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Solar activity and earth rotation variability

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Abstract

The analysis of variability in Atmospheric Angular Momentum (AAM) and Length of day (LOD) of Abarca del Rio et al. [Ann. Geophys. 18 (2000) 347] is extended to investigate a possible connection with solar activity fluctuations from interannual to secular time scales. The southern oscillation index and records of sea surface temperature are used as proxy series in this analysis during the era prior to the availability of AAM analyses. At interannual times scales, the variability in AAM and LOD agrees with that in solar activity with regard to the decadal cycle in the stratospheric quasi biennial oscillation and solar activity but whose phases are slowly shifting from one another with time, while the stratospheric quasi biennial cycle agrees with the solar quasi biennial cycle, though led by 6 years. At decadal times scales, AAM varies statistically with the solar decadal cycle over much of the last century since 1930–1940. The decadal mode in AAM is suggested here to be generated by upward propagation of surface atmospheric modes, from the surface throughout the troposphere through the stratosphere. Equatorial Sea Surface Temperature (SST) variability may be considered a proxy index for AAM variability because of the relationship to the El Nino/Southern Oscillation; its analysis over the last three centuries (1730–2000) and that of LOD since 1830 confirm the agreement found over the last part of the 20th century, as well as the general disagreement before.

1. Introduction

The Sun drives the thermal balance of our planet and when modulated by orbit-based parameters, determines the seasonal weather cycles of our planet. Until recently Solar irradiance was

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assumed to be invariant and thus the power intercepting a unit area at the Earth's mean distance from the sun was called the solar constant. Current satellite- and rocket-based instruments demonstrate a variation in solar irradiance (Hoyt and Schatten, 1997) which is tied to the approximate decadal cycle seen in sunspot numbers (Parker, 2000). This variability is relatively small, 1–3 Wm^2, corresponding to between 0.1 and 0.3% of the total solar irradiance reaching the earth (Pap and Fröhlich, 1999).

Recently, a number of studies have shown that from interannual to secular times scales, meteorological and climatic data are correlated with solar variability (see reviews by Sadourny, 1994; Reid, 1995; Hoyt and Schatten, 1997; Lean and Rind, 1999; and Nesme-Ribes and Thuillier, 2000). The earlier solar-climate link debate (Pittock, 1978, 1983) was revitalized with new studies (Arnold and Robinson, 1998; Shindell et al., 1999) searching for a physical mechanism by which small changes in solar output could be amplified in the Earth's atmosphere. In fact, at wavelengths not visible to humans, such as the Ultraviolet and Extreme Ultraviolet, the percentage variability is much larger, changing by factors of 100 or more over time scales of minutes to hours, and the Earth receives other types of energy such as outflows of charged particles. According to the recent Sun-Climate (2000) connection workshop held by NASA the research on such links has been organized into general areas that we summarize here. (1) Direct forcing of tropospheric climate by changes in the near UV, visible, and IR radiation. (2) Indirect forcing of climate by solar induced changes in the stratosphere, such as through ozone interactions resulting in temperature and other changes around the 30 hPa level, possibly modulating the Quasi-Biennial oscillation (QBO). (3) Influence of energetic particles, such as the galactic cosmic rays and energetic electron precipitation modulated by the solar wind that can alter cloud cover as well as induce upper and lower atmosphere couplings.

Recent results by Friis-Christensen and Lassen (1991), Crowley and Kim (1996), Diamantides (1998), Kishcha et al. (1999), Mann et al. (2000) and Crowley (2001) as well as numerous references in Lean and Rind (1999) have intensified the debate. Many of these investigations correlate different indices of solar activity with hemispheric time series of surface temperature, suggesting that up to 30–50% of the interdecadal - century time scale variance in surface temperature could be attributed to solar forcing. However, numerical experiments (Cubasch et al., 1997; Tett et al., 1999; Bertrand et al., 1999; Meehl et al., 2003) show that although a combination of solar variability (interpreted nevertheless in view of reconstructed past solar activity indices), and volcanic activities (e.g. Mann et al., 2000; Crowley, 2001) could have forced climate at secular time scales up to roughly 1930, these can not be responsible for global warming, currently being observed and reported about by IPCC (2001).

Because of the absence of consensus regarding physical processes relating solar activity to climate variations, this topic has caused much speculation (Pittock, 1978, 1983) and controversy. Given results at secular and interdecadal time scales, one expects a similar relationship between the powerful 11-year Schwabe cycle in solar activity and decadal times scales in climate indices, though such results may be inconsistent; Nitta and Yoshimura (1993) as Parker et al. (1994), analyzing global air (land + marine) temperatures, suggest that decadal variability in global averaged air surface temperature anomalies and the 11-year solar cycle, though related, are unrelated linearly before 1940. On the other hand, Lau and Weng (1995) and White et al. (1997), found significant solar-related signals in the equatorial sea surface temperature over the entire 20th century. Recently, though contested (Gierens and Ponater, 1999) it has been shown that global cloud coverage (Svensmark and Friis-Christensen, 1997) contains a decadal cycle. Additionally, suggestions of the 11-year cycle appear in stratospheric parameters like geopotential height, zonal winds and temperatures (Labitzke and van Loon, 1997) and noted in general for some characteristics of the quasibiennial oscillation (Baldwin et al., 2001) over the last 40 years.

On this topic, much of the analyses has been performed with climate indexes at the surface in the troposphere or in the stratosphere, or at individual geographically located parameters. In the present study however, we will analyze an index representing and measuring the dynamic state of the whole atmosphere, the atmospheric angular momentum (AAM). In fact, much of the historic development of modern meteorology is connected with the study of how atmospheric momentum is maintained locally or transported from one region to another and how it is exchanging momentum with the oceans and solid Earth (Peixoto and Oort, 1992). Its conservation properties are closely linked with those of energy conservation (White, 1989). It is therefore a fundamental circulation index used to characterize the dynamic state of the general circulation of the atmosphere, and climate (Peixoto and Oort, 1992). AAM is known to exhibit pronounced high frequency (Schuh and Schmitz-Hübsch, 2000) and seasonal fluctuations (Marcus et al., 1998; Höpfner, 1998, 2001), interannual times scales associated with large scale flow anomalies (Rosen et al., 1991; Dickey et al., 1992; Black et al., 1996; Chen et al., 1996; Dickey et al., 1999; Abarca del Rio, 2000) and decadal oscillations (Abarca del Rio, 1997; Rosen and Salstein, 2000). In addition, its knowledge is also important for space geodesy and interplanetary navigation, since on all the above time scales, AAM is highly correlated with length of day (LOD) variations, a measure of the Earth's rotation rate (see review by Eubanks, 1993).

The present paper explores relations between solar activity (SA) described in indices like the Wolf sunspot number (WSN), and atmospheric angular momentum (AAM), from interannual to decadal times scales. This study covers two time scales; interannual and decadal. In the first part, we emphasize stratospheric quasi biennial (QB) variability as evidenced in AAM. We also investigate the triennial-quadrennial and six year oscillation (TQO and SYO respectively). In the second section, we will concentrate our analysis in the decadal oscillation in AAM and LOD.

