fig. **??**a) shows, as for the NCEP data, a deep cyclonic structure over the Balkans and two high pressure systems located over Russia and Western Europe. Anticyclones are weaker for the RCP-8.5 (Fig. **??**c) and stronger for the 4K-SST simulation (Fig. **??**c). Despite the warmer ocean, cold air advection at 850 hPa (Figure **??**d,e,f) in the Mediterranean basin is deeper in the 4K-SST simulation than in the RCP-8.5 one. This corresponds to a larger geopotential height wave structure (Figure ??g,h,i) with a trough on the Mediterranean sea. This also produces more snowfall over the Alps and Eastern Europe for the 4K-SST run than in the RCP 8.5 simulation (Figure ??j,k,l). We also remark that the average snowfall amounts in the RCP 8.5 scenario are almost zero (Figure ??k) although some events actually show positive values on the Mediterranean basin.

To better quantify the degree of similarity among cold spells in space and time, we computed pairwise correlations between the events of the anomalies of three atmospheric fields (SLP, T850 and Z500) at time lags of a few (60) days before and after the event. We construct matrices of those pairwise correlations and average them (Fig. ??a). For the scenario runs we applied the same pairwise correlation as for NCEP dataset and control run and we find correlations significantly non zero for ~ 10 days (Fig. ??b,c,d). We tested the significance of these correlations by bootstrapping with 1000 random samples of 32 days during winter within 120 time-lag from the sample, finding always correlation values smaller than 0.1.

2.1 Roles of anthropogenic forcing and climate change

Once assessed the capability of PlaSim in detecting cold spell events with a large-scale dynamics alike observations, we study the response of cold spells dynamics to CO_2 concentration increase and global SST warming by studying the temporal evolution of CTRL, RCP8.5 and 4K-SST simulations against the events detected in NCEP datasets. First, we perform a spatial average of both T850 (Fig. ??a,b) and snow depth (Fig. ??c,d) variables on the region where the documentary sources about the extreme events are available 35–47.5N, 7.5–20E. Once performed the mean, we construct the anomalies either just by subtracting the seasonal average (Fig. ??a,c) or by subtracting the seasonal average and dividing by the standard deviation (Fig. ??b,d) over the selected region at different time lags for each simulation and for the NCEP reanalysis.

Figure ??a) displays different minima of 850 hPa temperature anomaly in CO_2 and SST-forced runs with respect to control conditions around lag 0. Furthermore, the spread of the negative temperature anomalies among all simulations is small, implying that the dynamical evolution is comparable through different events. The minimum of the temperature anomaly for the 4K-SST (-6.7 C) is slightly lower compared to all other cases (-6 °C in NCEP reanalyses, -5.6 °C in CTRL, -4.8 °C in RCP8.5). This is a counter intuitive result as warmer anomalies are expected under anthropogenic forcing. It can however be explained by looking at the deep geopotential ridge in Figure ??i) associated with the two large anticyclonic structures over Western Europe and Russia (Figure ??c). The anomalies of snow depth show a peak around lag 0 for each simulations and for NCEP reanalyses (1.83 kgm^{-2}). Although the RCP8.5 scenario shows a small amount of snow at lag 0 (0.31×10^{-2} kgm^{-2}) compared with all other cases, we find a signal during the cold spells compared to the seasonal mean (Fig. ??d).

We also find the highest snow depth in 4K-SST simulation at lag 0–5 (2.65 kgm^{-2}). This can be explained for Italy by the amplification of one effect related to cold air passing over warmer waters (the so called "Lake-effect snow" (Eichenlaub, 1970)). Lake-effect snow forms when a very cold winter air mass flows over relatively warmer waters of large area as for example a lake: the lower layer of air picks up water vapor from the lake surface. This warmer and wetter air rises and cools as it moves away from the lake. These conditions form convective clouds (see Fig. ??) that transform all the moisture into snow. In our case the warm waters are represented by the Mediterranean sea that get even warmer under climate change. The cold air coming from the Scandinavian region across the warm sea becomes moist and rises over the cooler Italian Apennines mountain range. This effect is amplified by a warmer ocean in the case of 4K-SST simulation causing a cooler and a more snowy cold spell event. Given the low resolution of PlaSim simulation, we need to confirm this hypothesis with information about atmospheric stability and see whether the 4K-SST run favor instability during cold and snowy spell events. We do this by using the convective precipitation (Kuo, 1965, 1974), whose definition (see Eq. (**??**) in the Experimental set up) includes the lapse rate parameter so that when the convective precipitation is lower the instability of the atmosphere is higher. In figure **??** the difference of convective precipitation between 4K-SST run and CTRL run exhibits atmospheric instability over the Ionian sea agreeing with the low pressure persistence on the corresponding area (Fig. **??**a). Due to the higher instability in the 4K-SST simulation with respect to the control run, snowfall precipitations are more intense. Other studies have pointed out the role of instability in triggering heavy snowfalls in the proximity of large water basins. For the Mediterranean sea, Faranda (2020) has shown that large Convective Available Potential Energy values are associated with more intense snowfall events in the Balkans. For Japan, Kawase et al. (2016) have shown that anthropogenic forcing may enhance extreme snowfalls in future climates via a thermodynamics feedback occurring during the interaction of polar air mass convergence zone with the Japanese topography.

We now turn the analysis of changes in the frequency of occurrence of the cold spells. The recurrence rate of cold spells in simulations is defined by the number of days that yield atmospheric features that are close to those identified in the NCEP reanalysis. We use both compound SPL-T850 anomalies and SLP-Z500 anomalies to obtain a distance to identified cold spells, and compare those distances to the closest analogues within the NCEP reanalysis. In order to check the robustness of our results against the change of minimal threshold, we use different low quantiles of the distances (Tab. 1). In Table 1 the frequencies of the two scenarios are expressed as the frequency rate of cold spells with respect to the control simulation.

The RCP8.5 run shows a frequency comparable (≈ 1.01) to the control run. This means that the chance of cold event happening in this region does not decrease under anthropogenic forcing. In the 4K-SST simulation, the frequency of the cold spells shows two slightly different decreasing trends: one based on the T850 anomalies that has frequency about ≈ 0.89 compared with the control run and the second one based on Z500 anomalies has a frequency almost similar to the control run (≈ 0.98). This proves that under ocean warming conditions the dynamic processes (related to the atmospheric circulation) are more favored than those due to thermodynamic processes (related to land atmosphere interactions) to determine hazardous cold spell conditions.

3 Discussion and conclusion

We have characterized high impact cold spells over Italy over the past 60 years by assessing their common dynamical large scale signature. Despite the difference in duration, snow depth and intensity recorded during each event, they are all associated to the amplification of planetary waves and cold air advection from the East. These patterns seem to play a prominent role in present and future climate in generating hazardous cold spell conditions even in a warming climate. Our results bring two possible outcomes (or a combination of the two) in the future: one is a decrease of heavy snowfall driven by the RCP-8.5 scenario and the second one features an increase of heavy snowfall following the 4K-SST simulation. The discriminating factor will be the rate of warming of the Mediterranean sea, which is expected to be faster than the oceans (Volosciuk et al., 2016; Shaltout and Omstedt, 2015). If the Mediterranean sea will warm faster than the atmosphere, larger atmospheric instability could still trigger heavy snowfall in the area. On the other hand, if the atmosphere will warm fast enough as in the RCP8.5 scenario conditions, then snowfalls in the area will be suppressed. In the current climate, recent snowfall events seem to benefit from this enhanced thermodynamics feedback through increased instability (Faranda, 2020). In our simulations this feedback is only evident in the 4K-SST simulation. Our results therefore point to a complex response of extreme snowfalls with respect to the average decline of snowfall and snow cover observed (Diodato, 1995; Mangianti and Beltrano, 1991; Mercalli and Berro and that thermodynamics feedback could still produce extreme snowfalls in future climates (Pachauri et al., 2014, Working Group 1, Chapte .

These conclusions are motivated by a combination of dynamical and thermodynamic analyses. Indeed, in our simulations i) the abundance of patterns corresponding to the amplification of planetary waves does not depend on the absolute global temperature but rather on the tropics-to-poles temperature difference which is then linked to ocean warming and sea-ice melting, ii) a warmer ocean can trigger snow-lake-like effects over the Mediterranean sea during cold spell events, enhancing convective precipitations and favoring heavy snowfalls. These combined effects show that when dealing with compound extreme events, the thermodynamic average climate change signal must be weighed against other dynamical and physical feedbacks. This mechanism is a robust signal and it can be generalized to other cold spells affecting other countries at mid-latitudes where great water masses can have an impact on convection such as Japan, Korea, the region of Great Lakes of North America.

This study comes with some caveats and limitations: although we have validated the behavior of PlaSim against NCEP reanalysis, results on frequency changes for cold spells crucially depends on the position and the destabilization of the jet stream. It is known that different climate models have a different response of jet stream dynamics to climate change (Arctic Amplification (Cohen et al., 2014) or Zonalization (Francis and Vavrus, 2012)). Further studies should also take into account that snowfall amounts are better predicted using humidity and air temperature in large-scale land surface model runs, than just using the current and past scheme used in PlaSim as well as in other general circulation models (Jennings et al., 2018).

We doubt however that an analysis of forced non-stationary simulations as those produced in scenario runs may provide a better understanding, because of their limited duration and the inter-decadal variability superimposed to the non-stationary signals. Furthermore, we have investigated the lake effect from the point of view of large-scale instabilities. Future studies with regional climate simulations may focus on the robustness of this phenomenon on smaller scales.

3 Appendix

Cold-spells detection

In this appendix we In this section, we describe each extreme cold event selected as a cold spell in this study. The mains characteristics of the events are the occurrence of snowfalls in region where snow-cover regions where snow cover has usually been rare or absent since a long time (e.g. lowlands and coasts), the societal impact was disaster large socioeconomic impacts (e.g. in 2017), extreme minimum temperatures, and extreme amount of snowfalls. The date reported at the beginning of each event is the one selected as the most representative day of each cold-spell event and it is the one used for the ~~analogs~~ analogues search. The information about the duration of the events are reported in the text for each description.

~~04th~~ 1) 4th January 1954. A cold spell rapidly built in the Mediterranean in January 1954 (an exceptional month in Spain). Heavy snowfalls ~~in lowland areas (Po Valley)~~ affected all of northern Italy, including lowland areas in the Po Valley. In 24 hours, 60 cm of snow fell over Turin, Brescia, Milano, Piacenza, Cremona, Reggio Emilia, Bologna and Vicenza (~~-5~~ -5°C at 1400 m Osservatorio Meteorologico del Collegio Alberoni of Piacenza) according to information found in the press (Resto del Carlino 05/01/1954). ~~Many traffic blocks~~ Traffic disruption occurred mainly in Piacenza and Cremona (daily local journal of Cremona 06/01/1954).

~~04th~~ 2) 4th February 1956. One of the coldest and snowiest ~~event~~ events of the 20th century in Europe. The ~~Po Valley was below a~~ -15°C isotherm at 850 hPa was located above the Po Valley (1-2/02/1956 Wetterzentrale.de (last access: 26/07/2020))~~, and~~ ; snow storms affected the entire country~~. Rome experienced~~ , with a historical snowfall in Rome. A powerful extratropical cyclone embedded in very cold mid-tropospheric air core struck the ~~southern~~ Southern regions causing heavy snowfalls in Rome and throughout central and ~~southern~~ Southern Italy, with blizzards and ~~freezing temperatures, frostand snow. In those days it snowed~~ heavy frost. Significant snowfall was reported even on the Sicilian ~~coasts. In~~ coast: in Palermo, the minimum temperature dropped to 0° C (daily data of Palermo and Sicily on 1956, ANNALI/A1956) and the city was blanketed by several centimeters of snow, which also fell on the southern coasts of Sicily and the island of Lampedusa (Corriere del mezzogiorno of 07/02/2011).

3) 17th December 1961. December was a very cold month for most of Italy with a historical snowfall in southern Italy coastal areas as in Bari (30 cm, Protezione Civile Puglia of 17/12/1961). After 3 days of heavy snowfall, a record snow height of 370 cm was reported in Roccacaramanico (1050 m ~~of altitude~~above sea level on the East side of the Central Appennini) on December ~~20th~~ 20 (Annali idrologici Sezione Autonoma del Genio Civile Pescara 12/1961), and all the Adriatic regions were affected by heavy snowfalls (meteogiornale.it (last access: 26/07/2020) of 18-12-2014).

4) 31st January 1962. Sicily reported several historical records of ~~minimal~~ daily low temperature as in Lentini città (-2.5°C~~, 43 m of altitudine~~), Caltanissetta (-4.5°C), Caltagirone (-3.2°C), Castronovo di Sicilia/Piano del Leone (-8.5°C)(Osservatorio delle Acque 01-02/1962). Heavy snowfall occurred on the North coast, in Palermo and Capo d'Orlando ~~(8 m of altitude) (~~meteolive.it (last access: 26/07/2020) of 28/02/2002, meteosicilia.it (last access: 26/07/2020) of 07/12/2007).

5) 22nd January 1963. Winter 1963 was one of the coldest ~~winters in the records for Western Europe. That year,~~ in Western European records. Sea frost trapped Norway's islanders~~in ice and caused severe hardships to millions of Europeans. The cold primates belong to Sweden and Finland. In northern Sweden it went below~~ , while a record low temperature of -41.2°C ~~(record of Karesuando, SMHI (last access: 26/07/2020) of 19-01-2014)~~was recorded in Northern Sweden village of Karesuando. Average temperatures for the month were in excess of -5°C below normal from southern England across Europe to the Urals. Warsaw reported an average temperature of -12.4°C for January, while Paris averaged -5.5°C below normal. ~~Even~~ Mediterranean regions averaged about -3°C below normal (James, 1963). The upper reaches of the ~~River Thames~~ Thames river froze thamesweb.co.uk (last access: 26/07/2020) and the lowest temperature in the Germany was measured on January 20th 2 at Quedlinburg at −30.2°C (Eichler, 1971). In Italy the temperature dropped due to drop was brought by strong bora winds (110 km/h, Annali Idrologici Ufficio Idrografico del Po 01/1963) and heavy snow settled snow accumulation over Friuli-Venezia Giulia (5 cm to 10 cm) reaching Venezia(The Venetian Lagoon turned into ice-pack deep 10-15 cm). Arctic , where the Lagoon also froze. Very low temperatures (Trieste: −9°C, Udine: −10°C, Pordenone −15°C, Milano: −8°C, Bologna −7°C, Annali Idrologici Ufficio Idrografico del Po, Arpae.it (last access: 26/07/2020) 01/1963) affected all other regions of Italycausing , with snowstorms over Toscana, Marche, Abruzzo, Molise, Apulia, and several cities were completely isolated (meteogiornale.it (last access: 26/07/2020) of 21/01/2011, Randi and Ghiselli (2013), regione.abruzzo.it (last access: 26/07/2020); protezionecivile.puglia.it (last access: 26/07/2020) 01/1963).

