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Stratosphere-troposphere coupling at inter-decadal time scales: Implications for the North Atlantic Ocean

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[1] Evidence of stratosphere-troposphere coupling at inter-decadal time scales is searched for in a 260-year simulation performed with a climate model including a state-of-the-art stratosphere. The boundary conditions of the simulation are specified according to preindustrial conditions and are kept constant from year to year. It is shown that long lasting (∼20 years) positive and negative anomalies of the northern winter stratospheric polar vortex exist in the simulation. Given that there are no externally imposed low frequency time variations, these persistent variations are due to internal dynamical processes of the modeled coupled atmosphere ocean system. By composite analysis, it is shown that the long lasting stratospheric vortex anomalies are connected through the troposphere to mean sea level pressure, surface temperature and sea ice cover anomalies. These connections are reminiscent of intra-seasonal stratosphere–troposphere coupling. Over the ocean, the surface temperature and sea ice cover anomalies are indicative of the delayed Atlantic meridional overturning circulation response to atmospheric forcing. The latter is indeed found to be anomalously strong/weak during the long lasting positive/negative stratospheric vortex anomalies, providing evidence for a potential role of the stratosphere in decadal prediction. **Citation:** Manzini, E., C. Cagnazzo, P. G. Fogli, A. Bellucci, and W. A. Müller (2012), Stratosphere-troposphere coupling at inter-decadal time scales: Implications for the North Atlantic Ocean, *Geophys. Res. Lett.*, *39*, L05801, doi:10.1029/2011GL050771.

1. Introduction

[2] The stratospheric flow is known to be characterized by considerable variability of dynamical origin at intra- and inter-annual time scales. Dynamical processes are responsible for the occurrence of Stratospheric Sudden Warming (SSW) events in the extra-tropics [e.g., *Matsuno*, 1971; *Charlton and Polvani*, 2007; *Butchart et al.*, 2010] and the Quasi-Biennial Oscillation (QBO) in the Equatorial stratosphere [e.g., *Lindzen and Holton*, 1968; *Baldwin et al.*, 2001, *Giorgetta et al.*, 2002; *Kawatani et al.*, 2010a, 2010b]. At longer timescales, the 11-yr solar cycle is a driver of stratospheric variability [*Gray et al.*, 2010]. Given the nonlinear nature of the climate system, there is also the possibility of dynamically driven inter-decadal variability of the stratospheric flow. For instance, *Butchart et al.* [2000] found that atmospheric model integrations with identical boundary conditions but different initial conditions developed significantly different inter-decadal variation of the Northern winter stratospheric polar vortex. By means of a wavelet analysis, *Schimanke et al.* [2011] found coherent multi-decadal variability (∼50-year period) in the number of SSW events, planetary waves activity emerging from the troposphere and North Atlantic Ocean heat flux, in a climate model simulation not subject to external forcings.

[3] Here, the possibility of inter-decadal stratospheric variability is examined in a 260-year simulation with constant year-to-year external forcing, done with a coupled atmosphere-ocean general circulation model that includes a state-of-the-art stratosphere. The averaged impact of long lasting (∼20 years) Northern winter stratospheric vortex anomalies on averaged surface fields, such as sea level pressure, sea ice and surface temperature is evaluated, in order to determine the direction of the ocean-troposphere-stratosphere connection. The focus is on inter-decadal variation, to investigate the potential role of the stratosphere in decadal prediction, a topic of current interest in climate research, for its societal, economic and environmental implications [*Meehl et al.*, 2009]. Given the relationship between the strength of the stratospheric polar vortex and surface anomalies in sea level pressure [*Baldwin and Dunkerton*, 2001] related to the Arctic Oscillation (AO) and the more regional North Atlantic Oscillation (NAO); and in turn between the NAO and the Atlantic Meridional Overturning Circulation (MOC) [*Deshayes and Frankignoul*, 2008], it is plausible to search for vertical connectivity from the stratosphere to the ocean. The possibility for this vertical connectivity is here tested.

