Trends in and closure of the atmospheric angular momentum budget in the 20th century in ERA-20C

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Abstract
It is well known that global warming in the 20th century has influenced the global circulation of the atmosphere. Atmospheric angular momentum (AAM), a measure of the rotation of the atmosphere around the Earth’s axis, is a useful quantity to investigate changes in the global atmospheric circulation. In this study, 20th century trends in the AAM budget are determined using the ERA-20C reanalysis data of the European Centre for Medium-Range Weather Forecasts (ECMWF). In addition, the closure of the AAM budget is determined to assess the ability of ERA-20C to conserve angular momentum. The total AAM has increased in the 20th century, associated mainly with an increasing relative (zonal wind) AAM in most of the stratosphere and the tropical upper troposphere, and a poleward redistribution in the midlatitudes. These trends can be related to the warming in the troposphere and cooling in the lower stratosphere found in this study, likely caused by increasing atmospheric CO₂ concentrations. The Ω-AAM, representing the rotation of the atmosphere along with the Earth, shows no clear trend, but a spurious peak around 1920. This peak is caused by a global increase in surface pressure and is considered an artefact of changes in the amount of assimilated observations. It is also found that the AAM budget is not well closed in ERA-20C, which is mainly the result of the assimilation of observations during production of the reanalysis. The trends in the AAM budget in ERA-20C are likely affected by changes in the number of assimilated observations and should be validated with other reanalyses in further research.

KEYWORDS
20th century, angular momentum, balance, budget, ERA-20C, trends

1 | INTRODUCTION
Global warming in the 20th century (IPCC, 2013) has resulted in several changes in the global atmospheric circulation. Hu and Fu (2007) found a poleward shift of the boundaries of the Hadley circulation and Chen and Held (2007) reported a poleward shift and intensification of the storm tracks in the late 20th century. Climate models also predict a further widening of the Hadley cells in the 21st century, due to global warming (Lu et al., 2007). These trends can be attributed to both decreasing stratospheric ozone concentrations and increasing CO₂ concentrations in the 20th century (e.g., Chen and Held, 2007; Lorenz and DeWeaver, 2007)

A useful quantity to study the global circulation of the atmosphere is the atmospheric angular momentum (AAM), which is related to the global surface pressure and zonal
wind distributions. The AAM is a measure of the rotation of the atmosphere around the north–south axis of the Earth. Since angular momentum is a conserved quantity, the angular momentum of the atmosphere, the solid Earth, and oceans combined is constant in the absence of external torques (Peixoto and Oort, 1992). However, angular momentum is exchanged between the atmosphere and the Earth and oceans by torques. The two main torques acting on the atmosphere are the friction and mountain torque, caused by friction at the Earth’s surface and surface pressure gradients across orography, respectively (Peixoto and Oort, 1992).

Although angular momentum is a conserved quantity, weather and climate models often fail to conserve it, meaning that there are discrepancies between AAM tendencies and the sum of the torques. Huang et al. (1999) found a large AAM imbalance in reanalysis data, which they attributed to the gravity-wave drag parametrization. Comparable AAM imbalances have been reported by Berrisford et al. (2011) and Madden and Speth (1995) in other data sets. Berrisford et al. (2011) also observed that in two reanalysis data sets of the European Centre for Medium-Range Weather Forecasts (ECMWF), ERA-40 and ERA-Interim, the closure of the AAM budget improves in time. They also found a better closure in the more recent ERA-Interim, indicating the higher quality of this data set (Berrisford et al., 2011). The degree to which AAM is actually conserved in weather or climate models can thus be used to assess the performance and accuracy of atmospheric models and reanalyses (e.g., Huang et al., 1999; Berrisford et al., 2011).

Long-term changes in AAM have been related to trends and variations in the atmospheric circulation by several studies (e.g., Huang et al., 2001; 2003; Räisänen, 2003). Studies have also shown a good anticorrelation between AAM and the Earth’s rotation speed, and thus a correlation between AAM and the length of a day (e.g., Rosen and Salstein, 1983). An increase in AAM due to increasing atmospheric CO₂ concentrations in climate models has been shown by, for example, Huang et al. (2001), Räisänen (2003), and Paek and Huang (2013). This response to CO₂ has been attributed mainly to an increase in stratospheric and upper tropospheric zonal winds, which can be associated with stronger meridional temperature gradients around the tropopause (e.g., Räisänen, 2003).

Interannual AAM variations have been related to atmospheric variabilities such as the El Niño Southern Oscillation or the Quasi-Biennial Oscillation (Rosen et al., 1984; Chao, 1989; Abarca del Rio et al., 2000; Huang et al., 2003). These oscillations correspond to fluctuations in zonal wind speed, and thus AAM, in the tropical troposphere and stratosphere, respectively (Holton and Hakim, 2012). AAM also has a clear variability on shorter time-scales (e.g., Anderson and Rosen, 1983; Rosen and Salstein, 1983; Weickmann et al., 1997), such as an annual cycle related to seasonal shifts in the jet stream (Rosen and Salstein, 1983).

