Future Trends in Upper-Atmospheric Shear Instability from Climate Change

Joana de Medeiros & Paul D. Williams

EGU26
GENERAL ASSEMBLY

Why This Matters

Aviation Impact

- >70% of weather-related accidents
- Injuries & financial costs
- Flight routing & efficiency
- Certification standards (**outdated**)

Climate Connection

- Changes in jet stream structure
- Changes in meridional temperature gradient
- Increased vertical wind shear

Clear-air turbulence (CAT) is invisible, dangerous, and projected to worsen

Background

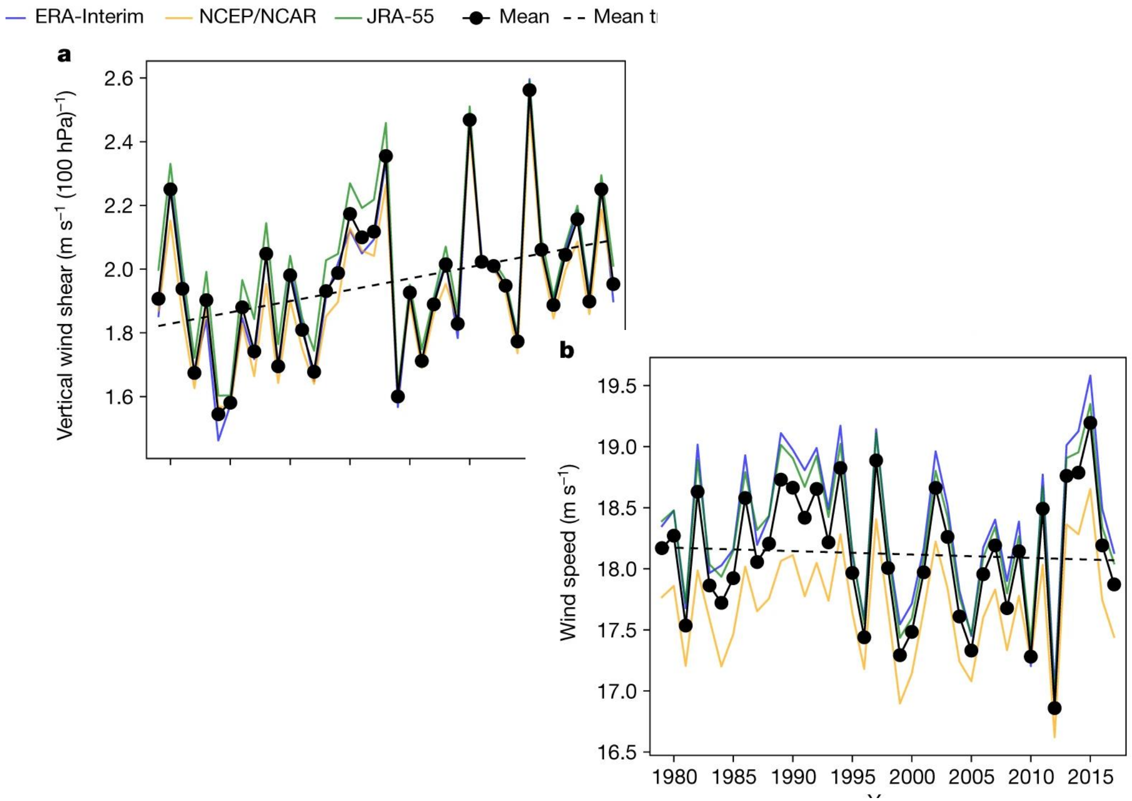
Earth and Space Science

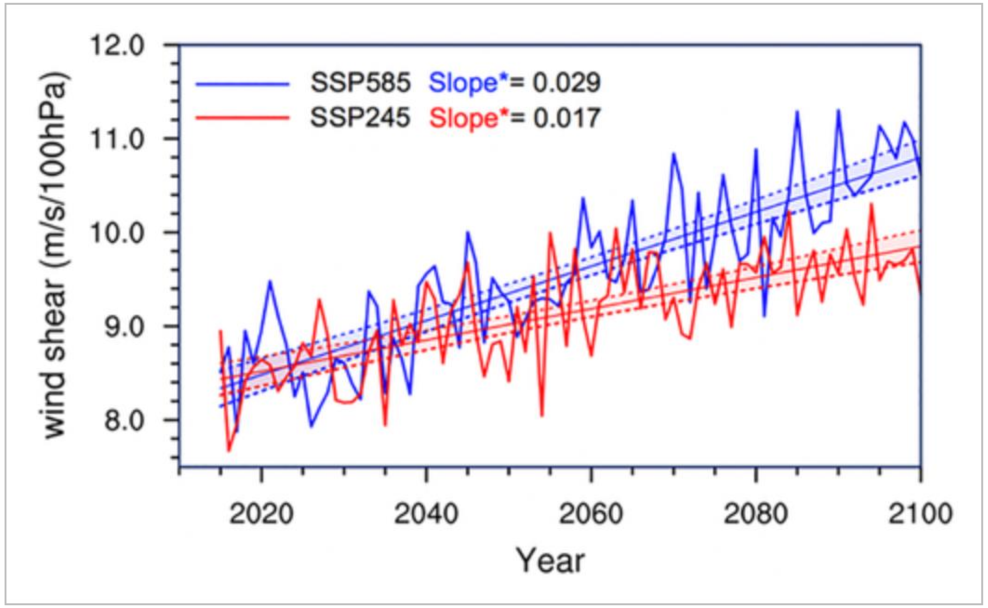
Research Article | Open Access

Increased Turbulence in the Eurasian Upper-Level Jet Stream in Winter: Past and Future

Yanmin Lv, Jianping Guo, Jian Li, Yi Han, Hui Xu, Xiaoran Guo, Lijuan Cao, Wenhua Gao

First published: 29 December 2020 | https://doi.org/10.1029/2020EA001556 | VIEW METRICS





nature > letters > article

Letter | Published: 07 August 2019

Increased shear in the North Atlantic upper-level jet stream over the past four decades

Simon H. Lee, Paul D. Williams & Thomas H. A. Frame

Nature **572**, 639–642 (2019) | Cite this article

Future Trends in Upper-Atmospheric Shear Instability from Climate Change

Data: 26 CMIP6 models, SSP2-4.5 & SSP5-8.5, 2015 – 2100, Global & Regional Analyses

