THE USE OF EQUIVALENT TEMPERATURE TO ANALYSE CLIMATE VARIABILITY

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ABSTRACT

Equivalent temperature based in the NCEP/NCAR reanalysis database has been used as a simultaneous measure of temperature and humidity. Its variations during the 1958–1998 added to the effect of the inclusion of satellite data during the late seventies have been analyzed. An increase of the globally averaged equivalent temperature has been detected, the trend has been considerably greater during the first half of the study period and significant differences can be found between continental and oceanic areas. The relation of the trend with four of the main modes of climate variability has been assessed. The North Atlantic Oscillation and the Artic Oscillations are closely related to the equivalent temperature over the North Atlantic basin, extending toward Northern Asia in the second case. El Niño/Southern Oscillation and the Antarctic Oscillation seem to have a more global effect.

Keywords: climate change, temperature, humidity

1. INTRODUCTION

Increases in both tropospheric temperature and water vapor concentration are among the attributed climate changes due to the rising of the atmospheric concentration of greenhouse gases. However, both increments could be originated by changes in the natural variability of the atmospheric circulation regimes. Changes in the long-wave patterns, dominant air mass types, strength or position of atmospheric features like anticyclones or stormtracks have a significant influence on local humidity and temperature. For example, it is known that the recent upward trend in the North Atlantic Oscillation (NAO) accounts for much of the observed regional warming in Europe and cooling over the Northwestern Atlantic (*Hurrell, 1996*). However, our knowledge about the influence of the NAO on humidity distribution is limited. In three studies on global climatologies (*Peixoto and*

Oort, 1996; Ross and Elliot, 1996; Randel et al., 1996), much information was not given about the mechanisms controlling the spatial distribution and evolution of the humidity.

The pair temperature-humidity has only been simultaneously studied on a regional scale. In a recent paper regarding the apparent temperature as a measure of human comfort (a measure of the combined effect of humidity and temperature, see *Steadman, 1984*) in the United States of America, increments in surface temperature and humidity leading to a positive trend in the apparent temperature were found (*Gaffen and Ross, 1999*). In the same study, no significant influence from large-scale dynamics in the interannual variations of the humidity was detected. Neither the El Niño/Southern Oscillation (ENSO) nor the NAO were significatively correlated with specific humidity anomalies.

Another way for quantifying simultaneously humidity and temperature in a single variable is the use of the equivalent temperature (ET thereafter). ET is the temperature a sample of air would have if all its latent heat were isobarically converted to sensible heat. Its expression is:

$$ET = T + \frac{L}{C_p} \frac{q}{1-q} , \tag{1}$$

where T is the air temperature (K), L the latent heat of vaporization (approx 2.5×10^6 J kg^{-1}), C_p the specific heat of dry air at constant pressure (approx. 1004 J K^{-1} kg^{-1}) and q the specific humidity (the ratio of the mass of water vapor to the mass of the moist air parcel).

The objective of this study is to explore the potential of the ET as an indicator of climatic change, which includes not only the temperature, but the humidity, and is very closely related to human comfort. The relationship between ET and several climatic indices will be investigated.

2. DATA AND METHODS

Temperature and specific humidity from the 41-year period between 1958 and 1998 at 850 hPa from the NCEP-NCAR reanalysis data (*Kalnay et al., 1996*) were used to compute the ET values over the entire globe on a uniform 2.5° × 2.5º grid according to Eq.1.

Annual and seasonal ET series were computed. Seasons have been defined as January to March (JFM thereafter), April to June (AMJ), July to September (JAS) and October to December (OND). Spatially averaged ET values have been computed for Global, Northern Hemisphere (NH), Southern Hemisphere (SH), continental and oceanic areas. The area represented by the 2.5º × 2.5º rectangular square centered at each grid-point was used as weighting factor to account for the change in the surface represented by each grid point in a regularly spaced grid.