6) **12th January 1968**. In Between the 9th and the 15th January 1968was , Tuscany and nearby areas were affected by one of the strongest cold spell that ever affected Tuscany. The cold period lasted from 9th to 15th January. Very low minimum temperatures were reached and even some highs were very coldspells on record for the region. Extreme daily low temperatures were recorded: Città di Castello (Umbria, 295 m, Ufficio Idrografico di Roma) −23°C, Arezzo (S. Fabiano) (277 m) −14.2°C, Verghereto (812 m) −15.2°C, Cortona (393 m) −8.7°c (Annali Idrologici Genio Civile Pisa 01/1968). Snow fell all over that area: Heavy snowfall affected the area, with snow depth measuring: 65 cm in Eremo di Camaldoli (1111 m) 65 cm, above sea level), 60 cm in Verghereto (812 m) 60 cm, a.s.l.) , 15 cm in Arezzo (S. Fabiano) (277 m) 15 cm, Laterina (191 m) 18 cm also a.s.l.), and 19 cm in Florence (Ximeniano) (Ximenian Observatory, 51 m) 19 cm of snow a.s.l.) (Annali Idrologici Genio Civile Pisa 01/1968); (La Nazione of 11/11/1968).

7) **28th February 1971**. On February 24th, the penetration of Arctic air into the Mediterranean sea from the eastern edge of an anticyclone extended 24, the presence of an omega blocking with an anticyclone meridionally elevated towards the British isles , triggered heavy snowfalls and a cold spell over Italy. Initially, the event affected northern European countries. The most sensitive drops in temperatures affected Italybetween the evening of February 28th and the morning of March 1st. and a trough with a pressure minimum over Central Mediterranean, triggered a flow of Arctic air towards the Mediterranean. After affecting Northern Europe, the cold spell reached Italy, causing a severe temperature drop between February 28 and March 1. On the morning of 1st March March 1st, almost all of Italy recorded minimum temperatures below zero even on the lowland in lowland and coastal areas: −5°C in Florence and Pisa (Annali Idrologici Genio Civile Pisa), −4°C in Rome (Ardea, Ufficio Idrografico di Roma 02/1971), −1°C in Naples (Annali Idrologici Genio Civile Napoli 02/1971) with a snowfall that also reached the coastal areas of the city (La Stampa of 6-7/03/1971).

8) **1st December 1973**. Very Low temperatures leading to negative values were recorded in 1973 throughout the North and Central Italy .The isotherms reach At the beginning of December, a cold air mass associated to a low pressure area reached Italy from Scandinavia, with the −15°C at 850 hPa in isotherm located over the Alps. Cold conditions persisted for long time, yelding to low minimum temperatures during the first two weeks of December(, reaching −7°C in Novaraand Treviso , Treviso and Arezzo, −6°C in Udine , but also −6.4°C in Potenza and and Potenza, −5°C in Foggia, in Apulia). Temperatures decreased

to −2°C in Trieste, −7°C/−8°C in Novara and Arezzo, and −19°C on Monte Cimone with Nord-East (2173 m a.s.l.), where North-Easterly wind at 133km/h was also recorded. Due to these conditions, the highways remained closed in Tuscany for half a day. In Florence, , disrupting important road networks. Snow fell in Florence, (17 cmof snow fell, as it did not happen for many years. In), and Valle del Serchio received 30 cm of snowfell where for over , after around 40 years the during which snow was almost absent. Heavy snowfall (Snow accumulations (≈15 cm) fell was also recorded in Perugia, Gubbio, Assisi, Spoleto, Sangemini . In Friuli, temperatures of −17°C were recorded in Fusine and −12°C in Tarvisio (sienanews.it (last access: 26/07/2020) 13/12/2016, Annali Idrologici Ufficio Idrografico Magistrato delle Acque di Venezia.; Annali Idrologici Genio Civile Pisa; Annali Idrologici Genio Civile Catanzaro; Annali Idrologici Genio Civile Bari; Annali Idrologici Ufficio Idrografico del Po, Arpae.it (last access: 26/07/2020), 12/1973, Aeronautica.Militare (last access: 26/07/2020)).

9) 15th January 1979. This cold spell A large pool of Arctic air stretching up to the North African coasts brought a cold spell that affected most of Europe, including Italy. This exceptional irruption of cold air claimed numerous casualties. In Italy the arrival of cold air first manifested itself with strong winds and storms on the Tyrrhenian coasts; subsequently there was a sharp decrease in temperature causing several fatalities. The cold air caused wind storms in the Thyrrenian Sea, followed by a severe temperature drop. Snowfall occurred in Tuscany (Annali Idrologici Genio Civile Pisa 01/1979), Sardinia and most of central Central and Southern Italy, with snowstorms in the Marche, in Abruzzo, Molise (regione.abruzzo.it (last access: 26/07/2020)) and Basilicata (evalmet.it (last access: 26/07/2020)) regions. The most abundant snowfalls were observed on January 9th with the arrival 19 with the advection of more temperate and humid masses, mainly from South-Western currents. Ice problems air from the South-West. Traffic problems due to frost on the roads and in the to iced pipes were reported (Resto del Carlino 13/11/1979).

08th 10) 8th January 1981. Western and Central Sicily remained blocked on 08th January 1981 for An very cold air mass penetrated deeply in the Central Mediterranean Sea, accompanied by an intense storm over the South of Italy. On January 8, Western-Central Sicily was disrupted by unprecedented amounts of snow and minimum temperature were recorded. That day it even snowed on the small island of Pantelleria (for the area, with 30 cm of snowfall even on the coasts. Extremely unusual snowfall was observed even on Pantelleria, a small island located South of Sicily, with only 5 m elevation). Many cities , from Palermoto Trapanifrom Messina to above sea level. Some cities in the provinces of Palermo, Trapani, Messina and Enna, remained isolated for whole days. The whole south of Italy was swept by an immense storm with 30 cm of snow fell on Sicilian coasts and the temperature days. Temperature reached a historical minimum of −0.5°C in Palermo, where continuous snow precipitations for more than 24 hours are an exceptional event (Giornale di Sicilia 7/01/1981, meteolive.it (last access: 26/07/2020) of 28/02/2002, Annali Idrologici Genio Civile Palermo 01/1981).

07th 11) 7th January 1985. From 1st to 15th 17th January 1985, Italy and most of Western Europe were affected by a disruptive and persistent cold spell. The cold air (associated to a Bora wind that blew up 100km/h) favored cyclogenesis over the country and a minimum of low pressure formed A cyclogenesis over Central Italy, between Tuscany and Lazio. This triggered , triggered strong Bora winds and historical snowfalls that abundantly interested affected Florence with 40 cm of accumulation (up to 80 cm in the Val di Cecina) and Rome with 30 cm. The pressure minimum moved towards south-east between the South-East between the 6th and 9th January, and the snow reached also Campania and the rest of the south South with accumulations up to 25 cm on the hilly zones of Naples, as it had not happened since 1956 (Annali Idrologici Genio Civile Napoli 07/1985). ~~In the Northern regions −20°C were registered on the Po Valley. Between 10th~~ Between January 1 and 11th ~~January further~~ temperature records were broken in the minimum values ~~as~~ in Florence (Peretola, −23.2°C) and Piacenza (S. Damiano, −22.2°C). The Northern regions were particularly affected a few days later, between January 14 and 17: temperatures around −20°C were registered in the Po Valley, and exceptional snowfalls disrupted traffic and industrial activities in the cities of the North, including Milan, with historical accumulations. (Aeronautica.Militare (last access: 26/07/2020); valdarnopost.it (last access: 26/07/2020) of 14.01.2015, Il Mattino of 27/02/2018, firenzemeteo.net (last access: 26/07/2020) of 19/01/2017).

12) 24th December 1986. ~~The situation for Christmas day 25th December~~ Christmas day 1986 was characterized by strong winds and 850 hPa isotherms of −10°C that covered most of Italian Peninsula (meteociel.fr (last access: 26/07/2020) 25/12/1986). In Pescara, on the evening of December ~~26th~~26, the temperature reached −9°C and about 15 cm of snow fell. Snowfall affected the entire Adriatic side of the country (5 cm in Perugia, more than 30 cm in Molise). In Ancona (Falconara) wind gusts exceeded 95 km/h with a minimum temperature of -6°C (Aeronautica.Militare, last access: 26/07/2020). The snow then reached Sardinia and even Apulia, where the temperature in Bari dropped to −1°C (Annali Idrologici Genio Civile Bari 12/1986). A ~~minimum (December) temperature record was held in Pantelleria~~record low temperature for December was measured in Pantelleria, with 2.6°C on December ~~25th~~ 25 (Annali Idrologici Genio Civile Palermo 12/1986, meteolive.it (last access: 26/07/2020) of 31/01/2008, meteogiornale.it (last access: 26/07/2020) of 31/12/2014).

~~03th~~ 13) 03rd March 1987. Cold air and stormy weather reached the extreme ~~south/east~~ South-East of Italy, with ~~the maximum~~ a peak on 8th March 1987 when the -12°C 850 hPa isotherm covered the whole of Apulia (Annali Idrologici Genio Civile Bari 03/1987). Snow fell ~~also in~~ on the Southern cities of Naples, Crotone and even in Palermo. ~~The most impressive element was the snow accumulations that were recorded in~~ Impressive snow accumulations were recorded on those days: ~~at~~ in Gioia del Colle ~~the snow~~ snowfall reached 72 cm~~of accumulation~~, for a total of 9 days of permanence of snow on the ground, exceptional for the area (Annali Idrologici Genio Civile Bari 03/1987, 3bmeteo.com (last access: 26/07/2020) of 08/03/2019; La Repubblica of 12/03/1987, meteogiornale.it (last access: 26/07/2020) of 13-03-2005).

14) 31st January 1991. ~~The temperature cooled down under the effect of a Bora wind up and dropped to~~ Cold air entered the Mediterranean as strong Bora winds, causing temperature to drop to −4.2°C in Trieste (Annali Idrologici Ufficio Idrografico e Mareografico di Venezia 01-02/1991). Snow fell on Bologna, Rimini, Forlì, and ~~finally even~~ eventually on the Marche coastal area, with 5 cm of ~~snow that fell~~ accumulation in the harbour city of Ancona. ~~During the day, the cold air moved to the west~~ The cold air mass also spreaded West over the Po Valley, from Veneto to Piemonte, with widespread snowfalls. Minimum temperatures of −21.2°C were recorded at Passo Rolle, −12°C ~~at~~ in Novara, −11.6°C ~~at~~ in Bologna (Aeronautica.Militare, last access: 26/07/2020). February ~~7th~~ 7 is one of the coldest (Annali Idrologici Ufficio Idrografico e Mareografico di Venezia; Annali Idrologici Ufficio Idrografico e Mareografico di Parma 01-02/1991) days in the history of Northern and Central Italian climatology (Randi and Ghiselli (2013), meteoservice.net (last access: 26/07/2020) of 05/02/2016, recordmeteo.altervista.org (last access: 26/07/2020) of 01/03/2012, La Repubblica of 02/02/1991).

~~01st~~ 15) 1st January 1993. ~~The first day of the year a massive continental polar~~ A zonally tilted anticyclone with pressure maxima between the UK and Scandinavia draw a large Arctic air patch, ~~the Buran, reached Italy.~~ from Russia towards Italy. Due to the peculiar configuration, cold air flowed from Russia through Ukraine, Romania and the Balkans, then mostly affecting Southern and Central Italian regions~~were mostly affected~~, especially the Adriatic ~~slopes~~ side, where the snow fell also in coastal areas. The absolute minimum temperature record was broken in Bari (−5.9°C) (Aeronautica.Militare, last access: 26/07/2020). Snow fell in the southern part of the Italian ~~boot (Messina and Reggio Calabria), in the north plains~~ peninsula and Sicily (Reggio Calabria and Messina), but also on the Po Valley (Parma, Modena, Reggio Emilia)~~and~~ , on the Adriatic coast, from Rimini to Cattolica~~. Abundant snowfalls affected the Po Valley, especially Emilia, Tuscany, up to Central Italy. It also snowed in Rome, in the northern areas of the city. In the National Park of Casentino, next to Arezzo, amount of 30 cm of snow fell in few hours. At the same time was snowing simultaneously in the two sides of the Tyrrhenian and the Adriatic coasts~~, and in Tuscany. Snowfall was also observed in the Northern part of the Rome metropolitan area. Snowfall affected the Thyrrenian and Adriatic sides of Italy simultaneously, which is rare. The cold air moving westward ~~caused extensive new~~ then caused additional extensive snowfalls in the North and Central Italy. Intense cold conditions persisted for a long time in the Po Valley with record-breaking temperatures, such as −13°C in Milan and almost −20°C in Emilia (meteolive.it (last access: 26/07/2020) of 11/11/2009, meteo.ansa.it (last access: 26/07/2020) of 17/12/2015, Corriere della Sera of 03/01/1993.

16) **27th December 1996**. This cold spell has also ~~covered England~~ affected the UK and France (−7°C in Paris; Le Parisien 03/01/1997) causing the Thames river to freeze in London and 200 ~~deaths and freezing over the river Thames in London~~ fatalities (Jordan-Bychkov and Murphy, 2008). On December ~~27th heavy snowfalls striked the~~ 27 snow storms striked the North and the Adriatic side of Italy from Romagna to the South. On December ~~29th a very~~ 29, heavy snowfall affected Central Italy and Southern Tuscany in unusual areas (20 cm were recorded on the Lazio coast, 35 cm in Porto Santo Stefano, Aeronautica.Militare (last access: 26/07/2020)). On December ~~30th snow appeared~~ 30 snow fell again over the North in Milan, Como, Varese, Pavia and throughout the whole of Piedmont. A snow storm ~~blowed in Genova. In Bolzano snow fell up 30 cm.~~ blew the coastal city of Genoa. Extremely low minimum temperatures affected the areas covered by snow (between −10°C and −15°C in Southern Tuscany and Umbria, Annali Ufficio Idrografico e Mareografico di Pisa 12/1996). The official weather station of the city of Arezzo (Molin Bianco, 248 m ~~) on December 30th~~ a.s.l.) recorded a minimum of −15°C on December 30 (Aeronautica.Militare, last access: 26/07/2020), a monthly record for December from the beginning of records (1957).(La Repubblica 27/12/1996 and 28/12/1996, meteolive.it (last access: 26/07/2020) of 20/10/2017).