Vertical uShear ↑

+16-34% at 250 hPa

0.04-0.11 m/s per 100 hPa decade^{-1}

Stability (N^2) ↓

-10% to -20% at 250 hPa

Reduced buoyancy resistance

Richardson (Ri) ↓

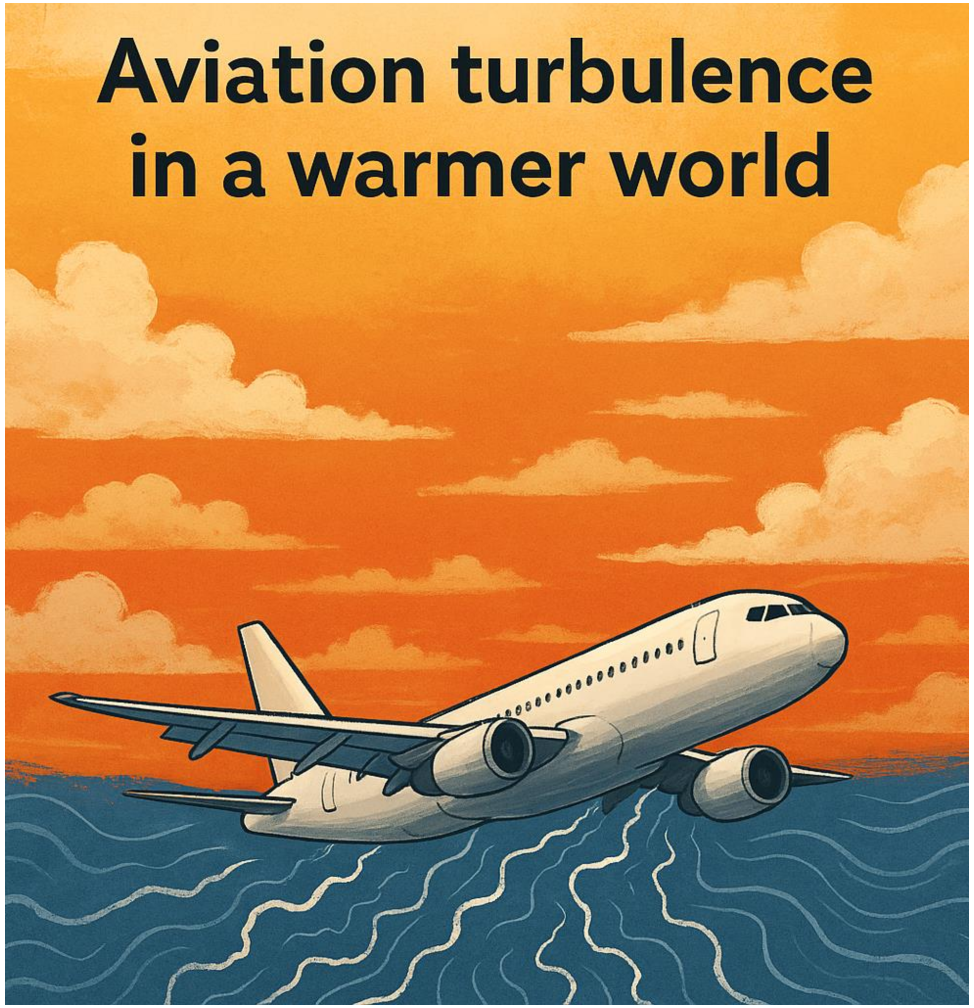
-38% to -47% at 250hPa

More turbulence-prone

$Ri = N^2 / Shear^2$

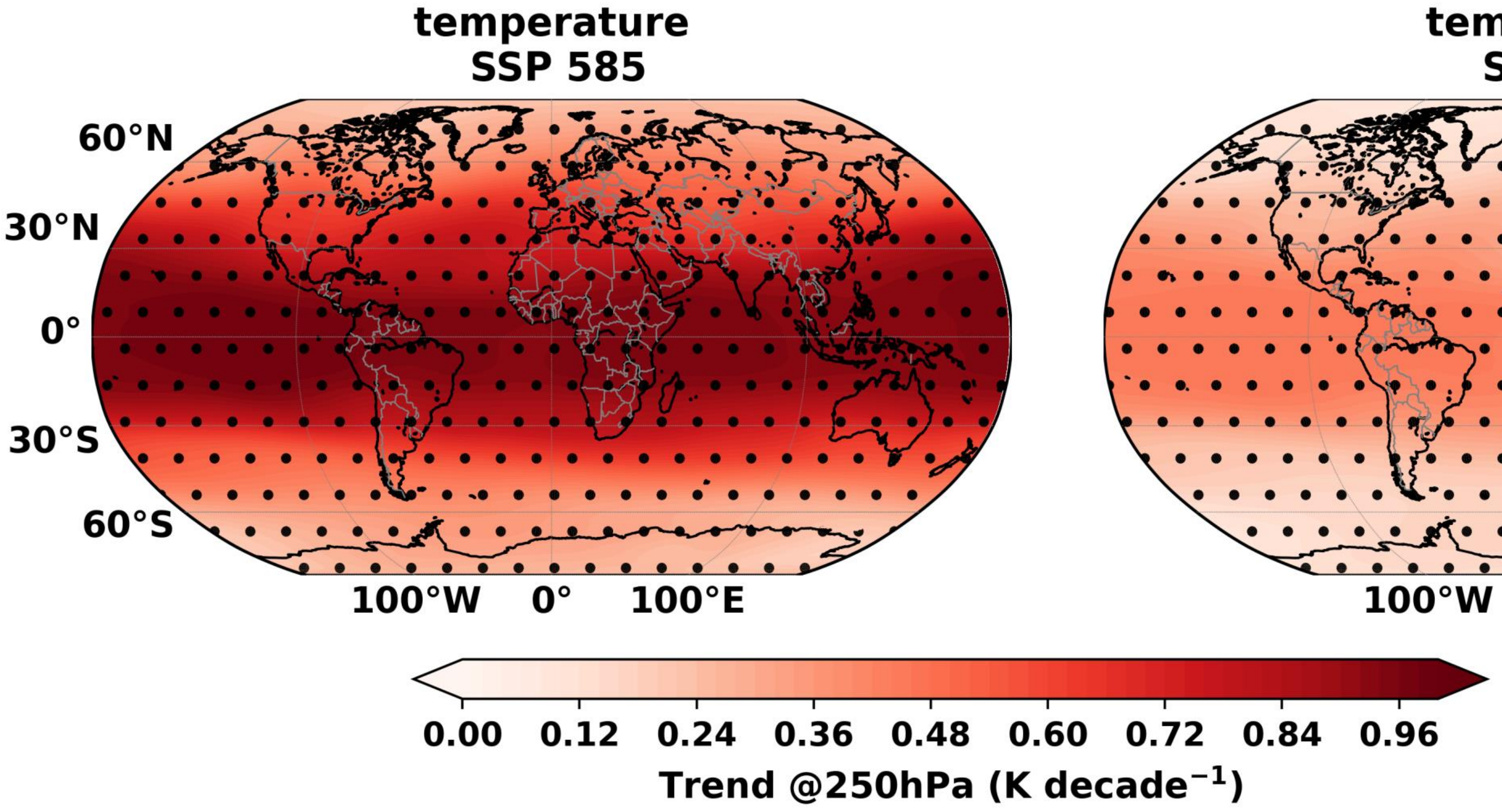
→ Atmosphere becoming more favorable for CAT generation

- Results
  a) Temperature @250 hPa
  b) Thermal Gradient Wind Balance @250 hPa
  c) Vertical Shear of Zonal Wind
  d) Meridional Temperature Gradient
  e) Atmospheric Stability (N^2) and Ri @250 hPa
  f) Time series and Trends of uShear, N2 and Ri @250 hPa
- Summary & Discussion



