Seasonal and regional variations of long-term changes in upper-tropospheric jets from reanalyses

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1 **Seasonal and Regional Variations of Long-Term Changes in**
2 **Upper Tropospheric Jets from Reanalyses**

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ABSTRACT

11 Long-term changes in upper tropospheric jet latitude, altitude, and strength
12 are assessed using five modern reanalyses, MERRA and MERRA-2, ERA-
13 Interim, JRA-55, and NCEP-CFSR. Changes are computed from jet locations
14 evaluated daily at each longitude to analyze regional and seasonal variations.
15 The changes in subtropical and polar (eddy-driven) jets are evaluated sepa-
16 rately. Good agreement among the reanalyses in many regions and seasons
17 provides confidence in the robustness of the diagnosed trends. Jet shifts show
18 strong regional and seasonal variations, resulting in changes that are not ro-
19 bust in zonal or annual means. Robust changes in the subtropical jet indicate
20 tropical widening over Africa except during northern hemisphere (NH) spring,
21 and tropical narrowing over the eastern Pacific in NH winter. The Southern
22 Hemisphere (SH) polar jet shows a robust poleward shift, while the NH po-
23 lar jet shifts equatorward in most regions/seasons. Both subtropical and polar
24 jet altitudes typically increase; these changes are more robust in the NH than
25 in the SH. Subtropical jet windspeeds have generally increased in winter and
26 decreased in summer, while polar jet windspeeds weakened (strengthened)
27 over Africa and eastern Asia (elsewhere) during winter in both hemispheres.
28 The Asian monsoon has increased in area and appears to have shifted slightly
29 westward towards Africa. Our results highlight the importance of understand-
30 ing regional and seasonal variations when quantifying long term changes in
31 jet locations, the mechanisms for those changes, and their potential human
32 impacts. Comparison of multiple reanalyses is a valuable tool for assessing
33 the robustness of jet changes.

34 **1. Introduction**

35 The upper tropospheric (UT) jet streams are a key component of the atmospheric circulation
36 and closely linked with weather and climate phenomena such as storm tracks, precipitation, and
37 extreme events (Koch et al. 2006; Harnik et al. 2016; Mann et al. 2017, and references therein).
38 The UT jets and the tropopause are themselves sensitive to climate change and ozone depletion
39 (e.g., Seidel and Randel 2006; Lorenz and DeWeaver 2007; McLandress et al. 2011; WMO 2011;
40 Hudson 2012; Grise et al. 2013; Waugh et al. 2015), as well as to natural modes of variability
41 such as ENSO and QBO (Hudson 2012; Lin et al. 2014, 2015; Olsen et al. 2016, and references
42 therein).

43 Upper tropospheric jets are often categorized conceptually as radiatively-driven or eddy-driven
44 jets. Radiatively-driven jets arise via heating of the tropics, which drives the Hadley circulation
45 and through conservation of angular momentum leads to strong westerly winds in the subtropical
46 upper troposphere (e.g., Held and Hou 1980). Eddy-driven jets are maintained by disturbances in
47 the atmospheric zonal mean flow (Held and Hoskins 1985; Lorenz and Hartmann 2003; Robinson
48 2006; Baldwin et al. 2007; Garfinkel et al. 2013, and references therein). However, observations
49 show a complex seasonally and regionally varying picture in which distinct radiatively-driven or
50 eddy-driven jets cannot be identified (e.g., Manney et al. 2014), consistent with idealized modeling
51 studies that show a complex interplay of these processes (e.g., Lee and Kim 2003). The observed
52 complex jet structures arise primarily from the distributions of land-mass and orography (e.g.,
53 Hoskins and Valdes 1990; Held et al. 2002). Because of the combination of several mechanisms
54 involved in generating and maintaining the upper tropospheric jets (Lee and Kim 2003; Wang and
55 Lee 2016, and references therein), it is not straightforward to predict how they would respond to
56 climate change.

57 Changes in climatological jet stream characteristics (latitude, altitude, windspeed) are, however,
58 expected to lead to changes in weather patterns and regional climate impacts (see, e.g., reviews
59 by Lucas et al. (2014) and Harnik et al. (2016)). UT jet variations have been linked to rainfall
60 changes and hence water stress for populations in the subtropics (e.g., Price et al. 1998; Raible
61 et al. 2004; Karneuskas and Ummenhofer 2014; Lucas et al. 2014; Screen and Simmonds 2014;
62 Huang et al. 2015; Xie et al. 2015). Regional rainfall decline in Australia has been associated with
63 a poleward shift of the jets (and accompanying rain-producing storms) that is in turn linked to
64 circulation changes caused by Antarctic ozone depletion (Kang et al. 2011; Thompson et al. 2011;
65 Delworth and Zeng 2014; Bai et al. 2016). Jet variability has also been linked to destructive wind
66 storms (e.g., Pinto et al. 2009, 2014; Gómara et al. 2014; Messori and Caballero 2015; Messori
67 et al. 2016) and extreme temperature events (e.g., Cohen et al. 2014; Screen and Simmonds 2014;
68 Harnik et al. 2016; Röthlisberger et al. 2016).

69 Both modeling and observational studies suggest a poleward shift of the subtropical jet (thus
70 widening of the tropical belt) resulting from the changing climate (e.g., Santer et al. 2003; Lorenz
71 and DeWeaver 2007; Seidel et al. 2008; Strong and Davis 2007, 2008; Archer and Caldeira 2008;
72 Davis and Rosenlof 2012; Lucas et al. 2014; Staten et al. 2016). A possible mechanism for
73 this is increasing subtropical upper tropospheric meridional temperature gradients, which would
74 strengthen the jet (Held 1993; Lucas and Nguyen 2015; Barnes and Screen 2015, and references
75 therein). Different observational datasets and methods yield widely varying and highly uncertain
76 estimates of tropical expansion, with most estimates under one degree per decade (e.g. Birner et al.
77 2014; Lucas et al. 2014) and additional uncertainties in the asymmetry between the hemispheres
78 and the seasonality of the expansion rates (e.g., Lucas et al. 2014). Several studies suggest strong
79 regional variations in tropical width, including regions of narrowing rather than widening (e.g. Lu-
80 cas et al. 2012; Peña-Ortiz et al. 2013; Lucas and Nguyen 2015). Robust information on regional

81 variations and long-term changes is crucial for planning and climate change adaptation. The an-
82 nual and/or zonal averaging commonly used may mask clear signals in jet trends in individual
83 regions and seasons, from which more information on the main drivers and processes behind the
84 changes could be gained (Lucas et al. 2014; Zappa et al. 2015). In the Southern Hemisphere (SH),
85 modeling studies indicate that the poleward shift in the edge of the tropics has been exacerbated by
86 chemical ozone depletion, especially during Austral summer, and will be counteracted to some ex-
87 tent by the recovery of the ozone hole (e.g., Son et al. 2010; Arblaster et al. 2011; McLandress et al.
88 2011). Waugh et al. (2015) showed that the extent to which the models are capable of reproducing
89 observed trends in jet position depends strongly on their accuracy in representing ozone depletion
90 and tropical sea-surface temperatures. Current models generally do not capture the full magnitude
91 of observed changes, although this may be more closely related to natural internal variability than
92 to incorrect representation of anthropogenic forcings (Garfinkel et al. 2015).

