Interdecadal oscillations in Atmospheric Angular Momentum variations

Communication

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Abstract:
Global Atmospheric Angular Momentum (AAM) is an intrinsic index for describing processes that affect the atmospheric circulation on time scales ranging from intraseasonal to secular. It is associated with length-of-day (LOD) variability through conservation of global angular momentum in planet Earth and thus is of considerable importance for quantifying how the Earth acts as a system. The availability of lengthy AAM time series computed from the recent 20th Century atmospheric reanalyses (1870–2008), complemented by the NCAR-NCEP reanalysis in the overlapping period of 1948–2008 allows the investigation of the role of decadal and interdecadal cycles as well as the recent overall trend in AAM. Thus, we extend to the entire 20th century (and prior, back to 1870) results concerning decadal time scales and a secular positive trend detected over recent decades by different authors. In addition, we also note that AAM has features of interdecadal time scales that modulate the lower frequency variability. These interdecadal time signals oscillate with periods of about 30–50 years, and we found an indication of an 80–90 year period. Short term signals interact with the long-term (secular) trend. Particularly over the years 1950–1985 the global positive trend in AAM appears to result from a conjunction of constructive positive slopes from all lower frequency signals (interdecadal short-term trends and the long-term positive secular trend). Since the mid 1980s, however, the interdecadal oscillation short-term trend contribution decreases, as does the total signal in global AAM. These oscillations appear as two interdecadal modes originating within the Pacific (associated principally with the Pacific Decadal Oscillation and also ENSO) from which they propagate poleward, with differing characteristics in each hemisphere.

Keywords:
Length of day • global Atmospheric Angular Momentum • XX century atmospheric reanalyses • decadal and interdecadal variability • pacific decadal oscillation • ENSO

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1. Introduction

Atmospheric Angular Momentum (AAM) is one index, which, together with global temperature, an index of the energy cycle, and global moisture, an index of the hydrologic cycle, describe climate evolution on a wide range of time scales (Peixoto and Oort, 1992). Thus, diagnosis of the origin and transport of angular momentum, an index of the atmospheric circulation, is a variable of importance to the dynamics of the atmosphere both regionally and globally (e.g. Egger et al., 2007) and central to describing variations and trends in climate.

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spheric quasi-biennial oscillations (Lambeck and Cazenave, 1977, Abarca-del-Río et al, 2000), associated with analysis of planetary wave activity in the middle and high latitudes of the stratosphere, has helped to decipher the origin and transport of ozone within the stratosphere (Jadin, 1997, Jadin et al, 2005).

Due to conservation of angular momentum within the whole Earth system (Barnes et al, 1983), atmospheric fluctuations are compensated by equal but opposite fluctuations of angular momentum in the solid Earth, implying changes in Earth rotation. Also, by quantifying how angular momentum is exchanged across its lower boundary, by means of the dynamic torques with the oceans and solid Earth below, one can better understand how the Earth acts as a system.

The analysis of the axial term of AAM, related to length of day (LOD), can be expressed as the sum of two components, the mass (pressure) and motion (wind) terms. But investigations (Barnes et al, 1983; Eubanks, 1993; Gross, 2007) of excitation of LOD variations have shown that the wind term, directly related to the zonal flow, is the dominant, explaining on average at least 90% of the total variability on many time scales. Additionally at different time scales, from intra-seasonal to interannual time scales, within the wind term, the role played in the LOD budget by the stratospheric winds though not insignificant are not meaningful compared with that of the troposphere (Rosen and Salstein, 1985, Aoyama and Naio, 2000, Abarca del Rio and Mestre, 2006, Zhou et al, 2008). Also, records of measured LOD variations serve to corroborate the series of global axial momentum, essentially a weighted measure of the zonal winds over the atmosphere. At lower frequencies, however, with time scales around a decade or longer, the contemporary relationship between AAM and LOD disappears because angular momentum exchanges between the mantle and core components progressively play the leading role (see Gross, 2007). It is essential however to investigate the presence of these lower frequency modes in the AAM. These, after filtration, are needed in particular to clarify the full angular momentum/Earth rotation budget. This helps determining the remaining sources of excitation mechanisms from the oceans, hydrology, and the mantle/core.