2. Model and Simulation

[4] The coupled atmosphere–ocean-sea-ice general circulation model used is the Centro Euro-Mediterraneo per i Cambiamenti Climatici – Climate Model with Stratosphere (CMCC-CMS). Results presented here are from a 260-years run of the Coupled Model Inter-comparison Project – Phase 5 (CMIP5) piControl experiment. The experiment was started from a stable control simulation (a few thousand years). Estimated conditions at 1850 determine the external forcings of the piControl experiment and follow the CMIP5 protocol (http://cmip-pcmdi.llnl.gov/cmip5/). External forcings are prescribed constant in time for well-mixed greenhouse gases, including CO_2, CH_4, N_2O, and incoming solar irradiance (total value: 1367 Wm^{-2}); the seasonally varying ozone distribution is repeated every year. The atmospheric component of CMCC-CMS is ECHAM5, with top at

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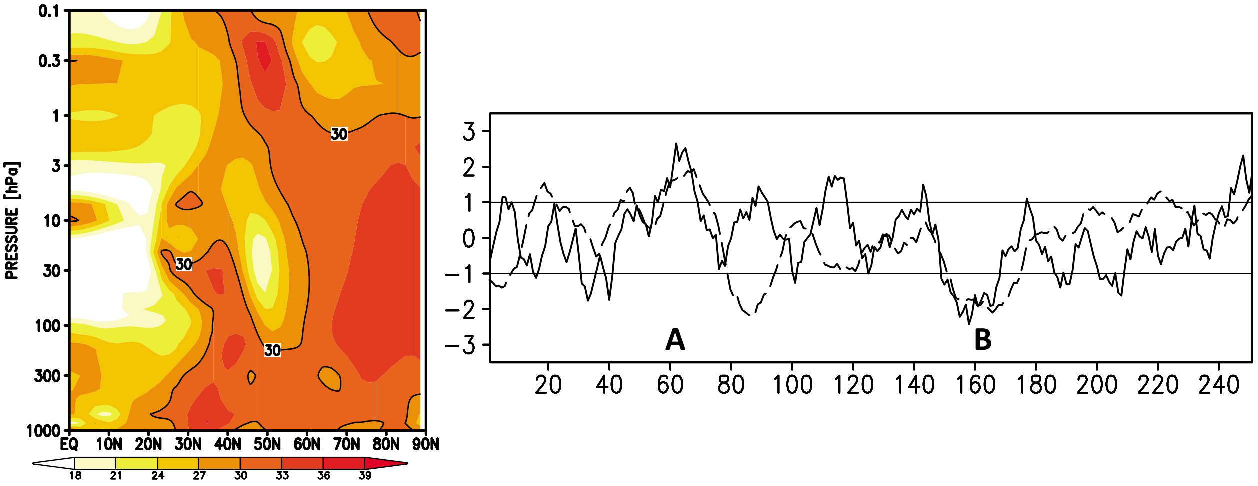

Figure 1. (left) November to March (NDJFM) zonal mean zonal wind: ratio (%) between the standard deviations of the 11-yr running mean anomalies and the inter-annual anomalies; (right) NDJFM zonal mean zonal wind anomaly time series at 70°N and 10 hPa (solid) and Atlantic MOC maximum annual anomaly time series (long dashed). The MOC maximum has been searched in the range: 40°–50°N and 500–1000 m depth. The time series are smoothed with an 11-year running mean and are standardized, respectively by 1.8 ms^{-1} and 0.6 Sv. Abscissa is in model years from beginning of the piControl run.

0.01 hPa and 95 vertical layers, T63 horizontal resolution and with the shortwave radiation scheme implemented by *Cagnazzo et al.* [2007]. This version of ECHAM5 includes a well-resolved stratosphere in the sense that stratospheric planetary wave – mean flow interaction, possibly leading to SSW events, is explicitly resolved and the effects of both orographic and non-orographic gravity waves on the stratospheric and mesospheric large-scale flows are parameterized [*Manzini et al.*, 2006; *Charlton et al.*, 2007; *Cagnazzo and Manzini*, 2009]. It also includes a spontaneously occurring QBO [*Giorgetta et al.*, 2006]. The ocean-sea-ice component of CMCC-CMS is OPA-LIM, with 31 levels and horizontal resolution of 2° × 2° with refinements around the Equator [*Madec et al.*, 1999; *Timmermann et al.*, 2005]. The physical and technical coupling interface is described by *Fogli et al.* [2009]. The climate of the piControl run is stable, in the sense that the global mean of the near surface air temperature does not show any significant drift and the top of the atmosphere radiative balance is close to zero (slightly positive).

