

# Climate Dynamics

## Influence of the Eurasian snow on the negative North Atlantic Oscillation in subseasonal forecasts of the cold winter 2009/10

--Manuscript Draft--

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<b>Abstract:</b>	<p>The winter 2009/10 was remarkably cold and snowy over North America and across Eurasia, from Europe to the Far East, coinciding with a pronounced negative phase of the North Atlantic Oscillation (NAO). While previous studies have investigated the origin and persistence of this anomalously negative NAO phase, we have re-assessed the role that the Eurasian snowpack could have played in contributing to its maintenance. Many observational and model studies have indicated that the autumn Eurasian snow cover influences circulation patterns over high northern latitudes. To investigate that role, we have performed a suite of forecasts with the coupled ocean-atmosphere ensemble prediction system from the European Centre for Medium-Range Weather Forecasts. Pairs of two-month ensemble forecasts with either realistic or else scrambled snow initial conditions are used to demonstrate how an anomalously thick snowpack leads to an initial cooling over the continental land masses of Eurasia and, within two weeks, to the anomalies that are characteristic of a negative NAO. It is also associated with enhanced vertical wave propagation into the stratosphere and deceleration of the polar night jet. The latter then exerts a downward influence into the troposphere maximizing in the North Atlantic region, which establishes itself within two weeks. We compare the forecasted NAO index in our simulations with those from several operational forecasts of the winter 2009/10 made at the ECWMF, and highlight the importance of relatively high horizontal resolution.</p>	

We are grateful to the two reviewers for their insightful comments and suggestions, which led to our inclusion of three new figures (two in Supplementary Material).

### Response to Reviewer #1

The model experiments are initialized on December 1, 2009, however there was a sudden stratospheric warming (SSW) already in November 2009 that I feel was important for the large negative NAO values observed in December 2009. The stratospheric warming in November is discussed later in the manuscript and even shown in Figure 5. But in order to see the impact of snow cover variability on the stratosphere there are advantages to a November 1 model initialization. Admittedly there is a downside in that models do not simulate well the downward propagation or control from the stratosphere to the troposphere (Furtado et al. 2015) so a model initialization on November 1 may not simulate very well the strongly negative NAO December 2009. This is merely a suggestion but maybe the inclusion of some model runs initialized November 1 with a possible nudging of snow cover anomalies throughout the run or even just on December 1 to observations may prove beneficial and provide further insights.

We had made similar two-month simulations for several start dates (OCT15, NOV1, NOV 15, DEC 1). The skill improvement due to snow initialisation using this grand ensemble of simulations over 2004-2009 was the focus of our ClimDyn 2013 paper. To demonstrate the robustness of our results concerning the present case study with regard to the start date, we have now included a brief discussion of the NOV 15 start date in the manuscript Discussion section, with the two figures in supplementary material.

In this case study of the 2009/10 winter, we rely solely on making snow composite differences. For the DEC 1 start date, the snow perturbation is one-sided (by design). For start dates in November, the perturbed snow in Series2 can be higher or lower than in Series1, hence we had to do a conditional compositing: e.g. retaining the ensemble members in Series2 for which the initial snow is lower than Series1, in order to make a “high – low” snow composite, hence using a reduced ensemble size.

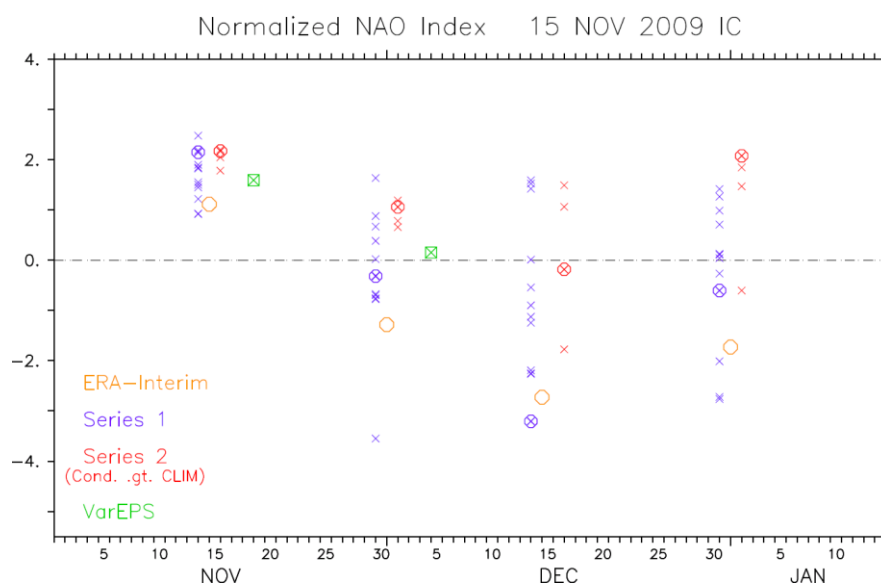


Figure Suppl1: Normalized NAO index based on SLP anomaly differences. Indices are shown for Series 1 (blue crosses and circled cross for ensemble-mean), Series 2 (same in red), ERA-Interim (orange circles), and VAREPS (green squares). (as in new Figure 5)

In the above figure (now Figure Supplement 1), the NAO index for Series1 is closer to re-analyses than the index for Series2, which becomes rapidly neutral. Hence, the results are similar to those for the DEC 1 start date. In Figure Suppl2, composite differences between S1 – S2 at the 30-lead indeed show a displaced jet stream and SLP anomalies characteristics of a negative NAO.

For the NOV 1 start date, the observed NAO is increasing slightly, so this case is not an appropriate period to show the negative NAO/snow feedback. For the earliest start date (OCT 15), the snow depths are small and well below climatology (Fig 1).

Effects of the stratospheric warming in November would be partly accounted in the realistic initial conditions, and they may well influence the NAO variability during the autumn, as we pointed out. Our simulations use realistic snow initialisation but were not designed as nudging experiments.

Another comment is the immediacy of the model stratospheric response to snow cover variability is different than what has been show in the observations. The response in poleward heat flux and the resultant changes in the stratospheric circulation can be between six weeks to two months after the greatest variability in snow cover (e.g. Cohen et al. 2014). In the results shown here the heat flux and stratosphere respond within two weeks. The faster atmospheric response in the models to snow cover forcing has been shown previously (Fletcher et al. 2009) but maybe some discussion from the authors would benefit the manuscript.

We are grateful to the reviewer for pointing out this discussion in Fletcher's paper. We have incorporated his points in the discussion, which already reported such rapid strat-trop interaction by Shaw et al. (2014), and by Orsolini et al. (2011). This rapid response comes in addition to the slower response discussed in Cohen et al. (2014). Revisiting this issue, we are now able to demonstrate differences in the heat flux diagnostics between Series1 and Series2 at the 15-day lead time already. In Series2, there is a region of negative total heat flux at high latitudes, a fact that which point toward wave reflection and downward propagation as a mechanism prohibiting the snow/stratosphere interaction. We have expanded that discussion.

Minor comment:

1. Line 57 - and an "s" at the end of "model." Done

We are grateful to the two reviewers for their insightful comments and suggestions, which led to our inclusion of three new figures.

## Response to Reviewer #2

### Major comments:

>>The most important concern I have is in the experimental design. First, I fully understand the difficulties in performing ensemble hindcast experiments with such a high-resolution model but think additional experiments starting other month (say November or January) or for other year(s) of negative NAO are necessary to draw the general conclusion.

(This is the same response to a point raised by Reviewer #1).

We had made similar two-month simulations for several start dates (OCT15, NOV1, NOV 15, DEC 1). The skill improvement due to snow initialisation using this grand ensemble of simulations over 2004-2009 was the focus of our ClimDyn 2013 paper. To demonstrate some robustness of our results with regard to the start date, we have now included a brief discussion of the NOV 15 start date in the manuscript Discussion section, with the two figures in supplementary material.

In this case study of the 2009/10 winter, we rely solely on making snow composite differences. For the DEC 1 start date, the snow perturbation is one-sided (by design). For start dates in November, the perturbed snow in Series2 can be higher or lower than in Series1, hence we had to do a conditional compositing: e.g. retaining the ensemble members in Series2 for which the initial snow is lower than Series1, in order to make a “high – low” snow composite, hence the reduced ensemble size.

Fig\_letter1: Normalized NAO index based on SLP anomaly differences. Indices are shown for Series 1 (blue crosses and circled cross for ensemble-mean), Series 2 (same in red), ERAINT (green circles). Indices are for 15-day periods and plotted at the beginning of each period. (e.g. December 1 corresponds to December 1-15). Symbols for the different forecast set are shifted by a day along the time axis for clarity of the display.

In the above figure (now Figure Suppl1), the index for Series1 is closer to re-analyses than the index for Series2, which becomes rapidly neutral. Hence, the results are similar to the DEC 1 start date. In Figure Suppl2, composite differences between S1 – S2 at the 30-lead show similar results as the figure 4 (formerly figure 3), with a displaced jet stream and SLP anomalies characteristics of a negative NAO.

For the NOV 1 start date, the observed NAO is increasing slightly, so this case is not an appropriate period to show the negative NAO/snow feedback. For the earliest start date (OCT 15), the snow depths are small and well below climatology (Fig 1).

In addition, we reckon that having a few extra diagnostics for additional winters might be misleading, given the large inter-annual variability, and an extensive study of each winter separately would be warranted. This is beyond the aim and scope of this paper, which is a case study. In the revised version, we have highlighted this limitation in our conclusions.

The second point is the choice of snow-related variables in the Series 2. Why the snow-related variables (which variables exactly?) in Series 2 were chosen from 'earlier' autumn start dates (even 1-month

earlier)? As far as I understand, this is for simulating low (relative to S1) snow conditions. If this is true, then would it be better to choose low snow conditions at the same start dates from other years in the entire ERA-Interim reanalysis period? I think the spatial pattern and thickness of snow-pack in the 'earlier' starts are quite different from those in the other years of 'low' snow at the same start dates.

