Atmospheric Angular Momentum from reanalyses: An index relevant to studying climate variations.

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1.0 ABSTRACT

Global Atmospheric Angular Momentum (AAM) mirrors many aspects of the signature of climate and weather, and as such is an important index pertaining to climate systems, on time scales from Interannual to intraseasonal and synoptic. Along with global temperature, an index of the energy cycle, and global moisture, an index of the hydrologic cycle, the diagnosis of the origin and transport of angular momentum, an index of the atmospheric circulation, is also fundamental to the climate. Angular momentum is a property of mass in motion about a given axis, which in a closed domain is conserved. Therefore, how angular momentum is exchanged across its lower boundary, by means of the interactive torques with the oceans and solid Earth below, is important to quantify so that one can understand how the Earth acts as a system.

As angular momentum is conserved in a closed system, small but measurable changes in the Earth's rotation rate are a consequence of the exchanges of angular momentum between the solid Earth and its fluid envelope, with the atmosphere being the most important component on many time scales. The relevance of atmospheric angular momentum changes to geodesy and many fields in geophysics has been recognized by the formal organization of the Special Bureau for the Atmosphere (SBA) of the International Earth Rotation and Reference System Service (IERS) to quality test and supply such atmospheric data to geoscientists for purposes of studies of Earth properties, and for reference frame purposes involving navigation.

As part of the 20th century reanalysis project, we are evaluating how well the current set simulate relative atmospheric angular momentum (AAM) about the Earth's mean axis, a fundamental measure of the atmosphere's circulation that depends on the strength and distribution of the zonal winds.

We will diagnose the mean climate and variability of the angular momentum of the atmosphere, and assess errors on mean, seasonal, and interannual time scales by concentrating on past reanalyses (NC EP-NCAR (1948-2010) and ECMWF (1958-2002)) as a benchmark. Here we use principally the NCEP-NCAR between 1958 and 2001.

2.0 DATA

[2.1] Long term Reanalysis from the 20th century reanalysis project.
For our comparison, we used the 138-year-long time series (1871-2008) of monthly mean winds from the surface (1000 hPa) to upper level within the stratosphere (10 hPa), encompassing 20 levels: From these we computed atmospheric angular momentum.
Relative Atmospheric Angular Momentum is computed following

$$\mathrm{AAM} = \frac{2\pi R^3}{g}\int_{Ps}^{Pt}\int_{\pi/2}^{-\pi/2}\int_{0}^{2\pi} u\cos^2\varphi\,\partial\lambda\,\partial\varphi\,\partial p$$

where R is the radius of the Earth, g the acceleration due to gravity and u denotes zonal wind. The term is integrated over all latitudes, longitudes and pressures. Because the wind fields are archived at constant pressures levels, it is convenient when using these data sets to set the lower boundary in the integration Ps to 1000 hPa. Therefore we can also compute relative AAM for specific layers of the atmosphere (for example over the stratosphere, defined here by integrating only between layers centered at the 100 to 10 hPa layers, or over the sole troposphere, by integrating between 1000 to 100 hPa).

[2.2] Old NCEP-NCAR and ECMWF reanalysis.
We also computed AAM from the 61-years-long monthly time series (1948-2008) of the NCEP-NCAR reanalyses (hereinafter NCAR60) as well as from ECMWF ones (1958-2002). Both reanalyses extend from the surface to different levels in the atmosphere (NCEP-NCAR to 10 hPa). However for the purpose of this inter-comparison we only analyze years from 1958 to 2002.

All results are here presented in equivalent milliseconds of length of the day (LOD).
It is possible to infer changes in LOD from global AAM time series, assuming that changes in AAM for the entire atmosphere are accompanied by equal, but opposite, changes in the angular momentum of the earth, through the relation :

delta (LOD) (ms)= $1.68\ 10^{-29}$ delta(AAM) (kg m^2/s),

where delta(LOD) is given in milliseconds.

3.0 METHODOLOGY

We will first show the time series of global AAM (Fig 1) and its spectrum (Fig 2). Then we compare the global and its hemispheric components (Fig 3). We will then separate between stratospheric and tropospheric contribution to the global AAM (Fig 4 and Fig 5). Following, we will concentrate on the tropospheric variability only, and analyze main components (seasonal (annual and semi annual) cycle, high and low frequencies) (Fig 6). The low frequencies will be detailed, separating them into interannual and decadal time scales (Fig 7).