We already analyzed elements of these lower frequencies, including the decadal and bidecadal oscillations in LOD and AAM (see Abarca del Rio et al, 2003). To do so, we took into account the complementarities of the NCAR/NCEP atmospheric reanalyses over 1948–2000 and century-long model atmospheric simulations over the same time interval (1880–2000) forced only by sea surface temperature by both the NCAR model and the Hadley Center models. This investigation allowed us to identify the decadal and interdecadal oscillations present in NCAR/NCEP reanalyses, to confirm its presence in the century long simulations and extract the corresponding oscillations in LOD. Other authors extended these results to both polar motion and LOD. Thus, de Viron et al (2004) analyzed atmospheric variability in one of the century-long simulations, that of the Hadley Center, and the NCAR/NCEP reanalyses over 1949–2002 and looked more broadly at the spectral make up of the variability of atmospheric excitation with both the torque and the angular momentum approaches. Also with a wide spectral band around decadal scales, Gross et al (2005) analyzed both the atmospheric and oceanic excitation over 1949–2002, using NCAR/NCEP reanalysis, and oceanic angular momentum from a near-global ocean model that was forced by surface fluxes from the NCEP/NCAR reanalysis project itself. In particular, these two investigations provided insights in the fact that atmospheric and oceanic excitation at decadal-scales (taken as a broadband) is found to be only about 10% of that observed in LOD. This result is not surprising, since decadal-scale variations in LOD are caused mainly by interactions between the mantle and core. Finally Dickey et al, (2003) analyzing the poleward propagation of AAM over the 1981–1991 period showed that interannual and decadal time scales presented similar variability.

In parallel, different authors noted a possible trend in AAM; initially, Abarca del Rio, (1999), used different AAM analysis sets available from the IERS Sub Bureau of AAM (Salstein et al, 1993), including the NCAR/NCEP reanalyses. A century-long atmospheric model simulation by the Hadley center was used to note differences in the interdecadal fluctuations of interannual variability (Rosen and Salstein, 2000). The overall signals in AAM were broadly confirmed as well with a coupled atmosphere-ocean model (Canadian Centre for Climate Modelling and Analysis, CCCMA, Huang et al, 2001), and by the ECHAM5 atmosphere general circulation model (Winkelnkemper et al, 2008). Attempts to model the AAM taking into account increasing atmospheric greenhouse gas concentration and sulfate aerosol loading were made using earlier coupled models of the atmosphere and ocean (De Viron et al, 2001) or recently by Winkelnkemper et al, (2008); more recently, they were examined as well noting the sensitivity of different coupled models to different global warming scenarios (Salstein et al, 2011); in general increases in greenhouse gases were noted to be related to increases in AAM. Thus, decadal variability and trend are well-established characteristics of global AAM variability. However, the lack of a single century-long global atmospheric reanalysis set precluded the identification of other lower frequencies, on interdecadal time scales from analyses, though estimates could be made from models.

The interdecadal time scales may play a role by modulating (enhancing or moderating) the global signal. It is noteworthy that interdecadal and even centennial time scales in climate do exist. Variability on such scales was identified over European temperatures (Abarca del Rio and Mestre, 2006), global mean or gridded temperature records (Schlesinger and Ramankutty, 1994, Shabalova and Weber, 1999, Andronova and Schlesinger, 2000), oceanic and tropospheric data sets (Enfield and Mestas-Nuñez, 1999, Chen et al, 2010). These are usually associated with known ocean-atmospheric modes such as El Niño Southern Oscillation (ENSO) (Liet al, 2011), the Pacific Decadal Oscillation (PDO) (McDonald and Case, 2005) or Atlantic Multidecadal Oscillation (AMO) (Gray et al, 2004) which show such multidecadal
significant signals. Indeed such longer scales may also be modulating the temperature changes over continents (Knight et al., 2006, Compo and Sardeshmukh, 2009).

So global AAM, which reflects clear ENSO-related interannual signals, identified already almost four decades ago (see review in Abarca del Rio et al., 2000) has been found to contain also decadal and interdecadal signatures as well, so may be involved in the variability of atmospheric state and transports at interdecadal time scales as well. Given the above discussions, we attempt here to identify the low frequency signals in AAM. We will take advantage of the longest global atmospheric gridded reanalysis data set available, data from the recently developed 20th Century Reanalysis Project (1871−2008, 138 years) (Compo et al., 2006; Compo et al., 2011). We will also make use of the NCEP−NCAR reanalyses (Kalnay et al., 1996; Kistler et al., 2001), which may be more comprehensive than the 20th Century Reanalysis in the more recent period (1948−2010). The 20th century atmospheric reanalysis differs with the NCAR/NCAR reanalyses in that the first is performed assimilating only surface boundary conditions, that is, observations of synoptic pressure, monthly sea surface temperature and sea ice distribution. It uses an ensemble filter data assimilation method that directly yields each six-hourly analysis as the most likely state of the global atmosphere. The NCAR/NCAR reanalysis, in addition, assimilates also observations throughout the depth of the atmosphere from rawinsondes and satellite missions. Our earlier comparative study (Abarca del Rio and Salstein, 2011) has shown that the 20th century reanalysis reproduces well the troposphere variability, but is deficient in the description of stratospheric wind variability. As the stratospheric part does not play a meaningful role in the LOD budget (see above), dismissing its variability will not affect the results. This is the reason that essentially led us to concentrate our effort in the troposphere.

