

1                   **Seasonal and Regional Variations of Long-Term Changes in**

2                   **Upper Tropospheric Jets from Reanalyses**

3                   Gloria L Manney\*<sup>†</sup>

4                   *NorthWest Research Associates, Socorro, New Mexico, USA*

5                   Michaela I Hegglin

6                   *University of Reading, Reading, United Kingdom*

7 \**Corresponding author address:* Dept. of Physics, New Mexico Institute of Mining and Technol-  
8 ogy, Socorro, New Mexico, 87801, USA.

9 E-mail: manney@nwra.com

10 <sup>†</sup>Also at New Mexico Institute of Mining and Technology, Socorro, New Mexico, USA.

## 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; Karauskas 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  $\sim 0.8$  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  $0.5^\circ$  latitude  $\times$   $0.667^\circ$  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

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

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

#### 208 *b. Jet and Tropopause Characterization and Analysis*

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

212 An upper tropospheric jet is identified wherever there is a windspeed maximum greater than  
213 40 m/s; the boundaries of the jet region are the points surrounding that (in both horizontal and  
214 vertical directions) where the windspeed drops below 30 m/s. When more than one maximum  
215 above 40 m/s appears within a given 30 m/s contour, they are defined as separate cores if the  
216 latitude distance between them is greater than  $10^\circ$  or the decrease in windspeed between them is  
217 greater than 30 m/s. These parameters were optimized to approximate as closely as possible the  
218 choices that would be made by visual inspection.

219 Manney et al. (2011, 2014) used a simple latitude criterion (appropriate for climatological stud-  
220 ies) to identify subtropical and polar UT jets. A more robust physically-based definition is needed  
221 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

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

286 Manney et al. (2017b) provide a comprehensive comparison of the climatology of upper tro-  
287 pospheric and lower stratospheric jets and multiple tropopauses in the reanalyses used here. In  
288 general, the large-scale patterns seen in jet frequency distributions are similar in all the reanaly-  
289 ses. Notable exceptions include evidence of generally stronger tropical circulations in MERRA  
290 and MERRA-2 than in ERA-Interim and JRA-55 (especially the equatorial easterlies associated  
291 with the Asian Summer Monsoon and the Australian monsoon, and the equatorial westerlies in SH  
292 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  $100^{\circ}\text{W}$  and  $160^{\circ}\text{W}$ , 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  $50^{\circ}\text{S}$  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  $40^{\circ}\text{N}$ . 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

363 consistent with a poleward shift of both jets except in the longitude region from about 130°W to  
364 45°W. The SH polar jet is prominent from 0 to 180°E in JJA, and is shifted poleward with respect  
365 to the early years. The cross-sections (see also those in Figures S2 and S6) suggest a poleward  
366 shift and greater persistence of the subtropical jet, and a downward shift of the polar jet, which has  
367 two preferred latitude locations over many longitude regions. The anomalies suggest a larger Asian  
368 monsoon circulation in that the easterlies bounding the equatorial edge of that circulation shifted  
369 equatorward and the westerlies bounding the mid-latitude edge shifted poleward. Stronger posi-  
370 tive than negative anomalies near the western edge suggest a slight westward shift of this monsoon  
371 circulation.

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

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

383 In SON, the SH anomalies are similar to, but weaker than, those in JJA, except over the eastern  
384 Pacific, where changes are more pronounced. The NH anomalies show a high-low-high pattern  
385 over Asia that could arise from various changes, including (as supported below) the NH subtropical  
386 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  $\sim 0.3$  (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  $160^\circ\text{W}$ ); there is a robust and  
450 significant poleward shift from about  $40^\circ\text{W}$  to  $140^\circ\text{E}$  (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  $140^\circ\text{W}$  to  $40^\circ\text{W}$ , and about  $60^\circ\text{E}$  to  $100^\circ\text{E}$ , 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

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

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

470 In JJA (Figure 9) the subtropical jet latitude shifts are also highly variable with longitude, with  
471 robust poleward shifts in the NH over Asia (near  $\sim 30^\circ\text{E}$  and between  $\sim 80$  and  $120^\circ\text{E}$ ); a consistent  
472 equatorward shift in the western Pacific ( $\sim 180$ - $160^\circ\text{W}$ ); and very small or inconsistent shifts else-  
473 where. In the SH, the subtropical jet shifts poleward from about the Greenwich meridian eastward  
474 to about  $140^\circ\text{W}$ ; equatorward in the eastern Pacific; and shows small/inconsistent shifts over the  
475 Atlantic. The combined shifts in the NH and SH result in a widening of the tropics across most of  
476 the 0 to  $120^\circ\text{E}$  region, and over the eastern Pacific; these changes are significant at the 95% level  
477 in the  $80^\circ\text{E}$  to  $120^\circ\text{E}$  longitude bands. Subtropical jet altitude shifts in the NH are consistently  
478 positive except from about 80 to  $120^\circ\text{E}$ , and are significant at the 90–95% level (see also supple-  
479 mentary Figure S11) from about  $120^\circ\text{W}$  to  $40^\circ\text{W}$ . SH altitude shifts are generally small and often  
480 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,

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

595 Our results highlight strong seasonal, regional, and hemispheric differences in the trends in  
596 upper tropospheric jets seen in reanalyses. When zonally averaged, only a few seasons/regions  
597 show robust changes in subtropical or polar jet locations and/or windspeeds. The mean values  
598 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  $1-\sigma$  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.

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

629 The most robust changes in the polar jet are:

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

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

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

653 While some evidence is seen of the poleward and upward shift of the subtropical jet that is ex-  
654 pected based on model simulations (Hartmann et al. 2013, and references therein), the presence  
655 and significance of these changes depends on region and season. From these evaluations it fol-  
656 lows that tropical widening is clearly not a zonal feature either, perhaps consistent with the lack  
657 of consensus in observational studies based on varying datasets and methods largely based on  
658 zonal means (e.g., Seidel et al. 2008; Birner et al. 2014; Davis and Birner 2017). In particular,  
659 the strong equatorward shift in the eastern Pacific off the west coast of North America has not  
660 been widely recognized and is largely responsible for the lack of a robust poleward shift of the  
661 subtropical jet (and hence widening of the tropics) in zonal mean evaluations. On the other hand,  
662 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  $\sim 30$  years, but also have farther-reaching implications for

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

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

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



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

## 716 **References**

- 717 Arblaster, J., G. Meehl, and D. Karoly, 2011: Future climate change in the Southern Hemisphere:  
718 Competing effects of ozone and greenhouse gases. *Geophys. Res. Lett.*, **38** (2).
- 719 Archer, C. L. and K. Caldeira, 2008: Historical trends in the jet streams. *Geophys. Res. Lett.*, **35**,  
720 L08803, doi:10.1029/2008GL033614.
- 721 Bai, K., N.-B. Chang, and W. Gao, 2016: Quantification of relative contribution of Antarctic  
722 ozone depletion to increased austral extratropical precipitation during 1979-2013. *J. Geophys.*  
723 *Res.*, **121**, 1459–1474, doi:10.1002/2015JD024247, URL [http://dx.doi.org/10.1002/](http://dx.doi.org/10.1002/2015JD024247)  
724 [2015JD024247](http://dx.doi.org/10.1002/2015JD024247).
- 725 Baldwin, M. P., M. Dameris, and T. G. Shepherd, 2007: How will the stratosphere affect climate  
726 change, *Science*, in press, 2007.
- 727 Barnes, E. A. and L. Polvani, 2013: Response of the midlatitude jets, and of their variability, to  
728 increased greenhouse gases in the CMIP5 models. *J. Clim.*, **26** (18), 7117–7135.
- 729 Barnes, E. A. and L. M. Polvani, 2015: CMIP5 projections of Arctic amplification, of the North  
730 American/North Atlantic circulation, and of their relationship. *J. Clim.*, **28** (13), 5254–5271.

- 731 Barnes, E. A. and J. A. Screen, 2015: The impact of Arctic warming on the midlatitude jet-stream:  
732 Can it? has it? will it? *Wiley Interdisciplinary Reviews: Climate Change*, **6 (3)**, 277–286.
- 733 Barton, N. P. and A. W. Ellis, 2009: Variability in wintertime position and strength of the North  
734 Pacific jet stream as represented by re-analysis data. *Int. J. Climatol.*, **29**, 851–862.
- 735 Bayr, T., D. Dommenges, T. Martin, and S. B. Power, 2014: The eastward shift of the Walker  
736 Circulation in response to global warming and its relationship to ENSO variability. *Clim. Dyn.*,  
737 **43 (9-10)**, 2747–2763.
- 738 Birner, T., S. M. Davis, and D. J. Seidel, 2014: Earth's tropical belt. *Phys. Today*, **67 (12)**, 38.
- 739 Bosilovich, M., et al., 2015: MERRA-2: Initial evaluation of the climate. Series on Global Mod-  
740 eling and Data Assimilation, NASA/TM2015-104606, Vol. 43, NASA.
- 741 Butler, A. H., D. W. Thompson, and R. Heikes, 2010: The steady-state atmospheric circulation  
742 response to climate change-like thermal forcings in a simple general circulation model. *J. Clim.*,  
743 **23 (13)**, 3474–3496.
- 744 Cohen, J., et al., 2014: Recent Arctic amplification and extreme mid-latitude weather. *Nature*  
745 *Geosci.*, **7 (9)**, 627–637.
- 746 Compo, G. P., et al., 2011: The twentieth century reanalysis project. *Q. J. Roy. Meteorol. Soc.*,  
747 **137 (654)**, 1–28.
- 748 Davis, N. and T. Birner, 2017: On the discrepancies in tropical belt expansion between reanalyses  
749 and climate models and among tropical belt width metrics. *J. Clim.*, **30**, 1211–1231.
- 750 Davis, S. M. and K. H. Rosenlof, 2012: A multidiagnostic intercomparison of tropical-width time  
751 series using reanalysis and satellite observations. *J. Clim.*, **25**, 1061–1078.

752 Davis, S. M., et al., 2017: Assessment of upper tropospheric and stratospheric water vapour and  
753 ozone in reanalyses. *Atmos. Chem. Phys. Disc.*, submitted.

754 Dee, D. P., et al., 2011: The ERA-Interim reanalysis: configuration and performance of the data  
755 assimilation system. *Q. J. R. Meteorol. Soc.*, **137**, 553–597.

756 Delworth, T. L. and F. Zeng, 2014: Regional rainfall decline in Australia attributed to anthro-  
757 pogenic greenhouse gases and ozone levels. *Nature Geosci.*, **7**, 583–587.

758 Dragani, R., 2011: On the quality of the ERA-Interim ozone reanalyses: comparisons with satellite  
759 data. *Q. J. R. Meteorol. Soc.*, **137**, 1312–1326.

760 Ebita, A. et al., 2011: The Japanese 55-year Reanalysis “JRA-55”: An interim report. *SOLA*, **7**,  
761 149–152.

762 Fujiwara, M., et al., 2017: Introduction to the SPARC Reanalysis Intercomparison Project (S-  
763 RIP) and overview of the reanalysis systems. *Atmos. Chem. Phys.*, **17**, 1417–1452, doi:10.5194/  
764 acp-17-1417-2017, URL [www.atmos-chem-phys.net/17/1417/2017/](http://www.atmos-chem-phys.net/17/1417/2017/).

765 Garfinkel, C. I., D. W. Waugh, and E. P. Gerber, 2013: The effect of tropospheric jet latitude on  
766 coupling between the stratospheric polar vortex and the troposphere. *J. Clim.*, **26**, 2077–2095.

767 Garfinkel, C. I., D. W. Waugh, and L. M. Polvani, 2015: Recent Hadley cell expansion: The role  
768 of internal atmospheric variability in reconciling modeled and observed trends. *Geophys. Res.*  
769 *Lett.*, **42 (24)**.