93 Many studies do not clearly separate trends in the subtropical jet from those in the eddy-driven
94 or “polar” jet. The many potential feedbacks and interactions involved in the response of the polar
95 jet to a changing climate (Simpson et al. 2014; Barnes and Screen 2015; Woollings et al. 2016, and
96 references therein) make it difficult to argue for an expected sign of changes in its strength or posi-
97 tion. Moreover, considerable controversy exists as to the effects of Arctic Amplification (Serreze
98 and Barry 2011, and references therein) on the position and strength of the eddy-driven jet (Co-
99 hen et al. 2014; Screen and Simmonds 2014; Barnes and Polvani 2015; Barnes and Screen 2015;
100 Overland et al. 2016; Shepherd 2016, and references therein). Temperature gradients in the lower
101 troposphere may be expected to weaken in response to Arctic amplification, which would lead to
102 a weakening and equatorward shift of the jets (Held 1993; Barnes and Screen 2015, and refer-
103 ences therein). However, many models predict a strengthening of upper tropospheric temperature
104 gradients, which would lead to a strengthening and poleward shift of the jets – lower and upper

105 tropospheric jet responses may thus not be the same. Moreover, dynamical feedbacks resulting
106 from the changing background winds (e.g., from changing waveguide conditions that affect wave
107 activity, heat, and momentum fluxes) could play as large as or a larger role than changes in tem-
108 perature gradients (e.g., Simpson et al. 2009; Woollings et al. 2016). The modeled response of the
109 polar jet to climate change shows a tendency for models with well-resolved stratospheres to have a
110 weaker poleward, or even an equatorward, shift of the polar jet compared to low-top models (e.g.,
111 Butler et al. 2010; Sigmond and Scinocca 2010; Scaife et al. 2012; Screen et al. 2013; Manzini
112 et al. 2014). As is the case for the subtropical jet, modeling and observational studies suggest re-
113 gional and seasonal differences in trends in polar jet strength and location (Woollings et al. 2011,
114 2014; Barnes and Polvani 2013; Peña-Ortiz et al. 2013; Simpson et al. 2014; Simpson and Polvani
115 2016, and references therein). Results from modeling studies show a large spread and dependence
116 on biases in jet position, with models with more equatorward jets showing stronger poleward shifts
117 (Kidston and Gerber 2010; Woollings et al. 2011; Barnes and Polvani 2013; Simpson and Polvani
118 2016, and references therein).

119 Previous studies have examined regional and/or seasonal changes in the jet streams using sev-
120 eral methods of characterizing jet locations. Strong and Davis (2007) used National Centers for
121 Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis
122 data and windspeeds on the “surface of maximum wind” to examine trends in jet streams during
123 northern hemisphere (NH) winter, and found an increase in jet core frequencies and windspeeds
124 over mid-latitudes and a decrease north of 60°N, suggesting an equatorward shift of the polar jet.
125 Archer and Caldeira (2008) used NCEP/NCAR and European Centre for Medium-range Weather
126 Forecasts (ECMWF) ERA-40 reanalysis data to examine global trends in jet streams in a 2D view
127 using a mass-weighted average throughout the upper troposphere; they showed evidence of a pole-
128 ward and upward shift of polar jets in both hemispheres and weakening jets with the exception of

129 the SH polar jet. Barton and Ellis (2009) examined variability and trends in the north Pacific jet
130 stream using NCEP/NCAR Reanalysis 300-hPa winds, and showed a strengthening jet between
131 1949 and 2005, with a suggestion of an equatorward shift in its position. Manney et al. (2011)
132 introduced a method of characterizing the upper tropospheric and lower stratospheric jets and the
133 tropopauses in three dimensions. Manney et al. (2014) used this method to describe the climatol-
134 ogy of upper tropospheric jets in relation to multiple tropopauses and the stratospheric subvortex
135 using the NASA Global Modeling and Assimilation Office (GMAO) Modern Era Retrospective-
136 analysis for Research and Applications (MERRA) reanalysis. Peña-Ortiz et al. (2013) used a jet
137 characterization method that closely parallels that of Manney et al. (2011, 2014) to study regional
138 and seasonal trends in the UT jets in the NCEP/NCAR and the NCEP-20th Century (NCEP-20CR)
139 reanalyses; they used a simple latitude criterion to analyze subtropical and polar jets separately in
140 the SH, but could not distinguish these jets in the NH. Overall, they found the largest poleward
141 shift and windspeed increase in the SH polar jet during 1979 through 2008 in austral summer and
142 fall. Their study often showed conflicting results between the two reanalyses; results in many
143 regions and seasons were thus unclear.

144 The above studies, with the exception of Manney et al. (2011, 2014), used older reanalyses
145 (NCEP/NCAR, ERA-40) that have coarse horizontal (2 to 2.5 degrees) and vertical (standard
146 pressure level grids with >2 km levels spacing in the UTLS) resolution, use outdated models and
147 assimilation methods, and have been shown to be inadequate for studies of the UT and strato-
148 sphere (see Fujiwara et al. 2017, for a review of reanalysis system characteristics and evaluations).
149 Peña-Ortiz et al. (2013) also used the NCEP-20CR reanalysis, which assimilates only surface ob-
150 servations and also has coarse horizontal and vertical resolution and limited skill in the UT (e.g.,
151 Compo et al. 2011; Fujiwara et al. 2017). Manney et al. (2017b) compared jet and tropopause
152 climatologies from five modern high-resolution reanalyses analyzed on their native model levels:

153 ECMWF’s ERA-Interim, GMAO’s MERRA and MERRA-2, NCEP’s Climate Forecast System
154 Reanalysis (CFSR) and CFSR version 2 (collectively referred to as “CFSR” hereinafter), and
155 the Japanese Meteorological Agency’s JRA-55. Even among these latest generation reanalysis,
156 evaluated at 0.75 to 0.5 degree horizontal resolution, there is substantial sensitivity of results to
157 resolution and assimilation model characteristics.

158 Thus, both observational and model results have so far shown an inconsistent picture of upper
159 tropospheric jet variability and trends. Observational studies have yet to provide a complete and
160 robust picture with which model results can be evaluated. To achieve this goal, studies must
161 account for seasonal, interannual, and regional variations in jet locations and windspeeds that are
162 expected to be much larger than any underlying climate-induced trends. Moreover, systematic
163 observational studies have not been published that examine long-term changes in the jets using
164 modern reanalyses and jet characterization methods that can distinguish between subtropical and
165 polar jets and elucidate regional and seasonal variations.

166 In this paper, we extend the methods of Manney et al. (2011, 2014, 2017b) to evaluate trends in
167 UTLS jets, using an improved and more robust identification of subtropical and polar jets through-
168 out the year in both hemispheres. We derive changes in both tropical width and polar jet positions
169 for 1979 through 2014. We pay special attention to the three-dimensional character of jet behavior,
170 and quantify trends in location (altitude and latitude) and strength as a function of longitude and
171 season. By analyzing jet cores identified in 3D, and by breaking the analysis down by region and
172 season, we focus on detecting changes that may be diluted or masked in zonal and seasonal aver-
173 ages and in views based solely on windspeed as opposed to jet core characteristics. All evaluations
174 are done for the five modern reanalyses studied by Manney et al. (2017b), using the data on the
175 native model vertical levels and high-resolution horizontal grids with spacing comparable to the
176 model grids; in absence of independent verification methods, consistency or inconsistency among

177 the reanalyses is a key measure of the robustness of long-term jet changes. Section 2 describes the
178 reanalysis datasets and the methods used. Sections 3a and 3b present an evaluation of long-term
179 changes in the UTLS subtropical and polar jets, respectively, as represented in the reanalyses. A
180 summary and conclusions are presented in Section 4.

