Understanding the link between the extreme weather conditions in central Europe in spring 2018 and a preceding record-breaking sea ice reduction in the Bering sea.

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Abstract: This study examines a series of extreme weather events, including large-scale droughts and heatwaves, over Northern and Central Europe between April and June of 2018, and explores their potential link with an unprecedent low sea-ice anomaly in the Bering Sea during January-April of the same year. Analysis of observational and reanalysis data shows that the development of a persistent blocking pattern over Scandinavia is likely behind the occurrence of the extreme weather episodes in Europe. To asses if this and the extreme weather conditions are associated with the record-breaking sea-ice reduction in the Bering Sea, we have performed a composite analysis based on six similar previous events in the Bering Sea. One month after the driving sea-ice signal in March-April, the composite of geopotential height at 500 hPa reproduces a significant blocking pattern Southeast of Scandinavia, which persists during the next three months in the same way of the blocking in 2018, although slightly shifted. Additional composites based on surface temperature and precipitation show that general tendency towards drier and hotter conditions over the region of the blocking, and therefore also displaced with respect to those in 2018. These differences, however, could be accounted by internal variability effects, as the position of the blocking center of action moves slightly around for each of the individual composited years. Finally, these results allow us to suggest that a linkage between Bering Sea ice and Europe weather is plausible. We cannot, however, definitively conclude that a casual link exists between them, for which additional attribution studies based on climate models would be needed.

I. INTRODUCTION

During the spring and early summer of 2018, Central and Northern Europe experienced extremely dry and hot conditions reaching unprecedented levels and had a big socioeconomic impact. Due to this persistent weather situation, both renewable and conventional energy sources were affected, with huge effects on the run-of-river hydropower generation, most significantly in Sweden and Germany. The low river levels impacted river transport causing coal supply problems to power plants, and affected river cooled nuclear power plants having to shut down temporarily to protect the river environment because the level was too low to keep introducing hot water (*Agora Energiewende and Sandbag* 2019). By contrast, solar energy generation increased during the same period, wherein some parts of northern and central Europe had up to 40% more sunshine hours than average that year (*Copernicus* 2019). Germany achieved a record of solar production in July, producing 15.1% of the total electric production in the country (*Burger* 2018). Due to the drought and enhanced by the high temperatures, the agriculture sector experienced a yield reduction of the main crops up to 50% (*Toreti et al.* 2019). In June, dry and hot conditions favoured unprecedented forest fires in Scandinavia, affecting mainly in Sweden where the government had to call international assistance (*NASA Earth Observatory* 2018). During the second half of July, northern and central Europe suffered an extreme heatwave, with some record-breaking, that was intensified by the persistent conditions in the preceding months caused by a continuous circulation anomaly (*Yiou et al.* 2019).

From April to July, the circulation was characterized by high pressure conditions moving over Scandinavia, western Europe and the North Atlantic. The persistent and intense atmospheric blocking was essential for developing the large-scale heatwave and drought enhanced by the soil-moisture feedbacks (*Toreti et al.* 2019). Some studies show evidence that extreme events like this are favoured by amplified planetary waves (Rossby waves); this pattern was also observed during the European heatwaves of 2003, 2006 and 2015 and other extreme events (*Kornhuber et al.* 2019, *Screen and Simmonds* 2014). Amplification of planetary waves has been proposed as a possible mechanism linking mid-latitude weather extremes with the faster warming of the Arctic than the rest of the world, known as Arctic Amplification (*Screen and Simmonds* 2013b). Even though there is still no observational evidence that larger amplitude planetary waves are enhanced by the Arctic Amplification (*Barnes* 2013, *Screen and Simmonds* 2013a). Large-scale changes in the mid-latitude circulation have also been directly associated with sea-ice loss (*Budikova* 2009, *Overland and Wang* 2010). Ocean ice-free conditions when sea-ice retreats allow for larger air-sea exchanges of heat and moisture increasing the near-surface temperature and affecting the lower-troposphere by increasing the geopotential thickness. As the whole Arctic is warming, the poleward

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thickness gradient between 1000-500 hPa is diminishing and therefore the upper-level zonal winds too, resulting in a lower progression and higher amplitude of the large-scale Rossby waves, and a northern elongation of ridges in 500 hPa waves enhancing the probability of extreme weather due to more prolonged weather conditions (Francis and Vavrus 2012).