In principle, low snow conditions for S2 could have been achieved by choosing low snow Decembers in the ERAINT record. However, this approach was abandoned since there is a large change in inter-annual snow variability in ERAINT in 2003. This is due to the beginning of satellite snow cover assimilation in 2003, which ensured a higher inter-annual variability in the post-2003 period than in the preceding years, when it was extremely low. This was explained in our Clim Dyn 2013 paper. Hence, there are not enough low snow Decembers in the post-2003 period to build an 11-member ensemble.

In the future, we will use ERAINT-land as initial conditions, and a new comprehensive set of simulations will be done.

The ensemble mean difference in the snow-related variables between S1 and S2 should be presented. Also, in Figure 1, the spatial pattern of snow depth or snow cover anomalies should be included. The depth averaged for the whole Eurasian was close to normal, but the snowcover showed a large difference between eastern and western part of Eurasian continents in autumn 2009.

We now include as a new figure 2 a map of the S1 minus S2 difference in snow depth at the zero lead (showing the high snow conditions in S1), as well as the difference between S1 and climatology. We can see that -as pointed by the reviewer- while the mean Eurasian snow depth was close to climatology (Fig 1), there is actually less snow than climatology in the east and north of Siberia.

The large part of section 4 can be moved to discussion section since it doesn't give anything originally found in this study.

I believe the reviewer meant the first part of Section 4. These paragraphs however contains the background information on stratospheric variability, which is necessary to understand the rest of the section. The stratospheric connection is not mentioned earlier in the paper, and it would not be clear why the stratosphere is suddenly discussed at this point in the article. We prefer to keep it there.

Does S1 minus S2 of zonal-mean zonal wind show any similar signal like in Figure 5?

Figure 5 shows the observed polar night jet evolution and hence is the results of many confounding factors. I would not expect S1 minus S2 to resemble the observed winds.

Figure 6 needs to be modified. Zonal wind of ERA-interim, VarEPS, and Oper-sys3 are not so much useful to explain the weakening of the stratospheric jet, it's better to show a difference map.

We have followed that suggestion and we have now included a new figure (Figure 8), which not only shows the jet cross-sections for all runs, but also the relevant the differences over the 15-day period. The new figure 8 now clearly shows the jet weakening in the case of VAREPS, and a lack of weakening in the case of the low-resolution operational forecast S3.

In conclusions, authors argue that the relatively high horizontal resolution might be important for the

model to simulate the snow/stratosphere coupling accurately as the resolution-dependent biases might deteriorate the model forecasts. I think this is one of important findings from this study but needs to be supported more by objective evidences. At least, the resolution-dependent model biases or drifts need to be presented and explained.

We have now included a new figure 9 with the climatological eddy geopotential height at 500hPa in VAREPS, S1 and S3, during the first month of forecast (December). For Series1, the mean eddy is evaluated over 2004-2008, while for the other forecast models, the 1998-2010 period is used. One can see that, in the low resolution S3 model, the ridge extending across Siberia is not so elongated zonally, hence the Siberian High is weaker than in the high resolution models. This could explain why the interaction of the snow anomaly with the background climatological wave (e.g. through linear interference, see Smith K. et al., 2011) is not so pronounced.

68: missing reference for ERA-Interim re-analyses. Corrected.

81: check "a on the impact" Corrected.

92: What are the snow-related variables? Please specify. The four snow-related variables are now specified.

98-100: please check the sentence. Hard to understand. Rephrased.

In Figure 4, there is a distinct outlier, extremely negative NAO, in Series 2 (below -6). Any comment on this?

Yes, indeed the most negative NAO is found in the perturbed Series2, but this could be generated by internal variability. When addressing such prediction issues, it is hence important to consider ensemble means.

161: then-operational ?

The current operational model is called S4 and is an upgraded version of the operational model that was in force in 2010, i.e. then called S3.

185-187: any evidence or reference?

This is described in the following sentences, which summarize the cited findings of Ouzeau, Fereday and Jung.

193: independently of. Corrected.

244: Fig2 > Fig. 2 (and elsewhere in the manuscript, please check the use of Fig., Fig, and Figure) We consistently now use Fig. X, except at the beginning of a sentence.

1 **Influence of the Eurasian snow on the negative North Atlantic**  
2 **Oscillation in subseasonal forecasts of the cold winter**  
3 **2009/10**

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11

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13

14 **Abstract**

15 The winter 2009/10 was remarkably cold and snowy over North America and across Eurasia,  
16 from Europe to the Far East, coinciding with a pronounced negative phase of the North Atlantic  
17 Oscillation (NAO). While previous studies have investigated the origin and persistence of this  
18 anomalously negative NAO phase, we have re-assessed the role that the Eurasian snowpack  
19 could have played in contributing to its maintenance. Many observational and model studies  
20 have indicated that the autumn Eurasian snow cover influences circulation patterns over high  
21 northern latitudes.

22 To investigate that role, we have performed a suite of forecasts with the coupled ocean-  
23 atmosphere ensemble prediction system from the European Centre for Medium-Range  
24 Weather Forecasts. Pairs of two-month ensemble forecasts with either realistic or else  
25 scrambled snow initial conditions are used to demonstrate how an anomalously thick snowpack  
26 leads to an initial cooling over the continental land masses of Eurasia and, within two weeks, to  
27 the anomalies that are characteristic of a negative NAO. It is also associated with enhanced  
28 vertical wave propagation into the stratosphere and deceleration of the polar night jet. The  
29 latter then exerts a downward influence into the troposphere maximizing in the North Atlantic  
30 region, which establishes itself within two weeks. We compare the forecasted NAO index in our

31 simulations with those from several operational forecasts of the winter 2009/10 made at the  
32 ECWMF, and highlight the importance of relatively high horizontal resolution.

### 33 **1. Introduction**

34 The winter 2009/10 was remarkably cold and snowy over North America and across Eurasia,  
35 from Europe to the Far East, bringing record snow storms and bitter cold air outbreaks (Wang  
36 and Chen, 2010; Cohen et al., 2010; Hori et al., 2011). These cold conditions over North America  
37 and Europe coincided with one of the most extreme negative phases of the North Atlantic  
38 Oscillation (NAO) in the observational record (e.g. Fereday et al., 2012). The North Atlantic jet  
39 stream also had an extremely pronounced southward displacement through most of the  
40 December-to-February period (Santos et al., 2013).

41 Several studies investigated the external factors that, in addition to internal atmospheric  
42 variability, could have potentially contributed to the negative NAO phase: sea surface  
43 temperature (SST) over the Atlantic or over the equatorial Pacific, late-summer Arctic sea ice  
44 extent, land-atmosphere coupling involving the Eurasian snow cover, stratospheric polar vortex  
45 variability and low solar short-wave radiative forcing (Cohen et al., 2010; Fereday et al., 2012;  
46 Jung et al., 2011). Jung et al. (2011) noted that, in the operational forecasts with the European  
47 Centre for Medium-Range Weather Forecasts (ECMWF) coupled ocean-atmosphere ensemble  
48 prediction system started at the beginning of December or January, the NAO index rapidly  
49 relaxed to near-neutral values following the initial negative anomaly. Through a series of  
50 dedicated experiments with the ECMWF monthly coupled forecasting system, they eliminated  
51 successively each of the above-mentioned factors as capable of producing the magnitude of the  
52 observed NAO anomaly. Their conclusion was that natural atmospheric variability was  
53 responsible for the onset and persistence of the negative NAO phase. Intriguingly, in that paper,  
54 other coupled forecasts with the ECMWF Variable Resolution Ensemble Prediction System  
55 (VAREPS) showed remarkable persistence of the initial NAO index in the late winter period.

56 The snow-covered land plays a key role in the climate system, and observational as well as  
57 studies using atmosphere-only or coupled ocean-atmosphere models have shown that the  
58 Eurasian snowpack in autumn influences the horizontal and upward propagation of planetary  
59 waves (PWs) and modulate the Arctic Oscillation (Allen et al., 2011; Cohen et al., 2010; Orsolini  
60 and Kvamstø, 2009; Smith et al., 2011; Henderson, 2013; Fletcher et al., 2009; Peings et al.,  
61 2012). Since the land-sea thermal contrast is a strong driver of PWs, it is not surprising that the  
62 presence of a continent-wide surface cooling due to an anomalously thick snowpack may  
63 modulate their amplitudes. Furthermore, recent studies demonstrate that initialization of the  
64 snowpack has an impact on subseasonal forecasts (Jeong et al., 2013; Orsolini et al., 2013).

65 In December 2009, the Eurasian snow cover extent was the second largest on record (Cohen et  
66 al., 2010). The observed snow depths anomalies at the beginning of autumn 2009 were not  
67 exceedingly large however. Figure 1 shows that the snow depth averaged over Eurasia (40°E-  
68 140°E; 40°N-75°N) derived from ERA-Interim re-analyses (hereafter, ERAINT, [Dee et al., 2011](#))  
69 was below its climatological value in October 2009. However, it increased very rapidly  
70 throughout November and December, and it exceeded the long-term climatological value by  
71 the end of that period. Interestingly, an autumn snow cover advance index has been recently  
72 used in empirical statistical prediction model of the NAO predictor (Cohen et al., 2011; Brands  
73 et al., 2012).

74 In this study, we have revisited the possible influence of the Eurasian snowpack on the  
75 negative NAO in early winter 2009/10 in coupled forecasts. Our strategy has been to follow the  
76 approach developed in the GLACE2 (Global Land Atmosphere Coupling Experiments, e.g. Koster  
77 et al., 2011) model inter-comparison study. To this end, we carry out twin ensemble forecasts  
78 using either realistic or randomized snow initial condition, so that forecast differences can be  
79 attributed to the snow initialization.

## 80 2. Model simulations

81 The forecasts were made with the coupled ocean-atmosphere forecast model of the ECMWF.  
82 While GLACE2 was devoted to ~~a-on~~ the impact of soil moisture on subseasonal forecasts in the  
83 warm season, we have transposed their methodology to investigate the impact of snow in the  
84 cold season. Further details about these runs -which we will refer to as the SNOWGLACE runs-  
85 are provided in Orsolini et al. (2013).