181 **2. Data and Analysis**

182 *a. Reanalysis Data*

183 The reanalyses datasets used here are GMAO’s MERRA and MERRA-2 (Rienecker et al. 2011;
184 Bosilovich et al. 2015; Molod et al. 2015; Takacs et al. 2016; Gelaro et al. 2017; Global Modeling
185 and Assimilation Office (GMAO) 2015); ECMWF’s ERA-Interim (e.g., Dee et al. 2011; Dragani
186 2011); JMA’s JRA-55 (Ebita et al. 2011); and NCEP’s CFSR (e.g., Saha et al. 2010). An overview
187 of these reanalyses, the data assimilation systems that produced them, and their primary input
188 datasets, is given by Fujiwara et al. (2017); several different data assimilation methods are used,
189 and, while the major input data sources tend to be quite similar (e.g., operational satellite radiances,
190 radiosondes, etc), there are numerous differences in usage of additional inputs, such as ozone
191 observations (e.g., Dragani 2011; Fujiwara et al. 2017; Wargan et al. 2017; Davis et al. 2017)
192 and recent satellite datasets. There are also differences in the vertical and horizontal grids used
193 in different models. The reanalyses are used on their native model levels; the vertical grids and
194 resolutions are critical to jet and tropopause characterization (e.g., Manney et al. 2017b). The DAS
195 model grids result in ~ 0.8 to 1.3 km vertical resolution in the UTLS; the placement levels and how
196 level spacing changes with height also vary (see Fujiwara et al. 2017, Figure 3, for details). The
197 model horizontal grid spacing for MERRA is 0.5° latitude $\times$ 0.667° longitude; for MERRA-2 it is
198 $0.5^\circ \times 0.625^\circ$. The other reanalyses use spectral models, and the data used here are on the finest

latitude/longitude grids publicly available: $0.75^\circ \times 0.75^\circ$ for ERA-Interim, $0.5^\circ \times 0.5^\circ$ for CFSR, and a Gaussian grid with approximately 0.5625° spacing for JRA-55.

The seasonal jet distributions and time variations shown are evaluated for December/January/February running from December 1979 through February 2014, and for other seasons and monthly fields from 1980 through 2014. All the evaluations have been done using all five reanalyses, and, where feasible, all of these are shown. Where it is only feasible to show results from one dataset, MERRA-2, the most recent of these reanalyses, is shown. All results have been checked in each of the reanalyses, and conclusions drawn are based on that full inspection where all could not be shown.

b. Jet and Tropopause Characterization and Analysis

The JET and Tropopause Products for Analysis and Characterization (JETPAC) is used to identify and characterize the jets and tropopause. The methods and output products used here are described by Manney et al. (2011, 2014), and briefly summarized below.

An upper tropospheric jet is identified wherever there is a windspeed maximum greater than 40 m/s; the boundaries of the jet region are the points surrounding that (in both horizontal and vertical directions) where the windspeed drops below 30 m/s. When more than one maximum above 40 m/s appears within a given 30 m/s contour, they are defined as separate cores if the latitude distance between them is greater than 10° or the decrease in windspeed between them is greater than 30 m/s. These parameters were optimized to approximate as closely as possible the choices that would be made by visual inspection.

Manney et al. (2011, 2014) used a simple latitude criterion (appropriate for climatological studies) to identify subtropical and polar UT jets. A more robust physically-based definition is needed for regional and variability studies. Here, the subtropical jet is defined as the most equatorward

222 westerly jet for which the thermal tropopause altitude at the equatorward edge of the jet is greater
223 than 13.0 km and that tropopause altitude drops by at least 2.0 km from the equatorward to the
224 poleward side of the jet. (The thermal tropopause is identified using the WMO definition (a review
225 of issues related to definition of the thermal tropopause is given by Homeyer et al. 2010).) The
226 polar jet is then defined as the strongest westerly jet poleward of the subtropical jet, or poleward
227 of 40° latitude if no subtropical jet is identified. The observed upper tropospheric jets often have
228 a hybrid nature (e.g., Lee and Kim 2003) and a spectrum of jet characteristics is seen in the cli-
229 matology (Manney et al. 2014), and numerous choices could be made for these definitions. The
230 choices made here identify the subtropical jet as one across which a “tropopause break” occurs,
231 consistent with primarily radiative driving, and the polar jet as the dominant jet consistent with
232 primarily eddy driving. These choices allow us to automate identification of the set of jets that
233 best represents these two idealized types. Extensive testing shows that the identification of cli-
234 matology and variability in jet positions is most sensitive to the use of a physically-based rather
235 than latitude-based criterion to identify the subtropical jet since it often meanders far from its cli-
236 matological latitude near 30°; once this jet is excluded, the results for the polar jet are generally
237 insensitive to the exact details of how that jet is identified.

238 Differences between jet core location frequency distributions (as described in detail by Manney
239 et al. 2014) in composites for 10-year periods between the beginning (1980-1989) and end (2005-
240 2014) of the available record are compared to the 35-year climatology to provide an overview of
241 the spatial distribution of variability and long-term changes in jet core locations. The frequency
242 distributions are normalized by the number of jets that would “fill” each 6° longitude bin if there
243 was a jet present at each longitude in the bin, and by the number of days in the season, as described
244 in detail by Manney et al. (2014, 2017b); the results are expressed as a percentage.

245 To analyze the evolution of the jets in detail, the jet core locations (latitude and altitude) and
246 windspeeds for both subtropical and polar jets are calculated for every longitude on the reanalysis
247 grids, for 12:00UT on each day in the 35-year timeseries. These are then averaged over monthly
248 and seasonal periods, both globally and for each season for 20° longitude regions, to provide a
249 detailed picture of the seasonal and regional changes in the timeseries of jet locations. The number
250 of individual jets averaged for each 20° longitude region depends on the longitude spacing of the
251 reanalyses and the frequency of jet occurrence in the region; the minimum number of jets in a 20°
252 region for a season is 216, 362, 366, 399, and 548 for ERA-Interim, MERRA, MERRA-2, JRA-
253 55, and CFSR, respectively (for polar jets; the minima for subtropical jets are much larger); most
254 regions and seasons have many more, up to over 3000 for CFSR (which has the finest longitude
255 spacing). Thus there are sufficient jets averaged in each bin that none of the results are expected
256 to be dominated by a few outliers.

257 Linear fits to the jets' latitude, altitude, and windspeed are used to examine long-term changes,
258 which we refer to as apparent "trends", without intending any inference / speculation as to the
259 origin of these changes. We show the $1-\sigma$ uncertainties in the slopes of the fits as one rough
260 measure of significance – this is statistically permissive and thus is a necessary, but not suffi-
261 cient, standard that must be applied before any trend could be considered robust. Significance is
262 problematic to assess given that seasonal, interannual, and regional variations are all much larger
263 than any potential trends. A permutation analysis (e.g., Wilks 2011, Section 5.3.4) was done that
264 provides a measure of the significance of the slopes of individual curves: For each time period
265 (month, season, and full year) and region (20° longitude bins from -180° to -160° through 160°
266 to 180°), the 35-year time series analyzed here were randomly shuffled to produce 100,000 pos-
267 sible arrangements of the values, and the linear regression analysis applied to those. A two-sided
268 p-value is derived by counting how many permuted slopes are larger than those derived from the

reanalyses, and dividing by the number of instances (100,000) in the permutation distributions. While spatial or temporal autocorrelation can in general make the results of permutation tests misleading (e.g., Wilks 2011, Section 5.3.5), it is reasonable here to consider the points in the time series independent since we are applying the test individually to time series constructed separately from each regional and monthly or seasonal mean diagnostic. However, as will be seen, there can be cases where the trend from one reanalysis is significant according to that test, but is inconsistent with those in the other reanalyses. This is not too surprising, since there are documented regions/conditions for which some reanalyses are negatively affected by choices made in the data assimilation system or processing (see, e.g., Long et al. 2017), and significance in general does not imply correctness (e.g., Nicholls 2000; Nuzzo 2014). The agreement between the results for different reanalyses, as an indicator of likely consistency with the common physics represented in each model, is thus a critical indicator of the robustness of our results. If the signs of the trends for all reanalyses do not agree, the results are not considered robust regardless of how statistically significant the permutation analysis indicates those slopes to be. Agreement in the signs of the slopes among the reanalyses combined with slopes that are greater than the $1\text{-}\sigma$ uncertainty indicates some robustness; the most robust results are those for which, in addition to these criteria, the permutation test indicates statistical significance at the 95% confidence level.

