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Ministry of Transport

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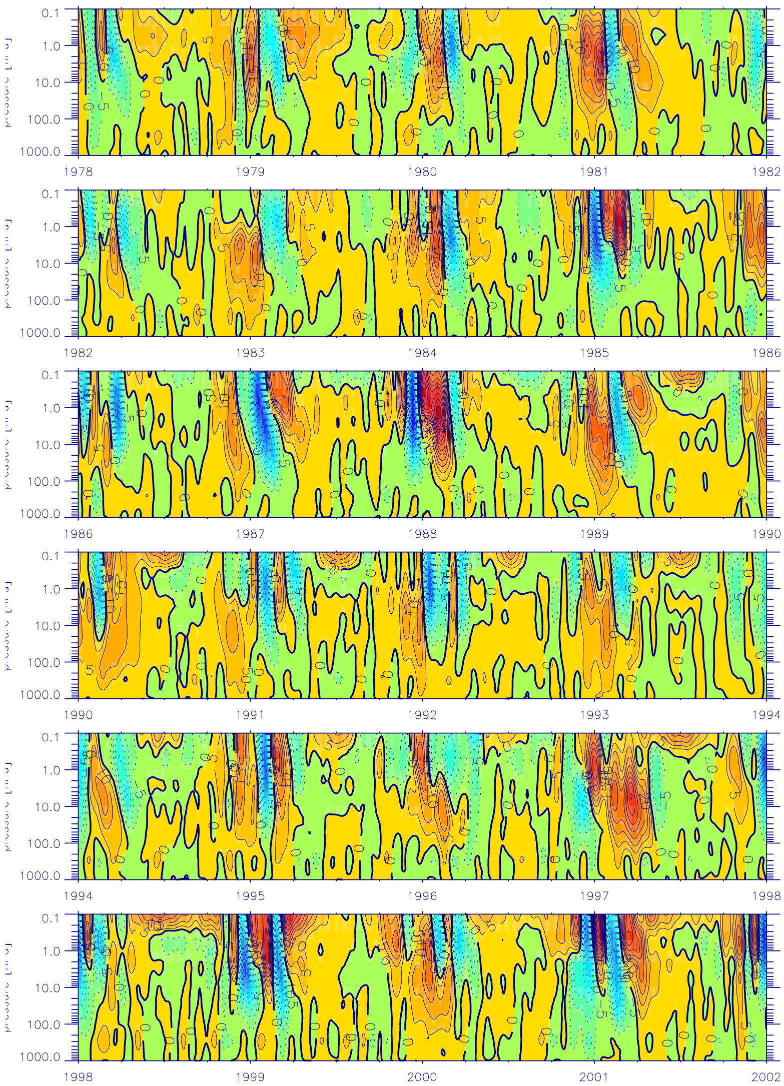
Downward propagation and statistical forecast of the near surface wind

Bo Christiansen



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Contents

Colophone	2
Abstract	4
Introduction	4
Data and methodology	4
Downward propagation and correlations	5
Statistical forecast	8
Conclusions	12
Acknowledgments	14
References	15
Previous reports	16

Abstract

We investigate the potential for utilising the downward propagation of anomalies from the stratosphere to the troposphere in extended range statistical forecasts of the near surface zonal mean zonal wind at 60 ° N. It is found that the inclusion of stratospheric information increases the skill of the forecast on lead times larger than 5 days. Similar skill can not be obtained if the forecast model only includes tropospheric information. The largest skills are obtained for predictors in the lower stratosphere. Including more than one predictor - either in the stratosphere or in the troposphere - does not increase the skill. For lead times larger than 25 days daily mean values are predicted as well as values averaged over longer periods. The model that forecasts the wind averaged over 10 days with a lead time of 20 days explains about 14 % of the total variance of the wind. The skill can be improved by considering only strong anomalies.

Introduction

Downward propagation of anomalies in mid- and high latitudes was first observed in mechanistic models of the stratosphere in the 70ies (Holton and Mass 1976). In typical perpetual January experiments the variability has an oscillating form where the death of an anomaly at the lower boundary is followed by the birth of a new anomaly at the upper boundary. The phenomena is known as "stratospheric vacillations". The typical time-scale of the downward propagation is 50-100 days although it depends on the parameters of the mechanistic model. A parameter of particular importance is the strength of the wave-forcing at the lower boundary. The stratospheric vacillations were recently (Christiansen 1997, 2000) observed in general circulation model (GCM) experiments. It is important to note that in both the mechanistic models and the GCM (Christiansen 1999) the stratospheric vacillations are a result of a stratospheric instability and the vacillations exist even if all boundary conditions, including the wave forcing at the tropopause, are constant in time.

In the last two decades the group led by Kodera has published a series of papers analysing the observed poleward and downward propagation in the stratosphere (Kodera et al. 1990, Kodera 1995). However, it was first with the discovery of the Arctic Oscillation (Thompson and Wallace 1998) and the connection between the downward propagation and this global circulation mode (Baldwin and Dunkerton 1999) that the interest in the field grew remarkably. The major drive of the interest is the possibility of using the downward propagation to improve extended range forecasts. Several papers show significant connections between stratospheric anomalies and anomalies near the surface when the surface lags the stratosphere with 10-60 days (Christiansen 2001, Baldwin and Dunkerton 2001, Thompson et al. 2002, Kuroda 2002, Black 2002). A natural first step would be to develop statistical forecast models which incorporate this connection. This direction was taken in Charlton et al. 2003 and will be elaborated on in the present paper. Dynamical forecasting with GCMs are also an attractive possibility as the downward propagation is very well represented at least in some GCMs (Christiansen 2001). However, it is not known how well the downward propagation is represented in current extended range and seasonal forecast systems.

It should be noted that the possibility of using the downward propagation for forecasts is not directly linked to the underlying physical mechanism. It is still an open question how active the role of the stratosphere is. Even with a totally responding stratosphere which only reflects on the tropospheric state the stratosphere may still display information about the zonal mean and large scale waves that would be hard to obtain from the troposphere due to its higher level of small scale waves and temporal noise.

