Anthropogenic Contribution to the Record-Breaking Warm and Wet Winter 2019/20 over Northwest Russia

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CMIP6 simulations suggest that the 2019/20 extremely warm and wet winter over northwest Russia would have been extremely unlikely without human influence despite a strong positive phase of the NAO.

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Northwest (NW) Russia has been experiencing increased snow-free days since 1966 (Bulygina et al. 2011), and the 2019/20 winter was warmest on record since 1902. It resulted in a significant shrinkage of snow cover and thus required the delivery of artificial snow from dispatching trucks for the New Year celebrations (Ilyushina and Miller 2020). The 2019/20 winter was also wettest on record since 1902, in line with the northern high-latitude moistening trend under greenhouse warming (Min et al. 2008; Wan et al. 2015). The NW Russian winter climate plays an important role in shaping the Eurasian spring/summer climate through its delayed impacts. Typically, the regional warm winter during the positive phase of North Atlantic Oscillation (NAO) or Arctic Oscillation can cause premature snowmelt and drier soil, providing a favorable condition for severe heatwaves and wildfires (Bamzai 2003; Kim et al. 2020). However, understanding of anthropogenic contribution to the 2019/20-like extremely warm and wet winter over NW Russia remains to be determined.

Here, we investigate the anthropogenic impact on the likelihood of the 2019/20-like warm and wet winter over NW Russia by quantifying the contributions of anthropogenic (greenhouse gas and aerosol) forcing, natural (solar + volcanic) forcing, and internal variability (focusing on the NAO) to the 2019/20 NW Russia winter. The findings of this study alert policy makers and local stakeholders of the expected change in the risk of climate change–driven extremes.

Data and methods.

First, we computed the geopotential height anomalies at 850 hPa and vertically integrated moisture flux anomalies relative to the 1981–2010 climatology from the latest version of the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA5)[1] for analysis of NAO influences (Fig. 1a). We calculated regional averages of wintertime [December through February of the following year (DJF)] 2-m air temperature (T2m) and precipitation (PREC) over NW Russia (30°–52°E, 58°–68°N) from Climate Research Unit (CRU) version TS v4.04 (Harris et al. 2020) and 42 station observations from the Russian Research Institute of Hydrometeorological Information, Water Data Center (RIHMI-WDC)[2] (Figs. 1b,c). Then, we computed the anomalies of T2m and PREC relative to the 1902–31 climatology to analyze global warming influences. Based on the temporal correlation maps, we found that this region is highly correlated with the regional climate of the western part of Russia (up to 70°E and 50°N; not shown).

[1] https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

[2] http://meteo.ru/english/climate/cl_data.php

Here, we used 76, 65, 74, and 68 ensemble members of 12 models from the phase 6 of the Coupled Model Intercomparison Project (CMIP6) with historical (H), greenhouse-gas (G), historical-natural only (N), and aerosol (A) forcing, respectively (Eyring et al. 2016). First, we selected these ensemble runs of the 13 models based on the availability of multiple ensemble members (≥ three ensemble members for H-, G-, N-, and A-forcing, except for BCC and CAS), and then we selected the ensemble runs of the 12 models based on the performance in the seasonality of simulated T2m and PREC anomalies (see Figs. S1 and S2 in the online supplemental material). The runs with H-forcing (ending in 2014) were extended up to 2020 using the corresponding Shared Socioeconomic Pathway (SSP) 2-4.5 scenario runs, which were chosen based on the data availability considering their similar radiative forcing over 2015–20 (O'Neill et al. 2016). We chose the SSP 2-4.5 scenarios runs for H-forcing for consistency with other forcing runs (Gillett et al. 2016). Details of the ensemble members for each model are provided in Table S1.