a. Temperature @250 hPa

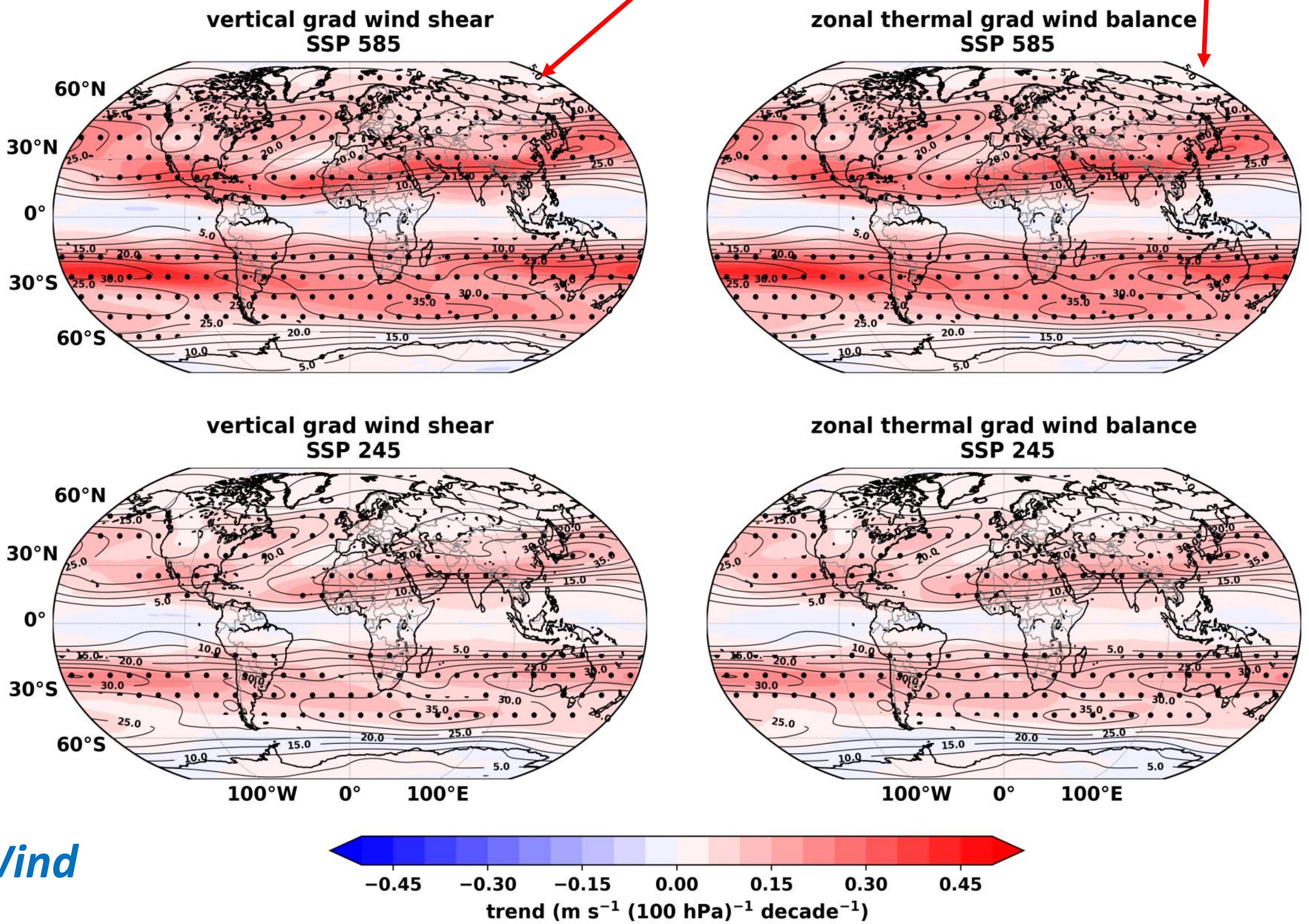
Ensemble mean of temperature trends @250 hPa



Warmer conditions (**stronger** trends) near the equator and progressively **cooler** temperatures (**weaker** trends) toward the poles,

$$\frac{U_{\mathrm{gr}}^2}{R} + fU_{\mathrm{gr}} = -g\frac{\partial Z}{\partial Y} \Rightarrow \frac{d}{dp}\left(\frac{U_{\mathrm{gr}}^2}{R}+fU_{\mathrm{gr}}\right) = \frac{R_d}{p}\frac{\partial T}{\partial Y} \Longleftrightarrow \frac{dU_{\mathrm{gr}}}{dp} = \left(\frac{R_d}{fp}\frac{\partial T}{\partial Y} + \frac{U_{\mathrm{gr}}^2}{fR^2}\frac{\partial R}{\partial p}\right)\left(1+\frac{2U_{\mathrm{gr}}}{R}\right)$$

(Knox, 1997)



Vertical Wind gradient Shear @250 hPa

Changes driven by **intensified upper troposphere temperature** gradients that **enhance vertical wind shear** near subtropical jets;
Stronger in SSP 585

