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Historical trends in the jet streams

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[1] Jet streams, the meandering bands of fast winds located near the tropopause, are driving factors for weather in the midlatitudes. This is the first study to analyze historical trends of jet stream properties based on the ERA-40 and the NCEP/NCAR reanalysis datasets for the period 1979 to 2001. We defined jet stream properties based on mass and mass-flux weighted averages. We found that, in general, the jet streams have risen in altitude and moved poleward in both hemispheres. In the northern hemisphere, the jet stream weakened. In the southern hemisphere, the sub-tropical jet weakened, whereas the polar jet strengthened. Exceptions to this general behavior were found locally and seasonally. Further observations and analysis are needed to confidently attribute the causes of these changes to anthropogenic climate change, natural variability, or some combination of the two. **Citation:** Archer, C. L., and K. Caldeira (2008), Historical trends in the jet streams, *Geophys. Res. Lett.*, *35*, L08803, doi:10.1029/2008GL033614.

1. Introduction

[2] Jet streams are narrow bands of fast, meandering air currents that flow around the globe near the tropopause level in both hemispheres. They are often classified in two categories: sub-tropical jets, found at the poleward margin of the upper branch of the Hadley circulation, and polar jets, located above the polar-frontal zone, a region of sharp thermal contrast between cold polar air and warm tropical air [*Holton*, 1992; *Bluestein*, 1993].

[3] Jet streams are important because synoptic scale disturbances tend to form in the regions of maximum jet stream wind speed and to propagate downstream along storm tracks that follow the jet axes [*Holton*, 1992]. Changes in jet stream location, intensity, or altitude can therefore cause variations in frequency and intensity of storms. Also, jet streams inhibit formation and development of hurricanes, which preferentially develop in low-shear regions of the atmosphere [*Gray*, 1968; *Vecchi and Soden*, 2007]. They affect air transport not only because of their high winds, but also because of the clear-air turbulence associated with jet cores [*Bluestein*, 1993].

2. Data

[4] To study if and how the jet streams have changed in the past few decades, we used two reanalyses of historical weather data: ERA-40 [*Uppala et al.*, 2005], from the European Centre for Medium-Range Weather Forecasts, which covers 44 years from 1958 to 2001, and NCEP/NCAR [*Kalnay et al.*, 1996; *Kistler et al.*, 1999], from the National Centers for Environmental Protection and the National Center for Atmospheric Research, covering the years from 1948 to 2006. Monthly averages of zonal and meridional (u and v respectively) wind velocity components were available at 2.5 degrees horizontal resolution and with 6 vertical levels between 400 and 100 hPa. Whereas conventional observations (e.g., upper-air winds, temperature, and humidity from radiosondes; surface data from various land and buoy networks; ocean wave heights) were assimilated in both datasets throughout the entire periods, satellite-borne observations (e.g., infrared and microwave radiances; total and column ozone; surface-pressure and winds over ocean) were only assimilated from 1979 on. For this reason, this study will focus only on the period 1979-2001. Despite limitations [*Pawson and Fiorino*, 1999], the ERA-40 and NCEP/NCAR datasets are the best sets of reanalyzed weather data available [*Uppala et al.*, 2005].

3. Methods

[5] In both hemispheres, the jet streams are located between the 400 and the 100 hPa levels. The Northern Hemisphere (NH) jet has a single-band spiral-like structure, generally beginning south of the Canary Islands and ending one eastward circumnavigation later over England. The Southern Hemisphere (SH) jet has a more concentric structure, with a persistent ring around Antarctica, hereafter referred to as Southern Hemisphere Polar (SHP) jet, and a seasonally varying second ring at about 30 S, hereafter referred to as the Southern Hemisphere sub-Tropical (SHT) jet [*Koch et al.*, 2006].

[6] Jet streams are not continuous, but rather fragmented, meandering, and with notable wind speed and elevation variations. As such, the task of clearly identifying jet stream boundaries at a given time can be difficult and ambiguous [*Koch et al.*, 2006]. To overcome this problem, we define jet stream properties via integrated quantities, which are more numerically stable and less grid-dependent than are simple maxima and minima.