To show how well transport of momentum during ENSO events is represented in the new reanalyses, the evolution of well known Interannual time scales in zonal bands is shown (Fig 8). To investigate for where the little differences are coming from, we computed correlation over latitude bands over the whole atmosphere, stratosphere and troposphere (Fig 9). Finally we show also some correlation of the zonal mean zonal winds for the troposphere, when zonal data is filtered over its main representative bands (seasonal, interannual and low frequencies).

4.1 RESULTS (PRESENTATION)

First the analysis of all the reanalysis fields shows that they represents efficiently the seasonal cycle in both hemispheres (Fig 3B and Fig 3C) and therein in the global AAM (Fig 3A).

This is mainly related to the fact that the Troposphere, which includes roughly 90% of the total mass of the atmosphere and therein in global AAM, is very well reproduced (Fig 5). This happens over all it spectral bands (see Fig 7 and Fig 10). Main differences found over the equator (Fig 9 and Fig 10) are related with the upper levels of the troposphere (200 to 100 hPa) (not shown).

Secondly, although the Stratosphere is not a big participant to total AAM, its analysis (Fig 4) shows that the seasonal cycle although presenting the correct amplitude, does not presents the correct modulation on both hemispheres (Fig 4B and 4C). Therein explaining the difference with NCEP-NCAR (Fig 4A). The analysis of the correlation by zonal bands (Fig 9) shows that the main difference over the stratosphere is related with the equatorial variability (red line in Fig 9), and the quasi biennial and decadal variability (not shown).

Thirdly, the analysis of the variability (Fig 1) and power spectrum (Fig 2) of the AAM from the new reanalyzes fields show some interesting features.
It presents peaks at the well know interannual time scales, period going from 1.5 to 9 years. These time scales has been intensely investigated and related to ENSO events. Interannual time scales are very well represented in the new reanalyses (Fig 6A, Fig 7A). So well represented that when comparing the NCEP-NCAR and new reanalyses in the zonal x time evolution diagrams (Hovmoller plots) (Fig 8), both shows almost exact patterns, principally over the main ENSO events (1972-73, 1982-87 and 1997-98) or related to transport from the poles to tropics probably related with annular modes.
It (Fig 1 and Fig 2) also shows decadal to interdecadal time scales, that, as presented by Fig 7B, traduces much of the variability present in the old NCEP-NCAR reanalyses. In addition it also present almost the same secular trend that on the NCEP-NCAR reanalyses, which has been related with global warming.

4.2 RESULTS (FIGURES)

Fig 1:

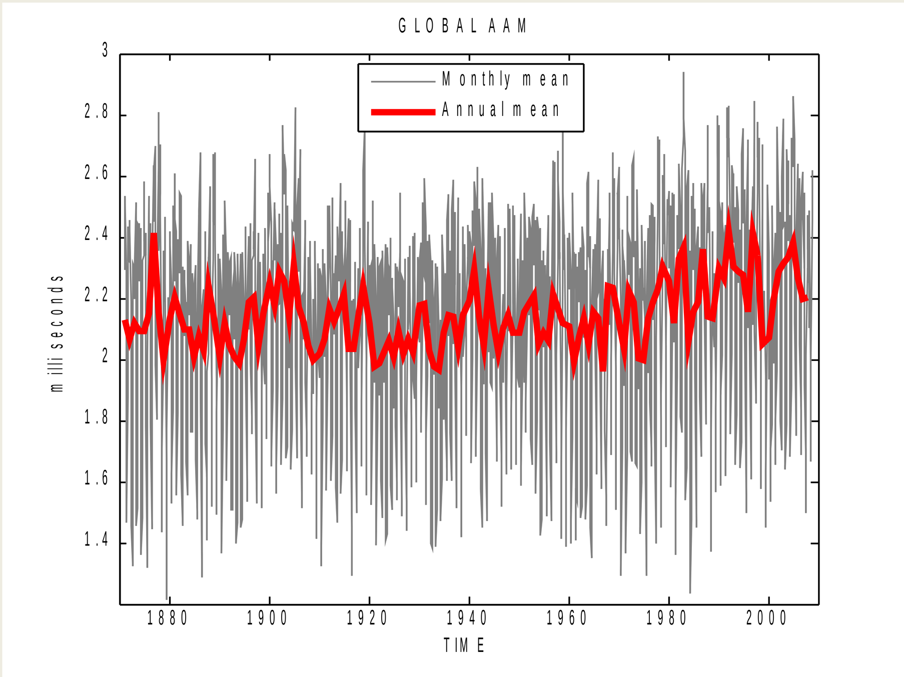

Figure 1: Grey solid line: Monthly time series of AAM (in milliseconds, of equivalent length of day variability). Red solid line, annual mean time series of AAM.

