Supplementary information

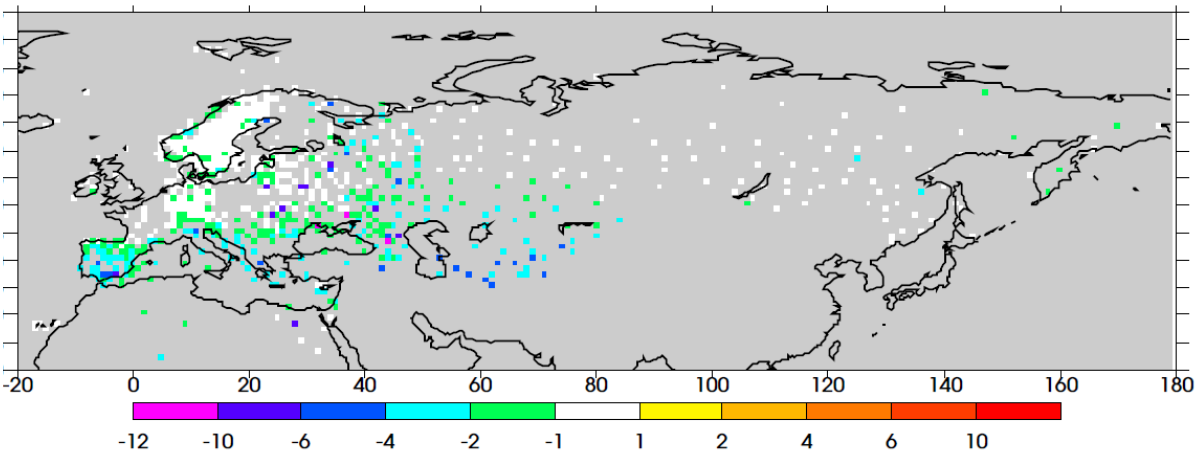
This supplement consists of 4 parts describing the impact of precipitation weighted temperature on daily meteorological records (Part A), the analysis of NAO-$\delta^{18}O$ relationships from GNIP and Greenland ice core data (Part B), a comparison of the temperature biases weighted by precipitation at different resolutions (Part C) and a sensitivity test for the definition of the NAO index, defined both from fixed stations or from the first EOF of SLP (Part D).

A. Precipitation intermittency bias calculated from daily meteorological observations

There are uncertainties in the quality of precipitation in atmospheric general circulation models (in analyses and LMDZiso). We have explored the precipitation intermittency bias using daily temperature and precipitation data from the European Climate Assessment and Database (ECA&D, http://www.eca.knmi.nl), stations (Klein Tank et al., 2002) for which mean temperature and precipitation are available. More than 1600 station data were used and data gaps were identified.

The overall structure of the precipitation intermittency bias from direct observations is in good qualitative agreement in the observations and the three datasets (Figures 3a and S1). In terms of magnitude, the best consistency with observations corresponds to ERA-interim, both in summer and in winter. This might be directly linked to its good performance in the representation of precipitation events, thanks to its fine resolution (e.g. 0.72°x0.72°) allowing for the representation of orographic effects, and also to the realism of physical parameterizations such as atmospheric convection (Jung, 2010).

a) JJAS



b) DJFM

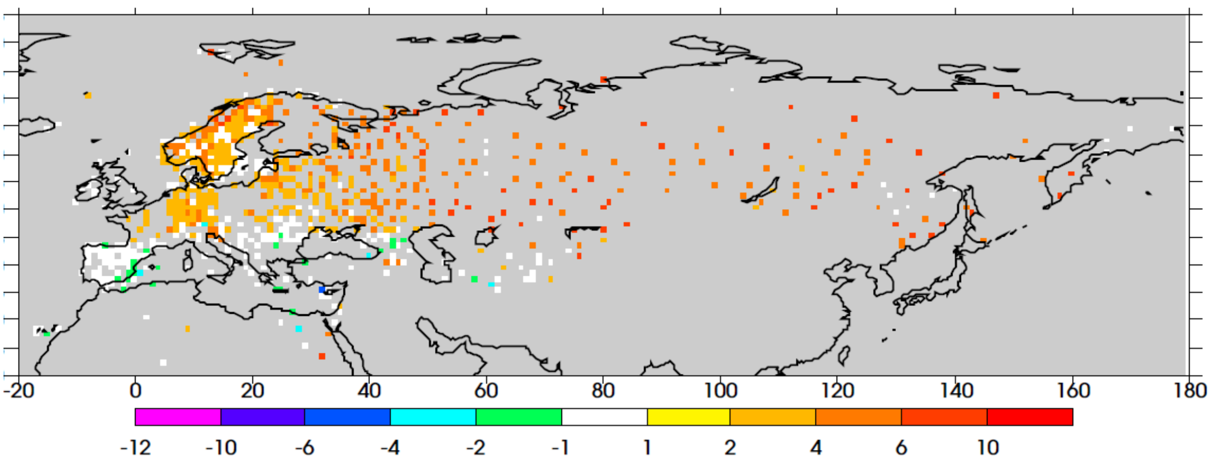


Figure S1. Precipitation intermittency bias, calculated as T_p-T from daily temperature and precipitation from ECA&D stations (same as in Figure 3a,b). The ECA&D database consists of a non homogeneous set of daily meteorological observations from 1622 stations throughout Europe, Russia and the Mediterranean. The longest time series (from Bologna) covers the period 1814-2012. In this plot, a subset of 788 stations has been used so that only one station is represented in each grid-point.