Most previous studies on AAM changes in the 20th century studied its temporal variability on seasonal to decadal time-scales (e.g., Rosen and Salstein, 1983; Chao, 1989; Huang et al., 2003; Paek and Huang, 2012; 2013) or investigated trends in only the second half of the 20th century (del Rio, 1999). The latter may be associated with the lack of sufficient upper-air and satellite observations in the early 20th century (Poli et al., 2016). However, due to natural climate variabilities on decadal scales, using only half a century may be insufficient to determine long-term AAM trends accurately (Huang et al., 2003). Analysing the 20CR reanalysis (Compo et al., 2011), produced by the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR), Paek and Huang (2012) have already observed an increase in relative AAM since 1871. This has been attributed mainly to an increase in zonal wind in the upper troposphere (Paek and Huang, 2012). However, they also found that the evolution of AAM in the 20CR data in the second half of the 20th century did not match the evolution found in other reanalysis data sets (Paek and Huang, 2012), indicating that the reliability of the AAM trend in 20CR could be questioned (Paek and Huang, 2012). Using the NCEP1 (NCEP/NCAR) and ERA-40 (ECMWF) reanalyses, Lehmann and Névir (2012) showed that differences in AAM between reanalyses may partly be attributed to uncertainties in the assimilation of zonal winds.

In this study, the first goal is to determine the closure of the AAM budget, which indicates how well angular momentum is conserved in the ERA-20C reanalysis. The AAM budget closure is used as an indication of model performance and also serves to assess the reliability of trends in the AAM budget. The second goal of this study is to analyse trends in AAM and torques during the 20th century using the ERA-20C reanalysis data set, which was produced in 2014 by ECMWF (Poli et al., 2016). Changes in both the global integrals and the meridional distributions of the monthly mean AAM and torques are studied. In addition, changes in the zonal wind and temperature distributions are determined. Understanding how trends in AAM and torques relate to trends in zonal wind and air temperature, caused by, for example, increasing CO₂ and decreasing stratospheric ozone concentrations (IPCC, 2013), can help us improve our knowledge of the effects of, for example, global warming on the atmospheric circulation. The two main research questions on which this study is based are therefore as follows.

1. How well is the atmospheric angular momentum budget closed in the ECMWF ERA-20C reanalysis, and how has this closure changed during the 20th century?
2. What have been the trends in atmospheric angular momentum and torques during the 20th century, and how are these trends related to 20th century climate change?
A more elaborate background on the concept of angular momentum, the torques, and their relation to the atmospheric circulation is provided in section 2. In section 3, the data and methods used in this study are presented. The results are given in section 4: first the results concerning closure of the AAM budget (section 4.1) and subsequently the trend analysis (section 4.2). A discussion of the results and conclusion are provided in section 5.

2 | METHODOLOGY

2.1 | Data description

The data set used in this research is the ECMWF reanalysis of the 20th century (ERA-20C), which was released in 2014 and covers the time period 1900–2010 (Poli et al., 2016). Due to the lack of sufficient (upper-air) observations in the early 20th century, only surface pressure and marine surface wind observations have been assimilated during the production of ERA-20C (Poli et al., 2016). In this respect, ERA-20C differs from reanalyses such as ERA-Interim and ERA-5, which assimilate other quantities and upper-air observations as well. The data are retrieved on a regular latitude–longitude grid of 161 by 320 points, with a horizontal resolution of 1.125° × 1.125° (≈125 km × 125 km near the Equator), and on all original 91 model levels. These model levels form a hybrid coordinate system (Simmons and Burridge, 1981) that is terrain-following in the lower atmosphere and transitions to pressure levels in the upper atmosphere. The lower edge of the lowest layer is coincident with the surface pressure, the highest model level is at 0.01 hPa. In this study, we still use the ECMWF EMOSLIB library for interpolation, which was replaced by the Meteorological Interpolation and Re-gridding (MIR) library (Maciel et al., 2017) in January 2019.

The available temporal resolution of the data is 3 hr, but monthly mean data are used where possible to reduce data size and computation time. Since the focus of this research is on long-term trends, using monthly means should not affect the results. The entire time span of the data is used for the trend analyses. In further reference, the full 111-year period is nevertheless referred to as the 20th century. The main variables of interest are the surface pressure, zonal wind, and parametrized gravity-wave and turbulent surface stresses.

Both the forecast data and the analysis data of ERA-20C are available. The forecast data consists of all the 27-hr model forecasts, integrated each day from 0600 UTC until 0900 UTC the next day (Poli et al., 2013), and the analysis data are the results of the assimilation of observations into the model forecasts (Poli et al., 2013). To study trends in the AAM budget, only the analysis data set is used, because we assume it to be more accurate due to the assimilation. The closure of the AAM budget is investigated with both forecast and analysis data.

2.2 | AAM budget

To study trends in the AAM budget during the 20th century, the monthly mean AAM and monthly mean torques are calculated throughout the 20th century. Since the focus of this study is on trends in the angular momentum budget of the whole atmosphere, the terms of the AAM budget are integrated over all latitudes, longitudes, and model levels. However, the latitudinal contributions to the global trends are also determined, by integrating only in the zonal direction. Investigating the latitudinal contributions to the trends is useful to detect meridional shifts in the atmospheric circulation.

The angular momentum per unit mass of an air parcel (m) is the product of its absolute velocity and its distance to the centre of the Earth:

\[ m = (u + \Omega \ a \cos \phi) a \cos \phi, \]  

where \( u, \Omega, \phi, \) and \( a \) are the zonal wind, angular velocity of the Earth \((7.29 \times 10^{-5} \text{ m/s})\), latitude, and Earth’s radius \((\approx 6,367,470 \text{ m})\), respectively.

The total angular momentum of a column of air \( M \) can be obtained by integrating Equation 1 vertically. This integral is approximated by a summation over all 91 model levels (Simmons and Burridge, 1981):

\[ M = \frac{1}{g} \sum_{\eta=1}^{91} m \Delta p_\eta, \]  

where \( g \) and \( \eta \) are the gravitational acceleration \((9.81 \text{ m/s}^2)\) and the model level, respectively. \( \Delta p_\eta \) is the thickness (in Pa) of the atmospheric layer represented by each model level. The total angular momentum can be separated into a relative component, related to the zonal winds \((u)\), and an omega \((\Omega)\) component, related to the rotation of the Earth \((\Omega \ a \cos \phi)\).