2. Data

2.1. Atmospheric angular momentum (AAM)

The axial AAM about the polar axis of a layer of the atmosphere, may be calculated following Barnes et al. (1983):

$$\mathrm{AAM} = \frac{2\pi R^3}{g} \int_{Ps}^{Pt} \int_{\pi/2}^{-\pi/2} \int_0^{2\pi} u \ \cos^2\varphi \partial\lambda \, \partial\varphi \partial p \tag{1}$$

where R is the radius of the Earth, g acceleration due to gravity and u zonal wind speed. The term is integrated over all latitudes, φ, longitudes, λ, and pressures, p (from 1000 hPa, near the surface, to 10 hPa in the stratosphere. A second AAM term, related to changes in the mass distribution of the atmosphere (surface pressure variations), plays a much smaller role in global AAM budget (less than 5%) on most time scales (Eubanks, 1993), and is not accounted for in the following.

Using the zonal wind fields from the recent NCEP reanalysis (Kalnay et al., 1996), we constructed a 52-year long set of monthly global AAM from January 1949 to December 2000. The reanalysis fields are available on 2.5°×2.5° latitude-longitude grids over 17 layers from 1000 hPa to 10 hPa, with five levels over the stratosphere (70, 50, 30, 20 and 10 hPa). These fields allow computation of AAM up to 10 hPa using Eq. 1. Recently, Rosen and Salstein (2000) showed that AAM data issued from an atmospheric model (UKMO Hadley Center Model) forced by SST fields (GISST) over 1870 to 1998 showed comparable variability to that of the reanalysis (over 1950–1998) in seasonal to interannual times scales. With this in mind, we construct another AAM set with data issued from similar model experiments (NCAR CCM3, Kiehl et al., 1998), forced by the same sea surface temperature fields (GISST) over 1870–1997. From these models runs we constructed two ensemble averages of simulations of AAM, respectively for the UKMO and NCAR models.

The AAM data can be expressed in millisecond (ms) of length of day (LOD) variability, assuming that changes in AAM for the entire atmosphere are accompanied by equivalent changes in the angular momentum of the Earth, through the following relation (Rosen and Salstein, 1983):

$$\Delta \mathrm{LOD(ms)} = 1.68\ \ 10^{-29} \Delta \mathrm{AAM}\left(\mathrm{kg\ \ m^2/s}\right) \tag{2}$$

2.2. Length of day (LOD)

The LOD data are taken from the compilation of the International Earth Rotation Service (IERS annual report, 1999) based on a combination of astrometric and space-geodetic methods, from 1700 to 1830 at an annual resolution, from 1830 to 1949 seasonally, and from 1949 to 2000 monthly. From this data set we constructed a continuous series extending from 1700 to 2000. This data set matches well with the recent combined annual LOD data series from Gross (2001).

2.3. Sea surface temperature (SST)

We will also analyze the equatorial SST variability from year 1730 up to 1980, taking advantage of the recent annual reconstructed (marine + land) fields by Mann et al. (2000). For comparative purposes we will also investigate the Kaplan et al. (1998) monthly fields of sea surface temperature from to 1856 to 2000. From these fields we constructed two main time series: Kaplan20 and Mann5. The Kaplan20 time series is constructed by averaging globally (all oceans) from 20°S to 20°N the Kaplan et al. (1998) SST anomaly fields which are available monthly over 1855–2000 on equal 5° latitude–longitude grids. The Mann5 time series is constructed by averaging globally (all oceans) from 5°S to 5°N the anomaly fields of SST of the Mann et al. (2000) reconstruction, which are available annually from 1730 to 1980 on 5°×5° latitude–longitude grids. For both fields we choose only grids which were complete over the entire time span and we constructed Pacific, Atlantic, and Indian Ocean equatorial SST averages. In the case of the Kaplan fields, for comparative purposes, we also constructed 5° and 10° averages (Kaplan5 and Kaplan10 respectively). Finally we will also use the global temperature (marine + land) time series by Mann et al. (2000), extending from 1700 to 2000 hereinafter named GT.

2.4. Solar variability

For analytical purposes the intensity of the solar radio flux values at 2800 MHz (the 10.7 cm radiation or $F_{10.7}$ index), which measures the variable solar photon inputs into the atmosphere, is likely the best suited for comparison with climate indices, though it starts in the 1950s (Gorney, 1990). For studies involving longer data series, the varying number of sunspots has been subject of observation through several hundred years and may be regarded as reliable since 1750 (Eddy, 1976). The Wolf sunspot number (WSN) is highly correlated with Sun's output of the radiation in the extreme ultraviolet (EUV) wavelength band, and it varies identically with the 10.7 cm radiation, with the eleven year period being its dominant oscillation (Gorney, 1990). In preliminary analyses, we performed comparative analyses between the WSN and the $F_{10.7}$ index over their overlapping period (1950–2000) in all the frequency bands studied. We confirm that both series are identical. Therefore we will use the Wolf sunspot numbers (the WSN) as a solar activity index (herein after SA). Let's note here that the decadal oscillation in solar activity is also called the Schwabe cycle following its discovery by Schwabe (1843).

3. Analyses

3.1. Interannual times scales

Interannual signals in AAM and LOD are dominated by a number of distinct bands (Abarca del Rio et al., 2000). A 6-year oscillation can be noted (Abarca del Rio et al., 2000) in LOD and up to 5 years, a pair of scales, related to ENSO emerges (Dickey et al., 1992; Black et al., 1996) in both AAM and LOD, those at 3–5 years, and 2–3 years, also related to the quasi biennial oscillation. We separate below the interannual fluctuations into low and higher frequency (LF and HF respectively) variability.

3.1.1. LF interannual variability

Association between ENSO and SA at interannual time scales have not been documented to date. Results connecting the two processes appear to be confined to much longer times scales, the 80–90 year Gleissberg cycle (Michaelsen, 1986), but such scales are far beyond those under consideration here.

Given the close relationship documented between the southern oscillation index SOI and AAM (see Abarca del Rio et al., 2000), and the availability of the SOI for over a century, since 1866, we compared the interannual variability in this monthly SOI with the WSN series We computed the spectra of each series, as well as co-spectra and squared coherence spectra (Fig. 1). We separated the analyses into three spectral regions addressed in AGS, the six-year oscillation (SYO), the triennial-quadrennial oscillation (TQO) and the quasibiennial band (which is presented in the high frequency section).

3.1.1.1. The six-year oscillation (SYO). Though neither the SOI nor the WSN peak near 6 years, they do cohere strongly with each other at this frequency. Wavelet analysis of both series (Torrence and Compo, 1998), are in phase in the 5.5–7 year band over 1866–2000 (not shown) though

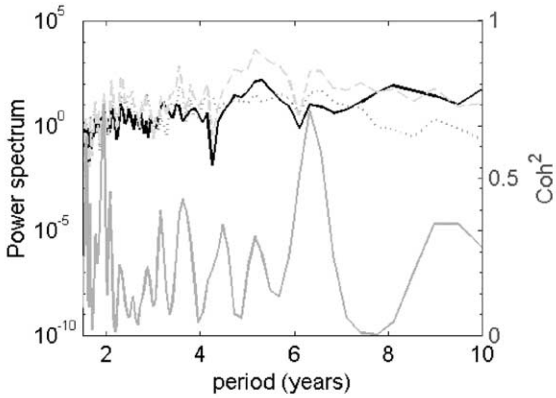

Fig. 1. Spectra of the solar activity (bold line), SOI (dotted line), co-spectra (grey dashed line) and squared coherency (grey line) for the monthly time series for 1866–2000.