86 We performed two 11-member ensemble retrospective two-month forecasts starting on  
87 December 1, 2009. These are part of a larger set of winter forecasts covering the period 2004-  
88 2009, described in further detail in Orsolini et al. (2013). This larger set will be used for  
89 normalization and calibration. The experiments are true forecasts, with no use of future  
90 information. Both series have realistic initial atmospheric and oceanic states, derived from  
91 ERAINT and from oceanic analyses, respectively. The initial land states for both ensembles are  
92 derived from ERAINT, but differ wherever snow is present on land (in either hemisphere). In the  
93 first ensemble, hereafter Series1, the snow-related prognostic variables (snow density, albedo,  
94 temperature, and snow water equivalent) variables are realistically initialized from ERAINT and  
95 are identical for all members. In the second set however, hereafter Series2, the snow-related  
96 variables are scrambled randomized separately for each member, taken ~~at random~~  
97 autumn start dates and other years. ~~Each ensemble member in Series2 has different~~  
98 randomised snow initial conditions, and it also has. Since snow initial conditions in Series2 are  
99 taken smaller snow depths than Series1 since taken from earlier in the season start dates,  
100 Series2 has smaller snow depths than Series1. The difference between the Series1 and Series2

101 ensemble means can hence be interpreted as a composite difference (high minus low snow).  
102 The scrambling of initial dates across the autumn when the snow seasonal cycle induces rapid  
103 variations in snow depth implies that the snow perturbations in Series2 can be large. Fig.1 also  
104 shows the evolution of the ensemble-mean Eurasian snow depth for both Series1 and Series2,  
105 and it can be seen that at the forecast start, Series2 has a lower depth roughly corresponding to  
106 a one-month lag in the seasonal cycle (e.g. November instead of December).

107 We used the cycle 36R1 atmospheric model, which has 62 levels with an upper boundary near 5  
108 hPa and a relatively high spatial resolution (T255). This model cycle is close to the one used to  
109 produce ERAINT re-analyses, which will be used to validate the forecasts. It also has a new one-  
110 layer snow scheme that has been shown to reduce a warm forecast bias in surface temperature  
111 during winter over snow covered areas, due to increased snow depth and a better insulating  
112 snowpack (Dutra et al., 2010; 2012). Several diagnostics were averaged in 15-day sub-periods,  
113 four per forecast, corresponding to lead time of 0 (days 1-15), 15 (days 16-30), 30 (days 31-45)  
114 and 45 (days 46-60) days, respectively. The outputs are re-gridded to a 1 degree by 1 degree  
115 grid.

### 116 3. Forecasts of the NAO

117 [Figure 2 shows a map of the Series1 minus Series2 difference in snow depth at the zero lead,](#)  
118 [hence revealing the high snow conditions in Series1, as well as the difference between Series1](#)  
119 [and climatology. While the mean Eurasian snow depth was close to climatology \(Fig. 1\), there is](#)  
120 [actually less snow than climatology in the east and north of Siberia.](#) Figure 2-3 shows the  
121 difference between the two simulations (Series1 minus Series2) in 15 day-averaged surface  
122 temperature for the 0- and 15-day lead times, with statistically significant values at the 95%  
123 level highlighted (green contour). Starting at the 0-day lead, cold anomalies in surface  
124 temperature are seen over snow-covered land at mid and high latitudes over Eurasia and North  
125 America, mostly statistically significant over Eurasia. Hence the presence of a thicker snowpack  
126 in Series1 readily leads to an anomalous surface cooling (Dutra et al., 2010; Peings et al, 2012;  
127 Orsolini et al., 2013). At the 15-day lead time, the differences in Series1 minus Series2 in surface  
128 temperature ([Figure-Fig. 23](#)), sea level pressure (SLP), [and 200-hPa wind speed and SST \(Figure](#)  
129 [Fig. 34\)](#) display the characteristics of negative NAO anomalies across the Atlantic: i.e. a  
130 quadrupole in surface temperature, a north/south dipole in SLP, a jet stream displaced  
131 southwards and a tripole of SSTs. The surface temperature differences are not limited to the  
132 quadrupolar pattern (cold over Central Europe and warm over Northeast America-Greenland,  
133 with opposite anomalies to further south), and cold anomalies are present over China and the  
134 Far East.

135 These differences are also reflected in the normalized NAO index ([Figure-Fig. 45](#)). Following Li  
136 and Wang (2003), we use an index based on normalized SLP anomaly differences between 65°N

137 and 35°N averaged over the 80°W-30°E longitudinal band. The daily SLP anomaly is calculated  
138 as a deviation from the climatology of our ensemble of forecasts (66 forecasts, corresponding  
139 to six 11-member started December 1 over the years 2004-2009). The daily SLP anomaly is then  
140 normalized by its standard deviation over the two-month period (1 December 2009 to 31 Jan  
141 2010). For ERAINT, the SLP anomaly is based on the 2004-2009 daily climatology and the  
142 normalization is carried out in a similar fashion as the model forecasts. At the 0-day lead, the  
143 15-day averaged ensemble-mean indices for Series1 and Series2 are nearly identical, having the  
144 same initial atmospheric conditions. However, Series2 relaxes quickly to near-neutral NAO  
145 conditions, while the initial negative NAO index is maintained throughout the two months in  
146 Series1. Hence, in presence of a thick snowpack, the forecasted NAO index in Series1 remains  
147 negative and is closer to the observations than Series2. While the accentuation of the negative  
148 NAO index in December and the swing to a more weakly negative index in January are not  
149 captured in either forecast, it appears that the snowpack contributes to the persistence of the  
150 initially negative NAO. Other forcings or internal variability may govern the evolution of the  
151 observed NAO, but our argument is that the thick snowpack contributes to the negative phase  
152 maintenance.

153 This is further supported by additional analysis of the operational monthly forecasts carried out  
154 in December 2009 with the ECMWF Variable Resolution Ensemble Prediction System (VAREPS;  
155 Vitart et al., 2008). These runs are very similar to our SNOWGLACE runs in that they use the  
156 same model cycle and land surface module, but they are launched weekly and are of shorter  
157 duration (32 days) with a large ensemble size (51 members). The only differences are that (i)  
158 the snow is initialized using operational analyses rather than ERAINT in the VAREPS forecasts,  
159 (ii) the latter have a higher horizontal resolution (T399) during the first 10 days while having the  
160 same T255 resolution than our SNOWGLACE runs thereafter, and (iii) the ocean coupling is  
161 introduced at day 10. The normalization of the NAO index for the VAREPS ensemble-mean  
162 forecasts is based on the daily SLP using VAREPS reforecasts started in early December over the  
163 same 2004-2009 period. For the VAREPS forecasts from December 3 (the closest day available  
164 to December 1 start date of our SNOWGLACE simulations), the 15-day averaged ensemble-  
165 mean NAO index remains close to its initial value, just as the Series1 simulations ([Figure-Fig. 4](#),  
166 green squares).

167 To further support the notion that a relatively high horizontal resolution and realistic snow  
168 initialization is important for the maintenance of the NAO initial negative conditions, we also  
169 analysed the then-operational seasonal forecasts (System 3; Stockdale et al., 2011) which were  
170 referred to in Jung et al. (2011; their [Fig\\_1](#)). These forecasts are initialised with realistic,  
171 operational initial snow conditions and consist of 41 members; they were also normalized  
172 relative to the same 2004-2009 period. It can be seen on [Figure-Fig. 4-5](#) that the initially

173 negative values of the NAO index (Figure-Fig. 45, pink squares) do not persist in these lower  
174 resolution (T159) simulations.

175 We next demonstrate that the complete feedback involves the stratosphere. We will come back  
176 to the role of the horizontal resolution in the Discussion section.

#### 177 **4. Role of the stratosphere in the snow/NAO coupling.**

178 Fluctuations in the strength of the wintertime polar stratospheric vortex contributes to the NAO  
179 variability, both in observations and models (e.g. Baldwin and Dunkerton, 2001; Orsolini et al.,  
180 2011; Shaw et al., 2014). During the 2009/10 winter, the stratospheric zonal-mean zonal flow at  
181 60°N (Figure-Fig. 56) was anomalously weak in the second half of November and in early  
182 December, before a brief period of intensification in early January and a major stratospheric  
183 warming in late January (Wang and Chen, 2010; Cohen et al., 2010; Ayarzagüena et al., 2011;  
184 Dornbrack et al., 2012). The occurrence of the early December stratospheric vortex weakening  
185 is followed by a period (approx. from December 5 to 25) of weaker zonal-mean flow in the mid  
186 and lower troposphere (e.g. 500 hPa and below, Figure-Fig. 56). That period is characterized by  
187 a southwardly displaced jet over the Atlantic and marks the onset of the large negative NAO  
188 (Wang and Chen, 2010; Santos et al., 2013). The downward propagation of the stratospheric jet  
189 intensification from 1 hPa in early January to tropopause level by mid-January is quite clear  
190 (Figure-Fig. 56), and there is eastward zonal wind acceleration in the troposphere later during  
191 the month (approx. January 20-29). This is also a period when the Atlantic jet stream briefly  
192 returns to more northern latitudes (Santos et al., 2013). Hence, the evolution of the NAO  
193 through the winter is qualitatively consistent with a stratospheric influence. However, hindcasts  
194 with nudged stratospheric variables offer contradictory results concerning the causal role of the  
195 stratosphere on the NAO variability in winter 2009/10. On the one hand, the winter-mean  
196 500hPa NAO pattern was better reproduced when the stratosphere was nudged as in Ouzeau  
197 et al. (2011) using the Meteo-France Arpege model. Also, the high-top model in Fereday et al.  
198 (2012) which better resolves the stratosphere and better predicts stratospheric sudden  
199 warmings showed improved NAO forecasts. On the other hand, Jung et al. (2011) found that  
200 nudging the ECMWF forecast model in the stratosphere did not improve NAO forecasts.