It is widely accepted that sea-ice conditions in the Arctic play a role for mid-latitudes weather, although it is still not clear which mechanisms connects the two regions. This teleconnection is more pronounced during autumn and winter than during spring when the sea-ice coverage has spread again, and the positive feedbacks from the sea-ice retreat are not longer active (Francis and Vavrus 2012). An example of these Arctic in uences is described in Acosta Navarro et al. (2019), linking a record low December 2016 precipitation event in Europe to extremely low sea-ice conditions in Barents and Kara Seas in the month before.

In this study, we aim to understand the possible relation between the extreme and persistent weather over Europe in 2018 and the record breaking reduced sea-ice conditions observed in the Bering sea from January to April of the same year, the lowest winter-maximum areal sea-ice coverage on record from 1980 (Thoman JR et al. 2019). In the following section we describe the di erent data sets and the methodology used. Section III characterizes the event and discusses it in the context of previous similar episodes. Finally, in section IV, we outline the main conclusions and consider future prospects.

II. DATA AND METHODS

A. Data

This analysis is exclusively based on monthly gridded observation and reanalysed products, to be able to characterise better the large-scale features of the 2018 event. We give preference to widely used long datasets to maximise the period for the identi cation of similar events. The longest time interval covered by all products is 1958-2018, which will be our analysis period.

1. Sea-ice data

The sea-ice state in the Arctic is characterized with sea-ice concentration (SIC) data describing the fraction over an area covered by sea-ice (in %). Two di erent datasets, both regridded onto a 1ºx1º regular grid, are used to characterize the 2018 and assess the sensitivity to the observational record considered. These are the satellite-derived SSM/I (Special Sensor Microwave/Imager) SIC from CERSAT/IFREMER (Note1) for 1958-2018, which covers a longer time period by combining passive microwave satellite data and historical sources. Both SIC sources are compared for the Bering region during March-April in Figure 1 and discussed in section III.

2. Atmospheric data

The characterization of the conditions over Europe is done using monthly mean near-surface mean temperature [K], and total precipitation [m s^{1}] from the observational data set E-OBS version 19.0e (Haylock et al. 2008). This product is derived from a spatial interpolation of daily climate observations from land-only stations. The data used is in a high-resolution regular grid data of 0,1º for the European region (25N-71.5N; 25W-45E) and covers the period from 1958 to 2018.

The mid-troposphere circulation over the northern hemisphere is characterised and analyzed using the geopotential height at 500 hPa (z500, in gpm) from the JRA-55 reanalysis (Kobayashi et al. 2015). This dataset starts in 1958, when the global scale radiosonde observations began, and has a spatial resolution of 1,25º. The monthly mean data for this variable is computed from 6 hourly frequency data.

B. Methods

All the scripts developed for analyzing the data and generating the plots and graphics have been done using the free software environment R (R Core Team 2019) and the "s2dveri cation" package (Manubens et al. 2018).

1. Event characterization

To determine the extremeness of the weather conditions from December 2017 to July 2018 have been compared with the climatological state between 1958-2017. Each variable is analyzed in a di erent way, depending on its characteristics.

