



HAL
open science

The Arctic winter sea ice quadrupole revisited

Sally Close, M.-N. Houssais, C. Herbaut

► **To cite this version:**

Sally Close, M.-N. Houssais, C. Herbaut. The Arctic winter sea ice quadrupole revisited. *Journal of Climate*, 2017, 10.1175/JCLI-D-16-0506.1 . hal-01452684v1

HAL Id: hal-01452684

<https://hal.sorbonne-universite.fr/hal-01452684v1>

Submitted on 2 Feb 2017 (v1), last revised 16 May 2017 (v2)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



AMERICAN METEOROLOGICAL SOCIETY

Journal of Climate

EARLY ONLINE RELEASE

This is a preliminary PDF of the author-produced manuscript that has been peer-reviewed and accepted for publication. Since it is being posted so soon after acceptance, it has not yet been copyedited, formatted, or processed by AMS Publications. This preliminary version of the manuscript may be downloaded, distributed, and cited, but please be aware that there will be visual differences and possibly some content differences between this version and the final published version.

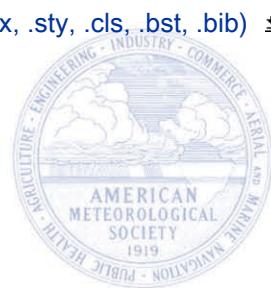
The DOI for this manuscript is doi: 10.1175/JCLI-D-16-0506.1

The final published version of this manuscript will replace the preliminary version at the above DOI once it is available.

If you would like to cite this EOR in a separate work, please use the following full citation:

Close, S., M. Houssais, and C. Herbaut, 2017: The Arctic winter sea ice quadrupole revisited. *J. Climate*. doi:10.1175/JCLI-D-16-0506.1, in press.

© 2017 American Meteorological Society



The Arctic winter sea ice quadrupole revisited

S. Close*, M.-N. Houssais and C. Herbaut

Sorbonne Universités (UPMC, Univ Paris 06), CNRS-IRD-MNHN, LOCEAN Laboratory, Paris.

PRELIMINARY ACCEPTED VERSION

*Corresponding author address: LOCEAN, Université Pierre et Marie Curie, 4 place Jussieu,

75252 Paris Cedex 05, France

E-mail: sally.close@locean-ipsl.upmc.fr

ABSTRACT

7 The dominant mode of Arctic sea ice variability in winter is often main-
8 tained to be represented by a quadrupole structure, comprising poles of one
9 sign in the Okhotsk, Greenland and Barents Seas, and opposing sign in the
10 Labrador and Bering Seas, forced by the North Atlantic Oscillation. In this
11 study, we revisit this large-scale winter mode of sea ice variability using mi-
12 crowave satellite and reanalysis data. We find that the quadrupole structure
13 does not describe a significant covariance relationship amongst all four com-
14 ponent poles. The first empirical orthogonal mode, explaining covariabil-
15 ity in the sea ice of the Barents, Greenland and Okhotsk Seas, is linked to
16 the Siberian High, whilst the North Atlantic Oscillation exhibits a significant
17 relationship only with the Labrador Sea ice, which varies independently as
18 the second mode. The principal components are characterised by a strong
19 low-frequency signal; the satellite record still being short, statistical analyses
20 should thus be applied cautiously.

21 **1. Introduction**

22 The climate of the Arctic has been reported to have undergone substantial change over recent
23 decades, manifest notably in increasing air temperature (e.g. Serreze et al. 2009) and decreasing
24 sea ice extent (e.g. Maslanik et al. 2007; Comiso et al. 2008), particularly in summer. Whilst the
25 winter sea ice loss has thus far been much less dramatic than that of summer, the changes occurring
26 in this season are nevertheless important, both because of their link to large-scale atmospheric
27 conditions (e.g. Petoukhov and Semenov 2010; Inoue et al. 2012; Screen et al. 2013) and because
28 of their potential role in determining sea ice conditions in the following summer via persistence
29 mechanisms (Day et al. 2014).

30 The large-scale variability of winter (January-March) sea ice concentration (SIC) has previously
31 been analysed by a number of authors (Walsh and Johnson 1979; Cavalieri and Parkinson 1987;
32 Fang and Wallace 1994; Deser et al. 2000; Ukita et al. 2007, amongst others). Consistent patterns
33 of variability emerge from these studies, suggesting the existence of a “double-dipole”, referred to
34 hereafter as a quadrupole, of variability, whereby increases in SIC in the Sea of Okhotsk, Green-
35 land and Barents Seas occur concomitantly with decreases in SIC in the Labrador and Bering
36 Seas (and vice versa). Based on analyses of satellite and atmospheric reanalysis data, a number
37 of studies have hypothesized that the North Atlantic Oscillation (NAO) forces the sea ice mode
38 associated with the quadrupole pattern (Yi et al. 1999; Deser et al. 2000; Ukita et al. 2007), par-
39 ticularly emphasizing the influence on the Atlantic (Barents/Greenland - Labrador) dipole. Such
40 a relationship between Arctic sea ice and the NAO was first proposed prior to the satellite era
41 by Rogers and van Loon (1979), who found a significant link between observation-based indices
42 of sea ice severity in the Baltic Sea and Davis Strait (spanning approximately 90 years) and the
43 NAO. Examining the early winter (October-December) period, Yang and Yuan (2014) suggested

44 that, with recent changes in the large-scale Arctic climate, the “early winter” quadrupole pattern
45 (a pattern that is distinct from that discussed above and in this work, which is formed over the
46 January-March winter season), may have broken down in recent years, primarily due to changes
47 in ice-atmosphere coupling in the Barents Sea region.

48 In this study, we revisit the large-scale variability of the winter SIC with the aims of ascertaining
49 the robustness of the quadrupole pattern and exploring the hypothesized link with the NAO. Our
50 results demonstrate that the SIC quadrupole pattern does not represent a significant relationship
51 in the covariability of its constituent poles, and that low-frequency variability, which is likely not
52 well resolved by the satellite record at its present length, characterises the form of the associated
53 principal component time series. The influence of the NAO is found to be limited to the Labrador
54 Sea and a small region of the Greenland Sea, and is not well correlated with the dominant mode of
55 sea ice variability. This dominant mode links subregions of the Greenland, Barents and Okhotsk
56 Seas, and appears rather to be predominantly influenced by the Siberian High.

57 **2. Data and Methods**

58 In this work, we analyse SIC using the SMMR-SSM/I-SSMIS data set (for brevity, referred to
59 simply as SSMI hereafter), processed using the bootstrap algorithm (Comiso 2000, updated 2014)
60 and covering the period 1979-2013. As in previous studies, we use empirical orthogonal function
61 (EOF) analysis to describe the large-scale modes of winter SIC. We define the January-March
62 mean SIC field as winter, based on an initial analysis to assess the stability of the modes¹. The
63 longer-term context is explored using the ECMWF ERA20C reanalysis (Poli et al. 2016), which
64 covers 1900-2010. A preliminary analysis confirms that the data give the same results as the SSMI

¹Monthly EOF SIC analysis were performed between November and April. The individual monthly January, February and March PC were well correlated amongst themselves and had the same loading pattern; November, December and April, in contrast, yielded weaker correlations and had loading patterns that varied from the other months.