Manney et al. (2017b) provide a comprehensive comparison of the climatology of upper tropospheric and lower stratospheric jets and multiple tropopauses in the reanalyses used here. In general, the large-scale patterns seen in jet frequency distributions are similar in all the reanalyses. Notable exceptions include evidence of generally stronger tropical circulations in MERRA and MERRA-2 than in ERA-Interim and JRA-55 (especially the equatorial easterlies associated with the Asian Summer Monsoon and the Australian monsoon, and the equatorial westerlies in SH summer downstream of the Australian monsoon), as well as slightly weaker/less persistent upper

293 tropospheric jets in ERA-Interim than in MERRA-2, and stronger/more persistent jets in CFSR
294 than in MERRA-2. These differences in strength/persistence likely reflect the lower (higher) hor-
295 izontal resolution in ERA-Interim (CFSR) than in MERRA-2. MERRA and MERRA-2 also tend
296 to show slightly higher jet altitudes in the zonal mean than do the other three reanalyses, espe-
297 cially in middle to high latitudes where the vertical spacing of MERRA/MERRA-2 model levels
298 is slightly coarser than that of the other reanalyses.

299 **3. Results**

300 A global overview of jet changes during 1980 through 2014 is given in Figures 1 through 4,
301 which show the climatological distribution of jet core locations during each season from MERRA-
302 2, along with the differences between the jet core distributions in the first (1980–1989, referred to
303 below as “early”) and last (2005–2014, referred to as “late”) 10-year periods of the record. This
304 view of frequency distributions provides direct information on the persistence and geographic
305 variability of the jets; it also provides indirect information on jet strength since jets are identified
306 based on a windspeed threshold. The results for the other reanalyses are generally very consis-
307 tent with these, and our discussion focuses on features that are consistent among the reanalyses.
308 These figures include all jets that are identified in the season shown rather than only those that
309 are identified as subtropical or polar jets later in the paper. To help clarify when changes are
310 specifically related to those jets, we have examined analogous frequency distributions constructed
311 from the subtropical jets only (supplemental Figures S1–S4) and the polar jets only (supplemental
312 Figures S5–S8).

313 Looking first at the solstice seasons, we see several notable features in the changes over the
314 35-year period:

315 In the DJF maps (Figure 1, left side), the NH subtropical jet shifted poleward with respect to
316 climatology between the early and late periods, as indicated by a dipole pattern of high anomalies
317 poleward of low anomalies in the frequencies near 30°N from about 45°W to 135°E and over
318 the eastern US and western Atlantic. (Note that, except if otherwise noted, west to east longi-
319 tude ranges span the prime meridian, and east to west ranges span the date line.) Between about
320 135°E and 135°W, the jet distributions are more complex (with frequent poleward excursions of
321 the subtropical jet and/or concurrent presence of strong subtropical and polar jets, e.g., Manney
322 et al. 2014), and there is an apparent equatorward shift of both jets (seen clearly as dipole pat-
323 terns in supplementary Figures S1 and S5). Negative anomalies from about 50–60°N to 80°N
324 with positive anomalies on the equatorward flank (see also supplementary Figure S5) suggest an
325 equatorward shift of the polar jet, except over the north Atlantic where the patterns of changes are
326 more complex, consistent with the varying patterns of multiple jets there (e.g., Woollings et al.
327 2010).

328 In the SH during DJF, positive anomalies flanking a negative anomaly near 45°S are seen from
329 about 90°W to 120°E. These changes, along with the polar jet changes shown in supplementary
330 Figure S5, indicate an equatorward shift of the subtropical jet and a more frequent or persistent
331 polar jet (which also may have shifted slightly poleward, see Section 3a). An additional positive
332 anomaly is seen poleward of 60°S over the western Pacific (near 180 to 90°W); the patterns here
333 and in supplementary Figures S1 and S5 indicate a poleward shift of the subtropical jet, but a
334 complex change in the preferred polar jet locations and frequency that suggests a more persistent
335 polar jet in a narrower region near 65–70°S. The subtropical jet over Australia extends farther
336 west (positive anomaly centered near 90°E and negative anomaly from about 125 to 160°E); along
337 with a corresponding shift in equatorial easterlies in this region, this suggests a westward shift of
338 the Australian monsoon circulation.

339 The westerlies just south of the equator between 100°W and 160°W , downstream of the Aus-
340 tralian monsoon, were much more persistent in the late than in the early period (this is also ap-
341 parent in the cross-section view on the RHS of Figure 1). These westerlies represent a realization
342 of the “Gill solution”, wherein convective heating results in upper-level westerlies downstream of
343 the upper-level easterlies demarking the equatorial side of the monsoon anticyclone (Gill 1980;
344 Sardeshmukh and Hoskins 1988). This pattern is associated with the Walker circulation, which
345 strengthens during La Niña periods (e.g., Julian and Chervin 1978; Bayr et al. 2014). During
346 DJF, the early period considered here was more dominated by El Niño than the late period (mean
347 Multivariate ENSO Index of 0.30 and -0.27, respectively); thus, more persistent westerlies in this
348 region is consistent with differences in ENSO conditions during the two periods. The Australian
349 monsoon easterlies were also more persistent in the late period, consistent with this view.

350 The poleward shift of the NH subtropical jet seen over a broad longitude range is weakly appar-
351 ent in the zonal mean (Figure 1 and supplemental Figure S1, right side). The cross-section shows
352 an upward shift of the NH winter jets at all latitudes, accompanied by less persistent high-latitude
353 jets (north of $\sim 50^{\circ}$). In the SH, a single jet near 50°S appears to dominate the zonal mean pic-
354 ture; however, Figures S1 and S5 show that to be a superposition of narrowly separated polar and
355 subtropical jets, with the polar jet showing increased persistence and the subtropical jet complex
356 changes reflecting the large variations in position of that jet with longitude.

357 In JJA (Figure 2; also supplemental Figures S2 and S6), the NH subtropical jet shows a a pole-
358 ward shift over Asia, but the most striking difference from climatology is the altitude increase of
359 all NH jets poleward of about 40°N . As was the case in DJF, an equatorward shift of the polar
360 jet is indicated, with less frequent or persistent jets north of $\sim 60^{\circ}\text{N}$. The SH wintertime patterns
361 are more difficult to interpret because of the persistence of at least two strong zonal jets, but the
362 patterns in both the maps and cross-sections (as well as in supplemental Figures S2 and S6) are

consistent with a poleward shift of both jets except in the longitude region from about 130°W to 45°W. The SH polar jet is prominent from 0 to 180°E in JJA, and is shifted poleward with respect to the early years. The cross-sections (see also those in Figures S2 and S6) suggest a poleward shift and greater persistence of the subtropical jet, and a downward shift of the polar jet, which has two preferred latitude locations over many longitude regions. The anomalies suggest a larger Asian monsoon circulation in that the easterlies bounding the equatorial edge of that circulation shifted equatorward and the westerlies bounding the mid-latitude edge shifted poleward. Stronger positive than negative anomalies near the western edge suggest a slight westward shift of this monsoon circulation.