Trend analysis is based on a least squares regression. This analysis has been applied to both, averaged and grid-point ET series for the periods 1958–1978, 1979–1998 and the complete series 1958–1998.

To represent the most significant modes of climate variability, we considered four atmospheric patterns characterized by their respective indices:

- The ENSO is represented by the Southern Oscillation Index (SOI), which is defined as the normalized pressure difference between Tahiti and Darwin (*Ropelewski and Jones, 1987*). The index series was extracted from the Climate Research Unit (CRU) web-page. This index is a measure of large-scale fluctuations in air pressure between the western and eastern tropical Pacific. Negative/positive SOI values coincide with abnormally warm/cold sea surface temperatures across the eastern tropical Pacific typical of El Niño/La Niña episodes.
- The Arctic Oscillation (AO) and the Antarctic Oscillation (AAO) (*Thompson and Wallace, 2000; Gong and Wang, 1999*) are the leading modes of variability of the extratropical circulation in the NH and the SH respectively. They are defined as the leading EOF of SLP poleward of 20 degrees based on monthly data, and were extracted from the NOAA Climate Data Center webpage They are characterized by zonally symmetric structures with geopotential anomalies of the opposite sign between the polar cap and the mid latitudes. Positive AO/AAO index are related to more intense westelies along the NH/SH mid latitudes.
- The NAO can be defined as a meridional oscillation in atmospheric mass between the Icelandic low and the Azores High. The NAO index used in this paper was obtained from the CRU webpage, and is defined as the normalized pressure difference between Gibraltar and SW Iceland (*Jones et al. 1997*). The NAO and the AO are considered two ways of describing the same phenomenon (*Wallace, 2000*). The AO is usually thought to be a hemispheric phenomenon that can be found throughout the whole year, while the NAO is a more local pattern centered in the North Atlantic, and most intense during the NH cold season.

The influence of these climatic patterns on the ET has been assessed through the grid-point Pearson correlation coefficients between ET and the circulation indices. The significance of both, correlation and trends is based on t-tests (see *von Storch and Zwiers, 1999*).

3. RESULTS

3.1. Trends and variations in the ET series

The variations of the averaged ET series are shown in Fig. 1. Table 1 gives the numerical values and the seasonal contribution, along with the trends during the sub-periods 1958–78 and 1979–98.

During the entire study period (1958–98), ET increments between +0.05 and +0.29 $K \cdot decade^{-1}$ were detected for all the chosen subsets, which were also found for the seasonal analysis. In general, the seasonal trends follow the annual behavior. Continental areas and, in consequence, the NH due to the continental nature of this hemisphere, shows lower and non-significant trends (but for AMJ). Nevertheless, Fig. 1 evidences signs of an ET shift toward higher values during the late seventies. To asses the significance of this leap in the detected trends, the analysis was performed for the separate periods 1958–78 and 1979–98. The significant ET increment for the entire study period of

