RESEARCH



Assessment of trends in an integrated climate metric—analysis of 200 mbar zonal wind for the period 1958–2021

Nenghan Wan¹ · Xiaomao Lin¹ • Roger A. Pielke Sr²

Received: 22 June 2022 / Accepted: 2 October 2022 © The Author(s) 2022

Abstract

Using two reanalysis datasets on latitude bands of nearly equal area, we analyze the trend of 200 mbar zonal wind anomalies for the period 1958–2021 as well as annual-mean latitude of the zonal mean jet stream. We do not find much change of 200 mbar zonal wind in both two datasets although the increasing trend over the high latitude bands from 45 to 61 $^{\circ}$ S for both datasets, and the decreasing trend in 0–5 $^{\circ}$ N and 0–10 $^{\circ}$ S for ERA5 are significant with small magnitudes. In addition, the polar jet core moves poleward in the Northern Hemisphere, but the movement is not statistically significant, while no poleward shift at all has occurred in the Southern Hemisphere. This work provides us a way to look for the long-term changes and variability in atmospheric circulation.

1 Introduction

The assessment of the global average surface temperature as the main metric to monitor changes in climate has become a major international policy measure. The Paris Agreement of holding the global average surface temperature change to well below 2 °C and limiting it to 1.5 °C has become an international policy goal (Rogelj et al. 2016). However, the surface temperature data suffers from large spatial variations in coverage, biases (Karl et al. 2015) from site exposure and representativeness, etc., which must be accounted for (Pielke et al. 2007). Using spatially heterogeneous and relatively sparse (in many regions) data is also applying a two-dimensional dataset to characterize the three-dimensional climate system. Rather, it is much more robust to analyze the three-dimensional atmosphere. Indeed, it is optimal to let the atmosphere itself do the averaging.

There are particular weather observations in which the atmosphere itself performs the integration best suited to evaluate trends. As is well known, integration of data

- ⊠ Roger A. Pielke Sr pielkesr@gmail.com

Published online: 07 October 2022

- Department of Agronomy, Kansas Climate Center, Kansas State University, Manhattan, KS, USA
- Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA

reduces the effect of random errors, although systematic errors, if any, would still persist. For mid- and high latitudes, the gradient wind relationship can be used to quantitatively relate the thickness between pressure surfaces to depth-integrated temperatures when following the ideal gas law and the hydrostatic balance requirement (Pielke 2013). The gradient wind is the same as the geostrophic wind when horizontal curvature of the flow is relatively small. Even in low latitudes, this relationship is reasonably accurate as winds are still closely related to the gradient winds at larger spatial scales.

Previous studies have successfully used zonal wind as a zonal mean temperature proxy applying the thermal wind equation with reanalysis, radiosonde data, and pilot balloons to characterize warming (Allen and Sherwood 2008; Pralungo and Haimberger 2015; Lee et al. 2019). In Pielke et al. (2001), the 200 mbar zonal winds (u component) for the period 1958–1997 were analyzed using National Centers for Environmental Prediction reanalysis data. From the thermal wind relation, the winds at 200 mbar (which are very close to the gradient wind speed) are an effective integrator of the tropospheric meridional temperature gradient averaged from the surface up to the altitude of the 200 mbar pressure surface. The monitoring of trends in the 200 mbar winds, therefore, provides an approach to examining longterm changes and variability in the atmospheric circulation of the troposphere.

The strong westerly winds generated as a consequence of the equator-to-pole temperature gradient near the tropopause



form the polar jet stream. Changes in the location, intensity, or altitude of the polar jet stream can influence mid-latitude weather systems as well as air transport (Hannachi et al. 2012; Williams 2016). Francis and Vavrus (2012, 2015) concluded that a wavier polar jet stream in combination with slowing of upper-level zonal wind due to rapid Arctic warming increases the likelihood of persistent weather patterns and extreme events. Williams (2016) reported that a strengthening of the prevailing jet stream winds causes east-bound flights over the north Atlantic to significantly shorten and westbound flights to significantly lengthen in all seasons. Eastbound and westbound crossings in winter become approximately twice as likely to take under 5 h 20 min and over 7 h 00 min, respectively, but this study did not take a global perspective.