3–4 oscillations is often the limit of the phase agreement. Interestingly, the 6-year signal in LOD noted by Vondrak (1977), and reconfirmed with new space-geodetic data sets by Liao and Greiner-Mai (1999) and Abarca del Rio et al. (2000), was shown by Djurovic and Pâquet (1996) to possess a significant relationship with SA. Our analysis of LOD and SA over 1830 to 2000, by both singular spectrum analysis (Vautard et al., 1992) with different embedding dimensions varying from 8 to 20 years, and wavelet analysis confirms a present but transitory relationship. The SA and LOD series peak in the 5–6 year and 6–7 year bands, respectively.

3.1.1.2. The triennial quadrennial oscillation (TQO). Although the SOI and WSN spectra in Fig. 1 are not significantly related at the TQ time scale, we investigate the variability in AAM and LOD at this scale, including a direct or lagged association with the decadal cycle in the solar activity. Confirming spectra results in Fig. 1, in the 3.5–5 year band, SOI and SA do not present comparable variability (not shown). We used the amplitude of the TQ oscillation in SOI as a proxy index of the possible modulation of the TQ band in AAM by the decadal-scale cycle in solar activity (Fig. 2a). Such results also agree with earlier studies at interannual times scales in AAM and LOD (Abarca del Rio et al., 2000), in which the TQ signal had a modulation of about 13–15 years, associated with ENSO (Wang and Wang, 1996), and therefore different from the 11-year period of the SA. The interannual and decadal variability in SA appears not to be related with the TQO in neither SOI, AAM, nor LOD.

3.1.2. HF interannual variability: The Quasi Biennial Oscillation (QBO)

In contrast to lower frequency interannual signals, the quasi-biennial oscillation, particularly in the stratosphere, appears to be related to both the phase of the decadal cycle in solar activity and to the amplitude of a QBO signal itself. Ramanathan (1964, cited in Berson and Kulkarni, 1968), found a break and phase shift in the QBO midway between times of sunspot maxims, based on analysis of a series of total ozone data taken at Arosa (47° N) from 1939 to 1963. Later Berson and Kulkarni (1968) analyzed a number of parameters including temperatures, total ozone and wind, over a longer period, 1908 to 1965 and further confirming the existence of the QBO, especially around the time of a solar minimum.

The period and amplitude of the solar cycle were noted to be related to rawinsonde-based zonal wind observations during 1951–1979 by Quiroz (1981), and since other authors (Labitzke, 1987; Labitzke and van Loon, 1990; Kodera, 1991; Naito and Hirota, 1997), have observed an even stronger relationship when the data are organized according to the phase of the QBO. However, such a stratifying approach has been criticized by Salby and Shea (1991) as introducing spurious covariance through aliasing, which is not present in the unstratified data. Other critics cite a

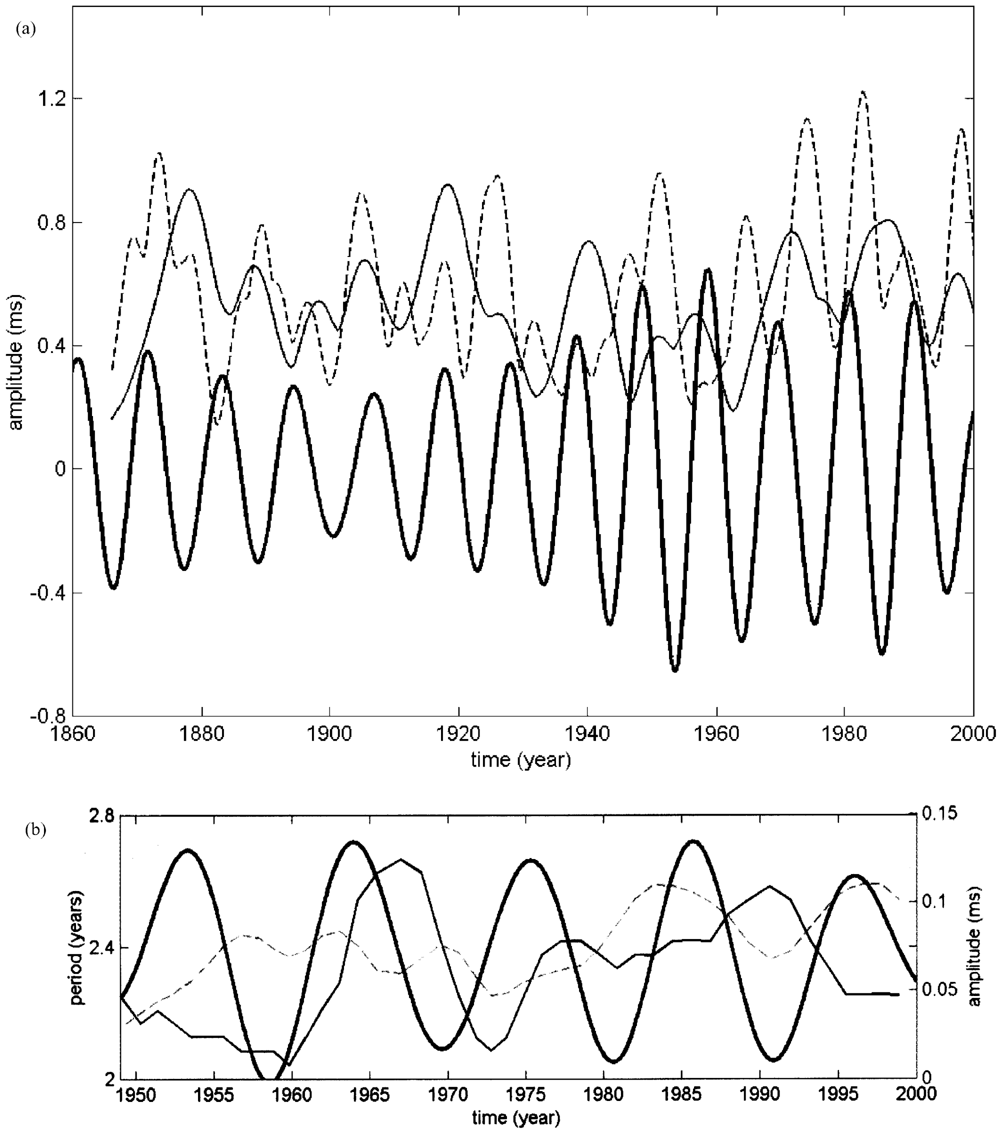

Fig. 2. (a) Comparison of the Schwabe cycle (bold solid line) and the amplitude variability of the QB (dashed grey) and TQ (solid line) in SOI. SA is dimensionless. (b) Comparison of the characteristics (period (solid line), amplitude(grey dashed line) of the s-QBO in AAM and the inverted Schwabe cycle in SA (bold solid line). SA is dimensionless.

relative short data length and the quality of data in the early part of the last century (Hamilton, 1990). Pessimistically, Hamilton (1998) provides a negative perspective on reconstructing a continuous and viable index of past stratospheric variability 1950.

Here we compare the quasi biennial variability in AAM (tropospheric and stratospheric) first with the decadal cycle in solar activity (subsection 3.1.2.1) and then with a comparable oscillation in solar activity (subsection 3.1.2.2).