65 data set over the period common to both (1979-2010). However, the earliest part of the record
66 (prior to 1953) shows negligible variability in an EOF analysis. It seems unlikely that this part of
67 the record is physically realistic, and thus we perform the analysis only on the post-1953 period,
68 over which the variance remains approximately constant. The link with the NAO is investigated
69 using the monthly NAO index supplied by the NOAA Climate Prediction Center (the results are not
70 sensitive to the choice of this index over the equivalent calculated using ERA20C/interim SLP).
71 The significance levels for all correlations are calculated using the effective number of degrees
72 of freedom to account for artificial skill arising from low-frequency variability, following Chelton
73 (1983) (their eq. 1).

74 **3. Results**

75 The loading patterns, percentage of variance explained locally and principal components (PC)
76 for the first EOF mode for the 35 year SSMI record and 58 year ERA20C record are shown in
77 Figure 1. The quadrupole loading pattern emerges as the first mode in both analyses (Figure 1a/c).
78 In both cases, whilst the loading pattern resembles the anticipated quadrupole structure, significant
79 variability is explained only in the Okhotsk and Greenland Seas, and along the coast of Novaya
80 Zemlaya in the Barents Sea (Figure 1b/d). The PC (Figure 1e) are characterised by a decreasing
81 tendency throughout the period. This tendency might equally be viewed as a series of steps, and
82 application of a regime shift algorithm (Rodionov 2004) yields breaks in 1973 (ERA20C only,
83 SSMI begins in 1979), 1983 and 2004 (both ERA20C and SSMI); ANOVA analysis confirms that
84 the means are significantly different over these subperiods. The variability of the Labrador Sea is
85 explained almost entirely by EOF2 (Figure 2), which describes significant variability exclusively
86 in this area (Figure 2b/d). No variability is explained in the Labrador Sea in EOF1, demonstrating
87 that the variability of this region is uncorrelated with that of the other poles of the quadrupole. This

88 can be verified independently of the EOF analysis simply by correlating the sea ice area (SIA) time
89 series of the marginal seas amongst one another (Table 1); the correlations between the SIA of the
90 Labrador Sea and all other regions are low, and in no case significant at either the 90% or 95%
91 level, either in ERA20C or SSMI.

92 To investigate the link between the quadrupole loading pattern and the NAO found in previous
93 studies (e.g. Deser et al. 2000), the PC are correlated with the DJF mean NAO index (this is the
94 3-month combination that yields the strongest relationship with JFM SIC in a lagged correlation
95 analysis). The correlation between PC1 and the NAO is low, with $r = 0.29$ ($p = 0.086$) for SSMI,
96 and $r = 0.52$ ($p = 0.104$) for ERA20C. To analyse the spatial extent of the NAO influence on SIC,
97 the winter mean SIC data are regressed on to the index (Figure 3). As for the EOF analysis, the
98 quadrupole loading pattern emerges from the data; however, significant variability is explained
99 only in Baffin Bay, the Labrador Sea and a small region of the Greenland Sea. The Labrador Sea
100 SIA and DJF NAO time series are correlated with $r = 0.48/0.46$ ($p = 0.006/0.003$) for SSMI and
101 ERA20C respectively.

102 Regression of the DJF SLP on to SIC PC1 does not produce coherent areas of significant corre-
103 lation for either the ERA20C or SSMI analyses. However, regression of the 700 hPa geopotential
104 height on to SIC PC1 yields a region of significant covariability based over eastern Siberia for both
105 SSMI (Figure 4a) and ERA20C (not shown). Motivated by the proximity of this correlated area
106 to the region forming the basis for the Siberian Index (mean winter normalised 700 hPa geopoten-
107 tial anomalies over 55-70°N, 90-150°E, Overland et al. 2008, shown by the white box in Figure
108 4a; here, the index is recalculated from ERA20C and over DJF for consistency), the relationship
109 between this metric and SIC PC1 is analysed. SIC PC1 and the Siberian Index (SI) are correlated
110 with $r = 0.62/0.59$ for SSMI / ERA20C respectively ($p = 0.002/0.008$; Figure 4b). The SI time
111 series is filtered with a 2nd order low-pass butterworth filter with a 4-year cutoff frequency to

112 decrease the interannual-scale signal, and the regime shift algorithm used above applied. Breaks
113 are again found in 1973, 1983 and 2004, consistent with the timing of those of SIC PC1 (note that
114 the interannual variability is large relative to the interdecadal signal, and thus no breaks are found
115 in the raw time series, which is dominated by the interannual signal). The SI and SIC PC1 covary
116 most strongly at low-frequencies (>8 yr), although a link is also in evidence at higher frequencies
117 (Figure 5a).

118 Analysis of subsets of the data reveals that the apparition of the quadrupole loading pattern
119 as the first mode is dependent on the time period chosen for the analysis: if the period 1983-
120 2013 is chosen, removing the sharp decline in the first 4 years of the SSMI record, the quadrupole
121 emerges only as the second PC, and explains significant variability only in the Odden feature of the
122 Greenland Sea (the first mode being the Labrador Sea mode shown in Figure 2). In contrast with
123 previous studies that have suggested the predominance of separate Atlantic and Pacific dipoles,
124 over the full period examined here an East Arctic connection, describing in-phase covariability
125 amongst the Greenland, Barents and Okhotsk Seas, appears rather to be the dominant connection.
126 The Okhotsk and Bering Seas, previously suggested to form a dipole pair in analyses performed
127 over shorter temporal records (Cavaliere and Parkinson 1987; Fang and Wallace 1994), are found
128 not to exhibit significant covariability over the full period of this analysis (Table 1).

129 SIC PC1 is predominantly characterised by the low-frequency signal: the time series has a
130 decorrelation period of approximately 10 years. Correspondingly, the SIA of the Barents, Green-
131 land and Okhotsk Seas appear to be linked by low-frequency variability: applying the regime shift
132 algorithm of Rodionov (2004) to the SIA time series over the 1979-2013 period, common break
133 points are found (1983 and 2004 in both the Okhotsk and Barents Seas and 2004 in the Greenland
134 Sea). Re-calculating the EOF over the 1983-2004 period (taken as an approximation of a period
135 when the low-frequency variability associated with PC1 is weak), the first and only significant

136 mode is again associated with the quadrupole loading pattern, but now explains significant vari-
137 ability only in the Labrador Sea. SIC PC1 of this reduced period is essentially unaltered compared
138 to the SIC PC2 of the full period ($r = 0.93$; $p = 0.020$). The low-frequency variability associated
139 with PC2 thus becomes the dominant influence over this subperiod in which the low-frequency
140 variability associated with the original PC1 is weak. No significant covariability amongst the Bar-
141 ents, Greenland and Okhotsk Seas is found over this subperiod, supporting the hypothesis that
142 these regions are linked predominantly by low-frequency variability. Extending this subperiod
143 backwards to 1979, thus corresponding to the 1979-2003 period used in the earlier analysis of
144 Ukita et al. (2007), the same scenario occurs. Here, the quadrupole loading pattern obtained as the
145 first mode again explains significant variability only in the Labrador Sea; consistently, Ukita et al.
146 (2007) noted a significant correlation between this mode and the NAO.