We used a bilinear method to interpolate all model data onto the observed grids (50 km × 50 km) and then computed the regional averages over NW Russia (Figs. 1d,e). Next, we estimated the contributions of H-, N-, G-, and A-forcing to the observed anomalies of T2m and PREC during the 2019/20 winter (Figs. 1f,g). Here we estimated individual forcing contributions to the observed anomalies, using the 10-yr (2011–20) averages of their multimodel multi-ensemble means (MMMs) of T2m and PREC anomalies, following Knutson et al. (2013) and Knutson and Zeng (2018), who compared multimodel mean forced anomalies with observations. To construct the 95% confidence interval (CI) of each forcing's contribution, we resampled the 10-yr (2011–20) segments 76 times [e.g., the total sample size for H-forcing is 760 (10-yr segment × 76 ensemble runs)] by weighing each model based on the model's contribution to the total ensemble runs [e.g., 10/76 for CNRM-CM6-1, which has 10 members] , and repeated resampling with replacement 1,000 times.

It is well known that the NAO shows the decadal-consistent impact on the western part of Europe winter climate, including NW Russia (Marshall 2021). It showed a very strong positive phase (NAO+) during 2019/20 winter (Juzbašić et al. 2021), ranking 7th highest (NAO index = +1.26; see below) since 1951 (the 2014/15 winter had a record high value of +1.66). To mea-

