Diffusivity Scaling for the Northern Hemisphere Winter Circulation Waviness and its Response to Climate Change

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Motivation

- Despite the profound impacts of midlatitude weather extremes, the mechanisms and underlying causes for these events in a changing climate remain a topic of debate.
- Chen et al. (2022) has proposed a tracer-based wave activity for measuring jet meandering, showcasing that waviness subject to changes in time mean winds can be constrained by a Potential Vorticity (PV)-like passive tracer in an advection-diffusion model (Nie et al. 2023). Here, we present a theory of diffusivity scaling to further quantify the Northern Hemisphere winter circulation waviness.

Data and Method

- **Data**
  - We use 6-hourly data from ERA5 reanalysis for the winters (December-February (DJF)) in 1980-2020.
  - We also employ initial-condition large ensembles from four coupled atmosphere-ocean models: CESM1 (40 members), CanESM2 (50 members), GFDL-CM3 (20 members), and CESM2 (50 members). To evaluate the projected future changes at the end of the 21st century, we calculate the difference between the historical period (1980-2004) and future period (2080-2099)
- **A diffusivity scaling theory for circulation waviness**

We perform a Galilean transformation from longitudinal position x to a new x_L-coordinate that moves at the zonal wind speed $\bar{u}$ (see the schematic in Fig. 1a). Physically, the moving coordinate will produce a Doppler shift in eddy frequency. Then, the eddy diffusivity for a passive tracer can be derived as

$$D_L = \tau_e \mathrm{EKE}, \quad \text{where } \tau_e = \frac{1}{2}\int_{-\infty}^{\infty} r_L^{\Delta t}\, d\Delta t,$$

where eddy autocorrelation in the moving coordinate x_L is evaluated at lag time Δt

$$r_L^{\Delta t} = \frac{\overline{v'(x_L,t)\,v'(x_L,t+\Delta t)}}{\overline{v'^2(x_L)}}.$$

Here $r_L^{\Delta t}$ is the lagged eddy correlation following the local time mean wind, and Δt is time lag. This can be approximated in the form of a damped oscillator, with frequency ω_i and day timescale τ.