These complementary reanalysis data sets enable the computation of global atmospheric angular momentum and the investigation of the role of decadal to interdecadal time scales in the recent long-term variability in AAM. To assess its validity, we also examine its meridional transports. Finally, we compare its variability with that of certain fundamental climate modes: the interannual El Niño-Southern Oscillation (ENSO), the interdecadal Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO).

2. Data and Methodology

2.1. Data

The 20th century reanalysis (Compo et al., 2011) extends over 24 atmospheric constant levels, from 1000 hPa up to 10hPa, with 8 levels over the troposphere, whereas that from NCAR/NCAR (Kalnay et al., 1996) is in the same vertical range with 17 levels, 5 of which cover the stratosphere.

Comparison of both data sets over 1958−2002 (Abarca del Río and Salstein, 2011) showed that the new reanalysis data set reproduces tropospheric AAM variability of the NCEP/NCAR reanalyses remarkably well, although not that of the stratosphere (Compo et al., 2011). However, as the stratosphere includes some 10% or so of the total mass of the atmosphere, its influence on the global AAM is relatively small, and so we concentrate on analyses of tropospheric variability alone.

We computed a monthly relative AAM on both data sets, by integrating between $P_s = 1000\ hPa$ and $P_t = 100 \ hPa$, as follows (Rosen and Salstein, 1983, Salstein, 2003):

$$AAM = \frac{2\pi R^3}{g} \int_{P_s}^{P_t} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_{\phi_{min}}^{\phi_{max}} u \cos^2 \phi \partial \lambda \partial \phi \partial r,$$

where $R$ is the radius of the Earth, $g$ the acceleration due to gravity, and $u \cos^2 \phi$ the wind. The term is integrated over longitude, latitude, and pressure.

It is possible to infer changes in the length of the day (LOD) from the 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 solid earth, through the relation (Rosen and Salstein, 1983):

$$\delta(LOD)(ms) = 1.68 \times 10^{-26} \delta(AAM)(km\cdot m^2/s).$$

All results here are represented in equivalent units of milliseconds of LOD. The above proportionality factor holds primarily for timescales up to about a decade; at the shorter scales, only the crust plus mantle takes up the angular momentum from the atmosphere (Barnes et al., 1983). On longer time scales, angular momentum may be transferred to the core as well, and so the proportionality factor in the equation above decreases by order 10% due to inclusion of the core's moment of inertia. However, in discussions here, we will refer to the equivalent as if we were dealing with the solid portion of the Earth alone. In order to investigate the role of lower frequencies, we compute annual mean on both time series, i.e., the 20th century reanalysis (1871−2008) and the NCAR/NCAR reanalysis (1948−2008). Over its overlapping time span, the variance is nearly equivalent in both time series (correlation of both time series over 1958−2008 (480 months) is 0.86). Thus, delivering confidence on the quality of the 20th century reanalysis. However, we must also take into account the NCAR/NCAR AAM reanalyses time series.

