Impact of ENSO on European Climate

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Abstract

The El Niño – Southern Oscillation (ENSO) affects many parts of the globe, particularly in the tropics where changes in rainfall and temperature due to the varying phase of ENSO are the single largest source of year-to-year change. Clear ENSO influences on the extratropics are found over North America and Australia but Atlantic links are much less clear. In this short paper we review some of the attempts to identify ENSO teleconnections to the Atlantic and Europe and unify some of the earlier studies to point to a clear ENSO teleconnection to the Atlantic basin. The main signal is for cold conditions over Northern Europe during El Niño and a circulation anomaly that corresponds to the negative phase of the North Atlantic Oscillation. Piecing together evidence from recent studies we show that there are at least two major pathways by which the tropical Pacific affects Atlantic-European seasonal climate. We also show evidence for non-linearity in the response that helps to explain the discrepancy between studies that focus on short time periods or individual events and those that include more comprehensive sets of ENSO events. Given the remarkable level of ENSO predictability already achieved in seasonal forecasts, these teleconnections offer the opportunity of at least a moderate level of predictability for Europe during active ENSO years.

1. Introduction: ENSO and its teleconnections

The climatological state of the equatorial Pacific Ocean is for a strong East to West increase in sea surface temperature. The ocean and atmosphere are strongly coupled in this region (Lindzen and Nigam, 1987). Relatively low sea level pressure and deep convection occur over the warm West Pacific ocean. This rising motion is fed by westward winds along the equator in the lower troposphere and outflows into an eastward Pacific wind in the upper troposphere. Descending motion further East completes the Walker circulation (Walker, 1924). The westward wind at the surface applies westward stress to the equatorial Pacific Ocean. This drives upwelling in the Eastern tropical Pacific, pulls cold water from depth to the surface near coast of South America and advects warm water into the West Pacific, helping to maintain the East-West surface temperature gradient. ENSO events disrupt this circulation every few years and lead to a breakdown (strengthening) of the Walker circulation during the warm (cold) ocean phases of the oscillation. The location and intensity of atmospheric convection undergo corresponding changes and increased rainfall occurs in the mid Pacific during the warm (El Niño) phase (Fig.1).

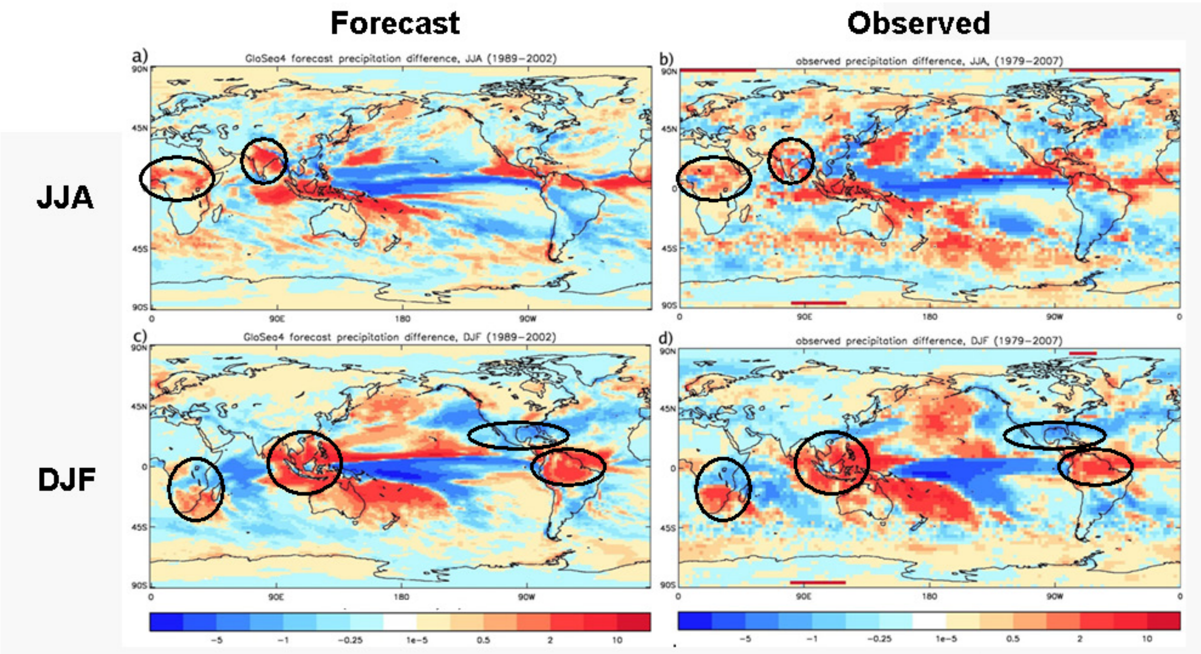

Figure 1: Differences in seasonal mean rainfall between La Niña and El Niño in seasonal forecasts (left) and observations (right). Blue implies more rainfall during El Niño than La Niña. Black circles highlight some of the better known tropical ENSO teleconnections. Units are mm/day. Figure from Arribas et al., Mon. Wea. Rev. 2011.