770 Gelaro, R. et al., 2017: The Modern-Era Retrospective Analysis for Research and Applications,  
771 Version-2 (MERRA-2). *J. Clim.*, doi:doi:10.1175/JCLI-D-16-0758.1, in press.

772 Gill, A. E., 1980: Some simple solutions for heat-induced tropical circulation. *Q. J. R. Meteorol.*  
773 *Soc.*, **106**, 447–462.

774 Global Modeling and Assimilation Office (GMAO), 2015: Merra-2 inst3\_3d\_asm\_nv: 3d, 3-  
775 hourly, instantaneous, model-level, assimilation, assimilated meteorological fields v5.12.4,  
776 greenbelt, md, usa, goddard earth sciences data and information services center (ges disc), ac-  
777 cessed 1 november 2015. doi:10.5067/WWQSQ8IVFW8.

778 Gómara, I., J. G. Pinto, T. Woollings, G. Masato, P. Zurita-Gotor, and B. Rodríguez-Fonseca,  
779 2014: Rossby wave-breaking analysis of explosive cyclones in the Euro-Atlantic sector. *Q. J. R.*  
780 *Meteorol. Soc.*, **140**, 738–753, doi:10.1002/qj.2190, URL [http://dx.doi.org/10.1002/qj.](http://dx.doi.org/10.1002/qj.2190)  
781 2190.

782 Grise, K. M., L. M. Polvani, G. Tselioudis, Y. Wu, and M. D. Zelinka, 2013: The ozone hole  
783 indirect effect: Cloud-radiative anomalies accompanying the poleward shift of the eddy-driven  
784 jet in the Southern Hemisphere. *Geophys. Res. Lett.*, **40**, 1–5, doi:10.1002/grl.50675.

785 Harnik, N., C. I. Garfinkel, and O. Lachmy, 2016: The influence of jet stream regime on extreme  
786 weather events. in “*Dynamics and Predictability of Large-Scale, High-Impact Weather and*  
787 *Climate Events*”, **2**, 79–94.

788 Hartmann, et al., 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Work-*  
789 *ing Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*,  
790 chap. Observations: Atmosphere and Surface. Cambridge University Press, Cambridge, United  
791 Kingdom and New York, NY, USA.

792 Held, I. M., 1993: Large-scale dynamics and global warming. *Bull. Am. Meteor. Soc.*, **74**, 228–241.

793 Held, I. M. and B. J. Hoskins, 1985: Large-scale eddies and the general circulation of the tropo-  
794 sphere. *Adv. Geophys.*, **28**, 3–31.

- 795 Held, I. M. and A. Y. Hou, 1980: Nonlinear axially symmetric circulations in a nearly inviscid  
796 atmosphere. *J. Atmos. Sci.*, **37**, 515–533.
- 797 Held, I. M., M. Ting, and H. Wang, 2002: Northern winter stationary waves: Theory and modeling.  
798 *J. Clim.*, **15**, 2125–2144.
- 799 Homeyer, C., K. P. Bowman, and L. L. Pan, 2010: Extratropical tropopause transition layer  
800 characteristics from high-resolution sounding data. *J. Geophys. Res.*, **115**, D13108, doi:  
801 10.1029/2009JD013664.
- 802 Hoskins, B. and T. Woollings, 2015: Persistent extratropical regimes and climate extremes. *Cur-*  
803 *rent Climate Change Reports*, **1** (3), 115–124, doi:10.1007/s40641-015-0020-8, URL [http:](http://dx.doi.org/10.1007/s40641-015-0020-8)  
804 [//dx.doi.org/10.1007/s40641-015-0020-8](http://dx.doi.org/10.1007/s40641-015-0020-8).
- 805 Hoskins, B. J. and P. J. Valdes, 1990: On the existence of storm tracks. *J. Atmos. Sci.*, **47**, 1854–  
806 1864.
- 807 Huang, D.-Q., J. Zhu, Y.-C. Zhang, J. Wang, and X.-Y. Kuang, 2015: The impact of the East Asian  
808 subtropical jet and polar front jet on the frequency of spring persistent rainfall over Southern  
809 China in 1997–2011. *J. Clim.*, **28**, 6054–6066, doi:10.1175/JCLI-D-14-00641.1.
- 810 Hudson, R. D., 2012: Measurements of the movement of the jet streams at mid-latitudes, in the  
811 Northern and Southern Hemispheres, 1979 to 2010. *Atmos. Chem. Phys.*, **12**, 7797–7808.
- 812 Julian, P. and R. Chervin, 1978: A study of the Southern Oscillation and Walker circulation phe-  
813 nomenon. *Mon. Weather Rev.*, **106**, 1433–1451.
- 814 Kang, S. M., L. M. Polvani, J. C. Fyfe, and M. Sigmond, 2011: Impact of po-  
815 lar ozone depletion on subtropical precipitation. *Science*, **332** (6032), 951–954, doi:10.

816 1126/science.1202131, URL <http://science.sciencemag.org/content/332/6032/951>,  
817 <http://science.sciencemag.org/content/332/6032/951.full.pdf>.

818 Karnauskas, K. B. and C. C. Ummenhofer, 2014: On the dynamics of the Hadley circulation and  
819 subtropical drying. *Clim. Dyn.*, **42**, 2259–2269, doi:10.1007/s00382-014-2129-1, URL <http://dx.doi.org/10.1007/s00382-014-2129-1>.  
820

821 Kidston, J. and E. P. Gerber, 2010: Intermodel variability of the poleward shift of the austral jet  
822 stream in the CMIP3 integrations linked to biases in 20th century climatology. *Geophys. Res. Lett.*, **37**, 09708, doi:10.1029/2010GL042873.  
823

824 Koch, P., H. Wernli, and H. C. Davies, 2006: An event-based jet-stream climatology and typology.  
825 *Int. J. Climatol.*, **26**, 283–301.

826 Langford, A., 1999: Stratosphere-troposphere exchange at the subtropical jet: Contribution to the  
827 tropospheric ozone budget at midlatitudes. *Geophys. Res. Lett.*, **26**, 2449–2452.

828 Lee, S. and H.-K. Kim, 2003: The dynamical relationship between subtropical and eddy-driven  
829 jets. *J. Atmos. Sci.*, **60**, 1490–1503.

830 Lin, M., A. M. Fiore, L. W. Horowitz, A. O. Langford, S. J. Oltmans, D. Tarasick, and H. E.  
831 Rieder, 2015: Climate variability modulates western US ozone air quality in spring via deep  
832 stratospheric intrusions. *Nature Commun.*, **6**.

833 Lin, M., L. W. Horowitz, S. J. Oltmans, A. M. Fiore, and S. Fan, 2014: Tropospheric ozone trends  
834 at Mauna Loa Observatory tied to decadal climate variability. *Nature Geosci.*, **7**, 136–143.

835 Long, C. S., M. Fujiwara, S. Davis, D. M. Mitchell, and C. J. Wright, 2017: Climatology and  
836 interannual variability of dynamic variables in multiple reanalyses evaluated by the SPARC

837 Reanalysis Intercomparison Project (S-RIP). *Atmos. Chem. Phys. Disc.*, **2017**, doi:10.5194/  
838 acp-2017-289, URL <http://www.atmos-chem-phys-discuss.net/acp-2017-289/>.

839 Lorenz, D. J. and E. T. DeWeaver, 2007: Tropopause height and zonal wind response to  
840 global warming in the IPCC scenario integrations. *J. Geophys. Res.*, **112**, D10119, doi:  
841 10.1029/2006JD008087.

842 Lorenz, D. J. and D. L. Hartmann, 2003: Eddy-zonal flow feedback in the northern hemisphere  
843 winter. *J. Clim.*, **16**, 1212–1227.

844 Lucas, C. and H. Nguyen, 2015: Regional characteristics of tropical expansion and the role of cli-  
845 mate variability. *Journal of Geophysical Research: Atmospheres*, **120 (14)**, 6809–6824, doi:10.  
846 1002/2015JD023130, URL <http://dx.doi.org/10.1002/2015JD023130>, 2015JD023130.

847 Lucas, C., H. Nguyen, and B. Timbal, 2012: An observational analysis of southern hemisphere  
848 tropical expansion. *Journal of Geophysical Research: Atmospheres*, **117 (D17)**, n/a–n/a, doi:  
849 10.1029/2011JD017033, URL <http://dx.doi.org/10.1029/2011JD017033>, d17112.

850 Lucas, C., B. Timbal, and H. Nguyen, 2014: The expanding tropics: A critical assessment of the  
851 observational and modeling studies. *WIREs: Climate Change*, **5**, 89–112, doi:10.1002/wcc.251,  
852 URL <http://dx.doi.org/10.1002/wcc.251>.

853 Mann, M. E., S. Rahmstorf, K. Kornhuber, B. A. Steinman, S. K. Miller, and D. Coumou, 2017:  
854 Influence of anthropogenic climate change on planetary wave resonance and extreme weather  
855 events. *Nature Scientific Reports*, **7**, doi:10.1038/srep45242.

856 Manney, G. L., M. I. Hegglin, W. H. Daffer, M. J. Schwartz, M. L. Santee, and S. Pawson, 2014:  
857 Climatology of upper tropospheric/lower stratospheric (UTLS) jets and tropopauses in MERRA.  
858 *J. Clim.*, **27**, 3248–3271.

- 859 Manney, G. L., Z. D. Lawrence, and M. I. Hegglin, 2017a: Interannual variability in upper tropo-  
860 spheric jets in reanalyses: Relationships to ENSO and QBO, *to be submitted to J. Clim.*
- 861 Manney, G. L., et al., 2011: Jet characterization in the upper troposphere/lower stratosphere  
862 (UTLS): Applications to climatology and transport studies. *Atmos. Chem. Phys.*, **11**, 6115–  
863 6137.
- 864 Manney, G. L., et al., 2017b: Reanalysis comparisons of upper tropospheric/lower stratospheric  
865 jets and multiple tropopauses. *Atmos. Chem. Phys.*, *in press*, doi:10.5194/acp-2017-400.
- 866 Manzini, E., et al., 2014: Northern winter climate change: Assessment of uncertainty  
867 in CMIP5 projections related to stratosphere-troposphere coupling. *J. Geophys. Res.*,  
868 **119** (13), 7979–7998, doi:10.1002/2013JD021403, URL [http://dx.doi.org/10.1002/](http://dx.doi.org/10.1002/2013JD021403)  
869 [2013JD021403](http://dx.doi.org/10.1002/2013JD021403), 2013JD021403.
- 870 Martius, O., 2014: A lagrangian analysis of the northern hemisphere subtropical jet. *J. Atmos. Sci.*,  
871 **71**, 2354–2369.
- 872 McLandress, C., T. G. Shepherd, J. F. Scinocca, D. A. Plummer, M. Sigmond, A. I. Jonsson, and  
873 M. C. Reader, 2011: Separating the dynamical effects of climate change and ozone depletion.  
874 Part II: Southern Hemisphere troposphere. *J. Clim.*, **24**, 1850–1868.
- 875 Messori, G. and R. Caballero, 2015: On double Rossby wave breaking in the North Atlantic. *J.*  
876 *Geophys. Res.*, **120**, 11,129–11,150, doi:10.1002/2015JD023854, URL [http://dx.doi.org/](http://dx.doi.org/10.1002/2015JD023854)  
877 [10.1002/2015JD023854](http://dx.doi.org/10.1002/2015JD023854).
- 878 Messori, G., R. Caballero, and M. Gaetani, 2016: On cold spells in North America and storminess  
879 in Western Europe. *Geophys. Res. Lett.*, 6620–6628.