Fig 2:

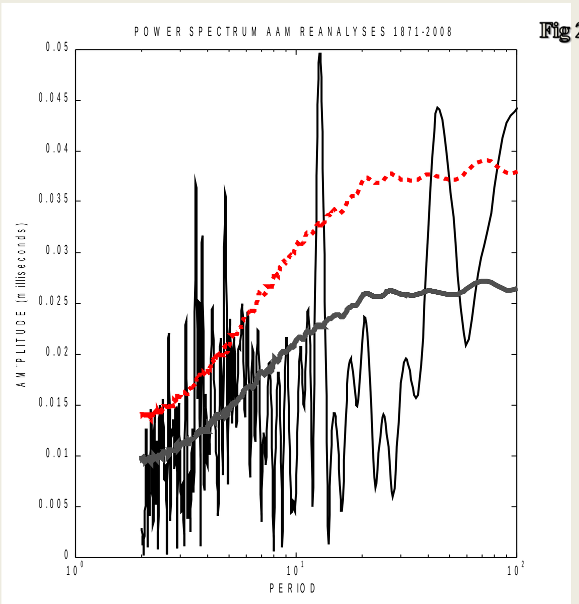

Figure 2: Solid Black: Amplitude spectrum of annual mean time series of AAM. Bold Grey : Mean amplitude spectrum of Monte Carlo AR1 simulation(1000 runs). Red line : 99% significance level.

Fig 3:

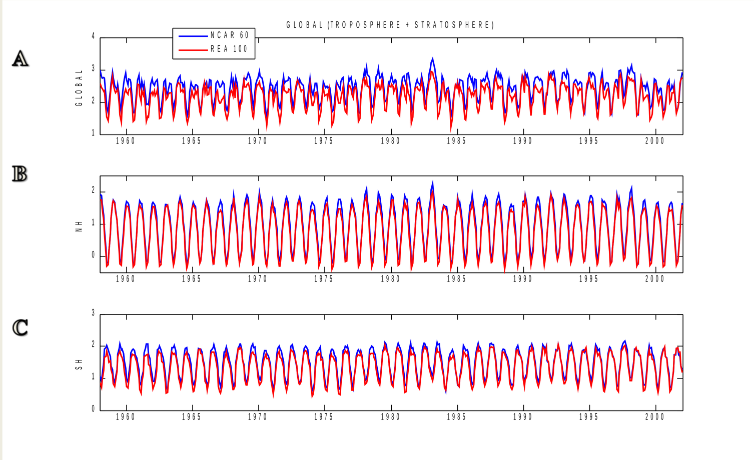

Figure 3: ALL ATMOSPHERE(1000 hPa-10 hPa) : Global (A), northern (B) and southern (C) hemisphere contributions to AAM. BLUE : from NCEP-NCAR reanalyzes (hereinafter called NCAR60) and RED from the new reanalyzes (hereinafter called REA100).

Figure 4: STRATOSPHERE (70-10 hPa) : Global (A), northern (B) and southern (C) hemisphere contributions to AAM. BLUE : from NCEP-NCAR reanalyzes (NCAR60) and RED from the new reanalyses (REA100)

Fig 4:

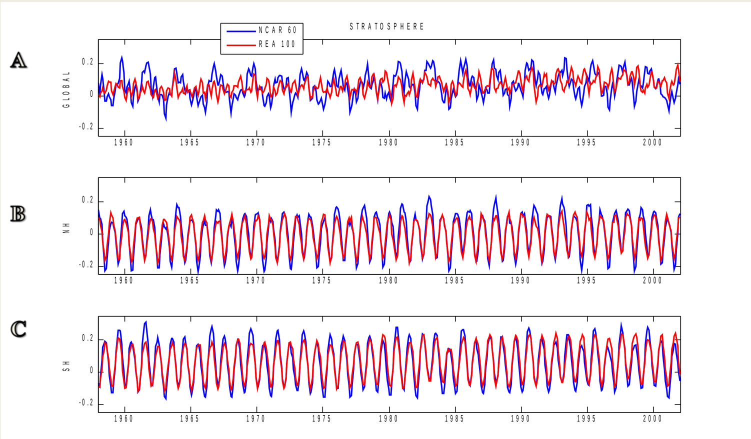

Figure 5: TROPOSPHERE(1000-100 hPa) : Global (A), northern (B) and southern (C) hemisphere contributions to AAM. BLUE line from NCEP-NCAR reanalyzes (NCAR60) and RED line from the new reanalyses (REA100).