3.1.2.1. Association of the quasi biennial variability in AAM with the decadal cycle in solar activity. The quasi biennial oscillation in AAM appears to originate from two separate processes, one in the troposphere and linked with ENSO (the t-QBO), and the stratospheric (the s-QBO). Whereas we were unable to note a link between the amplitude and phase of the t-QBO in AAM and the decadal cycle in solar activity (Fig. 2a), we did determine, in contrast, a relationship, though weak, with the s-QBO.

The evolution of the period and amplitude of the s-QBO are presented along with the inverted decadal solar signal in Fig. 2b. Over much of the 50 years analyzed, a relationship ship exists whose phase lag with the inverted decadal solar cycle appears to average 4 years, though it vacillates from about 3 years in 1965 to 5 years in 1995. The variability in this lag might indicate an origin for the decadal modulation other than solar activity, and furthermore the annual resolution of earlier studies can partially mask the QBO period, particularly when segregated into the east and west phases. To mitigate these issues in part, we were able to confirm the above relationship, with the vacillating time lags, using the expanded QBO index of Naujokat (1986) from the mid-1950s between the 100 and 10 hPa levels. Following earlier studies separating the east and west-directed phase, we found that part of the association between the decadal cycle in SA and the period of s-QBO in AAM was due to a contraction of the east-to-west (through to peak) changeover. When the contraction and expansion of the east to west change over is taken alone the correlation appears to be amplified, but the association is also present in the west to east change over.

3.1.2.2. Association with the quasi biennial cycle in SA. Djurovic and Pâquet (1993) noted the relationship between a QB oscillation in green corona activity and one in Earth rotation. AAM being the main contributor to LOD at these scales, it is therefore important to understand the solar imprint, if there is one, within this band over the atmosphere.

Solar activity presents a quasi-biennial cycle, observed especially in sunspot numbers (Shapiro and Ward, 1962; Akioka et al., 1987) as well as other solar activity indexes: solar variability (Bao and Zhang, 1998; Benevolenskaya, 1998), neutrino flux (Sakurai, 1979, 1981), magnetic field (Riven and Obidko, 1992), radio flux at 10.7 cm, solar flare rate, X-ray burst, sunspot area, solar diameter variations in addition to the green corona activity noted above. It is a well-established peak in solar activity although its amplitude is rather weak when compared to the 11-year cycle. We will study its relationship respectively with the t-QBO and the s-QBO of AAM.

The t-QBO. The correlation of the quasi biennial oscillation in SA (QBO-SA) with the QBO of AAM in the troposphere, is weak (correlation found is 0.41 SA at a time lead of 73 months) while the correlation with the global AAM (troposphere and stratosphere) is 0.6, with the SA leading (also by 73 months). An extended analysis of SA with SOI over 1866 to 2000 reveals correlations of about 0.3, and moreover with the SOI leading SA by 50 months. However when considering only the recent period since 1950, a similar level of correlation exists, though with a reversal in the sense of the lag, with SA leading SOI.

The s-QBO. The significant correlation found by Djurovic and Pâquet (1993) between LOD and the QBO-SA is explained by the relationship with the stratospheric contribution to AAM at this band (the s-QBO). The s-QBO and the QBO-SA are correlated (0.54), with the solar cycle leading the stratospheric angular momentum by 73 month (roughly 6 years), although the association increases over the last 30 years (0.6 with the sun leading by 73 months). If we extract the quasi biennial variability through SSA (Vautard et al., 1992), a method to focus the data, over the last 30 years the correlation is as high as 0.66 for LOD and 0.7 for s-QBO with the SA leading by 73 months. Using the 10.7 cm radio as alternative time series for SA, we obtained similar correlation values, therefore confirming previous results with sunspots data. The comparison of QBO in SA, though lagged by 73 months, with that in LOD, stratospheric AAM and tropospheric AAM are shown in Fig. 3 (a, b and c respectively). It may be noted that when the QBO-SA signal is at higher amplitude (1955–1960, 1975–1980, 1985–1990, 1995–2000), its phase is closer to that in the stratospheric AAM lagged by 6 years (Fig. 3b). Elsewhere the phase is lost. Because the

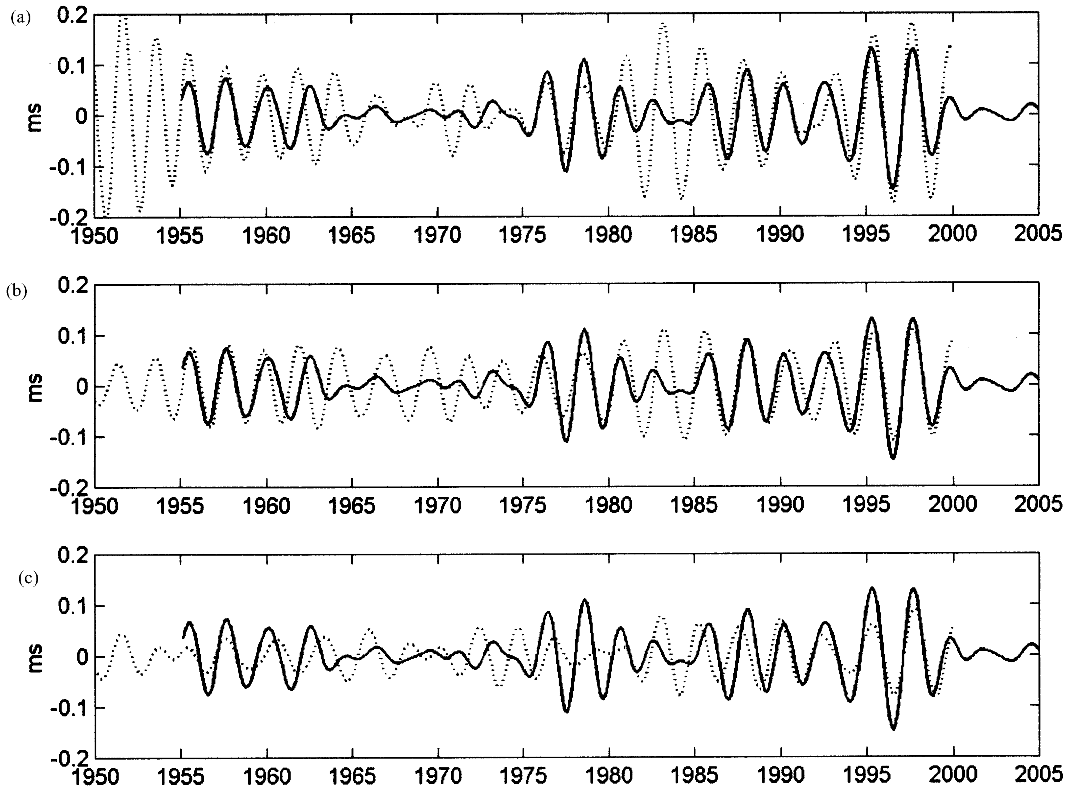

Fig. 3. Comparison of the evolution of the quasi biennial (QB) cycle in SA (bold) with the quasi biennial (QB) cycle in LOD (Fig. 3a), stratospheric (Fig. 3b) and tropospheric (3c) contributions (dashed line). All AAM series has been lagged by minus 6 years towards the SA.

stratospheric AAM signal showed in this figure is the sum of all contributions from 70 hPa up to 10 hPa [see Eq. (1)], we also investigate the correlation of the QBO in solar activity with the QBO in each layer over the stratosphere. In an analysis for the period between 1949 and 2000, AAM at the10 hPa level leads SA by 12 months, and such lags increase up to 76 months at the lower 50 and 70 hPa levels. Similar analysis with a monthly QBO index of three location in the equatorial zonal winds during 1956–1999 (Naujokat, 1986) reveals a downward signal propagation, with phases, at the 20, 30, 40, 50 and 70 hPa layers, increasingly lagging the solar signal by 64, 68, 71, 73, and 76 months, respectively. Such correlations approach 0.5 over this 44-year period, but increases if we only take in account the last 30 years. Longer periods would be necessary to reconfirm the relationship with the quasi biennial oscillation characteristics (Hamilton, 1998), though historical series are likely unobtainable.