147 Whilst SIC PC1 is characterised by a strong low-frequency signal, the high-frequency compo-
148 nent is also intermittently correlated with the SI (Figure 5a), suggesting that interannual changes
149 in the Greenland, Barents and Okhotsk Seas also experience some influence from the pressure sys-
150 tem. In contrast, SIC PC1 is not well correlated in any frequency range with the Arctic Oscillation
151 index ($r = -0.25 / -0.40$, $p = 0.15 / 0.09$ for SSMI and ERA20C respectively), which, as a metric
152 of the large-scale variability, might be expected to better represent the covariability of all three
153 major Arctic pressure centres. This lends support to the idea that it is the gradient at the interface
154 of the Siberian High that is key in determining the sea ice evolution (discussed further below),
155 and that this regional variability is not necessarily well represented by large-scale metrics such
156 as the Arctic Oscillation. This result is consistent with previous studies that have suggested local
157 SLP gradients to control interannual Barents Sea ice variability (Sorteberg and Kvingedal 2006;
158 Schlichtholz and Houssais 2011; Inoue et al. 2012; Herbaut et al. 2015), and with studies that
159 have suggested a combined role of both the Aleutian Low and Siberian High in driving ice-ocean

160 conditions in the Sea of Okhotsk (e.g. Parkinson 1990; Tachibana et al. 1996; Nakanowatari et al.
161 2014, amongst others).

162 **4. Discussion**

163 The primary modes of winter SIC variability obtained from the above EOF analyses do not
164 describe significant covariability amongst all of the various seas comprising the Northern Hemi-
165 sphere marginal ice zone (MIZ); rather, subregions of the Greenland, Barents and Okhotsk Seas
166 covary in the first mode and the Labrador Sea varies independently in the second mode. The
167 quadrupole loading pattern itself thus cannot be interpreted to represent a significant relationship
168 amongst its four poles. This can be demonstrated further simply by correlating the SIA calcu-
169 lated over the various seas (Table 1). The only relationship that is significant at the 95% level is
170 that between the Barents and Greenland Sea SIA using ERA20C data. Recent studies have also
171 noted that the co-variability amongst the marginal seas is only weak both at interannual time scales
172 (Chen et al. 2016) and in terms of long-term behaviour (Close et al. 2015) in autumn (November-
173 December), suggesting that this independent regional evolution may not be unique to the winter
174 season examined here.

175 The link between the strength of the Siberian High and the SIC PC1 inferred here appears phys-
176 ically reasonable given that this feature lies directly adjacent to the Barents and Okhotsk Seas,
177 where PC1 describes variability in the sea ice. Given the length of the available time series, it is
178 not possible to perform a robust physical analysis of the low-frequency signal, which is poorly
179 resolved; we hence focus here on examining the 2004 event, for which the data quality is well
180 known and the step-change in sea ice conditions prolonged and statistically significant (cf. Close
181 et al. 2015). Large-scale changes in the SLP field can be noted before and after 2004, leading to a
182 re-orientation of the isobars over the Barents and Kara Seas (Figure 5b) associated with the expan-

183 sion of the Siberian High and contraction of the Icelandic Low centre. A statistically significant
184 step-change also occurs in the time series of maximum pressure at the centre of the Siberian High
185 (not shown), corresponding to an increase of ~ 2 hPa between the 1983-2004 and 2005-2013 mean.
186 As shown in Close et al. (2015), there is a corresponding change in the direction of sea ice export
187 from the Kara Sea before and after this time, with the ice passing predominantly west into the
188 Barents Sea before 2004, but north into the Arctic Ocean afterwards. (At an Arctic-wide scale, the
189 Siberian High was also suggested to trigger changes in the circulation regime of the large-scale sea
190 ice motion in the model-based study of Proshutinsky and Johnson 1997.) Qualitative examination
191 of the pre/post 1973 and 1983 periods (the potential transition dates identified in SIC PC1 by the
192 regime shift algorithm) similarly shows changes either in the strength of the Siberian High itself,
193 or in the adjacent Aleutian or Icelandic Low pressure centres, that translate into a modification of
194 the SLP gradient at the interface with the Siberian High (i.e. over the Okhotsk and Barents Seas
195 respectively). The break points identified statistically here do not correspond to the 1998 cutoff
196 used by Yang and Yuan (2014) for the early winter period; this may suggest a lack of continuity
197 between the autumn/early winter period (Oct-Dec) and the Jan-Mar period analysed here (consis-
198 tent with their suggestion that the influence of autumn forcing is reduced in the months analysed
199 here and the fact that the atmospheric combination of months that is best correlated with JFM SIC
200 variability here is DJF).

201 In situ ocean observations remain sparse in the high latitudes, and it has thus not been possible
202 to undertake a direct comparison of the sea ice variability with oceanic heat transport within the
203 context of this study. However, in a model-based analysis, Kawasaki and Hasumi (2016) found
204 that changes in the Siberian High modulated the partitioning of volume transport of the inflowing
205 Atlantic Water between the Fram Strait and Barents Sea Opening. This may implicate a second,
206 consistent mechanism by which the Siberian High could affect the ice cover of the Barents Sea

207 (and thus, partially, the variability associated with PC1) by modulating the volume transport of
208 inflowing warm Atlantic Water, and thus potentially oceanic heat transport to the region. Nev-
209 ertheless, in contrast with this notion, using an ocean-ice model Herbaut et al. (2015) found that
210 the sudden decline in the SIA of the Barents Sea in 2004 was not preceded by any changes in the
211 inflowing Atlantic Water, and thus suggested that other mechanisms must have been implicated in
212 the sudden ice loss. Herbaut et al. note that ocean heat anomalies that are formed in the Barents
213 Sea Opening take approximately one year to propagate to the ice edge; this suggests that if ocean
214 heat anomalies were forced in phase with changes in the Siberian High at the Barents Sea Open-
215 ing, any potential impact on the ice edge might be expected to occur at lag. Various authors have
216 also suggested a role of the combined Siberian High - Aleutian Low system in modulating the sea
217 ice cover of the Sea of Okhotsk (e.g. Parkinson 1990; Tachibana et al. 1996). Direct ice advection
218 by the wind (e.g. Kimura and Wakatsuchi 1999; Martin et al. 1998) and oceanic variability (e.g.
219 Nakanowatari et al. 2010) are both generally accepted to play a role in forcing the ice cover in this
220 region, with Nakanowatari et al. (2014) also suggesting the combined Siberian High - Aleutian
221 Low system to have contributed to driving recent oceanic warming in the region.

222 By definition, the NAO partially describes the variability of the Icelandic Low. The strength of
223 the low can influence the SLP gradient over the Barents Sea, which may suggest an intermittent
224 link between the NAO and PC1 at times when the variability of the Icelandic Low, rather than of
225 the Siberian High, is the dominant control on the SLP gradient over the Barents Sea. An approx-
226 imation of this gradient is thus defined between the Greenland Sea and northern Russia (shown
227 by the purple boxes in Figure 4a), and found to be well correlated with SIC PC1 ($r = 0.57/0.57$,
228 $p = 0.000/0.012$ for SSMI/ERA20C). The SLP gradient is further found to be correlated with both
229 the SI and NAO ($r = -0.68/-0.56$, $p = 0.000/0.000$ respectively). Wavelet coherence analysis
230 (Figure 6a) highlights the strong relationship between SIC PC1 and this SLP gradient over a range

231 of frequencies. Further analyses exploring the link with the individual SI and NAO time series (not
232 shown) reveal that the covariance between the SLP gradient and SI strongly resemble the results
233 obtained between SIC PC1 and the SI (Figure 5a); in contrast, the correlation between the SLP
234 gradient and the NAO is limited to low frequencies and to the period 1965-1995. These results
235 support the idea that the SI has exerted an influence on SIC PC1 through its control on the SLP
236 gradient throughout the study period, whilst the influence of the NAO via this same mechanism ap-
237 pears to have been temporally limited to approximately 1965-1995. In early work carried out prior
238 to the satellite era, Rogers and van Loon (1979), employing indices of sea ice severity covering
239 approximately 90 year periods for the Davis Strait and Newfoundland Seas, found covariability
240 between the NAO and Davis Strait sea ice variability, but observed no connection between the
241 NAO and the sea ice of the Barents or East Greenland Seas. The consistency between their results
242 and those obtained here suggests that it might be reasonable to generalise these findings to longer
243 periods.