$$\tilde{r}_L^{\Delta t} = \cos(\omega_i \Delta t)\exp(-\tau^{-1}|\Delta t|).$$

Calculation of Diffusivity Scaling

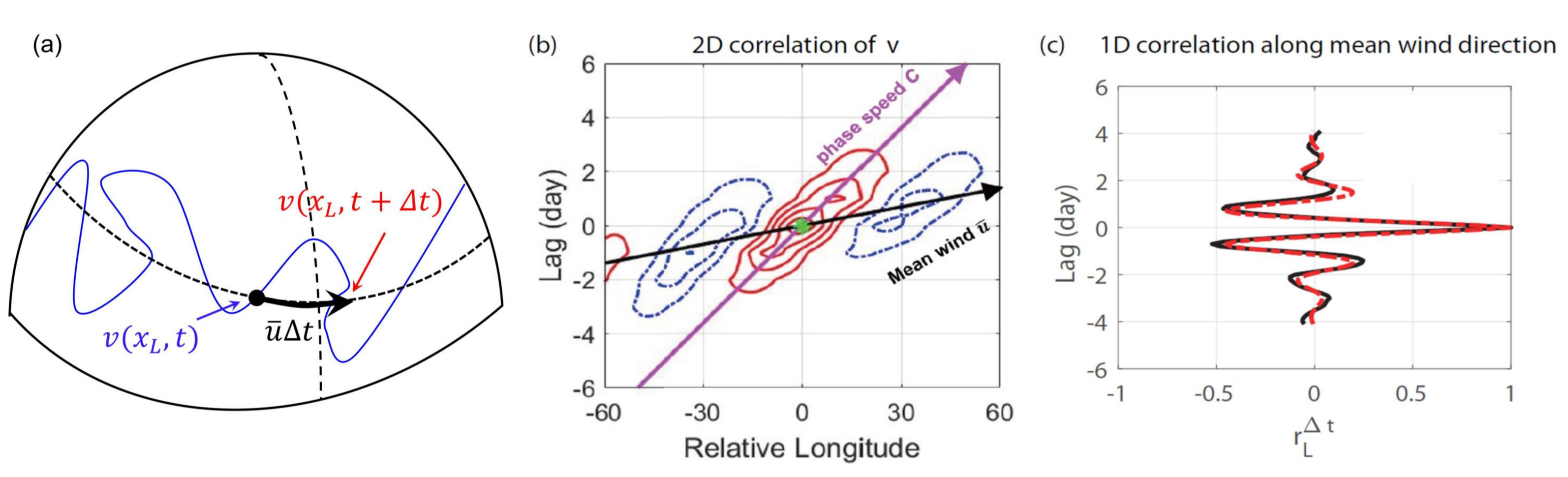

Figure 1. Schematic for the calculation of eddy autocorrelation in the x_L-coordinate that moves at the zonal speed $\bar{u}$. (a) From time t to $t+\Delta t$, the x_L -coordinate is displaced by the distance $\bar{u}\Delta t$ relative to the ground. The eddy autocorrelation at lag Δt is calculated as the correlation between $v(x_L,t)$ and $v(x_L,t+\Delta t)$. **(b)** The 2D one-point correlation map of eddy meridional wind as a function of longitude and time lag. The purple line indicates the direction of eddy phase speed, while the black line marks the direction of time mean zonal wind $\bar{u}$. **(c)** The autocorrelation (black line) along the mean wind direction in (b). The red dashed line depicts the best fit of the autocorrelation function to a damped oscillator.