[7] First, for each horizontal grid point in the reanalyses, we define the mass weighted average wind speed between 400 and 100 hPa (WS) as:

$$WS_{i,j} = \frac{\sum_{k=400\text{hPa}}^{k=100\text{hPa}} m_k \times \sqrt{u_{i,j,k}^2 + v_{i,j,k}^2}}{\sum_{k=400\text{hPa}}^{k=100\text{hPa}} m_k}, \quad (1)$$

where $u_{i,j,k}$ and $v_{i,j,k}$ are the monthly-average horizontal wind components at grid point *(i,j,k)*, and m_k is the mass at level k. Figure 1a shows the 23-year average of *WS*,

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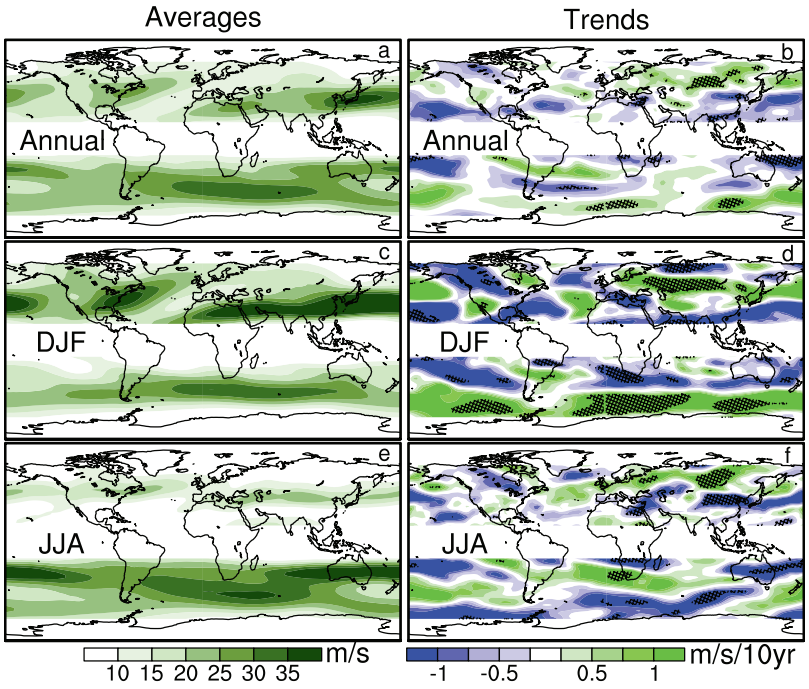


Figure 1. Jet stream wind speed from the ERA-40 reanalyses in 1979–2001: (a, c, e) annual, DJF, and JJA averages (m/s); (b, d, f) linear regression trends (m/s/decade), hatched where statistically significant (P-value <0.15), taking auto-correlation into account.

hereafter referred to as the jet stream wind speed, obtained from the ERA-40 dataset for all grid points (the pattern of *WS* from NCEP/NCAR is almost identical and is shown in the auxiliary material Figure S1).[1] Figure 1a shows wind maxima to the East of the continents in the Northern Hemisphere, and to the East of Australia and to the South of Africa in the Southern Hemisphere, as observed [*Koch et al.*, 2006]. Seasonal differences between the two hemispheres were also found (Figures 1c and 1e). The NH jet forms a nearly continuous band between northern Africa and Hawaii in DJF (Figure 1), but it shifts northward, fragments, and weakens in JJA. In the SH, the Polar jet is omnipresent in all seasons, with wind speed maxima south of Africa; the SH sub-Tropical jet is only present in JJA as a nearly continuous band between Australia and South America.

[8] Given mass and wind speed at each pressure level z between 400 and 100 hPa, for each horizontal grid cell, the mass-flux weighted pressure P is defined as:

$$P_{i,j} = \frac{\sum_{k=400\text{hPa}}^{k=100\text{hPa}} \left(m_k \times \sqrt{u_{i,j,k}^2 + v_{i,j,k}^2} \right) \times p_k}{\sum_{k=400\text{hPa}}^{k=100\text{hPa}} m_k \times \sqrt{u_{i,j,k}^2 + v_{i,j,k}^2}}, \qquad (2)$$

where p_k is the pressure at level k. P represents the average pressure of flows near the tropopause, and therefore the average altitude of these flows. Because jet streams are found near the tropopause, we can use P to characterize the height of both the jet streams and the tropopause. In both hemispheres, the jet streams are lower (and closer to the poles) in the summer than they are in the winter, but the NH jets are generally lower than the SH jets (Figures 2a, 2c, and 2e for the ERA-40 and auxiliary material Figure S2 for the NCEP/NCAR). In the NH, the jets are lowest downwind of their wind speed maxima, whereas in the SH the jets are lowest where they are fastest.