244 Whilst there is no overall link between SIC PC1 and the NAO, the two experience common
245 low-frequency variability over the approximate period 1965-1995 (Figure 6b). The link between
246 the NAO and SIC PC1 found by earlier studies (e.g. Walsh and Johnson 1979; Deser et al. 2000)
247 likely arises from this temporally limited connection over an isolated period, rather than repre-
248 senting a continuous influence. In contrast, the link between SIC PC2 and the NAO (again, at low
249 frequencies) is rather consistent, albeit weaker, throughout the study period (Figure 6c). Previous
250 authors have suggested that the link between Arctic sea ice and the NAO is non-stationary (e.g.
251 Smedsrud et al. 2013); however, particularly given the length of the available observational record,
252 the temporally-limited correlation between PC1 and the NAO shown in Figure 6b should also be
253 considered in the context of the cautionary note of Wunsch (1999), where it was emphasized that
254 two uncorrelated stochastic time series may exhibit isolated periods of common low-frequency

255 variability simply by chance. Although, as outlined above, we suggest that the NAO may have
256 played a role in modulating the pressure gradient over the Barents Sea over the 1965-1995 period,
257 the possibility that this correlation (which is based predominantly in the low-frequency range) is
258 fortuitous should thus also be considered. Whilst these factors do not suggest a clear role of the
259 NAO in driving the variability associated with SIC PC1, the consistent correlation between the
260 SI and SIC PC1 found throughout the study period and over multiple frequencies, in contrast,
261 supports the hypothesis of a connection between these two variables.

262 Both PC1 and PC2 of the winter SIC have a strong low-frequency component. Whilst the two
263 PC are, by definition, uncorrelated over the period of calculation, over certain subperiods (notably
264 1965-1995), the correlation between the two time series is significant in the low-frequency range
265 (Figure 6d). The dominance of the low-frequency signal, in combination with this evidence that
266 periods of common low-frequency variability can occur in multiple modes (again, cf Wunsch
267 1999), suggests that long time scales are necessary to achieve separation of the modes. This
268 raises the question of whether, at 35 years, the satellite record is yet long enough to permit robust
269 statistical analysis. Although it is not possible to know whether SIC prior to the advent of the
270 satellite era is realistically reproduced in ERA20C, the modes obtained in this study are consistent
271 between the longer ERA20C period and SSMI.

272 EOF analyses ultimately provide a statistical, rather than physical, description of the variabil-
273 ity of a system and, as noted by numerous authors (e.g. Dommenget and Latif 2002; Monahan
274 et al. 2009), cannot be assumed a priori to represent a physical mode of the system under con-
275 sideration. The results obtained in the analysis presented here can, however, also be obtained by
276 complementary methods: correlations and wavelet coherence analyses of the SIA of the MIZ sup-
277 port the notion that the individual poles of the quadrupole are, overall, uncorrelated. EOF mode 1
278 describes covariability amongst only restricted subregions of the Greenland, Barents and Okhotsk

279 poles: regression of the SIC on to the mean SIC calculated along the coast of Novaya Zemlaya
280 confirms the covariability of this region with the significantly correlated subregion of the Sea of
281 Okhotsk that emerges from the EOF analysis. Calculations of the correlations between the SIA
282 of the different MIZ regions and the NAO also support our interpretation that the NAO does not
283 covary significantly with any region outside the Labrador Sea, and regression of the SIC on to the
284 SI confirms that this metric explains significant variability in the Greenland, Barents and Okhotsk
285 Seas. The same results are thus obtained through both the EOF-based and counterpart methods,
286 suggesting that they are not dependent on our choice of analysis method.

287 **5. Conclusions**

288 In summary, we suggest that the quadrupole loading pattern that emerges from EOF analysis of
289 JFM SIC data should not be interpreted physically in and of itself. The loading pattern is found
290 not to be implicitly associated with a particular empirical mode of variability, and should not be
291 assumed to indicate a robust relationship amongst the component poles. This result can be verified
292 by a simple correlation analysis of the SIA of the marginal seas, which shows that the various
293 regions do not covary over the length of the available data record.

294 EOF1 of both the 1979-2013 sea ice satellite record and the 1953-2010 ERA20C reanalysis
295 represents an East Arctic mode of SIC variability linking restricted sub-regions of the Barents,
296 Greenland and Okhotsk Seas; this contrasts with previous results that found the dominance of an
297 Atlantic dipole of sea ice variability, linking the Barents, Greenland and Labrador Sea. Our anal-
298 ysis suggests that the East Arctic mode is linked to variations in the Siberian High; specifically,
299 we hypothesize that changes in the SLP gradient at the interface between the Siberian High and
300 adjoining Aleutian and Icelandic Low pressure systems modulate the ice cover, either by direct
301 mechanical forcing of the ice cover or indirectly via the ocean (i.e. thermodynamically). These

302 ideas are consistent with existing analyses of regional variability in these regions. The NAO co-
303 varied with PC1 only over a temporally limited period (ca. 1965-1995), but shows more consistent
304 correlation with the Labrador Sea ice cover, which varies independently as EOF2.

305 Finally, the EOF modes of winter SIC are characterised by low-frequency variability. This is
306 likely not yet well resolved by the satellite record at its present length, highlighting the need for
307 caution when interpreting statistically-based analyses of short records.

308 *Acknowledgments.* The research leading to these results has received funding from the European
309 Union 7th Framework Programme (FP7 2007-2013) under grant agreement 308299, NACLIM
310 Project. We are grateful to the reviewers for their helpful comments on the manuscript.

311 **References**

312 Cavalieri, D. J., and C. L. Parkinson, 1987: On the relationship between atmospheric circulation
313 and the fluctuations in the sea ice extents of the Bering and Okhotsk Seas. *J. Geophys. Res.*,
314 **92 (C7)**, 7141–7162, doi:10.1029/JC092iC07p07141.

315 Chelton, D. B., 1983: Effects of sampling errors in statistical estimation. *Deep Sea Res. A*, **30 (10)**,
316 1083 – 1103, doi:10.1016/0198-0149(83)90062-6.

317 Chen, H. W., R. B. Alley, and F. Zhang, 2016: Interannual Arctic sea ice variability and associated
318 winter weather patterns: a regional perspective for 1979–2014. *J. Geophys. Res.*, in press, doi:
319 10.1002/2016JD024769.

320 Close, S., M.-N. Houssais, and C. Herbaut, 2015: Regional dependence in the timing of onset
321 of rapid decline in Arctic sea ice concentration. *J. Geophys. Res.*, **120 (12)**, 8077–8098, doi:
322 10.1002/2015JC011187.