Data and methodology

Most previous studies of the downward propagation have relied on the NCEP reanalysis. In this study we will use the ERA40 reanalysis which has the advantage that it extends to 0.1 hPa where the NCEP (Kalnay et al. 1996) reanalysis stops at 10 hPa. We will see that concerning the zonal mean zonal wind at 60 ° the two data sets agree exceptionally well below 10 hPa. We use daily averages of the zonal wind defined on 16 (6 above 100 hPa) pressure levels for the NCEP data set and 26 (16 above 100 hPa, 5 above 10 hPa) pressure levels for the ERA40 data set. For both data sets the 44 years from 1958 to 2001 are used.

The present study deals exclusively with anomalies, i.e., deviations from the annual cycle. These anomalies were calculated by subtracting from each day the long term mean over the same calendar days.

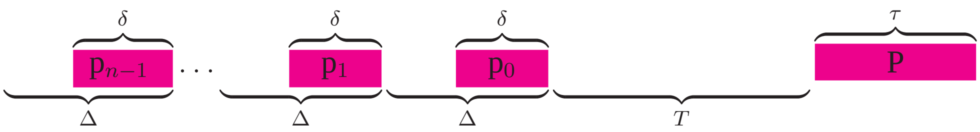

Figure 1: Schematic overview of the forecast model. The predictand P is separated from the n predictors p_i, $i = 0, 1, \ldots n-1$ by the lead time T. The predictand is averaged over a time interval τ. The predictors are averaged over a time interval δ and separated by a time interval Δ.

Our forecast model is based on simple multiple linear regression. Denoting the n predictors p_i, $i = 0, 1, \ldots n-1$, we determine the coefficient a_i such that $\sum a_i p_i(t)$ is the best fit to the predictand $P(t)$, i.e., the squares of the residuals are minimised. As a measure of the goodness of the fit we use the multiple correlation coefficient, i.e., the correlation between $\sum a_i p_i(t)$ and $P(t)$. We want to predict the zonal mean zonal wind at the surface from previous values of the zonal mean zonal wind at the surface or at another level. We want to allow for time averaging of both the predictand and the predictors so we put $P(t) =< u(0) >_{t+T}^{t+T+\tau}$ and $p_i(t) =< u(p) >_{t-i\Delta-\delta}^{t-i\Delta}$, where $< x >_{t1}^{t2}$ denotes the time average of x over the interval from $t1$ to $t2$. The situation is shown schematically in Fig. 1. Note, that with these definitions the predictand and the predictors are separated by the lead time T despite the time averaging. By the way the data have been treated any dependence of the predictand on the predictors is therefore a consequence of a dependence in the data being it physical or by chance.

To estimate the significance of the correlations we use the Monte Carlo approach described in Christiansen 2001. This approach involves the construction of surrogate time-series with the same length, the same auto-correlation spectrum and the same seasonal asymmetries as the original time-series. The distribution of the correlations calculated with the surrogate time-series (these correlations are different from zero only because of the finite sampling) are then compared to the correlation calculated with the original time-series.

Downward propagation and correlations

As mentioned in the previous section most work on the downward propagation have been based on data from the NCEP reanalysis. Before we use the ERA40 reanalysis we want to investigate if the two reanalysis differ with respect to the details of the downward propagation. The downward propagation at 60 ° N is clearly seen when the zonal mean anomalies are plotted as function of time and pressure as in Fig. 2 for the NCEP data and Fig. 3 for the ERA40 data. A figure similar to Fig. 2