Indeed, we will utilize mainly the 20th century AAM time series, because of its homogeneity. However, for investigating how the interdecadal time scales emerges from the NCAR/NCAR AAM data, and how it affects the actual variability, we append the 20th century reanalyses from the beginning of this time series to form a continuum to the past. Therefore, additionally we construct a time series taking in account the 20th century series up to 1948 and the AAM from the NCAR/NCAR thereafter. Since 1948, the NCEP/NCAR may be considered the more comprehensive series because of the use of more observations than is the case of the 20th century AAM, particularly in the recent post-1970s satellite era. However as shown in Fig 1, both time series differ in their mean.
It is necessary to adjust the 20th century reanalysis with a +0.25 millisecond mean step to fit with the 1958 with each frequency analyzed and by shifting the window in time. A measure of similarity. Basically, the CWT representation is a correlation between a wavelet (here a Morlet) at different frequencies are analyzed with different resolutions. Thus, the CWT Transform uses a multi-resolution technique by which different (visualize) signals in various spectral bands of interest. The Wavelet and its companion global wavelet power allow us to identify which the 20th century interannual, decadal, interdecadal, or other low frequencies over composition (EMD) will be used here to identify and extract the Discrete Wavelet Transform (DWT), plus the Empirical Modal Decomposition (EMD) (Huang et al, 1998; Flandrin and Goncalves, 2004). EMD is an empirical and totally adaptive method, that does not require any predetermined basis functions (as in wavelets). Decomposition (EMD) (Huang et al, 1998; Flandrin and Goncalves, 2004). EMD is an empirical and totally adaptive method, that does not require any predetermined basis functions (as in wavelets). In addition, only to corroborate the existence of the interdecadal oscillations, we also employ a entirely different and complementary time series decomposition methodology: the Empirical Modal Decomposition (EMD) (Huang et al, 1998; Flandrin and Goncalves, 2004). EMD is an empirical and totally adaptive method, that does not require any predetermined basis functions (as in wavelets). The decomposition is designed to identify locally an intrinsic mode function (IMF) that satisfies the condition that at any time instant, the mean value of the upper envelope as defined by the local maxima and the lower envelope as defined by the local minima is zero (Yang and Yang, 2009). In this way, an IMF is a pure oscillatory mode that bears amplitude and frequency modulations. The IMFs are extracted level by level: first the highest frequency

Figure 1. Plot of the annual mean global AAM time series data (solid black-line). The associated least squared trends for the whole period (1871−2008) shown in the dashed line. The associated trends for 1871−1947, 1948−2008 for the upper curve and 1871−1933, 1934−2008 for the lower curve shown in red point line Up: Composite AAM (20th century (1871−1947) +NCAR/NCEP (1948−2008)). Down: 20th century AAM time series (1871−2008)

2.2. Methodology

2.2.1. Time series methods

Different time series analysis methodologies, such as complementary wavelet transforms, Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT), plus the Empirical Modal Decomposition (EMD) will be used here to identify and extract the interannual, decadal, interdecadal, or other low frequencies over which the 20th century AAM time series evolves.

A CWT power spectrum diagram (Torrence and Compo, 1998) and its companion global wavelet power allow us to identify (visualize) signals in various spectral bands of interest. The Wavelet Transform uses a multi-resolution technique by which different frequencies are analyzed with different resolutions. Thus, the CWT is a correlation between a wavelet (here a Morlet) at different frequencies and the signal with the frequency being used as a measure of similarity. Basically, the CWT representation is performed by changing the size of the analysis window according with each frequency analyzed and by shifting the window in time.

The Morlet wavelet used here, is widely used in geophysics and is a reasonable compromise between time localization and frequency resolution (see Torrence and Compo, 1998).

A digital wavelet multi-resolution analysis [Craigmile and Percival, 2002, Murguià and Rosu, 2011] is used to extract the different spectral bands. The DWT decomposes the signal into different frequency resolutions by successive high pass and low pass filtering of the time domain signal. This is done using an orthonormal basis which is obtained by shifting and stretching a mother wavelet (here the Meyer). The DWT is based on a decimation methodology. Thus, the generic steps successively split the last low pass part into two parts; a vector of detail information (D) and a vector of a coarse approximation (A). Details at different decomposition levels are orthogonal to each other, ensuring that the information contained within details is unique. The frequency bands resolution and the number of levels to which the signal can be decomposed is only determined from the sampling and the time series length, respectively. Finally, as an example let us consider an original time series and call it approximation at level 0, denoted by A0. Suppose that we choose 3 levels for the decomposition: As A0= A1+D1 it implies that A0 = A3+D3+D2+D1. Thus, within the latest approximation (A3) are contained all the lowest frequencies that are not captured within the band-passed time series D1, D2 and D3, respectively, going from high to low frequencies.

We chose 6 levels of decomposition considering the annual resolution of the time series, and because fewer levels did not allow us to capture the interdecadal time scales. This decomposition resulted in 6 details (D1-D6, from high to low frequencies), as well as one approximation (A6) that represents the low frequency oscillations not captured within the details. Interdecadal time scales are separated naturally within the 5th (D5: 30-to-55 year periods) and 6th levels (D6: 55-to-90 years period) while the lower frequency oscillations, that is, the long-term trend the long-term trend is always contained in the highest approximation used are represented in the approximation A6. Higher frequencies are captured within the first four details (1-to-4); the interannual time scales are located in the first two levels (D1 and D2: 2-to-9 years periods), decadal time scales being given in the 3rd and 4th levels (D3 and D4: 9-to-30 years periods).