The equinox seasons show both similarities to and difference from the solstice seasons:

The SH anomalies in MAM (Figure 3; supplemental Figures S3 and S7) are qualitatively similar to those in DJF. The positive anomalies near 30° and negative ones near 40°S over South America and the Atlantic indicate an equatorward shift of the subtropical jet. In the NH in MAM, the anomalies show quite different patterns than during either solstice season, suggesting an equatorward rather than a poleward shift of the subtropical jet over northern Africa and Asia, though a poleward shift is still seen over the western North America and most of the Atlantic; the subtropical jet over the eastern Pacific (see Figure S3) shifts towards two preferred positions. Greater rather than less (as in DJF) persistence of the high-latitude (poleward of about 60°N) jets is seen in some longitude regions, but Figure S7 still indicates an equatorward shift of the polar jet in most regions.

In SON, the SH anomalies are similar to, but weaker than, those in JJA, except over the eastern Pacific, where changes are more pronounced. The NH anomalies show a high-low-high pattern over Asia that could arise from various changes, including (as supported below) the NH subtropical and polar jets shifting closer together in this longitude region; a significant negative anomaly

387 is seen associated with the strong northeastward tilting jet over the eastern US and Atlantic, in
388 contrast to a strong positive one associated with that jet in DJF and weaker anomalies of both
389 signs in JJA and SON.

390 The maps and cross-sections provide a broad qualitative picture of the long-term evolution of the
391 jet frequency distributions. Because of the large regional and seasonal variability, a more focused
392 set of diagnostics is needed to quantify these long-term changes. In the following sections, we use
393 jet location and strength diagnostics to explore in detail the regional and seasonal variations in the
394 subtropical and polar jets separately in each hemisphere.

395 *a. Subtropical Jet Time Series and Tropical Width*

396 Figures 5 and 6 show time series of the subtropical jet core latitude and altitude, respectively,
397 averaged around the globe and over each solstice season (similar plots for the equinox seasons are
398 shown in supplementary Figures S15 and S16). The latitudes of the subtropical jets vary among the
399 reanalyses by up to over a degree in the NH and nearly three degrees in the SH, with CSFR (ERA-
400 Interim) subtropical jets located most (least) equatorward in both hemispheres. The altitudes vary
401 by up to ~ 0.3 (0.6) km in the NH (SH).

402 Interannual variability is much larger than any apparent trends in all cases. In this zonally
403 averaged view, most apparent trends are either clearly insignificant (that is, don't even exceed the
404 $1-\sigma$ uncertainty) or disagree among the reanalyses. Robust trends are seen in a few cases: NH
405 subtropical jet altitudes increase very consistently for all reanalyses in all seasons except MAM
406 (when there is consistently little or no altitude change), and SH subtropical jets shift poleward
407 in JJA (NH jets also shift poleward in JJA, but the uncertainties are large, so the change is not
408 significant). The largest inconsistencies among the reanalyses are in the SH, where the latitude
409 trends vary widely (often even in sign) except in JJA, and altitude trends vary widely in all seasons.

410 Jet core windspeeds were also examined (not shown), and indicate a robust decrease in the NH in
411 JJA over the 35-year period; in the SH, windspeed changes are inconsistent among the reanalyses.

412 The changes illustrated in these timeseries are summarized in the following figures as a function
413 of month/season and longitude by plotting bars indicating the slope of the fits shown above and the
414 $1-\sigma$ uncertainty in their slopes. Triangles point to the bars for which the change was significant at
415 the 95% confidence level in the permutation test.

416 Figure 4 summarizes the seasonal variations in subtropical jet latitude, altitude, and windspeed
417 tendencies averaged over all longitudes. In general, the zonally averaged latitude changes are ro-
418 bust (in that the slopes exceed the $1-\sigma$ uncertainty and agree among the reanalyses) only in a few
419 months, and less so when averaged over a season or annually. The NH subtropical jet latitude
420 shows a robust poleward shift in February and September, and a consistent (i.e., all reanalyses'
421 slopes have the same sign, but not all exceed the $1-\sigma$ uncertainty) equatorward shift in Novem-
422 ber and December; seasonal and annual shifts are not significant. Only the September shift is
423 significant in the permutation analysis.

424 The SH subtropical jet shows consistent poleward shifts in June through October, and in JJA and
425 SON; the shifts in May are significant at the 95% level. Consistent (robust and significant) equa-
426 torward shifts are seen in April (May). In combination, the width of the tropics, as measured by
427 the NH/SH subtropical jet separation, is positive (widening tropics) in June through October, and
428 in JJA and SON, while it is negative (narrowing tropics) in April, May, November, and December.
429 Only the September increase is significant at the 95% level in all reanalyses, though the decrease
430 in December is significant at the 90% or 95% level in several reanalyses (see Supplementary Fig-
431 ure S9). During months when the reanalyses do not agree, CSFR often shows the opposite sign to
432 the other reanalyses.

433 The jet altitude changes seen in Figure 4 are mostly robust, with consistent increases in NH
 434 subtropical jet altitude in the NH except in March, May, and MAM, when changes are near zero;
 435 largest increases are seen in November, December, and DJF, and these and the annual increase are
 436 significant at the 95% level in the permutation analysis. In the SH, robust (and often significant)
 437 positive changes are seen in April, May, and December; annual mean SH altitudes also increase,
 438 except in CSFR. The patterns of altitude shifts vary strongly by region (see below), and the
 439 appearance of abrupt shifts from positive to negative changes (e.g., SH altitudes in March and
 440 April) reflects month to month changes in the regional patterns and which of them dominate the
 441 zonal mean. Windspeed changes are small ($< \pm 0.05 \text{ ms}^{-1}/\text{year}$) and variable from month to
 442 month. Robust windspeed increases are seen in January, April, and May in the NH, with decreases
 443 in March and June (the last is significant at the 95% level). SH windspeed changes are not robust,
 444 but tend to be positive in most seasons.

445 Figures 8 and 9 show the trends as a function of longitude for DJF and JJA, respectively (the
 446 corresponding equinox season plots are shown in Supplemental Figures S17 and 18). The large
 447 longitudinal variations help explain why the global trends shown above are often small. In DJF
 448 (Figure 8) in the NH, a robust equatorward jet shift is seen over the Pacific, with large changes
 449 (significant at the 95% level) in the eastern Pacific ($\sim 120^\circ\text{W}$ to 160°W); there is a robust and
 450 significant poleward shift from about 40°W to 140°E (from the eastern Atlantic across Eurasia).
 451 In the SH, a poleward shift is seen near the dateline, and distinct equatorward shifts from about
 452 140°W to 40°W , and about 60°E to 100°E , except in CFSR, which shows large poleward shifts in
 453 these regions that are sometimes significant at the 90 or 95% level in the permutation analysis (see
 454 also Supplementary Figure S10). Opposite subtropical jet latitude shifts in the two hemispheres
 455 thus often lead to insignificant changes in tropical width as measured by the distance between
 456 the NH and SH subtropical jets. A significant negative change (narrowing tropics) is seen from

about 160°W to 40°W in most of the reanalyses, and a mostly robust (and significant in some reanalyses) positive shift (widening) from about 20°W to 40°E. Over Asia and South America, the large inconsistency between CFSR and the other reanalyses precludes identification of any robust trends.