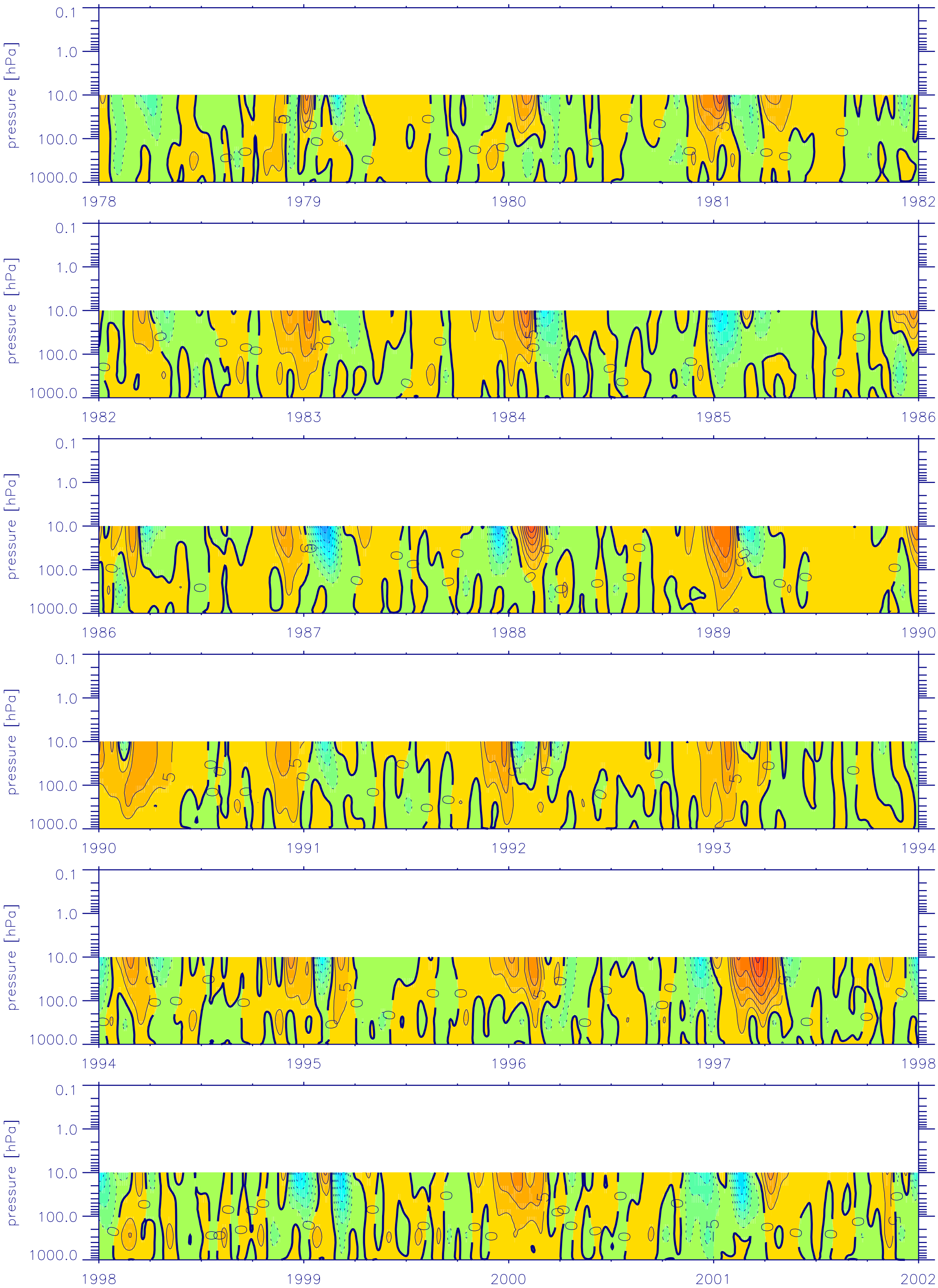

Figure 2: The zonal mean zonal wind at 60° N as function of time and pressure. The annual cycle and time-scales faster than 30 days have been removed. The data are from the ERA40 reanalysis. The contour levels are separated by 5 ms^{-1} and positive anomalies are yellow and red and negative anomalies are green and blue.

but for a shorter time period was shown in Christiansen 2001. Here we note the exceptional similarity of the two reanalyses although they are based on different models with different horizontal resolutions. This comparison suggests that the large scale features reflect the data and are only weakly affected by the model system.

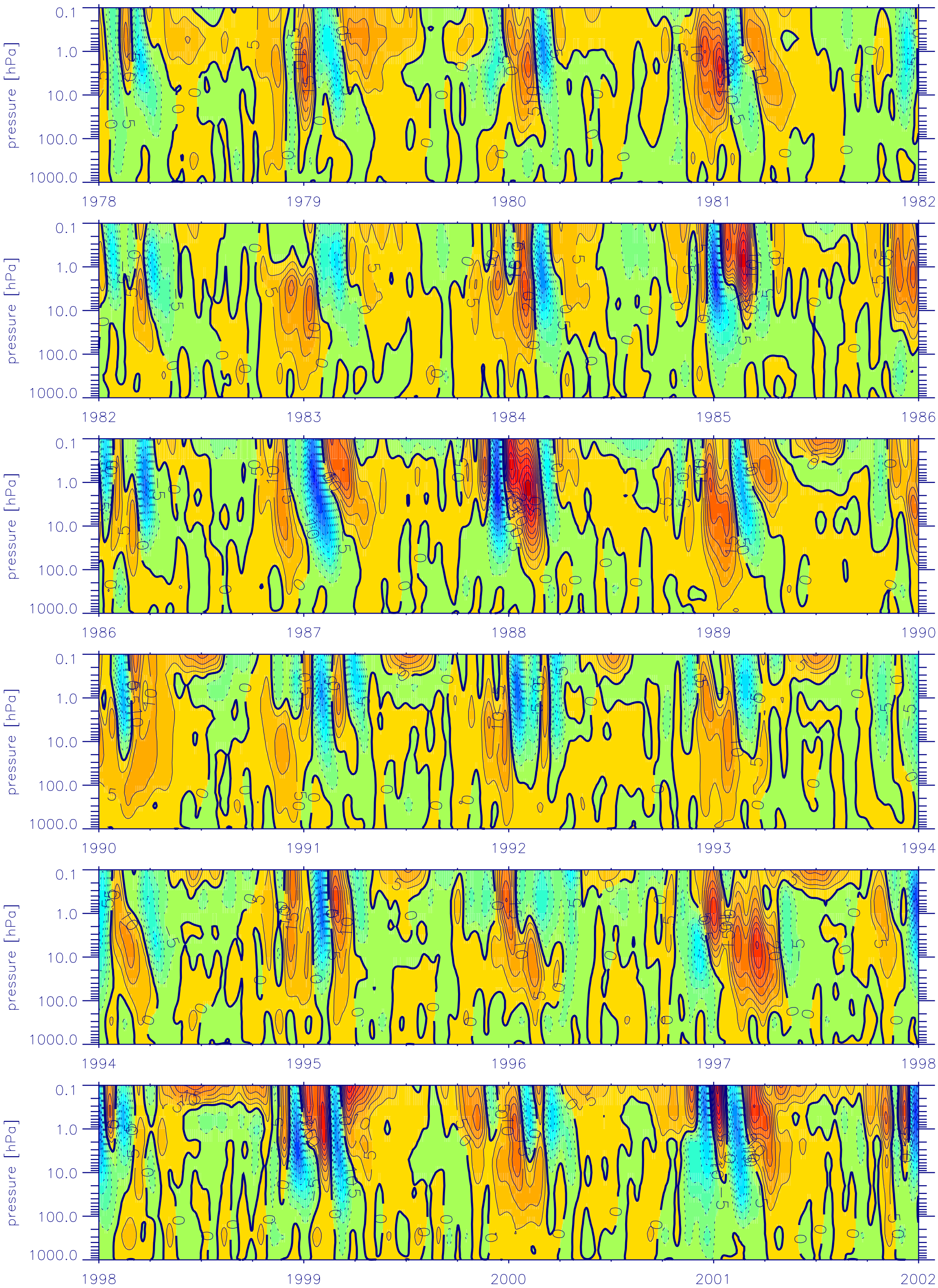

Figure 3: As Fig. 2 but for the NCEP reanalysis.