The vertically integrated relative \( (M_r) \) and omega \((M_\Omega)\) angular momentum components are

\[ M_r = \frac{1}{g} \sum_{\eta=1}^{91} u \ a \cos \phi \ \Delta p_\eta \]  

and

\[ M_\Omega = \frac{1}{g} \sum_{\eta=1}^{91} \Omega a^2 \cos^2 \phi \ \Delta p_\eta = \frac{p_s}{g} \Omega a^2 \cos^2 \phi, \]  

respectively, where \( p_s \) is the surface pressure. As Equation 3 shows, trends in \( M_r \) are related to changes in the magnitude or meridional distribution of zonal winds \((u)\). As shown by Equation 4, \( M_\Omega \) is due to the rotation of the mass of the atmosphere \((p_s/g)\) around the Earth’s axis, along with the rotation of the Earth \((\Omega)\).
The global AAM is then obtained by integrating $M$ (Equation 2) over the surface of the Earth, which is approximated by summing over all 161 latitudes and 320 longitudes on the horizontal grid of the retrieved data:

$$AAM_{\text{global}} = a^2 \sum_{i=1}^{161} \sum_{j=1}^{320} M_{ij} \cos \phi_i \Delta \lambda_j \Delta \phi_j. \quad (5)$$

where $\Delta \lambda_j$ and $\Delta \phi_i$ are the grid spacings in the longitudinal and latitudinal directions, respectively. The relative and $\Omega$-AAM components can be then obtained by integrating $M_r$ (Equation 3) and $M_\Omega$ (Equation 4) globally, analogously to Equation 5.

The zonal AAM budget, integrated over a latitude belt, can be written as (see Holton and Hakim, 2012; Peixoto and Oort, 1992, for a more detailed derivation)

$$\frac{\partial AAM_{\text{zonal}}}{\partial t} = -\left(\frac{\rho_s}{g} \frac{\partial \Phi_s}{\partial \lambda}\right) - \left[\tau_{gw} a \cos \phi\right] \left[\frac{\partial}{\partial \phi}(mv)\right] \Delta p_r, \quad (6)$$

where $\Phi_s$, $v$, $\tau_{gw}$, $\tau_{ts}$, and $\nu$ are the surface geopotential, the meridional wind speed, and the zonal components of the gravity-wave stress and turbulent surface stress. The square brackets on the right-hand side of Equation 6 denote zonal surface integrals (see Equation 5). The first term of Equation 6 is the AAM tendency and the first term on the right-hand side is the resolved mountain torque, which is calculated as the product of the surface pressure and the zonal gradient of the surface geopotential height. Since the data are periodic in the zonal direction, the geopotential height gradient is calculated with spectral differentiation using Fourier series. The second and third terms of Equation 6 are the parametrized gravity-wave torque and the parametrized frictional torque, respectively. The fourth term in Equation 6 is the divergence of the meridional AAM flux, which accounts for AAM transport across latitudes. The global AAM budget is obtained by integrating Equation 6 meridionally:

$$\frac{\partial AAM_{\text{global}}}{\partial t} = -\left(\frac{\rho_s}{g} \frac{\partial \Phi_s}{\partial \lambda}\right) - \left[\tau_{gw} a \cos \phi\right] - \left[\tau_{ts} a \cos \phi\right], \quad (7)$$

where angled brackets denote global integrals. Since the divergence term vanishes upon global integration, the global AAM tendency should equal the sum of the three torques (Equation 7).

2.3 | Budget closure

Since angular momentum is a conserved quantity, the closure of the global AAM budget (Equation 7) can be considered a measure of model performance (e.g., Huang et al., 1999; Berrisford et al., 2011). However, due to the assimilation of observations in the reanalysis, it may be expected that the global AAM budget is not exactly closed (e.g., Berrisford et al., 2011).

Both forecast and analysis data are used to study the closure of the global AAM budget. The balance in the analysis data is interesting, because this data set is used for the analysis of AAM trends in the 20th century. The balance in the forecast data is calculated to determine the closure of the AAM budget without the influence of the assimilation. For this purpose, the forecast budget is calculated from the full three-hourly temporal resolution of the forecast data. Forecast steps $T + 3$ (0900 UTC) to $T + 27$ (0900 UTC, next day) are used for the forecast budget. The tendencies are based on the change in AAM between each three-hour time step and the mountain torques are the averages of the mountain torques at the start and end of each three-hour time period. The parametrized torques are calculated as the difference in accumulated parametrized torques between the end and start of each three-hour time period. Since forecast steps $T + 3$ and $T + 27$ both represent 0900 UTC, there is temporal overlap between consecutive forecasts. Since observations are assimilated between consecutive forecasts, the tendency between 0600 UTC and 0900 UTC is based on forecast steps $T + 24$ and $T + 27$, whereas the tendency between 0900 UTC and 1200 UTC is based on forecast steps $T + 3$ and $T + 6$. For the analysis budget, the tendencies are calculated as the change in AAM over each month, based on the analysis data at 0000 UTC on the first day of each month. The torques in the analysis budget are equal to the monthly means of the torques in the forecast budget.

Because the budget closure in the forecast data does not depend on the assimilation of observations, it is assumed to be constant in time. Therefore, the AAM balance in the forecasts is only determined for the time periods 1900–1915 and 1995–2010 to reduce data and computation time.