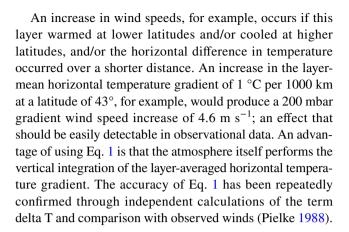
In this paper, the 200 mbar zonal wind was selected as an effective way to assess variability and trends in atmospheric circulation based on the thermal wind relationship (discussed in detail in the next section). We analyze the trend of the 200 mbar zonal wind (*u* component) anomaly for the period 1958–2021 as well as the annual mean latitude of zonal mean jet stream using ERA5 and JRA-55 reanalysis datasets at the global level. Data and methodology are explained in "Sect. 3." Zonal wind trends are presented in "Sect. 4." Finally, conclusions are presented in "Sect. 5."

2 Thermal wind relationship

The dynamical relationship known as the thermal wind equation is used to calculate differences in the geostrophic wind between the surface (1000 mbar level in this study) and the 200 mbar level. The component of the thermal wind equation in the east—west wind speed (*u*) in terms of the layer-averaged temperature gradient is expressed as Eq. 1 (Bluestein 1992; Pielke et al. 2001).

$$u = \frac{R_d}{f} \ln \left(\frac{1000 \text{mbar}}{200 \text{mbar}} \right) \left(k \times \nabla_p \overline{T} \right) \bullet i$$
 (1)

where f is the Coriolis parameter, R_d is the gas constant for dry air, and $\nabla_p \overline{T}$ is the horizontal temperature gradient averaged from 1000 to 200 mbar. The gradient operator ∇_p denotes a gradient on an isobaric level. k and i are the vertical unit vector and horizontal (east–west) unit vector. The westerly winds at 200 mbar, u 200 mbar, are thus directly related to the magnitude of the horizontal, north–south gradient in temperature averaged from the Earth's surface to the height of the 200 mbar winds where the surface geostrophic wind (the surface is defined to be at 1000 mbar) is assumed to be negligible compared to the 200 mbar winds. The zonal mean jet stream is represented as the latitudinal region with the strongest 200 mbar winds.



3 Data source and method

The fifth-generation ECMWF atmospheric reanalysis of the global climate (ERA5) dataset is the replacement for ERA-Interim reanalysis. Benefiting from developments in model physics, core dynamics, and data assimilation, this dataset has the advantage of much higher temporal and spatial resolution (Hersbach et al. 2020). Currently, data is available from 1950 and has two versions for 1950–1978 (preliminary back extension) and 1979 onwards (final release plus timely updates). We collected monthly averaged data from 1958 to 2021 on a 1440×721 grid with 0.25° latitude and 0.25° longitude grid increments.

The Japanese 55-year Reanalysis (JRA-55) is the second Japanese global atmospheric reanalysis commissioned by the Japan Meteorological Agency (JMA) which covers the period starting from 1958 (Kobayashi et al. 2015). It is the upgraded version of JRA-25 and has undergone a variety of improvements including higher spatial resolution and a new radiation scheme. Monthly averaged data were chosen on a grid of 288×145 points with a horizontal spacing of 1.25°×1.25° from 1958 to 2021.

We first calculated the monthly climatology from 1958 to 1997, and followingly the 200 mbar annual westerly wind anomaly for both 1958–1997 and 1998–2021 was obtained based on monthly averaged datasets from ERA5 and JRA-55. Then, linear trends were calculated from ordinary least-squares regression and statistical significance was tested at the 95% confidence level (p < 0.05) according to a two-tailed t-test for each period. All datasets were used on a standard latitude–longitude grid.