The downward propagation in the ERA40 reanalysis is summarised in Fig. 4, where the correlations of the zonal mean zonal wind at 10 hPa and at 1000 hPa with the zonal mean zonal wind at other levels are shown as function of time-lags between -50 and 50 days. The left panels are calculated from the low-passed filtered data and the right panel from unfiltered daily values. Downward propagation is clearly seen in all panels. The low-pass filtering has only little effect when the centre of the analysis is at 10 hPa. A larger effect of the filtering - up to a factor of two - is found when the centre is near the surface. An important feature of the upper panels is that the correlations for sufficient negative lags are larger in the stratosphere than in the the troposphere. This holds for lags

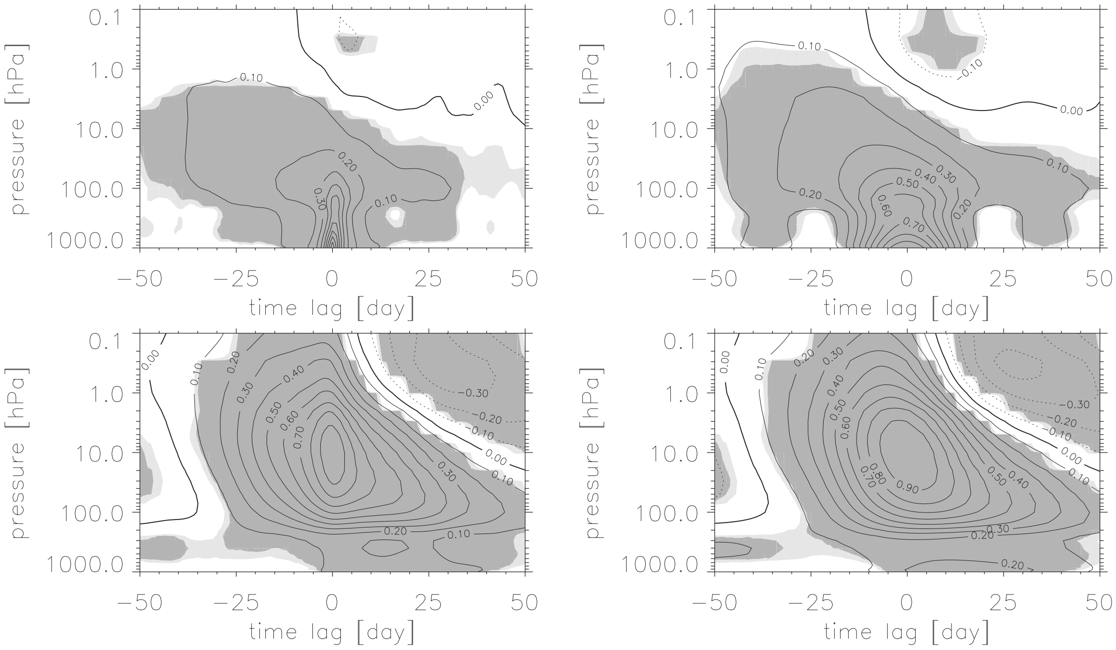

Figure 4: Lagged correlations at 60° N between the zonal mean zonal wind at the surface (upper panels) and at 10 hPa (lower panels) with the zonal mean zonal wind at other levels. The annual cycle has been removed. In the left panels are shown correlations for the unsmoothed daily data, in the right panels time-scales faster than 30 days have been removed. The data are from the ERA40 reanalysis.

less than -7 days for the unfiltered data and for lags less than -15 for the smoothed data. This observation suggests that the stratosphere may provide information for the prediction of the near surface wind that can not be found in the troposphere. However, the predictive power seems rather low with correlations in the stratosphere less than 0.2 for the daily data and less than 0.3 for the smoothed data.

The rather low correlations described above are related to a profound difference between the stratosphere and the troposphere concerning the time-scales of the circulation as demonstrated in Fig. 5. In the troposphere the major part of the variance is found at time-scales less than 60 days while only little power is found in the stratosphere on these time-scales. In the stratosphere below 10 hPa the larger part of the variance is found for time-scales between 70 and 250 days. A closer inspection shows that most of the strong spectral lines in the stratosphere extend into the troposphere and down to the surface giving some hope for the predictive power in particular if some of the rapid variability in the troposphere is averaged out.

Statistical forecast

In this section we present results from the statistical model described in Section 2. The model includes several parameters. We will in particular be interested in the lead time T and the time interval τ over which the predictand is averaged. Other parameters are the the number of predictors n, the time interval between the predictors Δ, and the time interval δ over which the predictors are averaged. The predictand will be the zonal mean zonal wind at the surface at 60 ° N and the predictors will be the zonal mean zonal wind at 60 ° N in different vertical levels in the troposphere and the stratosphere. In the following we consider the three winter months December, January, and February where the downward propagation is strongest.

