GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L18703, doi:10.1029/2009GL039334, 2009

Stratospheric polar vortex influence on Northern Hemisphere winter climate variability

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Received 8 June 2009; revised 29 July 2009; accepted 18 August 2009; published 23 September 2009.

[1] Given the low skill of seasonal forecasts in the Northern Hemisphere, it is important to look for extra sources of long-range predictability in addition to the global distribution of sea surface temperature (SST). Former studies have suggested the potential contribution of the stratosphere but have never really quantified this influence and compared it to the SST forcing. In the present study, two ensembles of global atmospheric simulations driven by observed SST and radiative forcings have been performed over the 1971–2000 period. In the perturbed experiment, the stratospheric dynamics and temperature is nudged towards the ERA40 reanalyses north of 25°N in order to mimic a "perfect" polar vortex. The comparison with the control experiment reveals a strong improvement in the simulation of the Arctic and North Atlantic Oscillation, with obvious positive impacts on the interannual variability of winter surface air temperature and precipitation, especially over Europe. **Citation:** Douville, H. (2009), Stratospheric polar vortex influence on Northern Hemisphere winter climate variability, *Geophys. Res. Lett.*, *36*, L18703, doi:10.1029/2009GL039334.

1. Introduction

[2] In the Northern Extratropics, the winter climate shows large interannual variability compared to other regions and seasons, which represents a major hazard for population and economic activity. Unfortunately, current dynamical seasonal forecasting systems still show low predictability in the northern mid-latitudes [e.g., *Palmer et al.*, 2004] and do not necessarily outperform simple empirical forecasting tools [e.g., *Cohen and Fletcher*, 2007]. Global atmospheric simulations driven by observed SST indeed suggest that only a very limited fraction of extratropical variability is controlled by the global ocean at the monthly to seasonal timescale. While such AMIP-type experiments do not necessarily measure accurately the upper limit of seasonal predictability [*Bretherton and Battisti*, 2000], dynamical forecasting systems are now based on coupled ocean-atmosphere GCMs and show skill scores which are consistent with, though generally lower than, ensembles of AMIP-type simulations [*Guérémy et al.*, 2005].

[3] Besides SST, it is therefore important to look for additional sources of long-range climate predictability, not only at the lower boundary conditions [e.g., *Douville*, 2009] but also in the middle atmosphere where the reversal of the climatological vertical temperature gradient leads to a stronger stability and thereby to a higher signal-to-noise ratio than in the troposphere. A first example is the persistent stratospheric signature of major volcanic eruptions through an interaction between radiative and dynamical processes. Another source of potential predictability is the quasi-biennial oscillation (QBO) of the equatorial zonal winds in the 10–70 hPa pressure range, whose influence on the extratropical troposphere could be however limited [*Thompson et al.*, 2002; *Boer and Hamilton*, 2008]. In Northern Hemisphere high latitudes, the winter variability is dominated by the episodic weakening and strengthening of the stratospheric polar vortex (SPV). Such vacillations are controlled by a balance between planetary wave breaking and relaxation toward radiative equilibrium. They occur on timescales of weeks to months during the winter season and are also potentially important for long-range climate predictability in the Northern Hemisphere [*Thompson et al.*, 2002; *Charlton and Polvani*, 2007].

[4] Recent numerical studies based on a perturbation of the SPV [*Scaife et al.*, 2005; *Scaife and Knight*, 2008] confirm the possible stratospheric influence on European winter climate through a modulation of the North Atlantic Oscillation (NAO) at both seasonal and multi-decadal timescales. In the present study, we go one step further by quantifying the relative contribution of SST and SPV on the boreal winter climate variability simulated by an atmospheric GCM over the 1971–2000 period. The results show that the upper (i.e., stratospheric) boundary conditions are as important as the lower oceanic forcing for understanding interannual variability in the northern extratropics and, therefore, confirm the relevance of a realistic simulation of the polar stratosphere for dynamical seasonal forecasting.

