Eurasian cooling in response to Arctic sea-ice loss is not proved by maximum covariance analysis

Giuseppe Zappa[1,2], Paulo Ceppi[3], and Theodore G. Shepherd[1]

[1] *Department of Meteorology, University of Reading, Reading RG6 6BB, UK*
[2] *Istituto di Scienze dell'Atmosfera e del Clima, Consiglio Nazionale delle Ricerche (ISAC-CNR), Bologna 40129, Italy*
[3] *Grantham Institute for Climate Change and the Environment, Imperial College, London SW7 2AZ, UK*

The extent to which the ongoing decline in Arctic sea ice affects mid-latitude climate has received great attention and polarised opinions. The basic issue is whether the inter-annual variability in Arctic sea ice is the cause of, or the response to, variability in mid-latitude atmospheric circulation [1]. Mori et al. (M19, [2]) claims to have reconciled previous conflicting studies by showing that a consistent mid-latitude climate response to inter-annual sea-ice anomalies can be identified between the ERA-Interim reanalysis, taken as observations, and an ensemble of atmosphere-only (AMIP) climate model simulations. Here we demonstrate that such a conclusion cannot be drawn, due to issues with the interpretation of the maximum covariance analysis performed. After applying the M19 approach to the output from a simple statistical model, we conclude that a predominant atmospheric forcing of the sea-ice variability, rather than the converse, is a more plausible explanation of the results presented in M19.

A leading mode of internal atmospheric variability is associated, in its positive phase, with a Siberian anticyclone, a Warm Arctic and Cold Eurasia (WACE mode, Fig 1d in M19). It is debated whether anomalies in the extent of Barents and Kara sea ice can modulate the frequency of occurrence of this mode, given that the Siberian circulation anomaly could itself force sea-ice anomalies by warming the Arctic region. To discriminate between these two possible scenarios, M19 rely on identifying a mode of year-to-year co-variability in the winter-mean (DJF) Eurasian surface temperature between the ERA-Interim reanalysis and an ensemble of AMIP simulations, i.e. climate runs forced by observed oceanic conditions (including sea ice). The approach is well designed: if sea ice forces circulation, and models are realistic, the WACE modes in the ERA-Interim and AMIP simulations should covary in time. If instead sea ice merely responds to circulation, the WACE modes should not covary: in the real world the WACE mode would force sea-ice variability, while in the AMIP simulations the imposed observed sea ice would only force a monopole of Arctic temperature variability via local thermodynamic processes.

The leading mode of Eurasian surface temperature co-variability between ERA-Interim and the AMIP simulations is identified in M19 via maximum covariance analysis (MCA), as implemented through the singular value decomposition (SVD) of the covariance matrix between the two surface temperature fields in 0E-180E, 20N-90N. However, the pair of singular vectors that comprise the co-varying mode are not displayed in the paper. Instead, the authors discuss the mode in terms of the homogeneous regression maps obtained by regressing each field on the expansion coefficient (EC) of its own singular vector (see Supplementary Information for an overview of the methodology). The homogeneous regression maps are not necessarily directly related to the singular vectors, and hence to the structure of the co-varying mode [3, 4]. This is because the ECs are obtained by projecting the two analysed fields on their own singular vectors. Hence, in addition to reflecting the co-varying mode, the ECs include variance generated by any internal mode of variability that is not orthogonal to the singular vectors themselves. When the original fields are regressed on their own ECs, such internal modes can be aliased into the homogeneous regression maps. The way to isolate the structure of the co-varying mode is via heterogeneous regression maps, in which each field is regressed on the EC from the other field [3].

The potential pitfalls of solely examining homogeneous maps are explored by applying the statistical method from M19 to the output from a simple statistical model that qualitatively incorporates the influence of sea ice and of the WACE mode on surface temperature variability. In the simple model, the direction of the interaction between atmospheric circulation and sea ice can be directly controlled (see SI). Regardless of whether sea-ice variability forces atmospheric circulation or vice-versa, we find that the homogeneous regressions for the leading co-varying mode always show WACE-like patterns characterised by a warm Arctic, a cold Eurasia and a positive Siberian surface pressure anomaly. Because they alias in the internal variability in the WACE mode, homogeneous regressions are insufficient to discriminate between these different scenarios from the simple model. The same is not true for the heterogeneous regressions, which correctly identify distinct pairs of co-varying patterns - either WACE-like or an Arctic Temperature Monopole (ATM) - depending on the presence and direction of the interaction between sea ice and the atmospheric circulation (Table 1).