3. Variability

[5] To characterize the atmospheric variability of the extended Northern winter, November to March (NDJFM) averages of zonal mean zonal wind time series are considered. The inter-decadal variability of the Northern polar vortex is estimated by the ratio between the standard deviations of 11-yr running mean and inter-annual anomalies, calculated from the NDJFM zonal mean zonal wind time series (Figure 1). Poleward of 30°N (troposphere) and 60°N (stratosphere) the inter-decadal variability accounts for 30% or more of the total variability. In terms of surface temperature variance (not shown), this result translates into a diagnostic potential predictability variance fraction (ratio between the variance of the inter-decadal means to the total variance, with total variance calculated from the annual mean time series) of about ∼10%, significant at the 95% level (F-test) in the North Atlantic basin (around 60°N), favorably comparing with previous estimates [*Boer*, 2004].

[6] Given the spatial extent of the Northern hemisphere with relatively high (>30%) inter-decadal variability and its vertical extension poleward of 60°N, it is of interest to ask if there is a stratosphere-troposphere coupling at multi-decadal scales. Hence, a low frequency index of the stratospheric vortex strength is defined in Figure 1 (right, solid line), by calculating the NDJFM zonal mean zonal wind 11-yr running mean anomalies at 70°N, 10 hPa. This location is chosen as compromise between the most commonly used benchmark of vortex strength at 60°N, 10 hPa [*Baldwin and Thompson*, 2009] and the region with the largest ratio in Figure 1 (left). Figure 1 (right) shows intervals with ∼20-yr period oscillations and the existence of two exceptionally long lasting (∼20 years) periods of large anomalies (magnitude > 1 standard deviation). Namely, a period including an anomalously strong polar vortex (case A, years: 51–71), and a period with a weak stratospheric polar vortex (case B, years: 151–171). These variations are consistent with a change in the frequency of occurrence of SSW events (defined as by *Charlton and Polvani* [2007]), about twice as much in the weak vortex case (B) with respect the strong vortex case (A). The frequency of occurrence of SSW events for the whole 260-yr run is about 0.7/year, close to *Charlton and Polvani* [2007] estimate. For period A, the SSW frequency is 0.6/year, while for period B it is 1.2/year. In the next section, anomalies of key meteorological variables are composited according to the years belonging to case A and B, to characterize the troposphere-stratosphere system.

4. Spatial and Temporal Characteristics

[7] Figure 2 (top) confirms that the A and B periods selected using the Figure 1 index are characterized by an intensified and a weakened polar vortex, respectively. Virtually the entire winter stratosphere is significantly affected. Significant anomalies in zonal mean zonal wind are