Fig 5:

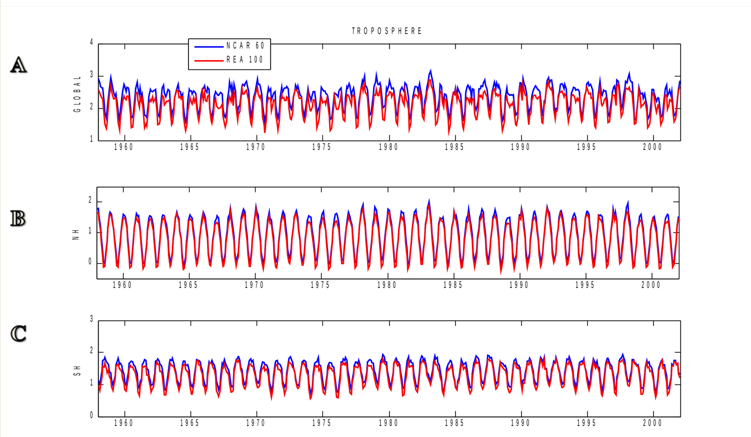

Fig 6:

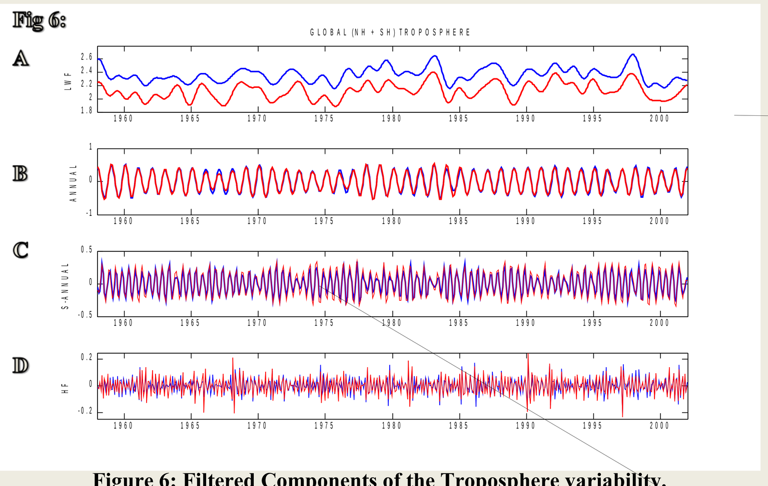

Figure 6: Filtered Components of the Troposphere variability. From bottom to upper part. High frequencies,(D) Semi annual (C), and Annual (B) cycle and all low frequencies (A). BLUE line from NCEP-NCAR reanalyzes (NCAR60) and RED line from the NEW REAnalyzes (REA100).

Fig 7:

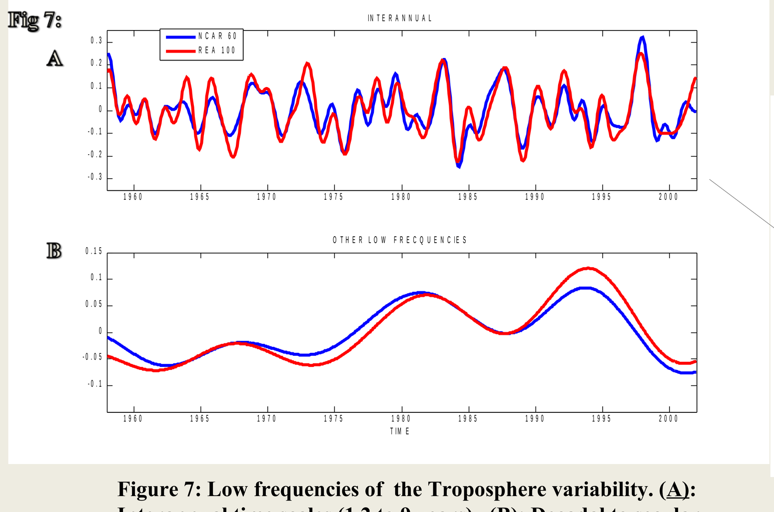

Figure 7: Low frequencies of the Troposphere variability. (A): Interannual time scales (1.2 to 9 years). (B): Decadal to secular time scales. BLUE line from NCEP-NCAR reanalyzes (NCAR60) and RED line from the NEW REAnalyzes (REA100).