In addition to the central Pacific, significant changes in rainfall also occur over many other tropical regions. Figure 1 also shows similar anomalies derived from seasonal hindcasts of El Nino and La Nina years at lead times of 1-3 months. This demonstrates the excellent level of predictability of tropical ENSO anomalies well beyond that supplied by the initial atmospheric conditions alone. Indeed ENSO events can usually be predicted many months ahead of their boreal winter peak and this forms a cornerstone of seasonal forecasting.

The changes in convection in Figure 1 are associated with changes in upper tropospheric outflow and hence divergence. If this divergence occurs in a region of significant atmospheric absolute vorticity then a strong regional source of anomalous Rossby wave activity results (e.g. James 1994). Rossby waves can easily propagate into the extratropics given the dominance of eastward flow in the troposphere and so there are established mechanisms that could in principle transfer the ENSO signal to the extratropics. Despite this, studies have not identified waves from Pacific sources that produce Atlantic-European effects consistent with observations.

2. Search for an ENSO effect over Europe

Observational studies of correlations between Euro-Atlantic climate and ENSO yield only weak and inconclusive results (e.g. Trenberth and Caron, 2000). However, given that ENSO is active only once every few years, and that there are many other influences on the seasonal climate of this highly variable region, it is perhaps not surprising that interannual correlation coefficients are small. If instead a composite analysis is carried out between European climate and ENSO, then more suggestive results start to emerge. Fraedrich and Müller (1992) carried out one such analysis using observational weather station data. They showed that on average Northern Europe tends to be colder (warmer) during El Niño (La Niña) winters and that the differences are related to a southward shift in the track of cyclones during El Niño.

A second reason that some studies failed to identify a strong ENSO teleconnection to Europe is that composites are often made on the tradition winter season (Dec-Feb). Nature on the other hand shows no respect for our definition of the winter season and there is intraseasonality in the cold (warm) signal during El Niño (La Niña) which is strongest in late winter. A different but statistically significant signal occurs in early winter (e.g. Moron and Gouirand, 2003, Fereday et al 2008). This explains the weakening of the apparent signal when calculated over the traditional season. We return to this intraseasonal variation later.

Since the strength of the results for an ENSO influence on Europe depend on the analysis method and intraseasonal variations in the signal, the skeptical researcher might well suspect that this could be a spurious signal that results from over examination of observational data. However, there are now a growing number of modeling results which reproduce the observed signal. For example, ensembles of simulations of the prolonged El Nino event of 1940-42 reproduce the anomalously cold signal during those winters (Brönnimann, 2004) and the European ENSO signal arises through a southward shift in the path of modeled Atlantic cyclones during El Niño (Bulić and Brankowić, 2007) as suggested above from observational studies.

3. Meanwhile in the stratosphere…

Since the late 1970s, satellite radiometer data has complemented existing radiosonde analyses and lead to a greater focus on year-to-year variability in the stratosphere. Early studies suggested unusually high amplitudes of the longest planetary waves, a weaker than usual polar vortex and higher than usual polar stratospheric temperatures under El Niño conditions (Quiroz, 1983, Van Loon and Labitzke, 1987). Simulations of ENSO effects with global climate models were able to reproduce the pattern of observed stratospheric anomalies (Hamilton, 1993) and subsequent simulations showed a significant weakening of the zonally averaged stratospheric circulation and corresponding increase in polar temperatures that agreed with satellite analyses (Scaife, 1998). More recent studies have confirmed that this is due to an increase of several tens of percent in the frequency of sudden stratospheric warmings during El Niño winters (e.g. Manzini et al 2006, Taguchi and Hartman 2006, Ineson and Scaife 2009, Bell et al 2009).