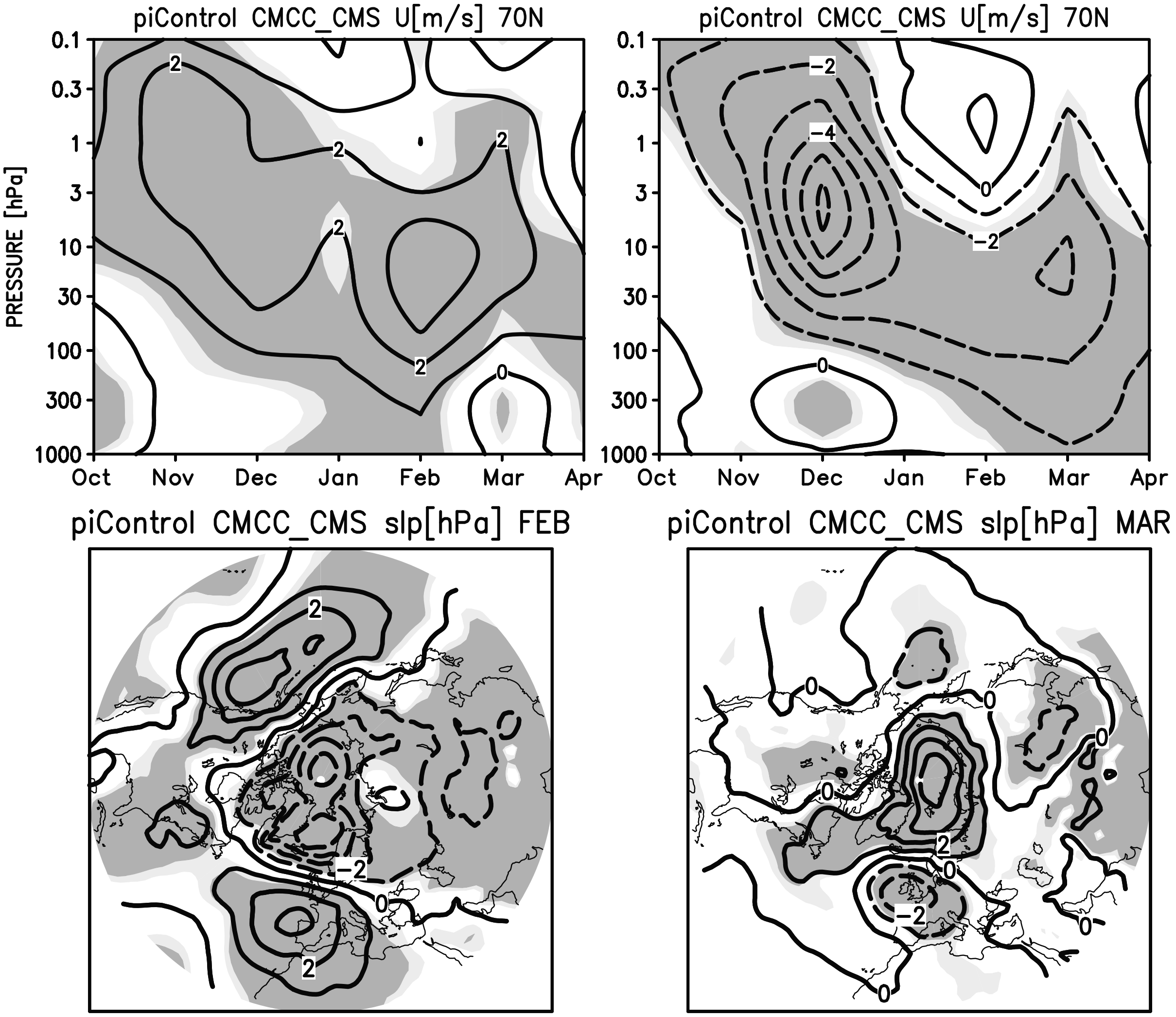

Figure 2. (top) Composite of 11-yr running mean monthly zonal mean zonal wind anomalies (contour: 1 ms^{-1}) at 70°N, from October to April, for period (top left) A and (top right) B. (bottom) Composite of 11-yr running mean sea level pressure anomalies (contour: 1 hPa) (bottom left) in February for period A and (bottom right) in March for period B. Light (dark) shading indicates 95 (99) % statistical significance level, calculated with the Student t-test.

seen to propagate downward, from early to late winter, and reach the surface in February (period A) and in March (period B). In the stratosphere in early winter and in the troposphere in late winter, the magnitude of the zonal wind anomalies is larger in the weak vortex case B (>4 ms^{-1} between 10–1 hPa, December; ∼1 ms^{-1} very close to the surface, March) than in the strong vortex case A (2 ms^{-1} between 10–1 hPa, December; ∼1 ms^{-1} at 300 hPa, February). The coherence of the zonal wind anomalies is reminiscent of the stratospheric early winter to tropospheric and surface late winter connections, from intra-seasonal variations [*Baldwin and Dunkerton*, 2001]. The connections of the vortex anomalies to the surface circulation are demonstrated in relatively large (2–4 hPa in magnitude) and significant mean sea level pressure (SLP) anomalies in February and March (Figure 2, bottom). February (period A) and March (period B) are shown, because corresponding to the months when the largest zonal wind anomalies are closest to the surface, respectively. Both SLP anomalies are indicative of AO-like patterns, with polar and mid-latitudes anomalies of opposite sign.