In addition, only to corroborate the existence of the interdecadal oscillations, we also employ a entirely different and complementary time series decomposition methodology: the Empirical Modal Decomposition (EMD) (Huang et al, 1998; Flandrin and Goncalves, 2004). EMD is an empirical and totally adaptive method, that does not require any predetermined basis functions (as in wavelets). The decomposition is designed to identify locally an intrinsic mode function (IMF) that satisfies the condition that at any time instant, the mean value of the upper envelope as defined by the local maxima and the lower envelope as defined by the local minima is zero (Yang and Yang, 2009). In this way, an IMF is a pure oscillatory mode that bears amplitude and frequency modulations. The IMFs are extracted level by level: first the highest frequency.
local oscillations riding on the corresponding lower frequency part of the data are extracted; then the next level highest-frequency local oscillations of the residual, and so on until no complete oscillation can be identified in the residual. A complete sifting process stops when the residue becomes a monotonic function from which no more IMF can be extracted (e.g., Wu et al., 2007). In practice, the EMD is implemented through a sifting process that uses only local extrema and depends solely on the sampling. It has been tested and validated exhaustively, particularly in geophysics (see Huang and Wu, 2008). Here, 7 intrinsic mode functions emerge (IMF1-IMF7, from high to low frequencies).

### 2.2.2. Strategy

We present the results in the following way. First we present the long-term and short-term trends present within the composite time series that we compare with those present within the 20\textsuperscript{th} century AAM time series (Fig 1). Second, because the 20\textsuperscript{th} century reanalyses AAM time series originates from a homogeneous field, i.e. constructed from a sole source (inversely to the composite), we analyze its variability in priority. After identifying its interdecadal and other low frequencies signals we compare their variability with what emerges from the composite series. Thus, we will perform both a CWT power spectrum diagram and its companion global wavelet power on the 20\textsuperscript{th} century reanalyses AAM time series (Fig 2). We extract the interdecadal time scales thanks to a DWT decomposition (Fig 3A). Then we perform a comparison with those that emerge from an EMD (Fig 3B). Having validated the presence of interdecadal time scales on the 20\textsuperscript{th} century reanalyses time series, we will analyze the DWT decomposition of the composite AAM time series (Fig 3C).

For the composite set, we concentrate particularly on describing the role of the different interdecadal modes in the modulation of global AAM, particularly in how the conjunction of the oscillatory modes through their short-term trends may appear to affect the global trend, particularly in the last decade. Statistical significance at different periods and the existence of trends was performed using the Mann-Kendall Univariate non-parametric test with a 95% confidence level (Libiseller and Grimvall, 2002). This well-known test is used routinely to assess trends in geophysical time series (Bihirat and Mehmet, 2003). All trends presented here achieve significance according to the Mann-Kendall test. We also wish to check if the poleward propagation of AAM anomalies occurs in the recently produced 20\textsuperscript{th} century reanalysis, as it did in the other reanalyses and models (see introduction). We compute therefore the relative AAM over separate latitude bands for the troposphere (integrating between 1000 and 100 hPa and for all longitudes, see equation 1) (see also Abarca del Rio et al., 2000), and construct annual means of the monthly solution. These bands were then filtered according with the same discrete wavelet decomposition (Fig 4).

Additionally we investigate the origin of the oscillatory modes in AAM. That is, we compare the AAM variability with that arising in different climatic indices related to the terrestrial main climate signals (Fig 5) by the mean of wavelet-based coherency (Grinsted et al., 2004). A cross-wavelet coherence in time-frequency space brings out the significance in any phase shift detected (Fig 6). The combination of power and coherence will allow a better understanding of the relationship at different time scales (Fig 6).

To bring out relationship at interdecadal timescales, both indexes are compared over their respective D5 and D6 components (Fig 7).