- 880 Molod, A., L. Takacs, M. Suarez, and J. Bacmeister, 2015: Development of the GEOS-5 atmo-  
881 spheric general circulation model: Evolution from MERRA to MERRA-2. *Geosci. Model Dev.*,  
882 **8**, 1339–1356.
- 883 Nicholls, N., 2000: The insignificance of significance testing. *Bull. Am. Meteor. Soc.*, **81**, 981–986.
- 884 Nuzzo, R., 2014: Statistical errors. *Nature*, **506**, 150–152.
- 885 Olsen, M. A., K. Wargan, and S. Pawson, 2016: Tropospheric column ozone response to ENSO in  
886 GEOS-5 assimilation of OMI and MLS ozone data. *Atmos. Chem. Phys.*, **16**, 7091–7103, doi:  
887 10.5194/acp-16-7091-2016, URL <http://www.atmos-chem-phys.net/16/7091/2016/>.
- 888 Overland, J. E. and M. Wang, 2005: The Arctic climate paradox: The recent decrease of the Arctic  
889 Oscillation. *Geophys. Res. Lett.*, **32**, L06701, doi:10.1029/2004GL021752.
- 890 Overland, J. E., et al., 2016: Nonlinear response of mid-latitude weather to the changing Arctic.  
891 *Nature Climate Change*, **6 (11)**, 992–999.
- 892 Peña-Ortiz, C., D. Gallego, P. Ribera, P. Ordóñez, and M. D. C. Álvarez-Castro, 2013: Observed  
893 trends in the global jet stream characteristics during the second half of the 20th century. *J.*  
894 *Geophys. Res.*, **118 (7)**, 2702–2713, doi:10.1002/jgrd.50305, URL [http://dx.doi.org/10.](http://dx.doi.org/10.1002/jgrd.50305)  
895 [10.1002/jgrd.50305](http://dx.doi.org/10.1002/jgrd.50305).
- 896 Pinto, J. G., I. Gmara, G. Masato, H. F. Dacre, T. Woollings, and R. Caballero, 2014: Large-  
897 scale dynamics associated with clustering of extratropical cyclones affecting Western Europe. *J.*  
898 *Geophys. Res.*, **119**, 13,704–13,719, doi:10.1002/2014JD022305, URL [http://dx.doi.org/](http://dx.doi.org/10.1002/2014JD022305)  
899 [10.1002/2014JD022305](http://dx.doi.org/10.1002/2014JD022305).
- 900 Pinto, S., Joaquim G. and Zacharias, A. H. Fink, and U. Leckebusch, Gregor C. and Ulbrich,  
901 2009: Factors contributing to the development of extreme North Atlantic cyclones and their

902 relationship with the NAO. *Clim. Dyn.*, **32**, 711–737, doi:10.1007/s00382-008-0396-4, URL  
903 <http://dx.doi.org/10.1007/s00382-008-0396-4>.

904 Price, C., L. Stone, A. Huppert, B. Rajagopalan, and P. Alpert, 1998: A possible link be-  
905 tween El Niño and precipitation in Israel. *Geophys. Res. Lett.*, **25**, 3963–3966, doi:10.1029/  
906 1998GL900098, URL <http://dx.doi.org/10.1029/1998GL900098>.

907 Raible, C. C., U. Luksch, and K. Fraedrich, 2004: Precipitation and Northern Hemisphere regimes.  
908 *Atmos. Sci. Lett.*, **5**, 43–55, doi:10.1016/j.atmoscilet.2003.12.001, URL [http://dx.doi.org/](http://dx.doi.org/10.1016/j.atmoscilet.2003.12.001)  
909 [10.1016/j.atmoscilet.2003.12.001](http://dx.doi.org/10.1016/j.atmoscilet.2003.12.001).

910 Rienecker, M. M. et al., 2011: MERRA: NASA’s Modern-Era Retrospective Analysis for Research  
911 and Applications. *J. Clim.*, **24**, 3624–3648.

912 Robinson, W. A., 2006: On the self-maintenance of midlatitude jets. *J. Atmos. Sci.*, **63**, 2109–2122.

913 Röthlisberger, M., S. Pfahl, and O. Martius, 2016: Regional-scale jet waviness modulates the  
914 occurrence of midlatitude weather extremes. *Geophysical Research Letters*, **43** (20).

915 Saha, S. et al., 2010: The NCEP Climate Forecast System Reanalysis. *Bull. Am. Meteor. Soc.*, **91**,  
916 1015–1057.

917 Santer, B. D. et al., 2003: Behavior of tropopause height and atmospheric temperature in models,  
918 reanalyses, and observations: Decadal changes. *J. Geophys. Res.*, **108**, 4002, doi:10.1029/  
919 2002JD002258.

920 Sardeshmukh, P. D. and B. J. Hoskins, 1988: The generation of global rotational flow by steady  
921 idealized tropical divergence. *J. Atmos. Sci.*, **45**, 1228–1251.

922 Scaife, A. A., et al., 2012: Climate change projections and stratosphere–troposphere interaction.  
923 *Clim. Dyn.*, **38** (9-10), 2089–2097.

924 Screen, J. A. and I. Simmonds, 2014: Amplified mid-latitude planetary waves favour particular  
925 regional weather extremes. *Nature Climate Change*, **4** (8), 704–709.

926 Screen, J. A., I. Simmonds, C. Deser, and R. Tomas, 2013: The atmospheric response to three  
927 decades of observed Arctic sea ice loss. *J. Clim.*, **26** (4), 1230–1248.

928 Seidel, D. J., Q. Fu, W. J. Randel, and T. J. Reichler, 2008: Widening of the tropical belt in a  
929 changing climate. *Nature Geoscience*, **1**, 21–24.

930 Seidel, D. J. and W. J. Randel, 2006: Variability and trends in the global tropopause estimated  
931 from radiosonde data. *J. Geophys. Res.*, **111**, D21101, doi:10.1029/2006JD007363.

932 Serreze, M. C. and R. G. Barry, 2011: Processes and impacts of Arctic amplification: A research  
933 synthesis. *Global and Planetary Change*, **77**, 85–96.

934 Shepherd, T. G., 2016: Effects of a warming Arctic. *Science*, **353** (6303), 989–990, doi:10.1126/  
935 science.aag2349, URL <http://science.sciencemag.org/content/353/6303/989>, <http://science.sciencemag.org/content/353/6303/989.full.pdf>.

937 Sigmond, M. and J. F. Scinocca, 2010: The influence of the basic state on the Northern Hemisphere  
938 circulation response to climate change. *J. Clim.*, **23**, 1434–1446.

939 Simpson, I. R., M. Blackburn, and J. D. Haigh, 2009: The role of eddies in driving the tropospheric  
940 response to stratospheric heating perturbations. *J. Atmos. Sci.*, **66** (5), 1347–1365, doi:10.1175/  
941 2008JAS2758.1.

942 Simpson, I. R. and L. M. Polvani, 2016: Revisiting the relationship between jet position,  
943 forced response, and annular mode variability in the southern midlatitudes. *Geophys. Res.  
944 Lett.*, **43** (6), 2896–2903, doi:10.1002/2016GL067989, URL [http://dx.doi.org/10.1002/  
945 2016GL067989](http://dx.doi.org/10.1002/2016GL067989), 2016GL067989.

- 946 Simpson, I. R., T. A. Shaw, and R. Seager, 2014: A diagnosis of the seasonally and longitudinally  
947 varying midlatitude circulation response to global warming. *J. Atmos. Sci.*, **71** (7), 2489–2515,  
948 doi:10.1175/JAS-D-13-0325.1.
- 949 Son, S.-W. et al., 2010: Impact of stratospheric ozone on Southern Hemisphere circulation change:  
950 A multimodel assessment. *J. Geophys. Res.*, **115**, D00M07, doi:10.1029/2010GL014271.
- 951 Staten, P. W., K. M. Grise, and S. M. Davis, 2016: The width of the tropics: Climate variations  
952 and their impacts. *SPARC Newsletter*, **46**, 26–31.
- 953 Strong, C. and R. E. Davis, 2007: Winter jet stream trends over the Northern Hemisphere. *Q. J. R.*  
954 *Meteorol. Soc.*, **133**, 2109–2115.
- 955 Strong, C. and R. E. Davis, 2008: Variability in the position and strength of winter jet stream cores  
956 related to Northern Hemisphere teleconnections. *J. Clim.*, **21**, 584–592.
- 957 Takacs, L. L., M. J. Suárez, and R. Todling, 2016: Maintaining atmospheric mass and water  
958 balance in reanalyses. *Q. J. R. Meteorol. Soc.*, **142**, 1565–1573.
- 959 Thompson, D. W., S. Solomon, P. J. Kushner, M. H. Grise, and D. J. Karoly, 2011: Signatures of  
960 the antarctic ozone hole in Southern Hemisphere surface climate change. *Nature Geoscience*, **4**,  
961 741–749.
- 962 Thompson, D. W. J., J. M. Wallace, and G. C. Hegerl, 2000: Annular modes in the extratropical cir-  
963 culation. Part II: Trends. *J. Clim.*, **13** (5), 1018–1036, doi:10.1175/1520-0442(2000)013<1018:  
964 AMITEC>2.0.CO;2, URL [https://doi.org/10.1175/1520-0442\(2000\)013<1018:](https://doi.org/10.1175/1520-0442(2000)013<1018:AMITEC>2.0.CO;2)  
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966 [AMITEC>2.0.CO;2.](https://doi.org/10.1175/1520-0442(2000)013<1018:AMITEC>2.0.CO;2)

- 967 Wang, L. and S. Lee, 2016: The role of eddy diffusivity on a poleward jet shift. *J. Atmos. Sci.*,  
968 **73 (12)**, 4945–4958.
- 969 Wargan, K., G. Labow, S. Frith, S. Pawson, N. Livesey, and G. Partyka, 2017: Evalua-  
970 tion of the ozone fields in NASA’s MERRA-2 reanalysis. *J. Clim.*, **30**, 2961–2988, doi:  
971 10.1175/JCLI-D-16-0699.1.
- 972 Waugh, D. W., C. I. Garfinkel, and L. M. Polvani, 2015: Drivers of the recent tropical expansion  
973 in the Southern Hemisphere: Changing SSTs or ozone depletion? *J. Clim.*, **28**, 6581–6586,  
974 doi:10.1175/JCLI-D-15-0138.1, URL <http://dx.doi.org/10.1175/JCLI-D-15-0138.1>.
- 975 Wilks, D. S., 2011: *Statistical Methods in the Atmospheric Sciences*. 3d ed., Elsevier Academic  
976 Press, volume 100, International Geophysics Series.
- 977 WMO, 2011: *Scientific assessment of ozone depletion: 2010*. Global Ozone Res. and Monit. Proj.  
978 Rep. 52, Geneva, Switzerland.
- 979 Woollings, T., C. Czuchnicki, and C. Franzke, 2014: Twentieth century North Atlantic jet vari-  
980 ability. *Q. J. Roy. Meteorol. Soc.*, **140 (680)**, 783–791.
- 981 Woollings, T., A. Hannachi, and B. Hoskins, 2010: Variability of the North Atlantic eddy-driven  
982 jet stream. *Q. J. R. Meteorol. Soc.*, **136**, 856–868.
- 983 Woollings, T., L. Papritz, C. Mbengue, and T. Spengler, 2016: Diabatic heating and jet stream  
984 shifts: A case study of the 2010 negative North Atlantic Oscillation winter. *Geophys. Res. Lett.*,  
985 **43 (18)**.
- 986 Woollings, T., J. G. Pinto, and J. A. Santos, 2011: Dynamical evolution of North Atlantic ridges  
987 and poleward jet stream displacements. *J. Atmos. Sci.*, **68**, 954–963.

988 Xie, Z., Y. Du, and S. Yang, 2015: Zonal extension and retraction of the subtropical westerly  
989 jet stream and evolution of precipitation over East Asia and the Western Pacific. *J. Clim.*, **28**,  
990 6783–6798, doi:10.1175/JCLI-D-14-00649.1.

991 Zappa, G., B. J. Hoskins, and T. G. Shepherd, 2015: Improving climate change detection through  
992 optimal seasonal averaging: the case of the North Atlantic jet and European precipitation. *J.*  
993 *Clim.*, **28 (16)**, 6381–6397.