B. NAO-δ^{18}O relationships in GNIP and ice core data

The International Atomic Energy Agency (IAEA) has maintained a Global Network for Isotopes in Precipitation (GNIP) and a database of monthly precipitation water isotope data. We have downloaded all stations available in July, 2012 and selected those that offered a sufficient amount of monthly data to quantify the correlation with winter (DJFM) or summer (JJAS) NAO, using the updated instrumental NAO index (Vinther et al., 2003). Table S1 (DJFM) and S2 (JJAS) describe this selection of data, through the station name and coordinates, the number of monthly data used to quantify seasonal correlations (N_{exist} for δ^{18}O, p, T and T_p), with p the monthly precipitation amount, T the monthly mean surface air temperature and T_p the seasonal temperature, weighted by the monthly precipitation amount. Note that the database is mostly focused on Europe, where patterns of correlation are consistent with results from atmospheric analyses (Figure 3).

Over this dataset and for DJFM, we observe that the relationship between T_p and NAO is very close to the relationship between T and NAO. The largest, positive correlations between winter NAO, T and δ^{18}O (R>0.75) are encountered in NW Europe. Correlations between NAO and δ^{18}O have the same sign as those with temperature, albeit with a slightly reduced strength.

In JJAS, the situation is quite different. First, the results obtained with T_p are less consistent with those obtained with T (R=0.6). Second, there is no consistency between the JJAS NAO-δ^{18}O correlation and those with T or T_p. We suggest that this is due to the impact of continental recycling and convection which probably induce a larger level of local noise in the precipitation δ^{18}O. While local, significant correlations between JJAS NAO and δ^{18}O are found for a few stations (e.g. in Spain or Turkey), the results are not consistent with the NAO-T relationships at the same stations.

Table S1. Site location, number of non-missing values, and winter (DJFM) correlations between the NAO, δ^{18}O, precipitation (p), mean surface air temperature (T), mean surface air temperature weighted by monthly precipitation (T_p) variables from the GNIP database. Correlations significant at the 95% confidence level are highlighted in bold. No correlation values are shown for variables with fewer than 10 non-missing values.

Station	*Longitude*	*Latitude*	*Corr. $\delta^{18}O$*	*N $\delta^{18}O$*	*Corr. P*	*N P*	*Corr. T*	*N T*	*Corr T_p*
ADANA	35.3	37	-0.12	36	-0.11	45	-0.20	43	-0.23
ANKARA	32.9	40	-0.16	41	**-0.4**	42	-0.23	41	-0.11
ANTALYA	30.7	36.9	-0.14	36	**-0.32**	40	**-0.36**	34	-0.16
ASTRAKHAN	48	46.3	**0.37**	16	-0.11	16	**0.43**	15	**0.31**
AVIGNON	4.8	44	**0.34**	12	**-0.52**	12	-	7	-
AZORES	-25.7	37.8	**0.31**	26	-0.27	32	**0.34**	29	**0.32**
BATUMI	41.6	41.7	0.17	10	**-0.36**	9	0.09	9	-0.02
BEEK	5.8	50.9	**0.35**	12	-	8	-	8	-
BERLIN	13.4	52.5	**0.49**	28	**0.37**	27	**0.76**	25	**0.62**
BERN	7.4	47	**0.42**	40	-0.09	39	**0.42**	37	**0.45**
BET DAGAN	34.8	32	0.12	40	0.08	40	**-0.48**	16	-0.20
BRAUNSCHWEIG	10.5	52.3	0.24	29	**0.56**	27	**0.73**	18	**0.64**
CALGARY	-114	51	**0.39**	11	**-0.55**	11	0.07	11	0.10
CHICAGO	-87.8	41.8	**0.48**	17	**0.4**	17	**0.48**	18	0.23
CHIHUAHUA	-106.1	28.6	0.23	13	**0.61**	19	-0.11	21	0.25
CUXHAVEN	8.7	53.9	**0.58**	29	**0.43**	29	**0.84**	17	**0.82**
DANMARKSHAVN	-18.7	76.8	**0.30**	18	-0.13	18	-0.23	17	**-0.33**
EMMERICH	6.6	51.8	**0.43**	27	**0.4**	29	**0.71**	19	**0.77**