17) **31st January 1999**. ~~This winter was rather cold and snowy with the peak that was reached between the third decade of January and the first part of February. The freezing~~ Arctic air reached Italy, particularly affecting the Central and Northern regions~~on February 5th.~~ , on February 5. The snow affected ~~all the~~ the entire Po Valley, from Venice to Turin, with accumulations up to 30 cm ~~or higher~~ on the plain. ~~The snow~~ Snow also fell abundantly in ~~Forlì,~~ the coastal cities of Rimini, Ancona, Grosseto,~~Parma, Florence, Lucca and Genova~~Genoa, and in the Tuscan cities of Florence and Lucca. A snowstorm struck Viterbo and snow flakes were also observed in Rome with a remarkable −6°C temperature (Annali Ufficio Idrografico e Mareografico di Roma 01-02/1999)~~where the fountains of the city froze, which is~~ , which caused the public city fountains to freeze, a rather unusual and damaging phenomenon~~for the historical heritage of the city~~, given the often ancient origin of the fountains. The temperatures decreased sharply and there were a few days of ice (maximum below zero) in the city. ~~Among very low~~

~~temperatures , we remark~~ Other notably low temperatures include 3.8°C ~~on 31st January at Palermo~~ in Palermo on January 31 (Osservatorio Astronomico di Palermo), −12°C in Norcia (Annali Ufficio Idrografico e Mareografico di Roma) and −21°C in Dobbiaco (1213 m of altitude, (Aeronautica.Militare, last access: 26/07/2020)). The strong Bora wind gusted up to 90 km/h in Trieste on ~~4th February~~ February 4 (Arpa Friuli Venezia Giulia last access: 26/07/2020 02/1999). Snow fell on Sicilian coasts and accumulated up to 5-10 cm ~~for~~ in a few hours on the beaches of the Nebrodi areas (Arpa Regione Emilia Romagna Annale Idrologico 01-02/1999, La Repubblica of 24/02/1999, meteoweb.eu (last access: 26/07/2020) of 05/01/2017).

~~**08th**~~ **18) 8th December 2001**. Before affecting Northern Italy, ~~the~~ cold air reached parts of Central-Eastern Europe from Russia. On the evening of December ~~13th a snowstorm caused transportdisruptions~~ 13, the air mass entered the Po Valley in the form of strong Bora, causing convection accompanied by a blizzard-like snowfall that caused transport, electricity and phone line disruptions, and isolated several small towns in Northern Italy. in Trieste the Bora wind blew at 116km/h with −4°C. In Tarvisio on 15th ~~of~~ December the temperature reached −16°C (Arpa Friuli Venezia Giulia last access: 26/07/2020 12/2001). ~~The Po Valley appeared frozen and white. That cold spell is~~ This storm is today remembered as the famous "Blizzard of Saint Lucia"~~. That cold spell was so intense that is~~ , long lived in the memories of the inhabitants of the ~~Northeast~~North, since the blizzard combined heavy snowfalls with ~~intense wind~~damaging winds. On that occasion, the origin of cold air masses was Eastern Europe and Russia. Due to the strong wind, snow fell horizontally and stuck to the walls of ~~the building~~buildings, rails and guardrails of highways with heavy transport disruptions ~~. The number of accidentscaused by ice was high~~and several accidents. The snow accumulation fluctuated between 5 and 25 centimeters on the plains, depending on the area ~~, with greater~~ and on exposure to wind, with larger values in Emilia-Romagna: temperatures of −16°C were recorded in Fiorenzuola (422 m of altitude), −7°C in Reggio Emilia and −5°C in Cesena on 17th and 18th ~~of~~ December (Arpae.it (last access: 26/07/2020))~~: the snow mantle was irregular due to the strong winds~~.(La Repubblica 17/01/2001, meteoweb.eu (last access: 26/07/2020) of 06/12/2011)

19) 20th January 2004. During this event, icy currents ~~flew~~ flowed from the Northeast towards Northern Italy, with weak snowfalls ~~on~~ over Emilia, up to medium-low altitudes. In the following days, however, it snowed again in the North and in the Central regions at lower altitudes: snow reached Tuscany, Lazio, with snow flakes even ~~on~~ in Rome. The temperatures in these days of January were particularly low on the north-eastern Alps (−11.2°C Dobbiaco, Protezione Civile Provincia Autonoma di Bolzano 01/2004) and on Central and Southern Italy, where widely negative values were ~~reached on~~ recorded over the usually mild Tyrrhenian plains (−5.2°C at Fiumicino, −6.3°C in Rome and −4°C ~~at~~ in Ciampino, Agenzia Regionale Protezione Civile Lazio Annali Idrologici 01/2004). The whole region of Lazio experienced particularly cold days. The cold also affected Irpinia and Basilicata (with ~~temperature~~ temperatures below zero on the Ionian sea coast, (evalmet.it, last access: 26/07/2020) 01/2004), Molise, Abruzzo and ~~APulia. The snow fell in abundance on the Murge, but also locally on the Apulian~~ Apulia, where the snow occasionally fell also on the coast. During this ~~exceptional event~~event, exceptionally low temperatures were measured in these areas: temperature dropped zero in Foggia, a coastal town in Apulia, (Annali Ufficio Idrografico e Mareografico di Bari 01/2004) and the coastal cities of Naples, Lamezia Terme and Catania. Low daily maximum temperatures (below the 10°C degrees) were recorded also on the Sicilian Tyrrhenian coast, from Messina to Trapani and even in the Syracuse area (Osservatorio delle Acque).(meteogiornale.it (last access: 26/07/2020) of 27/01/2004).

20) 22nd January 2005. ~~The cold spell hit~~ Western and Central Europe ~~yielding temperatures below the average for almost the entire winterand reached its peak~~ experienced below average temperatures throughout the winter, with the cold peaking during the month of January. In Northern Italy ~~abundant snow fell~~ snow fell abundantly: in Lombardy snow-height reached 30 cm, with peaks up to 40-45 cm~~. Even~~ , and even the coastal city of ~~Genova~~ Genoa suffered snowfalls (Arpa Liguria Annali Idrologici 01/2004, Aeronautica.Militare (last access: 26/07/2020)). Snow fell also ~~in~~ over Marche, Abruzzo, Campania and Basilicata~~where in inland areas it snowed for many days~~, where inland areas were affected by snowfalls for several days, and accumulations exceeded one meter in Abruzzo, as well as in some areas of Irpinia. ~~Snow also fell in Salerno.~~ There were road disruptions as car drivers were trapped in the snow on ~~the highway~~highways. Stormy weather also affected other European countries, particularly in France and Spain. In France four avalanches detached from the mountains in Savoy caused many victims in ski resorts.(meteogiornale.it (last access: 26/07/2020) of 23/01/2005; Corriere della Sera of 25/01/2005).

21) 02nd March 2005. ~~The~~ A cold and snowy ~~air~~ spell hit Central and Southern Italy. Snow ~~precipitated to~~ fell on the hills of Naples, ~~to a~~ at medium-low altitude in Calabria, with abundant accumulations on the ~~coasts of the Middle Adriatic (starting by the south of the~~ Central Adriatic coast (from Southern Marche to Molise). ~~After few days , the snowfall reached~~ A few days later, snowfall spreaded to the North and Tuscany (Servizio Idrologico Regionale Regione Toscana, last access: 26/07/2020). ~~Thirty centimeters~~ Up to 30 cm of snow fell ~~on~~ in Liguria (Arpa Liguria Annali Idrologici 03/2005), ~~it snowed with abundance~~ on Milan and on most of Lombardy, on the plains of Emilia, on Piedmont, on the ~~north~~ North of Tuscany; it snowed in Veneto, whitening Verona, Venice and Rovigo. On March ~~1st~~1, 2005, the lowest temperatures ~~were recorded throughout the winter , with an average over the country~~ of the winter were recorded, with a country average of −0.5°C, which entered Italy's climatic history. The temperatures in the Alps region reached peaks of −23°C (Marcesina record of −34°C, (Arpav, Arpa Veneto, last access: 26/07/2020)), ~~in the Apennines~~ −20°C at Cimone in the Appennines, −16°C at Terminillo (Agenzia Regionale Protezione Civile Lazio Annali Idrologici 03/2005), −10.8°C ~~at~~ in L'Aquila (Annali Idrologici Servizio Idrografico e Mareografico di Pescara 03/2005). ~~In the lowlands or at low altitude the temperature decreased to~~ Among lowland cities we mention −12°C in Piacenza, ~~to~~ −11°C in Novara (Arpa, Piemonte), ~~to~~ −10.4°C ~~at~~ in Udine (Arpa Friuli Venezia Giulia last access: 26/07/2020) and −9°C in Arezzo (Servizio Idrologico Regionale Regione Toscana, last access: 26/07/2020). (nordestmeteo.it of 02/11/2019; meteogiornale.it (last access: 26/07/2020) of 03/03/2016).

22) 13th December 2007. ~~This~~ The peculiarity of this cold spell was ~~an extraordinary event characterized by~~ the exceptional occurrence of abundant snowfalls, ~~blizzards~~ blizzard conditions and an extreme ~~drop~~ low in temperatures over most of the Sardinian territory, at altitudes on average above 400 m. Also noteworthy are the 2 meters accumulated over an altitude of 1000 m on the slopes of Mount Limbara. Towns were largely unprepared to manage the event. An electricity blackout affected for several hours Cagliari~~and the~~ , and schools remained closed for two days. ~~Difficulties~~ Disruptions were reported in road connections: the main road of the Sardinian network of state highways suffered numerous blocks due to some trucks blocking the roads. In Nuoro, the snowfall exceeded 50 cm, breaking the record (Annali Idrologici della Sardegna 12/2007). A strong wind and rough seas were observed ~~in Olbia (30 knots). The drop of~~ on the coasts. Low temperatures affected also the Central and Southern Italy: −10°C ~~degrees~~ and icy roads were reported in Calabria, snowfalls in Molise as well as in the ~~interland~~ hinterland of Bari, Foggia and Taranto (Annali Ufficio Idrografico e Mareografico di Bari 12/2007), in Basilicata (Agenzia Regionale Protezione Civile Basilicata Annali Idrologici 12/2007)~~and temperatures below zero~~ ; below-zero temperatures were recorded on the Ionian coast (evalmet.it (last access: 26/07/2020) 12/2007).(La Repubblica of 13/12/2007, meteolive.it (last access: 26/07/2020) of 19/12/2007).

23) **17th December 2009**. Most of the Central and Northern Europe has been struck by this cold spell. ~~In December 19th the snow fell in most of the areas of~~ On December 19, snow fell over most of Northern Italy, and it was especially copious in Tuscany (Servizio Idrologico Regionale Regione Toscana, last access: 26/07/2020). A strong glazed frost occurred in Emilia and Liguria (Arpae.it (last access: 26/07/2020)). ~~The absolute minimum~~ Extreme low temperatures were recorded in some lowland locations (especially on December ~~20th~~20) in Friuli Venezia Giulia (Arpa Friuli Venezia Giulia last access: 26/07/2020): Udine Rivolto −18°C, Pordenone −12.4 °C, Cervignano del Friuli −17.3 °C, in coastal locations as Lignano −6.3°C, in some alpine valleys as Tarvisio (754 m above sea level) −18.3°C, Fusine (850 m a.s.l.) −22°C. (La Repubblica 19/12/2009 ; meteogiornale.it (last access: 26/07/2020) of 19/12/2014; Il Quotidiano 19/12/2009).

24) **12th February 2010**. Snowfalls affected several regions, from Emilia Romagna to Calabria, ~~from the Marche to~~ Marche and Sardinia (Arpae.it (last access: 26/07/2020), Annali Idrologici della Sardegna 02/2010). Bologna airport was closed for several hours: 17 ~~canceled flights~~ flights were cancelled, 15 diverted~~ones~~. The heaviest snowfall in Rome (ARSIAL: Agenzia Regionale per lo Sviluppo e l'Innovazione dell'Agricoltura del Lazio, last access: 26/07/2020) since February 1986 was recorded~~. It caused the difficulties on ground transportation and~~ , causing transportation disruptions, with many roads were closed both inside and outside the city. Many interventions were ~~planned~~ required to rescue motorists involved in collisions and stuck on the highway between the Marche and Romagna (the distribution of comfort items for at least 2000 people stuck in cars was necessary). A blizzard hit the Sila region, where the schools were closed for a few days. (roma artigiana.it (last access: 26/07/2020) 26/02/2018, La Stampa of 12/02/2010; La Repubblica 12/02/2010; ansa.it (last access: 26/07/2020) of 12/02/2010).

25) **11th December 2010**. An ~~Arctic-continental mass of air reached Italy~~ Arctic air mass reached the Eastern side of Italy, giving rise to intense snowfalls on the Adriatic and Thyrrenian coasts (especially the coasts surrounding the city of Livorno). Snow also whitened Tuscany (25 cm fell in Florence), Umbria and part of Lazio, with snow flakes ~~that were~~ observed in Rome. An exceptional snowstorm hit Ancona and the surrounding areas between ~~14th~~ December 14 and ~~15th December .~~ 15. There, the Adriatic Effect Snow contributed to reach snow heights up to 30 cm in the Chieti area and 40 cm in Lanciano. The temperatures were extremely cold over most of Italy. Malpensa Milan airport measured a minimum temperature of −14°C and Rome reached −7.7°C, a record value for the month of December (ARSIAL: Agenzia Regionale per lo Sviluppo e l'Innovazione dell'Agricoltura del Lazio, last access: 26/07/2020). ~~Polar temperatures were~~ Very low temperatures were also recorded on 17th December in Forlì (−6°C), in Parma (−7.5°C, Arpae.it (last access: 26/07/2020)), as well as in Ancona -6.8°C (Annali Idrologici, Centro Funzionale Mutlirischi per la Meteorologia, l'Idrologia e la Sismologia Regione Marche 12/2010) and in Firenze with its −7.3°C (Servizio Idrologico Regionale Regione Toscana, last access: 26/07/2020), in Isernia −11.8°C , in Salerno (Tirrenean coast) −7.2°C (Annali Idrologici, Centro Funzionale Mutlirischi per la Meteorologia, l'Idrologia e la Sismologia Regione Capania)(Il Messaggero 17/12/2010, 3bmeteo.com (last access: 26/07/2020) of 19/12/2015, cemcer.it (last

access: 26/07/2020) of 17/12/2015, Randi and Ghiselli (2013)).