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  
 999 maps, and 2, 3, and 4% on the cross-sections. . . . . 48

1000 **Fig. 2.** As in Figure 1, but for JJA. . . . . 49

1001 **Fig. 3.** As in Figure 1, but for MAM. . . . . 50

1002 **Fig. 4.** As in Figure 1, but for SON. . . . . 51

1003 **Fig. 5.** Time series of subtropical jet latitudes for five reanalyses, 2 hemispheres, DJF & JJA. The  
 1004 lower panel of each pair shows the fits to slopes and the 1-sigma uncertainty envelope in  
 1005 those fits. . . . . 52

1006 **Fig. 6.** As in Figure 5, but for subtropical jet altitudes. . . . . 53

1007 **Fig. 8.** Bar charts of global subtropical jet and NH/SH subtropical jet separation trends as a function  
 1008 of longitude in 20° bins, for DJF showing five reanalyses. Layout is as in Figure 4. . . . . 55

1009 **Fig. 9.** Bar charts of global subtropical jet and NH/SH subtropical jet separation trends as a function  
 1010 of longitude in 20° bins, for JJA showing five reanalyses. Layout is as in Figure 4. . . . . 56

1011 **Fig. 10.** As in Figure 5, but for the polar jet. . . . . 57

1012 **Fig. 11.** As in Figure 6, but for the polar jet. DJF & JJA. . . . . 58

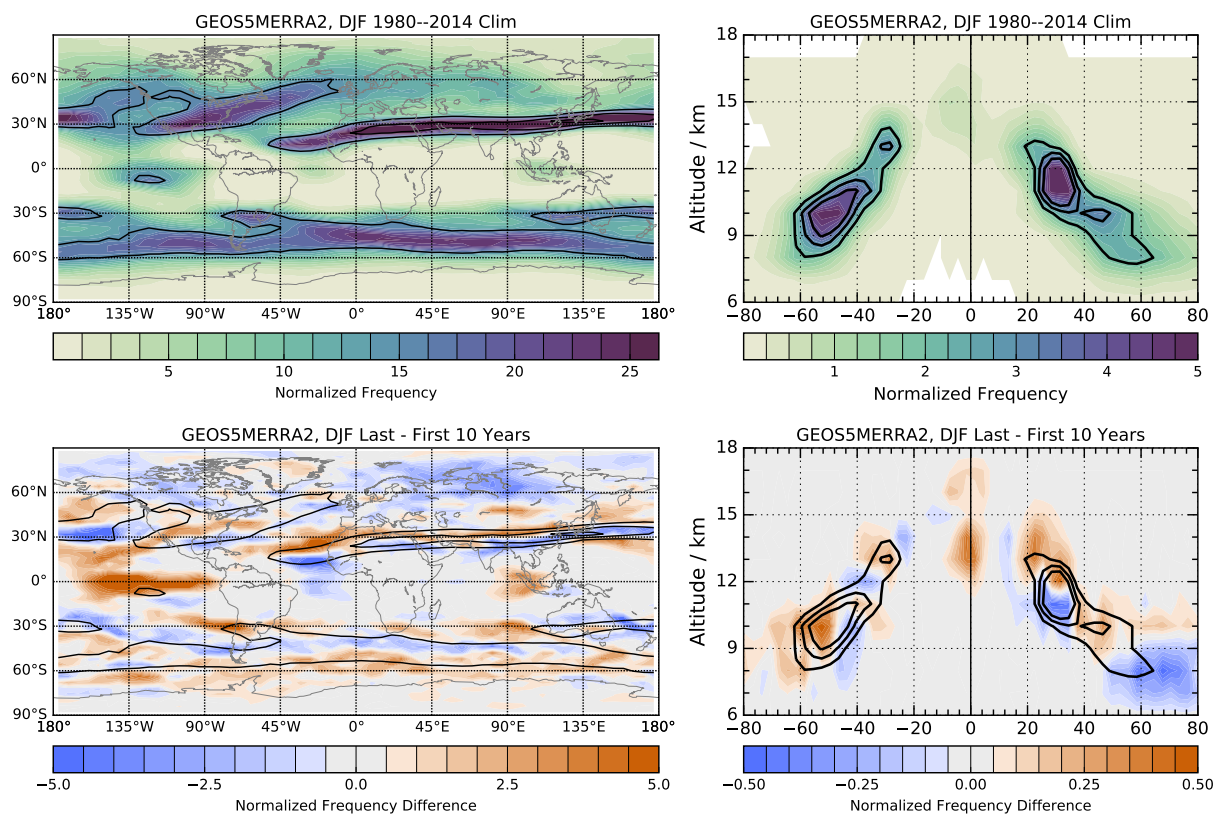
1013 **Fig. 12.** Bar charts of global polar jet and polar/subtropical jet separation trends as a function of  
 1014 month, season, and annual, showing five reanalyses. Layout is as in Figure 4. . . . . 59

1015 **Fig. 13.** Bar charts of global polar jet and polar/subtropical jet separation trends as a function of  
 1016 longitude in 20° bins, for DJF showing five reanalyses. . . . . 60

1017 **Fig. 14.** Bar charts of global polar jet and polar/subtropical jet separation trends as a function of  
 1018 longitude in 20° bins, for JJA showing five reanalyses. . . . . 61

1019 **Fig. 15.** Matrix plots for the subtropical jet showing colored boxes for MERRA-2 (red, upper left of  
 1020 each season / longitude region square), ERA-I (blue, upper right), JRA-55 (purple, lower  
 1021 left), and CFSR (green, lower right) where the signs of trends agree among all four of those  
 1022 reanalyses, and where the trend for that reanalysis is greater than the 1-σ uncertainty in  
 1023 that slope. Positive (negative) trends are indicated by bold (pale) colors. Plus signs indicate  
 1024 cases where the permutation analysis (see text) shows the slope to be significant at the 95%  
 1025 confidence level. The NH (SH) is shown on the left (right), and the diagnostics are arranged  
 1026 as in Figure 4. . . . . 62

1027 **Fig. 16.** As in Figure 15, but for the polar jets. The diagnostics are arranged as in Figure 12. . . . . 63



1028 FIG. 1. (Top) climatological jet frequency distributions (expressed as a percentage) as (left) maps and (right)  
 1029 cross-sections, and differences between distributions in the first and last ten years of the record (expressed in  
 1030 percentage points). From the MERRA-2 reanalysis for DJF. The overlaid black contours show climatological  
 1031 frequency contours of 15, 30, and 45% on the maps, and 2, 3, and 4% on the cross-sections.



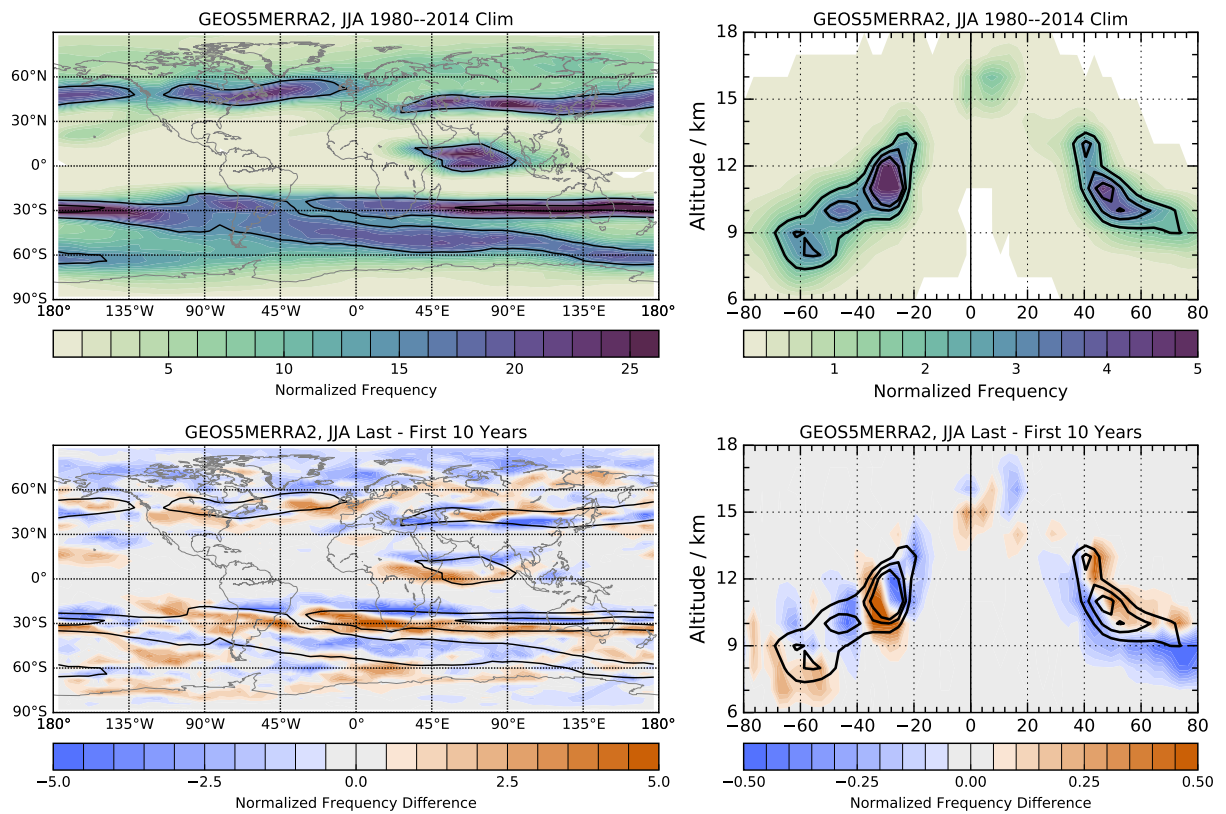


FIG. 2. As in Figure 1, but for JJA.

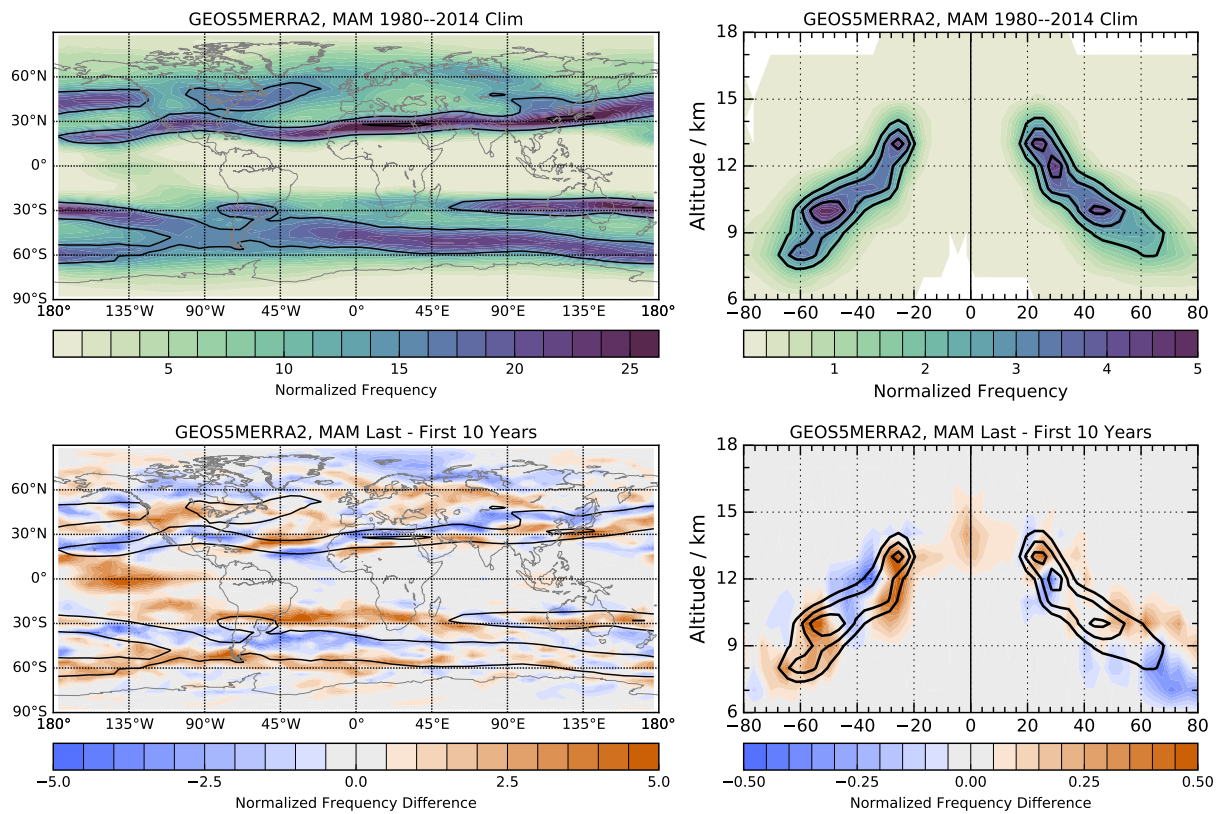


FIG. 3. As in Figure 1, but for MAM.