3.2. Decadal time scales

Five decades of AAM are available from the NCEP-NCAR reanalyzes; however to study the atmosphere during the last century, we rely on atmospheric models run with boundary sea surface temperature forcing. For even lengthier analysis, we also extend our study into the historic past by the use of a proxy climate indices of two equatorial sea surface temperature (SST) time series (Kaplan20 and Mann5) over 1730–2000.

3.2.1. Decadal times scales in AAM data

To isolate decadal and longer signals in AAM, we have chosen three independent analysis methods. Spectral analysis on unfiltered monthly AAM series, 1949–2000, reveals a powerful decadal peak near 10–11 years as well as an energetic interdecadal broad band, with a peak near 22 years. This spectrum and those of the first and second order autoregressive (AR) models of the detrended AAM series are represented in Fig. 4a. Both AR models highlight the statistical significance of the decadal peak, and the AR-1 model acknowledges the significance of the bidecadal peak. A further wavelet analysis (Fig. 4b; Torrence and Compo, 1998) confirms the presence of both scales throughout most of the last half century. The interdecadal oscillation passes above the 10% significance level, according to a red noise background spectrum. Additionally, multitaper methods (Vautard et al., 1992), shows that the decadal peak in AAM is statistically significant above the 95% confidence level by a Fisher test, and the bidecadal with a lesser significance at the 80% confidence level. We discuss further analysis of the statistically-significant decadal peak, and leave the more weakly significant bidecadal one for later study.

Using Eq. (1), we computed AAM up to different pressure heights: 850 hPa (1.5 km), 500 hPa (5.5 km), 200 hPa (12 km), 100 hPa (16 km) over the troposphere, and up to 50 hPa (20 km) and 10 hPa (33 km) in the stratosphere. From the spectrum performed on each of the time series, we derive spectral characteristics (power and phase) of the decadal peak. The decadal cycle in AAM results from a major contribution of the troposphere (up to 100 hPa) and a significant participation (up to 20% of the variance) of the stratosphere (100–10 hPa) (Table 1). The calculations within the lower tropospheric heights (850, 500 hPa) lead those computed over upper heights, while the troposphere (100 hPa) leads the stratospheric layers by roughly 3 months (above 100 hPa). Although phase shifts between AAM series are small compared to the decadal period, the mode propagates slightly upwards. Our alternative multichannel singular spectrum analysis on zonal wind in vertical layers (see Abarca del Rio et al., 2000) also confirms such upward propagation from the surface throughout the troposphere and into the stratosphere.

To quantify the common signal between solar activity and atmospheric angular momentum, we applied a co-herency applied coherency spectrum (Fig. 4c; Hinich and Clay, 1968) to the AAM and solar activity series. Results indicate significant relationship at decadal time scales with statistical significance (Julian, 1974) for the 95% limit ($P = 0.63$). The phase spectrum shows no significant phase lead or lag between the series. The coherency spectrum suggests as well that the series are unrelated at other low frequencies, such as the bidecadal peak in AAM. A wavelet coherency approach (Torrence and Webster, 1999) also confirmed these results.

When the series is subjected to low-pass filtering with a cut-off at 8 years (Fig. 5a), a relationship between solar activity and AAM at decadal time scales emerges. The maximum correlation between the two series is 0.74, solar activity leading LOD by 2-months.With these series

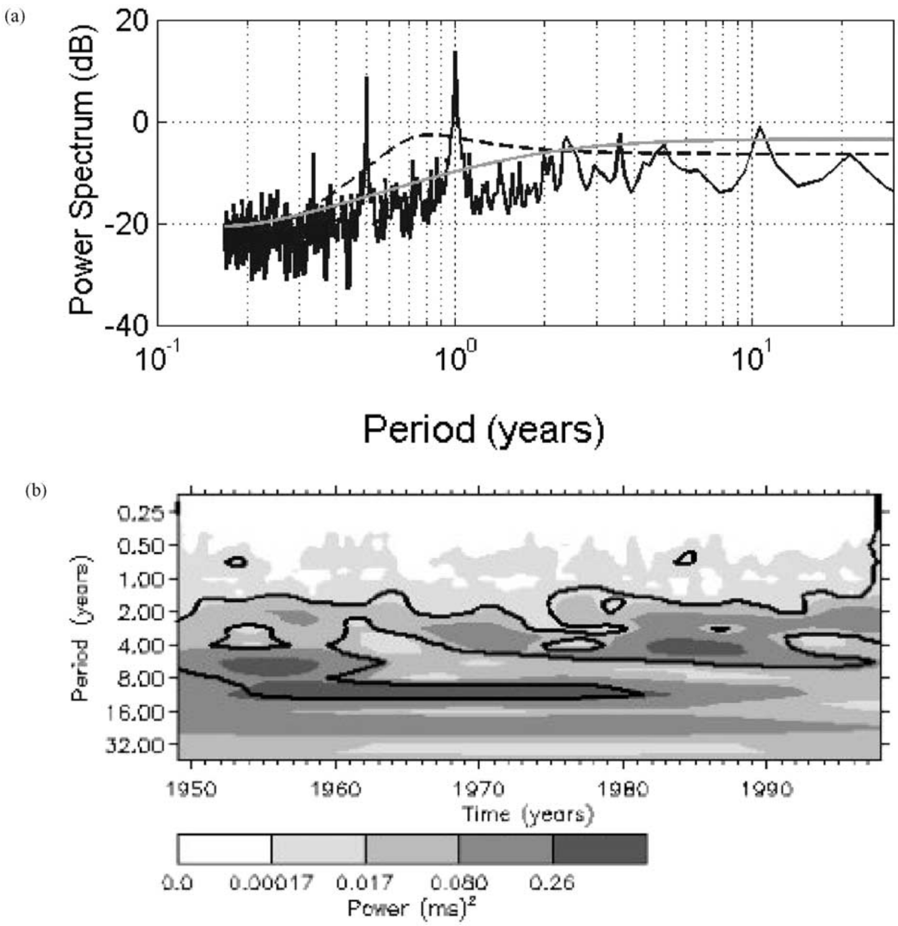

Fig. 4. Decadal variability in AAM. (a) Power spectra of AAM (solid), AR1 (dashed) and AR2 (solid grey) models. (b) Wavelet power spectrum. Contour levels are chosen so that 75%, 50%, 25% and 5% of the wavelet power is above each level, respectively. Black contour is the 10% significance level, using a red noise (autoregressive lag = 0.98) background spectrum. (c) Square Coherency (solid line) and phase shift (dashed grey line) of the AAM and SA for periods from 2 to 30 years.