201 ~~Nevertheless, independently of whether~~ internal variability or stratospheric influence  
202 are governing the NAO fluctuations, our twin simulations show that the stratospheric  
203 circulation is readily affected by the presence of the cold surface anomalies induced by the  
204 anomalously thick snowpack. Figure 6-7 shows the quasi-stationary zonal-mean meridional  
205 eddy heat fluxes for ~~Series1, Series2~~ the and their difference (~~Series1 minus Series2~~), averaged  
206 over December 16-30. The increased fluxes at the 15-day lead time in Series1 implies enhanced  
207 vertical propagation of quasi-stationary PWs. We further note that, in the polar stratosphere,  
208 weakly negative heat fluxes are found in Series 2, implying downward wave propagation.

209 Figure 6-8 also shows the 15-day averaged zonal-mean zonal wind for ERAINT as well as for  
210 Series1, Series2, and their difference. Consistent with the eddy heat flux enhancement, the  
211 vortex is weaker in Series1 than in Series2. Started from initial ERAINT zonal winds (also on  
212 Figure 6), the stratospheric vortex in Series1 is also weaker than ERAINT at the 15-day lead  
213 time. Figure 6-8 also shows the corresponding zonal winds for the VAREPS and for the  
214 operational (S3) forecasts, along with. The latter two forecasts were actually started from  
215 operational analyses, but the difference in from their initial wind conditions between the latter  
216 and ERAINT are negligible. Figure 6-8 reveals that a weakening of the stratospheric jet has  
217 occurred in VAREPS but not only very weakly so in S3, consistent with the snow-NAO coupling  
218 via the stratosphere acting similarly in the high-resolution forecasts VAREPS as in Series1.

219 From the comparative analysis of our twin forecasts, we can deduce that the weaker vortex in  
220 Series1 readily exerts an influence at the surface, modulating the NAO: the response  
221 maximizing over the North Atlantic appears once the stratospheric jet is being decelerated by at  
222 the 15-day lead time (see Figure Fig. 34). This is consistent with model studies of stratospheric  
223 downward influence on the surface circulation having both a fast (order of a week) component  
224 in addition to the slowly-propagating downward influence emphasized in Baldwin and  
225 Dunkerton (2001) or Cohen et al. (2014). For example, composites of weak vortex events in the  
226 Meteo-France ARPEGE model in Orsolini et al. (2011) showed a tropospheric response limited  
227 to the North Atlantic during their onset and growth stages, as the stratospheric vortex starts to  
228 weaken (one month to two weeks prior to the warming peak). Similarly rapid tropospheric and  
229 surface responses to stratospheric fluctuations were found in composites of stratospheric heat  
230 flux events in Shaw et al. (2014). Fletcher et al. (2009) studied the response to snow forcing in  
231 simulations with an atmospheric general circulation model, and also found an initial response in  
232 the first 2 weeks, which depended on the initial stratospheric state.

## 233 **5. Conclusions Discussion and Summary**

234 The presence of an anomalously high snow depth over Eurasia induces an anomalous surface  
235 and lower atmospheric cooling (Dutra et al., 2010; Orsolini et al., 2013). The cold hemispheric-  
236 wide temperature anomaly induces enhanced vertical wave planetary propagation into the  
237 stratosphere, contributing to decelerate the polar stratospheric jet. The rapid tropospheric  
238 response to the decelerating stratospheric jet maximizes over the North Atlantic sector, and  
239 readily appears on a 15-day time scale.

240 To demonstrate some robustness of our results with regard to the start date, we briefly discuss  
241 forecasts initiated on the November 15. For start dates in November, the perturbed snow in  
242 Series2 can be higher or lower than in Series1, hence a conditional compositing is used,  
243 whereby one retains only the ensemble members in Series2 for which the initial snow is lower  
244 than Series1, in order to make a “high – low” snow composite. In the supplemental Fig. S1, the

245 index for Series1 is seen again to be closer to re-analyses than the index for Series2, which  
246 becomes rapidly neutral. Hence, the results are similar to the December 1 start date. In the  
247 supplemental Fig. S2, composite differences between S1 – S2 at the 30-lead show similar results  
248 as the figure 4, with a displaced jet stream and SLP anomalies characteristics of a negative  
249 NAO.

250 Differences in snow depths used for initialization between operational analyses (as used in  
251 VAREPS or S3) or ERAINT (as used in SNOWGLACE2) are not very large (see Figure-Fig. 1). It  
252 hence appears that sufficiently high horizontal resolution like the one used in our  
253 SNOWGLACE2 or the VAREPS forecasts (> T255) is necessary to capture the snow/NAO coupling  
254 that maintains the negative NAO. The simulations in Jung et al. (2011), based on the same  
255 atmospheric model version as our SNOWGLACE2 runs (cycle 36r1), were at a lower horizontal  
256 resolution (T159). Climate model simulations investigating the snow/stratosphere coupling tend  
257 to be at a lower resolution too (e.g. Orsolini and Kvamstø, 2009; Hardiman et al., 2008; Furtado  
258 et al., 2015). We surmise that the relatively high horizontal resolution is an important factor  
259 because ~~of~~ resolution-dependent model biases ~~or drifts that~~ can appear very fast. This is  
260 supported by, as demonstrated by the departure of the forecasted stratospheric jet from  
261 ERAINT already at the 15-day lead time (Figure6)-Fig. 9 which shows the climatological eddy  
262 geopotential height at 500hPa in S1, VAREPS and S3, during the first month of forecast  
263 (December). For Series1, the mean eddy is evaluated over 2004-2008 (2009 is being excluded),  
264 while for the other forecast models, the 1998-2010 period is used. One can see that, in the low  
265 resolution S3 model, the ridge extending across Siberia is not so elongated zonally, hence the  
266 Siberian High is weaker than in the high resolution models. This could explain why the  
267 interaction of the snow anomaly with the background climatological wave (e.g. through linear  
268 interference, see Smith K. et al., 2011) is not so pronounced. We also noted that the  
269 operational model S3 has a stronger positive bias in the lower stratospheric zonal jet strength  
270 than the other models.

271 This rapid snow/NAO coupling displayed in our simulations ought to be also captured in an  
272 atmosphere-only model, as up to the monthly timescale, the SSTs are responding to the  
273 atmospheric forcing (Figure-Fig. 2). Nevertheless, coupled ocean-atmosphere simulations are  
274 needed to resolve the surface/stratosphere coupling on the longer monthly to seasonal time  
275 scale (e.g. Henderson, 2012).

276 The robustness of the results presented here as a case study of the winter 2009/10 needs to be  
277 further assessed over a longer period. In the future, we plan to perform a ~~more~~  
278 ~~extended~~ decadal set of SNOWGLACE simulations covering more recent cold winters as well as  
279 to extend the comparison to other models, a multi-model comparison, to further investigate  
280 the robustness of our conclusions.

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285 [grant 308378](#)).

286 **Compliance with ethical standards**

287 The authors declare that they have no conflict of interest.

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289 CAPTIONS

290 **Fig. 1** Snow depth averaged over Eurasia (40°E-140°E; 40°N-75°N) from August 2009 to July  
291 2010 in ERAINT (orange curve) along with the climatology over 2004-2009 (black curve) and a  
292 one-standard-deviation spread (grey shading). Also shown are snow depths averaged over  
293 Eurasia for the Series 1 (blue curve) and Series 2 (blue curve) forecasts started December 1st,  
294 for the VAREPS forecast started December 3rd (green curve) and operational S3 forecasts  
295 started December 1st (pink curve). Units are cm of water equivalent. Ensemble-mean forecasts  
296 are used.

297 **Fig. 2** Map of snow depth difference between Series1 and Series2 at the 0-day lead (a),  
298 showing the high snow conditions in Series1, as well as the difference between Series1 and the  
299 ERAINT climatology for the corresponding period (b).

300 **Fig. 3-4** Same as Figure 2 for sea level pressure (SLP), 200-hPa wind speed and SSTs but at the  
301 15-day lead time. Units are hPa, m/s and °C, respectively.

302 **Fig. 4-5** Normalized NAO index based on SLP anomaly differences between 65°N and 35°N  
303 averaged over the 80°W-30°E longitudinal band. Indices are shown for Series 1 (blue crosses  
304 and circled cross for ensemble-mean), Series 2 (same in red), ERAINT (orange circles), and for  
305 the ensemble-mean VAREPS forecasts (green squares) and for the ensemble-mean operational  
306 (S3) forecasts (pink squares). Indices are for 15-day periods and plotted at the beginning of  
307 each period. (e.g. December 1 corresponds to December 1-15). Symbols for the different  
308 forecast set are shifted by a day along the time axis for clarity of the display.

309 **Fig. 5-6** Height/time cross-section of zonal-mean zonal wind anomaly at 60°N from ERAINT in  
310 winter 2009/10. Anomaly is calculated from the period 2004-2009. Units are m/s.

311 **Fig. 6-7** Height/latitude cross-section of ~~(a)~~ 15-day averaged zonal-mean meridional eddy heat  
312 flux in (a) Series1, (b) Series2 and (c) their difference (Series1 minus Series2) at the 15-day lead  
313 time, difference (Series1 minus Series2). Units are m°K/s.

314 **Fig. 8** ~~Also shown are Height/latitude cross-section of~~ 15-day averaged zonal-mean zonal winds  
315 in ~~(ba)~~ Series1, ~~(eb)~~ Series2, and ~~(dc)~~ their difference (Series1 minus Series2), as well as for (ed)  
316 ERAINT, (f) VAREPS and (ge) Operational forecast S3, and the difference from their initial  
317 conditions in the latter two cases (f,g). All forecast cross-sections are at the 15-day lead time.  
318 Units are ~~m°K/s for heat flux and~~ m/s ~~for zonal winds.~~

319 **Fig. 9** Map of climatological geopotential eddy at 500hPa, in December, for (a) Series1, (b)  
320 VAREPS, (c) Operational S3. Climatology is calculated over the 2004-2008 period (a) or the  
321 1991-2008 period (b and c).