FARO	-8	37	0.03	21	-0.18	22	-0.14	19	-0.06
GARMISCH	11.1	47.5	**0.55**	29	0.28	30	**0.36**	18	0.26
GENOA	8.9	44.4	**0.34**	30	**-0.52**	37	0.24	27	-0.08
GIBRALTAR	-5.4	36.2	0.09	41	**-0.52**	48	0.21	38	0.20
GRAZ UNIVERSITAT	15.5	47.1	**0.32**	35	**-0.43**	35	-	1	-
GRIMSEL	8.3	46.6	**0.45**	39	0.23	39	**0.49**	34	**0.42**
GRONINGEN	6.6	53.2	**0.51**	46	**0.35**	44	**0.50**	39	**0.49**
KEYWORTH	-1.1	52.9	**0.36**	12	-0.08	11	-	9	-
KIROV	49.6	58.7	-	9	**0.35**	16	**0.74**	15	**0.69**
KOBLENZ	7.6	50.4	**0.51**	24	**0.51**	23	**0.79**	18	**0.61**
KONSTANZ	9.2	47.7	**0.54**	29	-0.05	30	**0.52**	26	**0.51**
KRAKOW	19.9	50.1	**0.59**	34	0.03	32	**0.69**	33	**0.65**
LEIPZIG	12.4	51.4	**0.42**	19	0.24	33	**0.56**	29	**0.49**
LIPTOVSKY	19.6	49.1	**0.55**	18	**0.29**	18	**0.64**	18	**0.59**
LISTA	6.6	58.1	**0.53**	12	**0.67**	17	**0.62**	14	**0.63**
LJUBLJANA	14.5	46.1	**0.32**	21	**-0.39**	21	**0.38**	21	**0.55**
MADEIRA	-16.9	32.6	**0.40**	13	**-0.89**	13	0.18	11	0.08
MADRID	-3.7	40.4	**0.63**	11	**-0.46**	11	-0.09	10	0.09
MONACO	7.4	43.7	0.25	10	**-0.51**	10	**0.34**	8	**0.45**
NY ALESUND	11.9	78.3	**-0.40**	20	**-0.71**	20	-0.12	19	**-0.34**
OTTAWA	-75.7	45.3	0.00	39	0.03	36	0.17	34	0.20
PENHAS DOURADAS	-7.5	40.4	**0.31**	16	**-0.6**	16	**0.56**	15	**0.49**
PORTALEGRE	-7.4	39.3	0.1	16	**-0.74**	17	**0.48**	15	**0.40**
PORTO	-8.6	41.1	-0.07	16	**-0.53**	17	0.12	16	0.02
REGENSBURG	12.1	49	**0.33**	29	0.18	30	**0.58**	19	**0.45**
REYKJAVIK	-21.9	64.1	**-0.32**	30	**0.34**	34	0.21	32	0.18
SFAX	10.7	34.7	0.26	15	-0.24	16	**-0.35**	11	0.06
SIDI BARRANI	25.6	31.6	0.24	24	**0.43**	26	**-0.44**	23	**-0.43**
ST PETERSBURG	30.3	60	-	9	**0.41**	10	**0.78**	10	**0.78**
STTUTGART	9.2	48.8	**0.44**	38	0.23	41	**0.73**	39	**0.63**
TEHERAN	51.3	35.7	0.01	20	**-0.31**	18	0.08	19	-0.01
THONON	5.9	46.4	**0.53**	38	-0.24	37	**0.42**	37	**0.38**

TRIER	6.7	49.8	**0.54**	28	**0.31**	27	**0.60**	19	**0.57**
TUNIS	10.2	36.8	-0.05	34	-0.25	37	-0.11	35	-0.19
VALENTIA	-9	51.9	0.24	40	0.17	47	**0.71**	38	**0.64**
VERACRUZ	-96.1	19.2	0.04	19	0.17	21	0.17	20	0.07
VIENNA	16.4	48.3	**0.62**	48	-0.16	45	**0.71**	48	**0.68**
VILLACHER	13.7	46.6	-0.05	30	**-0.35**	29	-	0	-
WALLINGFORD	-1.1	51.6	**0.48**	26	0.03	27	**0.63**	25	**0.65**
WASSERKUPPE	10	50.5	**0.73**	28	**0.39**	27	**0.60**	18	**0.37**
WEATHERSHIP F	-48	35	**-0.30**	12	**-0.29**	10	**0.77**	11	**0.47**
ZAGREB	16	45.8	**0.75**	17	-0.28	15	**0.69**	17	**0.68**

Table S2. Same as in Table S1 but for summer (JJAS).

Station	*Longitude*	*Latitude*	*Corr.* $\delta^{18}O$	*N* $\delta^{18}O$	*Corr.* *P*	*N* *P*	*Corr.* *T*	*N* *T*	*Corr* T_p
ADANA	35.3	37	0.25	30	-0.02	40	**-0.57**	34	-0.04
ANKARA	32.9	40	**0.32**	43	-0.09	42	**-0.46**	38	-0.09
ANTALYA	30.7	36.9	0.11	30	**-0.28**	33	**-0.41**	36	0.03
ASTRAKHAN	48	46.3	0.12	15	**0.37**	15	-0.23	15	-0.11
AVIGNON	4.8	44	0.20	13	-0.25	13	-	6	-
AZORES	-25.7	37.8	0.16	21	-0.11	32	0.04	29	-0.07
BATUMI	41.6	41.7	-0.21	10	0.23	11	**-0.48**	10	**-0.32**
BEEK	5.8	50.9	**0.59**	11	-	7	-	7	-
BERLIN	13.4	52.5	0.07	28	-0.10	25	0.02	24	0.12
BERN	7.4	47	0.01	38	-0.24	37	-0.21	37	-0.27
BET DAGAN	34.8	32	-	3	-0.21	3	0.06	18	-
BRAUNSCHWEIG	10.5	52.3	-0.01	28	**-0.42**	29	0.13	16	0.24
CALGARY	-114	51	**-0.41**	10	0.08	10	-0.18	10	-0.13
CHICAGO	-87.8	41.8	**-0.29**	18	-0.02	18	**-0.47**	17	**-0.34**
CHIHUAHUA	-106.1	28.6	-0.18	24	-0.04	20	-0.03	20	-0.09
CUXHAVEN	8.7	53.9	0.16	27	-0.21	28	0.07	13	0.06
DANMARKSHAVN	-18.7	76.8	**0.59**	19	0.12	19	-0.20	16	**-0.41**
EMMERICH	6.6	51.8	-0.12	26	**-0.30**	28	0.10	15	0.09