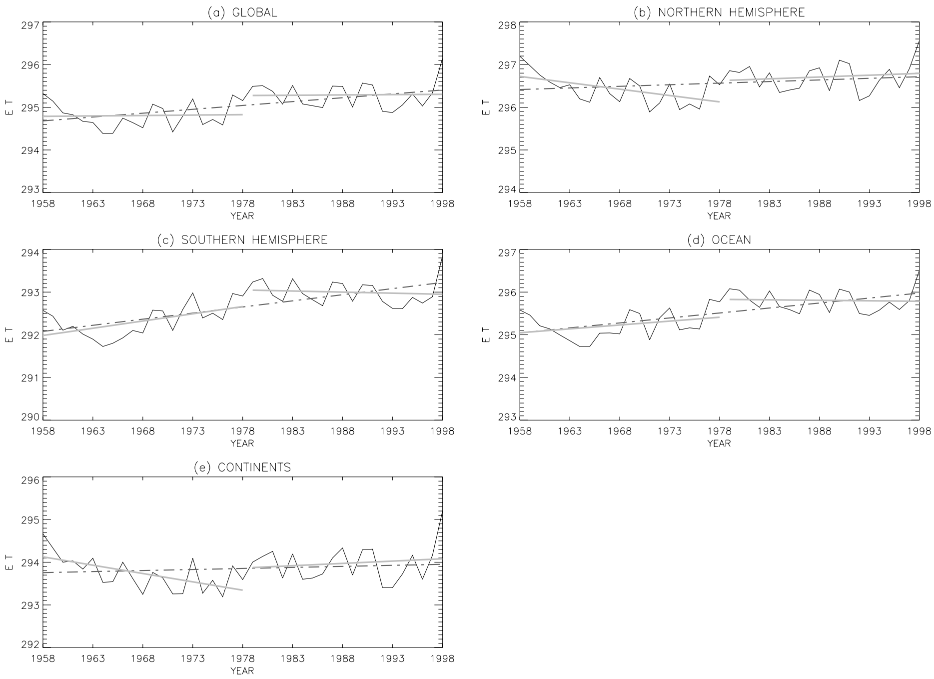

Fig. 1. a) Global, b) NH, c) SH, d) continental and e) oceanic annual ET series from 1958 to 1998. 1958–98 trend is represented by discontinuous black line. Solid gray lines represent trend for the 1958–78 and 1979–98 periods.

+0.18 K·decade^{-1}, is not found for the separate periods (trends of +0.02 and +0.01 K·decade^{-1}). However, the analysis for the different areas produces two interesting results (see Table 1).

The ET increment observed for the entire period over the oceans and the SH, is also found for 1958–78, while the continental areas (and the NH, Fig. 1c,d), are characterized by strong and significant negative trends not found for the 1958–98 period (Fig. 1b,e).

The trends for the 1979–98 period are lower and non-significant, not showing a definite seasonal pattern in the sign. Although non statistically significant, continental areas and the NH exhibit positive trends (Fig. 1b,e), opposite to those found during 1958–78.

Therefore, the absence of global ET trends obeys to different causes depending on the period. During 1958–78, continental and oceanic areas (as NH and SH) have opposite trends, thus they cancel each other. There is a strong (–0.39 K·decade^{-1}) decrease in the ET over the continents while an increase in the ET over the oceans is found (+0.18 K·decade^{-1}), leading to an almost null global trend (+0.02 K·decade^{-1}). On the other hand, during the 1979–98 period, no global trend is found, but now it is due to the lower values of both continental and oceanic areas (+0.11 and –0.02 K·decade^{-1} respectively).

To better analyze the trend distribution along the globe, grid-point trends have been computed and represented in Fig. 2. In general, for the complete 1958–98 period (Fig. 2a), the areas with significant trends are characterized by ET increments, which are higher in the SH, particularly over the oceans. Negative trends are observed over localized NH continental areas as Northwestern Africa and over Southern and Southeastern Asia.

The analysis for the two periods 1958–79 and 1979–98 evidences several new and different characteristics:

The 1958–78 trends (Fig. 2b) exhibit a similar pattern to that of the total study period, although greater values and broader significant areas are found. Accordingly to Table 1, positive trends can be seen for much of the oceanic areas of the SH, while comparatively smaller areas as Southern Australia, South Africa and the Peruvian coast show ET diminutions. On the other hand, the NH is dominated by ET decreases, especially noticeable over the Sahara, Southern and Southeastern Asia, Western North America and the North Atlantic.

The 1979–98 period (Fig. 2c) is characterized by weaker ET trends, but most interesting is the change in the trend pattern. Most of the areas characterized by ET increases during 1958–78, now exhibit decreases and vice versa. During 1979–98, the positive trends in the SH oceans are not found, instead, some significant ET decreases can be seen over the South Atlantic and Indian oceans. On the contrary, the NH now exhibits some areas of significant ET increases (western Asia, the North Atlantic and eastern North America) while the strong negative values found for the 1958–1979 period in continental areas of Africa and Asia are smaller or even not found during 1979–1998.