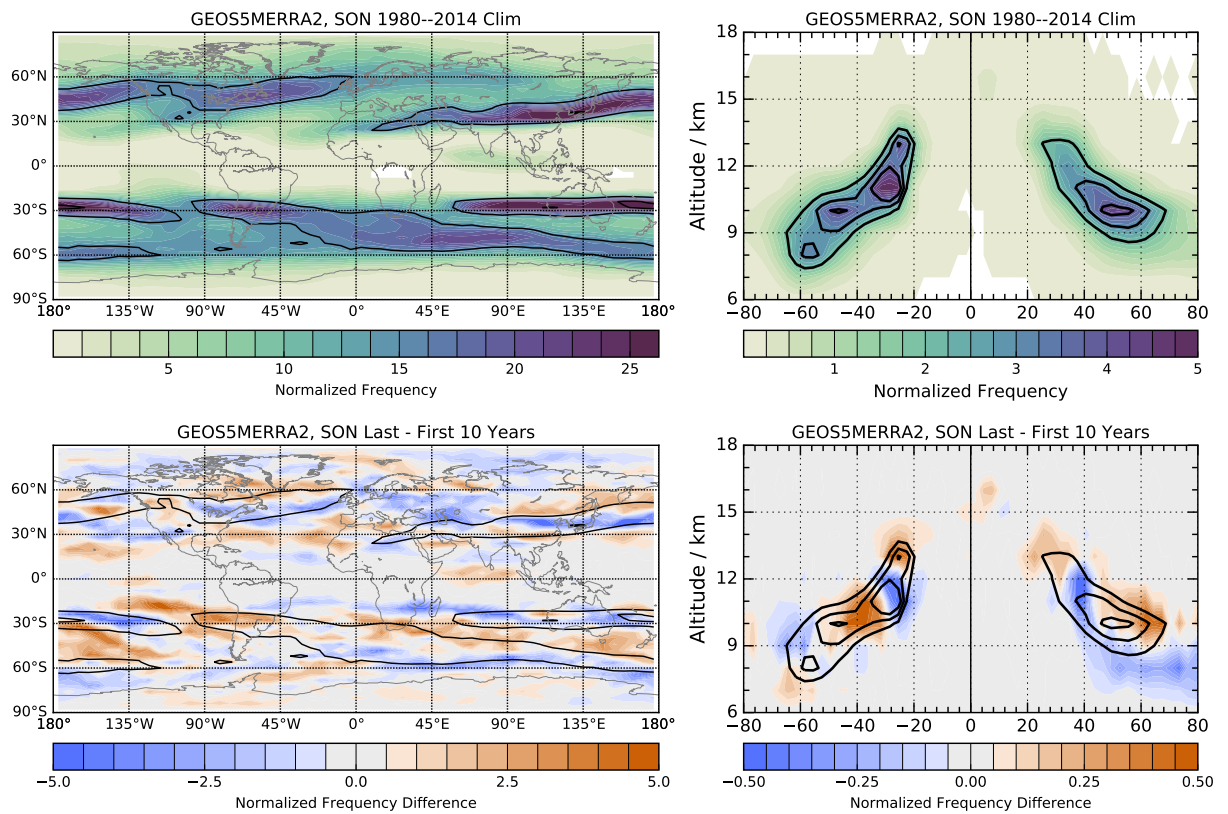
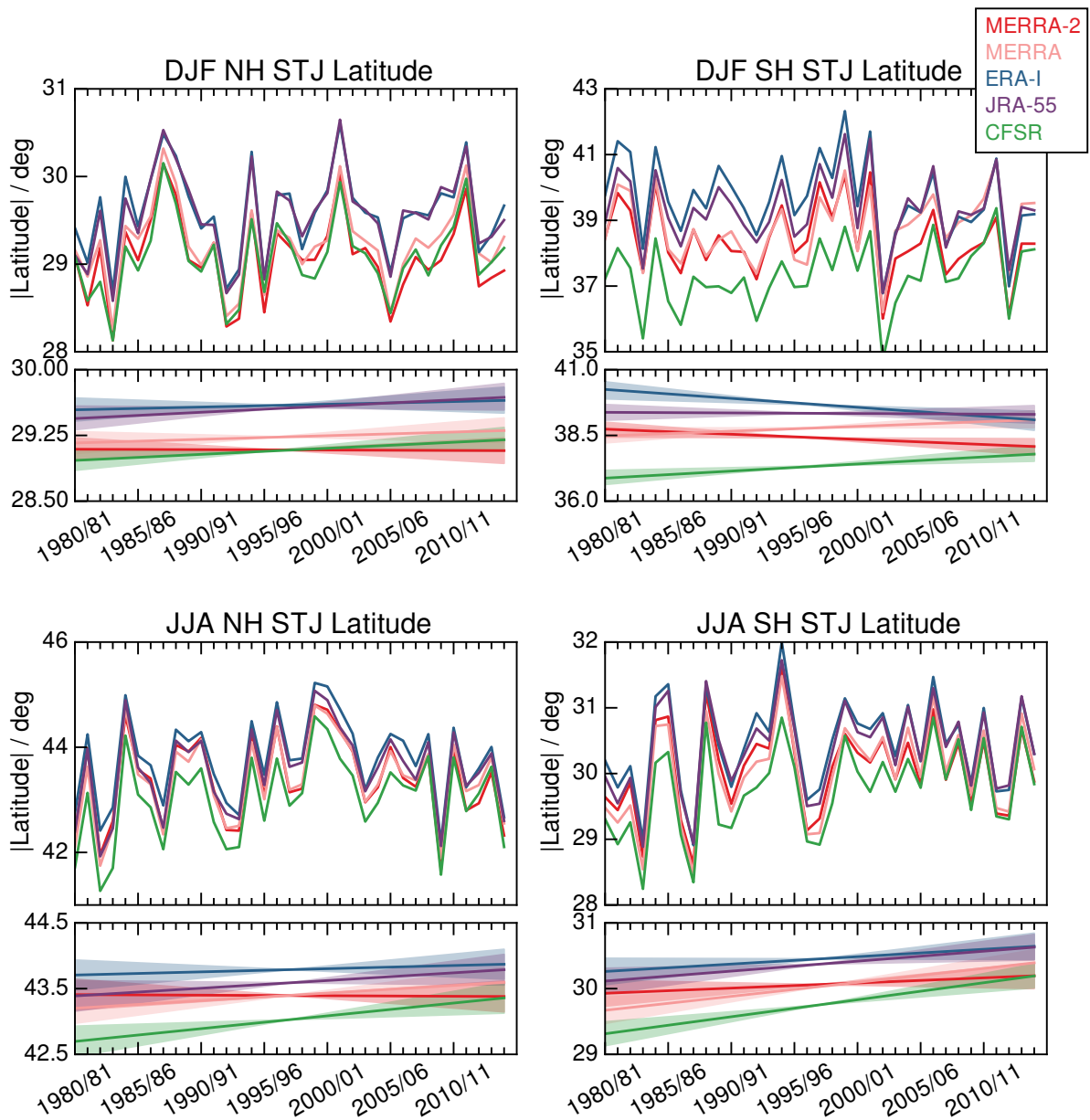


FIG. 4. As in Figure 1, but for SON.



1032 FIG. 5. Time series of subtropical jet latitudes for five reanalyses, 2 hemispheres, DJF & JJA. The lower panel  
 1033 of each pair shows the fits to slopes and the 1-sigma uncertainty envelope in those fits.