The mean of the westerly wind anomaly was calculated with a cosine (latitude) weighting factor to account for the convergence of grid points at near-equal area latitude bands that approximately account for 4% of Earth areas for each 0 to 5° , 5 to 10° , 10 to 15° , 15 to 20° , 20 to 26° , 26 to 32° , 32 to 38° , 38 to 45° , 45 to 52° , 52 to 61° , and 61 to 73° bands in the Southern and Northern Hemispheres. The $73-90^{\circ}$



bands in the Southern and Northern Hemispheres are defined separately and account for approximately 2% of the Earth's area. We also calculated trends in the annual-mean 200 mbar wind speed between 20 and 60° latitude for the Northern and Southern Hemispheres in a similar approach to that used in Bracegirdle et al. (2018). At each latitude, the all-longitude average was calculated for each month, and then all the locations of maximum wind speed in each month were averaged for each year. The averaged latitude was then selected as the polar jet core location.

4 Results

Averaged over the region of near-equal area latitude bands in the Northern Hemisphere, the time series of the 200 mbar zonal wind anomalies since 1958 are very similar between two reanalysis datasets in each band except for a slight difference in magnitude in the 0–5°N band (Fig. 1). Both

ERA5 and JRA-55 reanalysis datasets are in good agreement with respect to the inter-annual variability. The wind speeds decrease in the 0–5°N, 61–73°N, and 73–90°N latitude bands, but only the trend in 0–5°N of the ERA5 dataset shows a statistically significant decrease. The trend increases in 10–15°N as well as 26 to 61°N latitudes while only the values in 10–15°N and 45–52°N for JRA-55 dataset are significant at the 95% confidence level.

Similarly, the time series of the 200 mbar zonal wind anomalies is provided in Fig. 2 for the Southern Hemisphere since 1958, averaged over the region of near-equal area latitude bands. The agreement of the two reanalysis datasets is less good than that in the Northern Hemisphere as illustrated in their trends shown in Table 1. Since 1958, the latitude bands 0–5°S, 5–10°S, 10–15°S, and 15–20°S show a decrease in westerly wind speed in both the ERA5 and JRA-55 reanalysis datasets, but only the trends in 0–5°S and 5–10°S latitude bands are statistically significant at the 95% confidence level for the ERA5 dataset (Table 1).

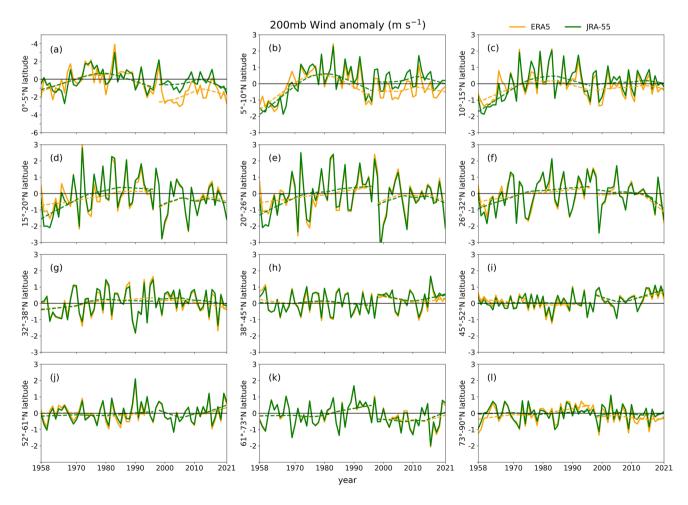


Fig. 1 The 200 mbar westerly wind anomaly in meters per second from the ERA5 (orange line) and JRA-55 (green line) for 1958–2021 in the Northern Hemisphere. (a) 0–5°N, (b) 5–10°N, (c) 10–15°N, (d)

 $15{-}20^{\circ}N,$ (e) $20{-}26^{\circ}N,$ (f) $26{-}32^{\circ}N,$ (g) $32{-}38^{\circ}N,$ (h) $38{-}45^{\circ}N,$ (i) $45{-}52^{\circ}N,$ (j) $52{-}61^{\circ}N,$ (k) $61{-}73^{\circ}N,$ and (l) $73{-}90^{\circ}N.$ The dash lines represent smoothed lines using locally weighted scatterplot method