We therefore compare the structure of the co-varying mode between the ERA-Interim and AMIP simulations obtained from the homogeneous (Fig. 1a-b) and heterogeneous (Fig. 1c-f) regression maps (see also the singular vectors in Extended Data Fig. 1). The only difference with M19 is that, since the MIROC4 simulations are unavailable to the authors, the AMIP multi-model ensemble consists of 6 rather than 7 models. Nonetheless, the homogeneous maps bear a strong resemblance to those presented in M19, featuring the WACE-mode temperature dipole between the Arctic and Central Eurasia together with the Siberian sea level pressure anomalies. All these three features are present, albeit with a weaker amplitude, in the heterogeneous map from ERA-Interim (Fig. 1c,e), but not in the heterogeneous map from the AMIP ensemble (Fig. 1d,f). In particular, while the warm anomaly in the Barents and Kara seas is still present due to thermodynamic forcing from sea ice, the cold anomaly in Central Eurasia is weakened and displaced southward and, most importantly, the Siberian anticyclonic anomaly is entirely missing (Fig. 1f). This implies the co-varying temperature pattern in the AMIP simulations is distinct from the WACE mode, since the weak cold anomalies that persist further south in Eurasia are not generated via cold advection by the Siberian anticyclone anomaly.

The missing Siberian SLP signature of the WACE mode in the heterogeneous maps is found in all individual models, with the possible exception of ECHAM5, where the signal is nonetheless not significant (Extended Data Fig. 2). In contrast, the SLP signal is present in all models' homogeneous maps, which we attribute to the aliasing of internal variability that affects Arctic temperature. Indeed, the magnitude of both the Siberian circulation and Eurasian temperature signals in the homogeneous maps are reduced, and made more similar to the heterogeneous maps, by averaging the models' ensemble members before the MCA (Supplementary Fig. 1). This would not be expected if the signal was forced, since ensemble averaging only suppresses the unforced internal variability.

The exact cause of the remaining southward-displaced cold anomaly in southern Eurasia is unknown, but we note that the co-varying mode is associated with a global pattern of SST anomalies (Extended Data Fig. 3). Some of these SST anomalies could drive southern Eurasian temperature and circulation co-variability without the need to invoke an Arctic mechanism (see Supplementary Fig 2 on the role of tropical Pacific SSTs). Understanding and isolating these connections should be a topic for future research.

Comparing the structure of the heterogeneous maps between the ERA-Interim and the AMIP simulations with those from the statistical model, suggests that a more plausible interpretation of the results in M19 is an atmospheric driving - via the WACE mode - of Barents and Kara sea-ice variability in the real world (Ice ← Atm). This interpretation is consistent with the comment by Screen and Blackport, 2019 [5], who examined the lead-lag covariance between sea ice and the WACE mode. M19 argue for the opposite direction of causality based on the negative correlation (r) in the year-to-year variability between the sea ice and the ECs, and later use r^2 to quantify the fraction of WACE variance that is forced from sea ice. However, the rationale is flawed since, as shown by the statistical model, the correlation between the ECs and the sea-ice anomalies is always negative regardless of whether sea ice forces circulation, or vice-versa (Table 1). This is a direct consequence of the fact that sea-ice anomalies directly affect Arctic temperature, hence projecting on the singular vector.

Another potential interpretation of Fig. 1 is that the models entirely fail to capture the observed dynamical WACE response to sea-ice anomalies. But in that case, the models certainly cannot be used to argue in favour of a causal linkage. Either way, the conclusion of M19 is not supported by the evidence presented.

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Data availability: The ERA-Interim reanalysis is publicly available from ECMWF (`https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim`). The AMIP FACTS simulations are publicly available from NOAA (`https://www.esrl.noaa.gov/psd/repository/alias/factsdocs`).

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Corresponding author: Correspondence and requests for materials should be addressed to GZ.