3 | CLOSURE OF AAM BUDGET

3.1 | Forecast budget

In the forecasts, there is a clear correlation between the monthly mean AAM tendency and the monthly mean total torque (Figure 1), the sum of the mountain, friction, and gravity-wave torques. The similar temporal evolution of the tendency and the torque is as expected, since conservation of AAM implies that both terms are equal (Equation 7). However, there is a small bias between both terms, because on
average the torque is lower than the tendency (Figure 1). Even in the forecast data, the AAM budget is thus not perfectly closed, but has a small positive mean budget residual of about $3.66 \times 10^{18}$ kg m$^2$ s$^{-2}$. The temporal variability of the bias, mainly on annual and biannual time-scales, is considerably smaller than the variability of the tendency and the torques. On longer time-scales, the bias is approximately constant, as it shows no clear trend within each 16-year period. Moreover, the biases in both time periods, 1900–1916 (Figure 1a) and 1995–2010 (Figure 1b), are very similar, which supports the assumption that the budget residual in the forecast data does not change very much throughout the 20th century.

The budget residuals suggest that the AAM budget in the forecast model (IFS Cycle38r1) is not perfectly closed. The residuals may also be partly attributed to numerical approximations in the calculation of the different terms of the AAM budget, or to the horizontal interpolation of the data (Trenberth, 1995) to the regular latitude–longitude grid used in this study. Additionally, as suggested by Berrisford et al. (2011), the actual three-hourly mean surface pressure may differ from the surface pressures available at each three-hour time step. This can result in errors in the mountain torque and thus a residual in the AAM budget. Although the residuals are relatively small, the monthly means of the tendency and the torques are predominantly negative (Figure 1), indicating that on average the AAM in the forecast model decreases with time. The mean tendency is $-8.57 \times 10^{18}$ kg m$^2$ s$^{-2}$ in the period 1900–1916 and $-9.13 \times 10^{18}$ kg m$^2$ s$^{-2}$ in the period 1995–2010. These mean tendencies have a larger magnitude than the tendencies fluctuating around zero observed by, for example, Berrisford et al. (2011) and Huang et al. (1999) in reanalysis data. This is an indication that the total torque has a large negative bias.

### 3.2 Analysis budget

The closure of the monthly AAM budget in the analysis data (Figure 2) is much poorer than the closure of the budget in the forecasts (Figure 1). The residuals are still predominantly positive, but on average considerably higher ($13.5 \times 10^{18}$ kg m$^2$ s$^{-2}$) than in the forecasts, due to the change in AAM tendencies. The monthly tendencies, the differences in AAM between the beginning of consecutive months, are still of the same order of magnitude as the tendencies in the forecasts. However, the temporal average of the AAM tendency is much closer to zero ($-8.53 \times 10^{15}$ kg m$^2$ s$^{-2}$) than in the forecasts, whereas the total torque is the same as in the forecasts. This difference in the mean AAM tendency between the analysis and forecast data is likely due to analysis increments resulting from the assimilation of observations. The analysis increments thus keep the tendencies close to zero, which causes the large residuals in the analysis budget but prevents the continual loss of AAM implied by the forecast tendencies.

The negative mean torque and positive mean budget residuals in the analysis data indicate that, on average, the torques in the forecasts have a large negative bias, which has also been observed in other reanalyses (e.g., Madden and Speth, 1995; Huang et al., 1999; Berrisford et al., 2011). Despite the large bias, investigating the changes in the magnitudes and zonal distributions of the individual torques may still give more insight into AAM budget trends.

### 3.3 Temporal evolution

As shown in Figure 2, there is no significant long-term improvement in the closure of the analysed AAM budget and
thus no improvement in the conservation of angular momentum, despite a strong increase in the number of assimilated observations during the 20th century (Poli et al., 2013). The consistently large budget residuals also suggest inaccuracies in the forecast model, causing the predicted atmospheric state to deviate from the observed atmospheric state in each forecast. The budget residuals have increased on average, with a linear trend of about $2.5 \times 10^{16}$ kg m$^2$ s$^{-2}$ per year, or about $6.6 \times 10^{22}$ kg m$^2$ s$^{-1}$ per year for the monthly integrated residual. However, the temporal variability of the residuals has decreased during the 20th century (Figure 2), which indicates that the precision of the forecasts in closing the AAM budget has improved.

Interestingly, there are three clear minima in the magnitudes of the residuals in the analysis budget during the first half of the 20th century, around 1900, 1920, and 1945 (Figure 2). These lower residuals are mainly the result of less negative torques during these periods. The timing of these minima corresponds roughly to the periods with the lowest number of assimilated wind observations (Poli et al., 2013). This connection suggests that long-term changes in the AAM budget observed in the data can be affected by changes in the number of assimilated observations.

4 | 20TH CENTURY AAM TRENDS

4.1 | Total AAM

The globally integrated total AAM in the analysis data has a small linear trend during the 20th century of approximately $8.59 \times 10^{22}$ kg m$^2$ s$^{-1}$ per year (Figure 3a), which amounts to an increase of about $9.53 \times 10^{24}$ kg m$^2$ s$^{-1}$ between 1900 and 2010. This increase is significantly smaller than the temporal mean and seasonal variations of the total AAM. In the first decade and in the second half of the 20th century, the temporal evolution of the total and relative AAM anomalies is similar (Figure 3b). This indicates that the total AAM trend is due mainly to an increase in its relative component. Around 1920, however, the total AAM deviates clearly from the relative AAM (Figure 3b), due to a large positive $\Omega$-AAM anomaly.