The near-surface temperature variability follows approximately a Gaussian distribution, so its anomaly can be expressed and interpreted in standard deviation units. The standardized anomaly from the climatology (1958-2017) is calculated for each grid point following the next equation:

$$tas^{0} = \frac{tas \quad \overline{tas}}{} \qquad (1)$$

Precipitation has a very irregular distribution, and instead of computing its standardized anomaly, we weigh the total amount of precipitation by the long-term monthly climatology (i.e. with respect to 1958-2017) as a percentage as it follows:

$$prlr^{0} = \frac{prlr}{\overline{prlr}} \quad 100 \qquad (2)$$

Finally, SIC and geopotential height at 500 hPa are not computed as standardized anomalies because we do not only want to assess the extremeness of the anomaly but to quantify how much anomalous it was, even though also have a good approximation to a Gaussian distribution like temperature. Thus, the anomaly from the mean climatology is computed as a single di erence between the monthly mean minus the climatology (1958-2017 for the geopotential height and HadISST SIC, and 1992-2017 for CERSAT SIC).

2. Composite analysis

The main hypothesis we seek to con rm is if the conditions in the Bering sea favoured the occurrence of a blocking pattern over Europe, leading to the large-scale drought and heatwave in 2018. For this purpose, this study makes use, as already mentioned, of observational and reanalysis data for the period between 1958 to 2017 in order to look for similar events with comparable conditions, thus potentially showing the same linkage within the two regions. By doing so, a composite with the events with the closest sea-ice conditions in the Bering Sea to 2018 is performed. A composite is just an average of climate elds in years that meet a speci c condition, in this case a low state in the sea-ice in the Bering sea.

In order to select the years more comparable to the 2018 conditions, a sea-ice state index for the Bering Sea is used. This Bering Sea Ice index (BSI) is computed as the area weighted regional mean of the SIC standardized anomalies in the northern Bering Sea (57-67N; 170-200E). The index is calculated as the average in March and April for the period 1958-2018 (Figure 1).

Excluding 2018, and using HadISST which is the longest record, the years within the 10th percentile are selected. This corresponds to the six years with the lowest SIC in the region before 2018.

Finally, composites are computed for other variables as the average during those six years. To asses the response to the low sea-ice, the composites are computed also in two month periods, delayed from 0 to 3 months with respect to March and April, when the lowest sea-ice anomalies happened. That is, 1-month delay corresponds to April and May, 2-month to May-June, and 3-month to June-July. The composite anomaly elds are: the geopotential height at 500 hPa, surface temperature and precipitation.

The statistical signi cance of the di erent composites is evaluated with a bootstrap method (Efron and Tibshirani 1986). This test consists of randomly sampling 6 years from the 1958-2017 period to create an "alternative" composite not constrained by the sea-ice state, repeating the process 1000 times to have a control distribution of "alternative" composites. We can then assess where the Bering Sea Ice constrained composite lays with respect to the control distribution, from which a significance level can be set. We use a signi cance level of p 0.05, leaving 2.5% on both sides of the distribution.

III. RESULTS AND DISCUSSION

A. Characterization of the event

1. Observed sea-ice state

Between January and April 2018, the Bering Sea experienced the most greatest sea-ice reduction in the whole Arctic, setting a new record of low sea-ice for the area in the observations and past reconstructions since 1850 (Thoman JR et al. 2019). The right hand panel of gure 1 shows the BSI time-series for March-April (computed over the purple box in the left panel) for the two datasets. The 2018 low-record is between 2 and 3 standard deviations lower than the climatological mean. Despite the di erence in the magnitude of the anomaly, both datasets show unprecedented values, and their timeseries show a high correlation with a Pearson coe cient of 0.94 increasing con dence in the exceptional nature of the event.

The left-hand panel of gure 1 provides a spatial description of the event. It shows how SIC anomalies for March and April in the west and north of the Bering Sea reached values as low as -80% implying that this region, usually covered completely by sea-ice, was virtually ice free. February shows almost the same anomaly magnitude and distribution than the two following months, and January was less intense but still reaching SIC reductions of up to 60% with the same spatial distribution. Finally, May is the month in which Bering sea-ice typically retreats up to the Chukchi Sea, so in 2018 the anomalies are no longer found in Bering Sea, but there is still a signi cantly low sea-ice state in the Chukchi Sea over the Bering straight.