26) 02nd February 2012. The February 2012 cold spell affected a large part of Europe and spread down to North Africa in the period between 27th January and 20th February 2012, causing over 650 deaths in the areas concerned . It concerned areas. The event was characterized by extremely low temperatures, especially in over Eastern Europe, which reached with an absolute minimum of −39.2°C in Finland, and heavy snowfall on the remaining European countries (Assessment of the observed extreme conditions during late boreal winter 2011/2012. WMO, 2015). On February 4th, 2012 the 4, snow fell even in Algiers with an accumulation of about 20 cm and the cold air brought snow even in the Sahara Desert (ansamed.info (last access: 26/07/2020) of 08/02/2012). In Italy the cold spell caused serious hardships and at least 57 victims (La Repubblica 12/02/2012). From the end of January, a stream of continental Arctic air reached the peninsula. At first, only the northern regions were affected (e.g. Alessandria reached low temperatures of recorded −20°Cand in Milan the minimum temperature downfall to , Milan −14.5°C)but then the cold extended also , but the cold later spreaded to the Central and Southern regions (Annali Idrologici, Centro Meteorologico Lombardo 02/2012). The snow Snow fell on most of Italy, especially in Emilia-Romagna and in the provinces of Pesaro-Urbino, Ancona, Macerata and Fermo on in the Central regions. Bologna reached A daily low of −7.6°C was recorded in Bologna on 6th of February, Parma February, −10.2°C , Rimini-6.2in Parma, -6.2°C , Arpae.it (last access: 26/07/2020)). In many areas of the South Italylike in Rimini, (Arpae.it, last access: 26/07/2020). Snow fell over several areas of Southern Italy, such as Basilicata and Calabriasnow fell. In Palermo (Sicily) snow fell on Monte Pellegrino , and on the Monte Pellegrino in Palermo on the 14th of February (Agenzia Regionale Protezione Civile Basilicata Annali Idrologici 2012; palermotoday.it (last access: 26/07/2020) of 14/02/2012). The hinterland and the rest of the region were affected by accumulations beyond 20-30 cm. (La Repubblica 12/02/2012), Annali Idrologici, Centro Meteorologico Lombardo 15/02/2012).

07th 27) 7th February 2013. This cold spell consisted of a polar trough spreading towards the Mediterranean region: the −12°C 850 hPa isotherm reached Central Europe and the isotherm a 850 hPa temperature of −6.7°C at the altitude of 850 hPa was measured at midnight on 10th February in the skies of February 10 in the Linate Milan airport radiosounding (Wetterzentrale.de (last access: 26/07/2020)). The minimum temperatures of 10th February are everywhere February 10 were very cold in the lower Ticino valley. , and February 11th was a snowy day on most of the northern Northern Italian plains, with diurnal temperatures around zero degrees. In Milan, in about 36 hours of snowfall, more than 20 cm of snow accumulated. It was This has been an important snow event on the Po Valley. In particular, : 20 cm accumulated in Milan during 36 hours of snowfall, and the largest accumulations were found on the Brianza province, near Lecco, in the Brianza area North of Milan, where peaks exceeding 35 cm were recorded Annali Idrologici, Centro Meteorologico Lombardo. Heavy snowfalls were reported in Emilia, in the Lombardy plain, Veneto, lower Trentino and Friuli. Accumulations reached up to 10-15 cm snow-height between Emilia, low Veneto, low Southern Veneto, and Southern Lombardy. Stormy weather also affected the rest of Italy, but snow affected only mountains areas. Only on the central regions snowflakes reached very low altitudes, fell only at mountain altitudes, with some episodes at lower altitudes especially in Tuscany. Annali Idrologici, Centro Meteorologico Lombardo 29/02/2016, Arpae.it (last access: 26/07/2020); Arpav (Arpa Veneto, last access: 26/07/2020), Servizio Idrologico Regionale Regione Toscana, last access: 26/07/2020, meteogiornale.it (last access: 26/07/2020) of 11/02/2018 milanotoday.it (last access:

26/07/2020) 18/12/2013; Milano.Repubblica (Milano Repubblica 11/02/2013)).

28) **28th December 2014**. ~~The~~ This cold spell affected the South of Italy with locally exceptional snowfalls, especially in Sicily ~~. Even Apuliarecorded huge~~ and Apulia, the latter recording important accumulations on the plains and ~~on the~~ coasts. Snow has also appeared in Naples and on the Amalfi ~~Coast. Sicily had the snowstorm on Messinaand whitewashed on the coasts, snow on the hills of Palermo and huge accumulations all over the hinterland , in particular over all the low hills of the northern part of Sicily. The snow appeared in Syracuse, the~~ coast. Snowfalls affected Sicilian coasts including the city of Messina, the hills and the hinterland of Palermo, with large accumulations, and Syracuse. The event was modest ~~in~~ on Catania, with accumulations only ~~in the reliefs~~ on the hills of the city. The extreme ~~south-eastern~~ South-Eastern tip of Sicily ~~, observed snow during the night of the New Year2015~~experienced snowfall on New Year's Eve, an extremely rare event~~for~~ , as these southernmost areas of the country ~~. These are the less snowy areas of Italy where it snowed last time in~~ had not received snow since January 1905. Historic snowfall were also recorded in Pachino, a city famous for the production of a special type of cherry tomatoes. ~~Intense snowfalls affected the~~ Snowfall also affected Sicilian towns of the Ionian side, like Avola and Noto. This cold spell was extraordinary also in the south of Sardinia, ~~for Cagliari and surroundings~~ where Cagliari and surrounding areas were covered by snow (Arpa Sardegna, Analisi Agrometeorologica e Climatologica della Sardegna. 2014-2015). (Annali Idrologici 12/2014, Osservatorio delle Acque, La Repubblica 27/12/2014).

~~**05th**~~ **29) 5th February 2015**. Italy was affected by stormy and snowy conditions. It snowed extensively in ~~Piemonte~~ Piedmont as well as in Liguria, a region also affected by strong winds. ~~A lot of snow, even at low altitude~~ Snow fell at low altitudes and in the lowlands in the Northern Italy and in part of the Centeral Italy. During this event, due to the strong winds, Sicily was isolated and the connections with the smaller islands were interrupted. In the surrounding of Etna~~a violent blizzard raging of~~ , snow, wind gusts and ice ~~suddenly caused freezing conditions. At~~ caused blizzard conditions. In Enna temperature dropped to −4.2°C (Annali Idrologici 02/2015, Osservatorio delle Acque). ~~In Ustica the~~ The most difficult situation was observed in Ustica, as ferries could not reach the island for 12 days, and essential medicines were delivered in dangerous operations by ~~helicopter~~helicopters. Many flights were canceled at Sicilian airports. Many roads and highways remained closed as the snow cover ~~in some places~~ exceeded 50 centimeters ~~. In Central Italy on~~ in some areas. On the 9th ~~of February~~February, ANAS (Azienda nazionale autonoma delle strade) ~~reports~~ reported that heavy snowfall ~~is~~ causing traffic jams in the provinces of L'Aquila and Teramo. In Northern Italy~~a snow and electrical blackouthappened~~, snow caused an electrical blackout: numerous municipalities in the Bologna area, and many others in the region, ~~had~~ experienced a blackout in light, heating and water supply, as well as malfunctions on the telephone network and the Internet. On ~~7th February~~ February 7 a big snowfall involved the city of Parma and the whole Emilia-Romagna region (−7.4°C on 9th ~~of~~ February, Arpae.it (last access: 26/07/2020)), with road accidents and problems in the supply of electricity for about 12 thousand customers in the Municipality of Parma. (livesicilia.it (last access: 26/07/2020) of 05/02/2015; today.it (last access: 26/07/2020) 09/02/2015; La Repubblica Bologna 10/02/2015).

30) **16th January 2016**. On ~~17th January an icy wind from Siberia~~January 17 cold air flowed from Russia, over-passed the barrier of the Alps and reached the Apennine chain. Due to the strong winds and rough sea, the Eolian islands were isolated and the highest peaks of the islands (Stromboli and Salina) were whitewashed. ~~Storm-surges~~ Storm surges stroke the Sicilian ~~north coasts~~ North coast (Palermo Osservatorio delle Acque). ~~The temperature suddenly dropped from 18°C to 8°C in~~

24 hours. In MoliseIn Molise, snow covered almost the entire region, even at low altitudes. At The city centre of Lanciano (Regione Abruzzo Dipartimeto Politiche dello Sviluppo Rurale e dell'Ambiente) , the city center was covered by up to 25 cm of snow. , and 50 cm to 60 cm snow height was also measured in the bordering side of the coasts. The snow Snow fell throughout Basilicata (Agenzia Regionale Protezione Civile Basilicata Annali Idrologici 01/2016) and temperatures reached -8°C. Whitewashed peaks appeared at lower altitudes, as well as the Aspromonte. In Savona were recorded −11°C degrees. Accumulations reached up to 20 cm on some area of Cosenza (150 m above sea level) and over 30 cm on the highest hills surrounding the city. The snow brought with it many accidents, above all to the viabilitySnow caused many issues, mainly to viability, with traffic jams on the Salerno-Reggio Calabria highway. Calabria has been the area most affected by the snowwuth few , even recording some casualties.(meteopalermo.it (last access: 26/07/2020) of 19/01/2016, La Repubblica 17/01/2016 , today.it (last access: 26/07/2020) of 19/01/2016)

05th 31) 5th January 2017. From the 5th to the 21st January 2017, a cold spell affected most of eastern Eastern and Central Europe and part of southern Southern Europe, causing the death of at least 60 people. The cold spell and the and snowfalls mainly affected Central and Southern Italy. The regions most affected by this cold spell were the Adriatic ones, namely Marche, Abruzzo, Molise, Puglia and Basilicata. Snow reached almost all coastal areas of these regions, with snow cover totals up to 40 cm. On January 8th8, the beach of Porto Cesareo (LE) in Apulia was covered at some points with accumulations of 22–23 22-23 cm, resulting as the third most snowy Italian beach since 2000. The situation was worse in inland areasof the regions, where the , where snow often exceeded 2 meters height. A strong snowstorm affected the entire Marsicano sector (Abruzzo) with temperatures ranging between −10°C and −13°C, with final accumulation and final accumulations near one meter and temperatures above below −20°C below 1300 meters of altitude (Regione Abruzzo, Servizio Presidi Tecnici di Supporto al Settore Agricolo.). On the 9th of Januarythe cold air moved to Central Italy (Abruzzo, Marche, Umbria e Molise). The heavy snowfall (with a series of earthquake January, the combination of heavy snowfall and a seismic swarm in Central Italy) caused triggered a disastrous avalanche that hit the town of Rigopiano in Abruzzo: a landslide swept and destroyed a hotel, causing several deaths. Heavy snowfalls (up to a meter of snow) the death of several people that were blocked there due to the exceptional snowfall, which also considerably complicated rescue operations in this region (Corriere della Sera of 19/01/2017). (Aljazeera of 07/01/2017 of 07/01/2017, severe weather.eu (last access: 26/07/2020) 05/01/2017 and of 08/01/2017, La Repubblica 05/01/2017 05/01/2017).

32) 18th February 2018. The Siberian cold spell affected Europe between the end of February 2018 and the beginning of March. The major anomalies concern concerned the Central and Northern sector of Europe with temperatures between 5°C and 9°C below the reference average 1971-2000. Strong anomalies of this brief but intense cold spell were recorded all , but consistent anomalies were however recorded also over Italy. The cold was felt more intensely in the Central and Northern and marginally in the far South Italy and on Sicily. In the Northern regionsthe values were also 8/9, temperature values were up to 8-9°C below the seasonal averages. Rome experienced a moderate snowfall (3–4 3-4 cm of snow), which caused temporary disruptions in ground transportation. The last snowfall in Rome, in chronological order, was February 2012, when the city was covered with snow for the first time after many years. At Cagliari, the Mistral In Cagliari, Mistral (North-Westerly) wind was extremely strongand the gusts reached , with gusts up to 100 km/h, creating disruptions in the maritime connections between the continent and Sardinia . The wind in Capo Caccia (Alghero) Sardinia and the rest of the continent. Gale force winds were recorded all over the regions, for example wind exceeded 70 km/h in Capo Caccia, on the North Coast, and 80km/h at in Capo Carbonara, on the south South coast (Decimomannu, Aeronautica.Militare (last access: 26/07/2020)). The snow-covered whitewashed Snow covered the slopes of the Riviera di Ponente, and fell in Rome, Naples (the last snowing event on 1956), Olbia and Bari Arpa (Puglia). The minimum temperatures of 27th-28th February , February 27-28 were the lowest in the last 20–30 20-30 years above 1500 m at many locations in the Alps. Low temperatures of , with up to −25°C were recorded at 2500 m near Bolzano (Protezione Civile Provincia Autonoma di Bolzano). A second pulse of cold air mass reached Italy through the Carso between night and morning on Sunday 25th February in the early hours of February 25, spreading throughout Northern Italy during the daytime, along with winds and irregular snowfalls on the plains between Emilia and Piedmont. At low altitude the absolute records remained unbroken, but some localities recorded new temperature records for February as New monthly records for February were observed in Bologna (−9.1°C in Bologna , −6.2°C(Arpae.it (last access: 26/07/2020))), in Rome-Ciampino (129 m, −6.2°C Arpae.it (last access: 26/07/2020), second lowest after the −6.5°C reached on 2nd March 1963it reached −6.5°C), −1.1°C in Brindisi (15 m, on 11th March 1956 it reached −4.2°C)(Aeronautica.Militare, last access: 26/07/2020). (Il Foglio 26/02/2017; La Gazzetta di Parma 14/02/2018; La Gazzetta del Serchio 22/02/2018, nimbus.it (last access: 26/07/2020) 02/03/2018).

2.1 Observed Cold Spell Dynamics

Besides the qualitative analysis involving the cities of Bologna and Campobasso briefly presented in Section 2.1, we now aim at characterizing the dynamic and thermodynamic features of the considered cold spells at the synoptic scale. To this purpose, we rely on the National Centers for Environmental Prediction (NCEPv2) Reanalysis dataset. In particular, we use sea-level pressure (SLP, Faranda et al., 2017; Faranda, 2020) as a dynamical fingerprint, temperature at 850 hPa (T850) to track cold air advection without surface disturbances (Grazzini, 2013), and snow depth (SNDP) as a proxy of snow precipitations.

Although our analysis is focused on cold spells affecting an area containing Italian borders, the dynamic determinants of such cold spells span much larger scales. For this reason, we consider a larger area, including Europe, European Russia, and the North Atlantic, over a 2.5 degree grid comprised between [22.5–70N, 80W–50E]. We first perform an unsupervised cluster analysis based on the SLP fields using a k-means algorithm (Michelangeli et al., 1995), and we inspect the SLP, T850 and SNDP fields averaged over each cluster. The scree plot (Fig. 2), obtained by plotting the deviance within clusters for an increasing number of clusters, does not give strong indications about the ideal number of clusters. However, we compared clustering results at different values of k, finding that for $k = 3$ clusters 2 and 3 displayed very similar features: we then decide to choose $k = 2$. We remark that the k-means algorithm and other clustering techniques are based on assumptions such as equal size and sphericity of the clusters, which can be met only in coarse approximation in real-world datasets. In particular, the poor indications from the scree plot may be due to the different number of events assigned to each cluster (respectively 12 and 20 for $k = 2$). However, we find the results consistent enough to allow for a qualitative analysis.