2. Experiment Design

[5] The control experiment, CTN, consists of a five-member ensemble of 1970–2000 global atmospheric simulations, driven by observed SST and radiative forcings (i.e., greenhouse gases and aerosols) and differing only by the atmospheric initial conditions on 1st January 1970. It is therefore considered as a benchmark for evaluating potential (not effective) seasonal predictability. The perturbed experiment, EXN, is very similar and consists of five parallel integrations (same initial conditions) where a realistic SPV is superimposed onto the observed SST and radiative forcings. The objective is to quantify the additional stratospheric contribution to the simulated interannual variability in the Northern Hemisphere. All simulations are performed with a medium-resolution configuration (linear T63 truncation, reduced 128 by 64 Gaussian grid, 31 vertical levels) of the Arpege-Climat spectral model with a hybrid σ-pressure vertical coordinate [*Guérémy et al.*, 2005]. While such a

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0094-8276/09/2009GL039334$05.00

vertical resolution is too coarse to resolve the stratosphere (only 5 vertical levels above 100 hPa), it is sufficient to simulate a realistic SPV using a simple nudging strategy.

[6] Nudging is a flexible technique that can be applied at each time step (every 30 min) to the wind components, and also here to the temperature, to control the evolution of the stratosphere. This is done by adding a $-\lambda(y - y_{ref})$ extra term in the model prognostic equations where y is the model state vector, y_{ref} is the reference field towards which the model is relaxed and λ is the strength of the relaxation. The coefficient λ is a function of the variable, the location (longitude, latitude and vertical level) and possibly the scale. In the present study, the nudging is applied only in the northern extratropical stratosphere (north of 25°N and above 100 hPa) and is therefore carried out in grid point space. The vertical and latitudinal profiles of the nudging strength are chosen in order to ensure a smooth transition between the nudged stratosphere and the free atmosphere. The maximum nudging strength is fixed at a 5-hour e-folding time ($\lambda = 0.1$) for both wind and temperature. The reference fields are the 6-hourly ERA40 data which are interpolated linearly at the model time step. The ERA40 reanalysis is also used to evaluate the impact of the stratospheric nudging on DJF (December–January–February) atmospheric circulation over the 1971–2000 period (i.e., after a 11-month spin-up).

3. Results

[7] Figure 1 shows the simulation of three winter climate indices that summarize the Northern Hemisphere interannual variability: the 10 hPa geopotential height anomalies averaged poleward of 60°N that characterize the vacillations of the SPV, an Artic Oscillation (AO) index based on the first EOF of mean sea level pressure poleward of 20°N, and a NAO index based on the first EOF of 500 hPa geopotential height over North Atlantic and Europe. Note that the EOF patterns are computed separately for each dataset, but that results would have been very similar using a projection onto a common pattern or a simple NAO index based on mean sea level pressure at two locations. All anomalies are relative to the 1971–2000 climatology and are based on raw DJF seasonal means without prior filtering. Both simulations are compared with ERA40. Besides ensemble mean anomalies, Figure 1 also illustrates the spread among the 5 members of each ensemble.

[8] Not surprisingly, the control experiment shows a poor skill at simulating the SPV variability. This might be partly due to the coarse resolution of the model but preliminary tests with T159L60 and T63L60 configurations of the model (not shown) suggest only a limited improvement with increasing resolution. Another issue is the overestimated radiative impact of volcanic aerosols in the Arpege-Climat stratosphere, in particular after the El Chichon and Pinatubo eruptions, which leads to spurious peaks of 10 hPa geopotential height (i.e., weak vortex anomalies) in DJF 1982–83 and DJF 1991–92 respectively. Nevertheless, the main problem is probably the weak stratospheric response to the prescribed SST forcing. In contrast and as expected, the SPV variability is perfectly simulated in the nudged experiment, thereby demonstrating the efficiency of the stratospheric relaxation.