4.2 | Omega-AAM

The $\Omega$-AAM component (Equation 4) is due to the rotation of the atmosphere along with the rotation of the Earth. The time series of the $\Omega$-AAM component (Figure 3b) have a negative linear trend of about $0.32 \times 10^{23}$ kg m$^2$ s$^{-1}$ per year. However, given the peak in $\Omega$-AAM around 1920, this linear trend is presumably of little value. The large $\Omega$-AAM peak is surprising, because the dry mass of the atmosphere should be approximately constant in time (Berrisford et al., 2011). Variations in $\Omega$-AAM may be caused by changes in atmospheric water content or changes in the meridional redistribution of atmospheric mass (Madden and Speth, 1995). The total mass of water in the atmosphere is over two orders of magnitude smaller than the dry atmospheric mass (Figure 4). It is not significantly larger around 1920 (Figure 4) and has thus not contributed to the $\Omega$-AAM peak. Nevertheless, the atmospheric water content in ERA-20C has increased significantly during the 20th century (Figure 4), which results in a linear trend in angular momentum of approximately $0.19 \times 10^{23}$ kg m$^2$ s$^{-1}$ per year. Although this trend may be considered uncertain because humidities are not assimilated, several studies have found globally increasing water-vapour contents near the surface (Willett et al., 2008) and in the upper troposphere (Shi and Bates, 2011) in observational data.

The dry atmospheric mass is obtained by subtracting the globally integrated total column water from the total mass of the atmosphere (e.g., Berrisford et al., 2011). The time series of both the global mean total and dry surface pressures show a similar peak around 1920 (Figure 4), which indicates that this $\Omega$-AAM anomaly period is mostly due to a spurious peak in the dry surface pressure. To understand this better, the meridional distribution of the evolution of
surface pressure is studied. At all latitudes, the surface pressure around 1920 is higher than the temporal mean surface pressure (Figure 5). This indicates that the 1920 peaks in dry surface pressure and $\Omega$-AAM occur globally. The surface pressure anomalies around 1920 are largest at higher latitudes, especially in the Southern Hemisphere (Figure 5), although the contribution of higher latitudes to the $\Omega$-AAM peak is relatively low (Equation 5).

Apart from the 1920 peak, two long-term surface pressure trends can be deduced from Figure 5. In both the Arctic and Antarctic regions, the surface pressure has decreased throughout the 20th century, whereas it has increased around 40°S. As shown by Hines et al. (2000), the surface pressure trend in the Antarctic may largely be considered an artefact of the increasing number and quality of assimilated observations. The 1920 peak in surface pressure is also attributed to changes in the availability of observations, because the dry atmospheric mass should be approximately conserved.

Trenberth and Smith (2005) estimated that surface pressure variations due to changes in the composition of the atmosphere are of the order of 0.01 hPa, which is insignificant compared with the observed peak surface pressure (Figures 4 and 5).

### 4.3 Relative AAM

The relative AAM component (Equation 3) has a linear trend of about $1.18 \times 10^{23}$ kg m$^2$ s$^{-1}$ per year (Figure 3b). This equals an increase in relative AAM of about $1.29 \times 10^{25}$ kg m$^2$ s$^{-1}$ during the 20th century. Since the relative AAM is related to the magnitude and meridional distribution of the zonal winds, we study the latitude–height distribution of the trends in relative AAM (Figure 6a) and zonal winds (Figure 6b) in more detail. Here, we use the relative AAM per unit mass (divided by $dp/g$), because the vertical layers are not of equal thickness.
FIGURE 5  Latitude–time distribution of the five-year moving average of the zonal mean surface pressure with respect to the temporal mean surface pressure at each latitude. The five-year moving averages of the anomalies are shown.

(a)  
(b)  

FIGURE 6  Linear trends during the 20th century of (a) relative AAM per unit mass (divided by dp/g) and (b) zonal wind at all 161 latitudes and 91 model levels. For clarity, the model levels have been converted to pressure levels (ECMWF, 2013)

To distinguish between the tropospheric and stratospheric contributions to the global trends, we determine the tropopause height as the first height at which the temperature decreases by less than 2 K/km, following the definition by WMO (1957) and using the algorithm described by Recking et al. (2003). The main contributions to the positive relative AAM trend come from the upper troposphere and lower stratosphere in the Tropics, roughly between 20°S and 20°N, and from the midlatitude stratosphere. These are associated with increases in zonal wind speed of up to 0.1 m/s per year. In part of the equatorial stratosphere (∼20–50 hPa), the relative AAM has a strong negative trend, corresponding to a decrease in zonal wind speed of up to 0.15 m/s per year. The magnitudes of these positive and negative AAM trends are up to about 1.9×10^{18} m^4/s per year and 4.8×10^{18} m^4/s per year, respectively. In contrast, the mean relative AAM trend in Figure 6a is only about 1.4×10^{17} m^4/s per year. Between about 20° and 40° in both hemispheres, the relative AAM has decreased over the entire depth of the troposphere (Figure 6a). Further poleward (∼40°–60°), the relative AAM has increased in the troposphere and the lower stratosphere. These negative and positive relative AAM trends in the midlatitudes correspond to a decrease and increase in zonal wind, respectively, and are strongest in the Southern Hemisphere. This pattern suggests that, in the midlatitude troposphere, the relative AAM is primarily redistributed to higher latitudes.
The trends in the relative AAM and zonal wind distribution can be related to changes in air temperature during the 20th century (Figure 7a). The temperature has increased in most of the troposphere, mainly in the Southern Hemisphere midlatitudes and the tropical upper troposphere. The temperature has decreased in most of the lower stratosphere, especially at high latitudes in the Southern Hemisphere. The temperature has increased in part of the Arctic stratosphere, although not directly above the tropopause. The temperature increase in the troposphere and decrease in the stratosphere can be related to increasing CO2 concentrations (IPCC, 2013). The temperature decrease in the stratosphere can also be caused by declining ozone concentrations (e.g., Ramaswamy et al., 2001; IPCC, 2013).