In Fig. 3 we show the SLP fields averaged for the 12 events in cluster 1 (upper panel) and cluster 2 (lower panel). The dynamic configurations in the two clusters differ deeply, suggesting the existence of at least two typical large scale cold spell drivers. Cluster 1 is characterized by an Omega structure associated to an Atlantic ridge (Falkena et al., 2020), with an anticyclone centered just West of Europe, stretching roughly from Iberia to Iceland, and a low pressure area centered over the Central-Eastern Mediterranean, and low pressure values over continental Easter Europe as well. In such a situation, cold air is drawn from the North by the Mediterranean cyclone, flowing from Scandinavia over Central-Western Europe and entering the Mediterranean from the Rhone Valley and the Gulf of Trieste due to the presence of the Alps.

Cluster 2 presents a drastically different picture, with an anticyclone stretching zonally in a W-SW/E-NE direction, rather than elevating along the meridians, and low pressure values again centered over the Central Mediterranean, mainly confined below 40 degrees N. The axis of the anticyclone is located at about 50-60 degrees N, so that cold Arctic air is free to flow on its Southern edge in a ENE-WSW direction, drawn by the Mediterranean low, after partially assuming continental air mass characteristics while passing over Russia and Eastern Europe. In this situation, cold air easily reaches Central-Southern Italy after increasing its humidity content over the Adriatic Sea. This causes snowy precipitation bands to form slightly offshore the East Italian coast, which can be later amplified by the orographic effect caused by the Appenninic range, with abundant snowfall even at low altitudes.

Fig. 4 shows the corresponding T850 fields. Despite the sensibly different dynamic setting, the penetration of cold air into the Mediterranean is quite similar in the two clusters, with below-zero temperature values embracing the whole Central Mediterranean including the entire Italian peninsula. The main differences can be noticed on extreme Western Europe, Iceland and Scandinavia, due to the very different direction of the high pressure axis. In cluster 1, the strongly meridional axis brings warmer air towards Greenland and Iceland, while the core of the cold air is located between Scandinavia and Central Europe. In cluster 2, the tilted high pressure drives warmer air towards the British Isles and Scandinavia, while colder air is located between Western Russia and Central-Eastern Europe. Finally, Fig. 5 displays cluster averaged near-surface temperature fields, exhibiting very similar features, except for the location of the coldest air mass over Scandinavia for cluster 1 and over Eastern Europe for cluster 2. In these conditions, the Northern half of Italy is characterized by negative daily average temperatures, whereas snowfall is possible even in locations with a positive daily average temperature (see, e.g., Wen et al., 2013), making negative daily low temperatures and snowfall still possible.

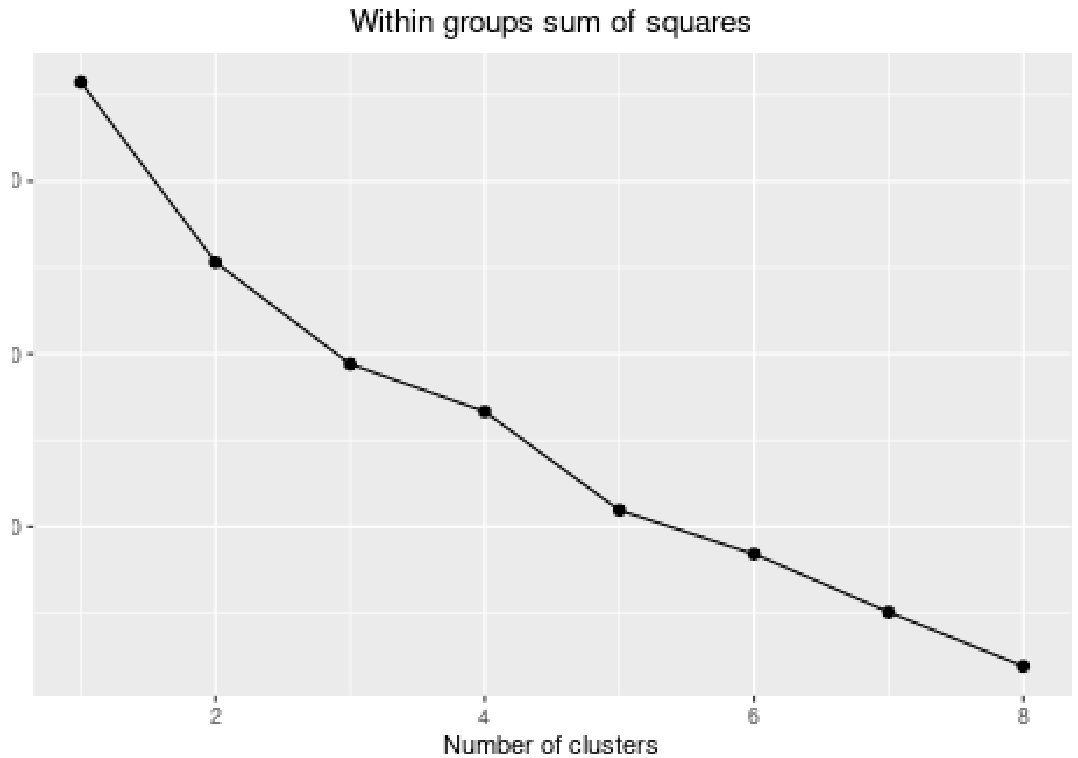

Figure 2. k-means scree plot. Within groups deviance as a function of the number of cluster obtained with the k-means on the SLP fields of the 32 cold spell events.

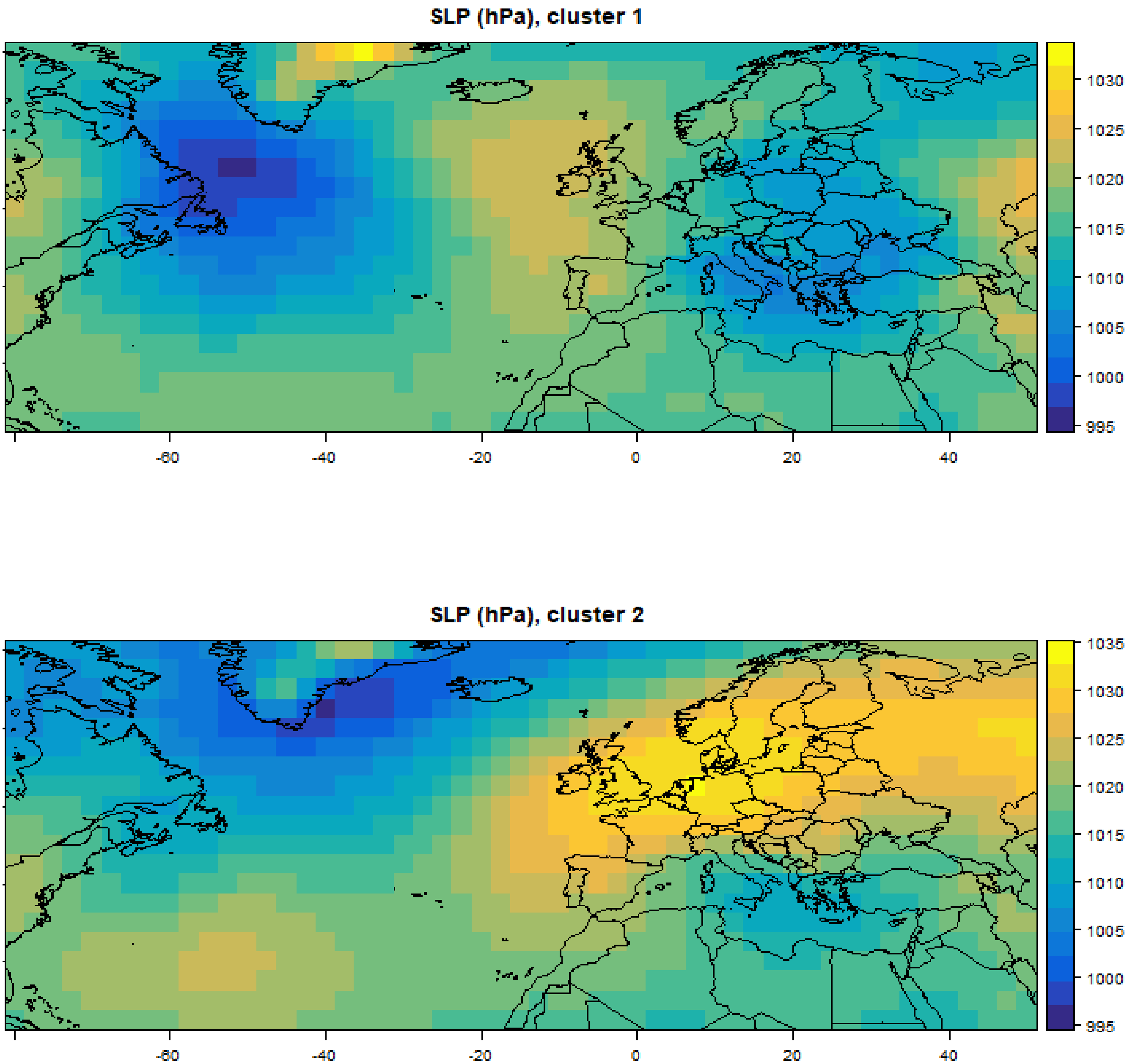

Figure 3. Cold spell dynamic fingerprint. SLP fields averaged over the two clusters found via k-means. Cluster 1 (upper panel) is characterized by an omega-blocking between the Atlantic and Europe, cluster 2 (lower panel) by a zonally tilted high pressure located between the British Islands and Russia.

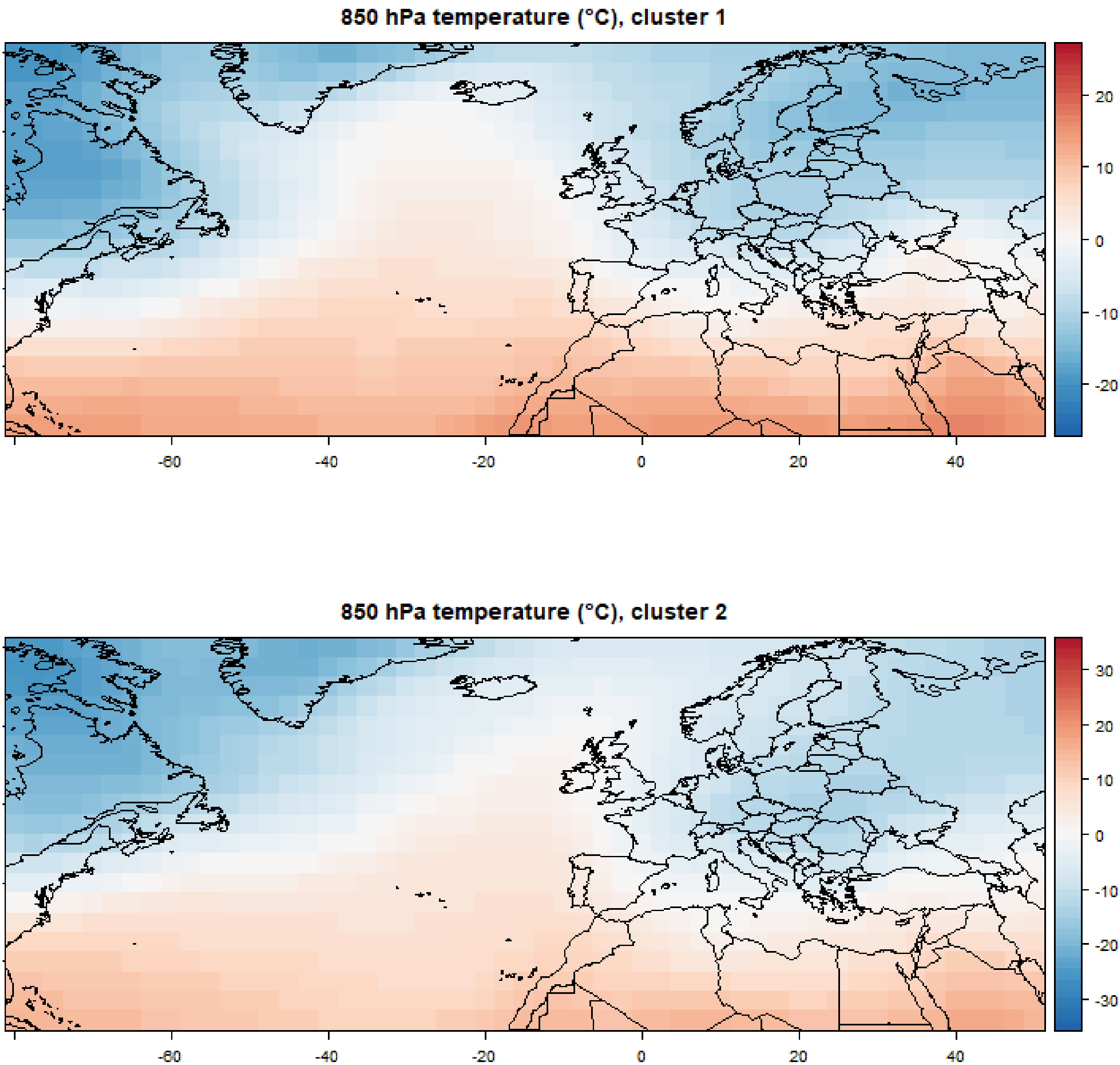

Figure 4. **Cold spell thermodynamic fingerprint.** T850 fields averaged over the two clusters found via k-means. In cluster 1 (upper panel) warm air extends North from the Azores to Iceland and cold air flows South from Scandinavia. In cluster 2 (lower panel) warm air is advected towards the British Islands and cold air flows mainly from Russia and Eastern Europe.