FARO	-8	37	**-0.47**	10	-0.15	17	-0.25	17	0.26
GARMISCH	11.1	47.5	-0.17	28	-0.17	29	0.00	16	0.03
GENOA	8.9	44.4	0.00	29	-0.09	31	**-0.29**	27	0.23
GIBRALTAR	-5.4	36.2	0.25	25	-0.10	39	-0.04	39	-0.13
GRAZ UNIVERSITAT	15.5	47.1	-0.14	37	0.26	35	-	1	-
GRIMSEL	8.3	46.6	0.09	39	-0.15	38	0.00	35	0.01
GRONINGEN	6.6	53.2	0.01	45	-0.18	43	0.07	33	-0.09
KEYWORTH	-1.1	52.9	-0.24	10	**0.36**	9	-	9	-
KIROV	49.6	58.7	-	9	**-0.30**	16	-0.02	15	-0.06
KOBLENZ	7.6	50.4	0.1	25	0.05	21	0.25	17	**0.44**
KONSTANZ	9.2	47.7	0.09	28	**-0.4**	30	-0.26	23	**-0.31**
KRAKOW	19.9	50.1	-0.15	33	**-0.38**	34	**-0.31**	31	-0.16
LEIPZIG	12.4	51.4	0.14	18	-0.17	30	-0.15	29	**-0.37**
LIPTOVSKY	19.6	49.1	-0.01	17	-0.22	18	0.03	18	-0.17
LISTA	6.6	58.1	0.07	12	**0.66**	17	0.20	16	0.16
LJUBLJANA	14.5	46.1	-0.01	21	**-0.36**	20	-0.16	20	0.00
MADEIRA	-16.9	32.6	**-0.73**	12	**0.48**	12	-0.18	11	**0.32**
MADRID	-3.7	40.4	**0.32**	10	0.05	11	-	9	0.21
MONACO	7.4	43.7	**-0.55**	11	**0.50**	11	0.15	6	-0.14
NY ALESUND	11.92	78.3	0.11	20	0.16	20	-0.04	17	0.26
OTTAWA	-75.7	45.3	-0.18	37	-0.1	36	-0.13	31	-0.09
PENHAS DOURADAS	-7.5	40.4	-0.12	17	**-0.38**	16	**0.31**	14	0.25
PORTALEGRE	-7.4	39.3	**-0.42**	17	-0.03	17	0.19	13	0.26
PORTO	-8.6	41.1	**0.34**	17	**-0.29**	16	0.13	13	0.13
REGENSBURG	12.1	49	0.16	28	-0.22	29	0.02	15	-0.09
REYKJAVIK	-21.9	64.1	-0.22	30	-0.06	35	-0.13	32	-0.03
SFAX	10.7	34.7	0.11	15	-0.12	16	**-0.36**	9	-0.01
SIDI BARRANI	25.6	31.6	-	1	-0.23	9	**-0.85**	20	-
ST PETERSBURG	30.3	60	-0.07	10	**-0.5**	11	**0.51**	11	**0.63**
STTUTGART	9.2	48.8	0.18	35	-0.11	41	0.23	38	**0.30**
TEHERAN	51.3	35.7	0.25	12	-0.24	13	-0.14	17	**-0.42**
THONON	5.9	46.4	-0.21	39	-0.09	36	-0.05	32	-0.02

TRIER	6.7	49.8	0.02	28	-0.22	28	0.03	16	0.11
TUNIS	10.2	36.8	0.25	23	-0.21	32	**-0.29**	35	0.00
VALENTIA	-9	51.9	0.19	41	-0.02	46	-0.26	37	**-0.35**
VERACRUZ	-96.1	19.2	**-0.42**	23	**0.40**	21	**-0.35**	18	**-0.44**
VIENNA	16.4	48.3	0.10	48	**-0.46**	44	-0.13	40	-0.03
VILLACHER	13.7	46.6	-0.04	30	-0.19	28	-	0	-
WALLINGFORD	-1.1	51.6	0.23	24	-0.09	26	-0.04	23	0.00
WASSERKUPPE	10	50.5	0.10	27	0.01	26	-0.27	17	**-0.28**
WEATHERSHIP F	-48	35	0.05	12	-	9	0.07	12	-
ZAGREB	16	45.8	**0.54**	16	**-0.53**	16	0.08	15	-0.11

Table S3. Site location, period covered by the ice core record, and both winter (DJFM) and summer (JJAS) correlation values between the NAO and the isotopic $\delta^{18}O$ series. Note that the correlations are calculated within the overlapping period with the NAO time series (1824-2010). Correlations significant at the 95% confidence level are highlighted in bold.