Sudden stratospheric warmings are themselves driven by zonal momentum forcing from dissipation and transience of planetary wave fluxes (Matsuno 1971). The non-conservative evolution of wave fluxes of heat and momentum in the stratosphere lead to a deceleration of the zonal circulation as encapsulated in the transformed Eulerian Mean equations of Andrews and McIntyre (1978):

$$\frac{\partial u}{\partial t} - 2\Omega \sin\phi \overline{v}^{*} = F$$

$$\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}\left(\overline{v}^{*}\cos\phi\right) + \frac{1}{\rho_o}\frac{\partial}{\partial z}\left(\rho_o \overline{w}^{*}\right) = 0$$

$$\Rightarrow \overline{w}^{*} = -\frac{1}{\rho_o a\cos\phi}\frac{\partial}{\partial\phi}\left\{\frac{\cos\phi}{2\Omega\sin\phi}\int_{z}^{\infty}\rho_o F dz\right\}$$

Figure 2: The transformed Eulerian Mean momentum and continuity equations. The final line shows the relationship between vertical residual velocity and the divergence of the EP flux (after Haynes et al 1991).

Given that it is this large scale wave driving that produces sudden stratospheric warmings, can we identify this process at work in the stratosphere during El Niño winters?

The vertical structure of ENSO anomalies shows a large increase in the amplitude of the longest planetary waves (wave 1) not only in the stratosphere as seen in the early observations mentioned above but also throughout the troposphere (Manzini et al 2006). This can be traced back to the surface teleconnections where wave amplitude is increased due to constructive interference of the North Pacific ENSO teleconnection with the Aleutian Low (Ineson and Scaife 2009). It has also been shown that due to their vertical propagation, these large scale waves increase the Eliassen-Palm flux into the stratosphere and hence its convergence (**F** in Figure 2, Garcia-Herrera et al 2006). A proportion of this convergence decelerates the stratospheric zonal circulation (eq. 1 in Fig.2) and leads to greater descent (eq. 3 in Fig.2) and hence a warmer stratosphere. The net effect is a filling of the usual polar cyclone in the stratosphere:

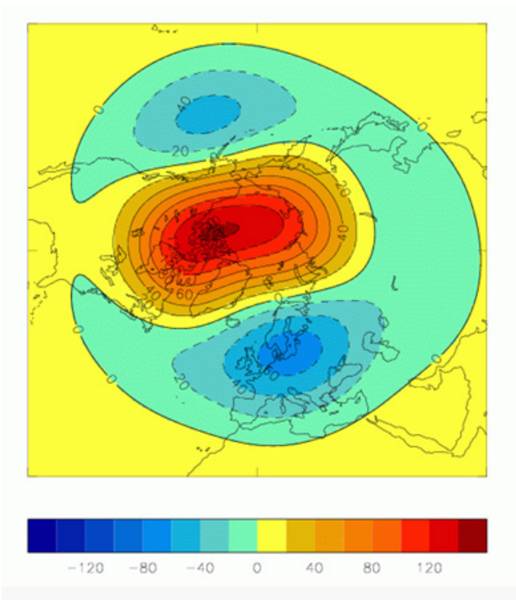

Figure 3: Geopotential height anomaly at 50hPa during El Nino conditions (after Ineson and Scaife 2009). Units are m.

4. Putting all this together

Interestingly, the filling of the polar stratospheric cyclone shown in Figure 3 shows a strong intraseasonal evolution in which it strengthens first in the upper stratosphere and then at progressively lower levels, weakening the westerly winds through the stratosphere as winter progresses (Manzini et al 2006, Ineson and Scaife 2009). This descending anomaly is a characteristic of wave-mean flow interaction where driving of the mean flow by atmospheric waves gradually burrows its way down towards a (quasi-steady) wave source. In late winter (February) the anomaly reaches the lower stratosphere, and with what appears to be a relatively fast response it connects across the depth of the troposphere to the surface.