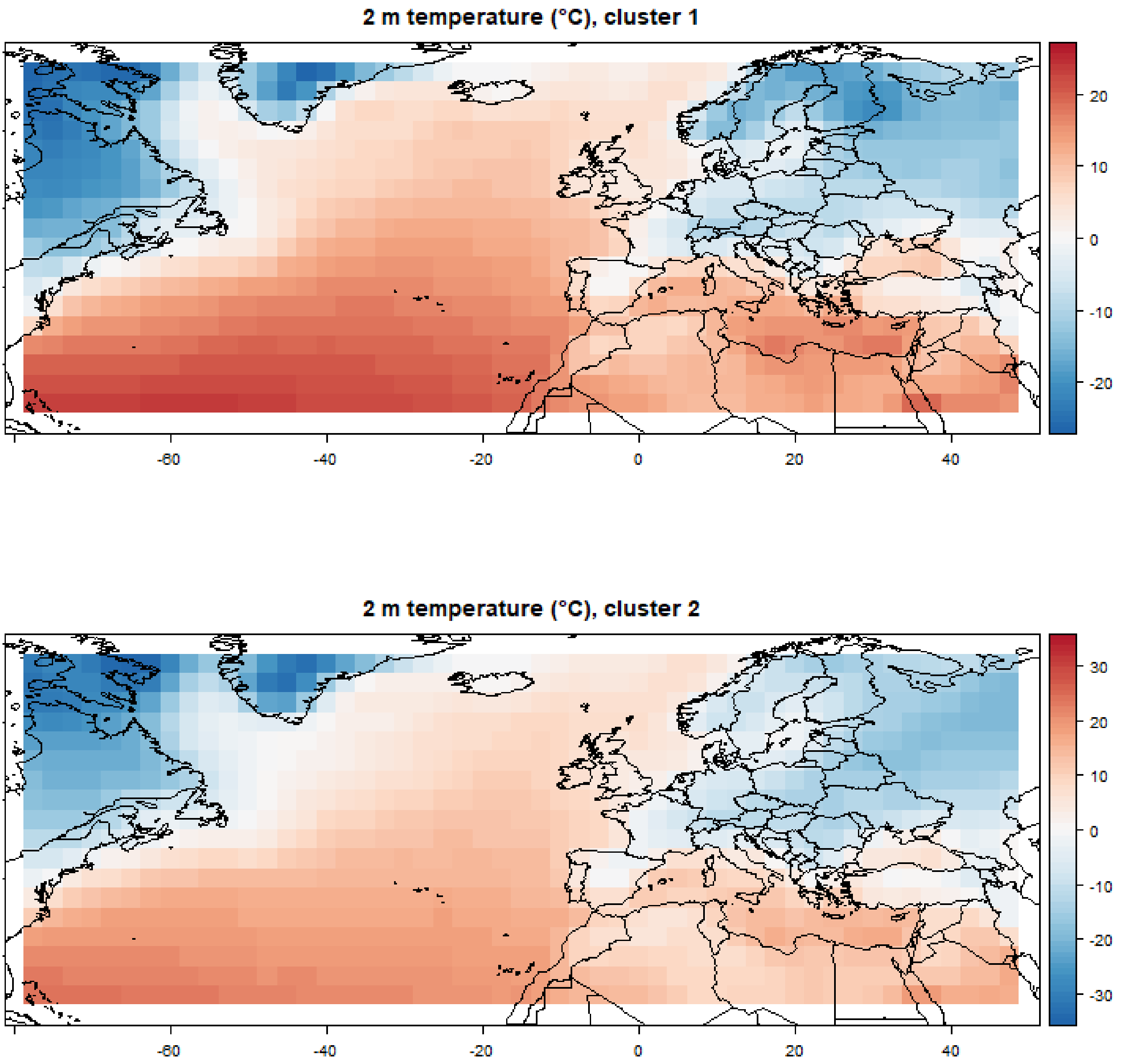

Figure 5. **Cold spell near-surface temperature.** Near surface (2 m) temperature fields averaged over the two clusters found via k-means. The temperature field at the surface is very similar, with cold temperatures over continental areas, and negative or very low positive daily values over Italy, especially the peninsular regions.

3 Climate Change of Atmospheric Circulations associated to Cold Spells in PlaSiM

3.1 Model Description

In order to understand how the frequency of cold spell events may change in a warmer climate, we simulate different emission scenarios using PlaSim (Fraedrich et al., 2005a, b), which is an intermediate complexity climate model developed at the University of Hamburg and released open source (see https://www.mi.uni-hamburg.de/en/arbeitsgruppen/theoretische-meteorologie/modell PlaSim has been applied to a variety of problems including climate response theory (Lucarini et al., 2014), storm tracks (Fraedrich et al., 2005b), climatic tipping points (Boschi et al., 2013; Lucarini et al., 2010a), the analysis of global energy and entropy budget (Fraedrich and Lunkeit, 2008; Lucarini et al., 2010b), the simulation of extreme European heatwaves (Ragone et al., 2018) , and the investigation of the late Permian climate (Roscher et al., 2011). The reason of using PlaSim with respect to higher complexity GCMs is the ability to generate long stationary simulations for which we compute reliable analogues. The horizontal resolution used in this study is about 300 km (T42, $\sim 2.8\,^{\circ} \times 2.8\,^{\circ}$) with ten vertical, non-equidistant levels. The dynamical core for the atmosphere is adopted from Portable University Model of the Atmosphere (PUMA). The model includes a full set of parameterizations of physical processes such as those relevant for describing radiative transfer, clouds formation, and turbulent transport across the boundary layer. The horizontal heat transport in the ocean can be prescribed or parameterized by horizontal diffusion. The parametrization by horizontal diffusion has a simplified representation of the large scale oceanic heat transport and then it ameliorates the realism of the resulting climate. The atmospheric dynamical processes are modelled using the primitive equations formulated for vorticity, divergence, temperature, and the logarithm of surface pressure. The governing equations are solved using a spectral transform method. In the vertical dimension, five non-equally spaced sigma (pressure divided by surface pressure) levels are used. The model is forced by diurnal and annual cycles.

Most of the events detected in the documentary sources include snowfalls that occur near coastal areas or on low lands. In PlaSim, snowfall accumulates for ground temperatures equal or less than zero, if surface energy balance prevents melting. If snow melts according to the energy budget, surface temperature is kept to freezing point until snow is melted completely. Snow cover significantly changes the surface properties like albedo and heat capacity amplifying cooling by a strong positive feedback. On the other hand, the transition from snow to snow-free strongly enhances warming trends. Thus, zero degree can be seen as a threshold were warming and cooling trends may be significantly intensified by a snow cover feedback.

The observational data often come as snow height values (in m), whereas models and reanalysis provide more reliable data on snowfall and then compute snow depth in kg m^{-2}. Since the conversion between these two quantities implies the use of a density which depends on the nature of the snow, there is no direct equivalence between observational data and model simulations. However, PlaSim assumes only a single value for the density involved in this conversion (330 kg m^{-3}) (Kiehl et al., 1996).

3.2 Experimental set up: the simulation ensemble

In this study we consider three simulations performed with T42 resolution at daily frequency, 500 years long, with a mixed layer ocean. The first 10 years are discarded, to avoid including the burn-in period. To get reasonable response and present-day climate one needs to add an oceanic heat transport in the mixed layer model (slab ocean, without motion). This can be done in several ways: for our set up, we tuned horizontal diffusion (h_{diff}) to have a reasonable global mean SST and a realistic response of SST and ice to the forcing ($h_{\text{diff}} = 4 \cdot 10^4$).

The first simulation is the control run (denoted CTRL) with radiative forcing levels representative of the recent climate: CO_2 concentration is set to a value of 360 ppmv, corresponding to the CO_2 concentration in the year 2000. The second simulation is the same as control run, except adding a uniform $+4$ K to the sea surface temperature (denoted 4SST) globally (Giorgetta et al., 2012). One of the reason for choosing such extreme boundary conditions is the faster warming of the Mediterranean sea compared with the other oceans (Vautard et al., 2014) expected to lead to $\sim +3.5$K SST at the end of the 21st century (Adloff et al., 2015 . The third simulation is based on one of the four Representative Concentration Pathways (RCPs) developed for the climate modeling community as a basis for long-term and near-term modeling experiments (Van Vuuren et al., 2011). We consider the RCP-8.5 scenario (Riahi et al., 2011), which consists of increasing CO_2 concentration from 2005 to 2100, to reach a radiative forcing increase of 8.5 W/m^2 compared to pre-industrial conditions. In our simulation (denoted RCP85), the CO_2 concentration is set to 1370 ppm, corresponding to the RCP-8.5 forcing, at the beginning, and kept constant afterwards. Our choice of using such a forcing is motivated by the fact that the RCP-8.5 is representative of the high range of non-climate policy scenarios and corresponds to a high greenhouse gas emissions pathway compared to the scenario literature (Fisher et al., 2007; Pachauri et al., 2014) . This way, we explore two scenarios where excess heat is stored only in the ocean (4SST) or in the the atmosphere (RCP85), and investigate which differences in the dynamics of cold and snowy spells appear, if any.

3.2.1 Bias correction

Climate models, even those with higher complexity than PlaSim, are characterized by a finite resolution, thus leaving smaller scales unresolved, and contain several physical and mathematical simplifications that make climate simulations computationally feasible, while also introducing a certain level of approximation. This results in statistical biases that can be easily observed when comparing control runs to observations or reanalysis datasets. In order to mitigate the effects of these biases, a bias correction step can be performed. Bias correction usually consists adjusting specific statistical properties of the simulated climate variables to a validated reference dataset in the historical period. The target statistics can be very simple, such as a central tendency index like the mean (Shrestha et al., 2017), or it may include dynamical features, such as a certain number of autocorrelation function lag or spectral density frequencies for time series data (Nguyen et al., 2016). It can aim at correcting the entire probability distribution of the observable. The correction can also be carried out in the frequency domain, so that the entire time dependence structure is preserved. For an overview of various BC methodologies applied to climate models see, for example, Teutschbein and Seibert (2012, 2013); Maraun (2016).

We found that the distribution of T850 at each grid point in the CTRL PlaSim run presents significant differences respect to the distribution of T850 in NCEP data, with systematically higher values. Given the lower complexity and the relatively coarse grid of PlaSim compared to other regional or global circulation models, we adopt the simplest possible method, linear scaling bias correction (Shrestha et al., 2017), which consists of matching the CTRL mean T850 to match the NCEP values, and applying the same transformation to 4SST and RCP85 simulations as well.

The bias on T850 reflects on the estimation of snowfall and then snow cover and snow depth, since temperature is strongly linked to the fraction of precipitation falling as snow, even when dealing with daily data (Murray, 1952). However, it is not possible to perform a successful bias correction of snowfall in a straightforward way: not only snowfall values may be biased, but too few or too many snowfall episodes may be present in model simulations, depending on the sign of the temperature bias. In such a situation, it is convenient to estimate the relationship between air temperature and the snowfall fraction from historical data or reanalysis, and use this relationship to reconstruct snowfall in climate simulations (see, e.g. Wen et al., 2013). Unfortunately, this requires the availability of total daily precipitation, which is not available in our case. For this reason, we are not able to correct snow depth following the adjustment of T850, and we acknowledge that this will lead to an underestimation of snow in the PlaSim runs, making a direct comparison with NCEP snowfall impossible.

3.3 Analogues detection

We base our analysis of cold spells in PlaSim on the search of dynamic analogues (Yiou et al., 2013) in a similar way as in Faranda et al. (2020). This way of defining analogues by embedding the extreme events of interest in the climate simulation is rooted in the link between dynamical systems and extreme value theory (Lucarini et al., 2012), and the events selected as analogues are linked to quantities such as the local attractor dimension and the persistent of the dynamical system state (Pons et al., 2020). Here we briefly sketch the methodology, redirecting the reader to the aforementioned papers.

Let X_t denote the value of a gridded variable of interest (e.g. the SLP field) at time $t = 1, \dots, T$. Let ζ represent the same variable in correspondence of one event of interest, in our case one of the 32 events described in Section 2.2. We compute the metric

$$g_t = -\{dist(X_t, \zeta)\},$$

where $dist(,)$ denotes a distance function, in our case the Euclidean distance. The choice of the Euclidean distance has been already motivated in Yiou et al. (2013) and in Faranda et al. (2017) for the computation of dynamical indicators such as the local dimension. Furthermore, the minus sign allows to interpret the g_t function as an indicator of proximity of analogues.

Let now g_c be a high quantile of the distribution of g, for example corresponding to the probability $P(g_t \geq g_c) = 0.98$: the events satisfying this condition are considered analogues of ζ. Since we are interested in dynamical analogues of the cold spells, we perform a two-step procedure based on SLP first, and then on T850 to select events that actually correspond to cold episodes. Moreover, we only include in our analysis an extended winter season, constituted by months of December, January, February and March (the only months involved in the 32 selected events) and abbreviated to DJFM in the following.

The procedure is carried out according to the following steps:

1. select one of the 32 events and define ζ as the corresponding NCEP SLP field, and X_t as the ensemble of the remaining NCEP SLP fields, excluding event date;

2. compute the metric $g^{SLP}_{t,NCEP}$ using data selected at step 1;

3. determine the critical value g^{SLP}_c such that $P(g^{SLP}_{t,NCEP} \leq g^{SLP}_c) = p_1$;

4. now take PlaSim SLP fields as X_t, while keeping the same reference field ζ;

5. compute the metrics $g_{t,r}^{SLP}$ using SLP from PlaSim runs, with $r =$ CTRL, 4SST, RCP85;

6. estimate probabilities $\pi_{1,r} = P(g_{t,r}^{SLP} \leq g_c^{SLP})$ and compare them to the reference value p_1;

7. compute the metric $g_{t,NCEP}^{T850}$ using reanalysis T850;

8. determine the critical value g_c^{T850} such that $P(g_{t,NCEP}^{T850} \geq g_c^{T850}) = p_2$;

9. compute the metrics $g_{t,r}^{T850}$ using SLP from PlaSim runs, with $r =$ CTRL, 4SST, RCP85;

10. consider cold spell analogues all events satisfying $P(g_{t,r}^{SLP} \geq g_c^{SLP}) = p_1 \cap P(g_{t,r}^{T850} \geq g_c^{T850}) = p_2$;

11. repeat from step 1 for each of the 32 events.

Steps 1 – 3 select the (1-p_1) fraction of closest winter analogues of the event of interest in the reanalysis dataset. Steps 4 – 5 allow to determine whether the frequency of the selected event is significantly different in the PlaSim scenarios compared to NCEP, and in which direction. This way, we can establish if climate change can affect atmospheric dynamics, leading to an atmosphere more or less conducive for synoptic configurations that can originate a cold spell. In steps 7 – 9 we repeat steps 1 – 5 but using T850: this way, we can select those dynamic analogues that also have a thermodynamic fingerprint close to the one of a cold spell. This step involving T850 is particularly important for the RCP85 run, where we can expect an overall warmer atmosphere, so that SLP fields normally associated to cold spell in the reanalysis may be characterized by a temperature field that is not able to produce neither cold temperatures nor snowfall over Italy. In our analysis we choose $p_1 = 0.98$ and $p_2 = 0.99$, to ensure sufficiently similar temperature patterns even in a markedly warmer climate.

3.4 Results

Our first results follow from the estimation of the probabilities described at step 6. in the previous paragraph. These are the probabilities $\pi_{1,r}$ that the SLP field at date t from run r is an analogue of the event of interest as close as the $(1-p_1)\%$ of the NCEP SLP fields. In particular, we are interested in the differences $\Delta p_{1,r} = (\pi_{1,r} - p_1)$. If $\Delta p_{1,r} > 0$, the reference event is more extreme and less frequent than in historical climate. On the contrary, values $\Delta p_{1,r} < 0$ indicate a more recurring event. The percentage change in frequency of events that are cold spell dynamic analogues can be obtained as $-\Delta p_{1,r}/(1-p_1)$.