	Ice $\rightarrow$ Atm		Ice $\nsim$ Atm		Ice $\leftarrow$ Atm	
	Real	AMIP	Real	AMIP	Real	AMIP
	Homogeneous regression					
T_{Arctic}	2.2	2.2	1.4	1.4	2.2	1.7
C	1.4	1.4	0.7	0.7	0.9	0.6
T_{Asia}	-1.4	-1.4	-0.7	-0.7	-0.9	-0.6
Pattern	WACE	WACE	WACE	WACE	WACE	WACE
	Heterogeneous regression					
T_{Arctic}	2.3	2.3	**1.4**	**1.4**	2.3	**1.7**
C	1.2	1.2	**0.0**	**0.0**	0.8	**0.0**
T_{Asia}	-1.2	-1.2	**0.0**	**0.0**	-0.8	**0.0**
Pattern	WACE	WACE	**ATM**	**ATM**	WACE	**ATM**
	Correlation between sea ice (I) and ECs					
$r_{I,EC}$	-0.86	-0.86	-0.71	-0.71	-0.93	-0.82

Table 1: **The application of the M19 approach to the output from a simple statistical model**. The modes of co-variability between the "real-world" (Real) and "AMIP-world" (AMIP) systems are described using homogeneous (top) and heterogeneous (bottom) regressions in terms of the following variables from the simple model (see Supplementary Information for details): T_{Arctic} (representing Arctic temperature), C (atmospheric circulation, positive for a Siberian anticyclone) and T_{Asia} (Central Eurasian temperature). The patterns are classified either as WACE-like (WACE), if formed by a temperature dipole and a circulation anomaly, or as an Arctic Temperature Monopole (ATM) with no circulation anomaly (also highlighted bold). Note that the exact values are of secondary importance. The columns report results from different setups of the statistical model: sea ice driving the circulation (Ice $\rightarrow$ Atm), no interaction between sea ice and circulation (Ice $\nsim$ Atm), and circulation driving the sea ice (Ice $\leftarrow$ Atm). The bottom line reports the correlation between the variability in the sea ice (I) and that in the expansion coefficients. Only the heterogeneous maps can discriminate between the different model setups: if the WACE pattern is found in both the real-world and the AMIP-world, then sea ice forces circulation, while if the WACE pattern is found in the real-world only, then it is the atmosphere that forces the sea ice.