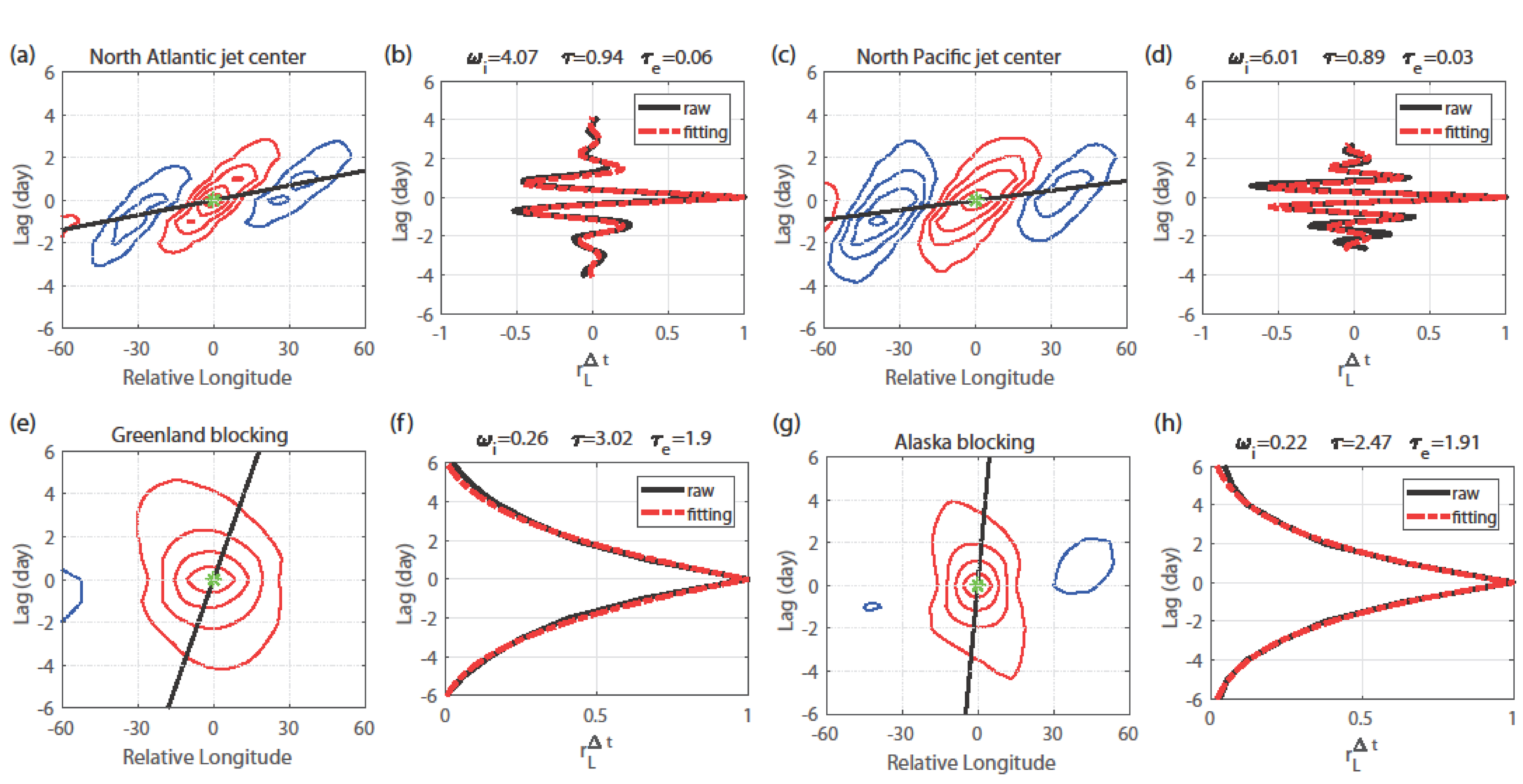

Figure 2. DJF-mean eddy correlations for Rossby wave packets at selected locations. (a)(c)(e)(g) Climatological one-point eddy correlation map in DJF as a function of relative longitude and lag day (contour intervals (CI): 0.2). The black lines indicate the paths of an air parcel moving at the speed of time mean zonal wind $\bar{u}$. **(b)(d)(f)(h)** Eddy autocorrelations in the moving coordinate (black) and the best fit (red) to a damped oscillator. Estimates of frequency ω_i, decay timescale τ, and effective eddy timescale τ_e for the damped oscillator are listed at the top of each subpanel. The four selected points are (a)(b) the Atlantic jet at (74ºW, 38ºN), (c)(d) Pacific jet at (143ºE, 33ºN), (e)(f) Greenland at (77ºW, 74ºN), and (g)(h) Alaska at (148ºE, 58ºN).

Spatial Patterns of Waviness, Interannual Variability, and the Response to Climate Change