[9] Given the total mass-flux between 400 and 100 hPa, we calculate the mass-flux weighted latitude in the NH for each longitude i in the gridded reanalysis fields as follows:

$$L_i^{NH} = \frac{\sum_{j=15N}^{j=70N} \left[\sum_{k=400\text{hPa}}^{k=100\text{hPa}} \left(m_k \times \sqrt{u_{i,j,k}^2 + v_{i,j,k}^2} \right) \right] \times \varphi_{i,j}}{\sum_{j=15N}^{j=70N} \sum_{k=400\text{hPa}}^{z=100\text{hPa}} m_k \times \sqrt{u_{i,j,k}^2 + v_{i,j,k}^2}} \qquad (3)$$

where $\phi_{i,j}$ is the grid cell latitude. We use this integrated value L^{NH} to characterize the latitude of the NH jet stream at each longitude i. The following latitude bands will be used in equation (3), and in the rest of the paper, to define the three jet streams: 15N-70N for the NH, 40S-15S for the SHT, and 70S-40S for the SHP jets. These intervals were chosen based on zonal mean wind speeds (not shown).

[10] Because these jet stream properties are, by design, weighted averages over large volumes (i.e., all grid cells between the 400 and 100 hPa levels within a given latitude band worldwide), it is possible that trends occurring in a sub-volume are partially masked by the lack of trends in other sub-volumes. Trends in jet stream properties calculated in

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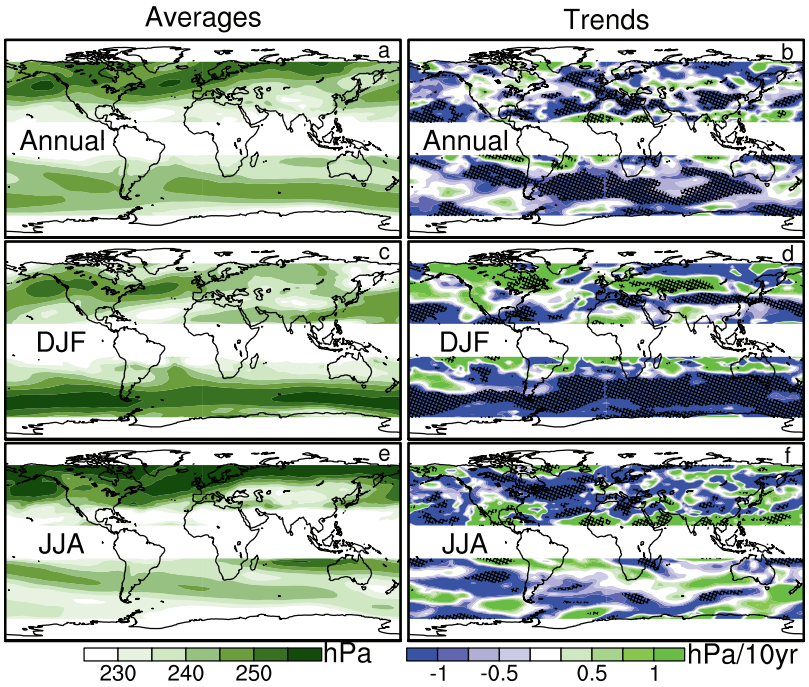


Figure 2. Jet stream pressure (as a measure for altitude) from the ERA-40 reanalyses in 1979–2001: (a, c, e) annual, DJF, and JJA averages (hPa); (b, d, f) linear regression trends (hPa/decade), hatched where statistically significant (P-value <0.15), taking auto-correlation into account. At an altitude of 10 km, the pressure is approximately 265 hPa in the standard atmosphere and a pressure change of 1 hPa represents an altitude change of about 26 m.

this study are therefore generally expected to be conservative lower-bound estimates.

4. Annual and Global Trends

[11] Using these jet stream properties, simple scalar metrics for the entire globe (or for regions of interest) can be obtained. We calculated global-average latitude, wind speed, and altitude for the three jet streams (NH, SHT, and SHP) for the period 1979-2001 from both the ERA-40 and the NCEP/NCAR datasets. Since the temporal evolution of the annual and seasonal averages from the ERA-40 and the NCEP/NCAR reanalyses were nearly identical, only the former are shown in Figure 3, whereas the latter are available in the auxiliary material Figure S3. Parameters of the linear regression against a linear trend from both reanalyses are listed in Table 1. The auto-correlation of the time series, when larger than 0.15, was taken into account to correct the P-value of the linear regression.