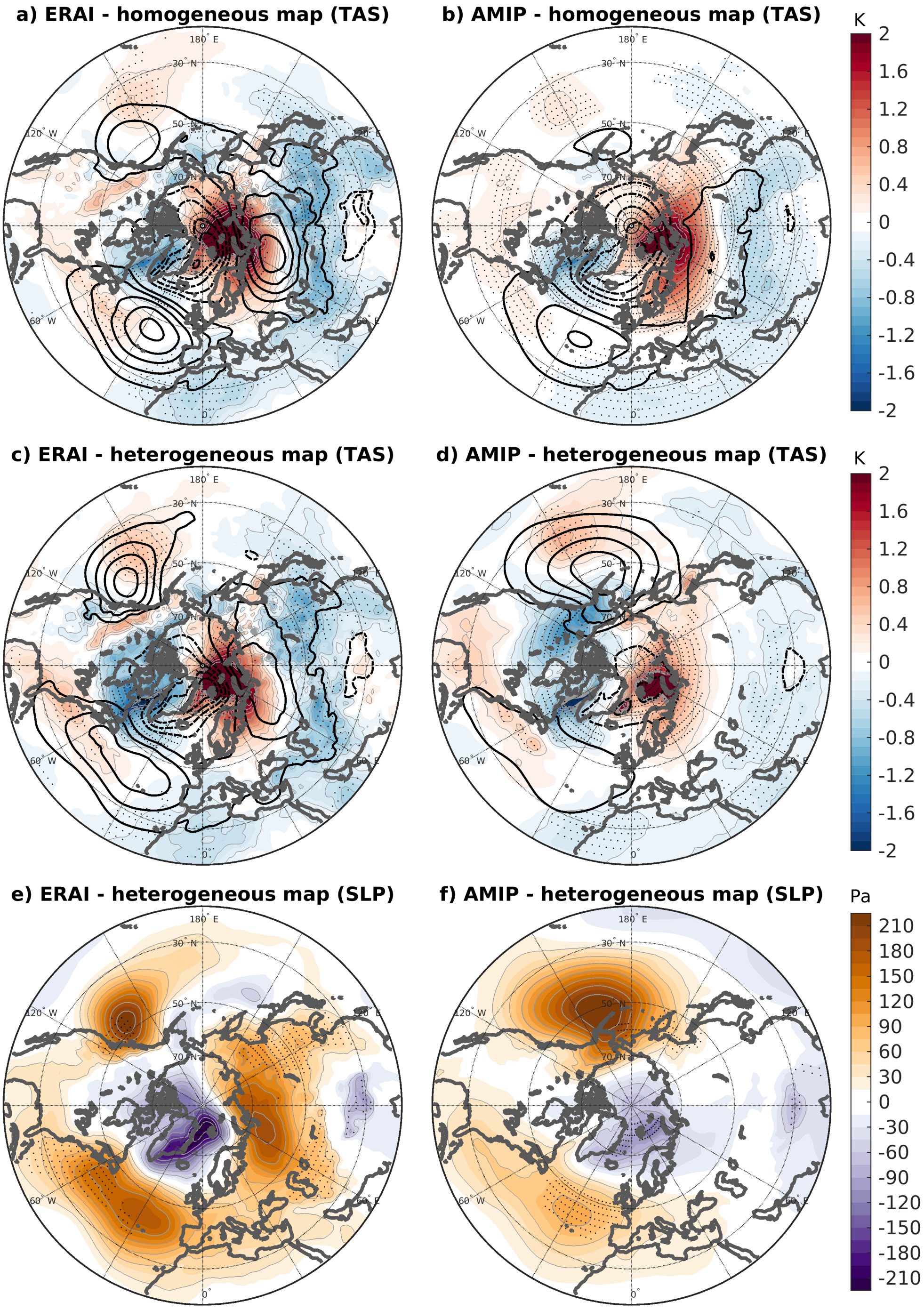
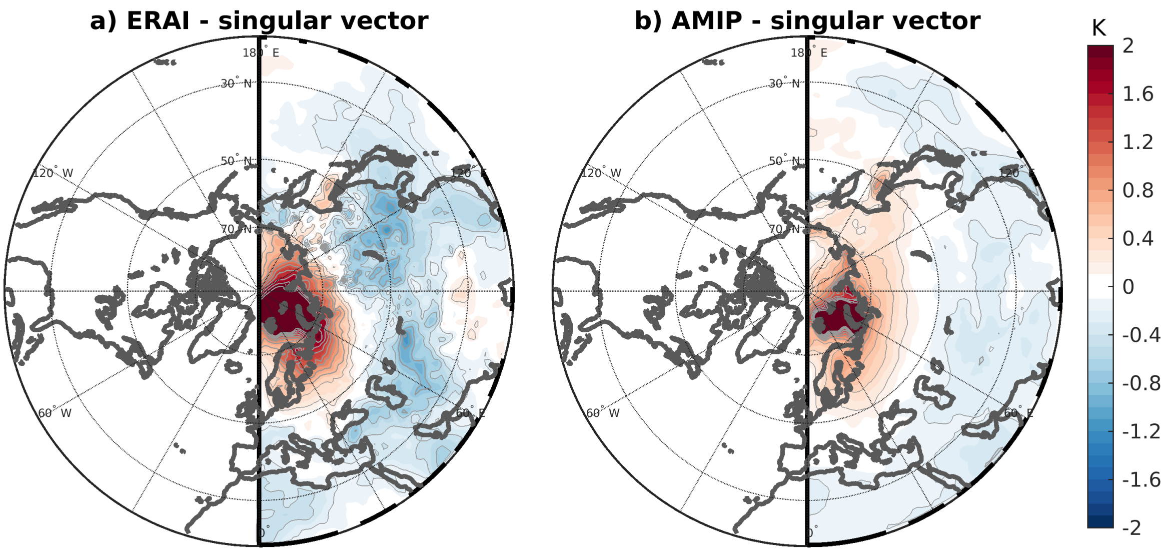
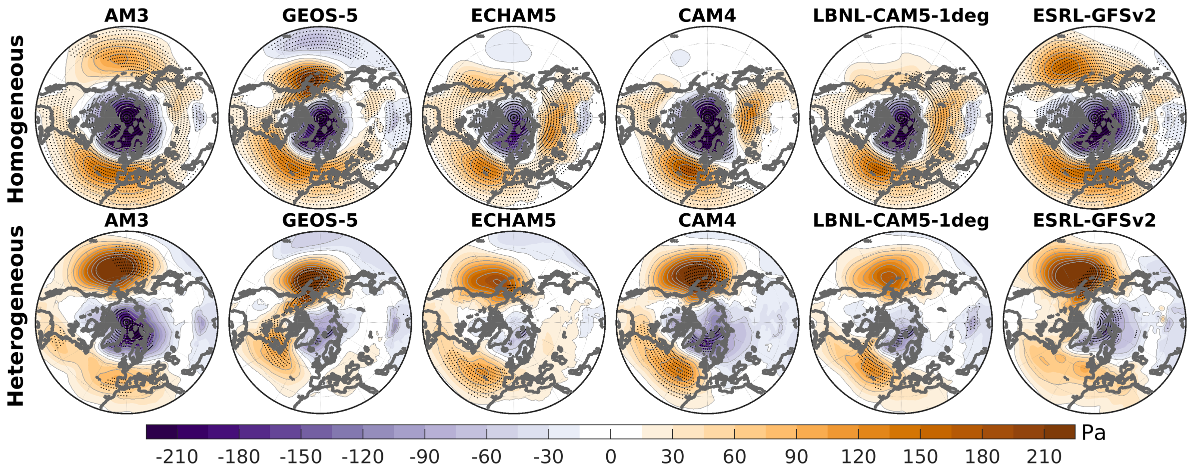


