Multiple Regression Analysis of the JRA-25 Monthly Temperature

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1 INTRODUCTION

Long-term global reanalysis of atmospheric observations generates a high-quality homogeneous climate data set using a fixed modern data assimilation system and quality-controlled comprehensive observations. Reanalysis products have been used for a wide variety of climate studies and applications. Despite this reanalysis concept and usefulness, the quality of current reanalysis products is generally not adequate for the detection and attribution of low-frequency climate variability mainly due to historical changes in observation systems. Unexpected defective procedure and fragmented computation streams during production processes may also result in erroneous changes in reanalysis products. Recent growing concerns about anthropogenic climate change lead to need for improvement of reanalysis quality regarding not only general climatology but also long-term variability. This study investigates temporal variability of JRA-25 (Onogi et al., 2007), the latest reanalysis produced jointly by the Japan Meteorological Agency and the Central Research Institute of Electric Power Industry, to provide basic information about its climate quality.

The motivation of this study also arises from the study by Crooks and Gray (2005), in which they found significant signals to the 11-year solar cycle using ERA-40 (Uppala et al., 2005) from the surface to the lower mesosphere. Solar signals from reanalysis were also investigated by Haigh (2003) using NCEP R-1 (Kalnay et al., 1996). Because the vertical domain of JRA-25 covers the whole range of the stratosphere, it can be compared with ERA-40 in view of how well climate signals are detected in the stratosphere. As reviewed by Gray et al. (2005), empirical studies based on various observations have shown a variety of atmospheric responses to the solar cycle with increasing confidence. Detected signals, however, show some differences in the amplitudes and geographical and altitudinal patterns depending on observation sources. This study discusses robustness of the detection and attribution of climate signals focusing on the solar cycle.

2 METHODOLOGY

This study applies multiple regression analysis to zonally-averaged monthly temperature anomalies from JRA-25 and compares results with those from ERA-40 and NCEP R-1 to discuss spatial structures of climate signals. Temperature data used in this study cover 1979–2004, the whole period of JRA-25, (or 1979–2001 for ERA-40) at reference pressure levels with 2.5-degree lat/lon resolution from 1000 hPa to 1 hPa (or 10 hPa for the top level of NCEP R-1). Although native reanalysis grid has a higher spatial resolution, it has been confirmed for JRA-25 that reduced resolution does not much affect results described below.

Explanatory variables include linear trend, the cold tongue index (Deser and Wallace, 1990) associated with El Niño and Southern Oscillation (ENSO), Arctic Oscillation (AO) index by Climate Prediction Center[1], 10.7-cm solar radio flux[2] as a proxy of solar activity, stratospheric aerosol optical depth (Sato et al., 1993) to represent volcanic eruptions, an orthogonal pair of quasi-biennial oscillation (QBO) indexes, and a unit step function to explain a major discontinuity of reanalysis. The QBO indexes are the first two principal components to represent equatorial zonal wind variations in the stratosphere derived from JRA-25. These QBO indexes are almost equivalent to indexes derived from ERA-40. The set of explanatory variables is similar to that used in Crooks and Gray (2005) and Haigh (2003), but they consider North Atlantic Oscillation instead of AO and use additional indexes to represent annual and semi-annual cycles.

As shown in Figure 1, JRA-25 temperatures include several discontinuities in the stratosphere associated with satellite transitions. The step function for JRA-25 is used to explain the major discontinuity at the end of October 1998 associated with TOVS-ATOVS[3] transition. No other step function is used to avoid ambiguity of

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[1]http://www.cpc.noaa.gov/products/precip/CWlink/
[2]http://www.ngdc.noaa.gov/stp/SOLAR/ftpsolarradio.html
[3]TOVS: TIROS (Television and Infrared Observational Satellite) Operational Vertical Sounder, ATOVS: Advanced TOVS

understanding regression results. The step function for ERA-40 is used to explain the discontinuity at the end of March 1986, as shown in Figure 2. Although NCEP R-1 possibly includes spurious changes associated with satellite transition, such as negative anomalies in the upper troposphere from the late 1990s, no step function is used considering its rather continuous behavior.