The observed air temperature trends (Figure 7a) result in stronger meridional temperature gradients across the tropopause (Chen and Held, 2007), especially in the mid-latitudes, where the tropopause height lowers quickly with latitude (Figure 7b). As shown in Figure 7b, the 20(30)-year mean tropopause height has risen by approximately 5 hPa in the Tropics during the 20th century, likely as a result of warming below and cooling above the tropopause (Yin, 2005; Seidel and Randel, 2006; Lorenz and DeWeaver, 2007). The strong tropopause rise in the Southern Hemisphere at high latitudes is remarkable, presumably occurring because the stratospheric temperature decrease is strongest here.

Several studies have shown that a higher tropopause and stronger temperature gradient across the tropopause can result in stronger and more poleward storm tracks, jet streams, and midlatitude westerlies (Yin, 2005; Chen and Held, 2007; Lorenz and DeWeaver, 2007). The increase and poleward redistribution of relative AAM in the midlatitudes can thus be related to increasing CO2 and decreasing ozone concentrations in the 20th century. Especially in the Southern Hemisphere, the meridional temperature gradient has decreased in the lower troposphere, which may have partially compensated for the effects of a higher temperature gradient across the tropopause. However, because only surface wind and pressure observations have been assimilated in ERA-20C, the exact upper-air trends may be uncertain.

### Torques

Since angular momentum is a conserved quantity, the positive AAM trend (section 4.1) must be the result of a positive mean total torque in the 20th century. However, the mean total torque is found to be negative (Figures 1 and 2), showing that the AAM trend and the mean torque can have different signs, due to poor closure of the AAM balance. Given the meridional shifts in relative AAM and zonal wind in the mid-latitudes, it is nevertheless interesting to study changes in the mountain, friction, and gravity-wave torques.
The globally integrated gravity-wave torque has decreased by about $1.1 \times 10^{16}$ kg m$^2$ s$^{-1}$ per year (Figure 8a). The friction torque has a negative linear trend as well, approximately $4.4 \times 10^{16}$ kg m$^2$ s$^{-1}$ per year, whereas the mountain torque has a positive linear trend of about $3.0 \times 10^{16}$ kg m$^2$ s$^{-1}$ per year. The magnitude of the global friction torque has thus increased, extracting more angular momentum from the atmosphere, whereas the magnitude of the global mountain torque has decreased. This suggests that the relative importance of the friction torque in the total torque has increased, although it should be noted that the negative mean torque implies a continual decrease in AAM, which is not observed in the analysis.

The meridional distribution of the trends in the zonally integrated torques (Figure 8b) has a pattern similar to the meridional distribution of the near-surface zonal wind and relative AAM trends (Figure 6), but with opposite sign. In both hemispheres, the torques have increased in the subtropics and the lower midlatitudes. Further poleward the torques have decreased, at around $55^\circ$ in the Southern Hemisphere and $45^\circ$ in the Northern Hemisphere. This pattern suggests that the regions with the strongest negative torques have shifted poleward, presumably as a consequence of the poleward redistribution of relative AAM. Since the trend in the zonal AAM tendency is relatively low (not shown), the trends in the divergence of the meridional AAM flux (Equation 6) should be of approximately equal magnitude to the zonal trends in the total torque, but with opposite sign. Meridional shifts in the AAM flux divergence may change the meridional distribution of the AAM tendencies to a large extent, which, in turn, drives the meridional redistribution of the relative AAM (Figure 6).

The poleward shift of the torques has likely also resulted in the changing contributions of the mountain and friction torques (Figure 8b). In the Southern Hemisphere, both mountain and friction torque have increased in the lower midlatitudes ($\approx 20^\circ$–$40^\circ$), whereas farther poleward ($\approx 55^\circ$) only the friction torque has decreased significantly. Around approximately $15^\circ$–$30^\circ$ in the Northern Hemisphere, the increase in mountain torque is similar to the increase in friction torque, but around $50^\circ$ the friction torque has decreased significantly more than the mountain torque.

This shift from mountain torques to friction torques is considered a result of the shift of midlatitude westerlies to latitudes with less orography (Figure 9a). This is most clear in the Southern Hemisphere, mainly where the Andes can contribute greatly to the mountain torque around $20^\circ$–$40^\circ$ (e.g., Weickmann et al., 1997; Iskenderian and Salstein, 1998). The increasing mountain torque in the Southern Hemisphere may be associated with the small decrease in surface pressure west of the southern part of the Andes, as well as the higher zonal pressure gradient across Southern Africa (Figure 9b). Around $60^\circ$S, there is little orography and therefore little change in mountain torque.

In the Northern Hemisphere, the increased mountain torque at lower latitudes may be caused by decreasing surface pressures west of the Rocky Mountains and over Northwest Africa and India, and higher surface pressures over the Himalayas (Figure 9b). The decreasing mountain torque at higher latitudes could be due to the lower surface pressure over the northern part of the Rocky Mountains and the eastern part of Siberia.

In both Hemispheres, the trends in zonal wind speed near the surface have been strongest over the oceans (Figure 9a). Since surface drag over water only results in friction torque, this can explain why the friction torque has changed more than the mountain and gravity torques at most latitudes.
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DISCUSSION AND CONCLUSIONS

5.1 AAM balance

In this research, the angular momentum budget of the atmosphere during the period 1900–2010 has been studied using the ECMWF ERA-20C reanalysis. The closure of the AAM budget was calculated with both analysis and forecast data to assess the ability of ERA-20C to conserve AAM, which we consider a measure of model performance. Because the AAM tendencies in the forecast budget were not calculated between consecutive forecasts, the AAM balance of the forecast budget is not affected by the assimilation of observations (Poli et al., 2013). A budget residual close to zero can thus be expected in the forecasts. A small bias between the mean total torque and the mean tendency was found, however, suggesting that the closure of the AAM budget in the forecasts is not perfect. The closure of the AAM budget in the forecast data has only been determined for the periods 1900–1916 and 1995–2010, because it was assumed to be constant on a multiannual time-scale. Despite the biannual and annual variability, the residuals show no long-term trend (Figure 1), so the assumption holds.