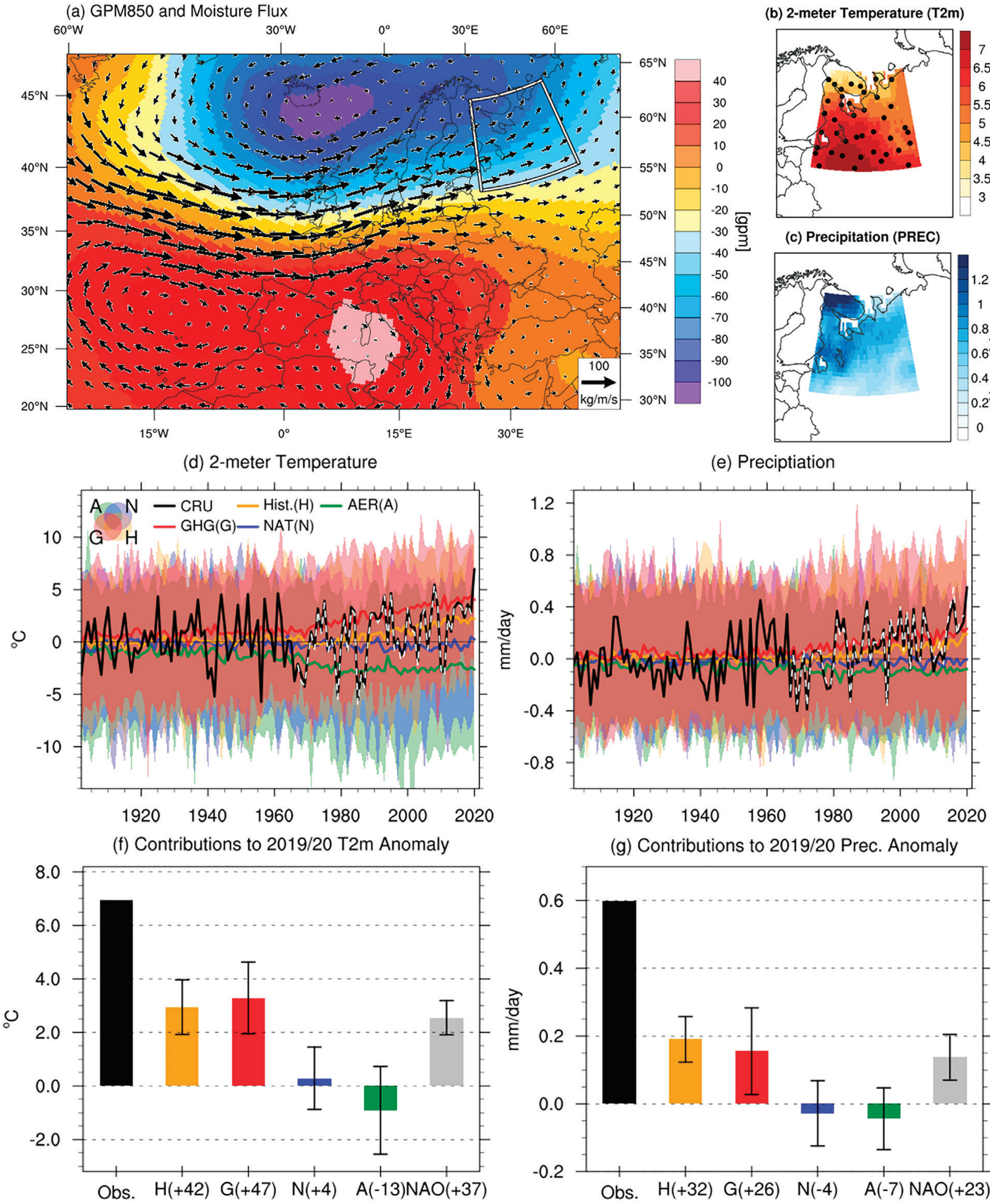

Fig. 1. (a) Geopotential anomalies at 850 hPa and vertically integrated moisture flux (black vectors) anomalies during the 2019/20 winter relative to the 1981–2010 climatology. (b) 2-m air temperature and (c) precipitation anomalies over the study region in the percentage relative to the 1902–31 climatology. In (b), circles depict the location of the 42 meteorological stations from RIHMI-WDC. Time series of (d) 2-m air temperature and (e) precipitation anomalies from the observational data (CRU: black solid lines and 42 stations: white dashed lines), and the CMIP6 simulation with H- (orange), G- (red), N- (blue), and A-forcing (green). In (d) and (e), the min-max ranges of the CMIP6 simulations with each forcing are shown at the center of the grand means. Also shown are the contributions of H- (orange), G- (red), N- (blue), A-forcing (green), and residual (gray) for the 2019/20 (f) T2m and (g) PREC. In (f) and (g), the error bars depict the 95% CIs from the 1,000 bootstrapping samples from the corresponding forcing runs and numbers in parentheses are the percentage contribution of each forcing/NAO to the observed 2019/20 anomaly value.

sure the NAO contribution to the observed NW Russian winter climate in 2019/20, we regressed the observed T2m and PREC anomalies onto the NAO index[3] over 1951/52–2018/19, excluding the 2019/20 winter. Then, we computed the NAO contribution by multiplying the NAO index in 2019/20 with the linear regression coefficient and also constructed its 95% CI based on the 2.5th and 97.5th percentiles of the linear regression coefficients. The CMIP6 model-based analysis of NAO shows that the frequencies of high NAO index values from H-forcing and N-forcing runs are similar to each other, indicating that NAO is an internal mode (see Fig. S3).

[3] www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii.table

To better understand whether the anthropogenic impact has been consistent at the decadal scale, we estimated the probability of occurrence of T2m or PREC anomalies (relative to 1902–31 means) exceeding the observed 2019/20 values through order statistics (i.e., counting the number of threshold exceedances) from the selected CMIP6 models with H-, N-, G-, and A-forcing from the 10-yr segments over 1986–95 (hereafter simply the 1990s) and 2011–20 (2010s). We selected these decades because the NAO index shows two positive phases over 1986–95 and 2011–20 from the observational data and CMIP6 simulations (see Fig. S3). Then we calculated the probability ratio (PR) for P_H/P_N, P_G/P_N, and P_A/P_N for 1990s and 2010s. The 95% CI of PR is estimated using resampled 10-yr segments with replacement (see above). Based on the sensitivity test, we found that the PR estimates are largely insensitive to the segment size between 5 and 10 years (not shown).

Results.

According to the ERA5 data, the North Atlantic region had a strong NAO+ pattern during the 2019/20 winter (Fig. 1a). This strong positive NAO phase led to increases in both T2m and PREC over NW Russia (Figs. 1b,c). The regional averages are consistent between the CRU gridded data and station observations (see white dashed lines in Figs. 1d,e). The CMIP6 simulations show a wide range of year-to-year fluctuations of T2m (–10° to +10°C) and PREC (–0.8 to +0.8 mm day^{-1}) anomalies, indicating that internal variability can play a role in generating extreme climatic events over the study region. The CMIP6 H-forcing simulations show consistency with observed anomalies, with similar interannual variability ranges of T2m and PREC. The MMMs of H-forcing runs exhibit linear trends of T2m and PREC since emerging around 1960 and 1970, respectively, indicating the growing anthropogenic impacts on the regional extreme climatic events over NW Russia over time.