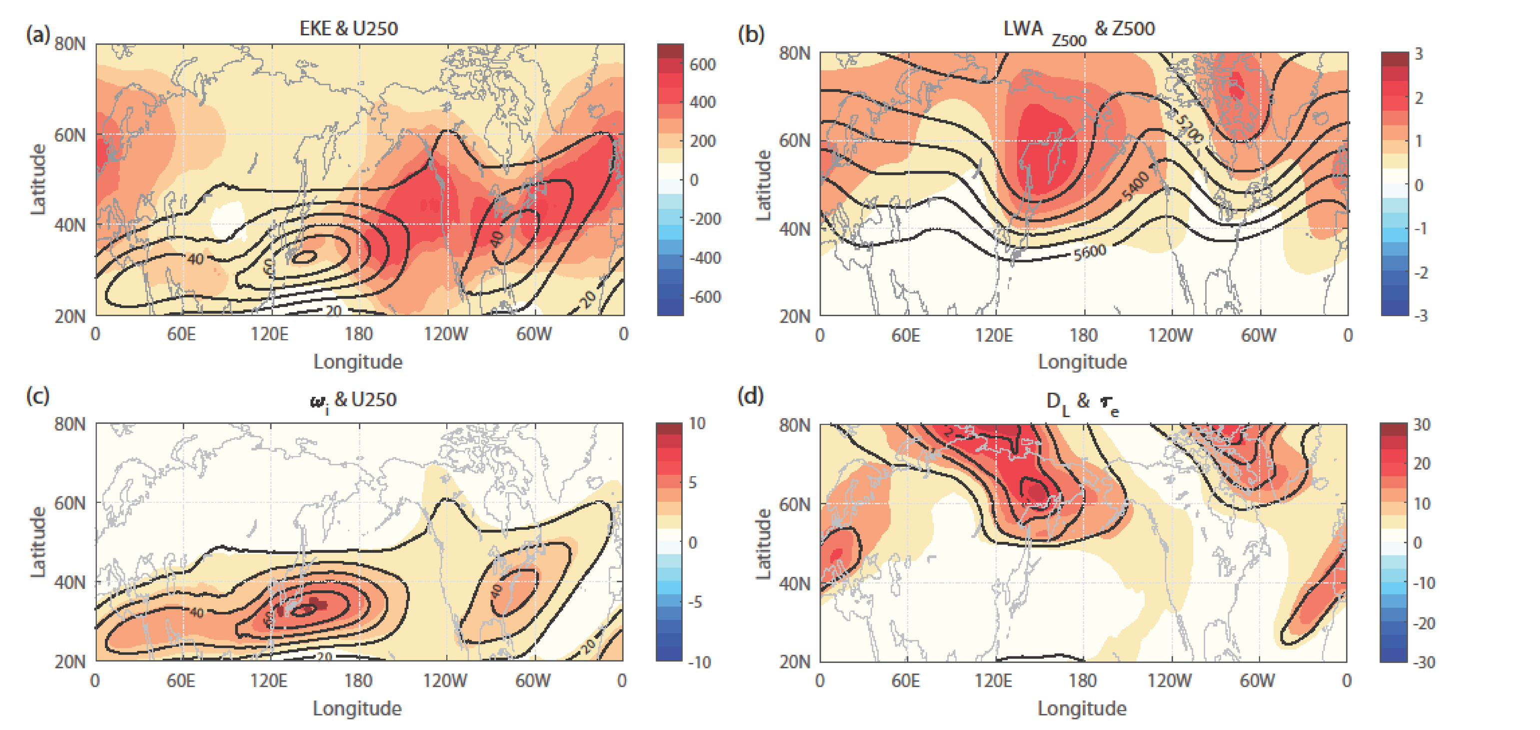

Figure 3. DJF-mean climatology of eddy statistics. (a) 250-hPa EKE (shading, m² s⁻²) and zonal wind (black contour, CI: 10 m s⁻¹). **(b)** LWA_{Z500} (shading, 10^8 m²) and Z500 (black contour, CI: 100 m). **(c)** Frequency ω_i (shading, day⁻¹) and zonal wind (contour, CI: 10 m s⁻¹). **(d)** Effective eddy timescale $\tau_e = \tau/(1+\omega_i^2\tau^2)$ (contour, CI: 0.5 day) and eddy diffusivity D_L (shading, 10^6 m² s⁻¹). The damped oscillator parameters (i.e., ω_i, τ, and τ_e) are estimated from local autocorrelation functions as in Fig. 2.