Figure 3 shows normalized time series of the ENSO, AO, solar, volcanic, and QBO indexes. Note that these explanatory variables have some relations to each other. For example, two peaks of the volcanic index, El Chichón and Mt. Pinatubo eruptions, correspond to a similar declining phase of the first and second solar cycles, respectively. Besides such an accidental relation, some of the indexes are possibly affected by non-linear interaction involving multiple factors. For example, the frequency of QBO varies systematically with the solar cycle (Salby and Callaghan, 2006), which makes difficulties in the attribution of climate signals in the tropical lower stratosphere.

The regression model used in this study incorporates auto-regression (AR) terms, considering that elements of residual time series are generally not independent of each other for climate variables. The model is formulated as follows:

$$Y_t = \sum_j x_{tj}\beta_j + W_t, \quad W_t - \phi_1 W_{t-1} - \cdots - \phi_p W_{t-p} = Z_t, \tag{1}$$

where Y, x, W, and Z are time series of temperature, explanatory variables, regression residual, and AR residual that is supposed to be white noise; β and ϕ are regression coefficient and AR coefficient; subscript t, j, and p are time index, explanatory variable index, and AR order. Regression coefficients are estimated by the generalized least-squares method considering covariance matrix of W according to Brockwell and Davis (2002). AR order and coefficients are basically estimated by likelihood maximization. Regression coefficients and AR coefficients are determined iteratively.

As an example, Figure 4 shows regression coefficients for JRA-25 temperature at 70 hPa, 10N by the generalized least-squares method in comparison with those by the ordinary least-squares method. While the magnitude of regression coefficients are not much different between the two method, confidence intervals are substantially larger in the generalized least-squares method, which is acceptable because residual dependency is appropriately incorporated in computing variance of regression coefficients. The ordinary least-squares method would overestimate climate signals.

3 RESULTS

Figure 5 to 9 compare the three reanalyses with regard to vertical-meridional distributions of regression coefficients for ENSO, AO, solar, and volcanic signals in units of kelvin per standard deviation and linear trend in units of kelvin per decade. Regression coefficients for QBO signals and the step function are also shown in Figure 10 for JRA-25. Although zonal averaging may result in reduced signals for zonally asymmetric phenomena like ENSO, spatial structures of climate signals represented by the regression coefficients are basically consistent with previous studies.

ENSO signals are characterized by tropospheric warming in the tropics and compensating cooling above (Reid, 1994). The warming signal indicates vertical propagation in the Northern Hemisphere, which is consistent with the fact that ENSO usually peaks in boreal winter when signal propagation is allowed in background westerlies in the Northern Hemisphere (García-Herrera et al., 2006).

AO signals show well-known dipole structure in northern mid to high latitudes throughout the troposphere. The cooling signal centered at the north pole extends to the lower stratosphere with increasing magnitude, and the surrounding warming signal in the extratropics appears to extend to the Southern Hemisphere toward the lower stratosphere, both of which are consistent with findings by Baldwin and Dunkerton (1999). Upper stratospheric AO signals comprise another dipole structure with those in lower altitudes and suggest changes in the polar night jet, leading to AO through the downward propagation mechanism (Kodera and Kuroda, 2000).

Although influences of the solar variability on the Earth's climate are not fully understood, some of the significant solar signals shown in the regression results are well documented in previous literature. Positive signals in the tropical upper stratosphere are likely due to direct solar ultraviolet (UV) heating. Because the