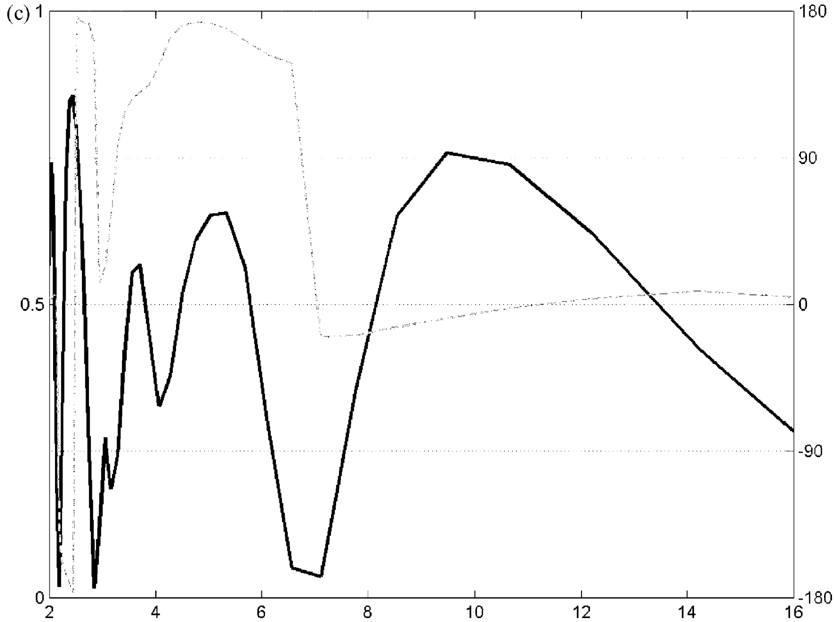

Fig. 4. (*continued*)

Table 1
Characteristics of the decadal cycle in the AAM series integrated up to different pressures heights (hPa) in the atmosphere

Height	Amp (%)	Lag (m)
10	100	0
50	93.2	−2.5
100	80.6	−3
200	60.4	−3.5
500	31.6	−4
850	6.3	−4.5

The first column presents the upper atmospheric height integrated. The second and third columns, the variance (in percentage), and the phase (in months), with respect to the AAM series integrated up to 10 hPa.

band-pass filtered between 8 and 16 years (Fig. 5b), the relationship at decadal time scales is further clarified. The AAM signal shows decadal fluctuations of about 0.07 ms, with peaks close to the years 1960, 1970, 1980 and 1990, almost coincident with those of the solar cycles. The correlation between decadal cycles increases to 0.91 with a 2-month lag (solar input leading). When the AAM and SA series of Figs. 5a and b are directly subtracted (5a−5b), separating lower time scales, the AAM series displays interdecadal fluctuations of about 0.02 ms, with peaks near 1960 and 1980, revealing a periodicity of about 20 years (in grey in Fig. 5b), agreeing therefore with the above spectral analysis (Fig. 4a and b).

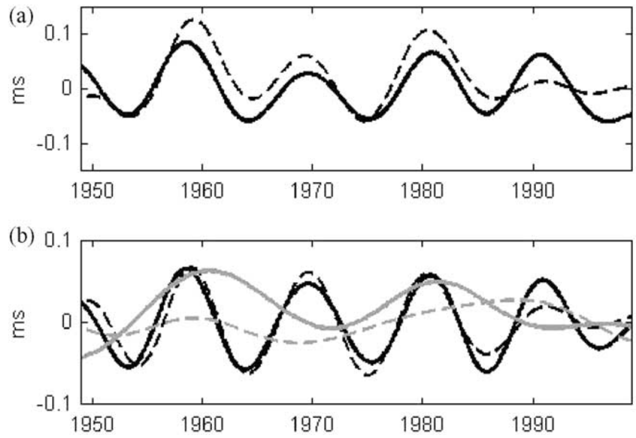

Fig. 5. Comparison of SA (solid line) and AAM (dashed). (a) Low pass filtered (> 8 years). (b) Band pass filtered (8–16 years) and low pass filtered (> 16 years, in grey).

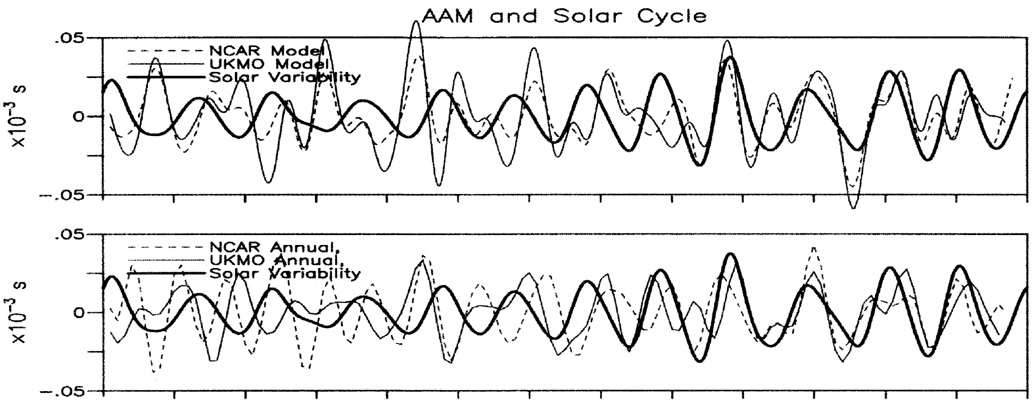

Fig. 6. Top: Comparison of ensemble averages of simulations of AAM by NCAR (dashed) and UKMO (solid) and the SA (bold solid), band pass filtered between 8 and 13 years since 1870. Bottom: Similar but for amplitude of the annual cycle.

This figure confirms that although AAM and the solar activity series present a related variability at decadal times scales, they appear to be unrelated at lower frequencies.

We take advantage of the long series of AAM from the model runs of both NCAR (Kiehl et al., 1998) and the Hadley Centre (Rosen and Salstein, 2000). We applied the same technique than above for filtering the raw data, i.e. resulting in a 8–13 years band pass filtering. In this figure, the solar decadal cycle and the decadal cycle in AAM agree only over the last decades (Fig. 6a). Moreover, the amplitude of the annual cycle of AAM (Fig. 6b) appears to be well related to the variability in the solar forcing.

3.2.2. *Decadal time scales in sea surface temperature (SST) fields*

Historical values of SA are compared to the lengthy nearly-three century long series in sea temperature Kaplan20 and Mann5 time series (Fig. 7a and b, respectively). We made sure to limit