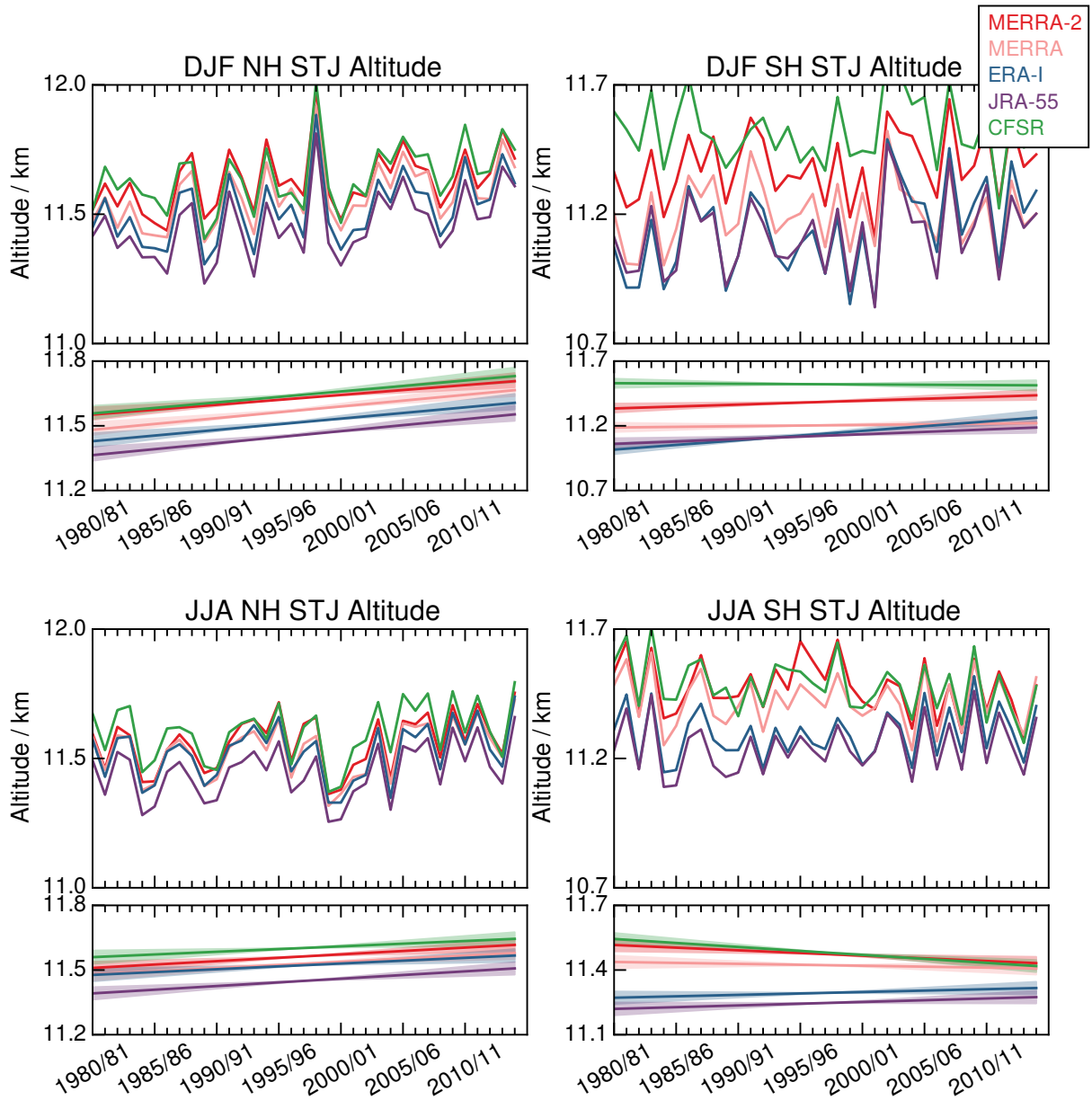
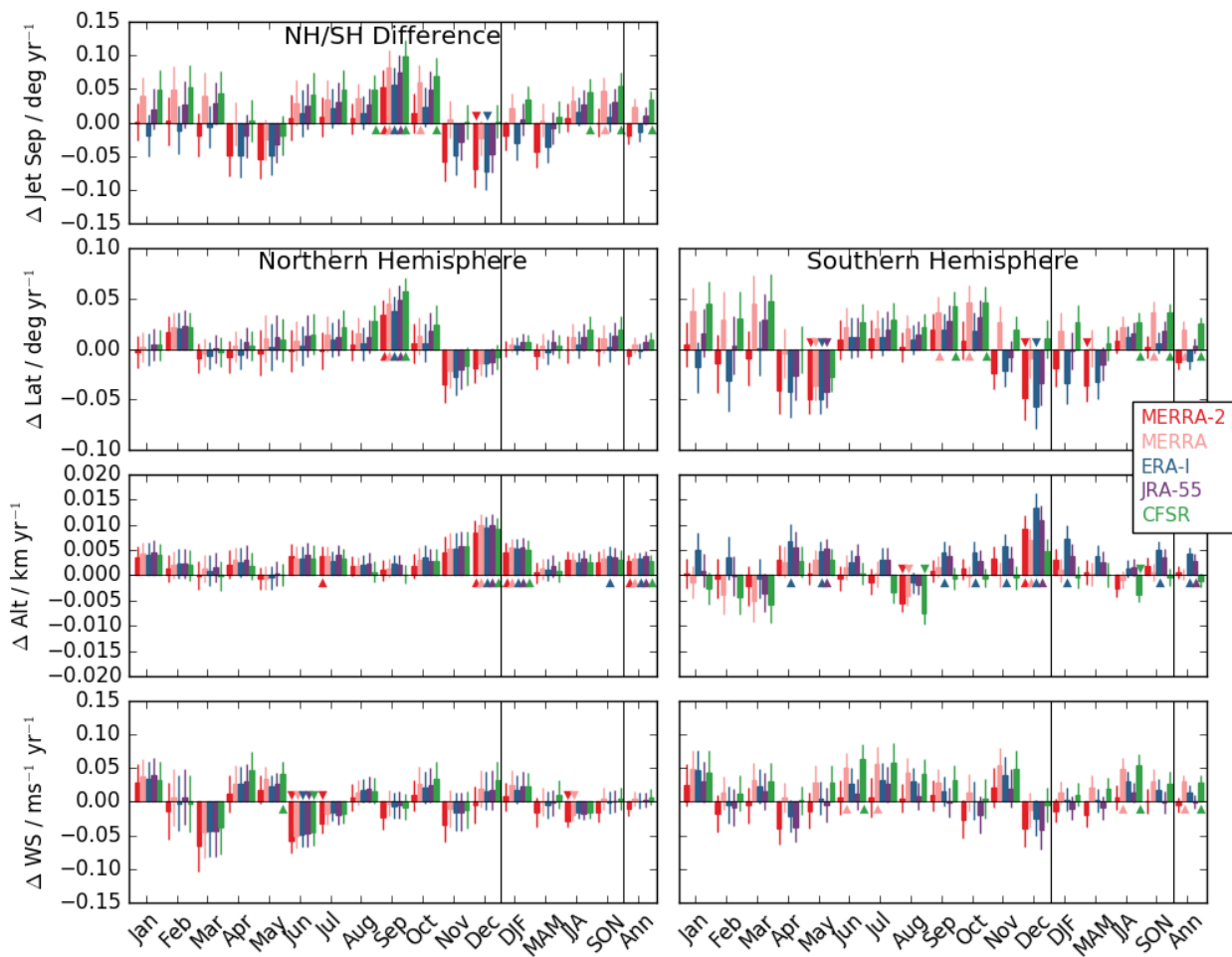
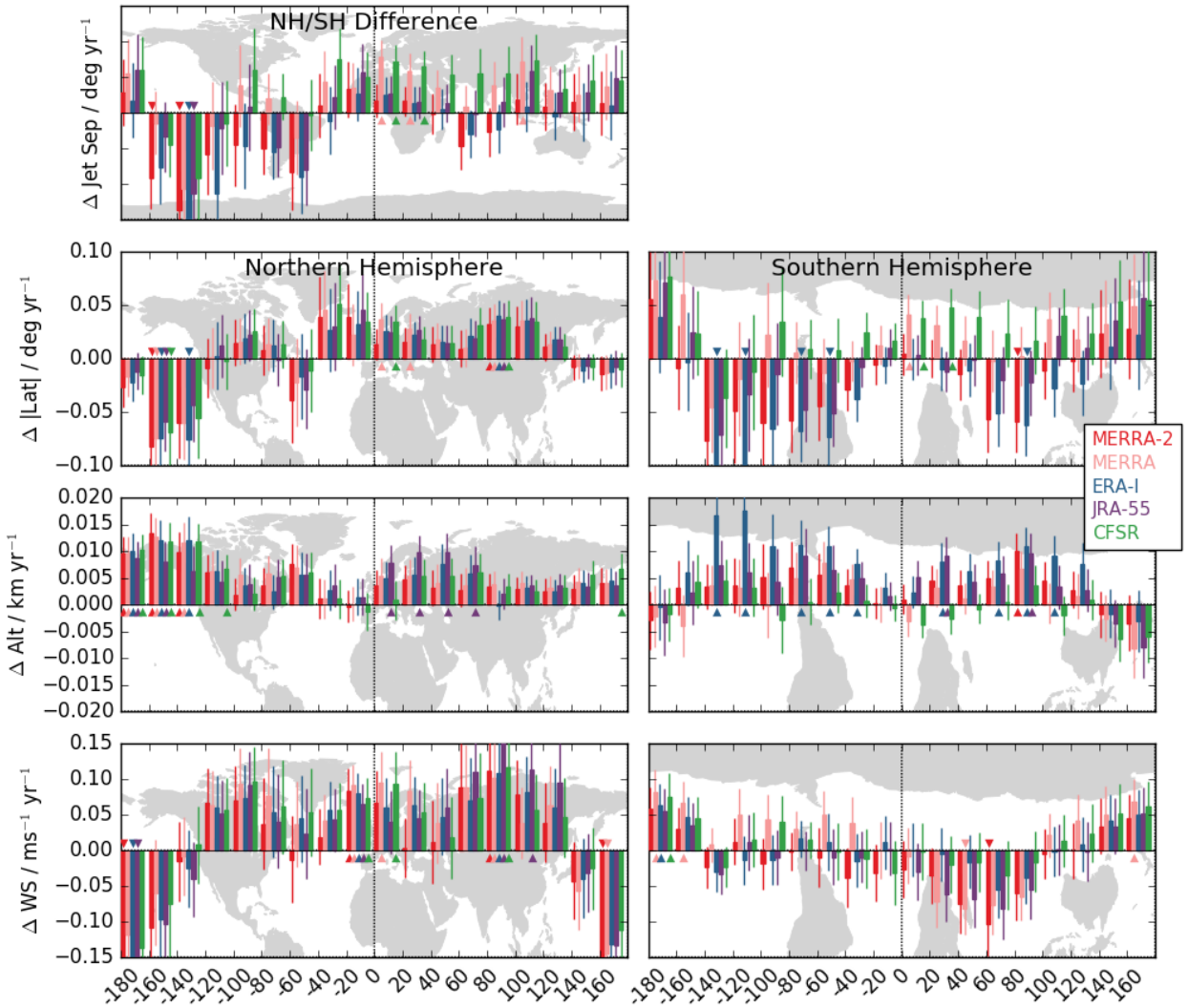


FIG. 6. As in Figure 5, but for subtropical jet altitudes.

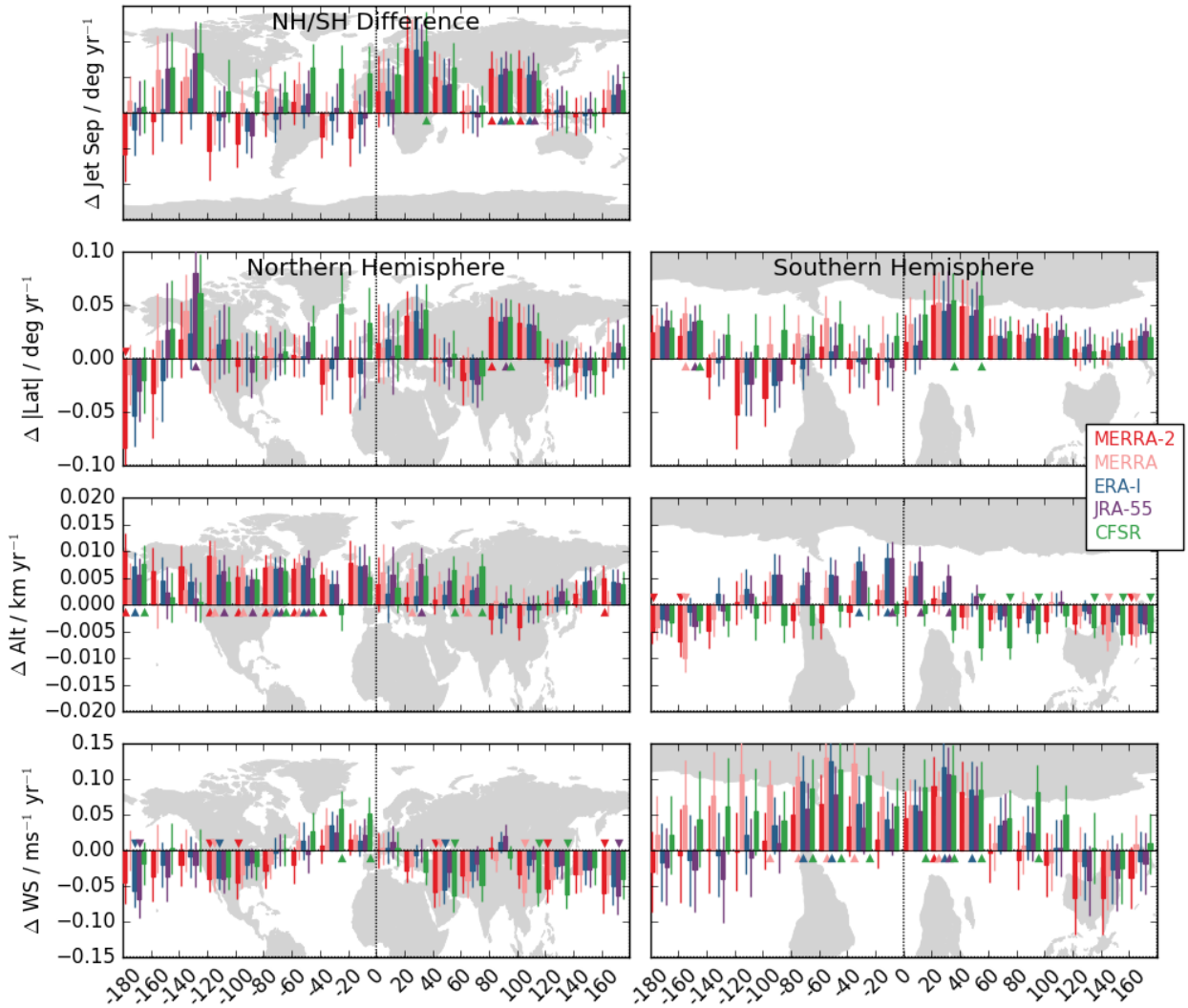


1040 FIG. 7. Bar charts of global subtropical jet and NH/SH subtropical jet separation as a function of month,  
 1041 season, and annual, showing five reanalyses. The bars show the slopes of the fits and the error bars (centered  
 1042 about the top of the bars) the 1-sigma uncertainty in that slope. Note that, in this and similar succeeding figures,  
 1043 absolute value of latitude is used, so positive slopes (bars extending upward from the zero line) indicate a  
 1044 poleward shift in both hemispheres. The zero line in each case indicates no trend in the quantity shown. Triangles  
 1045 indicate cases where the permutation analysis (see text) shows the slope to be significant at the 95% confidence  
 1046 level.