### 3. Results

The annual mean global AAM from the composite series (Fig 1, upper, solid black, curves) shows an apparent decrease from 1871 to roughly 1940 of -0.001 ms/yr followed by an increase. We note a related significant long-term trend (Mann-Kendall test) in the global time series (1871-2008) of +0.00032 ms/yr (upper black line). However it is clearly less important than a short-term trend of +0.0023 ms/yr, if computed only over the 1948–2008 period, which is almost 10 times greater. Let us confirm another visual impression (Fig 1 and Fig 3C-A): from the mid 1980s (roughly 1985) to today, the AAM is effectively decreasing, at -0.0043 ms/yr. Instead, the analysis of the annual mean global AAM based only on the 20\textsuperscript{th} century AAM (Fig 1, lower, solid gray, curves) shows that the long-term trend (1871-2008) of +0.0007 ms/yr is at least twice as large as that of the composite AAM. This difference is apparently related to the absence in 1955 of a minimum in the 20\textsuperscript{th} century AAM time series (Fig 1, lower curve) well present in the NCAR/NCEP reanalyses (upper curve). In the 20\textsuperscript{th} century AAM time series, instead, the lowest annual mean point is located in 1933. From then on, the AAM time series increases gradually (+0.0021 ms/yr in the 1933–2008 period).

We analyze the power on different time scales for the 20\textsuperscript{th} century...
Figure 3. Continued on next page

AA M term by the wavelet approach (Fig 2-A distributed with time and Fig 2-B for the full spectrum), with significance assessed against a red noise (AR(1)) background spectrum (Torrence and Compo, 1998). There is significant power from interannual to decadal time scales of about 8-16 yr period, including in many epochs and when considered overall. Significant variability in power is present at interdecadal time scales, particularly at the 30−50 year period (mostly in the earlier era), and at other lower frequencies (see Fig 2-A), the characteristics of which we investigate in the following.

Decomposition of the 20$^{th}$ century AAM signal through the discrete wavelet analysis allows us to disentangle these signals (Fig 3A), at decadal and longer time scales. We use the DWT method, whose six components are identified above. The results clearly show the existence of an oscillation in the 30 to 50 years band (D5 component, solid red line, Fig 3A-B); its periodicity fluctuates between 34 and 41 years, with an amplitude of about 0.03−0.05 ms. It indicates also another signal with a longer periodicity, greater than 80−90 years (D6 component, dashed red line, Fig 3), with an amplitude of about 0.03 ms, though this is a significant period of the whole period. The sum of the contributions (amount of increase or decrease per year) from these two longer oscillations (D5 and D6) explain much of the modulation variability over the last 50 years (see red line in Fig 3A-A).

The figure shows a decadal signal with a periodicity varying between 8 and 15 years (D3 component, solid blue line, Fig 3A-C), with an amplitude from about 0.02 to 0.08 ms. A lower frequency, say bi-decadal, with periodicity from 14 to 25 years (D4 component, dashed blue line, Fig 3A-C), occurs clearly. Its amplitude is almost equivalent to that of the decadal band, before 1930, and generally lesser after. This explains the absence of power in the continuous wavelet power diagram (Fig 2-A) over this band after 1960, and...
The continuous wavelet power spectrum revealed the presence of signals, whose oscillations are separated thanks to the discrete wavelet decomposition. To assess the validity of these oscillations, we applied an empirical modal decomposition (EMD) to the 20\textsuperscript{th} century reanalysis global AAM time series. Results are shown in Fig 3B, which reveal comparable oscillations. Thus, side by side comparison of the Intrinsic Mode Functions (IMFs) from the EMD and the details ($D_j$) from the DWT, associated with decadal to interdecadal time scales, i.e., $j=3,4,5$ and $6$, show high correlations, 0.61, 0.55, 0.74 and 0.94, respectively, all with no phase shift. Typically, here too in Fig 3B-B, we note interdecadal oscillations of about 30-50 years (solid red), and another at lower frequency greater than 80 years (dashed red). In Fig 3B-C are presented the decadal (solid blue) and bi-decadal signals (dashed blue).

After having demonstrated the presence of the interdecadal time scales in the 20\textsuperscript{th} century AAM signal, we may examine the composite time series, involving the short-term trends arising from the different interdecadal cycles. A discrete wavelet analysis of the composite signal is shown in Fig 3C. We may note that, since 1958, the D5 component (30−50 yr period) (solid red line, Fig 3C-B) increases at a rate of +0.0037 ms/yr. It reaches a maximum in 1980 and decreases at a rate of -0.0035 ms/yr thereafter. It has apparently reached or is about to reach its minimum. The D6 component (with a periodicity of about 80−90 yr, dashed red line, Fig 3C-B) increases at a rate of +0.0016 ms/yr since 1948 (during 1900−1948 it decreased at a rate of -0.0015 ms/yr) and reaches its maximum during the middle 90s (1993) with a subsequent decrease at a smaller rate of -0.0009 ms/yr.