Altitude shifts in DJF are consistently positive, except in the SH near the date line, and in both hemispheres near the Greenwich meridian, where the changes are very small; changes in the western Pacific are significant in the permutation analysis. A substantial increase (0.10 to 0.15 m/s/year) in windspeed is seen in the NH from western North America (~120°W) all the way across Asia (to ~140°E), with a similarly strong decrease in windspeed over the central to eastern Pacific. Increases/decreases in windspeed are correlated with increases/decreases in jet latitude, suggesting that angular momentum is largely conserved on the temporal and spatial scales of these changes (see, e.g., Martius 2014). Windspeed changes are smaller in the SH, with robust positive changes over the western Pacific and consistent negative changes over the Indian Ocean.

In JJA (Figure 9) the subtropical jet latitude shifts are also highly variable with longitude, with robust poleward shifts in the NH over Asia (near ~30°E and between ~80 and 120°E); a consistent equatorward shift in the western Pacific (~180-160°W); and very small or inconsistent shifts elsewhere. In the SH, the subtropical jet shifts poleward from about the Greenwich meridian eastward to about 140°W; equatorward in the eastern Pacific; and shows small/inconsistent shifts over the Atlantic. The combined shifts in the NH and SH result in a widening of the tropics across most of the 0 to 120°E region, and over the eastern Pacific; these changes are significant at the 95% level in the 80°E to 120°E longitude bands. Subtropical jet altitude shifts in the NH are consistently positive except from about 80 to 120°E, and are significant at the 90–95% level (see also supplementary Figure S11) from about 120°W to 40°W. SH altitude shifts are generally small and often inconsistent among the reanalyses. Supplementary Figure S17 shows a similar but more robust

481 pattern of SH jet altitude shifts in MAM, and examination of individual months shows that the up-
482 ward shift from about 100W to 80E is the dominant pattern in April and May, while the downward
483 shifts over Australia and the Pacific dominate in March – thus changes in regional patterns result
484 in the transition from downward to upward altitude shift from March to April noted in Figure 4.
485 NH windspeed changes are small, and negative except over the Atlantic. Relatively large (0.10 to
486 0.15 m/s/year) consistent (and often significant at the 95% level) windspeed increases are seen in
487 the SH from about 80°W to 60°E.

488 The above results highlight the strong regional and seasonal variations in the subtropical jets’
489 positions, which argues that there is no single consistent global and/or annually averaged trend.
490 In fact, our results show that averaging over different regional and seasonal regimes obscures
491 substantial regional and seasonal trends. In the following, we examine similar diagnostics for the
492 polar, or eddy-driven, jets.

493 *b. Polar Jet Time Series and Interjet Relationships*

494 Figures 10 and 11 show timeseries of polar jet latitude and altitude, respectively, during the
495 solstice seasons (the equinox seasons are shown in Supplementary Figures S21 and S22). Like
496 the subtropical jet, interannual variations in polar jet positions are much larger than any overall
497 trend. Unlike the subtropical jet, the polar jet latitudes and altitudes show distinct trends that are
498 usually fairly consistent among the reanalyses. A strong equatorward shift is seen in the NH polar
499 jet latitude in DJF, MAM, and JJA. The SH polar jet shows a small poleward shift in DJF and JJA
500 and a small equatorward shift in MAM except in CFSR. Increases in polar jet altitude are seen in
501 the NH in all seasons and in the SH in DJF and MAM; SH altitude trends are inconsistent among
502 the reanalyses in JJA and SON. Windspeed changes (not shown) are small in both hemispheres,
503 showing small but consistent increases (decreases) in the NH in DJF and MAM (JJA). Comparing

504 Figures 10 and 5 indicates that the typical jet separation is about 16–18° in the SH, 25–30° in NH
505 winter, and 20–22° in NH summer; the subtropical and polar jets are thus fairly well-separated in
506 latitude, but changes in jet separation discussed below may be expected to reflect changing roles
507 of eddy and radiative processes in driving the jets (see, e.g., Lee and Kim 2003; Martius 2014).

508 Global monthly, seasonal, and annual changes in the polar jets are summarized in Figure 12.
509 The NH polar jet shows a robust equatorward shift through three seasons, except in SON, and that
510 shift is significant in the permutation analysis in February, DJF, JJA, and the annual mean (see
511 also Supplementary Figure S12). Combined with the subtropical jet changes described above, this
512 results in a decrease in the polar/subtropical jet separation in January through September (with
513 the strongest decrease in February), and a robust increase only in November. The NH polar jet
514 altitude increases in all months and seasons. NH polar jet windspeed changes are small, but are
515 significantly positive (negative) in February and March (June, August, October, and JJA) (see also
516 Supplementary Figure S12).

517 The SH polar jet latitude shifts are small and vary in sign from month to month during much of
518 the year. Consistent poleward shifts are seen only in February, July, August, and JJA, and only the
519 shift in February is significant in the permutation analysis. The SH polar/subtropical jet separation
520 increases in February, April, May, and December, and decreases significantly in September and
521 SON. The SH polar jet altitude generally increases, except in MERRA-2 in May through October.
522 Significant increases in SH polar jet windspeed are seen in January through May, DJF, and MAM.

523 As was the case for the subtropical jet, Figures 13 (for DJF) and 14 (for JJA) indicate strong
524 regional variations in polar jet trends that account for the lack of a clear signal of zonally averaged
525 changes at many times:

526 In DJF (Figure 13), the NH polar jet latitude decreases strongly from just west of the Greenwich
527 meridian across Europe, Asia, and the Pacific to about 140°W (in many regions these changes are

528 significant in the permutation analysis at the 90–95% level, see also Supplementary Figure S13).
529 With the subtropical jet changes, this means that the polar/subtropical jet separation decreases from
530 the eastern Atlantic to the central Pacific, and shows a consistent (but small) increase only between
531 about 40°W and 60°W. The NH polar jet altitude increases at all longitudes, and is particularly
532 significant in the permutation analysis over the eastern Pacific. NH polar jet windspeeds change
533 significantly over most regions, strengthening over the Pacific and weakening over the eastern
534 Atlantic, Europe, and most of Asia. In the SH in DJF, robust poleward shifts of the polar jet are
535 seen from about 100°W to about 120°E. The SH subtropical jet (Figure 8, 9) generally shifts
536 poleward less than the polar jet, leading to a widening of the inter-jet distance from about 140°W
537 to 120°E in DJF.

538 The pattern of polar jet changes is similar during most of the year: Changes in JJA (Figure 14)
539 are similar to, but generally more significant than, those in DJF, with larger magnitude altitude
540 changes. There is a narrower longitude region of poleward jet shifts in the SH, resulting in less
541 extensive widening of SH subtropical/polar jet separation in JJA, extending only from about 80°W
542 to 40°E. NH JJA windspeed changes are typically smaller than those in DJF, and are mostly
543 negative except between 100°E and 180°E; the SH shows more robust windspeed decreases from
544 about 20°E to 100°E. In MAM (supplementary Figure S23), the NH polar jet shifts equatorward
545 from the eastern Pacific across to India. NH jet altitudes robustly increase from the 180°W to 80E,
546 and windspeeds show mostly consistent increases from 140°W to 60°E. In the SH, MAM polar
547 jet latitude trends follow the same pattern as in JJA, with small windspeed increases and mostly
548 robust altitude increases that are often significant at the 95% level for all longitudes. SH jet latitudes
549 in turn only show robust (and significant) negative changes from 160W to 40W. Supplementary
550 Figure S24 indicates that SON changes in the NH (SH) are qualitatively very similar to those in
551 the NH (SH) in DJF (JJA), but generally smaller and less robust for all diagnostics.