Table 1. Annual and seasonal ET trends for the periods 1958–98, 1958–78 and 1979–98 averaged over the entire globe, the Northern Hemisphere (NH), the Southern Hemisphere (SH), Oceanic and continental areas (the equator is not included in the NH and SH averages). Units are $K \cdot decade^{-1}$. Significant trends ($p < 0.05$) are marked with *.

		Global	NH	SH	Oceans	Continents
1958–1998	Annual	+0.18*	+0.08	+0.29*	+0.23*	+0.05
	JFM	+0.12*	+0.02	+0.23*	+0.17*	+0.00
	AMJ	+0.21*	+0.12*	+0.31*	+0.26*	+0.10
	JAS	+0.24*	+0.09	+0.38*	+0.30*	+0.08
	OND	+0.15*	+0.08	+0.23*	+0.21*	+0.01
1958–78	Annual	+0.02	–0.30*	+0.34*	+0.18	–0.39*
	JFM	–0.06	–0.36*	+0.25*	+0.05	–0.33*
	AMJ	+0.03	–0.22	+0.29*	+0.17	–0.30*
	JAS	+0.05	–0.33*	+0.42*	+0.27*	–0.52*
	OND	+0.06	–0.28*	+0.39*	+0.24*	–0.41*
1979–98	Annual	+0.01	+0.09	–0.05	–0.02	+0.11
	JFM	–0.11	+0.00	–0.21	–0.12	–0.08
	AMJ	+0.06	+0.08	+0.04	+0.01	+0.16
	JAS	+0.15	+0.17	+0.14	+0.11	+0.26
	OND	–0.04	+0.09	–0.17	–0.09	+0.08

In general, much of the ET increases are located over oceanic areas. A temperature increase in these regions implies more evaporation and in consequence, a more intense trend in the ET series than those found for the temperature alone. On the other hand, the areas characterized by ET decreases are usually located over the continent, far from water vapor sources. In addition, some of these areas (as the Sahara desert) are dominated by permanent or semi-permanent high-pressure systems. In these regions, the lack of water vapor along with the high radiative loss of energy contribute to ET decreases and might lead to the strong negative ET trends observed.

Seasonal analysis provides information about the time of the year when trends are more intense, and helps to determine some of the possible links between them and the modes of climate variability. A seasonal analysis similar to that on Fig. 2 (not shown) was performed. In general, the seasonal trends during the two sub periods 1958–78 and 1979–98 are similar to that observed at annual scale. Nevertheless, some differences must be pointed out:

- 1958–1978 period:

Over parts of the continental North America, slight ET increases were detected for JFM and AMJ and ET decreases for JAS and OND, resulting in the low trends for the annual average (Fig. 1b). Other region with marked seasonality during this period was found over central Asia; over this area, significant positive trends can be found for AMJ and OND which is almost cancelled by ET decreases during JFM and JAS.

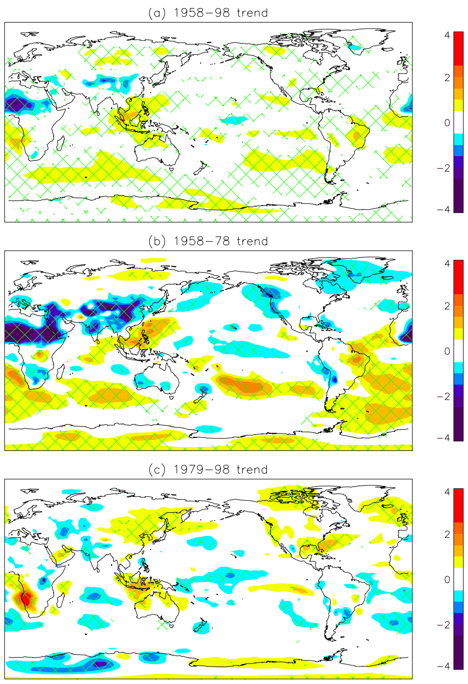

Fig. 2. Annual ET trends (K·decade^{-1}) for (a) 1958–98, (b) 1958–78 and (c) 1979–98. Significant trends are shaded.