323 Comiso, J. C., 2000, updated 2014: Bootstrap Sea Ice Concentrations from Nimbus-7 SMMR and
324 DMSP SSM/I-SSMIS. Version 2. doi:10.5067/J6JQLS9EJ5HU.

325 Comiso, J. C., C. L. Parkinson, R. Gersten, and L. Stock, 2008: Accelerated decline in the Arctic
326 sea ice cover. *Geophys. Res. Lett.*, **35** (1), doi:10.1029/2007GL031972.

327 Day, J. J., S. Tietsche, and E. Hawkins, 2014: Pan-Arctic and Regional Sea Ice Predictability: Ini-
328 tialization Month Dependence. *J. Climate*, **27** (12), 4371–4390, doi:10.1175/JCLI-D-13-00614.
329 1.

330 Deser, C., J. E. Walsh, and M. S. Timlin, 2000: Arctic Sea Ice Variability in the Context of Recent
331 Atmospheric Circulation Trends. *J. Climate*, **13** (3), 617–633, doi:10.1175/1520-0442(2000)
332 013<0617:ASIVIT>2.0.CO;2.

333 Dommenget, D., and M. Latif, 2002: A Cautionary Note on the Interpretation of EOFs. *J. Climate*,
334 **15** (2), 216–225, doi:10.1175/1520-0442(2002)015<0216:ACNOTI>2.0.CO;2.

335 Fang, Z., and J. M. Wallace, 1994: Arctic Sea Ice Variability on a Timescale of Weeks and Its
336 Relation to Atmospheric Forcing. *J. Climate*, **7** (12), 1897–1914, doi:10.1175/1520-0442(1994)
337 007<1897:ASIVOA>2.0.CO;2.

338 Herbaut, C., M.-N. Houssais, S. Close, and A.-C. Blaizot, 2015: Two wind-driven modes of winter
339 sea ice variability in the Barents Sea. *Deep Sea Res. I*, **106**, 97 – 115, doi:10.1016/j.dsr.2015.
340 10.005.

341 Inoue, J., M. E. Hori, and K. Takaya, 2012: The Role of Barents Sea Ice in the Wintertime Cyclone
342 Track and Emergence of a Warm-Arctic Cold-Siberian Anomaly. *J. Climate*, **25** (7), 2561–2568,
343 doi:10.1175/JCLI-D-11-00449.1.

- 344 Kawasaki, T., and H. Hasumi, 2016: The inflow of Atlantic water at the Fram Strait and its inter-
345 annual variability. *J. Geophys. Res.*, **121** (1), 502–519, doi:10.1002/2015JC011375.
- 346 Kimura, N., and M. Wakatsuchi, 1999: Processes controlling the advance and retreat of sea ice in
347 the Sea of Okhotsk. *J. Geophys. Res.*, **104** (C5), 11 137–11 150, doi:10.1029/1999JC900004.
- 348 Martin, S., R. Drucker, and K. Yamashita, 1998: The production of ice and dense shelf water in the
349 Okhotsk Sea polynyas. *J. Geophys. Res.*, **103** (C12), 27 771–27 782, doi:10.1029/98JC02242.
- 350 Maslanik, J., S. Drobot, C. Fowler, W. Emery, and R. Barry, 2007: On the Arctic climate paradox
351 and the continuing role of atmospheric circulation in affecting sea ice conditions. *Geophys. Res.*
352 *Lett.*, **34** (3), L03 711, doi:10.1029/2006GL028269.
- 353 Monahan, A. H., J. C. Fyfe, M. H. P. Ambaum, D. B. Stephenson, and G. R. North, 2009: Em-
354 pirical Orthogonal Functions: The Medium is the Message. *J. Climate*, **22** (24), 6501–6514,
355 doi:10.1175/2009JCLI3062.1.
- 356 Nakanowatari, T., T. Nakamura, K. Uchimoto, H. Uehara, H. Mitsudera, K. I. Ohshima, H. Ha-
357 sumi, and M. Wakatsuchi, 2014: Causes of the Multidecadal-Scale Warming of the Intermediate
358 Water in the Okhotsk Sea and Western Subarctic North Pacific. *J. Climate*, **28** (2), 714–736, doi:
359 10.1175/JCLI-D-14-00172.1.
- 360 Nakanowatari, T., K. I. Ohshima, and S. Nagai, 2010: What determines the maximum sea ice ex-
361 tent in the Sea of Okhotsk? Importance of ocean thermal condition from the Pacific. *J. Geophys.*
362 *Res.*, **115** (C12), doi:10.1029/2009JC006070, c12031.
- 363 Overland, J., S. Rodionov, S. Minobe, and N. Bond, 2008: North Pacific regime shifts: Definitions,
364 issues and recent transitions. *Prog. Oceanogr.*, **77** (2–3), 92 – 102, doi:10.1016/j.pocean.2008.
365 03.016.

366 Parkinson, C. L., 1990: The Impact of the Siberian High and Aleutian Low on the Sea-Ice Cover
367 of the Sea of Okhotsk. *Ann. Glaciol.*, **14** (1), 226–229, doi:10.3198/1990AoG14-1-226-229.

368 Petoukhov, V., and V. A. Semenov, 2010: A link between reduced Barents-Kara sea ice and cold
369 winter extremes over northern continents. *J. Geophys. Res.-Atmos.*, **115** (D21), doi:10.1029/
370 2009JD013568, d21111.

371 Poli, P., and Coauthors, 2016: ERA-20C: An Atmospheric Reanalysis of the Twentieth Century.
372 *J. Climate*, **29** (11), 4083–4097, doi:10.1175/JCLI-D-15-0556.1.

373 Proshutinsky, A. Y., and M. A. Johnson, 1997: Two circulation regimes of the wind-driven Arctic
374 Ocean. *J. Geophys. Res.*, **102** (C6), 12 493–12 514, doi:10.1029/97JC00738.

375 Rodionov, S. N., 2004: A sequential algorithm for testing climate regime shifts. *Geophys. Res.*
376 *Lett.*, **31** (9), doi:10.1029/2004GL019448, 109204.

377 Rogers, J. C., and H. van Loon, 1979: The Seesaw in Winter Temperatures between Greenland and
378 Northern Europe. Part II: Some Oceanic and Atmospheric Effects in Middle and High Latitudes.
379 *Mon. Wea. Rev.*, **107** (5), 509–519, doi:10.1175/1520-0493(1979)107<0509:TSIWTB>2.0.CO;
380 2.

381 Schlichtholz, P., and M.-N. Houssais, 2011: Forcing of oceanic heat anomalies by air-sea interac-
382 tions in the Nordic Seas area. *J. Geophys. Res-Oceans*, **116** (C1), doi:10.1029/2009JC005944,
383 c01006.

384 Screen, J. A., I. Simmonds, C. Deser, and R. Tomas, 2013: The Atmospheric Response
385 to Three Decades of Observed Arctic Sea Ice Loss. *J. Climate*, **26** (4), 1230–1248, doi:
386 10.1175/JCLI-D-12-00063.1.