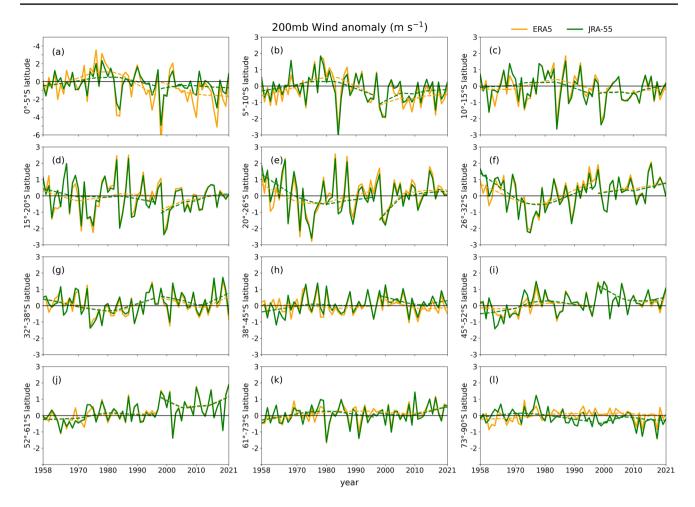


Fig. 2 The 200 mbar westerly wind anomaly in meters per second from the ERA5 (orange line) and JRA-55 reanalysis (green line) for 1958–2021 in the Southern Hemisphere. (a) 0–5°S, (b) 5–10°S, (c) 10–15°S, (d) 15–20°S, (e) 20–26°S, (f) 26–32°S, (g) 32–38°S, (h)

 $38\text{--}45^{\circ}\text{S},$ (i) $45\text{--}52^{\circ}\text{S},$ (j) $52\text{--}61^{\circ}\text{S},$ (k) $61\text{--}73^{\circ}\text{S},$ and (l) $73\text{--}90^{\circ}\text{S}.$ The dash lines represent smoothed lines using a locally weighted scatterplot method

The trend shows an increase between $26-32^{\circ}S$ and $32-38^{\circ}S$ as well as $45-52^{\circ}S$ and $52-61^{\circ}S$; however, only the $45-52^{\circ}S$ and $52-61^{\circ}S$ latitude bands had a significant increase in the westerly anomaly trend at a rate of approximately 0.1 m s^{-1} decade⁻¹ in both the ERA5 (p < 0.05) and the JRA-55 (p < 0.05) reanalysis. There are some discrepancies in latitude bands $20-26^{\circ}S$, $38-45^{\circ}S$, and $73-90^{\circ}S$, with ERA5 showing a decrease of zonal wind in the $38-45^{\circ}S$ and an increase in $20-26^{\circ}S$ and $73-90^{\circ}S$, while JRA-55 is opposite (Fig. 2(e), (h), (l)).

Table 1 shows the trend of different latitude bands from 1958–1997, 1998–2021, and overall. From 1958 to 1997, ERA5 and JRA-55 show a good agreement with the increase in zonal wind for 45–52°S and 52–61°S, while only the trend in the band 52–61°S is statistically significant (p < 0.05). In the Northern Hemisphere, wind significantly increases at around a rate of 0.4 m s⁻¹ decade⁻¹ in the JRA-55 dataset (p < 0.05) over 5–32°N and decreases for 38–45°N and 45–52°N but does not show a statistical significance.