322 **Supplement Fig. S1** As in Fig. 5, but for the November 15 start date. Indices are shown for  
323 Series 1 (blue crosses and circled cross for ensemble-mean), Series 2 (same in red), ERAINT  
324 (orange circles), and for the ensemble-mean VAREPS forecasts (green squares).

325 **Supplement Fig. S2** As in Fig. 4, but for the November 15 start date, and sea level pressure  
326 (SLP), 200-hPa wind speed at the 30-day lead time. Units are hPa and m/s, respectively.

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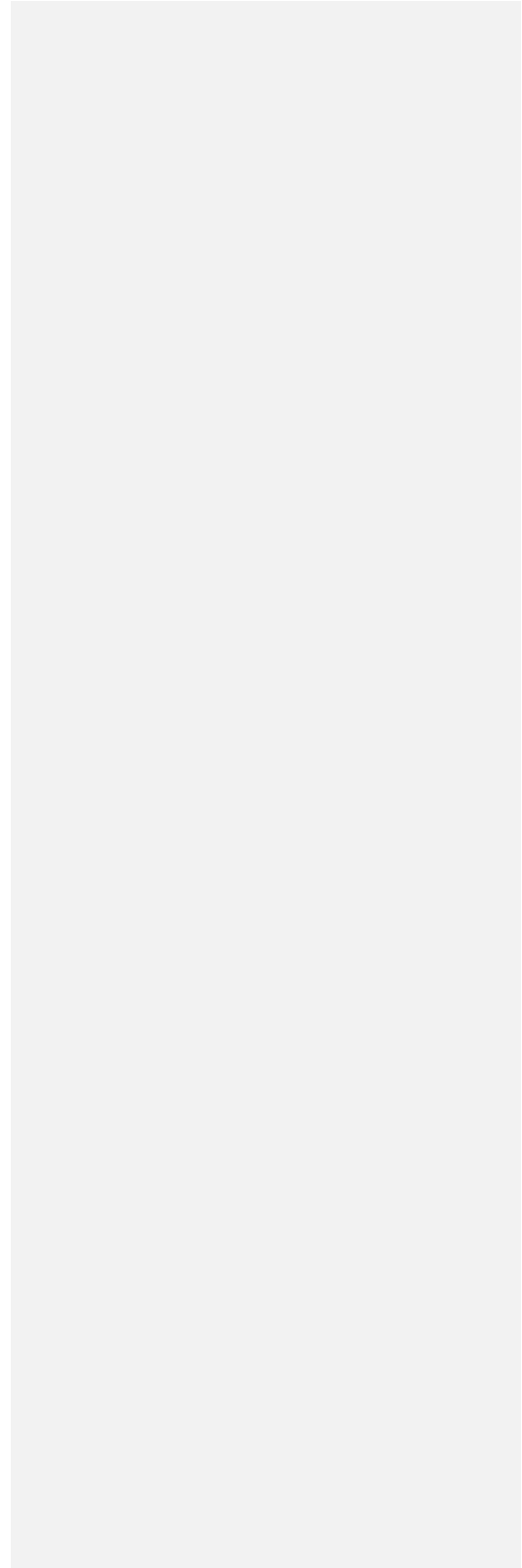


Figure1

Snow depth (cm of water eq.)  
Eurasia 40°E–140°E 40°N–75°N

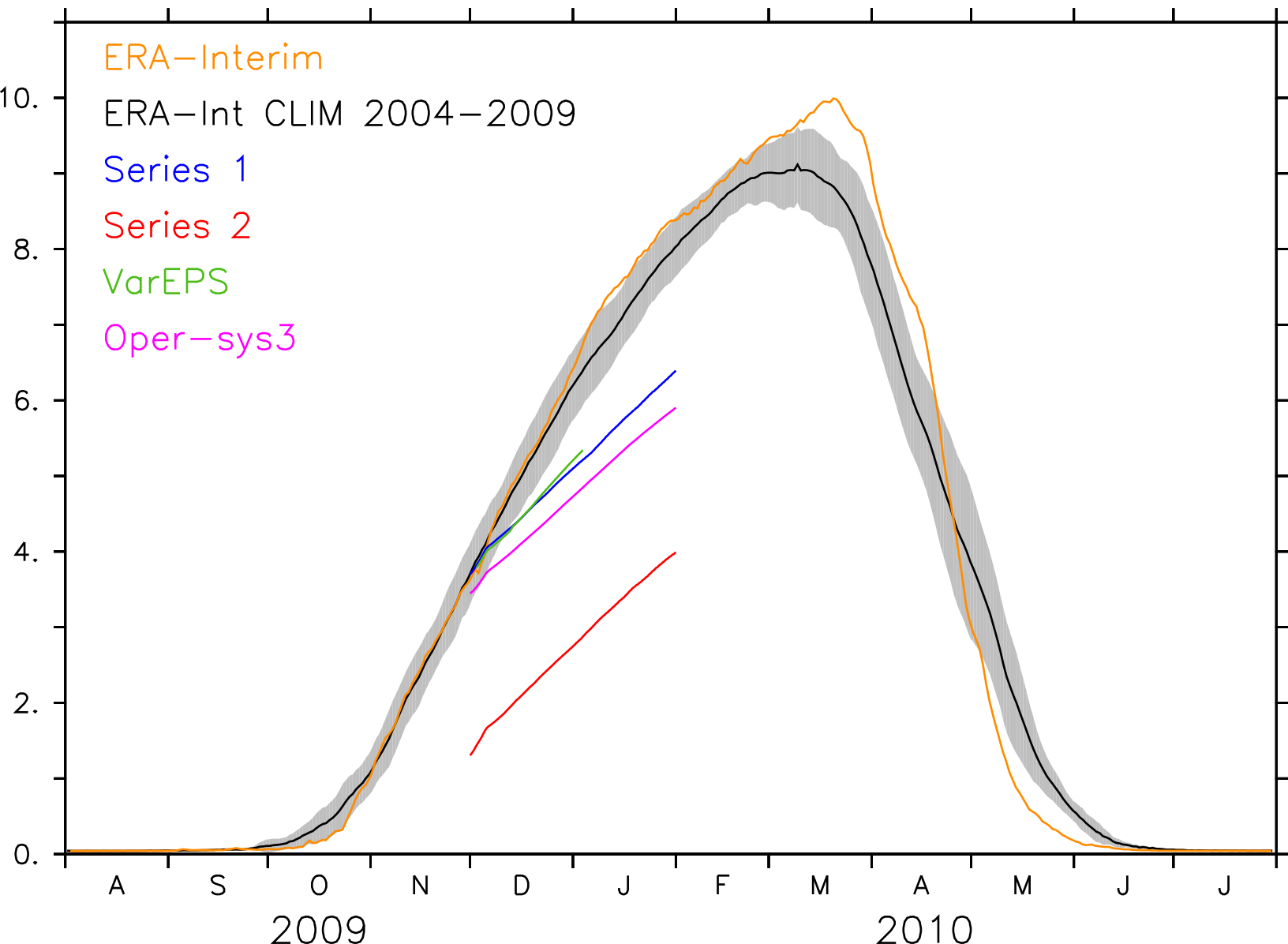
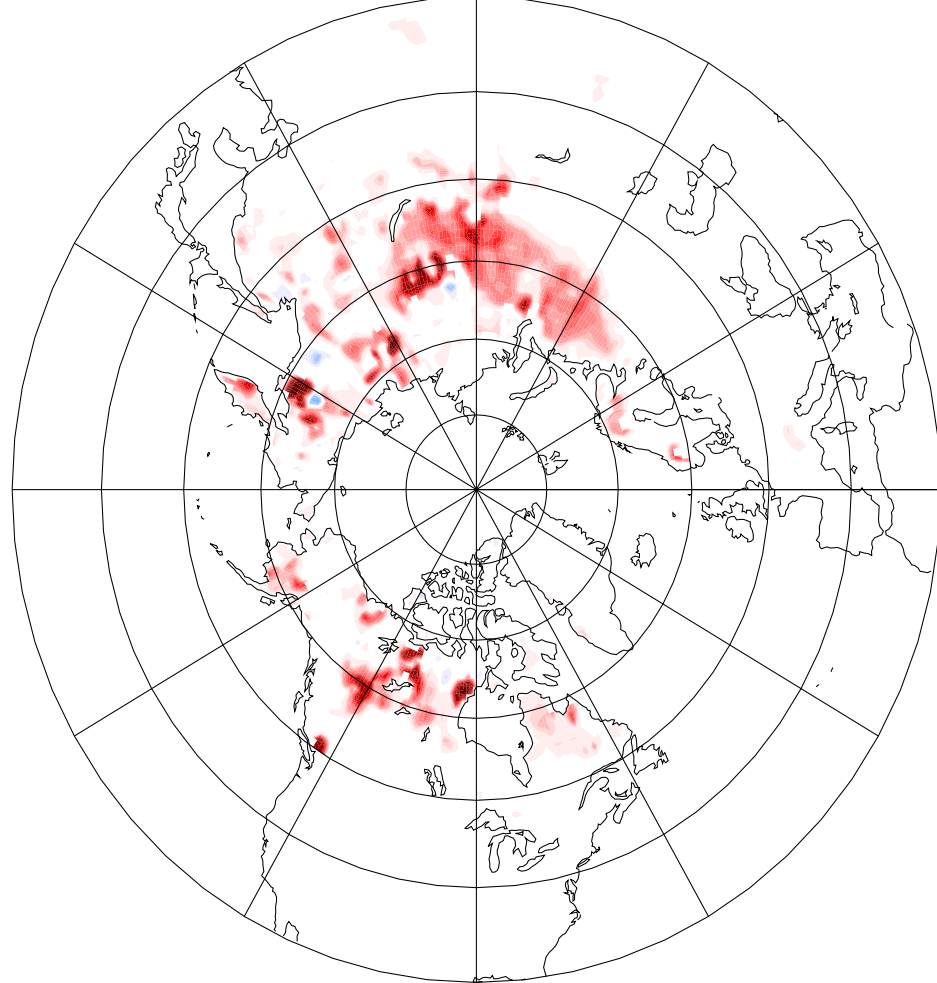