The timing of this average behaviour agrees remarkable well with the intraseasonal change in the ENSO teleconnection to Europe that was noted earlier from observations. Furthermore, the pattern of surface response in the model closely matches that seen in observational analyses (Ineson and Scaife 2009, Cagnazzo and Manzini 2009). It corresponds to a negative North Atlantic Oscillation/Arctic Oscillation pattern (Hurrell 1995, Thompson and Wallace 2000) with increased sea level pressure over the Arctic and a compensating decrease of pressure over mid latitudes. In balance with this anomaly there is also a decrease in the eastward winds across the Atlantic basin, a southward shift in the Atlantic storm track and a cold signal over northern Europe – just as was found in the earlier studies described above. It therefore seems that we have arrived at a consistent picture in which we can trace the teleconnection pathway from the tropical Pacific, to the Northern Pacific, into the stratosphere through vertically propagating Rossby waves which weaken the stratospheric polar night jet. Descending wave mean flow interaction then leads to an average delay of a few weeks while the ENSO anomaly propagates to the lower stratosphere. Finally, on reaching the tropopause there is a fast response, likely occurring through baroclinic eddies in the storm tracks which leads to the observed negative NAO response seen over the Atlantic-European region during most El Niño events. The schematic in Figure 4 illustrates this process.

The stratosphere varies in time with the changing surface climate during El Nino winters and even the intraseasonal aspect of the El Nino signal agrees with the timing of signals descending through the stratosphere to the tropopause, but does this really imply a stratospheric influence on surface climate? There are now several pieces of evidence which point to a stratospheric *effect* on surface climate. In a study with a climate model in which the stratosphere was only poorly resolved, Toniazzo and Scaife (2006) showed that the canonical negative NAO like response to ENSO did not appear in the model. They speculated that this was because of the absence of a well resolved stratosphere. In contrast, a more recent study with a stratosphere resolving model did produce the observed response (Ineson and Scaife, 2009) but only when the stratosphere was "active" and produced a sudden stratospheric warming. These are indirect pieces of evidence but there is also direct evidence from model studies where the stratospheric variability was carefully removed from the model while the tropospheric part of the model remained the same. Parallel 'high lid' and 'low lid' models (Cagnazzo and Manzini 2009) and experiments where the stratosphere was damped to remove any variability (Bell et al 2009) both show that the canonical response is much stronger when the stratosphere is active. In this sense at least, there is a real effect of the stratosphere on the troposphere.