- 1979−1998 period:

During this period, though the annual ET trend over the Sahara is almost null in an annual average (Fig. 2c), a strong and significant decrease, near −1 K·decade^{-1}, is found during JFM. Around the North Atlantic Area, significant trends can be found during the NH winter, with warming over the eastern coast of North America and Western Europe and cooling over Greenland and the subtropical North Atlantic. This pattern and the time of the year it is observed, is a first sign of the role that the NAO plays over the Atlantic ET trends, which is very likely related to the observed positive tendency in the NAO index observed during the last quarter of the 20th century (*Hurrell, 1995*). Finally, the broad area of ET increases found over East Asia in Fig. 2c, is mainly due to changes during the cold season (JFM and OND).

3.2. Influences of the atmospheric circulation patterns on ET

Fig. 3 shows the spatial distribution of the Pearson correlation coefficients for the 1958−98 period between the ET series and the AO, the AAO and the SO indexes at annual scale. Correlations coefficients for the NAO index correspond to the JFM season.

- Arctic Oscillation and North Atlantic Oscillation

The maps for the AO and the NAO (Fig. 1a,d) show a quiadripolar structure over the North Atlantic area, with negative correlation coefficients over Greenland and Northern Africa extending to Southern Asia, and positive correlation from North America to Europe and Western Asia. This pattern in the North Atlantic is detected mainly during JFM both for the NAO and the AO (In Fig. 3, the annual AO and the JFM NAO maps are shown). The seasonal response of ET to the NAO and the AO (not shown) is essentially the same over the North Atlantic. However, an evident difference between the seasonal response of ET to the AO and the NAO is located over northern Asia. The positive correlation in this area, which can be observed in Fig. 3 for the annual case (AO) or JFM (NAO), can be found all along the year for the AO (though sensibly weaker during the NH summer), while for the NAO, it is only found during JFM. For the rest of the year no correlations are detected (JAS and OND) or they may be even significantly negative (AMJ). These results must be attributed to the regional character of the NAO and the annular nature of the AO, affecting not only the correlation pattern but the seasonal behavior.

- Antarctic Oscillation

Fig. 3b shows that the areas where the AAO significant correlations are observed are not restricted to the SH, but have an almost global distribution. Only high latitudes on both hemispheres are poorly correlated with this mode. The AAO shows positive correlation with ET series over most of the oceans, while negative correlations areas are restricted to relatively small continental areas on Northern Africa, Asia and Antarctica. When seasonal analyses is performed (not shown) the annual correlation patterns are reproduced but with slightly lower values. However, two noticeable differences must be pointed out. First, during the austral warm season (JFM and OND) the negatively correlated area over the Antarctica is greatly enhanced, while the positive correlations found all along the Austral continent are slightly lower, which is in agreement with previous works where a more active SH vortex is detected during the warm season