[12] We found that all three jet streams moved poleward during the period 1979–2001, at rates varying from 0.06–0.11 degrees/decade in the SHT, to 0.07–0.10 degrees/decade in the SHP, and to 0.17–0.19 degrees/decade in the NH jet. The SHP jet, however, shifted equatorward in the austral winter, but not enough to compensate for the poleward shift in the austral summer (Figure 3, left panels). A poleward shift of the jet streams is consistent with numerous other signals of global warming found in previous studies, such as the expansion of the Hadley cell, the poleward shift of the storm tracks, the widening of the tropical belt, and the cooling of the stratosphere. However, this is the first study to examine jet stream latitude trends in the reanalyses.

[13] *Lorenz and DeWeaver* [2007] looked at climate projections from 15 models under the Intergovernmental Panel for Climate Change (IPCC) A2 scenario ("business as usual" in the 21st century) and found qualitatively consistent jet shifts poleward in both hemispheres. *Kushner et al.* [2001] found that strong anthropogenic greenhouse gas emissions can cause a similar poleward shift of the SHP jet (by ~0.08 degrees/decade) in a climate model. The connection of poleward expansion of the Hadley cell with global warming was identified by *Frierson et al.* [2007], in idealized simulations with increased mean temperature, and by *Lu et al.* [2007], who used climate models in a strong greenhouse gas emission scenario. Both studies found similar expansion rates, between 0.2 and 0.6 degrees/K (degrees of latitude per degree K of warming), equivalent to a poleward shift of the jet streams by 0.02–0.06 degrees/decade (given a 0.5 K of warming in 1979–2005), smaller than the values found in this study. On the other hand, other studies have reported larger poleward shifts of parameters related to the jets. *Fu et al.* [2006] and *Hu and Fu* [2007] estimated a widening of the Hadley cell of 2–4.5 degrees in 1979–2005, corresponding to a shift of the jets by 0.37–0.86 degrees/decade. Also, a poleward (and upward) shift in the storm tracks in both hemispheres ($\leq$ 0.6 degrees/decade from the plots) was found by *Yin* [2005] in a 15-member ensemble of 21st century climate models in a moderate green house gas emission scenario. *Seidel et al.* [2008] reported several estimates of the widening of the Tropics varying between 1 and 8 degrees during 1979–2005, corresponding to poleward shifts of 0.2–1.6 degrees/decade for the jets. Finally, *Williams* [2006] and *Haigh et al.* [2005] showed that stratospheric warming would cause a lowering

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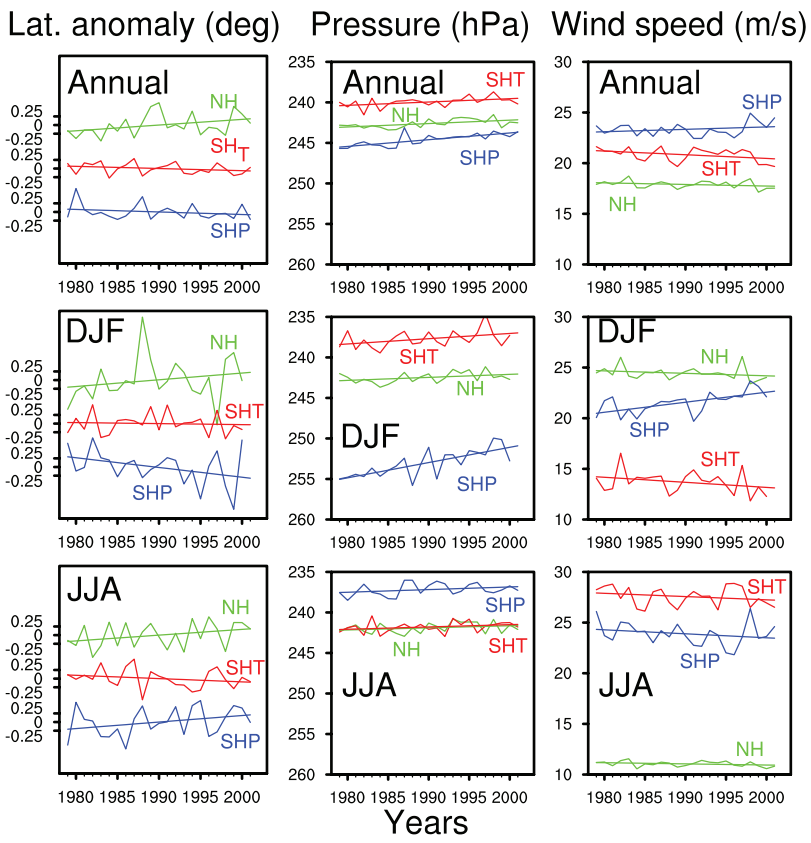