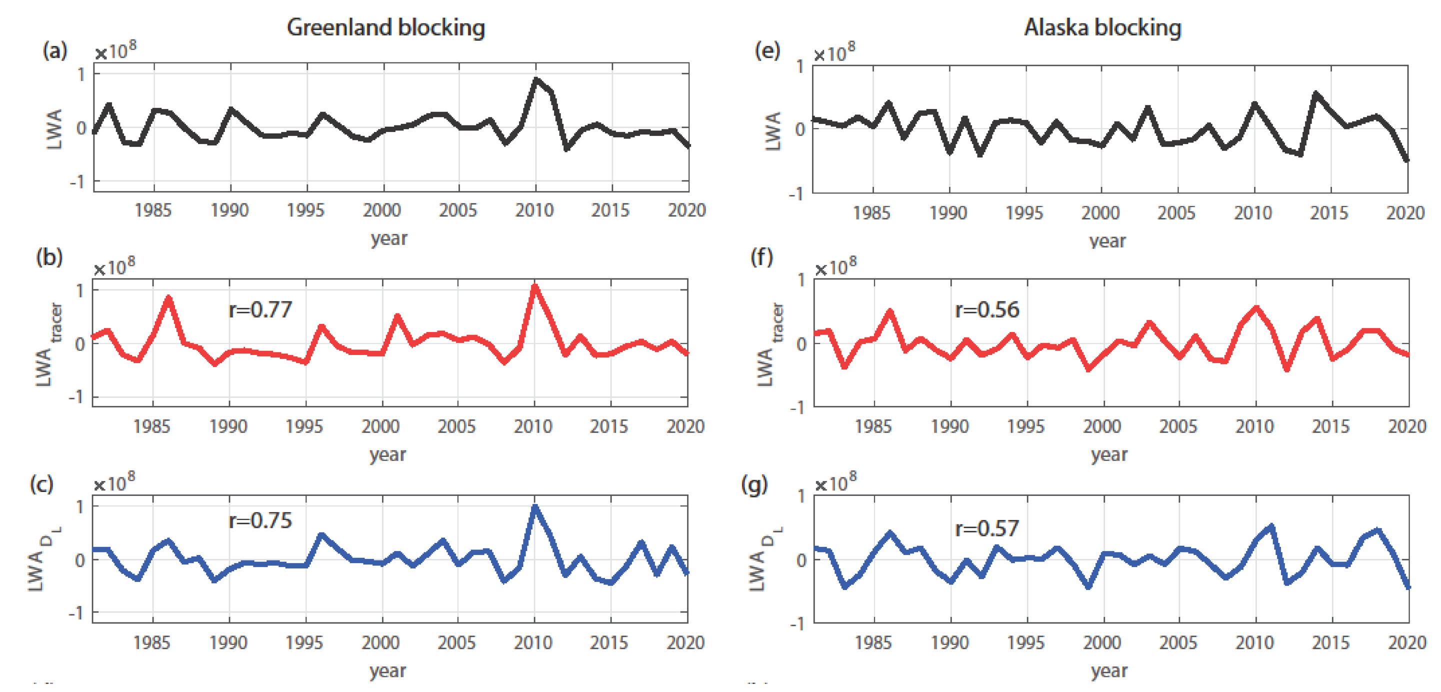

Figure 4. DJF-mean anomalies of different waviness metrics for 1981–2020 over (a)-(c) Greenland and (e)-(g) Alaska. **(a)(e)** LWA_{Z500}, **(b)(f)** LWA_{tracer}, and **(c)(g)** LWA_{DL}. The r values in (b)-(c) and (f)-(g) are the correlations with LWA_{Z500} in (a) and (b), respectively. The horizontal axis indicates the year of JF. Greenland represents the spatial average over (50ºN–60ºN, 70ºW–30ºW), and Alaska for the average over (50ºN–60ºN, 165ºW–125ºW).