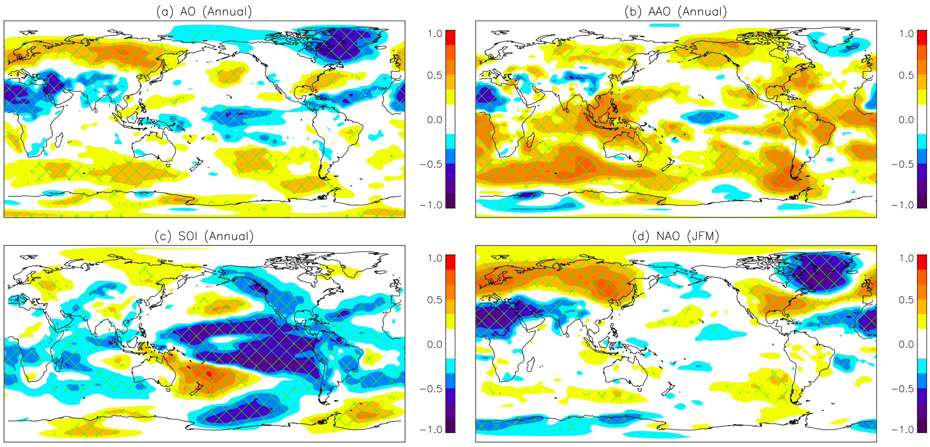

Fig. 3. Pearson correlation coefficients between annual ET and (a) annual AO, (b) annual AAO, (c) annual SOI and (d) NH winter NAO. Significant correlations are shaded.

(*Thompson and Wallace, 2000*). Second, during the JFM season, a NAO-like quadripole can be found on the North Atlantic (thus suggesting some kind of coupling between the AO and the AAO).

These results, suggest that the AAO effects over temperature and humidity are not restricted to the SH but can be found on a global scale. In this way, the AAO can thought to be responsible of an energy transfer from one hemisphere to the other.

- El Niño/Southern Oscillation

ENSO (Fig. 3c) appears highly correlated with ET over the equatorial Pacific and Indian oceans. The equatorial Pacific along with two mid latitude bands show high and significant negative correlation. The tropical and Southern Indian Oceans also display significant negative values. Positive correlations can be found over the subtropical Pacific in both hemispheres and in the Southern Atlantic. This structure is typical of the ENSO, and is related to changes in the Rossby waves associated to the temperature anomalies over the Pacific (*Diaz, 2000*).

The seasonal analyses (not shown) shows a similar pattern. During JFM, correlations are stronger over the tropical Pacific and specially over the tropical Indian and Atlantic Oceans. Probably indicating a more effective energy transmission from the tropical Pacific to rest of the tropical areas during this season.

4. CONCLUSIONS

This paper analyzes the trends of the ET and how ET is influenced by the main modes of atmospheric variability at hemispheric and global scales. ET combines information from temperature and humidity, and provides a good measurement of human comfort.

A trend analysis of the ET computed from the NCEP/NCAR reanalysis seems to indicate a strong ET increment during the 1958–98 period. Nevertheless, a shift in the ET series around 1979 has been identified, as previously documented (*Hurrell and Trenberth, 1998; Fiorino, unpublished data; Kistler et al., 2001*) and is attributed to the inclusion of new satellite measurements. The trend analyses are crucially dependent on that issue, thus the analysis has been performed independently before and after the inclusion of the satellite data.

The small global trend for the two separate periods 1958–78 and 1979–98 suggests that the trend for the entire study period could be due to the late 70's shift in the data. Nevertheless, not all the ET trends are attributable to this shift, which is neither spatially nor temporally uniform. Significant trends of different sign and strength can be found over continental or oceanic areas depending on the considered period.

The spatial analysis shows that the most intense ET variations are found over the SH oceans for the period 1958–78. This increment is not found during the 1979–98 period. The poor representation of SH oceanic areas in the NCEP/NCAR reanalysis during the first half of the study period does not allow a definite conclusion but the intensity of these trends, uniquely over the oceanic areas, could be related to the ET sensibility to coupled changes on temperature and humidity. In this way, a small warming of the air over the oceans increases the evaporation rate, with a combined contributing to ET rising and more intense ET variation.

Strong negative trends have been found over the Sahara desert and Southern Asia. As before, these trends are higher during the first half of the study period and in the case of Southeastern Asia, the ET trend even reverses during 1979–98. The area of strong ET decreases found over the Sahara at annual scales during 1958-78 is also found for 1979–98, but restricted to the NH winter. It should be noted that the existence of negative trends on ET is not contrary to the trend toward higher global temperature.

During 1979–98, ET increments are found over Eastern Asia, Northern Europe, the southeastern North America and South Africa, all densely populated coastal areas. The quality of the data coverage for these regions and period is considered to be good. Consequently, the scenario provided by this paper suggests that the global warming predicted by most models for future years will have its most severe impact for human comfort over coastal regions over these areas.