Figure 3. Annual, DJF, and JJA: anomalies from the 23-year (1979–2001) average latitude, average pressure (hPa, as a measure of altitude), and average wind speed (m/s) of the Northern Hemisphere (NH), Southern Hemisphere sub-Tropical (SHT), and Southern Hemisphere Polar (SHP) jet streams from the ERA-40 reanalyses. Positive latitude trends in the northern hemisphere indicate a poleward shift in the jet stream, as do negative trends in the southern hemisphere.

of the tropopause and a shift of the jets equatorward, therefore confirming that the stratospheric cooling expected from anthropogenic emissions would cause a poleward (and upward) shift of the jets.

[14] An increase in jet stream altitude implies a negative change in pressure and is reflected in a negative pressure trend in Table 1. All jet streams had negative pressure trends (except for a non-significant positive trend in the SHT jet

Table 1. Statistical Regression Analysis of Annual Averages of Latitude, Altitude, and Wind Speed for Each Jet Stream From Both the ERA-40 and the NCEP/NCAR Datasets in 1979–2001[a]

Parameter	Jet Stream	Dataset	Slope Per Decade	Correlation Coefficient	P-value
Latitude, deg	NH	ERA-40	0.165	0.363	**0.096**
		NCEP	0.185	0.399	**0.064**
	SHT	ERA-40	−0.063	−0.268	0.215
		NCEP	−0.111	−0.445	0.033
	SHP	ERA-40	−0.073	−0.222	0.308
		NCEP	−0.101	−0.279	0.195
Pressure, hPa	NH	ERA-40	−0.419	−0.545	**0.009**
		NCEP	−0.036	−0.066	0.765
	SHT	ERA-40	−0.412	−0.458	0.027
		NCEP	0.017	0.022	0.920
	SHP	ERA-40	−0.832	−0.746	**<0.001**
		NCEP	−0.410	−0.506	0.013
Wind speed, m/s	NH	ERA-40	−0.156	−0.287	0.183
		NCEP	−0.182	−0.337	0.115
	SHT	ERA-40	−0.365	−0.381	**0.214**
		NCEP	−0.422	−0.429	**0.153**
	SHP	ERA-40	0.237	0.251	**0.336**
		NCEP	0.404	0.429	0.045

[a]NH = Northern Hemisphere, SHT = Southern Hemisphere sub-Tropical, and SHP = Southern Hemisphere Polar. Bold values indicate P-values that have been corrected to take into account the auto-correlation of the series, if greater than 0.15.

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for the NCEP/NCAR reanalyses). Statistically significant pressure decreases occurred in the SHP jet (−0.41 to −0.83 hPa/decade, corresponding to +11 to +22 m/decade in the standard atmosphere with −26.3 m/hPa altitude decrease with pressure). The NH jet showed a decrease in pressure in both datasets (−0.04 to −0.42 hPa/decade or about +2 to +11 m/decade). Because of their highly averaged nature, these estimated trends in jet stream pressure are lower than those found in previous studies of tropopause height from climate models or observations. The increase in altitude of the jets occurred mostly in the boreal winter (Figure 3, center panels).

[15] *Santer et al.* [2003] reported an average decrease in tropopause pressure of −1.45 hPa/decade (+60 m/decade) for the 1979–1999 period. In a climate model under a "business as usual" CO_2 emission scenario, *Kushner et al.* [2001] found a rising of the SHP by up to −3 hPa/decade (+79 m/decade in standard atmosphere), and *Lorenz and DeWeaver* [2007] an average tropopause rising of 40 m/decade (−1.52 hPa/decade in standard atmosphere). *Seidel and Randel* [2006] used radiosonde data to estimate that the tropopause rose by −1.6 hPa/decade (+64 m/decade) during 1980-2004.