Station	*Latitude*	*Longitude*	*Initial Year*	*Final Year*	*Winter Corr. $\delta^{18}O$*	*Summer Corr. $\delta^{18}O$*
CRETE[1]	-37.3	71.1	552 AD	1973 AD	**-0.34**	-0.06
DYE3 (stack)[1]	-43.8	65.2	551 AD	1978 AD	**-0.38**	-0.08
GRIP (stack)[1]	-37.6	72.6	551 AD	1979 AD	-0.14	-0.12
MILCENT[1]	-44.6	70.3	1778 AD	1970 AD	**-0.32**	**-0.19**
NEEM[2]	-51.06	77.45	1963 AD	2004 AD	0.02	-0.18
RENLAND[3]	-26.7	71.3	1135 AD	1986 AD	**-0.24**	0.13
SITE A[1]	-35.8	70.6	1778 AD	1970 AD	**-0.29**	-0.01
SITE B[1]	-37.5	70.7	1778 AD	1970 AD	**-0.23**	-0.15
SITE D[1]	-39.6	70.6	1778 AD	1970 AD	**-0.37**	**-0.19**
SITE E[1]	-35.9	71.2	1778 AD	1970 AD	-0.07	0.11
SITE G[1]	-35.8	71.2	1778 AD	1970 AD	**-0.29**	-0.09

[1] (Vinther et al., 2010)[2] Data from the shallow ice core NEEM07S3 (Steen-Larsen et al., 2011)

[3] Unpublished data provided by Bo Vinther

C. Precipitation intermittency bias on temperature compared at different weighting timescales

In terms of their mean value (Figure S2a,b), the spatial distribution of biases is different for the three time resolutions, with the exception of the winter 6-hourly and daily outputs that show virtually identical patterns. In the summer, the largest biases are related to the 6-hour scale, and are concentrated at the northern latitudes. It is also worth mentioning the negative biases in the Mediterranean area for the daily precipitation weighted temperatures, not depicted in the other two cases. Concerning the standard deviation of these temperature biases (Figure S2c,d), a better agreement is observed, in particular for both the 6-hourly and daily outputs. This good agreement between the two finer time resolutions indicates that diurnal cycle has a negligible influence on the variability of the temperature bias due to precipitation intermittency. We can therefore restrict the analysis to the daily resolution. Also, we remark that for the monthly amounts standard deviation values remain comparatively small, which also justify the further analysis on the daily scales.