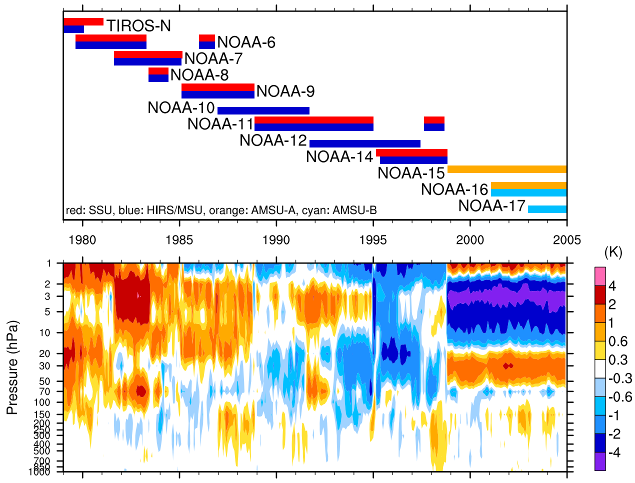

Figure 1: Assimilated periods of TOVS/ATOVS satellites in comparison with pressure-time cross section of globally-averaged temperatures from JRA-25.

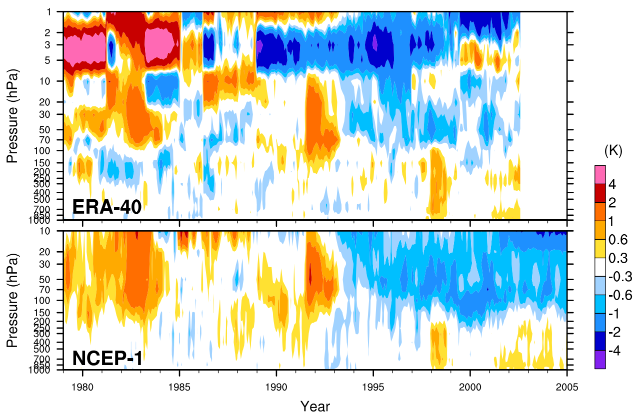

Figure 2: Pressure-time cross sections of globally-averaged temperatures from ERA-40 and NCEP R-1.

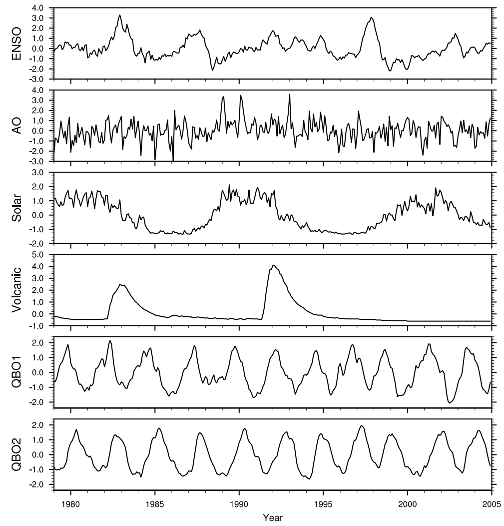

Figure 3: Normalized time-series of ENSO, AO, solar, volcanic, and QBO indexes.

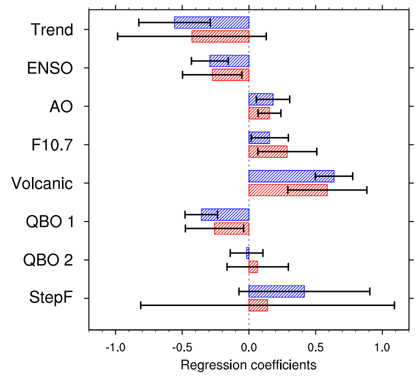

Figure 4: Regression coefficients for JRA-25 temperature at 70 hPa, 10N. Red/blue bar indicates results from generalized/ordinary least-squares with 95% confidence interval.

total solar irradiance is less variable than the UV irradiance, significant signals in the troposphere and the lower stratosphere are considered to be indirect solar influences. In comparison with Crooks and Gray (2005), the direct signal in the tropical upper stratosphere in this study is less clear; the peak response to the solar cycle, defined as 120-unit change in the 10.7 cm flux, is about 0.7 K and 0.9 K (values in Figure 7 are multiplied by 2.34) for JRA-25 and ERA-40, respectively, which are substantially smaller than 1.75 K found by Crooks and Gray (2005). Differences are also noticed for the lower stratospheric signal; Figure 7 indicates positive responses throughout low latitudes while Crooks and Gray (2005) detected a pair of positive responses centered about 25N and 25S and not significant equatorial region. Presumably, these differences are due to methodology differences in the multiple regression procedure, which remains a matter of debate in particular for the non-linear interaction between solar and QBO signals.