[9] Looking now at the tropospheric circulation, the impact of the stratospheric nudging on the AO and NAO modes of variability is still obvious and very positive. While the control ensemble shows a limited correlation (0.35 and 0.41) with ERA40 and a substantial spread, the nudged experiment looks much more realistic (correlation around 0.9) and better constrained (weaker spread). These results therefore provide a strong and quantitative evidence that a realistic SPV simulation is crucial for predicting the Northern Hemisphere winter climate variability.

[10] Moving to DJF surface temperature and precipitation, Figure 2 shows the spatial distribution of grid-cell correlations between the simulated ensemble mean anomalies and the Climate Research Unit (http://www.cru.uea.ac.uk/) observations over land (after interpolation on the model grid). In the control experiment, the correlations remain relatively low, especially for precipitation. The main exceptions are the coastal regions where the prescribed SST forcing plays an obvious role, as well as the North American continent where the Pacific SST variability has a well-known significant influence. Differences between the nudged and control experiments confirm the added value of the stratospheric forcing, even on surface climate parameters such as temperature and precipitation. The increase in grid cell correlations is particularly strong for DJF precipitation over southern and northern Europe. The large-scale pattern of this increase and its consistency with the improvement of the NAO variability make us confident in the robustness of this result. Note also that other seasons have been looked at (not shown) and also suggest a substantial increase in temperature and precipitation correlations in the northern extratropics despite a weaker amplitude of the AO/NAO variability.

4. Conclusion

[11] For the first time to the author's knowledge, the SPV influence on Northern Hemisphere winter climate variability has been quantified through an original experiment design where a realistic stratosphere is simulated in an atmospheric GCM using a nudging toward ERA40 reanalyses. Compared to a control experiment using only global SST and radiative forcings, the results indicate a strong improvement in the simulation of the Arctic and North Atlantic Oscillation, with obvious positive impacts on the interannual variability of winter surface air temperature and precipitation. Our experiment design does not allow us to disentangle the influence of the anomalies in the stratospheric winter circulation from that of the stratospheric mean state since both are corrected through the nudging technique. Note however that parallel simulations have been conducted with a nudging towards the ERA40 climatology, with no positive impact on the simulated tropospheric variability (not shown). The results therefore highlight the potential added value of a realistic stratospheric variability for understanding and predicting the European winter climate variability. This finding is consistent with the 2005–2006 case study of *Scaife and Knight* [2008], but the conclusion here applies to a 30-yr period and to the whole northern extratropics though Europe still appears as a "hot spot" where seasonal forecasting could particularly benefit from a better simulation and/or initialization of the stratosphere.