Therefore, it is possible to conclude the following. Over 1955 to 1985, the increase of the composite AAM time series (shown...
Figure 4. Relative AAM contribution as a function of latitude (20th century data). Interdecadal modes. A: D5, B: D6

Figure 5. Association with climatic indexes. A: The standardized El Niño34 (blue) and the standardized composite AAM (black). B: The standardized PDO (red) and the standardized composite AAM (black)

Figure 6. Squared wavelet coherence between; A: the standardized Niño34 time series and the standardized composite AAM time series. B: the standardized Pacific Decadal Oscillation (PDO) time series and the standardized composite AAM time series. The 5% significance level against red noise is shown as a thick contour

in Fig 1, up, solid black) is due to the role of these short-term signals plus the long-term signal associated with the A6 component. The A6 component (not shown), that is the long-term trend, presents a +0.0004 ms/yr increase over the whole time domains (1871–2008), which is decomposed into a slight decrease (-0.0008 ms/yr) over 1871–1882 and an sharp increase of +0.001 ms/yr over 1923–2008. Thus, over 1955 to 1985, [D5 +D6 +A6] signal =+0.006 ms/yr. Instead, after 1985, only the first two (D5 and D6) (D5 +D6 = -0.0042 ms/yr) explain much of the decrease seen in 1985–today (composite AAM) (-0.0043 ms/yr).

However, are these interdecadal oscillations associated with a structure of zonal flow propagation? Analysis of the zonal propagation based on the 20th reanalyses, reveals that both the 30-50 year oscillation (Fig 4-A) and the longer one (Fig 4-B), present propagation-like structures. The 30-50 year structure (Fig 4-A) however has somewhat vacillating timing. Over the northern hemisphere the migration starts within the tropics about 1900 and 1920, and takes about 60–80 years to reach higher latitudes. Over the southern hemisphere, it takes somewhat less time, under decades, to reach mid and higher latitudes, though with greater amplitude and lesser homogeneity. The longer oscillation (Fig 4-B) contain some intriguing features over the northern hemisphere. Equatorward zonal flows starting in 1870 reach the mid latitudes about 1940, where they interact with a poleward structure that begun within the tropics about 1920, the latter reaching high latitudes more recently. Over the southern hemisphere, the structure originates within the tropics about 1870–80/1920–30, reaching
mid latitudes about 1930−40/1970−80. Additionally, we note the existence of another migration structure that starts at mid latitudes about 1900 and reaches high latitudes in 1960.

What is the nature of the interdecadal oscillation? Is there any relationship of the AAM time series with main climatic indices and particularly with those related to tropical variability? The comparison of the time series, Niño34 (an index of ENSO) vs composite AAM (Fig 5-A) and PDO index vs composite AAM (Fig 5-B) confirms this possibility. The comparison extends first to the whole 20th century and even back to 1871 the well-known relationship between ENSO and AAM (correlation of 0.72, at 0 year lag). In addition, we can note too that the relationship with PDO is also meaningful (correlation of 0.58, at 0 lag). The coherency wavelet diagrams confirm this relationship, as it clearly shows such coherence from interannual to bidecadal time scales (almost no phase shift) between AAM and Niño34 (an index of ENSO) (Fig 6-A). Additionally, we also check for the exact relationship between interannual and decadal bands, by comparing their DWT decompositions. Thus, at interannual times scales (D1+D2) the correlation between the composite AAM and Niño34 is 0.80 (at 0 lag), while being only 0.49 (at 0 lag) with the PDO. At decadal/bidecadal time scales (D3+D4), the correlations are 0.82 (0 lag) and 0.63 (0 lag) respectively for El Niño and PDO.

At lower frequencies, the coherency wavelet diagrams show that the relationship with the Pacific Decadal Oscillation emerges (Fig 6-B), with the PDO index in phase or slightly being lead by the AAM signal. We also check for a relationship between equivalent spectral bands, the D5 and D6 components (in Fig 7-A and Fig 7-B respectively). Thus, within the D5 (30−50 yr period) component the Pacific Decadal Oscillation and AAM signals show almost no phase shift (correlation is 0.88 at 0 lag), while Niño34 index lead slightly the AAM signal (0.59, +3 year lag). For the D6 component, again the correlation with the PDO is high, 0.82, comparable to the D5 component (0.82 and 0.67 for the PDO and El Niño34, respectively), although both are being led (+14 and +15 years respectively) by the AAM signal.