- 387 Serreze, M. C., A. P. Barrett, J. C. Stroeve, D. N. Kindig, and M. M. Holland, 2009: The emergence
388 of surface-based Arctic amplification. *The Cryosphere*, **3** (1), 11–19, doi:10.5194/tc-3-11-2009.
- 389 Smedsrud, L. H., and Coauthors, 2013: The Role of the Barents Sea in the Arctic climate system.
390 *Rev. Geophys.*, **51** (3), 415–449, doi:10.1002/rog.20017.
- 391 Sorteberg, A., and B. Kvingedal, 2006: Atmospheric Forcing on the Barents Sea Winter Ice Ex-
392 tent. *J. Climate*, **19** (19), 4772–4784, doi:10.1175/JCLI3885.1.
- 393 Tachibana, Y., M. Honda, and K. Takeuchi, 1996: The abrupt decrease of the sea ice over the
394 southern part of the Sea of Okhotsk in 1989 and its relation to the recent weakening of the
395 Aleutian low. *J. Meteorol. Soc. Jpn.*, **74** (4), 579–584.
- 396 Ukita, J., M. Honga, H. Nakamura, Y. Tachibana, D. J. Cavalieri, C. L. Parkinson, H. Koide, and
397 K. Yamamoto, 2007: Northern Hemisphere sea ice variability: lag structure and its implications.
398 *Tellus A*, **59** (2), 261–272, doi:10.1111/j.1600-0870.2006.00223.x.
- 399 Walsh, J. E., and C. M. Johnson, 1979: Interannual atmospheric variability and associated
400 fluctuations in Arctic Sea ice extent. *J. Geophys. Res.*, **84** (C11), 6915–6928, doi:10.1029/
401 JC084iC11p06915.
- 402 Wunsch, C., 1999: The Interpretation of Short Climate Records, with Comments on the North
403 Atlantic and Southern Oscillations. *Bull. Amer. Meteor. Soc.*, **80** (2), 245–255, doi:10.1175/
404 1520-0477(1999)080<0245:TIOSCR>2.0.CO;2.
- 405 Yang, X.-Y., and X. Yuan, 2014: The Early Winter Sea Ice Variability under the Recent Arctic
406 Climate Shift. *J. Climate*, **27** (13), 5092–5110, doi:10.1175/JCLI-D-13-00536.1.

407 Yi, D., L. A. Mysak, and S. A. Venegas, 1999: Decadal-to-interdecadal fluctuations of Arctic
408 sea ice cover and the atmospheric circulation during 1954–1994. *Atmosphere-Ocean*, **37** (4),
409 389–415, doi:10.1080/07055900.1999.9649633.

410 **LIST OF TABLES**

411 **Table 1.** Correlation between JFM mean SIA for regions of MIZ in SSMI and ERA20C.
412 Correlations that are significant at the 95% level are in bold. The regions are de-
413 fined using the loading patterns resulting from EOF1 (for Okhotsk, Greenland,
414 Barents and Bering) and 2 (for Labrador) obtained using SSMI, corresponding
415 to areas where the magnitude of the loading pattern is greater than 4% within
416 the geographical domains associated with the seas. 22

	SSMI (1979-2013)							
	Labrador		Greenland		Barents		Okhotsk	
	r	(p)	r	(p)	r	(p)	r	(p)
Greenland	0.04	(0.912)	–	–	–	–	–	–
Barents	-0.02	(0.931)	0.68	(0.090)	–	–	–	–
Okhotsk	0.00	(0.997)	0.51	(0.060)	0.54	(0.130)	–	–
Bering	0.07	(0.722)	-0.41	(0.057)	-0.44	(0.063)	-0.32	(0.180)

	ERA20C (1953-2010)							
	Labrador		Greenland		Barents		Okhotsk	
	r	(p)	r	(p)	r	(p)	r	(p)
Greenland	0.00	(0.995)	–	–	–	–	–	–
Barents	-0.09	(0.640)	0.65	(0.042)	–	–	–	–
Okhotsk	-0.03	(0.804)	0.53	(0.172)	0.53	(0.139)	–	–
Bering	0.23	(0.270)	-0.20	(0.155)	-0.25	(0.115)	-0.16	(0.251)

417 TABLE 1. Correlation between JFM mean SIA for regions of MIZ in SSMI and ERA20C. Correlations that are
418 significant at the 95% level are in bold. The regions are defined using the loading patterns resulting from EOF1
419 (for Okhotsk, Greenland, Barents and Bering) and 2 (for Labrador) obtained using SSMI, corresponding to areas
420 where the magnitude of the loading pattern is greater than 4% within the geographical domains associated with
421 the seas.

422 **LIST OF FIGURES**

423 **Fig. 1.** (a) loading pattern and (b) percentage of variance explained locally for first EOF mode of
 424 winter SIC calculated using SSMI data. (c/d) as (a/b) but for ERA20C data. Black contours
 425 in a-d indicate the 95% significance level. (e) PC mode 1 for SSMI (black) and ERA20C
 426 (blue) data. 24

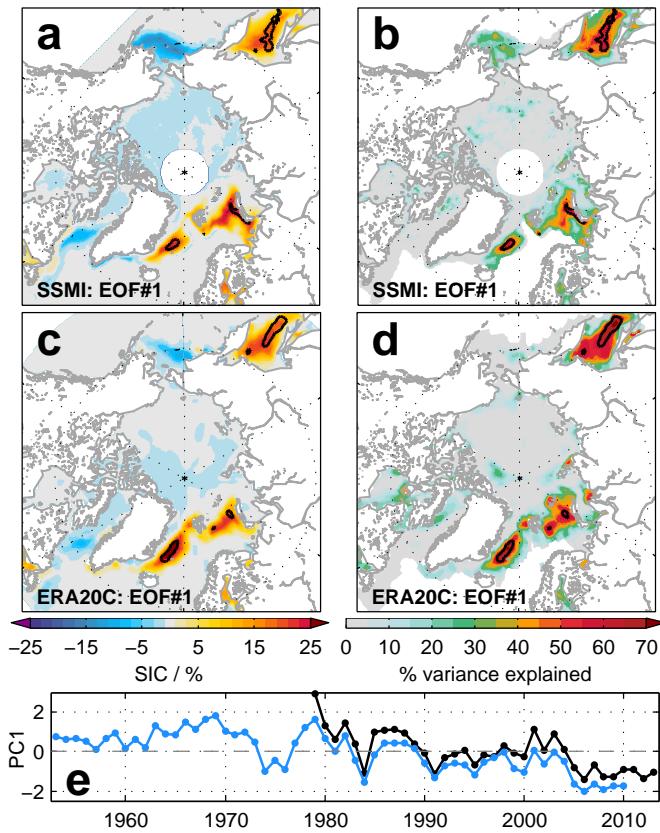
427 **Fig. 2.** (a) loading pattern and (b) percentage of variance explained locally for second EOF mode of
 428 winter SIC calculated using SSMI data. (c/d) as (a/b) but for ERA20C data. Black contours
 429 in a-d indicate the 95% significance level. (e) PC mode 2 for SSMI (black) and ERA20C
 430 (blue) data. 25

431 **Fig. 3.** (a) regression coefficients and (b) percentage of variance explained locally for regression of
 432 JFM sea ice on to DJF NAO for SSMI data. Black contours indicate the 95% significance
 433 level. (c) PC mode 1 for SSMI (black) and ERA20C (blue) data (as for Figure 1) and NAO
 434 index (red, sign inverted). 26