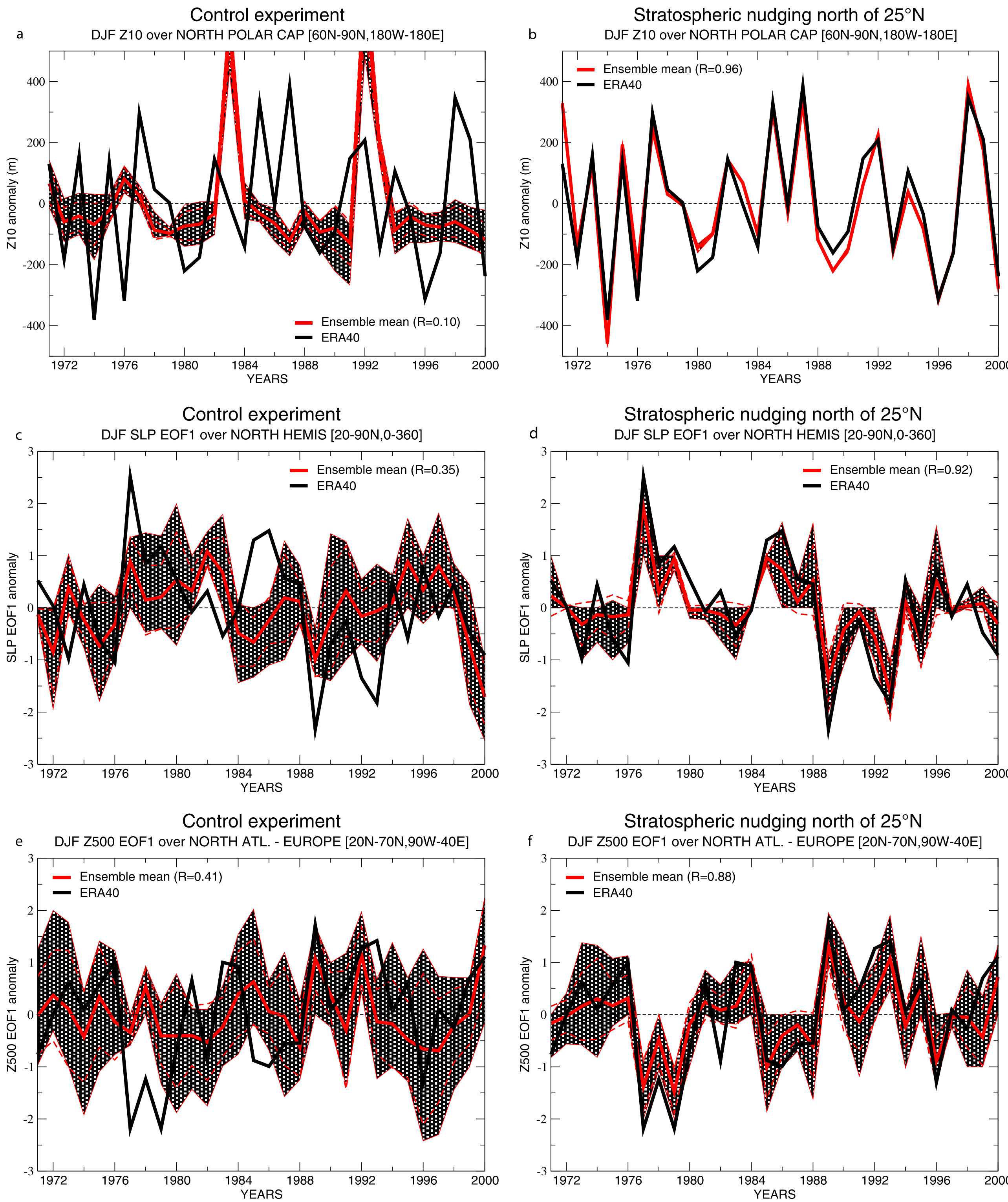

Figure 1. The 1971–2000 time series of DJF Northern Hemisphere climate indices: (a and b) north polar cap 10 hPa geopotential height, (c and d) Arctic Oscillation, and (e and f) North Atlantic Oscillation. For each experiment (in red, control on the left, nudging on the right), ensemble mean anomalies (thick line) are compared to ERA40 (in black) and spread is also shown (±1 standard deviation in dashed lines and minimum and maximum anomalies in solid lines). R is the ensemble mean anomaly correlation coefficient with ERA40.