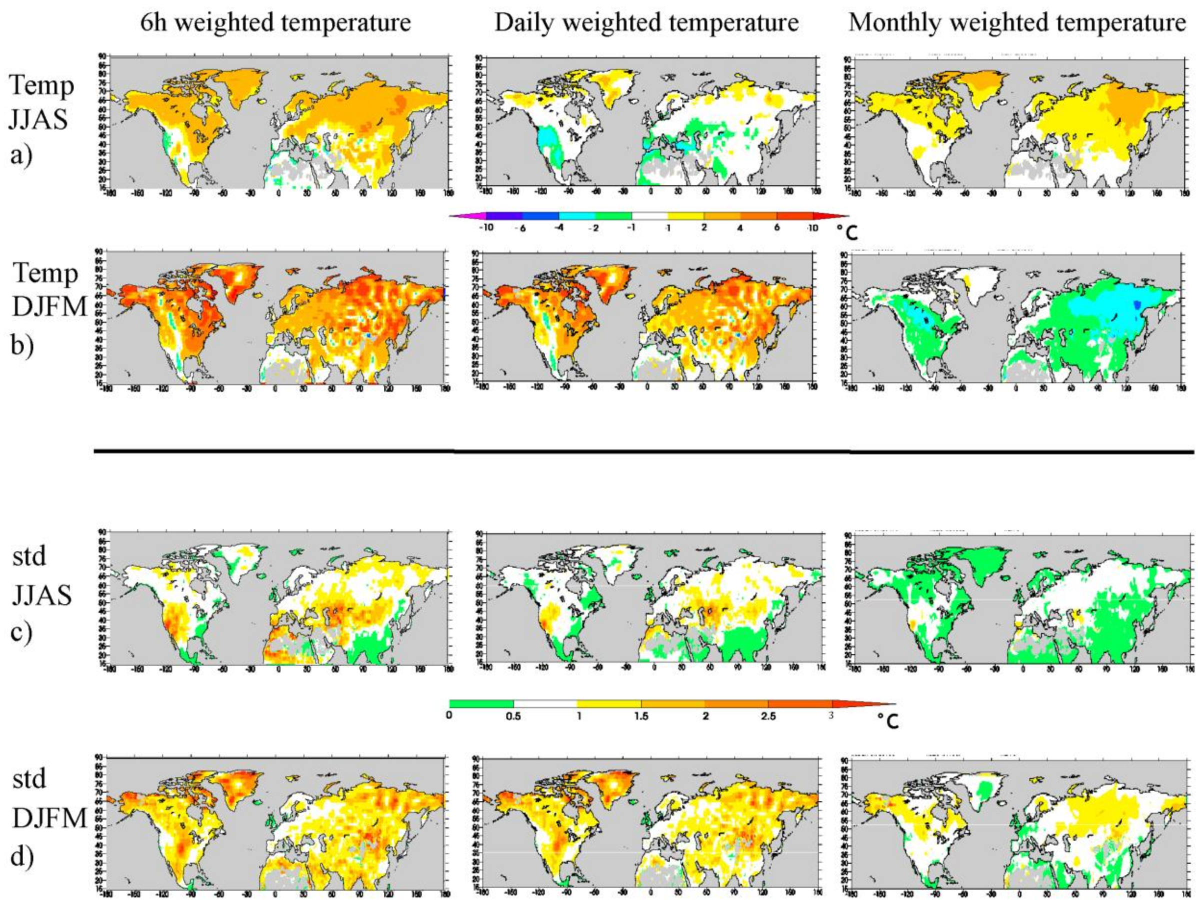


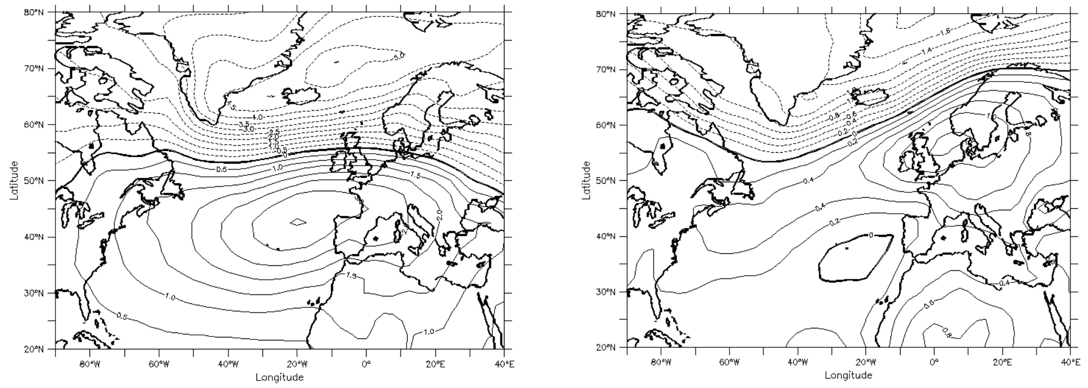
Figure S2. a) Mean precipitation intermittency bias in summer (JJAS), defined as the difference between the 6-hourly precipitation weighted temperature (Tp) and the mean seasonal temperature (T) in CRU-NCEP from 1990 to 2010; b) The same but for winter (DJFM) values; c-d) The same as the *upper panels but showing the inter-annual standard deviation (std) of the biases for summer and winter, respectively.*

D. Pressure centers of the NAO

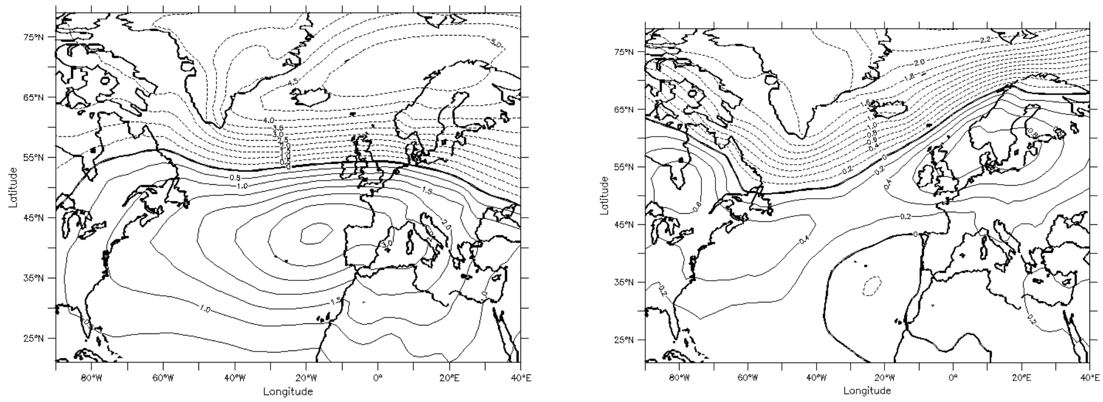
In all previous analyses, we have diagnosed an NAO index using the pressure difference between two fixed areas (corresponding to Gibraltar and Reykjavik). Recent studies have shown changes in the position of the NAO centers of action, shifting northward in summer, and west/eastwards at the decadal scale (Folland et al., 2009;Pinto and Raible, 2012).

In order to assess the sensitivity of our correlation analyses to the position of the NAO centers of action, an alternative NAO index has been calculated as the first principal component of sea level pressure in the North Atlantic (Figure S3). Note that the centers of action (identified as minima and maxima loadings of the first EOF) are indeed not exactly located in the Iberian Peninsula / Iceland, though, there are very similar modes between all the datasets even though the periods are a bit different.