Fig 8:

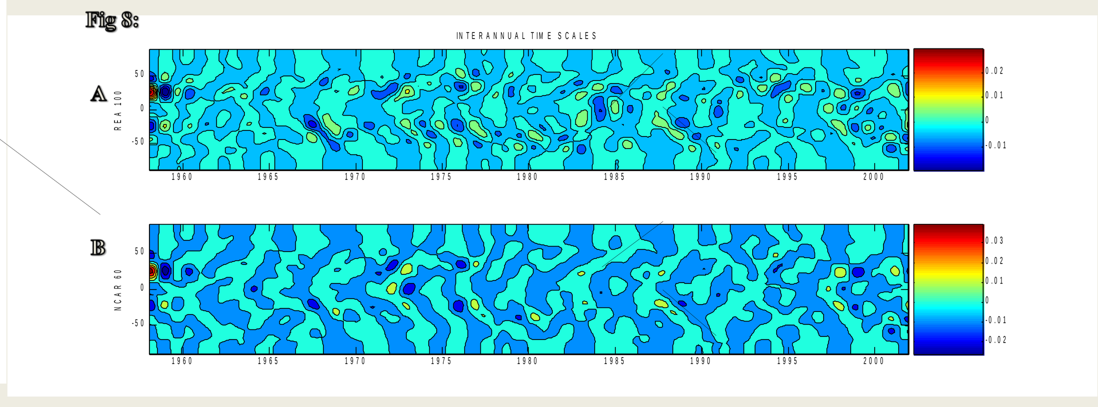

Figure 8: Evolution of the Interannual time scales (Zonal x Time). A: from New reanalyzes (REA100). B: from NCEP-NCAR reanalyzes (NCAR60).

Fig 9:

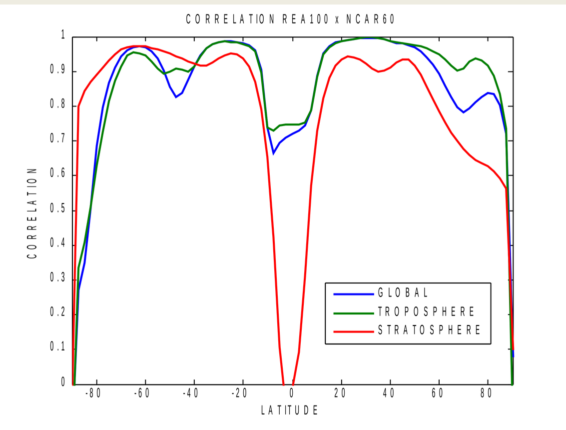

Figure 9: Correlation by zonal bands. Global (1000 hPa-10 hPa) in BLUE. Stratosphere (70-10 hPa) in RED and Troposphere (1000-100 hPa) in GREEN. All correlations are statistical significant at 0.05 except for the stratospheric ones, in the area surrounding the equator (-10 to +10).

Fig 10:

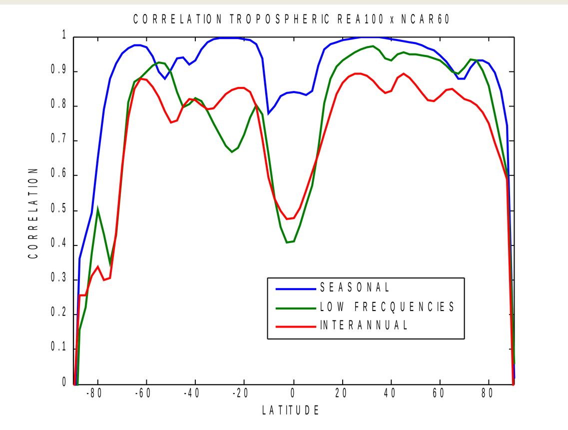

Figure 10: Correlation by zonal bands over the Troposphere (1000-100 hPa) when separated by spectral bands. BLUE: Seasonal time scales. RED: Interannual time scales. GREEN : Lower frequencies. All correlations are statistical significative at 0.05.

5.0 CONCLUSION

The results presented here are very encouraging for the probable use of new reanalysis fields in atmospheric dynamics as represented by the atmospheric angular momentum, and its interaction with the solid earth. This will allow the investigation of different ideas that are still needed to be understood better, confirmed or deciphered, or even discovered. The major exception is the inability of the new reanalyses to capture the interannual signals in stratopsheric AAM of the previous reanalyses.

For example, this result will give us confidence to use the reanalyses to study various phenomena over a lengthier time period. Some areas of interest are: how atmospheric angular momentum transports changes from the tropics to high latitudes, how this is accelerated during ENSO events, how particular ENSO events are noted in the dynamics of the solid earth, meridional transports, and annular modes. Long reanalyses will also help the investigation of transport related to decadal and interdecadal time scales, and ultimately the question of whether there is an imprint of anthropogenic forcing on the dynamic of the whole atmosphere.