Compared to ENSO and AO signals, differences among the three reanalyses are noticeable for solar signals. Parts of significant regions in the stratosphere from JRA-25 and ERA-40 are not necessarily consistent with each other. The vertical extent of positive signal in the tropical lower stratosphere is more confined in JRA-25. Mid-latitude troposphere signals are more clearly identified in NCEP R-1. These inter-product differences provide a measure of robustness of specific climate signals.

Volcanic signals are characterized by warming in the lower stratosphere due to enhanced absorption of short-wave radiation and resulting cooling in the troposphere. The lower-stratospheric warming distributes

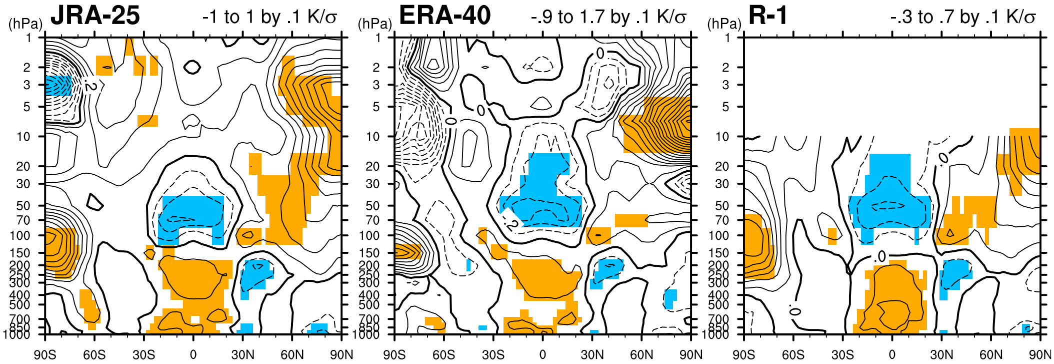

Figure 5: ENSO signal in zonally-averaged monthly temperature anomalies from JRA-25 (left), ERA-40 (center), and NCEP R-1 (right) represented by regression coefficients in units of kelvin per standard deviation of the ENSO index. Orange/blue shading indicates positive/negative values with 0.05 significance level. Thick/dashed contours denote zero/negative values.

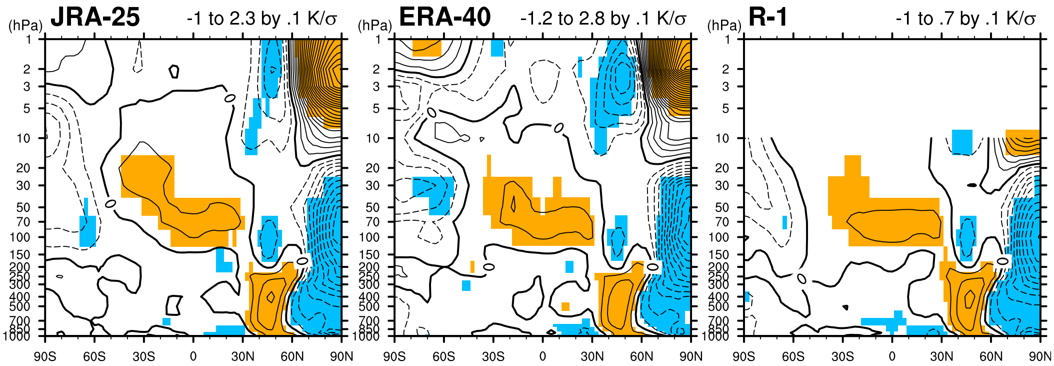

Figure 6: Same as Figure 5, except for AO signal.