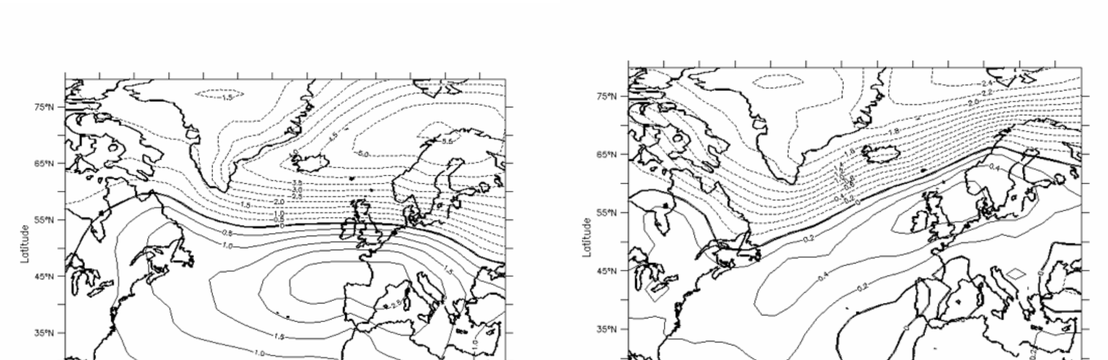
Figures S4 (DJFM) and S5 (JJAS) compare the correlation coefficients obtained for LMDZiso outputs (precipitation, T, T_p and $\delta^{18}O$), using both the classical pressure difference and the alternative leading PC NAO definitions. Basically, the DJFM results appear quite robust with respect to the choice of the index, the PC1 approach enhancing the strength of correlations for Siberia for temperature and isotopes. JJAS results appear more sensitive to the NAO index, with a decreased anticorrelation for Greenland using the PC1 approach, and the emergence of significant correlations in northern Scandinavia and Russia. Even if the centers of action (defined as the location of maximum loadings) are not placed exactly over Iceland and the Iberian Peninsula, both locations remain representative of the dipole behavior in winter and summer.



a)



b)



c)

Figure S3. *Spatial structure of the first Empirical Orthogonal Function component for the DJFM (left) and JJAS (right) mean sea level pressure fields in a)* NCEP-CRU (1990-2010); b) ERA-interim (1990-2010); and c*) LMDZiso (1979-2008)*.