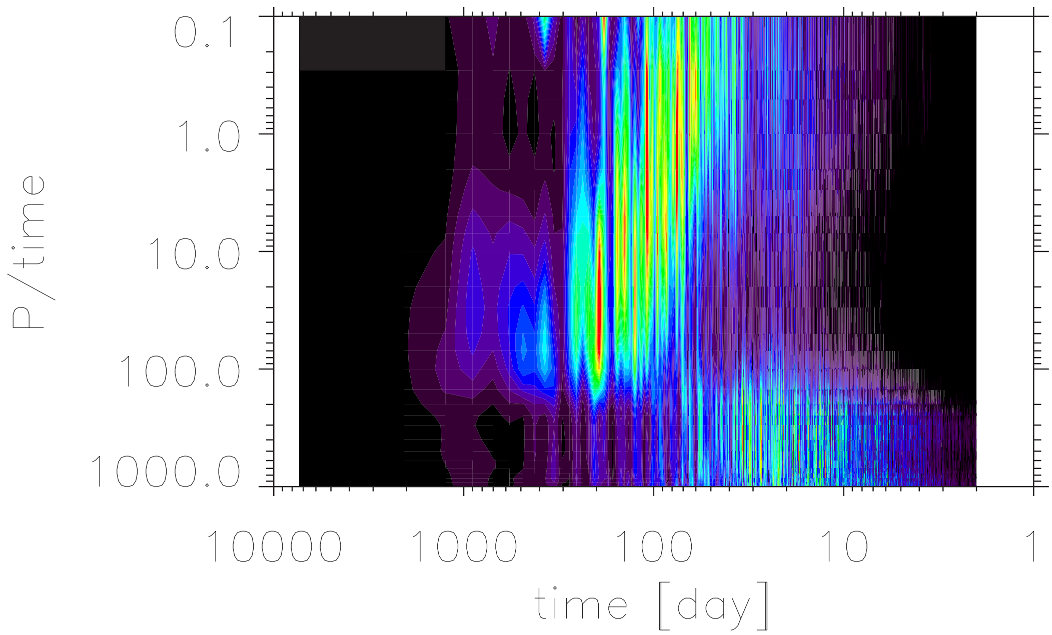

Figure 5: The power spectrum for the zonal mean zonal wind at 60 ° N at different altitudes. The ordinate shows the period [days] and the coordinate shows the vertical level [hPa]. The colours show the power divided with the period to facilitate comparison of the variance.

Fig. 6 shows the skill of the model as function of the lead time T for predictors chosen at the surface (red curve), at 70 hPa (blue curve), and at 10 hPa (green curve). In Fig. 6a $\tau = 1$ and in Fig. 6b $\tau = 15$. The other parameters are $n = 1$ and $\delta = 1$. With the zonal wind at the surface as the predictor and $\tau = 1$ the skill is larger than 0.6 for a lead time of 1 day but the skill decreases fast as function of the lead time. With the zonal wind at 70 hPa as predictor the skill is 0.4 for a lead time of 1 day. But now the skill decreases more slowly with the lead time and for lead times larger than 5 days the skill is larger than for the predictors at the surface. The largest difference in the skill is found for a lead time of 25-40 days where the difference is more than a factor of two. The skill for the predictor at 10 hPa is lower than for the predictors at 70 hPa especially for lead times less than 30 days while it is almost identical for lead times larger than 30 days. For $\tau = 15$ a similar picture is found but know a larger skill is obtained with the predictor in the stratosphere. This skill is now larger than the skill for the predictor at the surface for lead times between 10 and 50 days.

Calculating the distribution of the forecast skill from surrogate time-series resembling the predictand as discussed in Section 2 allow us to assess the value of the skill s_p such that skills larger than s_p are significantly different from zero with the possibility p. The value of s_p depends on the parameters of the model but mostly on τ. For the parameters in Fig. 6a (b) the value of $s_{0.95}$ is close to 0.1 (0.2), varying only little with T. Thus, significant skill at the 95 % level is obtained for $T < 25$ days for the predictor at 1000 hPa and for $T < 50$ days for predictor in the stratosphere.

More details of the dependence of the skill on the time interval τ over which the predictand is averaged and the lead time T are given in Fig. 7a. Here the predictor is at 70 hPa. It is seen that for small lead times ($T < 25$) days the skill increases strongly with τ and saturates for $\tau > 10$ days.

Fig. 8 offers a closer look at the dependence of the skill on the vertical level of the predictor. While the skill is almost constant with the predictor in the troposphere a large jump is seen around the tropopause. In the the stratosphere below 3 hPa the skill decreases slowly for lead times less than 25