The results of this analysis are summarized in Fig. 6 and Table 1, with the events divided according to the configuration clusters we found in the NCEP reanalysis. In Fig. 6, warm colors are associated to negative values and cold colors to positive values, to stress the variation in analogues frequency, rather than $\Delta p_{1,r}$ itself. The top panels display values of $\Delta p_{1,r}$ for both NCEP and the PlaSim runs (notice that probability differences are null in the reanalysis by definition). The CTRL and 4SST runs present remarkable similarities, with an overall decreased analogues frequency, except for events 15 (increasing), and 19 and 31 (unchanged). On the contrary, in RCP85 simulations, 15 out of 32 events show an increase in frequency, 9 remain unchanged and 8 a decrease. However, the positive $\Delta p_{1,r}$ values in the CTRL run point out to a tendency of PlaSim to produce less frequent analogues than found in present climate. To offset this effect, we shift the probability differences using CTRL as a baseline: $\Delta p'_{1,x} = \Delta p_{1,x} - \Delta p_{1,CTRL}$.

The bottom panels of Fig. 6 show the adjusted results for 4SST and RCP85. For 4SST, a few configurations experience a slight increase in frequency, especially in cluster 2. However, as shown in Table 1, the percentage changes are quite modest, ranging between -6.24% (event 18) and +7.59% (event 19). On the other hand, changes in frequency in RCP86 are all positive and mostly one to two orders of magnitude larger than for 4SST, ranging from +5.23% (event 26) to +197.33% (event 32).

Cluster 1												
Event	6	8	11	19	20	21	23	24	25	27	28	30
Date	68/01/12	73/12/01	85/01/07	04/01/20	05/01/22	05/03/02	09/12/17	10/02/12	10/12/11	13/02/07	14/12/28	16/01/16
4SST	-1.7	-1.9	-1.4	7.6	-1.4	-2.4	-3.0	-2.6	0.00	-2.7	-1.1	-3.1
RCP85	38.2	79.3	132.1	117.1	33.5	85.3	35.0	92.3	47.1	90.3	41.9	71.8

Cluster 2										
Event	1	2	3	4	5	7	9	10	12	13
Date	54/01/04	56/02/04	61/12/17	62/01/31	63/01/22	71/02/28	79/01/15	81/01/08	86/12/24	87/03/03
4SST	-0.7	-2.8	-3.3	-5.0	-1.4	0.8	-0.6	-6.0	3.6	-0.1
RCP85	43.5	22.7	69.1	37.4	65.5	8.2	46.3	11.4	34.9	30.4
Event	14	15	16	17	18	22	26	29	31	32
Date	91/01/31	93/01/01	96/12/27	99/01/31	01/12/08	07/12/13	12/02/02	15/02/05	17/01/05	18/02/18
4SST	3.6	1.8	-2.6	1.5	-6.2	5.3	-5.4	-1.1	4.8	2.1
RCP85	60.1	62.1	94.8	115.7	42.6	46.2	5.2	43.8	13.2	197.3

Table 1. Change in frequency (%) of cold spell analogues for each of the considered events, divided by cluster.

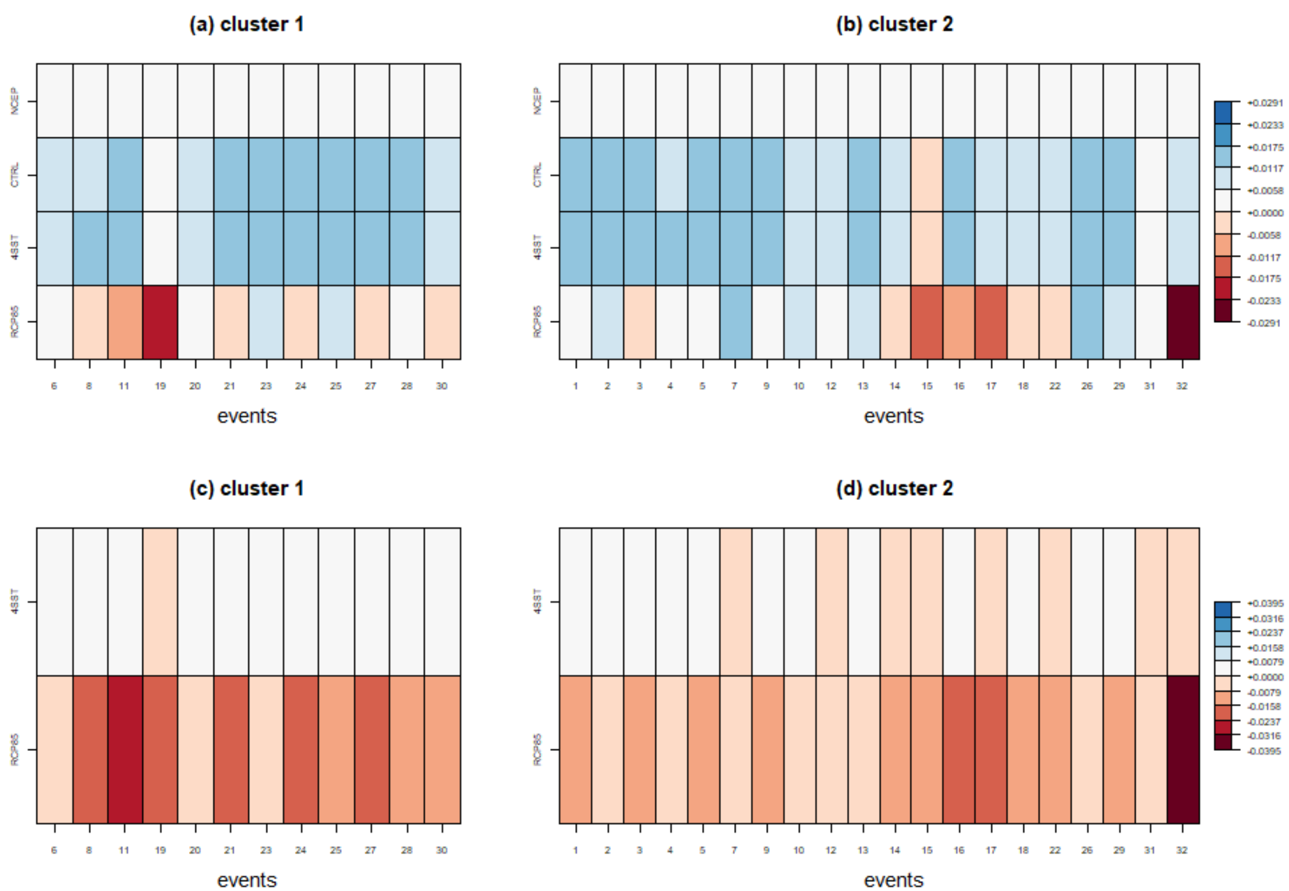

Figure 6. Analogues probability change. Change in the value of the probability distribution function of the dynamic observable g_t corresponding to the quantile value g_c, used as threshold to define analogues. Events are divided between cluster 1 (left panels) and cluster 2 (right panels). Upper panels represent raw values, lower panels the results for 4SST and RCP85 after offsetting bias in CTRL run.

Overall, the results point to a marginal if not null role of ocean SSTs in enhancing or damping cold spell dynamics, as well as in the amount of snow falling over the area, as shown in the upper panels of Fig. 7.

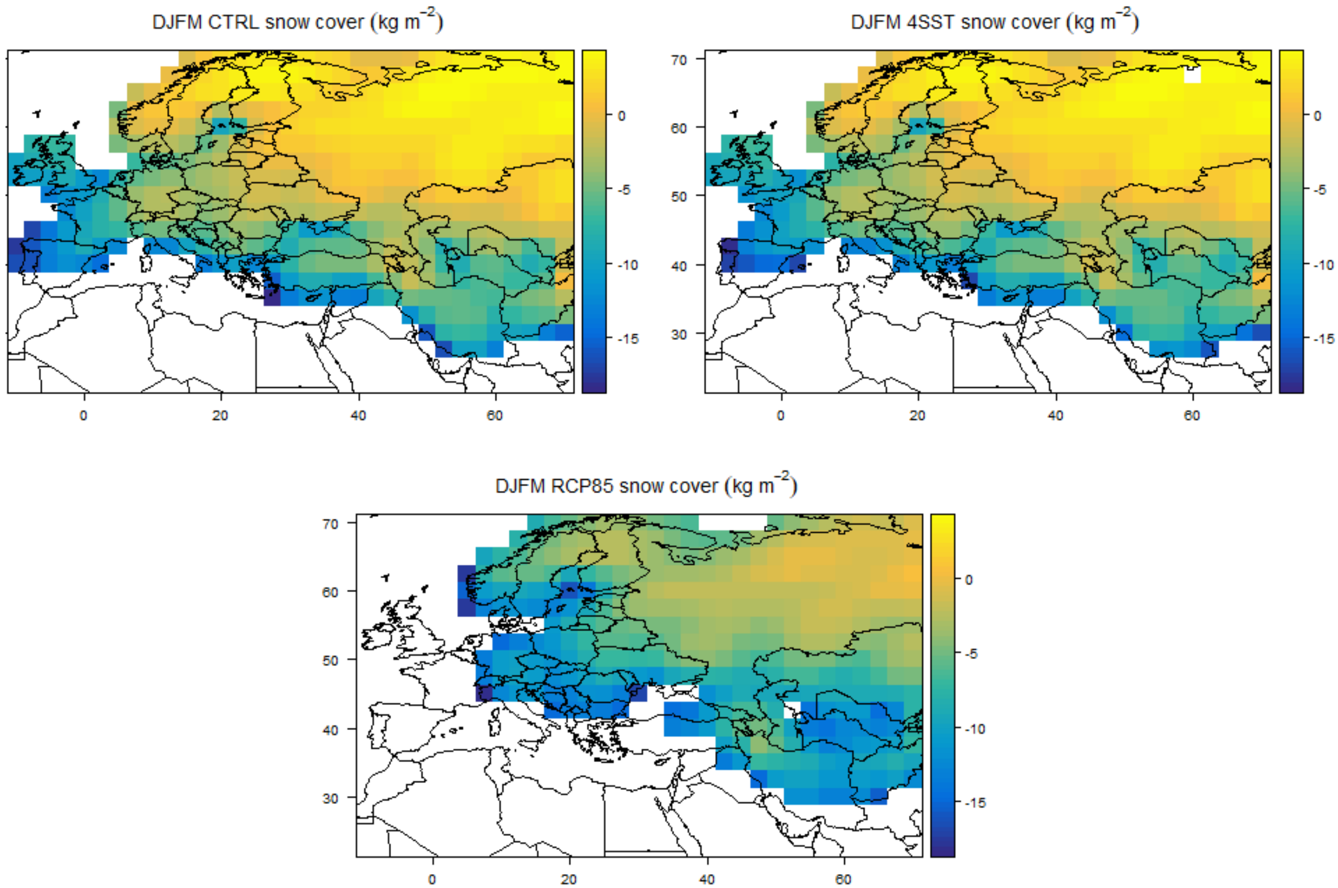

Figure 7. **PlaSim snow depth.** Snow depth simulated by PlaSim in natural logarithmic scale for the CTRL run (upper left), 4SST (upper right) and RCP85 (bottom panel).

On the other hand, in the much warmer RCP85 climate, the frequency of dynamic configurations leading to SLP fields similar to the pressure maps in Fig. 3 may increase dramatically. Clearly, this does not imply that Italy would paradoxically experience increasing snowfalls in the RCP85 climate. Indeed, the PlaSim simulations display a clear decrease of snow under RCP85, both in cumulated quantity and spatial extension, with Greece, Turkey, Central-Southern Italy and Western Europe not seeing any.

However, the Arctic and continental areas of Eurasia the formation of cold air masses would still be possible even in a sensibly warmer climate. To assess the residual potential for cold spells, we perform the analysis steps 7 to 10 described in Section 3.3. In practice, among all the dynamic analogues selected using SLP, we retain only those that are also thermodynamic analogues, i.e. that resemble the closest 1% analogues of the T850 historical field. This results in 179 analogues for each of the 32 selected events.

Figures 8, 9 show the averaged SLP, T850 and SNDP over all the events divided by cluster. Despite selecting these analogues with a constraint on T850, the penetration of cold air towards the Mediterranean and Western Europe is sensibly reduced compared to the fields shown in Fig. 4. Nevertheless, negative temperatures still appear capable of reaching Northern and Eastern parts of Italy. Snow depth is still reduced in its extension, with a complete absence over Western Europe, as shown for the entire DJFM season in Fig. 7. However, values of snow depth, where present, are larger than for DJFM days under RCP85, including the Balcans and Northern Italy.

Notice that there is a certain level of overlapping among the analogues of different events, meaning that certain PlaSim dates are analogues of more than one cold spell event; this implies that the number of analogues of the 32 events is smaller than 32×179. We do not deepen this aspect of the analysis, which we consider too detailed in view of the characteristics of PlaSim, and we plan to leave it for future analysis based on more refined GCMs. However, even in case of a complete overlapping, 179 is a lower bound of future cold spell analogues in PlaSim. Considering that PlaSim data span over 490 years, and each DJFM season consists of 121 days, this number of events concerns the 0.3% of all PlaSim dates, and suggests that dynamics potentially conducive for cold spells over Italy may have a return time of 2 to 3 years even under RCP85.