552 The polar jets in both hemispheres thus show stronger and more consistent changes than the sub-
553 tropical jets, but the variability still highlights the importance of regional and seasonal differences
554 in the patterns of long-term changes.

555 **4. Discussion and Conclusions**

556 Interannual and long-term variations in upper tropospheric jet locations and strength are eval-
557 uated by characterizing individual jet core locations (Manney et al. 2011), providing a detailed
558 picture of regional and seasonal differences in long-term changes using a 3D daily, rather than a
559 zonal and/or monthly mean, characterization of the jets. We examined changes in the subtropi-
560 cal and polar (aka “eddy-driven”) jets separately, and analyzed five high-resolution reanalyses to
561 assess the robustness of changes.

562 Maps and cross-sections of differences between jet frequency distributions in the first and last
563 ten years of the 35-year study period show a pattern of changes that is generally consistent among
564 the five reanalyses. The subtropical jets in both hemispheres shifted poleward and upward in many
565 regions except during MAM, when equatorward shifts dominated in both hemispheres. In the NH
566 over the eastern Pacific, the subtropical jet shifted equatorward in winter. NH high latitude jet
567 frequency changes are largely consistent with an equatorward shift of the polar jet. Jet altitudes
568 appear to have increased in most regions and seasons. With regard to the tropical circulations,
569 Australian monsoon easterlies and associated Walker circulation westerlies became more persis-
570 tent over the 35-year period, and the Asian summer monsoon increased in size and shifted slightly
571 westward.

572 Examination of differences between the first ten years and the second to last ten years (not
573 shown) suggest that many of the stronger changes are cumulative over the study period. However,
574 modes of natural variability such as ENSO also show differences over the 35-year period. In DJF,

the early period was dominated more by El Niño and the late period more by La Niña. As shown by Manney et al. (2017a, *in preparation*), the changes in the tropical jets are consistent with variations in the Walker circulation, with more persistent equatorial eastern Pacific westerlies downstream of the Australian monsoon in periods with strong La Niñas. The poleward shift of the NH subtropical jet in DJF also appears consistent with the shifts seen in El Niño vs La Niña periods, and with previous results relating ENSO to jet shifts (Langford 1999; Lin et al. 2014; Bai et al. 2016, and references therein). JJA was either dominated by El Niño or near neutral throughout the 35-year period of study, suggesting that the anomalies in JJA are largely the result of long term changes (such as climate change or ozone depletion) that are not closely linked to ENSO. The equinox seasons are more dominated by El Niño in the early period than in the late period; however, the patterns of early/late changes found here here are not obviously consistent with the variations seen in different ENSO phases, again suggesting other controlling mechanisms. Even in DJF when some patterns are consistent with expected ENSO-related changes, this does not preclude those changes being related to climate change impacts that may themselves be correlated with ENSO changes. Several other modes of natural variability such as the North Atlantic Oscillation, Arctic Oscillation, Southern Annular Mode, Quasi-Biennial oscillation, Pacific Decadal Oscillation, and Madden-Julian Oscillation may also be associated with changes in the in the upper tropospheric jets on decadal or longer timescales (Thompson et al. 2000, 2011; Overland and Wang 2005; Woollings et al. 2010, 2014; Lucas and Nguyen 2015, and references therein) and thus may be important to consider in interpreting the physical causes of the observed changes.

Our results highlight strong seasonal, regional, and hemispheric differences in the trends in upper tropospheric jets seen in reanalyses. When zonally averaged, only a few seasons/regions show robust changes in subtropical or polar jet locations and/or windspeeds. The mean values for jet core latitude, altitude, and windspeed for a month or season in a given year fold together

599 very large regional, interannual, and day-to-day variations. In addition, some reanalyses have
600 known discontinuities or shortcomings that affect detection of trends. Thus, assessment of the
601 statistical significance of apparent trends in individual reanalyses on its own does not provide
602 much information on the degree of certainty in atmospheric trends, and consistency between the
603 reanalysis datasets is a critical part of assessing the robustness of the trends. Robust trends are
604 identified where slopes exceed the $1\text{-}\sigma$ range of uncertainty and agree among the reanalyses; a
605 permutation analysis of the trends for individual reanalyses provides a measure of how statistically
606 significant those trends are. Figures 15 and 16 summarize these three measures of robustness and
607 significance by region and season for the subtropical and polar jets, respectively. The most robust
608 subtropical jet changes are:

- 609 • The NH subtropical jet shifts poleward in winter over Asia, and in fall over the western
610 Pacific; a strong equatorward shift is seen in winter over the eastern Pacific.
- 611 • The SH subtropical jet shows a poleward shift in most seasons (except DJF) over the eastern
612 Pacific, and over Africa in JJA and SON. It shows a strong equatorward shift in MAM over
613 South America, the Atlantic, and western Africa.
- 614 • Consistent with the above changes, tropical widening is seen during JJA, SON, and DJF
615 across Africa, and during JJA over Asia and the western Pacific. In contrast, significant
616 narrowing of the tropics is seen in DJF from the central Pacific across North America and the
617 western Atlantic.
- 618 • NH subtropical jet altitudes increased in all seasons except MAM, with most robust changes
619 over the eastern Pacific in DJF, and over the US and western Atlantic in JJA and SON.

- SH jet altitudes tended to increase, but only show robust changes in MAM over the Atlantic and Africa, and in SON over the eastern Pacific, and across North America to the western Atlantic.
- Regions of robust and significant NH windspeed increases are seen over the Atlantic in DJF and MAM, over central Asia in DJF, and over eastern Asia in MAM. A robust windspeed decrease is seen in over most of the Pacific DJF and over the western Pacific in JJA.
- SH windspeeds show robust and significant increases in JJA and SON over Africa and the western Pacific, as well as over South America and the Atlantic in JJA and over eastern Australia in MAM.

The most robust changes in the polar jet are:

- The NH polar jet moved equatorward in all seasons over much of the globe, except over eastern North America and the western Atlantic, where the shift varies with season and is sometimes poleward.
- The SH polar jet shifted poleward during summer and winter (and, less robustly, during fall and spring) across the Atlantic and Indian Ocean, but shifted equatorward over most of the Pacific except during DJF.
- NH polar jet altitudes increased significantly in all seasons around the globe, except over eastern Asia and the western Pacific in MAM.
- SH polar jet altitudes increased over the eastern Pacific in DJF and MAM, but showed inconsistent shifts among the reanalyses in other seasons/regions.

- NH polar jet windspeeds decreased over Europe and central Asia in fall and winter, and over North America and the Atlantic in summer. Windspeeds increased over the Pacific in DJF and over the eastern Pacific and western North America in MAM.
- SH polar jet windspeeds increased from the western Pacific across South America, the Atlantic, and Africa in summer and fall.

In regions and seasons where trends are strong, and in nearly all cases in the NH, the reanalyses usually show consistent results, supporting the robustness of the jet trends in these regions. The signs of the trends are typically in the same direction (although the magnitudes can differ considerably, as do the $1\text{-}\sigma$ ranges of uncertainties and the significance indicated by a permutation analysis). Notable exceptions to this are poleward rather than equatorward SH subtropical jet latitude trends in CSFR during DJF and decreasing rather than increasing altitude trends in CFSR during JJA. MERRA-2 also shows decreasing rather than increasing polar SH jet altitudes in JJA and SON in contrast to the other reanalyses.