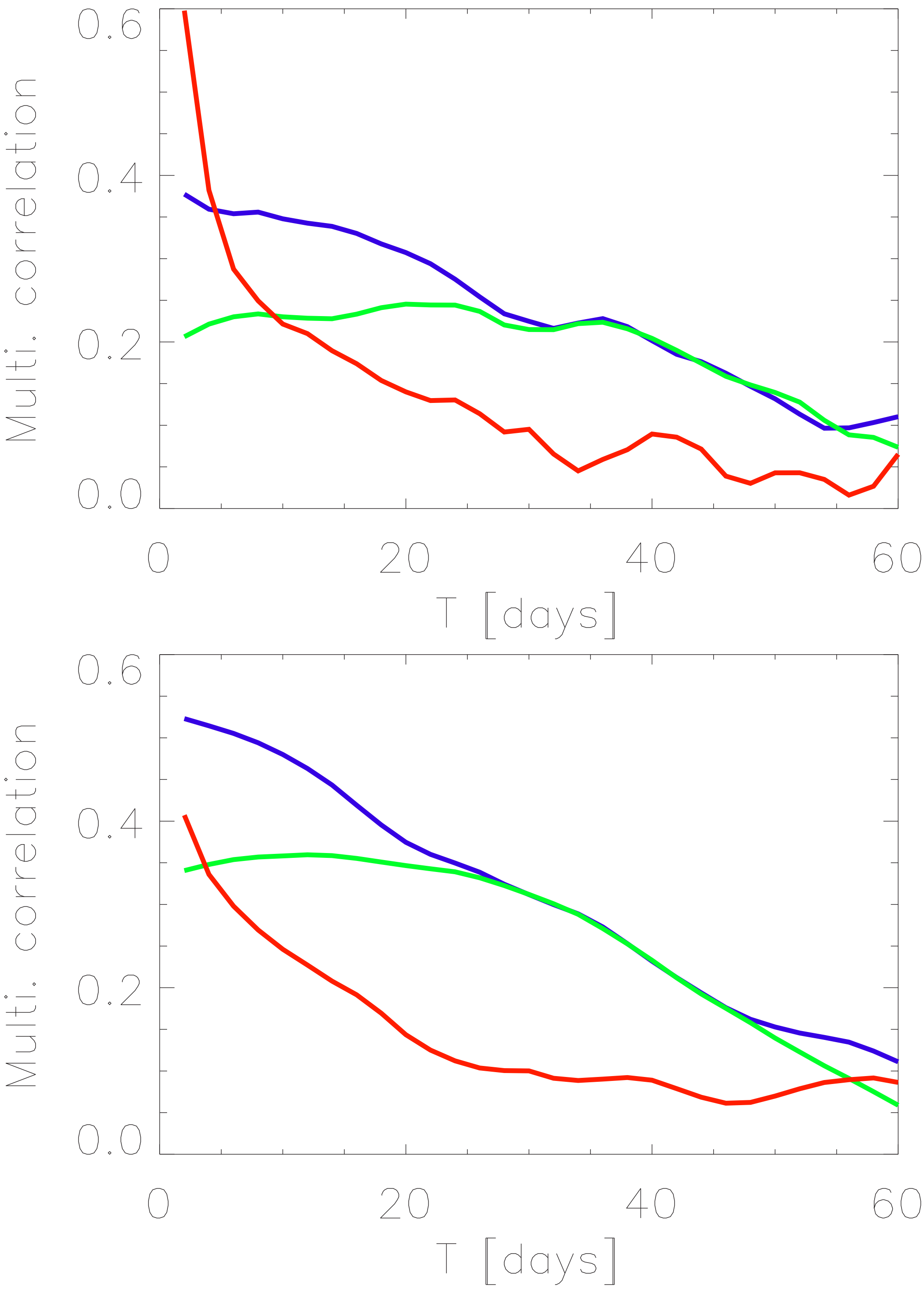

Figure 6: The forecast skill as function of lead time T. In the upper panel $\tau = 1$ day and in the lower panel $\tau = 15$ days. The other parameters of the model are $n = 1$ and $\delta = 1$ day. The vertical level of the predictors are 1000 hPa (red curve), 70 hPa (blue curve), and 10 hPa (green curve).

days while the skill is almost constant for lead times larger than 25 days. For lead times less than 25 days a maxima is found near 70 hPa.

The predictive skill increases only very weakly with the numbers of predictors as seen from Fig. 9. This means that only little is gained by including more information about the previous state of the stratosphere. Together with the implications of Fig. 8 this suggests that the model with only one

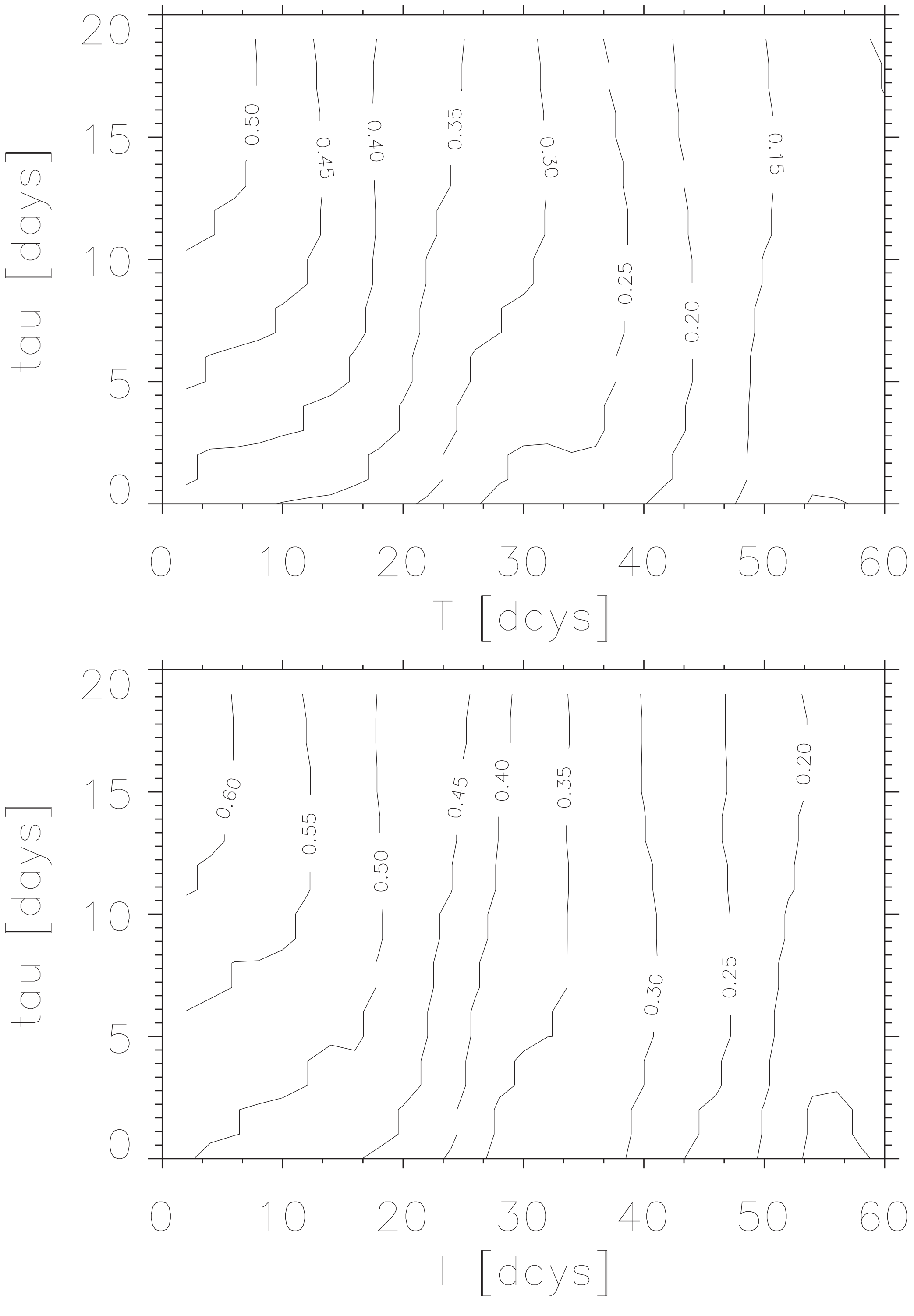

Figure 7: The skill as function of the lead time T and the time τ over which the predictand is averaged. The other parameters of the model are $n = 1$ and $\delta = 1$ day. The level of the predictor is 70 hPa. In the upper panel all winter days have been included while in the lower panel only strong events (where the absolute value exceeds 1.5 its median) have been considered.

predictor at a vertical level of 70 hPa will be hard to improve even in a model simultaneously allowing predictors at different vertical levels and with different lags. Additional calculations have confirmed this suggestion.