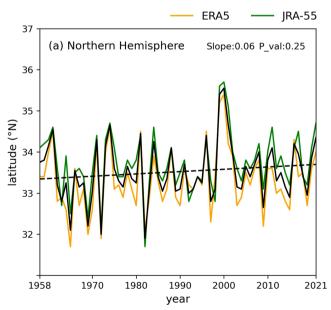
From 1998 to 2021, all trends in the Southern and Northern Hemispheres of both datasets are in good agreement except for the 0–5° latitude bands. Wind increases over the 5–26° latitude band as well as the 52–73° latitude band in both Hemispheres but decreases in the 26–32°N, 32–38°N, 38–45°S, and 45–52°S bands. Comparing the two periods, the trend shifts from a significant increase to a decrease in 26–32°N and 32–38°N while the wind increases over two periods from 5 to 26°N latitude. There is total 7 latitude bands out of 24 bands that have a significant trend in ERA5 and 5 in JRA-55 from 1958 to 2021 although the magnitudes are relatively modest, for example, the increasing trend over the high latitude bands from 45 to 61°S for both datasets, and the decreasing trend in 0–5°N and 0–10°S for ERA5.

Using the maximum 200 mbar zonal wind speed, a jet core location can be obtained. We calculated the annual mean latitude of maximum zonal wind speed between 20 and 60° over the Southern and Northern Hemispheres for the period 1958–2021 from both the ERA5 and JRA-55



Table 1 200 mbar observed westerly wind linear trend in meters per second per decade across different latitude bands from the ERA5 and JRA-55 reanalysis datasets, * represents p < 0.05

Latitude bands	1958–1997		1998–2021		1958–2021	
	ERA5 trend	JRA-55 trend	ERA5 trend	JRA-55 trend	ERA5 trend	JRA-55 trend
0–5°N	0.13	0.18	0.13	-0.22	-0.30*	-0.03
5-10°N	0.27*	0.48*	0.04	0.04	-0.01	0.17*
10–15°N	0.24	0.45*	0.08	0.08	0.01	0.13*
15-20°N	0.30	0.51*	0.18	0.09	-0.01	0.03
20-26°N	0.34*	0.49*	0.12	0.17	0.03	0.04
26-32°N	0.28*	0.38*	-0.14	-0.10	0.03	0.06
32-38°N	0.16	0.13	-0.24	-0.17	0.03	0.06
38–45°N	-0.08	-0.06	-0.01	0.08	0.02	0.06
45–52°N	-0.10	-0.03	0.16	0.22	0.05	0.08*
52-61°N	0.03	0.14	0.14	0.21	0.01	0.05
61–73°N	0.19	0.19	0.01	0.10	-0.04	-0.04
73–90°N	0.20*	0.04	-0.09	-0.02	-0.02	0.00
0–5°S	-0.12	0.06	-0.10	0.33	-0.37*	-0.13
5-10°S	0.11	-0.03	0.23	0.32	-0.12*	-0.10
10-15°S	0.15	-0.03	0.20	0.36	-0.04	-0.07
15-20°S	0.08	-0.08	0.36	0.46	-0.01	-0.06
20–26°S	0.07	-0.20	0.36	0.38	0.08	-0.02
26-32°S	0.08	-0.14	0.20	0.22	0.14*	0.07
32-38°S	-0.05	-0.03	0.02	0.07	0.03	0.07
38–45°S	-0.04	0.08	-0.26	-0.17	-0.03	0.06
45–52°S	0.10	0.16	-0.28	-0.19	0.10*	0.13*
52–61°S	0.15*	0.13	0.06	0.07	0.18*	0.16*
61–73°S	0.09	-0.01	0.22	0.24	0.09*	0.05
73–90°S	0.13*	-0.08	-0.14	-0.09	0.02	-0.10



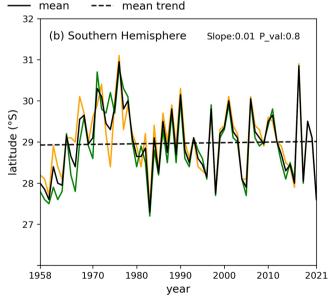


Fig. 3 Annual mean latitude of the maximum zonal wind speed from the ERA5 (orange line) and JRA-55 reanalysis (green line) and the linear trend in the mean (black line) for 1958–2021 in the (a) North-

ern and (b) Southern Hemispheres. The positive trend indicates a poleward shift in the jet core while the slope is shown in degrees decade. $^{-1}$