One cause of this bias may be that the forecast model used in ERA-20C (IFS Cycle38r1) does not conserve angular momentum perfectly. Part of the bias may also be attributed to numerical approximations in the retrieval and use of the data. Upon retrieval from the ECMWF data server, the data are automatically interpolated horizontally from their original T159 spectral resolution (Poli et al., 2016) to the regular latitude–longitude grid used in this study. Previous studies have shown that such changes in coordinate system and resolution may cause errors in the conservation of energy (Trenberth et al., 2002) and mass (Trenberth, 1991). Any interpolation errors may be partially attributed to the use of the ECMWF EMOSLIB library instead of the newer MIR library (Maciel et al., 2017), which is the default ECMWF interpolation package since January 2019. Numerical errors may also arise from calculation of the horizontal integrals (Equation 5) or zonal gradients (Equation 7). This error could be reduced by using the data at their original spectral resolution. Part of the bias may also be caused by errors in the calculated mountain torque (Berrisford et al., 2011). The mountain torque is based on three-hourly instantaneous surface pressures, which may differ from the actual mean surface pressure in each three-hour time period (Berrisford et al., 2011), since the time step in the model itself is 0.5 hr (Poli et al., 2016).

Although the residuals in the forecast budget are small, the negative tendencies and torques indicate that the model loses AAM most of the time. The tendencies in the analysis budget, based on the change in AAM between the start of consecutive months, are on average much closer to zero than in the forecasts, due to the assimilation of observations. This indicates that the analysis increments prevent the continual loss of AAM. As a result, however, the residuals in the analysis budget are significantly larger than in the forecast budget, because the mean total torque has a large negative bias (Figures 1 and 2). The mean budget residual in the analysis is about $13.5 \times 10^{18}$ kg m$^2$ s$^{-2}$, which is comparable to residuals found by other studies: Berrisford et al. (2011) found a mean budget residual of about $15 \times 10^{18}$ kg m$^2$ s$^{-2}$ between 1989 and 2002 in the ECMWF ERA-40 reanalysis and a mean balance residual of about $7 \times 10^{18}$ kg m$^2$ s$^{-2}$ between 1989 and 2008 in the more recent ERA-Interim. Madden and Speth (1995) found a mean negative bias of approximately $15.2 \times 10^{18}$ kg m$^2$ s$^{-2}$ over a period of 13 months in ECMWF analysis data. In NCEP/NCAR reanalysis data from 1968–1996, Huang et al. (1999) found a mean negative residual of about $10.9 \times 10^{18}$ kg m$^2$ s$^{-2}$.

Around 1920 and 1940, the analysis budget residuals are significantly lower (Figure 2). The lower residuals around 1920 correspond approximately to an increase in the friction
torque and the lower residuals around 1940 correspond to an increase in both the mountain and friction torque (Figure 8). This suggests that the residuals in the analysis budget can largely be attributed to a negative bias in both mountain and friction torques. A negatively biased friction torque was also observed by Madden and Speth (1995). On the other hand, Huang et al. (1999) found that the budget residuals were due mainly to a negative bias in the gravity-wave torque. Interestingly, the gravity-wave torque in this study is weaker than found by Huang et al. (1999), thus extracting less AAM from the atmosphere, whereas the mountain torque is much stronger. Part of this shift between gravity-wave and mountain torque may be due to differences in horizontal resolution and thus the scales of orography that can be resolved (Brown, 2004). The sum of the mountain and gravity-wave torques is more negative here than in the study of Huang et al. (1999), which contributes to the larger budget residual. Studying the contributions of the different torques to the residuals in more detail in further research may provide directions for further model improvement (Madden and Speth, 1995; Huang et al., 1999). Inaccuracies in the torques can be related to uncertainty in the representation of surface drag in stable conditions (Sandu et al., 2013; Tsiringakis et al., 2017). Sandu et al. (2013) demonstrated that, in numerical weather prediction models, increasing the turbulent diffusion in stable boundary layers artificially is necessary to simulate the large-scale atmospheric circulation accurately. Tsiringakis et al. (2017) showed that this additional drag can be provided by accounting for the gravity-wave drag generated in stable conditions by small-scale orography. This indicates that an accurate representation of small-scale drag generation is important for simulations of the large-scale circulation and thus for the conservation of AAM in models.

A decrease of the budget residuals in time would be an indication of improvements in model performance. Berrisford et al. (2011) found that, in both ERA-40 and ERA-Interim, the annual mean budget residuals have decreased since 1989. In this study, the residuals have also decreased slightly between about 1990 and 2000 (Figure 2), but throughout the whole 20th century there is no significant improvement in the closure of the AAM budget. In contrast, a positive linear trend in the budget residuals is observed, which corresponds to the negative total torque trend in the data and implies that the average rate at which the model loses AAM has increased. The lower negative bias in the torque and thus the lower budget residuals around 1920 and 1940 are presumably related to the decrease in the number of assimilated zonal wind observations in these periods (Poli et al., 2016). This relation, in combination with the relatively large budget residuals and the use of only surface observations (Poli et al., 2016), suggests that reliability of the trend analysis might be questionable. It is therefore important to compare trends with the literature as well as to assess their theoretical basis.