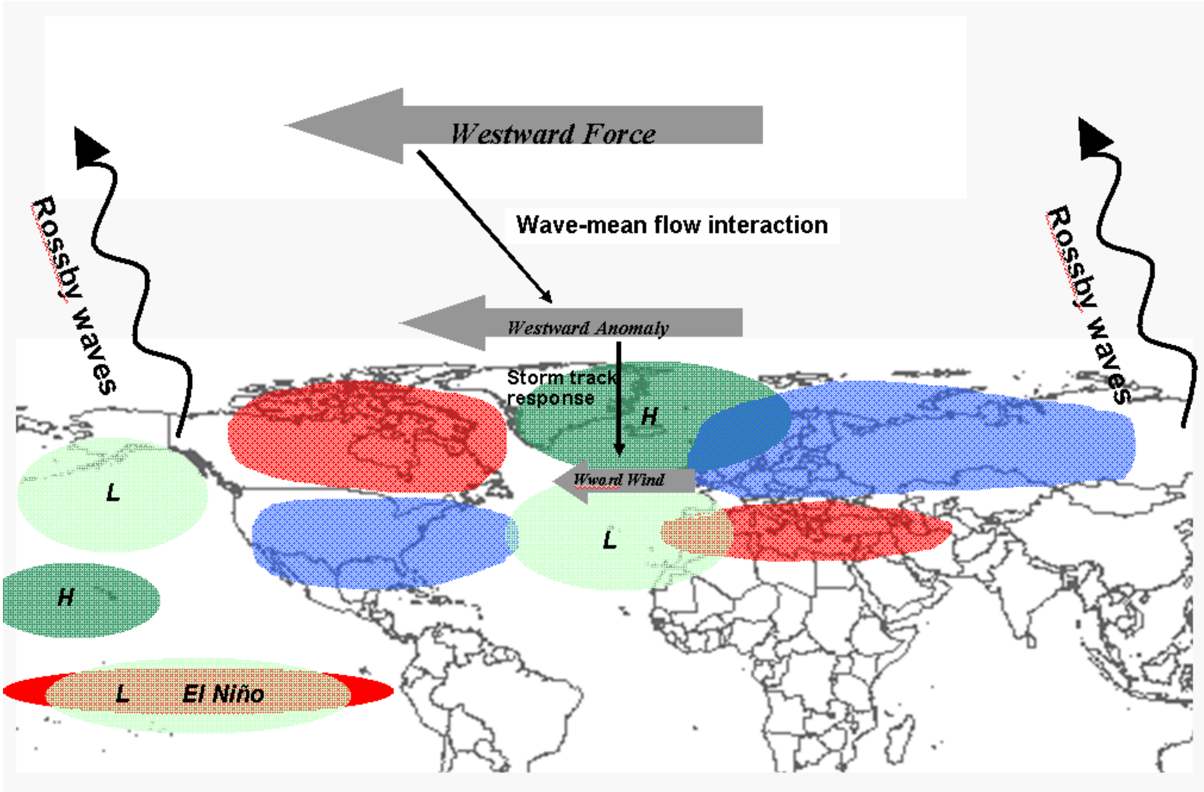

Figure 4: Schematic representation of the processes involved in connecting ENSO to Europe. El Nino produces a deepening of the Aleutian low in the North Pacific, this drives an increased flux of planetary wave activity into the stratosphere and subsequent descending wind anomalies lead to an NAO like response in the Atlantic basin. Sea level pressure anomalies are indicated in green. Red and blue shading indicate warm and cold near surface temperature anomalies.

5. Atypical events: "noise", non-stationarity or non-linearity?

The North Atlantic/European region is highly variable from year to year due to fluctuations in the strength of the storm track and the associated NAO pattern which dominates year to year changes (Hurrell 1995). Of course much of this variability is unassociated with ENSO and may simply be unpredictable internal variability. However, during many ENSO events this appears not to be the case. Mathieu and colleagues (2004) showed that North Atlantic anomalies during individual ENSO events appear to be reproducible in ensembles of climate model experiments. On the other hand, they also concluded that this reproducible signal differedbetween different ENSO events.

The reproducible but apparently variable impact of ENSO on the North Atlantic also appears in longer sections of the observational record. For example, the average effect of ENSO in the latter 20 years of the 20th century was quite different to the average signal in the previous 20 years. Given that these signals are reproducible in models the obvious conclusion might be that the signals are real but "non-stationary" and therefore time-varying (Greatbatch et al, 2004).

An alternative idea is that the Atlantic response to ENSO could be non-linear. If El Nino events are segregated into the strongest one third and the weakest two thirds of events then an apparent consistency emerges in the Atlantic response (Toniazzo and Scaife, 2006). Only the moderate to weak events show the canonical negative NAO pattern while the strongest events show a rather different pattern with a barotropic high to the west of Europe. This response has been explained as a tropospheric wave train from the tropical Atlantic which appears to dominate the Atlantic response during the strongest El Niño events (Toniazzo and Scaife 2006). As this was a primarily observational result one might be forgiven for thinking that the apparent non-linearity appears in the observational record due to a random 'fluke'. However, recent experiments with a climate model in which the amplitude of the El Niño signal in the tropical Pacific was artificially increased were able to reproduce the observed transition between a negative NAO like response and a pattern similar to the observed response strong El Nino events (Bell et al, 2009). This last piece of evidence adds weight to the idea that the observed non-linearity is indeed a real effect. Finally, it appears that the canonical response of the Atlantic to ENSO may continue for many years to come as it has been found to persist even under climate change conditions (Müller and Roeckner, 2006)

6. Conclusion

Both observational and modelling studies show a consistent Atlantic climate response to ENSO. The canonical response is for a negative winter NAO pattern during El Nino and cold winter anomalies over Northern Europe. The whole depth of the atmosphere is involved in transmitting this signal from the tropical Pacific to the Aleutian region, into the stratosphere and subsequently back down in to the Atlantic basin. Most steps in this pathway are at least partly understood.

A number of other important details have been added to this basic picture. The signal mentioned above is strongest during late Winter. This intraseasonality is reproduced in some GCM studies where it coincides with the descent of a westward wind anomaly through the stratosphere. There is also evidence for non-linearity in the Atlantic response to El Niño, with the few strongest events showing a different (but consistent) pattern which can be attributed to a tropospheric wave train emanating from the tropical Atlantic. La Niña shows roughly opposite signals to El Niño, including the intraseasonality of the signal, although some authors have argued that this signal is less clearly reproduced in numerical models.

Finally it is worth remarking on the practical use of these signals for seasonal forecasting. Quantification of the size of the ENSO signal against the total variability in the Atlantic region shows that ENSO produces a shift in basic climatological parameters such as temperature or rainfall over Europe that is several tens of percent of the magnitude of observed variability (Ineson and Scaife 2009). These teleconnections are therefore an important component for European seasonal prediction, when ENSO is active. A very recent example may be the winter of 2009/10 which contained a moderate El Niño event and a record negative NAO, which may be partly explained by the canonical teleconnetion described in this paper.