[16] The strength, or wind speed, decreased in the NH (−0.16 to −0.18 m/s/decade) and in the SHT jet (−0.37 to −0.42 m/s/decade), and increased in the SHP jet (+0.25 to +0.42 m/s/decade). Whereas no significant seasonal differences were found for the wind speed decrease in the SHT jet, the strengthening of the SHP jet occurred mostly in DJF, as did the weakening of the NH jet (Figure 3, right panels).

[17] The increasing trend in the SHP jet winds is consistent with findings by *Russell et al.* [2006], who reported an increase in the westerlies over the Southern Ocean of ∼20% in the past 20 years, by *Kushner et al.* [2001], who found small increases (+0.08 m/s/decade) due to green house gases alone, and by *Thompson and Salomon* [2002], who related wind speed increases to photochemical ozone losses.

5. Seasonal and Spatial Trends

[18] More details about changes in jet stream properties can be obtained by looking at two-dimensional and seasonal maps of trends from the ERA-40 dataset (the corresponding trends from the NCEP/NCAR dataset are available in the auxiliary material, Figures S1 and S2, right panels). In general, the SH trends are more horizontally homogeneous than in the NH, due to the greater ocean extent.

[19] The jet stream shift towards the poles can be detected in Figure 1, where the areas of high average wind speed (left panels) are generally bounded by areas with statistically-significant positive trends on their poleward sides, and by areas of statistically-significant negative trends on their equatorward sides (right panels). In the NH in DJF (Figure 1d), the jet wind speed has been increasing over a band covering northern Europe, central Asia, and the northern Pacific, to the north of the jet core (Figure 1c), accompanied by a second band with negative trends over southern Asia and the Pacific, to the south of the jet core. This pattern in the NH is also evident in the boreal summer (JJA, Figure 1f). In the SH during the austral summer (DJF), strong wind speed increases were found all around Antarctica and strong wind speed decreases were found further north along a band centered at about 40S (Figure 1d), again consistent with a poleward shift of the jets. In the SH during the austral winter (JJA), however, the SHP jet tended to shift equatorward (Figure 1f), but not enough to compensate for the poleward shift observed in the SH austral summer. This seasonal difference, with a strong poleward shift in the SH summer, was found in a climate model by *Kushner et al.* [2001], who related it to anthropogenic emissions.

[20] Figure 2b further confirms that jet stream pressure trends are overall negative on average, to indicate that they are rising in altitude. In both hemispheres, the jets have risen more in the summer than in the winter. For example, in DJF (Figure 2d), statistically-significant negative pressure trends in the SH are larger and more wide spread than in JJA (Figure 2f). In both hemispheres during their respective winters (DJF for NH and JJA for SH), there is a strong correspondence between wind speed and pressure trends (Figures 1d and 2d for the NH, Figures 1f and 2f for the SH). This suggests that, in both hemispheres in their respective winters only, jet stream wind speed either increases as the jet lowers (e.g., over central Asia), or decreases as the jet rises (e.g., over the Southern Ocean between Africa and Australia).

6. Conclusions

[21] Global warming is expected to affect the distribution of mass (and thus pressure) in the atmosphere and therefore affect the strength and location of the jet streams. Because of the complex nature of jet streams, which are discontinuous in time and space, meandering, and with notable wind speed and elevation variations, it is important to use objective and numerically stable metrics to define their properties. We introduced mass and mass-flux weighted averages of wind speed, pressure, and latitude of the jets in both hemispheres and used these quantities to study jet stream trends from a subset (1979–2001) of the ERA-40 and the NCEP/NCAR reanalyses. We found that, on average, the jets are generally moving poleward in both hemispheres. The northern hemisphere jet is weakening. In the southern hemisphere, the sub-tropical jet is also weakening, whereas the polar jet is strengthening. However, seasonal and local trends may differ from this general behavior. For example, the northern hemisphere jet strengthened while decreasing in altitude in the boreal winter over Asia.

[22] In general, trends of jet stream properties found in this study are consistent in sign, but smaller in magnitude, with those found in previous studies. This suggests that the weighted averages over large volumes used to characterize the jet streams in this study correctly capture the jet properties, but they must be considered conservative lower-bound estimates for larger trends that may manifest themselves in subsets of these volumes.

[23] These changes in jet stream latitude, altitude, and strength have likely affected, and perhaps will continue to affect, the formation and evolution of storms in the mid-latitudes and of hurricanes in the sub-tropical regions. Further observations and analyses are needed to confidently attribute the causes of these changes to anthropogenic

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climate change, natural variability, or some combination of the two.

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