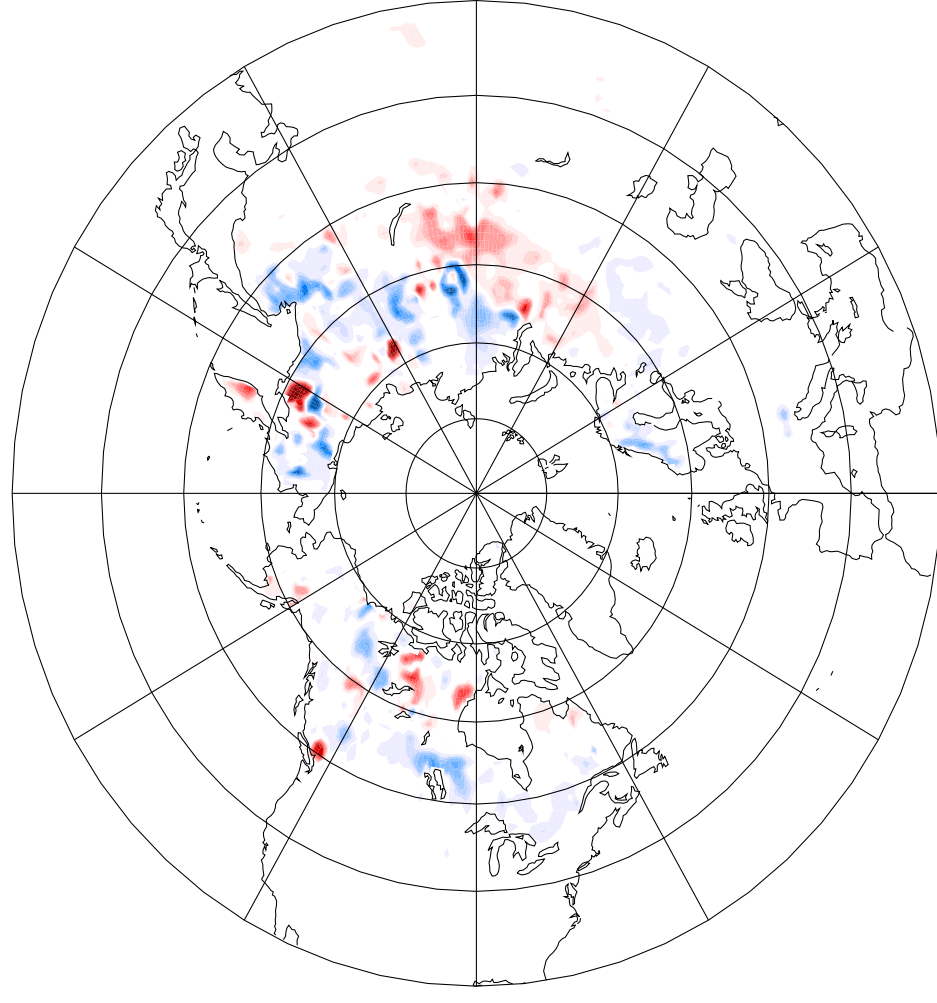
Figure2

Snow Depth (cm) Lead 0 (1-15 day) 01-DEC-2009 IC 95%

a. Series 1 minus Series 2



b. Series 1 minus Climatology



-40 -30 -20 -16 -14 -10 -6 -4 0 4 6 10 14 16 20 24 28 30 40

Figure3

2m Air Temperature Series1 minus Series2 95%

a. Lead 0 (1-15day)

b. Lead 15 (16-30day)

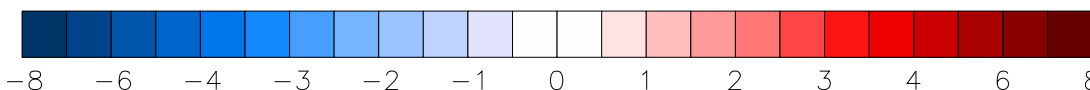
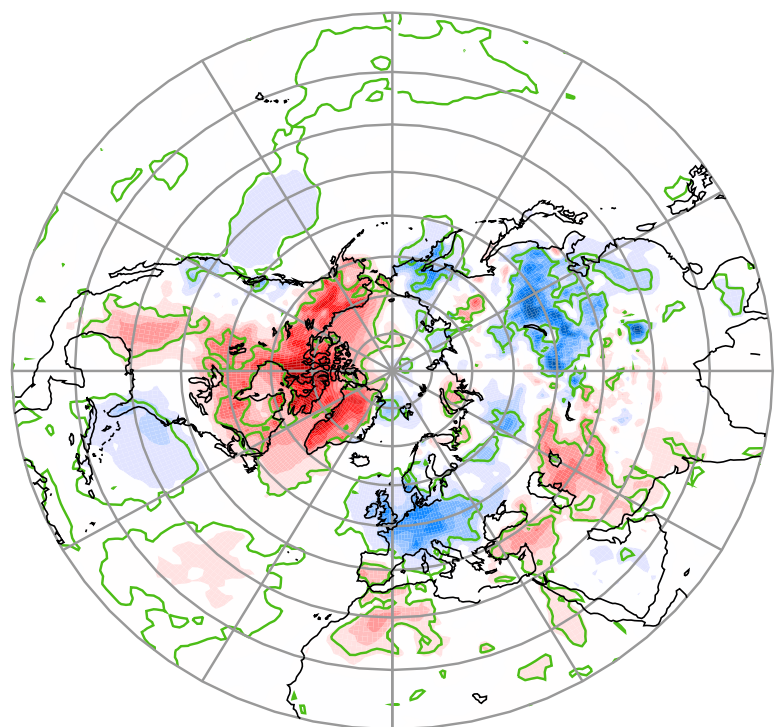
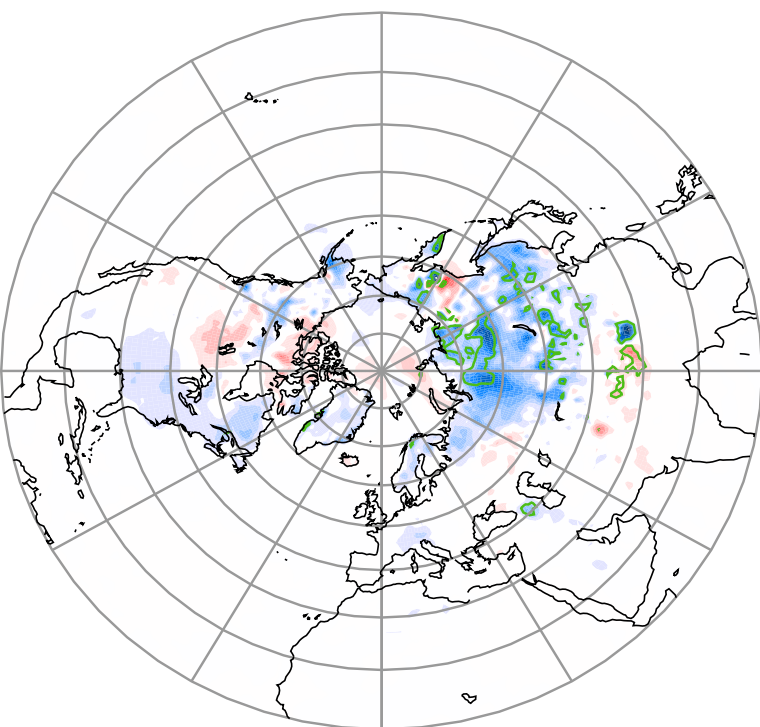
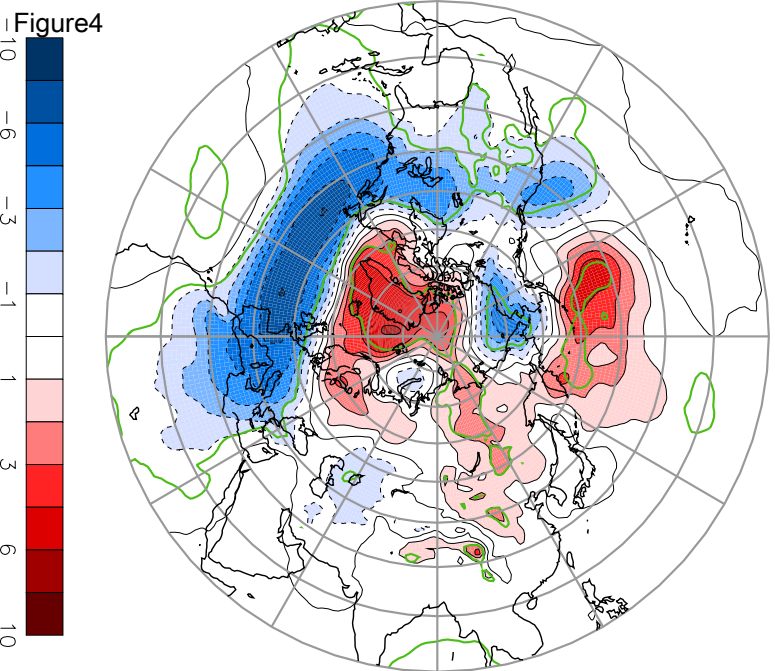
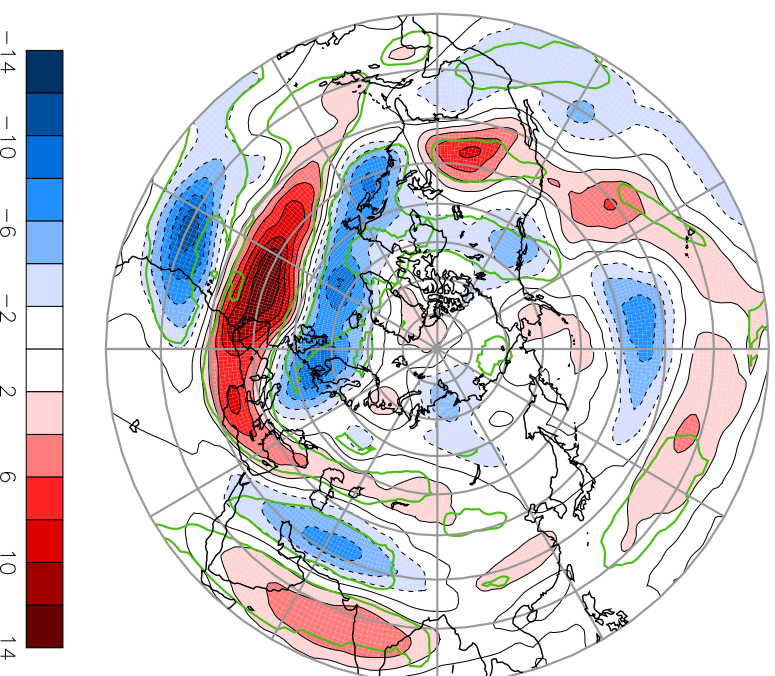