References

Bell C.J., L.J. Gray, A.J.Charlton-Perez, M. Joshi and A.A. Scaife (2009). Stratospheric communication of El Nino teleconnections to European Winter. *J. Clim*., **22**, 4083-4096.

Brönnimann S. et al (2004). Extreme climate of the global troposphere and stratosphere in 1940-42 related to El Niño. *Nature*, **431**, 971-974.

Bulić I.H. and Branković C. (2007). ENSO forcing of the Northern Hemisphere climate in a large ensemble of model simulations based on a very long SST record. *Clim. Dyn*., **28**, 231-254.

Cagnazzo C. and E. Manzini (2009). Impact of the Stratosphere on the Winter Tropospheric Teleconnections between ENSO and the North Atlantic and European Region. *J. Clim*. **22**, 1223–1238 (2009).

Fereday D., J.R. Knight, A.A. Scaife, C.K. Folland and A. Philipp (2008). Cluster analysis of North Atlantic-European weather types. *J. Clim*., **21**, 3687-3703.

Greatbatch, R. J., J. Lu, and K. A. Peterson (2004), Nonstationary impact of ENSO on Euro-Atlantic winter climate, *Geophys. Res. Lett*., **31**, L02208, doi:10.1029/2003GL018542.

Haynes, P. H. et al. (1991). On the `downward control' of extratropical diabatic circulations by eddy-induced mean zonal forces. *J. Atmos. Sci*. **48**, 651-678.

Hamilton, K. (1993). A general circulation model simulation of El Niño effects in the extratropical Northern Hemisphere stratosphere. *Geophys. Res. Lett*. **20**, 1803-1806.

Hurrell, J.W., 1995: Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. *Science,* **269**, 676-679.

Ineson S. and Scaife A.A. (2008). The role of the stratosphere in the European climate response to El Nino. *Nature Geoscience*, **2**, 32-36.

James I.N. (1994). *Introduction to Circulating Atmospheres*, Cambridge University Press.

Lindzen R.S. and S. Nigam (1987). On the role of sea surface temperature gradients in forcing low level winds and convergence in the tropics. *J. Atmos. Sci*., **44**, 2418-2436.

Manzini, E., Giorgetta, M. A., Esch, M., Kornblueh, L. & Roeckner, E. The influence of sea surface temperatures on the Northern winter stratosphere: Ensemble simulations with the MAECHAM5 model. *J. Clim*. **19**, 3863-3881 (2006).

Mathieu, P-P., R.T. Sutton, B. Dong and M. Collins (2004). Predictability of winter climate over the North Atlantic European region during ENSO events. *J. Climate*, **17**(10), 1953-1974.

Matsuno, T., (1971): A dynamical model of the sudden stratospheric warming. *J. Atmos. Sci*., **28**, 1479–1494.

Moron, V. and Gouirand, I (2003). Seasonal modulation of the ENSO relationships with sea level pressure anomalies over the North Atlantic in October-March 1873-1996. *Int. J. Climatol*. **23**, 143-155.

Quiroz, R. S., (1983): The climate of the “El-Niño” winter of 1982-83, a season of extraordinary climatic anomalies. *Mon. Wea. Rev*., **111**, 1685-1706.

Scaife A.A. (1998): *Interannual Variability of the Stratosphere*. PhD Thesis, University of Reading, UK.

Taguchi, M. and D. L. Hartmann, (2006): Increased occurrence of stratospheric sudden warmings during El Niño as simulated by WACCM. *J. Climate*, **19**, 324–332.

Thompson, D. W. J., and J. M. Wallace, 2000: Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Climate*, **13**, 1000-1016.

Toniazzo, T. and A.A. Scaife (2006). The influence of ENSO on winter North Atlantic climate. *Geophys. Res. Let*., **33**, L24704.

Trenberth, K. E., and J. M. Caron (2000): The Southern Oscillation Revisited: Sea level pressures, surface temperatures and precipitation *J. Climate*, **13**, 4358-4365.

Van Loon H. and Labitzke K., (1987). The Southern Oscillation. Part V: The Anomalies in the Lower Stratosphere of the Northern Hemisphere in Winter and a Comparison with the Quasi-Biennial Oscillation. *Mon. Wea. Rev*., **115**, 357-369.

Walker, G.T. (1924). Correlation in seasonal variations of weather, IX. A further study of world weather. *Memoirs of the India Meteorological Department*, **24**, (9) ,275-333.