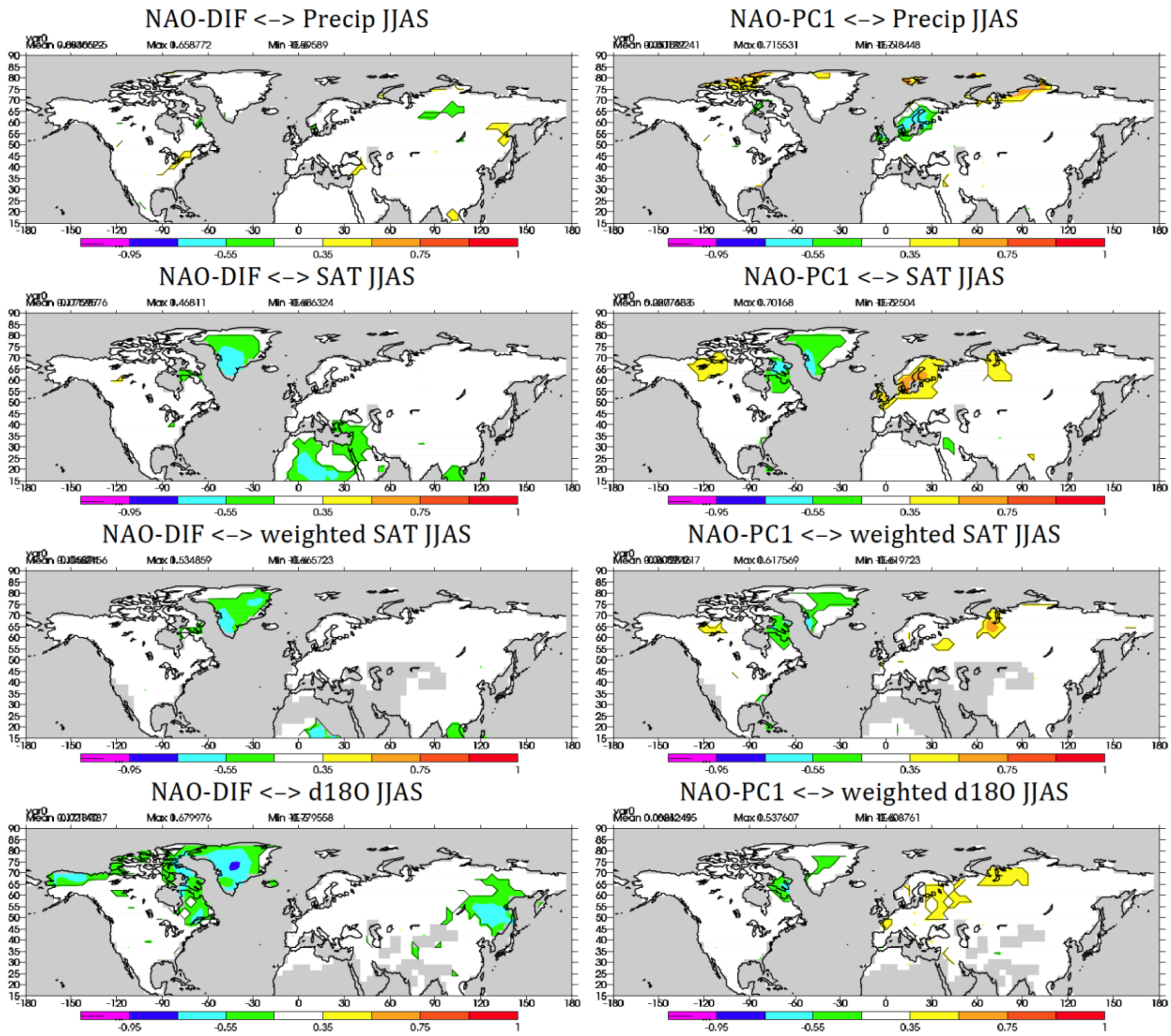


Figure S4. *Comparison between the correlation coefficients between the classical JJAS NAO index (defined as the normalised SLP difference between Gibraltar and Reykjavik; left) and the JJAS NAO-PC1 index (right) and JJAS LMDZiso precipitation (first line), temperature (second line), precipitation weighted temperature (third line) and* $\delta^{18}O$.

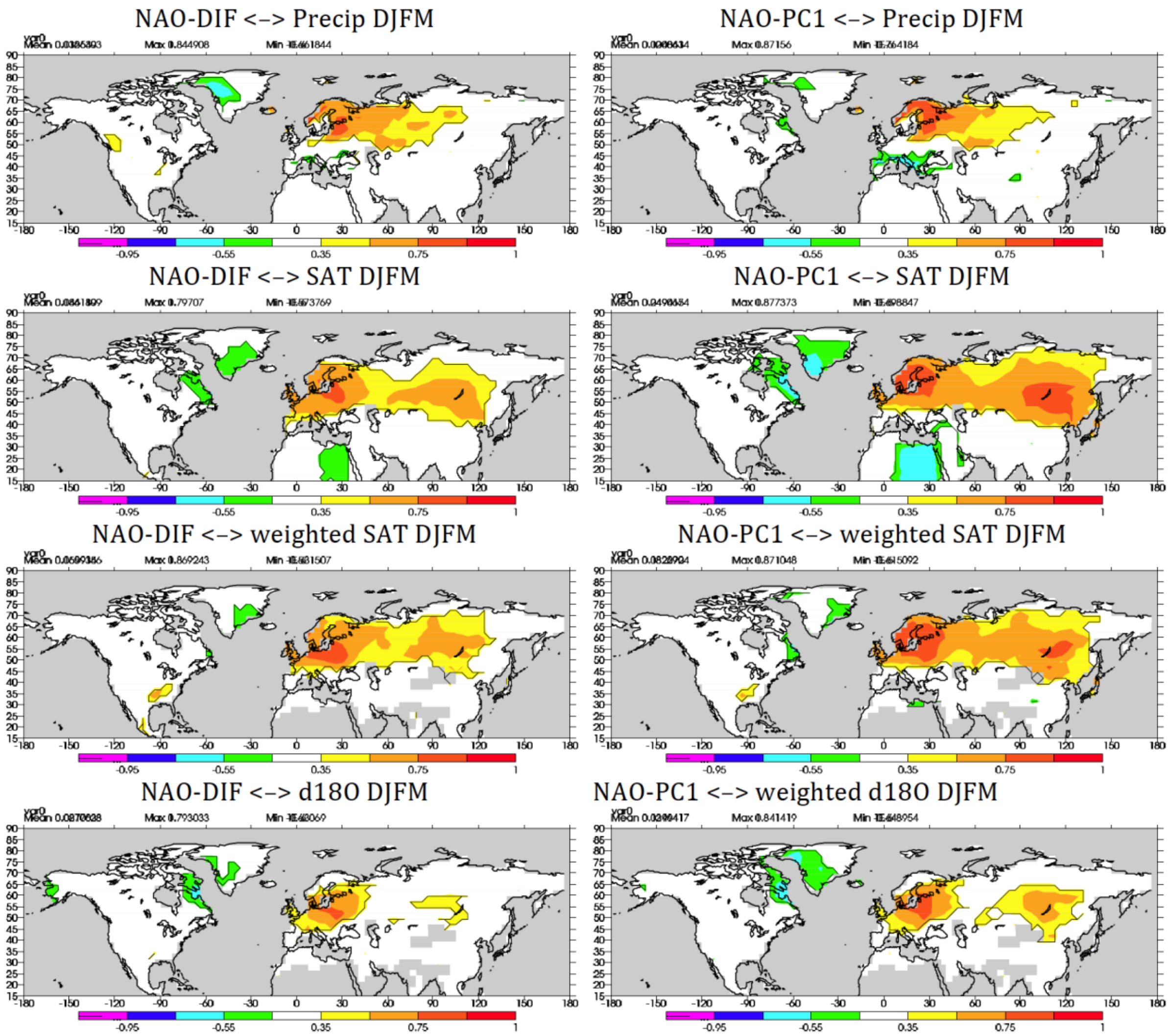


Figure S5*. Same as Figure S4 but for DJFM.*

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