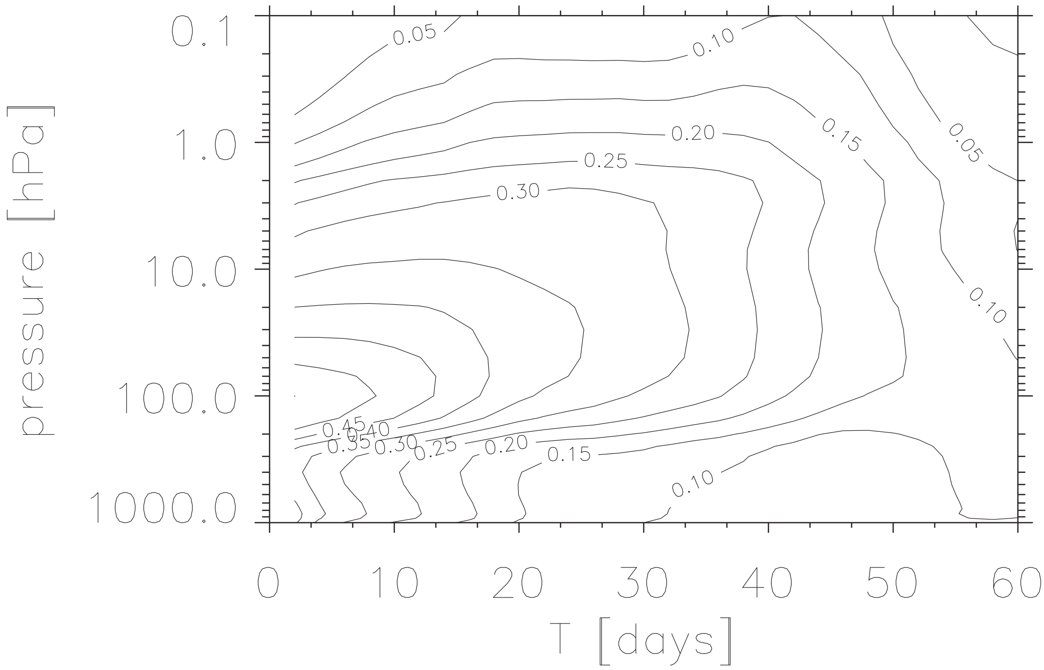

Figure 8: The skill as function of lead time T and the vertical level of the predictor. The other parameters are $n = 1$, $\delta = 1$ day, and $\tau = 15$ days.

We have also investigated if the inclusion of information from other latitudes in the stratosphere would improve the forecasts. As predictors we used the leading principal components obtained from an Empirical Orthogonal function Analysis of the zonal mean zonal wind in the northern hemisphere (north of 20 ° N) stratosphere. Again the result was negative.

Conclusions

We have investigated the potential for utilising the downward propagation of anomalies from the stratosphere to the troposphere in statistical forecasts for lead times up to 60 days. We have focused on forecasting the zonal mean zonal wind at the surface at 60 ° N. A simple forecast model based on linear regression was used (Fig. 1).

We have used data from the the ERA40 reanalysis which extends to 0.1 hPa. Most other studies of the downward propagation have been based on the NCEP reanalysis which has the upper boundary at 10 hPa. We therefore opened the paper with a comparison of the downward propagation in the two datasets. We found an excellent agreement of the zonal mean zonal wind anomalies at 60 ° N at all levels.

For lead times between 5 and 50 days we found that predictors in the stratosphere give better skill than predictors in the troposphere. The largest improvement - more than 100 % - is obtained for lead times between 20 and 40 days. Next to the lead time the skill is most dependent on the time over which the predictand was averaged. For small lead times less than 25 days averaging the predictand over 10 or more days improves the forecast. For larger lead times forecasting daily values give almost as good a skill as forecasting averaged values. The largest skills are obtained for predictors in the lower stratosphere. In particular for small lead times the skill has a distinct maximum for predictors near the tropopause. We found that including more than one predictor only improve the skill very little.