datasets. In Fig. 3(a), we found the jet core moved poleward in the Northern Hemisphere during this period at an average rate of 0.06° decade⁻¹ but the trend was not statistically significant for either dataset. This trend agrees with previous studies although the methods used are different and the trend is not as strong as found in Molnos et al. (2017) and Rikus (2018). The trend in the Southern Hemisphere also shows a poleward shift but with no statistically significant trend (Fig. 3(b)) although it has the same sign as in Archer and Caldeira (2008) and Pena-Ortiz et al. (2013) but a smaller value, this discrepancy might be due to different periods used for trend analysis.

5 Conclusions

The ERA5 and JRA-55 reanalysis provide the most accurate tool available to assess long-term changes in the tropospheric wind and temperature fields. Adding to this tool, we can utilize the fundamental concept in atmospheric physics that relates large-scale wind speed in the troposphere to the spatial gradient of the vertically integrated temperatures below that level. We focus on the east—west component of the wind at 200 hPa in order to assess the north—south gradient in layer-averaged temperatures below that level. For example, a larger spatial gradient will produce stronger winds at 200 hPa resulting in a much stronger winter polar jet than observed in the summer.

Using latitude bands of near-equal areas, only a few trends are statistically significant. The largest trend is 0.51 m s⁻¹ per decade in the 15-20°N bin in JRA-55 from 1958 to 1997, although not in the equivalent ERA5 reanalysis. Remarkably, over the entire period of 1958–2021, we do not find much change in trends either for the JRA-55 or ERA5 but there are several latitude bands with statistically significant change although with relatively small in magnitude, for example, the increasing trend over the high latitude bands from 45 to 61°S for both datasets, and the decreasing trend in 0-5°N and 0-10°S for ERA5. We also calculated anomalies from winter and summer seasons (see supplement information), and the results show that there is not much change in trends over different latitude bands, although zonal wind increases at the average of 0.21 m s⁻¹ per decade over 38-52°N for both datasets. The polar jet core does show migration to the north in the Northern Hemisphere at about 0.5° of latitude, but the change is not statistically significant. The Southern Hemisphere has essentially no trend. These findings document only small changes to the 200 hPa wind speeds from 1958 to 2021. In addition, climate model simulations (e.g., CMIP6 Earth system models) can be used in further work to evaluate the trends observed in reanalysis datasets.

One explanation for the lack of statistically significant trends is based on previous studies (e.g., Chase et al. 2002; Tsukernik et al. 2004; Herman et al. 2008). There is a constraint on warming in the tropical midtroposphere and cooling in the winter in the higher latitude mid-troposphere due to deep cumulus convection which limits the warmest 500 hPa temperatures to -3 °C and the coldest 500 hPa temperatures to – 42 °C (Chase et al. 2015). These coldest temperatures are achieved before the winter solstice occurs. The 500 hPa temperatures are accepted as the optimal individual tropospheric level to characterize tropospheric dynamics including tropospheric layer-averaged temperatures (Pielke 2013). This constraint on the tropospheric layer-averaged temperatures, therefore, constrains wind speeds at 200 hPa. From another perspective, an upper tropospheric layer maximum of warming in the tropics which increases the meridional temperature gradient in the upper troposphere could be the consequence of the increases in water vapor and the smaller moist-adiabatic lapse rate, while as the corresponding gradient in the lower troposphere could be reduced by the polar amplification of surface warming. These two effects would compete with each other and thus could result in only a modest change in the average jet stream speed.