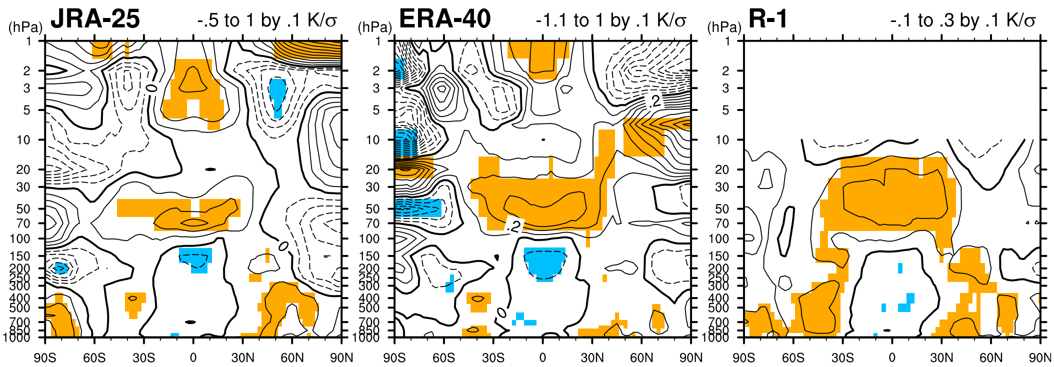

Figure 7: Same as Figure 5, except for solar signal.

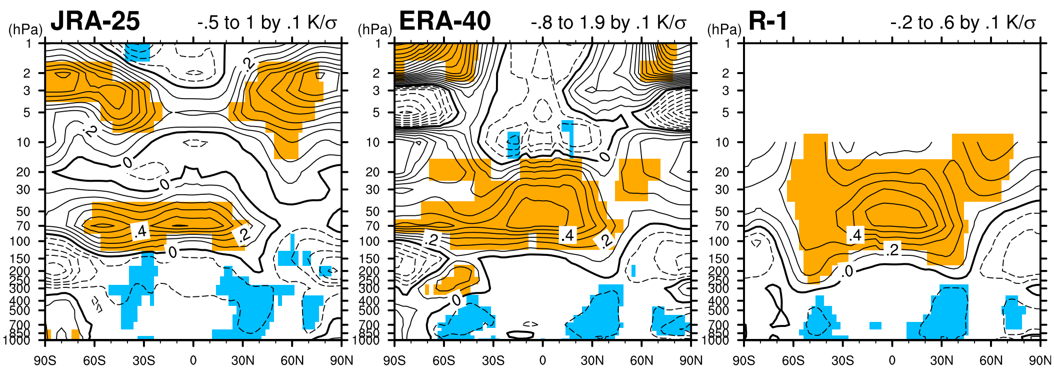

Figure 8: Same as Figure 5, except for volcanic signal.

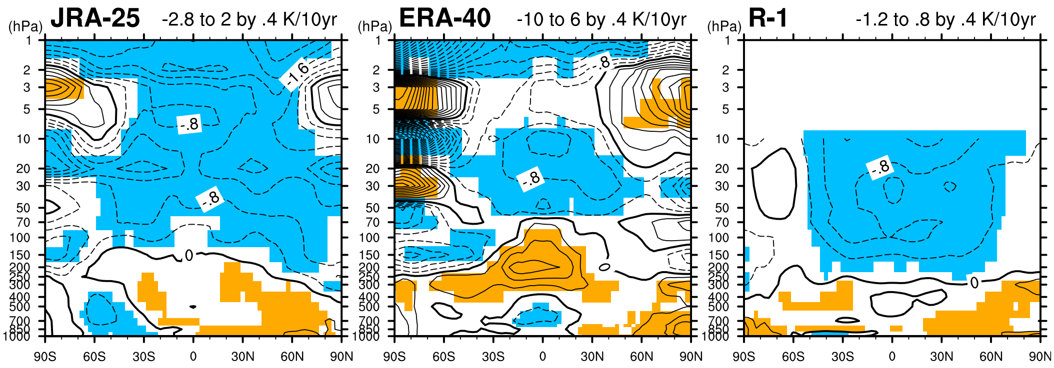

Figure 9: Same as Figure 5, except for linear trend in units of kelvin per decade.