The NW Russia had anomalously high T2m (+6.9°C) and PREC (+0.6 mm day^{-1}) during the 2019/20 winter (Figs. 1f,g). The MMM values from H-, G-, N-, and A-forcing runs show anomalies with the corresponding magnitudes of +42%, +47%, +4%, and –13% (+32%, +26%, –4%, and –7%) of the observed T2m (PREC) anomaly. The NAO index in 2019/20 explains the observed T2m and PREC anomalies by 37% and 23%, respectively, while NAO shows a significant correlation with wintertime T2m and PREC anomalies over NW Russia (0.7 and 0.46, respectively) during 1951–2020. The 95th percentile ranges of T2m (27.5%–46%) and PREC (12%–33%) are wider in the A- and H-forcing runs, respectively, than those in other forcing runs, indicating possible differences in T2m and PREC sensitivity to the aerosol forcing.

We counted the events of exceeding the observed T2m and/or PREC anomalies in the 2019/20 winter from the 10-yr segments of CMIP6 simulations. The 10-yr sample segments of H-, G-, N-, and A-forcing runs include 760, 650, 740, and 680 values, respectively. From the segments for the 2010s, the numbers of events exceeding the observed T2m (PREC) anomaly are 31, 76, 4, and 2 (38, 41, 1, and 1) for the H-, G-, N-, and A-forcing runs, respectively. We found 7 and 17 events of simultaneously exceeding the observed T2m and PREC anomaly in the H- and G- forcing runs, respectively. Sensitivity tests using the model samples with positive NAO phases indicate that warm-wet extremes occur more frequently due to the global warming influences (see heading S3 in the online supplemental material).

The segments for 1990s show a decreased number of the exceeding events as 18, 30, 6, and 1 (17, 27, 3, and 1) extreme cases for the H-, G-, N-, and A-forcing runs for T2m (PREC), respectively. We found four and six joint exceeding events of T2m and PREC anomalies in the H- and G-forcing runs for the 1990s, respectively. The results indicate that the anthropogenic forcing with emerging signal since the 1960s has increased the likelihood of warmer or wetter winter and that a 2019/20-like exceptionally anomalously wet and warm winter would have been extremely unlikely without human influences, particularly anthropogenic greenhouse gas increases.

For visualization, we fitted the Gaussian functions to multimodel T2m and PREC data from each forcing runs for 1990s and 2010s (Figs. 2a–d). Overall, the anthropogenic influence increased the likelihood of the extremely warm or wet winter in 2019/20 significantly because the warming or wetting response to G-forcing surpasses the cooling or drying response to A-forcing.