[8] The February (period A) and March (period B) surface temperature composite anomalies over land (Figure 3) are consistent with the AO-like patterns: strong/weak stratospheric vortex, polar low/high pressure, warmer/colder Northern Eurasia and colder/warmer Northwest America and Greenland. At Northern high latitudes (Eurasia), the land surface temperature anomalies are significant and reach up to 1–2 K (magnitude). Over the ocean, areas with significant but smaller (0.5–1 K, magnitude, in the North Atlantic) surface temperature anomalies (i.e., sea surface temperature, SST) are found. Specifically, Figure 3 shows warming/cooling of the North Atlantic and out of phase Southernmost Atlantic anomalies, for A/B. The SST anomalies in the North Atlantic are therefore not consistent with a short time scale connection between the NAO (or AO) and the SSTs, which would be accompanied by negative SST anomalies in the Northwest Atlantic Ocean, e.g., anomalies over Greenland and the Northwest Atlantic Ocean of the same sign

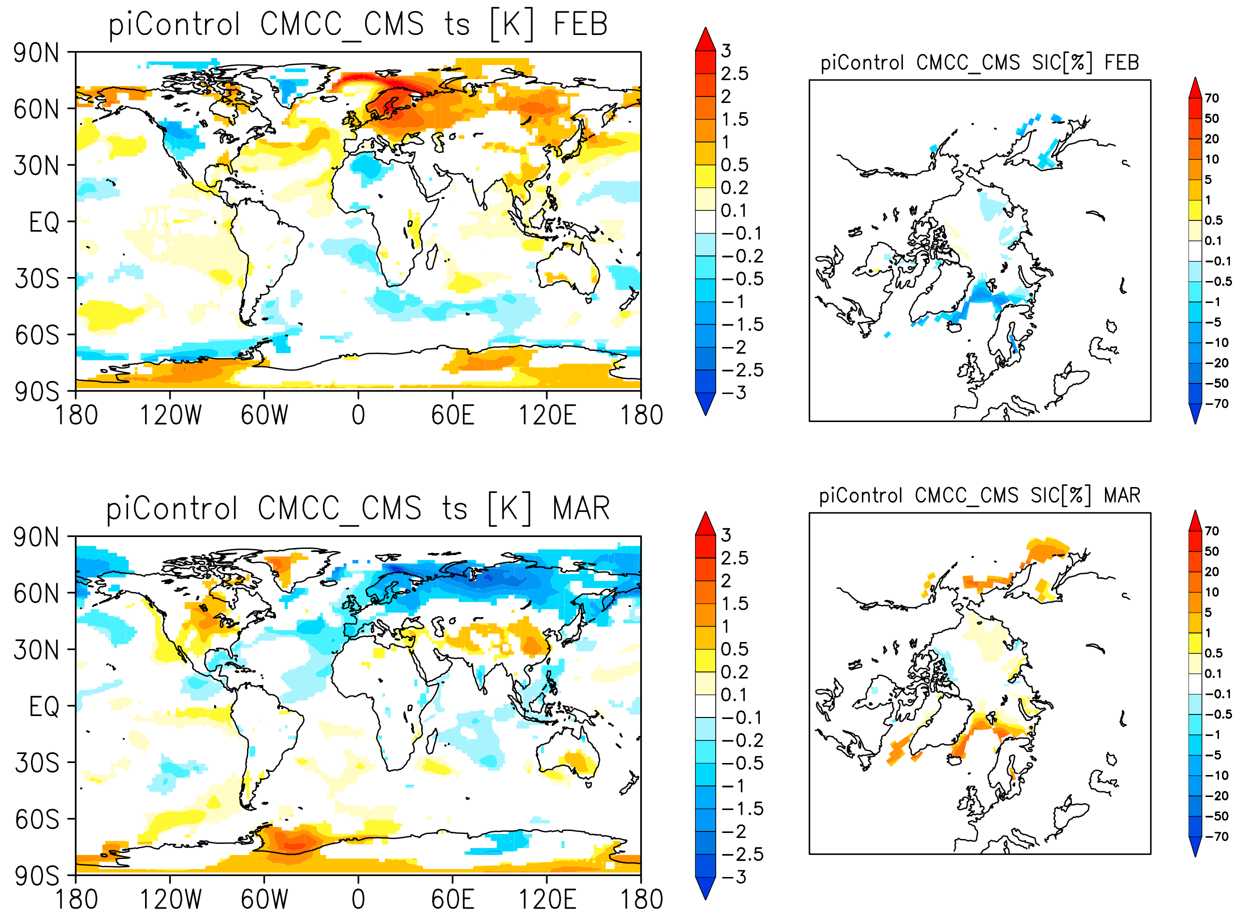

Figure 3. Composite of 11-yr running mean (left) surface temperature anomalies (K) and (right) sea ice cover anomalies (%). (top) February, period A. (bottom) March, period B. Plotted only areas with statistical significance above the 99% level, calculated with the Student t-test.