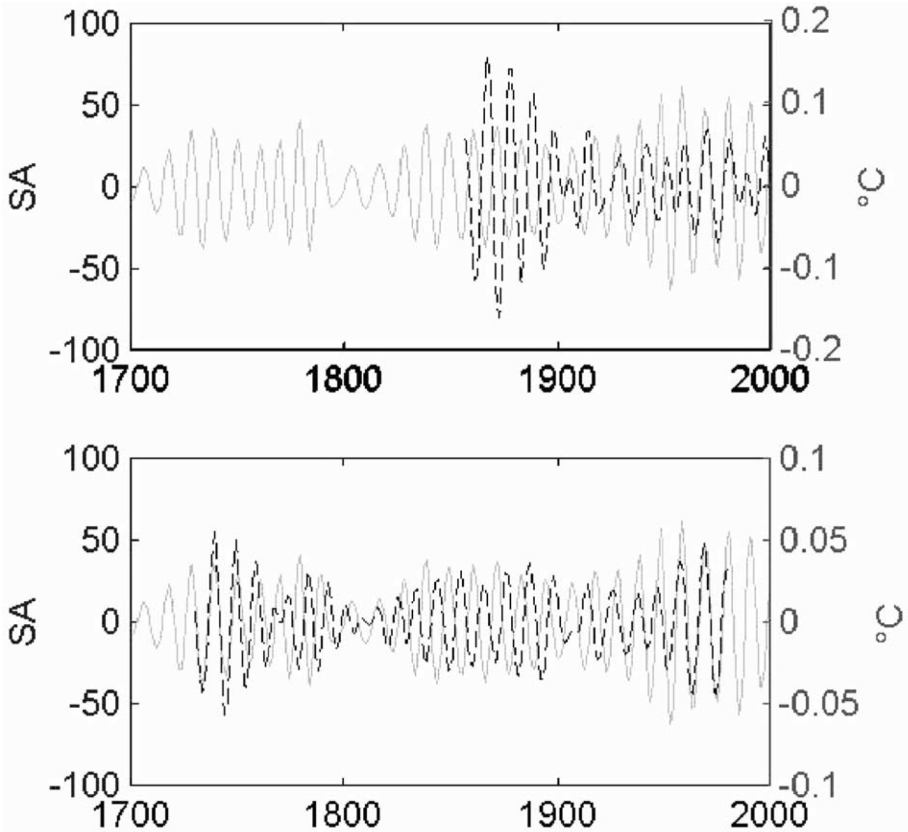

Fig. 7. Comparison of the decadal variability in SA (grey line) with the decadal variability seen in the SST Kaplan20 time series (8a), and the historical equatorial time series (Mann5) of SST fields from Mann et al. (8b).

the decadal band to the period between 8 and 13 years rather than longer as performed in White et al. (1997) to avoid the El Nino-related band at 14–15 years (Parker et al., 1994). The decadal variability of the Kaplan20 series was compared successfully, moreover with that in the Kaplan10 and Kaplan5 series (see Section 2.3), assessing the coherence of the equatorial SST fields at these bands.

The phase variability of the two series (Kaplan20 and Mann5) agree in the period prior to 1950. The two SST series match well, lagging or in phase with SA over much of the 20th century since 1930. However they are out of phase with SA for some periods, like the turn of the 19th to 20th century. The analysis of SST in all ocean basin times series (not shown) confirms the disagreement found at the turn of the last century. Another clear agreement with the decadal solar cycle found is found over the middle of the 18th century (1730–1770) in the historical (Mann5′s) equatorial SST time series, and confirmed by all the ocean basin (Pacific, Atlantic and Indian oceans) times series (not shown). As well the agreement over the last 50 years can be attributed for the most to the equatorial Indian and east Pacific ocean (not shown).

Similarly, decadal variability in AAM is linked to surface temperature (marine + land) time series, determined from Mann et al. (2000) over 1700 to 2000 at their decadal time scales with the Schwabe cycle (Fig. 8). This series confirms results found with SST and AAM, i.e., the decadal

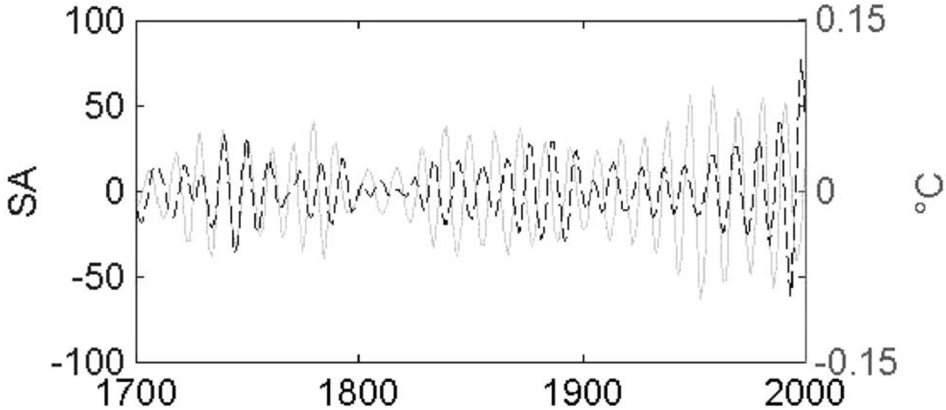

Fig. 8. Comparison of the decadal variability in SA (grey line) and that in the global (marine + land) surface temperature (GT) index by Mann et al. (2000).

variability in those climate indices agrees only coincidentally with the decadal oscillation (Schwabe cycle) in solar activity. Temperatures in turn may be linked to AAM through the distribution of the zonal winds responding to the meridional temperature gradient.

3.2.3. *Analysis of Length of day variability*

Independently, Challinor (1971), Vondrak (1977) and then Currie (1980) found, over different time spans a relationship between the Schwabe cycle in SA and the 10–11 year in LOD. However, the differences in the phase shift found by the authors prevent any definitive conclusion. Currie found a three years lag, whereas Vondrak found a relationship much closer to the one found in the present study between AAM and SA. In Fig. 9 are displayed the SA and LOD as obtained by a singular spectrum analysis with an embedding dimension of 13 years. The LOD and SA signal appears to be correlated over much of the last 40 years of the 20th century, in phase opposition

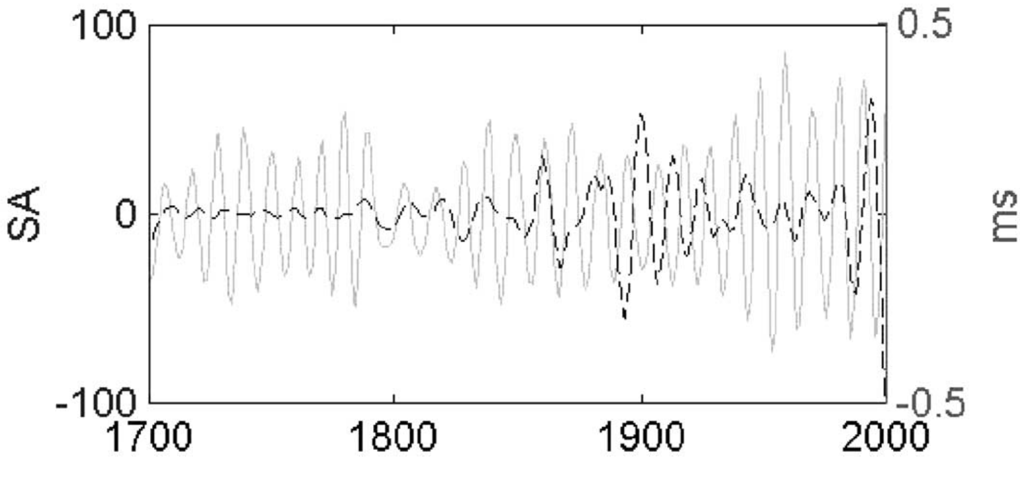

Fig. 9. Comparison of Schwabe cycle in SA and decadal cycle in LOD over 1700–2000, as obtained by SSA with an embedding dimension of 13 years.

about the turn of 19th to the 20th centuries and out of phase before. Determining such relationships with LOD data before 1950, particularly before 1920 is difficult due to the lower precision then (Jordi et al., 1994). In particular, the variable evolution of phase shift between the Schwabe cycle and the climatic decadal cycle, seen in number of surface parameters presented here is maintained.