The influence of the NAO and the AO on ET is evident in the NH over the Atlantic sector and adjacent continents, and is most intense during the NH cold season. ET exhibits a strong response to the AO at hemispheric scales and during the whole year, while the NAO influence is most intense over the North Atlantic basin during the NH cold season. The AAO influence on ET is observable throughout the whole globe, especially over Asia. The AAO signal on ET remains very similar for the whole year. In this case, seasonal variations are not as strong as for the AO/NAO cases but a center of significant negative correlation over the Antarctica can be observed during the warm SH season. Finally, the ENSO effect over large areas of the world has been documented for the ET. The ENSO signal is most intense over the Pacific Ocean, thought distant but significant teleconnections are also observable over the tropical Indian and Atlantic oceans, stronger during JFM, and over mid latitude areas in the Pacific and the Atlantic.

References

Diaz H.F. and Markgraff V. (Eds), 2000. *El Niño and the Southern Oscillation*. Cambridge University Press. Cambridge, 496 pp.

Gaffen D.J. and Ross R.J., 1999. Climatology and trends of U.S. surface humidity and temperature. *J. Climate,* **12**, 811–828.

Gong D. and Wang S., 1999. Definition of the Antarctic Oscillation index. *Geophys. Res. Lett.,* **26**, 459–462.

Hurrell J.W.,1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science*, **269**, 676–679.

Hurrell J.W., 1996. Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. *Geophys. Res. Lett.*, **23**, 665–668.

Hurrell J.W. and Trenberth K.E., 1998. Difficulties in obtaining reliable temperature trends: reconciling the surface and satellite microwave sounding unit records. *J. Climate*, **11**, 945–967.

Jones P.D., Jónsson T. and Wheeler D., 1997. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. *Int. J. Clim.,* **17**, 1433–1450.

Kalnay E., Kanamitsu M., Kistler R., Collins W., Deaven D., Gandin L., Iredell M., Saha S., White G., Woollen J., Zhu Y., Chelliah M., Ebisuzaki W., Higgins W., Janowiak J., Mo K.C., Ropelewski C., Wang J., Leetmaa A., Reynolds R., Jenne R. and Joseph D., 1996. The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteorol. Soc.,* **77**, 437–471.

Kistler R., Kalnay E., Collins W., Saha S., White G., Woollen J., Chelliah M., Ebisuzaki W., Kanamitsu M., Kousky V., van den Dool H., Jenne R. and Fiorino M., 2001. The NCEP-NCAR 50-year reanalysis. Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.*, **82**, 247–267.

Peixoto J.P. and Oort A.H., 1996. The climatology of relative humidity in the atmosphere*.* *J. Climate,* **9**, 3443–3463.

Randel D.L., Von der Haar T.H., Ringerund M.A., Stephens G.L., Greenwald T.J. and Combs C.L., 1996. A new global water vapor dataset. *Bull. Amer. Meteorol. Soc.*,, **77**, 1233–1246.

Ropelewski C.F. and Jones P.D., 1987. An extension of the Tahiti-Darwin Southern Oscillation Index. *Monthly Weather Review*, **115**, 2161–2165.

Ross R.J. and Elliot W.P., 1996. Tropospheric precipitable water: A radiosonde-based climatology. *NOAA Tech. Memo*. ERL-ARL-219, Springfield, VA., 132 pp,

Steadman R.G., 1984. A universal scale of apparent temperature. *J. Clim. Appl. Meteorol.,* **23**, 1674–1282.

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

Von Storch H. and Zwiers F.W., 1999. *Statistical Analysis in Climate Research*. Cambridge University Press, 484 pp.

Wallace J.M, 2000. North Atlantic Oscillation/Annular mode: Two paradigms - one phenomenon. *Quart. J. Royal Meteorol. Soc.*, **126**, 784–812.