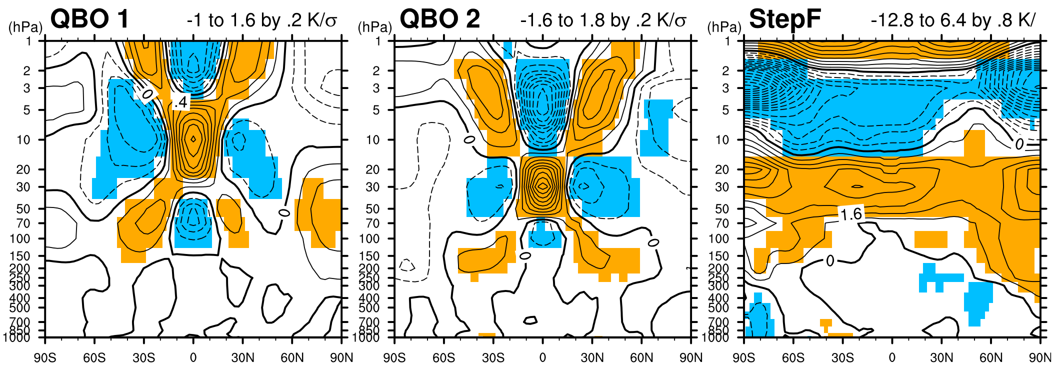

Figure 10: QBO signals (left and center) and discontinuities explained by the step function (right) in zonally-averaged monthly temperature anomalies from JRA-25 represented by regression coefficients in units of kelvin per standard deviation for QBO or kelvin for the step function. Contour properties are the same as in Figure 5.

over broader latitudes than that for the solar signal. Significant signals in the upper stratosphere are possibly indirect responses related to differential heating between sunlit areas and the polar night. As in the case of solar signals, the significant positive region in the lower stratosphere is more confined in JRA-25, and differences between JRA-25 and ERA-40 are relatively large in the upper stratosphere.

Linear trends basically indicate tropospheric warming and stratospheric cooling as an evidence of anthropogenic climate change due to increasing long-lived greenhouse gases and depleting ozone. One major exception is spurious cooling in the southern mid-latitude troposphere of JRA-25. In the stratosphere, the step function applied to JRA-25 reasonably explains TOVS-ATOVS differences and results in rather homogeneous trends. The satellite transition impacts are marginal in the troposphere, which has been confirmed from an experimental regression analysis excluding the step function variable. Regarding ERA-40, however, regression coefficients for the step function (not shown) indicate some significant values in the troposphere, which seems to add erroneous trend signals in the tropics.

Details in the tropical troposphere display some discrepancies among the three reanalyses, implying insufficient climate quality of current reanalysis as well as its source observations (e.g., Sterin et al., 2008). JRA-25 trends are about 0.1 K/decade (not significant) and around a lower bound of independent estimations summarized in the latest report of Working Group I of the International Panel on Climate Change. The amplification of upper tropospheric warming, which is theoretically predicted considering the moist adiabatic response to greenhouse-gas forcing, is vague in JRA-25, or extremely exaggerated in ERA-40 partly due to the side effect of the step function. NCEP R-1 trends are not statistically significant and partly negative at mid to upper levels. By contrast, greater amplitude in the upper troposphere is noticeable for ENSO signals from JRA-25 and ERA-40.

QBO signals (shown for JRA-25 only) clearly illustrate staggered structure around the tropical stratosphere and surrounding regions corresponding to the orthogonal pair of the QBO indexes. This structure is understood as a response related to thermal wind balance in the lower stratosphere, and signals in higher latitudes come from the winter hemisphere (e.g., Randel et al., 1999). Three-cell structure in the vertical alignment of significant regions has been recognized by Pascoe et al. (2005) from ERA-40.