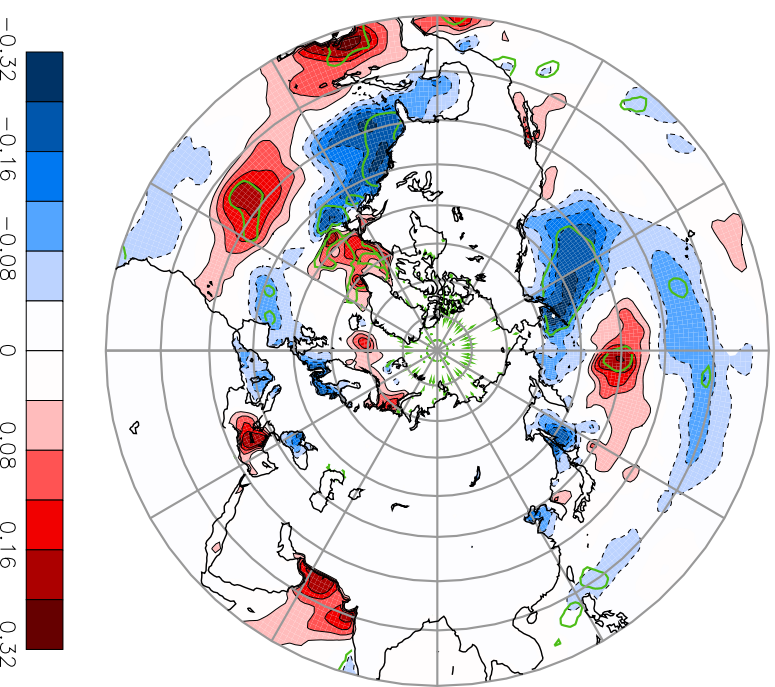
Figure 4



a. Mean Sea Level Pressure (hPa)



b. 200 hPa Wind Speed ( $\text{m s}^{-1}$ )



c. Sea Surface Temperature ( $^{\circ}\text{C}$ )

