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Increasingly Undulatory Jet Streams

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Introduction

Changes in the characteristics of the midlatitude polar jet stream have been noted in response to anthropogenic climate change. The poleward movement of both northern (NH) and southern hemispheric (SH) jets have been found through analysis of radiosonde data, satellite observations, in reanalysis, and global climate models (Lucas et al. 2014). The mean zonal wind of SH westerlies have been increasing in strength in reanalyses (Chen and Held 2007), and will likely continue to increase in response to climate change (Barnes and Polvani 2013) though the magnitude of those changes are model and regionally dependent (Ihara and Kushnir 2009, Woolings and Blackburn 2012). Due to this poleward movement, the 500 hPa height associated with the largest latitudinal extent of the Rossby waves has increased with time, even though the extent of those waves has remained unchanged (Barnes 2013). These changes appear to be caused by a rise in the tropopause height (Lorenz and DeWeaver 2007) and an increase in the baroclinicity in the upper troposphere in response to enhanced latent heat release in the tropics (Rivière 2011).

Although the movement, strength, and wave size of the jet has been studied, there remains a lack of knowledge as to changes in the 'waviness' of the jet. Through quasigeostrophic approximations, a strong, high-amplitude Rossby wave is often associated with a mature extratropical surface cyclone. Changes in the frequency of these high-amplitude Rossby waves can provide insight into the changes in the frequency of strong storms. What are the trends in historical jet stream Rossby wave patterns? Is their amplitude increasing?

Methodology - $\frac{\text{V} - \text{wind}}{\text{U} - \text{wind}}$ Symmetric Ratio

- Period of study: 1948-2013.
- Uses the 6-hourly NCEP/NCAR reanalysis product (Kalnay et al. 1996).
- Focuses on the 250 hPa and 500 hPa levels.
- Analyzed over six regions (Table 1).
- Symmetric Ratio (SR): At each time, the ratio of v-wind to u-wind components is calculated as in equation 1.
    - Each component summed over the extent of the region.
    - Only components of vector winds ≥ 20 m/s were used in the calculation.
    - Purely zonal (meridional) winds across the region would result in SR of -1 (+1).
    - Equal zonal and meridional components result in a SR of 0.
    - Example: Minimum (Fig. 1a) and maximum (Fig. 1b) SRs in the N. American region.
- The linear rate of change per 100 years is calculated for each SR, and is smoothed with a 9-SR centered average.

$$(1)\quad \left.\frac{V - wind}{U - wind}\right._{symmetric} = \begin{cases} \dfrac{\sum|v_{ij}|}{\sum|u_{ij}|} - 1 & \text{if } \sum|u_{ij}| > \sum|v_{ij}| \\ 1 - \dfrac{\sum|u_{ij}|}{\sum|v_{ij}|} & \text{if } \sum|v_{ij}| > \sum|u_{ij}| \end{cases}$$

	North	South	West	East
N. America	70° N	20° N	150° W	40° W
Europe	70° N	20° N	40° W	70° E
E. Asia	70° N	20° N	60° E	170° E
Australia	20° S	70° S	90° E	160° W
S. Africa	20° S	70° S	30° W	80° E
S. America	20° S	70° S	115° W	5° W

Table 1: Extents of the six regions of interest.

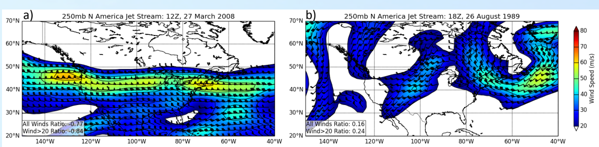

Figure 1: (a) 250 hPa vector winds (barbs) and wind speed (colorbar) for N. America region at 12 UTC, 27 March 2008. The SR is -0.84, the minimum for this region, indicating highly zonal winds. (b) as in a, but for 18 UTC, 26 August 1989. The SR is 0.24, the maximum for this region, indicating highly meridional winds.