This has implications for claims that the polar jet has become weaker (and wavier) due to a warming Arctic troposphere (Francis and Vavrus 2015). Our analysis contradicts that view; in Zolotov et al. (2018)'s work, the variability of the Southern Hemisphere jet stream and its poleward shift has been observed with statistical significance in reanalysis datasets; however, their analysis is based on seasons and several domains. Although Hallam et al. (2022) and Maher et al. (2020) found not only the structure but also the behavior of jet stream varied strongly in continents and seasons, and some changes cannot be represented by global or hemispheric annual means, Michael et al. (2022) did further research on 200 mbar winds on a mean annual cycle using both reanalysis and Earth system models. They found similar conclusion as us that a slight poleward movement in the latitude of the highest winds which cannot point to the jet stream becoming waiver. The polar jet is as strong in 2021 as it was in 1958. Since the polar jet stream results in extratropical cyclone development through baroclinic development (Holton 1973; Pielke 2013), a lack of a significant trend in the polar jet and in the 200 hPa winds indicates that these cyclones should be as frequent and intense in 2021 as they were in 1958.



Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00704-022-04225-y.

Acknowledgements This study was supported in part by the US Department of Agriculture, National Institute of Food and Agriculture (grant no. 2016-68007-25066). The contribution number of this manuscript is 22-276-J. We thank Ryan Maue who motivated us as to which reanalyzes products were the best to use, we also thank Dallas Staley for her outstanding contibution to editiong and finalizing the paper.

Author contribution All authors contributed to the study. Data collection and data analysis were performed by WN. The first draft of the manuscripts was written by WN and RAP. All authors checked and commented on the previous version. The authors declare that the manuscript has been read and approved by all named authors. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

Data availability ERA5 data are available to download for registered users at Copernicus Data Store: monthly data on pressure levels from 1950 to 1979 are available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means-preliminary-back-extension?tab=overview and monthly data on pressure level from 1979 onwards are available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=overview. NCAR and Japan Meteorological Agency data for JRA-55 is available at https://doi.org/10.5065/D60G3H5B. Accessed: 24 Mar. 2022.

Declarations

Ethics approval We declare that this submission follows the policies of the journal as outlined in the guide for authors and the ethical statement.

Consent for publication All authors consent to publish the study in a journal article.

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

- Allen R, Sherwood S (2008) Warming maximum in the tropical upper troposphere deduced from thermal winds. Nat Geosci 1. https://doi.org/10.1038/ngeo208
- Archer CL, Caldeira K (2008) Historical trends in the jet streams. Geophys Res Lett 35. https://doi.org/10.1029/2008GL033614