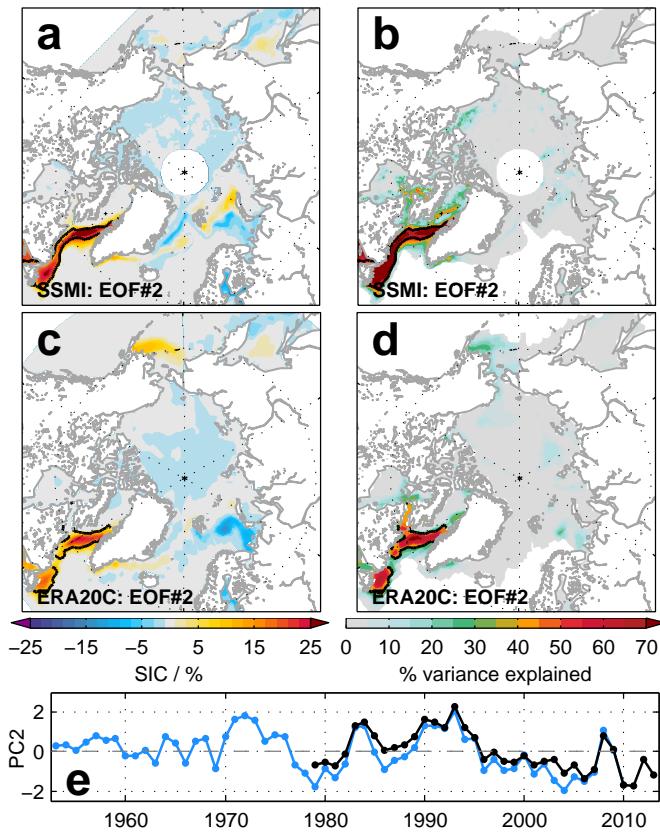
435 **Fig. 4.** (a) percentage of variance explained locally by regression of DJF ϕ_{700} on to SSMI SIC PC1.
 436 Black contours show the 95% significance level. White box defines the area over which
 437 the Siberian Index is calculated. Purple boxes show the two areas over which the SLP is
 438 averaged to estimate the cross-Barents Sea gradient. (b) SIC PC mode 1 for SSMI (black)
 439 and ERA20C (blue) data (as for Figure 1) and Siberian Index (red, sign inverted for ease of
 440 comparison). 27

441 **Fig. 5.** (a) Cross-wavelet coherence between SIC PC1 and Siberian Index. Black contours show the
 442 95% significance level. White hatching denotes results lying outside the cone of influence,
 443 where edge artefacts may contaminate the results. Arrows indicate the phase relationship
 444 between the two variables, where right/leftwards-pointing arrows indicate that the series are
 445 in phase / in anti-phase. (b) Mean SLP over 1983-2004 (thick lines, pale colours) and 2005-
 446 2010 (thin lines, dark colours); for clarity of comparison, only a limited number of isolines
 447 are shown. 28

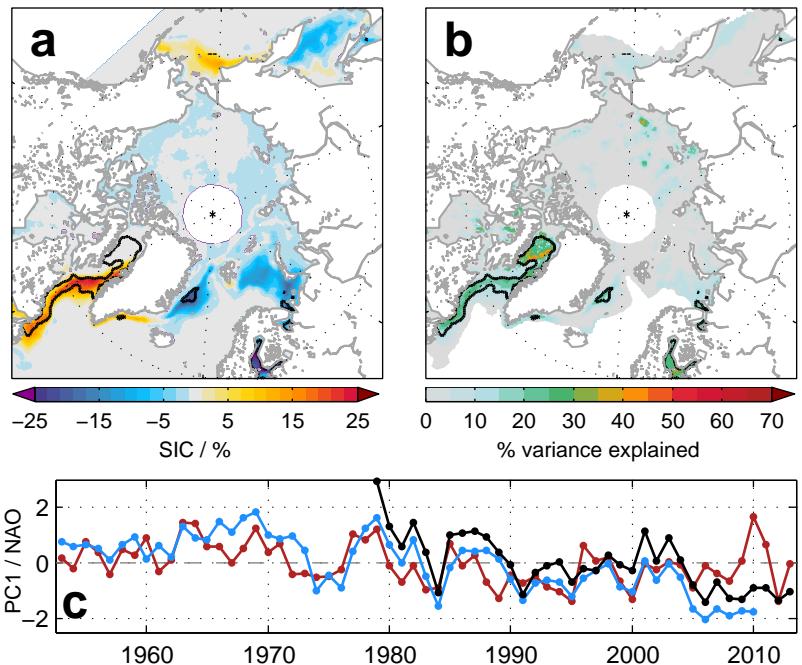
448 **Fig. 6.** Cross-wavelet coherence between (a) the cross-Barents Sea SLP gradient and SIC PC1; the
 449 NAO index and (b) SIC PC1 and (c) SIC PC2; (d) SIC PC1 and SIC PC2. Black contours
 450 show the 95% significance level. White hatching denotes results lying outside the cone
 451 of influence, where edge artefacts may contaminate the results. Arrows indicate the phase
 452 relationship between the two variables as in Figure 5. 29



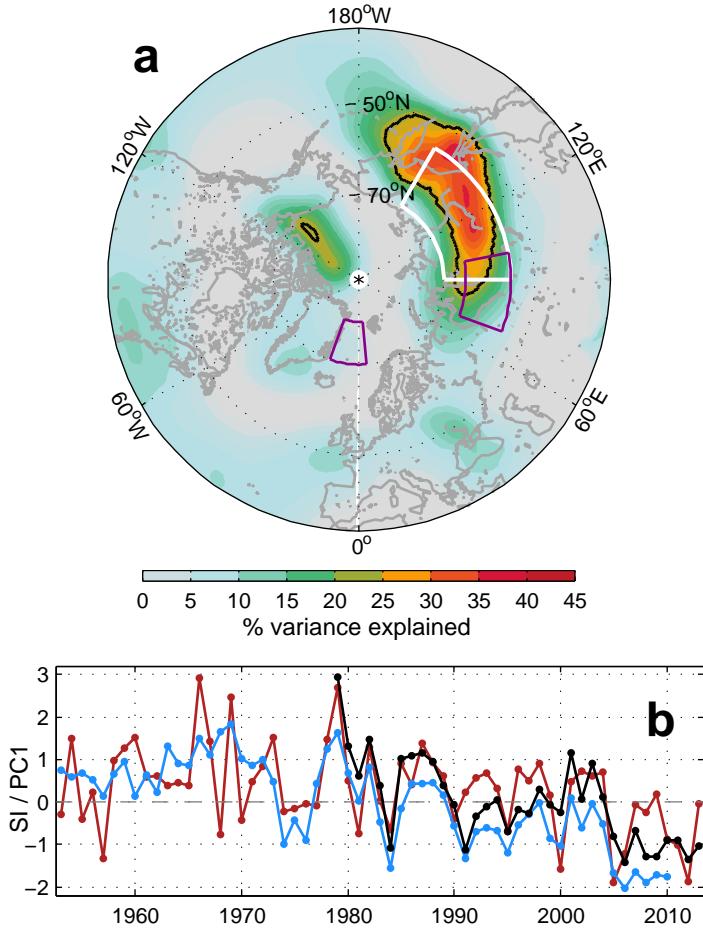
453 FIG. 1. (a) loading pattern and (b) percentage of variance explained locally for first EOF mode of winter
 454 SIC calculated using SSMI data. (c/d) as (a/b) but for ERA20C data. Black contours in a-d indicate the 95%
 455 significance level. (e) PC mode 1 for SSMI (black) and ERA20C (blue) data.