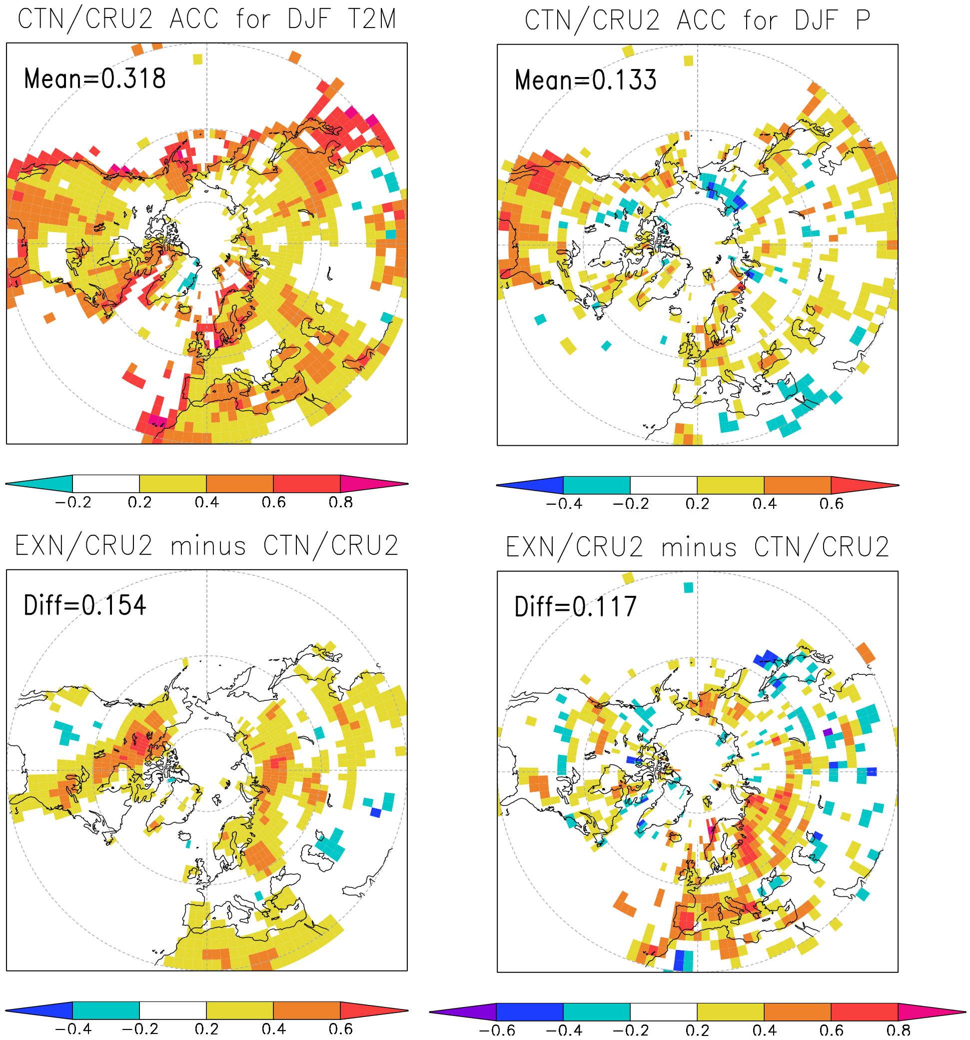

Figure 2. Northern extratropics distribution of land grid cell temporal correlations over the 1971–2000 period between ensemble mean and observed anomalies for DJF (left) temperature and (right) DJF precipitation. (top) Control experiment (Mean is the average correlation over the domain). (bottom) Impact of the nudging estimated as the difference between the ensemble mean correlation from the nudged and control experiments (Diff is the average difference between the correlations over the domain).

[12] Besides a deeper understanding of the mechanisms of the troposphere-stratosphere coupling, the main issue is now the predictability of the stratospheric dynamics itself. While recent studies do suggest a possible SPV sensitivity to various "slow components" of the global climate system such as tropical Pacific SST [*Ineson and Scaife*, 2009], Eurasian snow cover [*Cohen et al.*, 2007] or QBO in the equatorial stratosphere [*Anstey and Shepherd*, 2008], the SPV variability is also controlled by internal atmospheric dynamics which is still not correctly simulated by current GCMs [e.g., *Charlton et al.*, 2007]. A new generation of models with higher resolution and improved physics is therefore probably needed before the expected improvement of long-range forecasting in the Northern Hemisphere becomes reality.

[13] **Acknowledgments.** The author is grateful to M. Déqué, A. Voldoire, and S. Tyteca for providing efficient and original tools to carry on this numerical study. Thanks are also due to D. Saint Martin and D. Cariolle for useful discussion and comments on the manuscript.

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