Other climatic indices, alike the Atlantic Multidecadal Oscillation index, or others alike the Antarctic Oscillation have only intermittent and very short relationships with AAM, and so are not shown. The influence of the Pacific in the origin of these atmospheric modes is apparently vital.

4. Conclusions

The analysis performed here shows that the low frequency signals in the AAM from the recent 20th atmospheric reanalyses, covering 128 years, complemented by 60 years of the NCAR-NCEP reanalysis displays significant signals at time scales longer than the well-known scales, namely the interannual, decadal/bidecadal, or positive trend (see introduction). Thus, we extend our analysis to a lengthy period, over 128 years, with the use of a comprehensive composite reanalysis. We noted too that interannual to decadal time scales, up to 25 years, are highly coherent with ENSO variability. We extend the knowledge established over shorter time spans (1948-on) using NCAR/NCEP reanalyses to a lengthier time span using the recent 20th atmospheric reanalyses.

Those with periods of 30−50 and even longer than 80 years (though the longer is based on a limited coverage period of 128 years) significantly modulate the AAM signal over some special epochs and may play a role in LOD variations. The influence on LOD is particularly the case over the 1950-1985 epochs in which the global positive trend is due to a conjection of positive signals from principally the multidecadal cycles (30−50 and up to 80 year periods). Instead, since roughly the mid 1980’s the global AAM time series tend to decrease, explained by the conjunction of such signals from the 30-50 and 80 year periods.

The analysis reported here shows that these two modes originate within the tropics, associated directly with the Pacific Decadal Oscillation for the 30−50 signal, and delayed with the PDO/ENSO for the longer from which they propagate poleward, though have different characteristics in each hemisphere. Let’s note first that the Pacific Decadal Oscillation (PDO) is a long-lived El Niño-like pattern of Pacific climate variability. Thus, while the two climate oscillations have similar spatial climate fingerprints, they have very different behavior in time; the PDO typically persisting longer (decades), while ENSO may persist for up to 18 months. Let’s also note that climate indices provide a mean of summarizing spatio-temporal variability. Thus, although both indices (Niño34 and PDO) may represent different facets of the Pacific’s influence on global climate, AAM instead represents a mean by which it is possible to understand the mechanism by which these ocean-atmospheric coupled modes propagates worldwide.

As AAM is an important index of the atmospheric circulation, these results are also suggestive for the understanding aspects
of climate evolution. Other considerations, for example, include future improvement of the new 20th century reanalyses fields, as well as the need to compare these results with 20th century simulations, including coupled atmosphere-ocean model runs. A major issue to consider now, of course, is how to interpret the results on these long time scales, especially with regard to issues of forcing by anthropogenic, natural (internal climate, volcanic and solar activity effects) or external (other) factors. The groundwork for the investigation of these possibilities is being investigated now for a variety of indices, including AAM, on these climatic time scales, on interdecadal to century-long signals and beyond.

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References

Chen G., Shao B., Han Y., Ma J., Chapron B., 2010, Modality of semiannual to multidecadal oscillations in global sea surface temperature variability, J. Geophys. Res. 115, C03005
de Viron, O., V. Dehant, H. Goosse, and M. Crucifix, 2001, Effect of Global warming on the length-of-day Geophysical Research Letters
de Viron O., Salstein D., Bluzuard C., Fernandez L., 2004, Low-frequency excitation of length of day and polr motion by the atmosphere, J. Geophys. Res. 109, B03408
Dickey J.O., Marcus S.L. De Viron O., 2003, Coherent interannual and decadal variations in the atmosphere-ocean system, Geophysical Research Letters, 30(11), 1573
Eubanks T.M., 1993, Interactions between the atmosphere, ocean and crust, Possible oceanic signal in earth rotation, Advances in Space Research. 13(11), pp. 291–300
Jadin E., 1995, Total ozone and stratospheric angular momentum anomalies Meteorology and Hydrology. 7, pp. 48−55
Lambeck K., Cazenave A, 1977, The Earth's variable rate of rotation: a discussion of some meteorological and oceanic causes and consequences, Phil. Trans. R. Soc. Lond.,A284, pp. 495−506
Lee S., Son S.W., Grise K., Feldstein, S.B., 2008, A mechanism for the poleward propagation of zonal mean flow anomalies, Journal of Atmospheric Sciences. 64 (3), pp. 849−868