While some evidence is seen of the poleward and upward shift of the subtropical jet that is expected based on model simulations (Hartmann et al. 2013, and references therein), the presence and significance of these changes depends on region and season. From these evaluations it follows that tropical widening is clearly not a zonal feature either, perhaps consistent with the lack of consensus in observational studies based on varying datasets and methods largely based on zonal means (e.g., Seidel et al. 2008; Birner et al. 2014; Davis and Birner 2017). In particular, the strong equatorward shift in the eastern Pacific off the west coast of North America has not been widely recognized and is largely responsible for the lack of a robust poleward shift of the subtropical jet (and hence widening of the tropics) in zonal mean evaluations. On the other hand, the robust poleward shift of the NH subtropical jet over Africa in all seasons except NH spring

663 (together with the poleward shift of the SH subtropical jet in JJA and SON) leads to a clear sig-
664 nal of regional expansion, which is expected to be associated with drying of the subtropics and
665 sub-Saharan region.

666 As noted in the introduction, there is considerable disagreement over observed and expected
667 shifts in the NH polar jets; our results of a consistent equatorward shift in most regions are gener-
668 ally consistent with those of Barton and Ellis (2009) and Strong and Davis (2007). Several previous
669 studies suggest a poleward shift of the SH polar jet in DJF and MAM that has been attributed to
670 effects of ozone loss (see, e.g., Grise et al. 2013; Peña-Ortiz et al. 2013; Waugh et al. 2015); our
671 results indeed show a poleward shift in DJF over many regions (as well as a similar shift in JJA
672 that has not been widely reported, and less robust shifts in MAM and SON in the same direction
673 and regions), but the equatorward shift in all seasons over the Pacific highlights the necessity of
674 considering regional and seasonal variations. The strong regional and seasonal variability again
675 argues that there is no single consistent global and/or annually averaged trend. In fact, our results
676 show that averaging over different regional and seasonal regimes, and not clearly distinguishing
677 between the subtropical and polar jets, can obscure significant regional and seasonal trends.

678 The separate analysis of NH subtropical and polar jets supports previous results and theoretical
679 arguments that have suggested that, while the subtropical jet moves poleward, the NH polar jet
680 weakens and moves equatorward in a warming climate. The changes in the polar jet may be
681 a consequence of Arctic amplification, for which several mechanisms have been proposed (see
682 Hoskins and Woollings 2015, and references therein). Distinguishing between the subtropical
683 and polar jets separates changes that may be due to different mechanisms and thus have different
684 regional and seasonal variations.

685 Our results from multiple reanalyses can not only serve as an observationally-based reference
686 for model comparisons over the past ~ 30 years, but also have farther-reaching implications for

the evaluation of jet changes in global climate models (such as those used in CMIP). The spatial and temporal differences in jet behavior, and the mechanisms driving these changes, must be considered. Zonally, annually, or vertically averaged jet distributions span multiple regimes, which can obscure the true changes. Evaluations should hence focus on seasonally, zonally, and vertically resolved behavior. Characterizing jets using monthly mean wind data (such as those available for CMIP results) will thus provide much less complete information than using daily data. The availability of high-quality reanalyses, and ongoing comprehensive evaluation of these reanalyses (e.g., Fujiwara et al. 2017; Long et al. 2017; Manney et al. 2017b, and references therein), allows us to assess the robustness of features that are not directly observable, such as jet shifts, by analyzing the consistency among the reanalyses.

This study thus highlights the need to approach the analysis of trends in jet-related variables, and the mechanisms that drive those changes, in a more process-oriented way and with a focus on regional and seasonal signatures of the climate-induced changes that are most relevant for future climate change adaption and mitigation decisions.

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- MERRA-2: <https://disc.sci.gsfc.nasa.gov/uui/datasets?keywords=%22MERRA-2%22>

- MERRA: <https://disc.sci.gsfc.nasa.gov/uui/datasets?keywords=%22MERRA%22>
- ERA-I: <http://apps.ecmwf.int/datasets/>
- JRA-55: Through NCAR RDA at <http://dx.doi.org/10.5065/D6HH6H41>
- CFSR, model level data: Available upon request from Karen H Rosenlof (karen.h.rosenlof@noaa.gov)
- JETPAC products: Contact Gloria L Manney (manney@nwra.com)

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994	LIST OF FIGURES	
995	Fig. 1.	(Top) climatological jet frequency distributions (expressed as a percentage) as (left) maps
996		and (right) cross-sections, and differences between distributions in the first and last ten years
997		of the record (expressed in percentage points). From the MERRA-2 reanalysis for DJF. The
998		overlaid black contours show climatological frequency contours of 15, 30, and 45% on the
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FIG. 1. (Top) climatological jet frequency distributions (expressed as a percentage) as (left) maps and (right) cross-sections, and differences between distributions in the first and last ten years of the record (expressed in percentage points). From the MERRA-2 reanalysis for DJF. The overlaid black contours show climatological frequency contours of 15, 30, and 45% on the maps, and 2, 3, and 4% on the cross-sections.

FIG. 2. As in Figure 1, but for JJA.

FIG. 3. As in Figure 1, but for MAM.

FIG. 4. As in Figure 1, but for SON.

FIG. 5. Time series of subtropical jet latitudes for five reanalyses, 2 hemispheres, DJF & JJA. The lower panel of each pair shows the fits to slopes and the 1-sigma uncertainty envelope in those fits.

FIG. 6. As in Figure 5, but for subtropical jet altitudes.

FIG. 7. Bar charts of global subtropical jet and NH/SH subtropical jet separation as a function of month, season, and annual, showing five reanalyses. The bars show the slopes of the fits and the error bars (centered about the top of the bars) the 1-sigma uncertainty in that slope. Note that, in this and similar succeeding figures, absolute value of latitude is used, so positive slopes (bars extending upward from the zero line) indicate a poleward shift in both hemispheres. The zero line in each case indicates no trend in the quantity shown. Triangles indicate cases where the permutation analysis (see text) shows the slope to be significant at the 95% confidence level.

FIG. 8. Bar charts of global subtropical jet and NH/SH subtropical jet separation trends as a function of longitude in 20° bins, for DJF showing five reanalyses. Layout is as in Figure 4.

FIG. 9. Bar charts of global subtropical jet and NH/SH subtropical jet separation trends as a function of longitude in 20° bins, for JJA showing five reanalyses. Layout is as in Figure 4.

FIG. 10. As in Figure 5, but for the polar jet.

FIG. 11. As in Figure 6, but for the polar jet. DJF & JJA.

FIG. 12. Bar charts of global polar jet and polar/subtropical jet separation trends as a function of month, season, and annual, showing five reanalyses. Layout is as in Figure 4.

FIG. 13. Bar charts of global polar jet and polar/subtropical jet separation trends as a function of longitude in 20° bins, for DJF showing five reanalyses.

FIG. 14. Bar charts of global polar jet and polar/subtropical jet separation trends as a function of longitude in
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FIG. 15. Matrix plots for the subtropical jet showing colored boxes for MERRA-2 (red, upper left of each season / longitude region square), ERA-I (blue, upper right), JRA-55 (purple, lower left), and CFSR (green, lower right) where the signs of trends agree among all four of those reanalyses, and where the trend for that reanalysis is greater than the 1- σ uncertainty in that slope. Positive (negative) trends are indicated by bold (pale) colors. Plus signs indicate cases where the permutation analysis (see text) shows the slope to be significant at the 95% confidence level. The NH (SH) is shown on the left (right), and the diagnostics are arranged as in Figure 4.

FIG. 16. As in Figure 15, but for the polar jets. The diagnostics are arranged as in Figure 12.