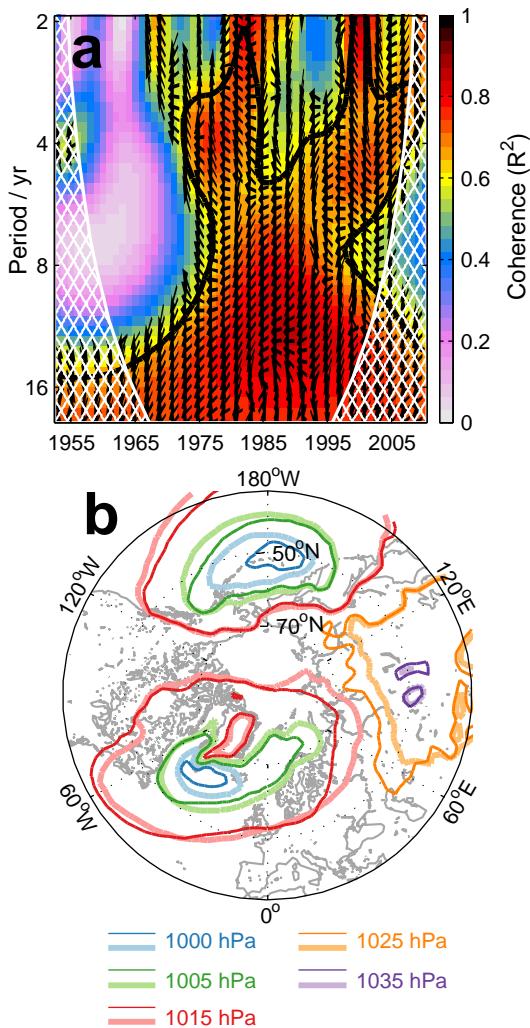
456 FIG. 2. (a) loading pattern and (b) percentage of variance explained locally for second EOF mode of winter
 457 SIC calculated using SSMI data. (c/d) as (a/b) but for ERA20C data. Black contours in a-d indicate the 95%
 458 significance level. (e) PC mode 2 for SSMI (black) and ERA20C (blue) data.



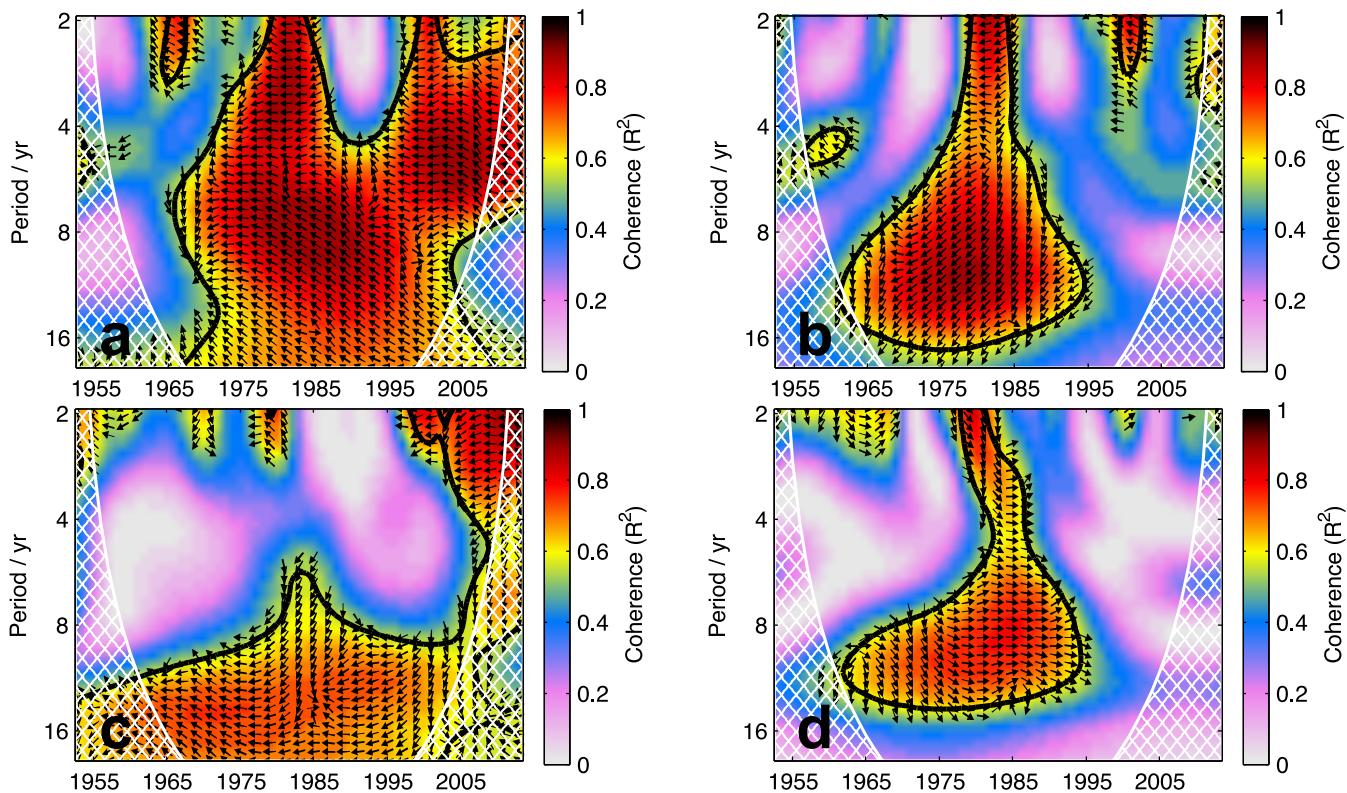
459 FIG. 3. (a) regression coefficients and (b) percentage of variance explained locally for regression of JFM sea
 460 ice on to DJF NAO for SSMI data. Black contours indicate the 95% significance level. (c) PC mode 1 for SSMI
 461 (black) and ERA20C (blue) data (as for Figure 1) and NAO index (red, sign inverted).



462 FIG. 4. (a) percentage of variance explained locally by regression of DJF ϕ_{700} on to SSMI SIC PC1. Black
 463 contours show the 95% significance level. White box defines the area over which the Siberian Index is calculated.
 464 Purple boxes show the two areas over which the SLP is averaged to estimate the cross-Barents Sea gradient. (b)
 465 SIC PC mode 1 for SSMI (black) and ERA20C (blue) data (as for Figure 1) and Siberian Index (red, sign inverted
 466 for ease of comparison).



467 FIG. 5. **(a)** Cross-wavelet coherence between SIC PC1 and Siberian Index. Black contours show the 95%
 468 significance level. White hatching denotes results lying outside the cone of influence, where edge artefacts may
 469 contaminate the results. Arrows indicate the phase relationship between the two variables, where right/leftwards-
 470 pointing arrows indicate that the series are in phase / in anti-phase. **(b)** Mean SLP over 1983-2004 (thick lines,
 471 pale colours) and 2005-2010 (thin lines, dark colours); for clarity of comparison, only a limited number of
 472 isolines are shown.



473 FIG. 6. Cross-wavelet coherence between (a) the cross-Barents Sea SLP gradient and SIC PC1; the NAO
 474 index and (b) SIC PC1 and (c) SIC PC2; (d) SIC PC1 and SIC PC2. Black contours show the 95% significance
 475 level. White hatching denotes results lying outside the cone of influence, where edge artefacts may contaminate
 476 the results. Arrows indicate the phase relationship between the two variables as in Figure 5.