4 CONCLUSION

Temporal variability of zonally-averaged upper-air temperatures is reasonably detected from reanalysis products using the multiple regression analysis with AR terms. Spatial structures of long-term trend and other component variability from JRA-25 are generally consistent with current scientific understanding. Intercomparison using multiple reanalysis products provides useful information about reanalysis quality and robustness of climate signals.

Further investigation is needed to ensure sensitivity to the choice of explanatory variables and to illustrate more complete structure of climate signals including other meteorological elements. Because of the limitation of regression analysis, comparison with climate model experiments would be helpful to isolate relevant components to a specific signal and to understand their non-linear interaction.

References

Baldwin, M. P. and T. J. Dunkerton, 1999: Propagation of the arctic oscillation from the stratosphere to the troposphere. *J. Geophys. Res.*, **104**, 30937–30946.

Brockwell, P. J. and R. A. Davis, 2002: *Introduction to time series and forecasting*. Springer-Verlag, New York, 2nd edition.

Crooks, S. A. and L. J. Gray, 2005: Characterization of the 11-year solar signal using a multiple regression analysis of the ERA-40 dataset. *J. Climate*, **18**, 996–1015.

Deser, C. and J. M. Wallace, 1990: Large-scale atmospheric circulation features of warm and cold episodes in the tropical Pacific. *J. Climate*, **3**, 1254–1281.

García-Herrera, R., N. Calvo, R. R. Garcia, and M. A. Giorgetta, 2006: Propagation of ENSO temperature signals into the middle atmosphere: A comparison of two general circulation models and ERA-40 reanalysis data. *J. Geophys. Res.*, **111**, D06101, doi:10.1029/2005JD006061.

Gray, L. J., J. D. Haigh, and R. G. Harrison, 2005: The influence of solar changes on the earth's climate. technical note 62, Hadley Centre.

Haigh, J. D., 2003: The effects of solar variability on the Earth's climate. *Philos. Trans. Roy. Soc. A*, **361**, 95–111.

Kalnay, E. et al., 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.

Kodera, K. and Y. Kuroda, 2000: Tropospheric and stratospheric aspects of the arctic oscillation. *Geophys. Res. Lett.*, **27**, 3349–3352.

Onogi, K. et al., 2007: The JRA-25 reanalysis. *J. Meteor. Soc. Japan*, **85**, 369–432.

Pascoe, C. L., L. J. Gray, S. A. Crooks, M. N. Juckes, and M. P. Baldwin, 2005: The quasi-biennial oscillation: Analysis using ERA-40 data. *J. Geophys. Res.*, **110**, D08105, doi:10.1029/2004JD004941.

Randel, W. J., F. Wu, R. Swinbank, J. Nash, and A. O'Neill, 1999: Global QBO circulation derived from UKMO stratospheric analyses. *J. Atmos. Sci.*, **56**, 457–474.

Reid, G., 1994: Seasonal and interannual temperature variations in the tropical stratosphere. *J. Geophys. Res.*, **99**, 18923–18932.

Salby, M. L. and P. F. Callaghan, 2006: Relationship of the quasi-biennial oscillation to the stratospheric signature of the solar cycle. *J. Geophys. Res.*, **111**, D06110, doi:10.1029/2005JD006012.

Sato, M., J. E. Hansen, M. P. McCormick, and J. B. Pollack, 1993: Stratospheric aerosol optical depths, 1850–1990. *J. Geophys. Res.*, **98**, 22987–22994.

Sterin, A. M., V. M. Khan, and K. G. Rubinshtein, 2008: Upper-air temperature trends: Current problems and some recent results. *Climate variability and extremes during the past 100 years*, Brönnimann et al., eds., Springer, 85–101.

Uppala, S. M. et al., 2005: The era-40 re-analysis. *Quart. J. Roy. Meteor. Soc.*, **131**, 2961–3012.