250 hPa Regional SR Frequencies & Changes

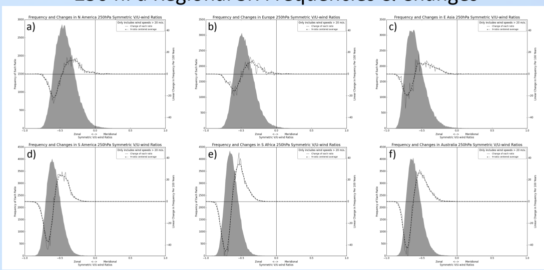

Figure 2: SR Frequency (gray fill), linear rate of change in SR frequency per 100 years (solid line), and 9-SR centered average of linear rate of change in SR frequency per 100 years (dashed line) at 250 hPa for (a) N. America, (b) Europe, (c) E. Asia, (d) S. America, (e) S. Africa, and (f) Australia.

500 hPa Regional SR Frequencies & Changes

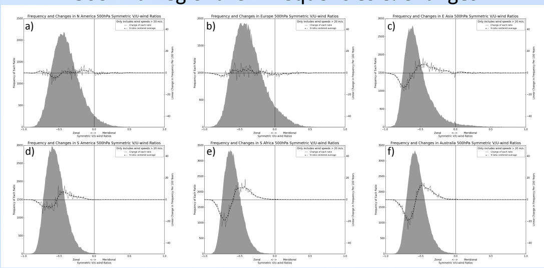

Figure 3: As in Fig. 2 but at 500 hPa.

N. America 400, 300, & 250 hPa SR Frequency Changes

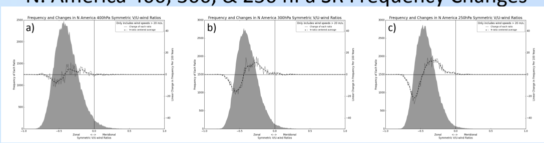

Figure 4: SR Frequency (gray fill), linear rate of change in SR frequency per 100 years (solid line), and 9-SR centered average of linear rate of change in SR frequency per 100 years (dashed line) for N. America at (a) 400 hPa, (b) 300 hPa, and (c) 250 hPa.

Sample SR Changes Over Time

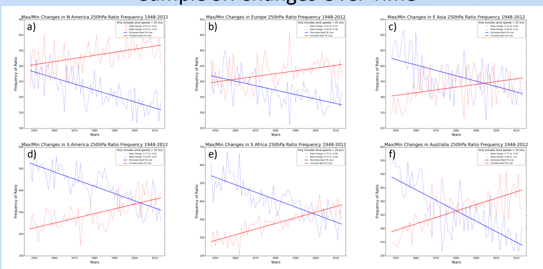

Figure 5: (a) 9-SR annual frequency (thin line) and linear best fit (thick line) for the largest increasing (red) and decreasing (blue) SRs at 250 hPa for N. America. Other panels are identical but are for (b) Europe, (c) E. Asia, (d) S. America, (e) S. Africa, and (f) Australia.

Conclusions

As expected, SRs in all regions at both 500 hPa and 250 hPa reflect the prevailing westerlies. The biggest variations of SRs are in the NH where terrain has its greatest influence. All regions of 250 hPa (Fig. 2) frequencies show a clear trend of increasing (decreasing) frequencies of greater (less) than average SRs. These trends are supported by annual changes in SRs shown in Figure 5. Thus, the 'waviness' of the jet stream is increasing with time, as indicated through increasing (decreasing) frequency of high-amplitude Rossby waves (zonal flow).

At 500 hPa (Fig. 3), both the N. American and European regions show only small changes in the frequency of all SRs and contain no uniform trend. S. America shows a reduction in its 500 hPa trend toward higher SRs compared to its 250 hPa trend that is greater than in other SH regions. The trend toward higher SRs increases with height in N. America (Fig. 4) and Europe (not shown). This appears to support the conclusion of Woolings and Blackburn (2012) that the layout of continents, mountain chains, and sea surface temperatures means the North Atlantic jet may respond differently to forcing than seen elsewhere.

However, the magnitude of the changes aloft and their subsequent impacts on extratropical cyclones remains most striking. An increase in the frequency of strong, high-amplitude Rossby waves is consistent with the conclusions of Rivière (2011) that larger wavelengths are associated dynamically with the observed poleward movements of the jet streams.

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