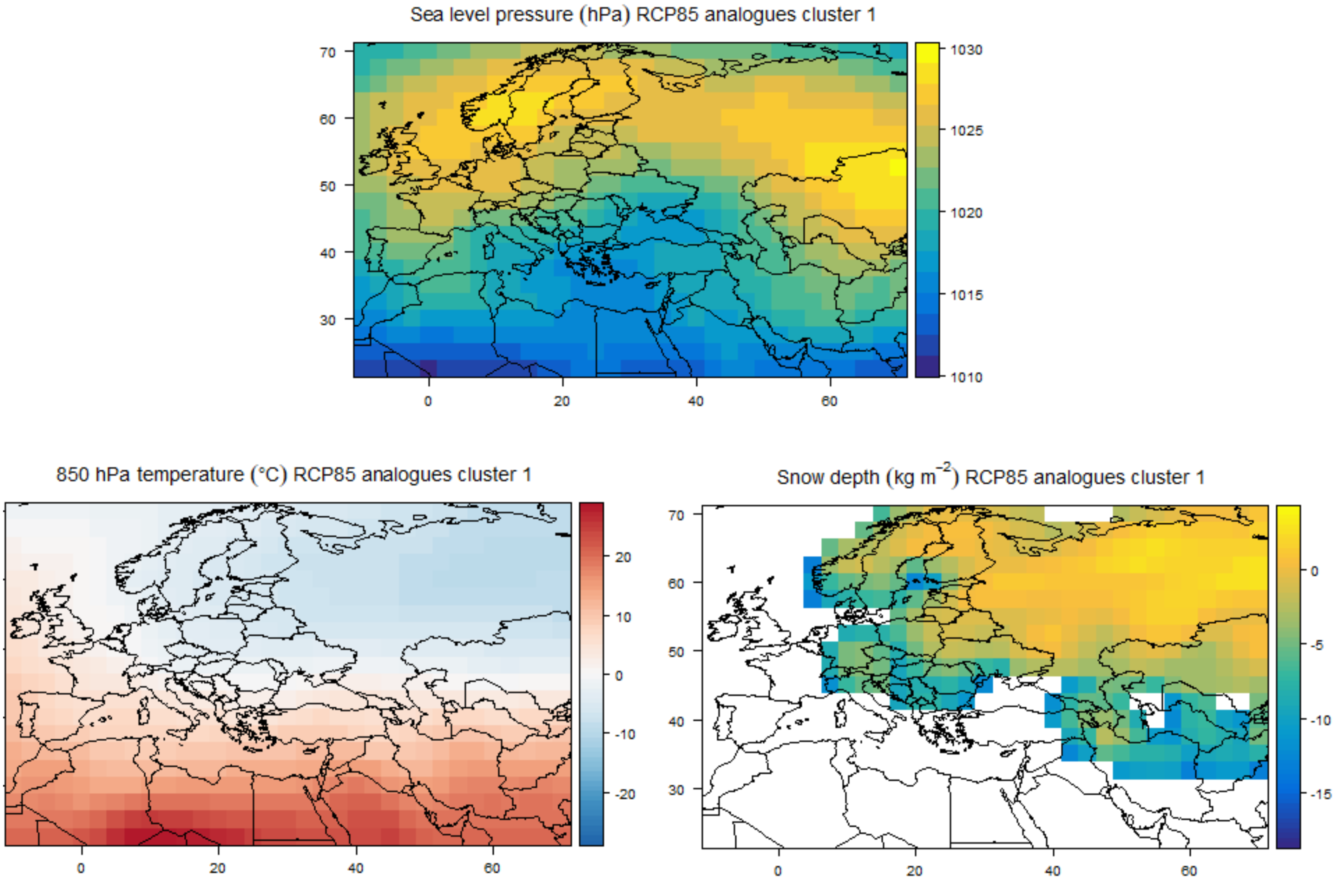

Figure 8. Analogues climatology, cluster 1. Average atmospheric fields if the analogues of cold spells assigned to cluster 1: SLP (upper panel), T850 (bottom left), snow depth (bottom right).

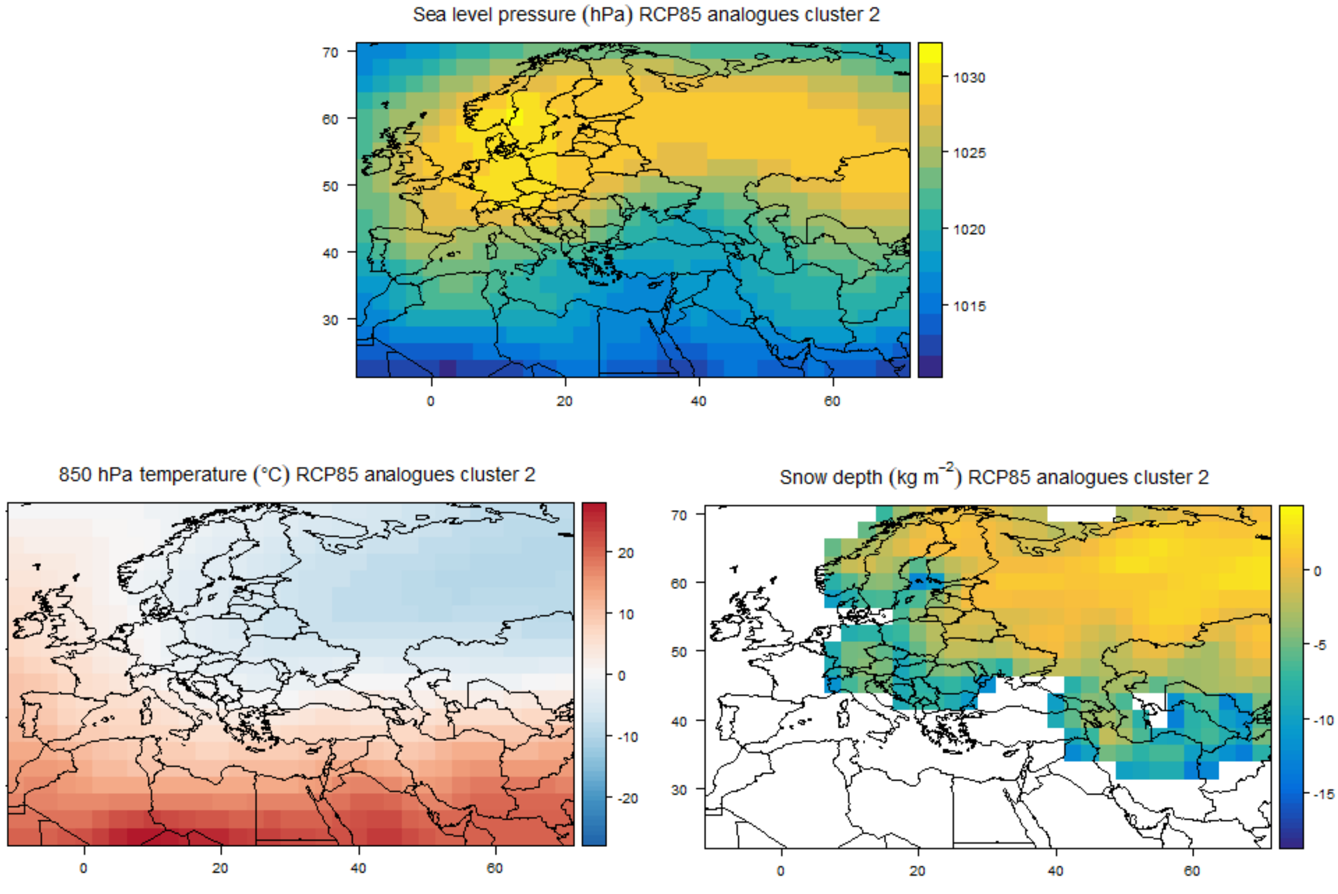

Figure 9. **Analogues climatology, cluster 2.** Average atmospheric fields if the analogues of cold spells assigned to cluster 2: SLP (upper panel), T850 (bottom left), snow depth (bottom right).

4 Discussion and conclusion

We have characterized high impact cold spells over Italy over the past 60 years by assessing their common dynamical large scale signature. Despite the differences in duration, snowfall and temperature recorded during each event, the corresponding SLP fields can be grouped according two main dynamic fingerprints. Both are characterized by the presence of a low pressure area over the Central Mediterranean, associated to an anticyclone either elevated over Western Europe (cluster 1), or zonally tilted between Western Europe and Russia, with pressure maxima over Central Europe (cluster 2). In both cases, cold air is drawn towards Italy by the Mediterranean low pressure area, flowing mainly from Scandinavia (cluster 1) or Russia (cluster 2).

Then, after assessing the capability of PlaSim to reproduce dynamic analogues of these events in the CTRL run, we have studied the influence of two climate change scenarios on the frequency of such analogues. The PlaSim control run showed a tendency to under-estimate the frequency of such events; no relevant differences are observed between CTRL and 4SST, suggesting that Mediterranean sea temperature does not influence the dynamic configuration generating the cold spells. Sea temperature also appears to have no influence on the distribution or magnitude of the snow depth associated to cold spell analogues. On the contrary, the RCP85 run is associated to much more frequent configurations potentially leading to cold spells. Since RCP85 is significantly warmer, cold spells and snow are naturally expected to decrease overall; however, we argue that the formation of cold air over the Arctic winter would not be completely suppressed, hence making cold spell events still possible. Indeed, selecting the dynamic analogues that are also close to the chosen events in terms of T850, we find that cold spells capable of bringing cold air from the East towards Italy would still be possible with relatively short return times. However, snow accumulation over Central-Southern Italy would be much less likely to happen, as it is also the case of Greece and Turkey.

This study comes with some caveats and limitations: although we have validated the behavior of PlaSim against the NCEP reanalysis, results on frequency changes for cold spells crucially depend on the position and the destabilization of the jet stream. It is known that different climate models have a different response of jet stream dynamics to climate change (Arctic Amplification (Cohen et al., 2014) or Zonalization (Francis and Vavrus, 2012)).

The use of an intermediate complexity model like PlaSim allowed us to evaluate the climate change of atmospheric dynamics associated to cold spells in a steady, much warmer climate, showing how the frequency and intensity of cold spells may decrease less than expected, due to a higher likelihood of synoptic configuration favourable for cold air to flow towards the Mediterranean. However, we plan to extend our analysis to higher complexity GCM end-of-century simulations such as CMIP6, to gain a more robust understanding of the distribution and phase of precipitation during this type of event.

Acknowledgements

This work was supported by ERC grant No. 338965-A2C2 and CEA grant DAMA. We thank Fabio D'Andrea and Aglaé Jézéquel (Laboratoire de Météorologie Dynamique, Paris, France) for useful discussion on the paper. FL acknowledge support by the Deutsche Forschungsgemeinschaft (DFG,German Research Foundation) through the University Hamburg's Cluster of Excellence Integrated Climate System Analysis and Prediction (CliSAP), and under Germany's Excellence Strategy - EXC 2037 'Climate, Climatic Change, and Society' (CliCCS) - Project Number: 390683824, as contribution to the Center for Earth System Research and Sustainability (CEN) of University Hamburg's. The authors acknowledge the support of the INSU-CNRS-LEFE-MANU grant (project DINCLIC).

Author Contribution

M.D. performed ~~computations~~simulations and F.P. performed the statistical analyses, D.F. conceived the idea and the study, D.F. C.N. designed methodology. M.D. made collection and analysis of the database and performed model simulations in consultation with F.L., M.D. wrote the manuscript and P.Y., C.N., F.L. and D.F. discussed the results and implications and commented on and edited the manuscript.

Competing interests. The authors declare no competing interest.

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Analog quantiles 2% 5 % 10 % CTRL a) 0.88 0.92 0.94 b) 0.97 0.98 0.98 RCP8.5 a) 0.91 0.94 0.95 (RCP8.5/CTRL) (1.03) (1.02) (1.01) b) 0.98 0.99 0.99 (1.01) (1.01) (1.01) 4K-SST a) 0.73 0.80 0.84 (4K-SST/CTRL) (0.83) (0.87) (0.89) b) 0.93 0.95 0.96(0.96) (0.97) (0.98)

Cold spell frequency per year in the control simulation (CTRL), RCP8.5 and 4K-SST scenarios. The cold spell is defined at different quantiles for analogues of observed cold spells for SLP and anomalies of a) T850 ; b) Z500. The values in parentheses indicate the ratios of frequencies with respect to the CRTL simulations. Values above 1 indicate an increase of frequency.

Mean temperature. Data of the winter mean temperature (°C) over Italy (35–45N,7.5–18E,) for the period 1950-2018 (E-OBS.v19 Cornes et al. (2018)).

Map. Italy with highlighted the cities of Bologna and Campobasso. The image is created using QGis 2.18 software (QGIS Development Team 2020. QGIS Geographic Information System. Open Source Geospatial Foundation Project.) and using image from NASA Worldview: we acknowledge the use of imagery from the NASA Worldview application , part of the NASA Earth Observing System Data and Information System (EOSDIS).

Cold spells from documentary sources. Data recorded in a) Campobasso (686 m of altitude); b) Bologna (54 m of altitude). Each ball represents one cold spell event. The size is proportional to the number of snowfall days. The y-axis shows the snowfall measured during each event. The color shows the minimum near surface temperature recorded during the event (see Sources and data-set).

Spatial average. Boxplots of the spatial average over Italy of SLP (hPa) (a), T850 (°C) (b), Geopotential Height HGT (dam) (c) and Snow depth (Kg/m^2) (d) for all winter days (grey) and for the analogues of cold spells (blue). **Averaged cold spells for NCEP reanalysis.** Average of the 32 cold events for a) Sea level pressure (hPa); b) Temperature at 850 hPa (°C); c) Geopotential height at 500 hPa (dam); d) Snow depth (kgm^{-2}) for the NCEP reanalysis.

Cold spell anomaly for NCEP reanalysis. The anomalies of the 32 cold spells are computed with respect to the winter season over 1948-2018 of a) temperature at 850 hPa (°C) and b) snow depth (Kg/m^2) for NCEP reanalysis.

Averaged cold spells for PlaSim The average of 32 best analogues of PlaSim for (a,b,c) Sea level pressure (SLP) , for (d,e,f) Temperature at 850 hPa (T850), for (g,h,i) Geopotential height at 500 hPa (Z500) and for (j,k,l) snow depth (Kg/m^2). a,d,g,j) CTRL run; b,e,h,k) RCP-8.5 run and c,f,i,l) 4K-SST run.

Mean of correlation matrix between the events. The pairwise correlations are computed among the anomalies of SLP (blue line), T850 (black line) and Z500 (green line) of the a) 32 cold spells in NCEP reanalyses; of the 32 best analogues in b) control run; c) RCP8.5 run and d) 4K-SST run at different time lags.

Cold spell anomalies. a,b) T850 (°C) and c,d) snow depth (kgm^{-2}) anomalies of the cold spells in NCEP reanalyses (black line) and of best analogues of PlaSim for control (blue line), RCP8.5 (10 $^{-2}$kgm^{-2}) (red line) and 4K-SST (green line) runs at different time lags. Standard deviation represented as shading;in a,c) anomalies are obtained by subtracting the seasonal average, in b,d) normalized anomalies are obtained by subtracting the seasonal average and dividing by the seasonal standard deviation.

NASA satellite image. The image shows the snow convective cloud bands associated to the cold spells (Visible Infrared Imaging Radiometer Suite (VIIRS), Aqua and Terra, images of 09-02-2015. NASA Worldview: . We acknowledge the use of imagery from the NASA Worldview application , part of the NASA Earth Observing System Data and Information System (EOSDIS).

Convective precipitation rate. The rate of the convective precipitation (mm/day, $\sim$10^{-8}m/s) is shown as difference of 4K-SST run and control run to highlight the atmospheric instability over the Mediterranean sea. The 4K-SST run is more unstable, thus explaining the convective feedback triggering heavy snowfalls.