[*Czaja et al.*, 2003; *Gastineau and Frankignoul*, 2011]. The striking difference is in the contrast between Greenland (land) and the adjacent surface ocean. The sea ice cover anomalies (Figure 3, right) are consistent with the SST anomalies: Between Greenland and Norway a 5–10% decrease/increase in sea ice cover corresponds to a warming/cooling. Comparable SST and sea ice cover anomalies are found in annual mean versions of Figure 3, while the respective land surface temperature anomalies substantially decrease in the annual mean.

[9] The anomalies in the North and Southernmost Atlantic are instead consistent with a multi-year (3–10 years) delayed response of the SSTs to the positive/negative phases of the NAO (or AO) driving of the ocean circulation, mediated by an enhancement/decrease of the Atlantic MOC [*Latif et al.*, 2004; *Deshayes and Frankignoul*, 2008]. This inference is based on the MOC role in regulating the Northward ocean heat transport in the Atlantic. A stronger Atlantic MOC leads to enhanced Northward ocean heat transport, in turn warming the high latitude North Atlantic Ocean. Positive SST anomalies in the North Atlantic (as those shown in Figure 3) are thereafter expected. The opposite is expected for a weaker Atlantic MOC. The involvement of the Atlantic MOC is demonstrated in Figure 1 (right, dashed line): During period A/B the low frequency Atlantic MOC anomaly is indeed found to be exceptionally strong/weak. Causal relationships between the MOC and the stratospheric vortex strength has been further elucidated through a lead-lag correlation analysis between the time series shown in Figure 1, indicating weak but significant correlation when the vortex leads the MOC by 3–4 yrs (not shown). It is also interesting to note from Figure 1, that after the A and B periods, the MOC anomalies change sign, suggesting a self-response of the MOC to its induced SST anomalies, and so resulting in strongly damped oscillations [*Griffies and Tziperman*, 1995].

5. Discussion and Conclusions

[10] We have documented the existence of Northern winter inter-decadal variability spanning from the stratosphere to the ocean, in a CMIP5 piControl 260-year run performed with the CMCC-CMS, a climate model with a state-of-the-art stratosphere. Specifically:

1. Long lasting (∼20 years) strong and weak stratospheric polar vortex variations are consistent with a change in the frequency of occurrence of SSW events, in the relative decades. These persistent variations are the consequence of internal dynamical processes of the atmosphere–ocean system.

2. The strong and weak vortex anomalies show coherent stratospheric early winter to tropospheric and surface late winter downward propagation. Both the strong and weak vortex anomalies are connected through the troposphere to significant SLP, surface temperature and sea ice anomalies. Given the SSW frequency change, it is concluded that processes responsible for intra-seasonal variations are also responsible for stratosphere-troposphere coupling at inter-decadal time scales.

3. The Atlantic Ocean surface temperature and Arctic sea ice cover anomalies can be interpreted as the signal of the delayed ocean response to the atmospheric surface forcing induced by the anomalously strong/weak stratospheric polar vortex. Although we have not addressed the details of the mechanisms linking the AO-like SLP anomalies to the Atlantic MOC, the direct diagnostic of the Atlantic MOC confirms this interpretation.

[11] In summary, our results provide evidence to the assumption that it is relevant to resolve stratospheric dynamics in models used for climate prediction. It is so inferred because (1) the selection of exceptional and persistent anomalies of the stratospheric polar vortex has led to Atlantic SST, sea ice and MOC anomalies, which imply downward atmosphere to ocean coupling; (2) SSW events and their interaction with the mean flow are the dynamical process behind the strengthening and weakening of the polar vortex, and the interaction of SSW with the mean flow is sensitive to the vertical resolution in the stratosphere [*Cagnazzo and Manzini*, 2009; *Karpechko and Manzini*, 2012]. What is here left open is the origin of the long lasting stratospheric polar vortex anomalies. Whereas the stratospheric anomalies are coming from the North Atlantic basin itself, Eurasian snow anomalies [*Cohen et al.*, 2007, 2009] or remote horizontal/vertical tele-connections (e.g., involving variability of other ocean regions) are the subjects of further investigations, possibly considering additional CMIP5 numerical experiments.

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