- Bluestein HB (1992) Synoptic-dynamic meteorology in midlatitudes: observations and theory of weather systems. Taylor & Francis
- Bracegirdle TJ, Hyder P, Holmes CR (2018) CMIP5 diversity in southern westerly jet projections related to historical sea ice area: strong link to strengthening and weak link to shift. J Clim 31:195–211. https://doi.org/10.1175/JCLI-D-17-0320.1
- Chase TN, Herman B, Pielke RA Sr et al (2002) A proposed mechanism for the regulation of minimum midtropospheric temperatures in the Arctic. J Geophys Res: Atmos 107:ACL 2-1-ACL 2-7. https://doi.org/10.1029/2001JD001425
- Chase TN, Herman BM, Pielke Sr RA (2015) Bracketing mid-tropospheric temperatures in the Northern Hemisphere: an observational study 1979–2013. J Clim Weather Forecast 3:131. https://doi.org/10.4172/2332-2594.1000131
- Francis JA, Vavrus SJ (2012) Evidence linking Arctic amplification to extreme weather in mid-latitudes. Geophys Res Lett 39(6). https://doi.org/10.1029/2012GL051000
- Francis JA, Vavrus SJ (2015) Evidence for a wavier jet stream in response to rapid Arctic warming. Environ Res Lett 10:014005. https://doi.org/10.1088/1748-9326/10/1/014005
- Hallam S, Josey SA, McCarthy GD, Hirschi JJ-M (2022) A regional (land-ocean) comparison of the seasonal to decadal variability of the Northern Hemisphere jet stream 1871–2011. Clim Dyn 59:1897–1918. https://doi.org/10.1007/s00382-022-06185-5
- Hannachi A, Woollings T, Fraedrich K (2012) The North Atlantic jet stream: a look at preferred positions, paths and transitions. Q J R Meteorol Soc 138:862–877
- Herman B, Barlage M, Chase TN, Pielke Sr RA (2008) Update on a proposed mechanism for the regulation of minimum midtropospheric and surface temperatures in the Arctic and Antarctic. J Geophys Res: Atmos 113(D24). https://doi.org/10.1029/2008J D009799
- Hersbach H, Bell B, Berrisford P et al (2020) The ERA5 global reanalysis. QJR Meteorol Soc 146:1999–2049. https://doi.org/10.1002/qj.3803
- Holton JR (1973) An introduction to dynamic meteorology. Am J Phys 41:752-754
- Karl TR, Arguez A, Huang B et al (2015) Possible artifacts of data biases in the recent global surface warming hiatus. Science 348:1469-1472
- Kobayashi S, Ota Y, Harada Y et al (2015) The JRA-55 reanalysis: general specifications and basic characteristics. J Meteorol Soc Jpn 93:5–48. https://doi.org/10.2151/jmsj.2015-001
- Lee SH, Williams PD, Frame THA (2019) Increased shear in the North Atlantic upper-level jet stream over the past four decades. Nature 572:639-642. https://doi.org/10.1038/s41586-019-1465-z
- Maher P, Kelleher ME, Sansom PG, Methven J (2020) Is the subtropical jet shifting poleward? Clim Dyn 54:1741–1759. https://doi.org/10.1007/s00382-019-05084-6
- Michael AB, Roger RA Sr, Xubin Z (2022) Possible self-regulation of mid-tropospheric. Temperatures and its effect on upper level winds. J Geophys Res-Atmos, preprint
- Molnos S, Mamdouh T, Petri S et al (2017) A network-based detection scheme for the jet stream core. Earth Syst Dynam 8:75–89. https://doi.org/10.5194/esd-8-75-2017
- Pena-Ortiz C, Gallego D, Ribera P et al (2013) Observed trends in the global jet stream characteristics during the second half of the 20th century. J Geophys Res: Atmos 118:2702–2713. https://doi.org/10.1002/jgrd.50305
- Pielke RA (1988) Synoptic weather lab notes. Colorado State University, Department of Atmospheric Science. https://pielkeclimatesci.files.wordpress.com/2010/01/nr-77.pdf



- Pielke RA, Chase TN, Kittel TGF et al (2001) Analysis of 200 mbar zonal wind for the period 1958–1997. J Geophys Res 106:27287–27290. https://doi.org/10.1029/2000JD000299
- Pielke RA Sr (2013) Mesoscale meteorological modeling. Academic press, San Diegoo
- Pielke RA Sr, Davey CA, Niyogi D et al (2007) Unresolved issues with the assessment of multidecadal global land surface temperature trends. J Geophys Res: Atmos 112(D24). https://doi.org/10.1029/2006JD008229
- Pralungo LR, Haimberger L (2015) New estimates of tropical mean temperature trend profiles from zonal mean historical radiosonde and pilot balloon wind shear observations. J Geophys Res: Atmos 120:3700–3713
- Rikus L (2018) A simple climatology of westerly jet streams in global reanalysis datasets part 1: mid-latitude upper tropospheric jets. Clim Dyn 50:2285–2310
- Rogelj J, den Elzen M, Höhne N et al (2016) Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534:631–639. https://doi.org/10.1038/nature18307

- Tsukernik M, Chase TN, Serreze MC et al (2004) On the regulation of minimum mid-tropospheric temperatures in the Arctic. Geophys Res Lett 31(6). https://doi.org/10.1029/2003GL018831
- Williams PD (2016) Transatlantic flight times and climate change. Environ Res Lett 11:024008. https://doi.org/10.1088/1748-9326/11/2/024008
- Zolotov SYu, Ippolitov II, Loginov SV, Kharyutkina EV (2018) Variability of the Southern Hemisphere subtropical jet stream in the second half of the 20th century and early 21st century. Izv Atmos Ocean Phys 54:430–438. https://doi.org/10.1134/S0001433818050146

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