1047 FIG. 8. Bar charts of global subtropical jet and NH/SH subtropical jet separation trends as a function of  
 1048 longitude in  $20^\circ$  bins, for DJF showing five reanalyses. Layout is as in Figure 4.





1049 FIG. 9. Bar charts of global subtropical jet and NH/SH subtropical jet separation trends as a function of  
 1050 longitude in 20° bins, for JJA showing five reanalyses. Layout is as in Figure 4.



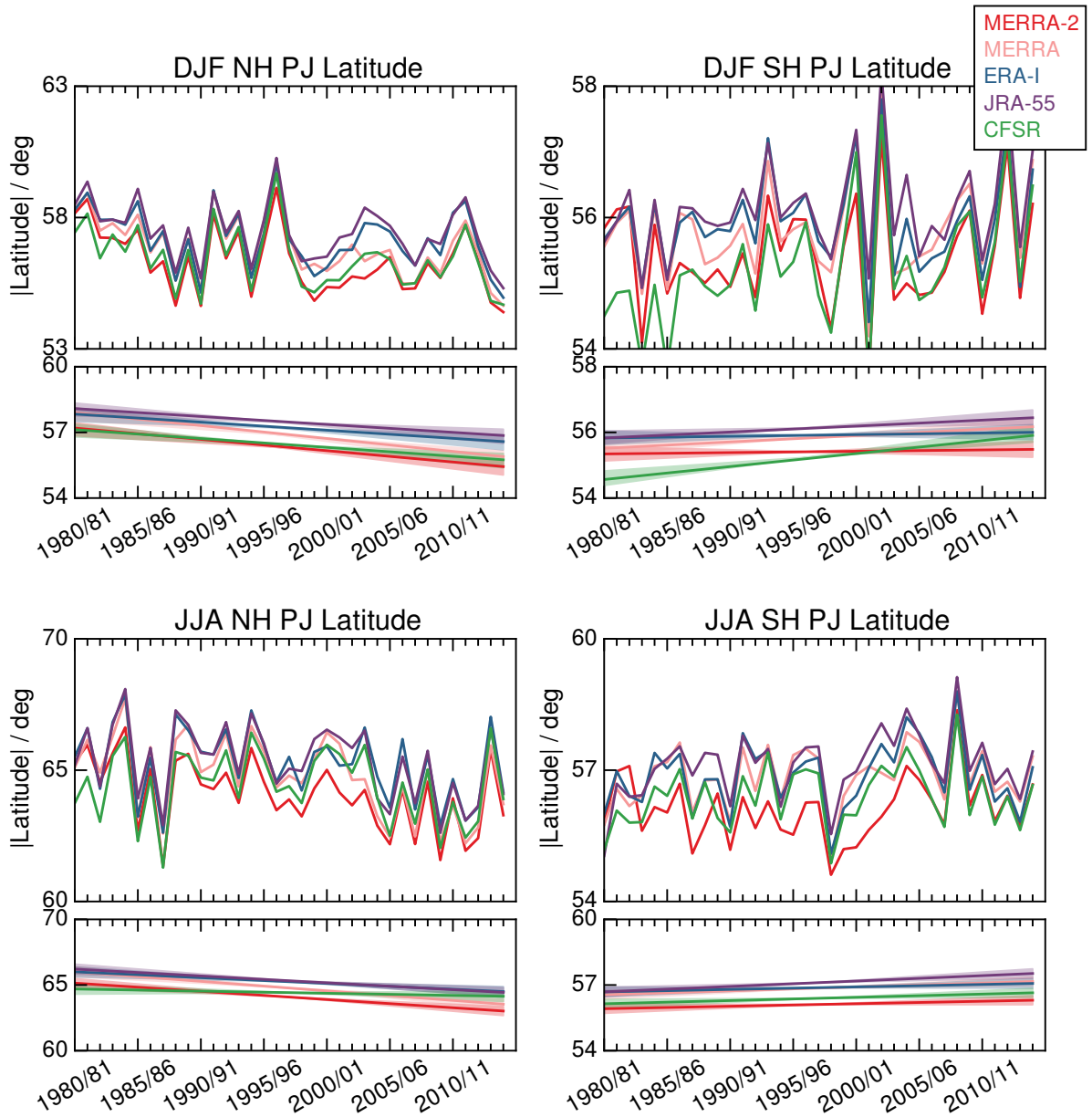


FIG. 10. As in Figure 5, but for the polar jet.

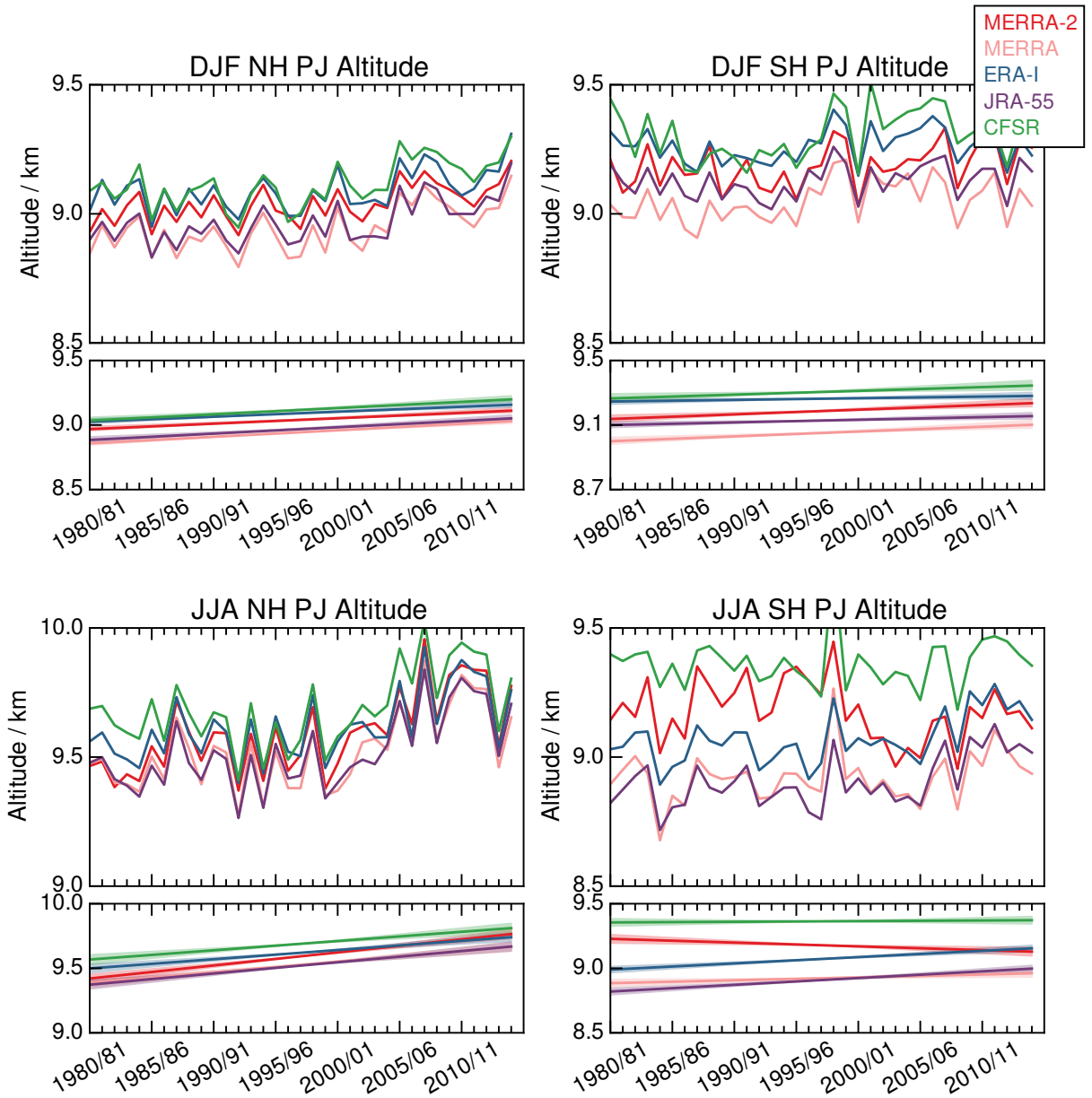
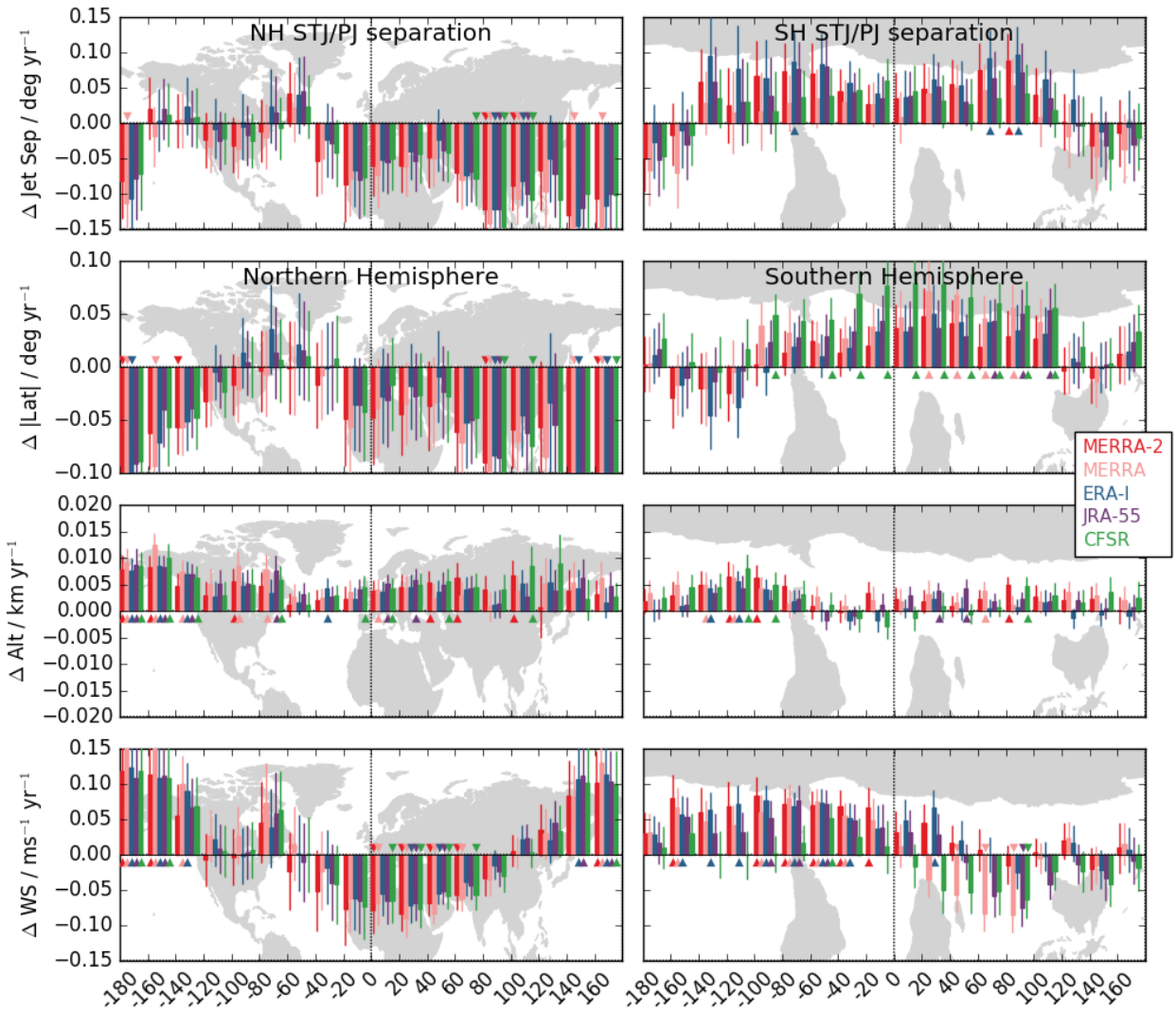