### 5.2 Trend analysis

To study trends in the AAM budget, the monthly mean AAM and monthly mean torques were calculated throughout the 20th century using the ECMWF ERA-20C reanalysis. We found that the total AAM has increased during the 20th century with a linear trend of approximately 0.86×10^23 kg m^2 s^-1 per year. In response to a doubling of the CO2 concentration in about 60 years, Huang et al. (2001) observed an increase in AAM of approximately 2.4×10^23 kg m^2 s^-1 per year. Averaged over 16 climate models, Räisänen (2003) found an increase in relative AAM of about 1.0×10^23 kg m^2 s^-1 per year when the CO2 concentration doubles in 70 years. Both increases are larger than the trend found in this study, which is not surprising, because the CO2 concentration has not doubled yet in the 20th century (IPCC, 2013). In reanalysis data, del Rio (1999) found an increase in the length of a day of about 5.6×10^-5 s per year between 1949 and 1997, which corresponds to an AAM trend of approximately 3.3×10^23 kg m^2 s^-1 per year (Rosen and Salstein, 1983). This trend is also significantly larger than the trend in this study, which may to some extent be explained by the shorter time period studied by del Rio (1999); as shown in Figure 3b, the AAM trend in the second half of the 20th century is slightly larger than the trend in the whole 20th century. Paek and Huang (2013) found a positive AAM trend in the 20th century in CMIP3 and CMIP5 simulations, due mainly to an increase in relative AAM. Using the NCAR/NCEP 20CR reanalysis data, Paek and Huang (2012) also found an increase in relative AAM between 1871 and 2008. Although they did not quantify the trend explicitly, it is of the same order of magnitude (figure 1a in Paek and Huang (2012)) as the trend in this study.

However, Paek and Huang (2012) also found that, in the second half of the 20th century, the relative AAM in 20CR was on average lower than in several other reanalysis data sets and had a different temporal evolution. The mean relative AAM in this study is higher than was found in 20CR by Paek and Huang (2012) and therefore more comparable with the other data sets, so presumably more accurate. However, the mean and temporal evolution of the AAM were not compared in detail with other data sets in this study, and should be subject to further research.

The total AAM trend is due mainly to an increase in the relative AAM, which is related to the zonal wind distribution. The main changes in relative AAM are a decrease in part of the tropical stratosphere, an increase in most of the stratosphere and in the tropical upper troposphere, and a poleward redistribution in the midlatitudes. A poleward shift of relative AAM was also found by Räisänen (2003), Huang et al. (2001), and Paek and Huang (2013) in response to higher CO2 concentrations. This shift is likely due to increasing tropospheric temperatures and decreasing lower stratospheric temperatures (e.g., Yin, 2005; Chen and Held, 2007; Lorenz and
DeWeaver, 2007). These temperature changes can be associated with the decrease in stratospheric ozone and increasing CO₂ concentrations in the troposphere (IPCC, 2013). The increase in relative AAM and zonal winds in the tropical upper troposphere has also been observed by Huang et al. (2001) and Räisänen (2003) in response to increasing CO₂ concentrations and global warming, but no definite explanation for this zonal wind increase has been found. However, Huang et al. (2001) suggested that this increase may be due to an intensification of El Niño events or Madden–Julian Oscillations, which would result in stronger westerly winds in the tropical upper troposphere (Lee, 1999). Another factor could be the weakening of the tropical easterly jet (Koteswaram, 1958) in the 20th century found by Abish et al. (2013), resulting in stronger mean zonal winds.

The total torque, the earth–atmosphere exchange of angular momentum, has increased in the Tropics and subtropics and decreased at higher latitudes. We interpret this as a poleward shift of the most negative torque, presumably caused by the poleward redistribution of relative AAM, because torques depend on the zonal winds. The poleward shift of the torques has changed the contributions of the friction and mountain torques to the total torque. Especially in the Southern Hemisphere, the relative AAM has decreased at latitudes with significant orography (≈ 35°S) and increased at latitudes with little orography (≈ 55°S). The mountain and gravity-wave torques have barely changed around ≈ 55°S, whereas the friction torque has decreased strongly, which implies that the relative importance of mountains in maintaining the AAM balance decreases due to the poleward shift of the relative AAM. However, the exact magnitude of the torque trends is uncertain, because the total torque has a strong negative bias.

No clear trend in the Ω-AAM component was found. However, the temporal evolution of the Ω-AAM shows a spurious peak around 1920. This peak is caused by a global increase in surface pressure, mostly in the high latitudes of the Southern Hemisphere. Since dry mass should be conserved, the peak is considered to be an artefact of the number and quality of assimilated pressure observations and changes therein (Poli et al., 2013; 2016; Hines et al., 2000). Such spurious surface pressure changes can also influence trends in mountain torque, which depends on the zonal surface pressure distribution. Similarly, the increase in the number and quality of assimilated zonal wind observations (Poli et al., 2013) has likely also impacted trends in relative AAM, zonal winds, and air temperatures, which is probably hard to overcome in long reanalysis datasets. Nevertheless, the large residuals in the AAM budget suggest that improving the parametrizations of gravity and turbulent stress drag can increase the reliability of trends in the AAM budget. The absence of temperature and upper-air observations in ERA-20C also lowers the reliability of the trends in the upper atmosphere (Poli et al., 2013), indicating the importance of comparing the trends in ERA-20C with reanalyses that incorporate the complete observing system. Nevertheless, the similarities of the trends in angular momentum, zonal wind, and temperature to trends reported by other studies and the theoretical basis of the trends indicate sufficient significance of our results.

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