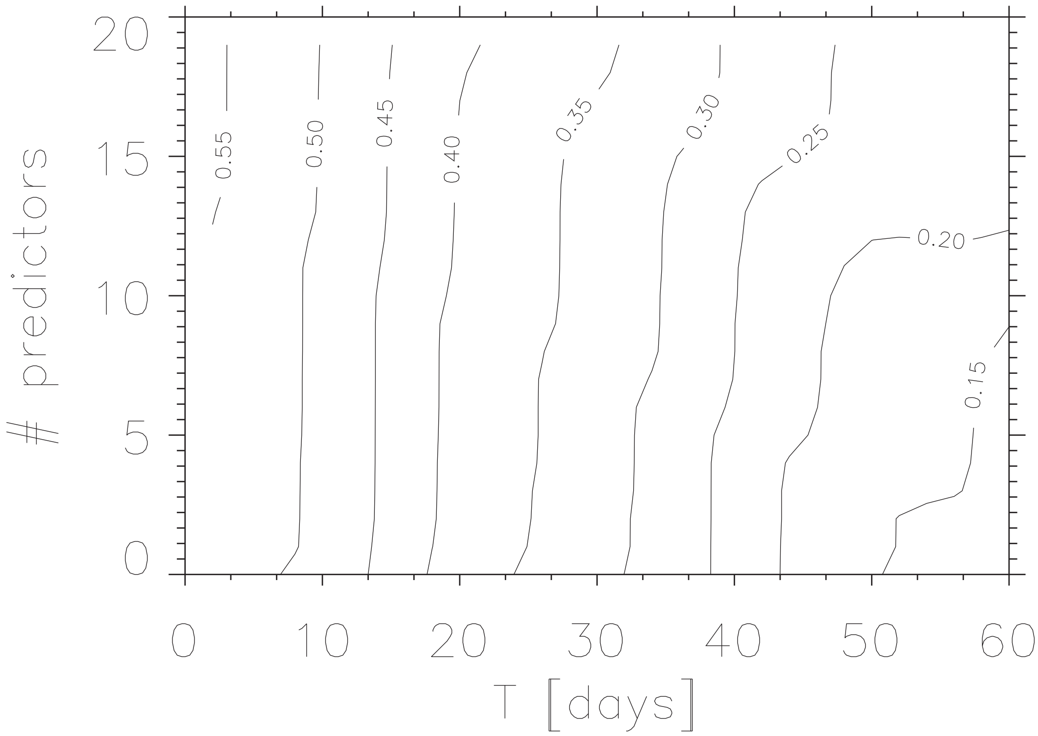

Figure 9: The skill as function of lead time T and the number of predictors n. The other parameters are $\delta = 1$ day, $\Delta = 5$ days, and $\tau = 15$ days. The level of the predictor is 70 hPa.

Our results show that the stratosphere holds information important for the future development of the troposphere and suggests that this information is not present in the troposphere itself. The last point should be taken with some caution as we have only reported work where the zonal mean zonal wind was used as predictors. Other tropospheric fields - perhaps related to the large scale waves - may hold the same information and if identified may be used as predictors instead of the stratospheric zonal mean wind. However, initial work in this direction has not revealed any possible tropospheric predictor with a skill near that of the the stratospheric zonal mean wind. Considering also the much higher noise level in the troposphere comparing to the stratosphere (here noise is understood as the variability on time scales comparable to the lead times of the forecast) we expect the predictive skill to be mainly of internal stratospheric origin.

Although a better skill can be obtained using a predictor in the stratosphere compared to a predictor in the troposphere the skills are not large. Forecasting the average wind over 10 days with a lead time of 20 days give a skill of 0.38. This corresponds to an explained variance of 14 %. It should be remembered that the forecast model is linear. With non-linear models more variance could be captured. This potential is illustrated in Fig. 7b where the skill is shown for a model restricted to periods where the absolute value of the predictand is large. The forecast over 10 days with a lead time of 20 days now explains 22 % of the variance. It should also be remembered that the skills of extended range forecasts are notoriously weak and that skills of the magnitude found in this paper may represent an important improvement. The importance of probability forecasts on lead times of 10-50 days is demonstrated in the recent exponential growth of weather derivative futures that allow companies to insure themselves against weather related losses. These contracts are typically traded monthly.

The statistical properties of the downward propagation are very well represented in some GCMs and it has also been demonstrated that the downward propagation in a GCM is robust to additional noise. Utilising the downward propagation in dynamical extended range forecasting is therefore a possibility. However, as mentioned in the introduction, until now no studies have been performed of the downward propagation in current weather forecast systems.

Acknowledgments

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References

Baldwin, M. P., and T. J. Dunkerton, Propagation of the Arctic Oscillation from the stratosphere to the troposphere, *J. Geophys. Res., 104,* 30937-30946, 1999.

Baldwin, M. P., and T. J. Dunkerton, Stratospheric Harbingers of Anomalous Weather Regimes, *Science*, **294,** 581-584, 2001.

Black, R. X., Stratospheric forcing of surface climate in the Arctic Oscillation, *J. Climate,* **15,** 268-277, 2002.

Charlton A. J., A. O'Neill, D. B. Stephenson, W. A. Lahoz, and M. P. Baldwin, Can knowledge of the state of the stratosphere be used to improve statistical forecasts of the troposphere? *Q. J. Roy. Met. Soc*, **129,** 3205-3224, 2003.

Christiansen, B., Guldberg, A., Hansen, A. W. and Riishøjgaard, L. P., On the response of a three-dimensional general circulation model to imposed changes in the ozone distribution, *J. Geophys. Res.*, **102**, 13051-13077, 1997.

Christiansen, B., Stratospheric vacillations in a general circulation model, *J. Atmos. Sci., 56,* 1858-1872, 1999.

Christiansen, B., A model study of the dynamical connection between the Arctic Oscillation and stratospheric vacillations, *J. Geophys. Res.*, **105**, 29461-29474, 2000.

Christiansen, B., Downward propagation of zonal mean zonal wind anomalies from the stratosphere to the troposphere: Model and reanalysis, *J. Geophys. Res.,* **106,** 27307-27322, 2001.

Holton, J. R., and C. Mass, Stratospheric vacillation cycles, *J. Atmos. Sci., 33,* 2218-2225, 1976.

Kalnay, E., et al., The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc., 77,* 437-471, 1996.

Kodera, K., K. Yamazaki, M., Chiba, and K. Shibata, Downward propagation of the upper stratospheric mean zonal wind perturbation to the troposphere, *Geophys. Res. Lett.*, **17,** 1263-1266, 1990.

Kodera, K., On the origin and nature of the interannual variability of the winter stratospheric circulation in the northern hemisphere, *J. Geophys. Res.*, **100,** 14077-14087, 1995.

Kuroda, Y., Relationship between the polar-night jet oscillation and the annular mode, *Geophys. Res. Lett.*, **29,** 10.1029/2001GL013933, 2002.

Thompson, D. W. J, and J. M. Wallace, The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophys. Res. Lett., 25,* 1297-1300, 1998.

Thompson, D. W. J., M. P. Baldwin, and J. M. Wallace, Stratospheric connection to Northern Hemisphere wintertime weather: implications for prediction, *J. Climate,* **15,** 1421-1428, 2002.

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