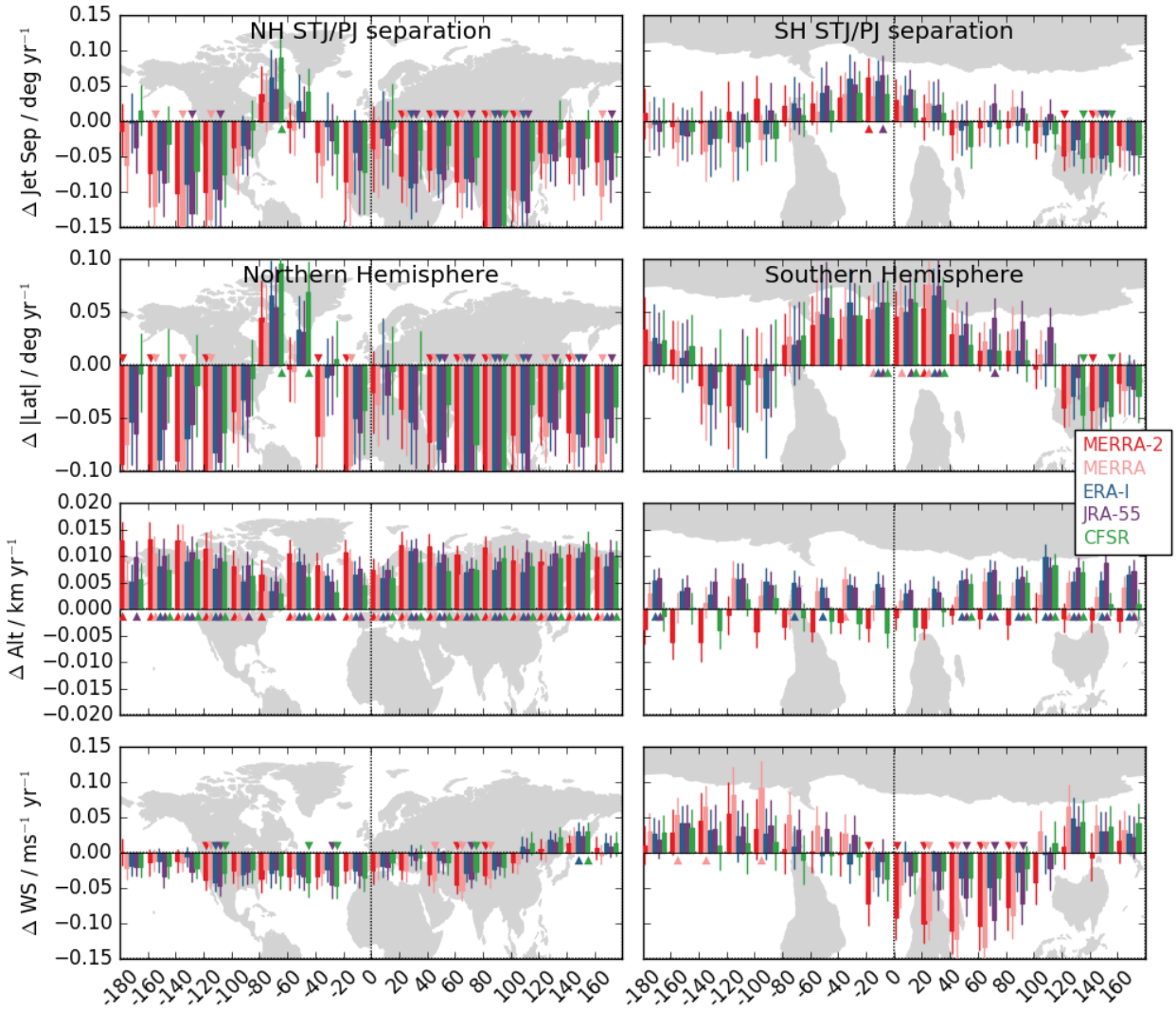
FIG. 11. As in Figure 6, but for the polar jet. DJF & JJA.



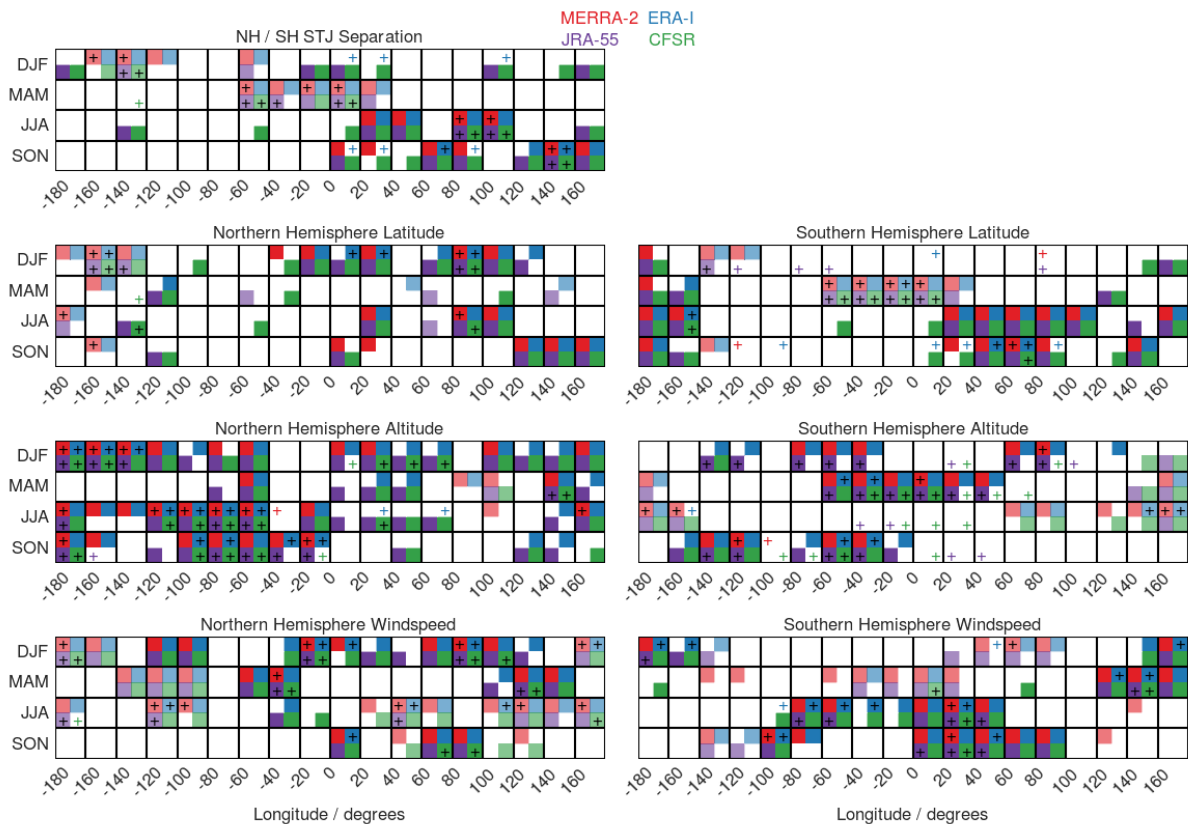
1051 FIG. 12. Bar charts of global polar jet and polar/subtropical jet separation trends as a function of month,  
 1052 season, and annual, showing five reanalyses. Layout is as in Figure 4.



1053 FIG. 13. Bar charts of global polar jet and polar/subtropical jet separation trends as a function of longitude in  
 1054 20° bins, for DJF showing five reanalyses.



1055 FIG. 14. Bar charts of global polar jet and polar/subtropical jet separation trends as a function of longitude in  
 1056 20° bins, for JJA showing five reanalyses.



1057 FIG. 15. Matrix plots for the subtropical jet showing colored boxes for MERRA-2 (red, upper left of each  
 1058 season / longitude region square), ERA-I (blue, upper right), JRA-55 (purple, lower left), and CFSR (green,  
 1059 lower right) where the signs of trends agree among all four of those reanalyses, and where the trend for that  
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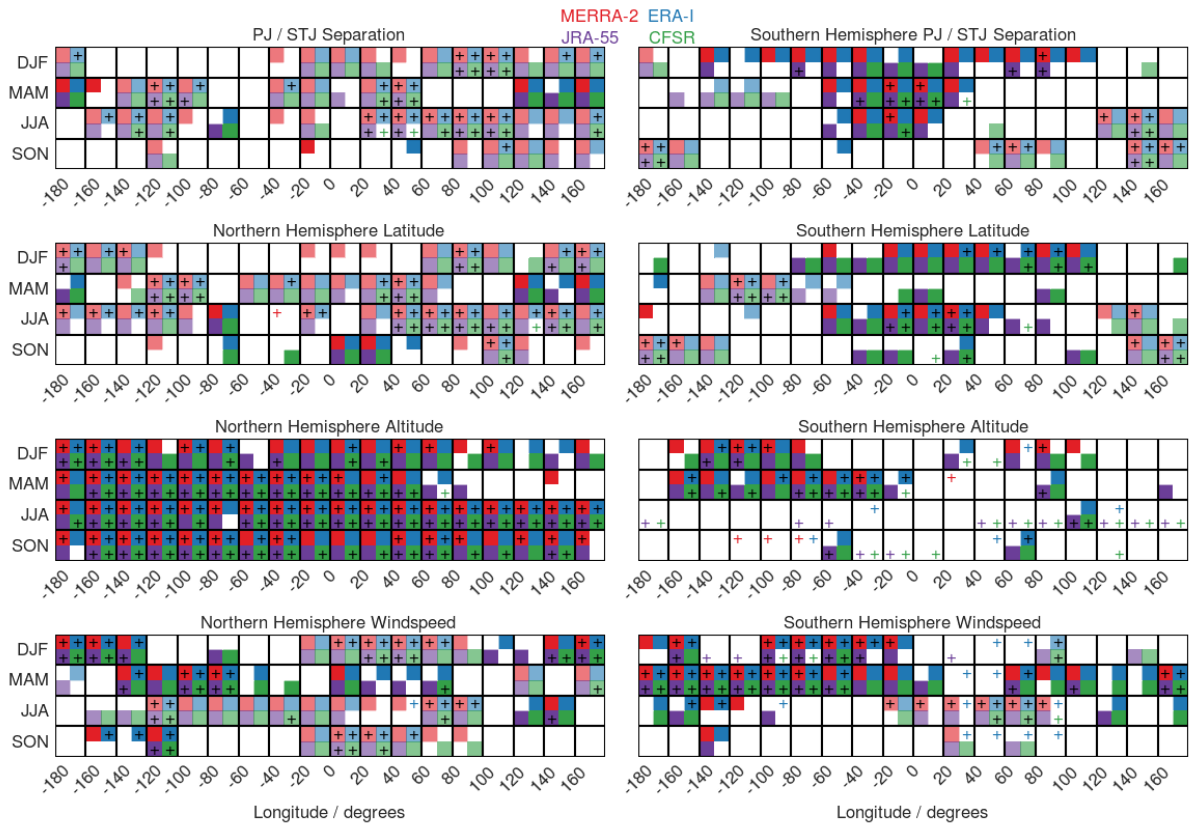


FIG. 16. As in Figure 15, but for the polar jets. The diagnostics are arranged as in Figure 12.