Series 1 minus Series 2    Lead 15 (16–30 day)    95%



Figure 6

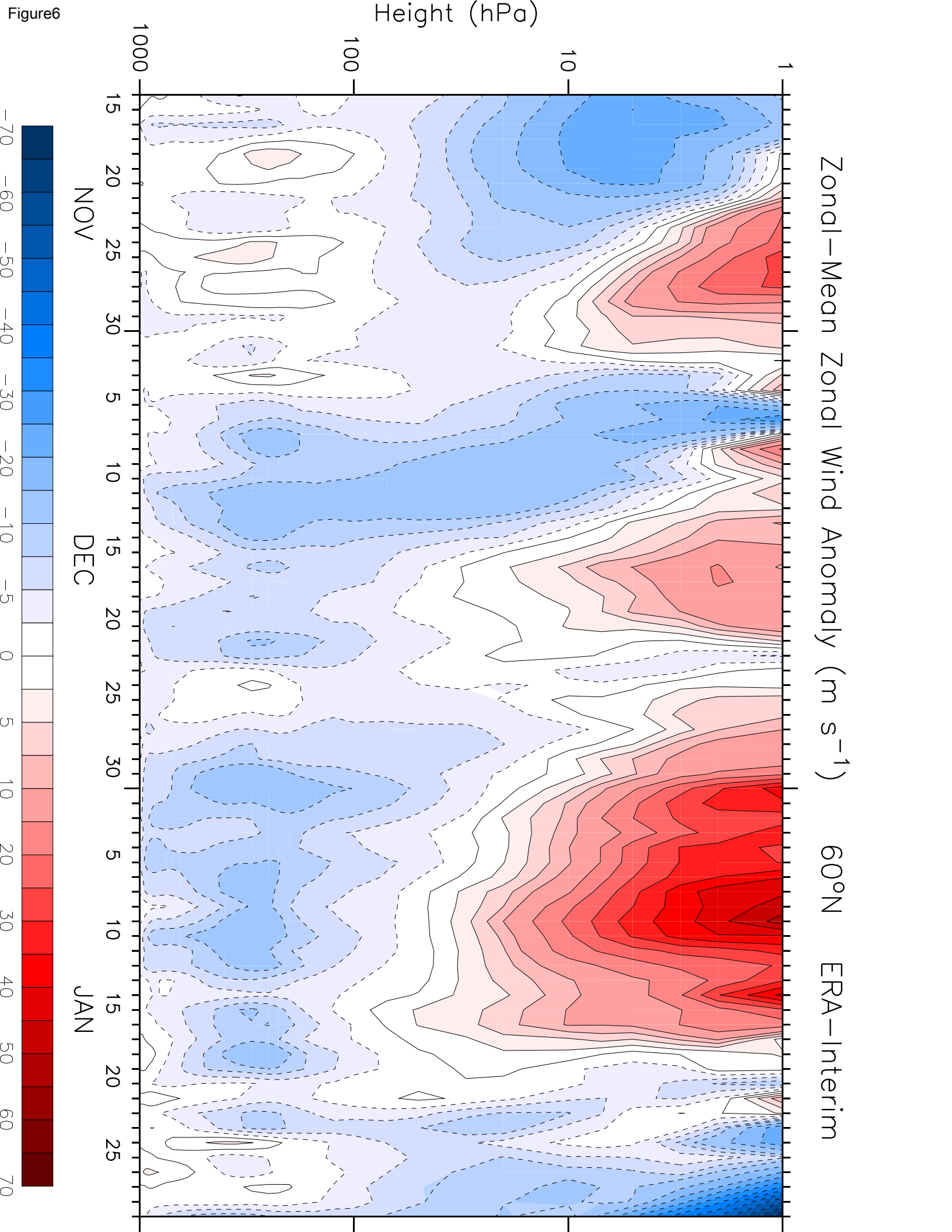


Figure 7

# Meridional Eddy Heat Flux ( $K m s^{-1}$ ) 16–30 Dec 2009

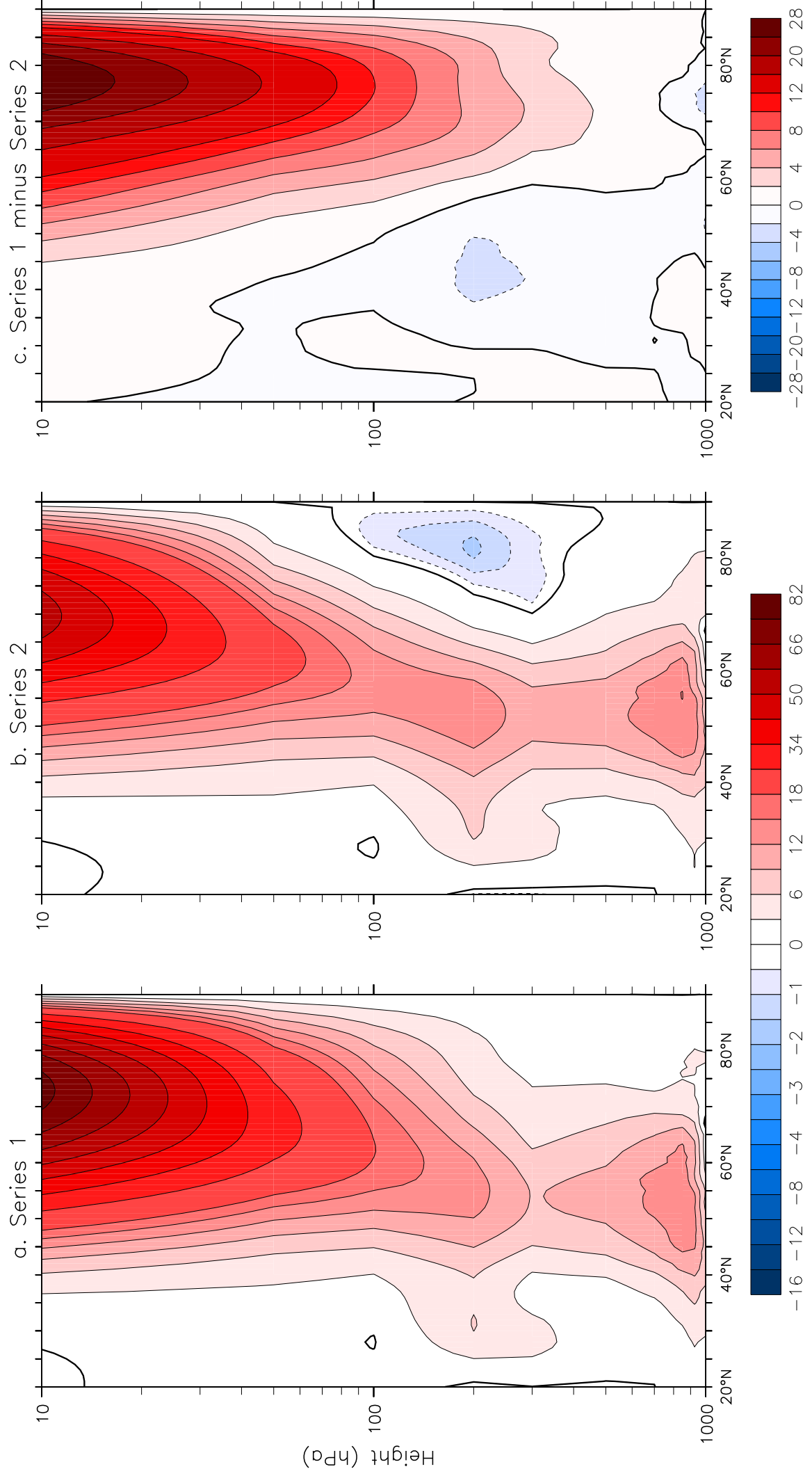
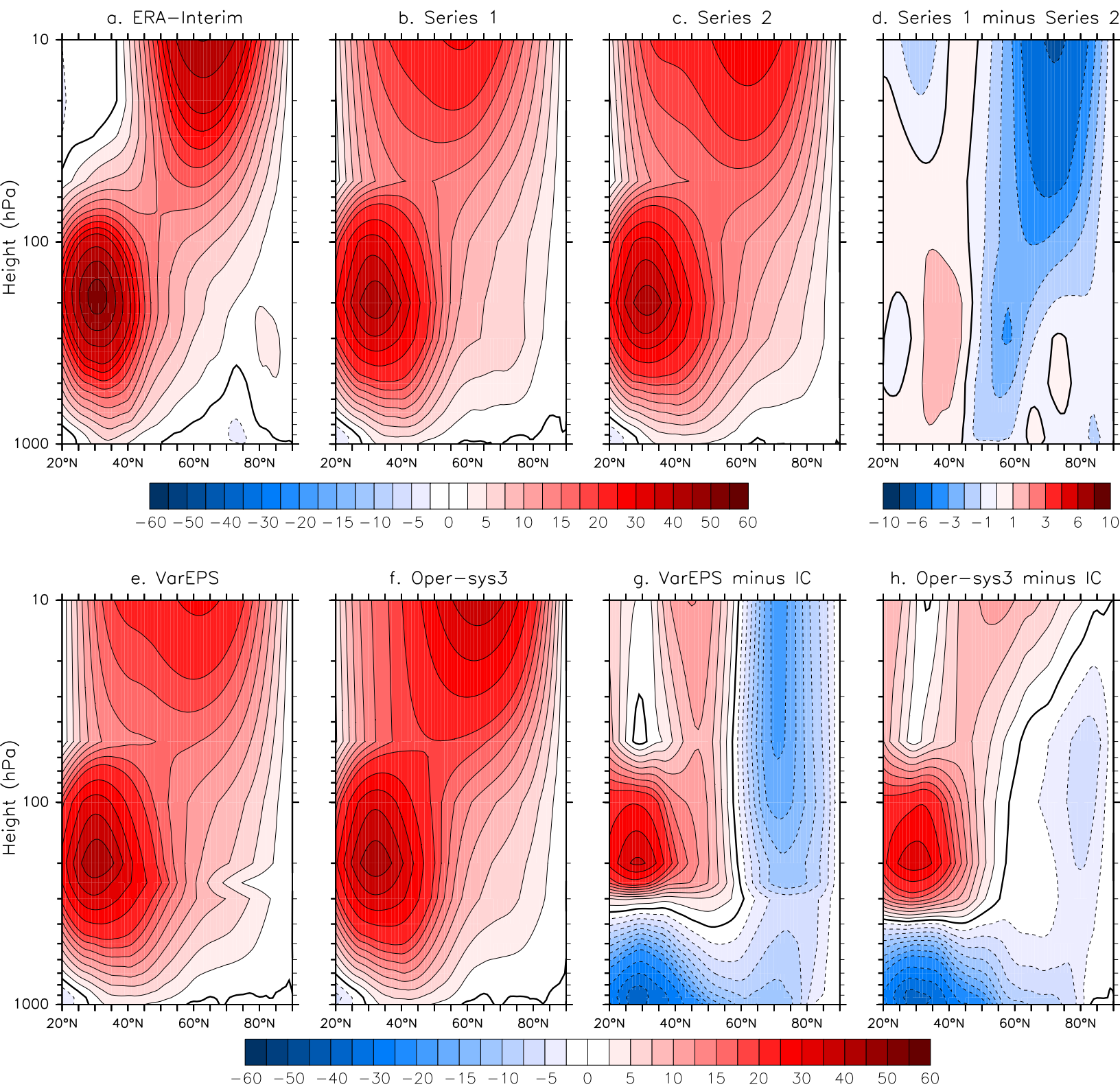
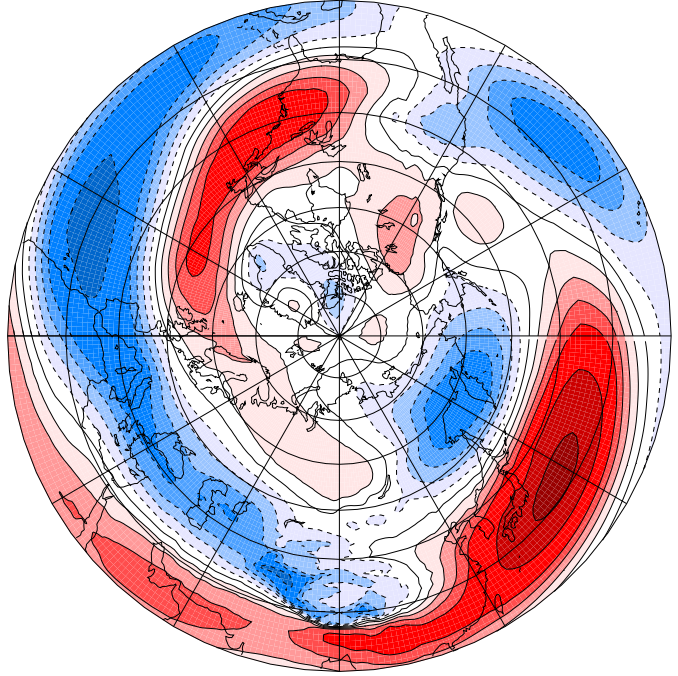


Figure8

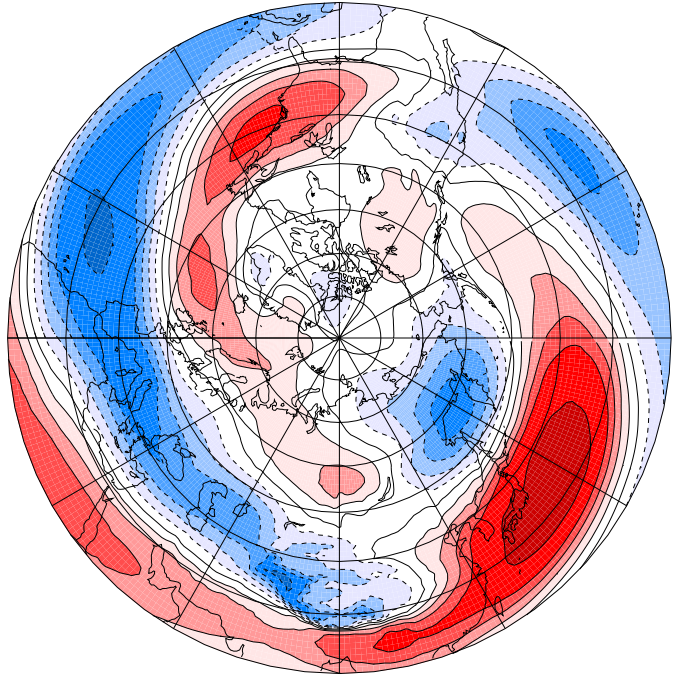
Zonal-Mean Zonal Wind ( $\text{m s}^{-1}$ ) 16–30 Dec 2009

500 hPa Eddy Zonal Wind ( $\text{m s}^{-1}$ ) Climatology 1–30 day

a. Series 1



b. VarEPS



c. Oper-sys3

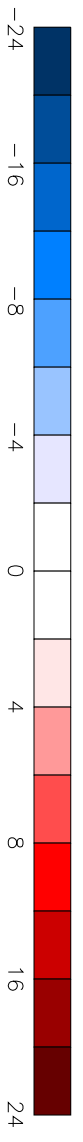
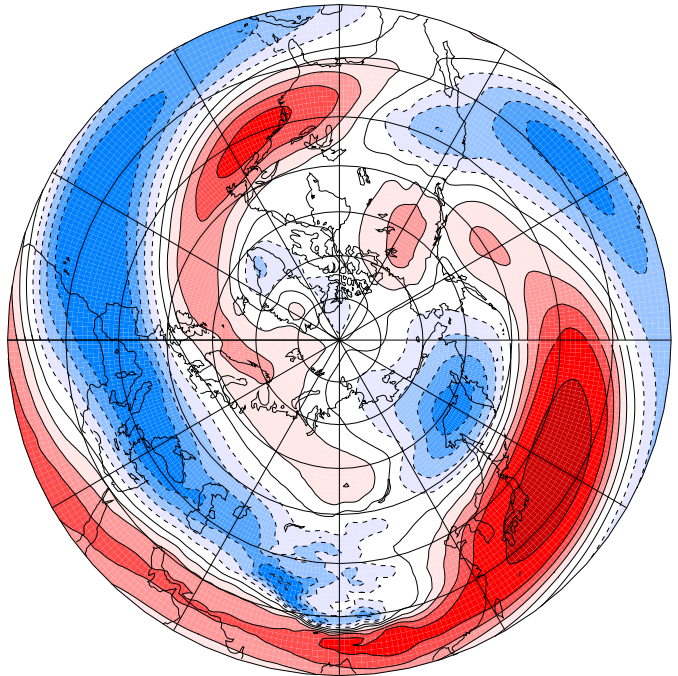


Figure9

Figure S1

[Click here to download Electronic Supplementary Material: fig\\_S1\\_nao\\_index\\_ensmean\\_spread\\_15-NOV-2009\\_IC\\_condtional\\_LT\\_eraclim](#)

Figure S2

[Click here to download Electronic Supplementary Material: fig\\_S2\\_slp\\_wspd\\_s1\\_minus\\_s2\\_15-NOV-IC\\_conditional\\_t3.eps](#)