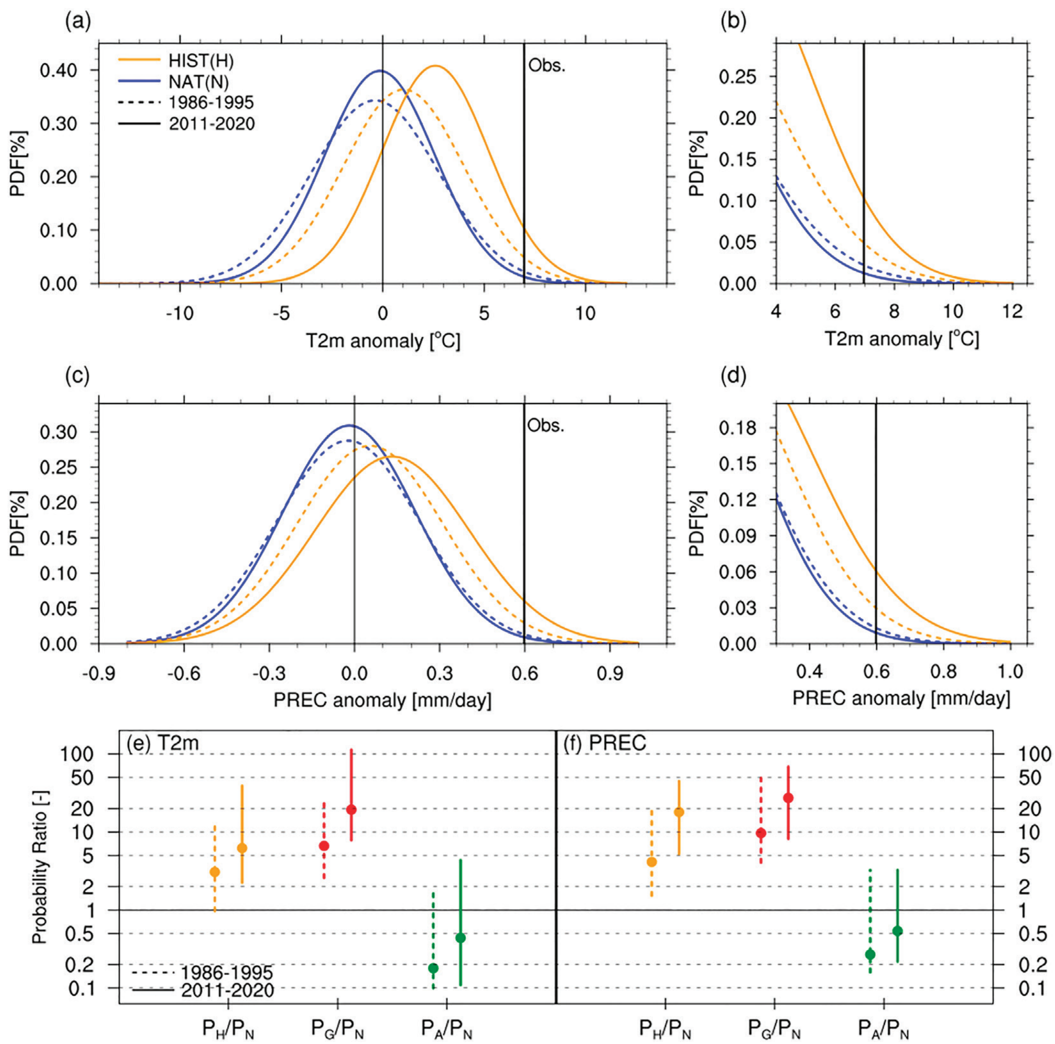

Fig. 2. Fitted Gaussian distributions of simulated (a) T2m and (c) PREC anomalies for 1990s (dotted lines) and 2010s (solid lines) by H- (orange line) and N- forcing (blue). (b),(d) The fitted distributions in (a) and (c), respectively, are zoomed in near the observed threshold values. (e) Circles and bars depict the median and 95th percentile range (2.5th–97.5th percentile) of PR values from the 1,000 bootstrapping 10-yr segment samples for the 1990s (dotted lines) and 2010s (solid lines).

Based on the order statistics, the estimates of P_H/P_N, P_G/P_N, and P_A/P_N for warm winter from the 10-yr segment for the 2010s (1990s) are 6.2 (3), 19.4 (6.6), and 0.4 (0.2) (Fig. 2e). The estimates of P_H/P_N, P_G/P_N, and P_A/P_N for the 2019/20-like wet winter are 18 (4.1), 27.3 (9.7), and 0.54 (0.3). The PR for the joint event with both T2m and PREC exceeding the 2019/20 observed threshold is infinite due to no cases being found in the N-forcing runs. The results confirm that the anthropogenic forcing has increased the likelihood of the 2019/20-like NW Russia winter in the last decade, suggesting more frequent warm and wet winters in the future.

In summary, the 2019/20 NW Russia winter was the warmest and wettest on record since 1902. Based on the 12 CMIP6 model simulations, which can reproduce the observed T2m-PREC seasonal cycles, H- and G-forcing have likely contributed to the increased probability of such warm (wet) winter, by a factor of 6.2 and 19.4 (18 and 27.3), respectively. In particular, the events of simultaneously exceeding the observed T2m and PREC anomalies in the 2019/20 winter were found only in the H- and G-forcing runs. These findings are in line with the CMIP6-based assessment of Ciavarella et al. (2021), who found that prolonged Siberian heat during January–June 2020 would have been almost impossible without human influence. It is concluded that the 2019/20 unusual warm and wet winter over NW Russia is strongly attributable to anthropogenic warming, surpassing the naturally driven ranges.

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