The climatological sea-ice in the Bering Sea reaches its maximum between March and April, with a southernmost bound around 57°N (the southern line of the purple box). In 2018 the maximum sea-ice extension was reached in early February corresponding to an advance of the melting season by 2-3 months (Perovich et al. 2018).

According to Stabeno and Bell (2019), Bering sea-ice is favoured by the cold northerly winds that dominate between November to March. These conditions were not dominant during most of the winter 2017/18. In November 2017 southerly warm wind delayed the arrival of the ice. Only during the next two months the northerly winds prevailed, but were warmer than usual. February and March were dominated by southerlies, pushing the sea-ice edge north and warming the surface air masses. Finally, between late March and May wind direction were relatively normal, but the warmer ocean and air conditions in the Paci c and the beginning of the natural melting season kept the low sea-ice conditions.

The southerly winds during March were driven by a sea level pressure dipole in both sides of the Bering straight, with higher pressures on the east of the straight and

(a) (b)

Figure 1. (a) Spatial pattern of the mean sea-ice concentration anomaly in March and April of 2018, calculated with respect to the climatology of 1992-2017 in the SSM/I CERSAT dataset. Dashed lines indicate the longitudes and latitudes grid at 20° and 10° separation respectively. (b) Time series of the standardized sea-ice concentration mean anomaly in March-April in the Bering sea (purple box on the panel on the left) for HadISST and SSM/I CERSAT. The reference period is 1958-2017 and 1992-2017, respectively. The horizontal dashed line sets the 10th percentile of the HadISST timeseries, the threshold for identifying low sea-ice events in the composite analysis.

lower on the west. This pattern can also be seen in the mid-troposphere in Figure 2a, during the months of March and April. The geopotential height at 500 hPa (z500) shows the same dipole but less intense than the sea level pressure eld. The e ect of the warmer ocean and air temperatures with positive z500 anomalies over the northern Paci c can also be seen in the same gure.

2. Evolution of atmospheric conditions

The analyzed event (described in detail in section 1), was a large-scale drought and heatwave associated with a persistent blocking pattern in Scandinavia that lasted from April to August. It a ected principally northern and central Europe, depending on the position of the blocking. We now describe the evolution of the atmosphere, and the associated regional climate signals that occurred during the following months.

Figure 2 shows the evolution of the z500 anomaly in bimonthly periods from March-April to June-July, which corresponds to 0 to 3 months after the occurrence of the sea ice anomaly in gure 1. For lags 1 to 3 a positive z500 anomaly established over Scandinavia. During April-May the blocking was more extended, covering also eastern Europe and reaching the southern and central part of the continent. One month later, the high pressure cell shifted west, covering southern Scandinavia, the UK, and northern Central Europe. Finally, in June and July, the blocking was more localised in an area around the North Sea. During all this period the anomaly reached values of 100 gpm above the climatological mean, making it a very persistent and intense blocking.

The blocking pattern was also observed in sea-level pressures (not shown), but the signal is noisier than in the mid-troposphere. We chose to show z500 precisely to minimise the noise from surface interactions, and focus on the signal that relates to the large-scale atmospheric circulation itself.

It is important to remark that during the particular month of March, the atmospheric circulation was radically di erent; an extremely negative NAO event prevailed during almost all the month. Figure 2a shows some clear features of this distinctive pattern, with a large negative z500 anomaly in the west coast of the European continent reaching the Iberian peninsula and high pressures North of Iceland. According to Ayarzagüena et al. (2018), this persistent situation was induced by a sudden stratospheric warming that happened in mid-February; it induced extremely wet conditions over southern Europe and brought to an end the 2016/2017 drought in the Iberian peninsula. Due to these strong signals, unre-