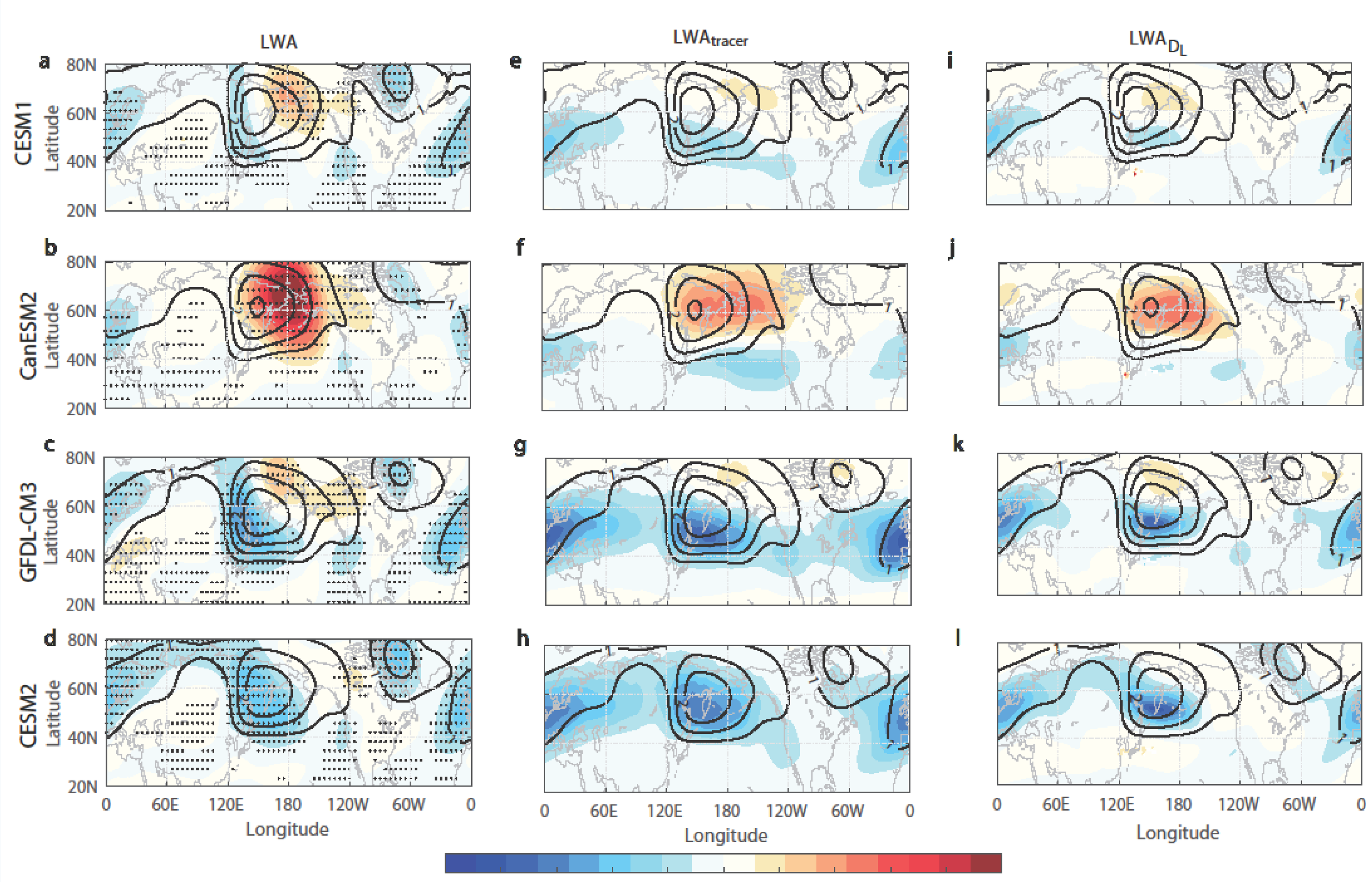

Figure 5. Future changes to circulation waviness from climate models. (a–d) Changes to the DJF ensemble-mean LWA between the historical period (1980–2004) and future period (2080–2099) from large ensembles of four climate models. Black contours denote the LWA climatology. The unit is 10^8 m². **(e-h)** as in (a-d) but for the estimated LWA changes using the tracer model driven by reanalysis winds and the projected changes in zonal wind. **(i-l)** as in (a-d) but for the LWA response from the eddy mixing theory due to projected changes in zonal wind.

Take-home Messages

- **Waviness is explained by a diffusivity scaling $D_L = \tau_e \mathrm{EKE}$, where the effective eddy timescale τ_e is inferred from eddies propagating at the mean wind speed.**
- **Interannual variability and climate change in waviness can be largely explained by the diffusivity scaling, due to changes in effective eddy timescale, not EKE.**

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