4. Discussion and conclusion

Atmospheric angular momentum (AAM) as a useful indicator of the whole atmospheric dynamic state, allows an unprecedented opportunity to test and understand solar-atmosphere connections. The results obtained in this research can be subdivided in two sections: interannual and decadal times scales.

4.1. Interannual times scales

At interannual time scales, we extended to AAM during 1949–2000, the relationship between the decadal cycle in solar activity (the so called Schwabe cycle) found by other authors and other parameters, and the period of the quasi biennial oscillation (QBO) over the stratosphere, here in the stratospheric part of atmospheric angular momentum (the s-QBO). A deeper analysis shows that the lag between those decadal oscillations is not constant and varies slightly from about 3 years in 1965 to 5 years in 1995. It is also possible that the internal tropospheric climate variability plays a role too in the quasi-biennial period variability, though less likely, according to our results. Additionally, these phase lags could be contaminated by other sources of internal variability, such as volcanism (Robock, 1978) which may affect stratospheric variability, or the proximity of a decadal oscillation in ENSO (Hanson et al., 1989; Dovgalyuk and Klimenko, 1996). Nevertheless, the amplitude variability of the stratospheric QBO in AAM is closer too to the decadal scales seen in ENSO (13–14 years) (Hanson et al., 1986; Dovgalyuk and Klimenko, 1996).

The quasi biennial cycle in solar activity is also interesting. QBO in the stratospheric component of AAM as well as that of the index of the stratospheric winds (Naujokat, 1986) presents a phase variability lagged by 6 years (73 months) with regards to the QB cycle present in solar activity, explaining a result found by Djurovic and Pâquet (1993) regarding a correlation between LOD and solar activity at this band. However the weak amplitude of this signal in solar activity (when compared to the more powerful Schwabe cycle) as well as the time dependence of the association found (the signals over the stratosphere are in phase only when the amplitude of the solar QB cycle is strong) prevents any definitive conclusion. It is difficult to believe that a powerful decadal cycle may not imprint the decadal variability in climate, and it is the case for a weaker QBO. An interesting possibility is to consider the Schwabe cycle to control the phase of the quasi biennial cycle in solar activity and in the stratosphere. Therefore, both relationships could support each other independently. The 6-year lag between both quasi biennial oscillations could be interpreted as an indication that the association between solar variability and climate is lagged. Consequently, we might consider that the atmosphere is imprinted by solar activity at this scale. This possible association needs further investigations.

Conversely, the quasibiennial oscillation and the tri-quadrennial oscillation over the troposphere do not appear to be related with solar activity, either directly or modulated by decadal variability and comparable phase variability. In the case of the quasi-biennial cycle, it appears that it is somewhat correlated with the quasi biennial oscillation in solar activity (QBO-SA) over the last 50 years, though leading SA through part of the last century. It is fortunate here that an monthly index of the southern oscillation went back as far as 1866, which allows us to test this lag through times. Unfortunately, determination of stratospheric variability typically requires in situ data, and thus is not extant prior to the rocket age as well as not much information is available prior to the International Geophysical Year, 1958.

4.2. Decadal times scales

Relative AAM, based on zonal wind reanalysis of NCEP/NCAR from 1949 to 2000, integrated up to 10 hPa (99% of the total mass of the atmosphere), exhibits a significant decadal period of 10–12 years and an interdecadal oscillations of 22 years, with somewhat less statistical significance. Its variance, roughly 0.07 and 0.03 ms, respectively, are important for the global angular momentum of the Earth and should be further investigated.

The decadal cycle in AAM is shown here to be due to the whole atmosphere in both magnitude and phase, with the troposphere contributing up to 80% of the total power. We also showed that this decadal cycle can originate in surface processes, as the troposphere leads the stratosphere. The decadal cycle in the global AAM presents no significant phase shift (2 months in average) with the solar decadal cycle.

At the turn of the 20th century, decadal variability in AAM as given by the NCAR and Hadley Centre atmospheric model runs, as well as in LOD, appears to be out of phase with the Schwabe cycle, and thus in phase with each other. It is interesting to note here, that although the quality of LOD data is considerably lower at the early part of the 20th century, it could kept well the phase of the atmospheric signature.

On the other hand, Lau and Weng (1995) as White et al. (1997), find significant solar-related signals in equatorial SST over the entire century. The discrepancy seen between their SST signals and our AAM series, given particularly that the UKMO and NCAR model runs from which is issued the AAM investigated here were forced by SST fluxes, lead us to investigate decadal variability in SST. The two SST series, the Kaplan20 (1856–2000) and Mann5 (1730–1980) indicate a lag with solar activity since 1930 but is out of phase prior to about 1900; however, partial agreement was present during the mid 18th century. We extended the comparison to decadal variability in the global surface (land + marine) temperature (GT) reconstruction by Mann et al. (2000) back to 1700 and found agreement with the above; series of GT are similar to those of SST regarding agreement with the solar signal. It appears therefore that independent measurements (SST, GT, AAM, LOD) confirms the out of phase lag of the climatic decadal variability at the turn of the 19th to the 20th century, as well as the partial agreement over the last 50 years. Based on this historical analysis of decadal variability in climate and geodetic variables, it is possible to say that the particular relationship found since at least 50 years between SA and equatorial SST is most probably coincidental.

Nonetheless, note that a partial relationship over the last few decades and phase opposition at the turn of the century, which may agree well with a relationship found at decadal times scales between solar activity, surface air temperature changes (Nitta and Yoshimura, 1993; Parker et al., 1994), decadal variability in SST, AAM and LOD, can be also very well explained by the presence of very close independent decadal periods in solar activity and climate (for example, 11 years and 10.2 years).

We may note here that the failure of decadal atmospheric variations to remain coherent with the solar cycle prior to around 1900 does not preclude such agreement since that time. As discussed by Feynmann and Crooker (1978), the yearly means of the geomagnetic index Aa, which is representative of solar wind velocity and magnetic field disturbances were between a half and a third of its strength during the last three decades when compared to that at the beginning of the century. With weaker forcing by the solar wind the phase lock to the solar cycle of internal decadal variability could have been lost. Also, reconstruction of past solar irradiance (Hoyt and Schatten, 1997) shows an increase since at least 1940, with the largest irradiance ever measured, a likely explanation for the current association. Moreover, since decadal atmospheric variability may not uniquely identified with the 11-year solar cycle, a lack of full agreement with the solar forcing even more recently does not exclude its impact on the climate and momentum-related indices.

However, whatever the source of the decadal cycle in AAM may be, internal or external, this oscillation in the global atmosphere (troposphere and stratosphere) is suggested here to be generated by upward propagation of surface atmospheric modes, from the surface throughout the troposphere through the stratosphere. Because AAM represents the dynamic state of the global atmosphere, decadal vacillations seen in different parameters over the stratosphere (geopotential height, temperature, zonal winds, clouds, see Section 1) are most probably associated with these dynamics, and show the influence of surface processes within the troposphere rather than an external forcing directly into the middle atmosphere. Also, because the long-term analysis performed here in either proxy, reconstructed or measurements associated with tropical SST or global temperature do not show a full association with the Schwabe cycle, such decadal stratospheric vacillations associated with the solar cycle may not have been evident in past times. However, the strength of the stratospheric QBO indicates an atmospheric role, through historical tropical surface temperature and other measurements. The present results indicate the need for better understanding of atmospheric dynamics at decadal time scales. It seems that the coming years will be fruitful in this regard, given the advent of extended and improved atmospheric and solar data.

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