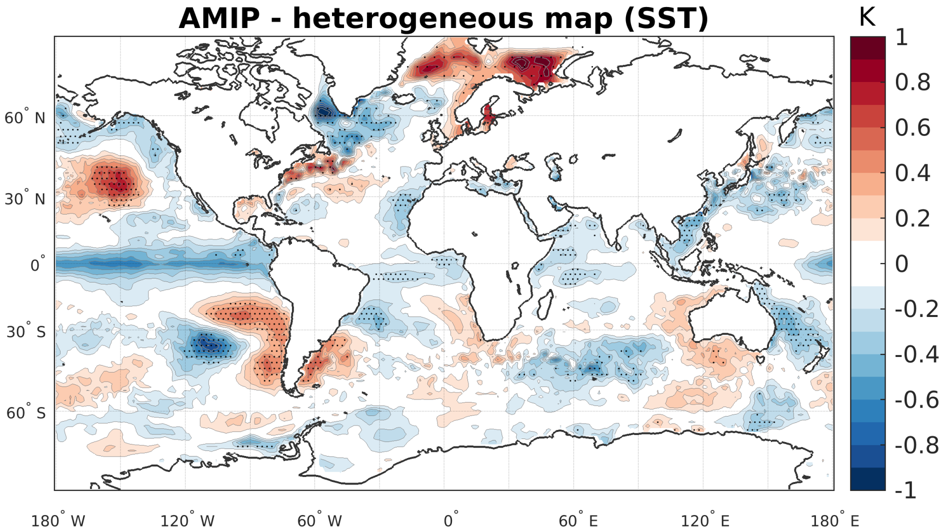
Figure 1: **The co-varying mode of Eurasian surface temperature between ERA-Interim and the AMIP simulations**. Comparison between a-b) the homogeneous and c-f) heterogeneous regression maps following the analysis in M19. a,c,e) refer to the ERA-Interim reanalysis, while b,d,f) refer to the AMIP simulations. In a-d), shading shows the near-surface atmospheric temperature (K), and the contours the sea-level pressure with a c.i. of 0.5 hPa, solid for positive and dashed for negative. The heterogeneous map for sea-level pressure is further shown in e-f) in shading. Stippling indicates statistical significance at the 5% level in the shaded variable, i.e. temperature in a-d) and pressure in e-f), as obtained by bootstrapping the individual years with replacement (see SI). All maps are scaled to one standard deviation anomaly in the expansion coefficients. Note how only the heterogeneous maps correctly reproduce the co-varying temperature signals shown by the singular vectors within their domain of definition in the Eastern Hemisphere (Extended Data Fig. 1).



Extended Data Figure 1: **The singular vectors.** The pair of singular vectors composing the first co-varying surface temperature mode between the a) ERA-Interim and b) AMIP simulations via the maximum covariance analysis proposed in M19. As in Fig. 1, the vectors are scaled to correspond to unit standard deviation in the expansion coefficients.



Extended Data Figure 2: **The robustness of the co-varying mode to model differences.** Homogeneous (top) and heterogeneous (bottom) regression maps of sea level pressure in the AMIP simulations obtained by separately performing the maximum covariance analysis for each individual model and using all the available ensemble members: 17 members are used for AM3, 12 for GEOS-5, 20 for CAM4, and 50 for all other models. Stippling shows statistical significance at the 5% level as in Fig. 1.



Extended Data Figure 3: **The potential confounding role of the SSTs.** Heterogeneous map of the SSTs associated to the co-varying mode in the AMIP simulations. Stippling denotes statistical significance at the 5% level. The potential of these SST anomalies, such as the ENSO-like pattern in the tropical Pacific, to force the circulation signals associated to the co-varying mode in Fig. 1f is discussed in the SI (Supplementary Fig. 2).

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