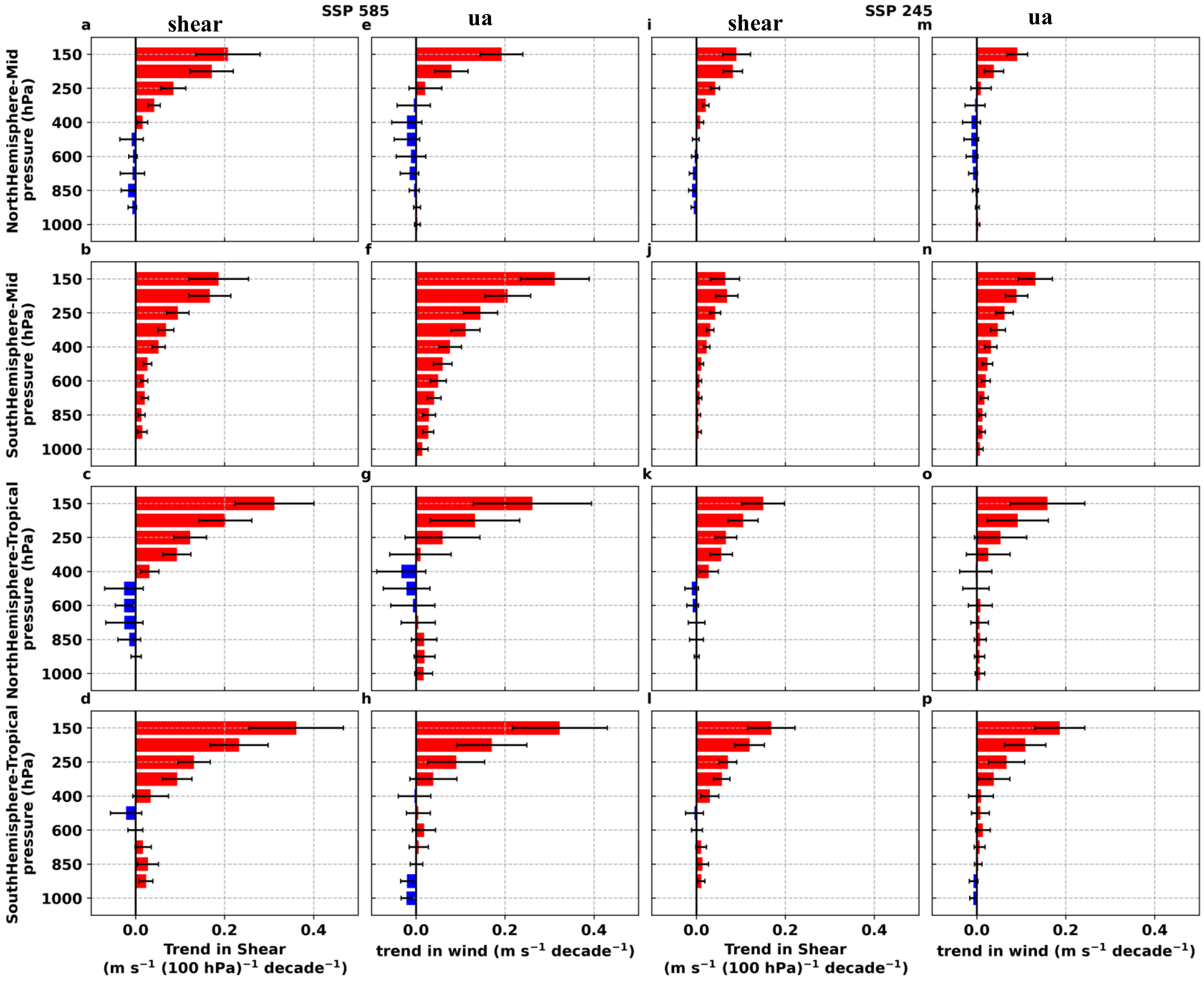
d. Thermal Gradient Wind Balance @250 hPa

b. Vertical Shear of Zonal Wind

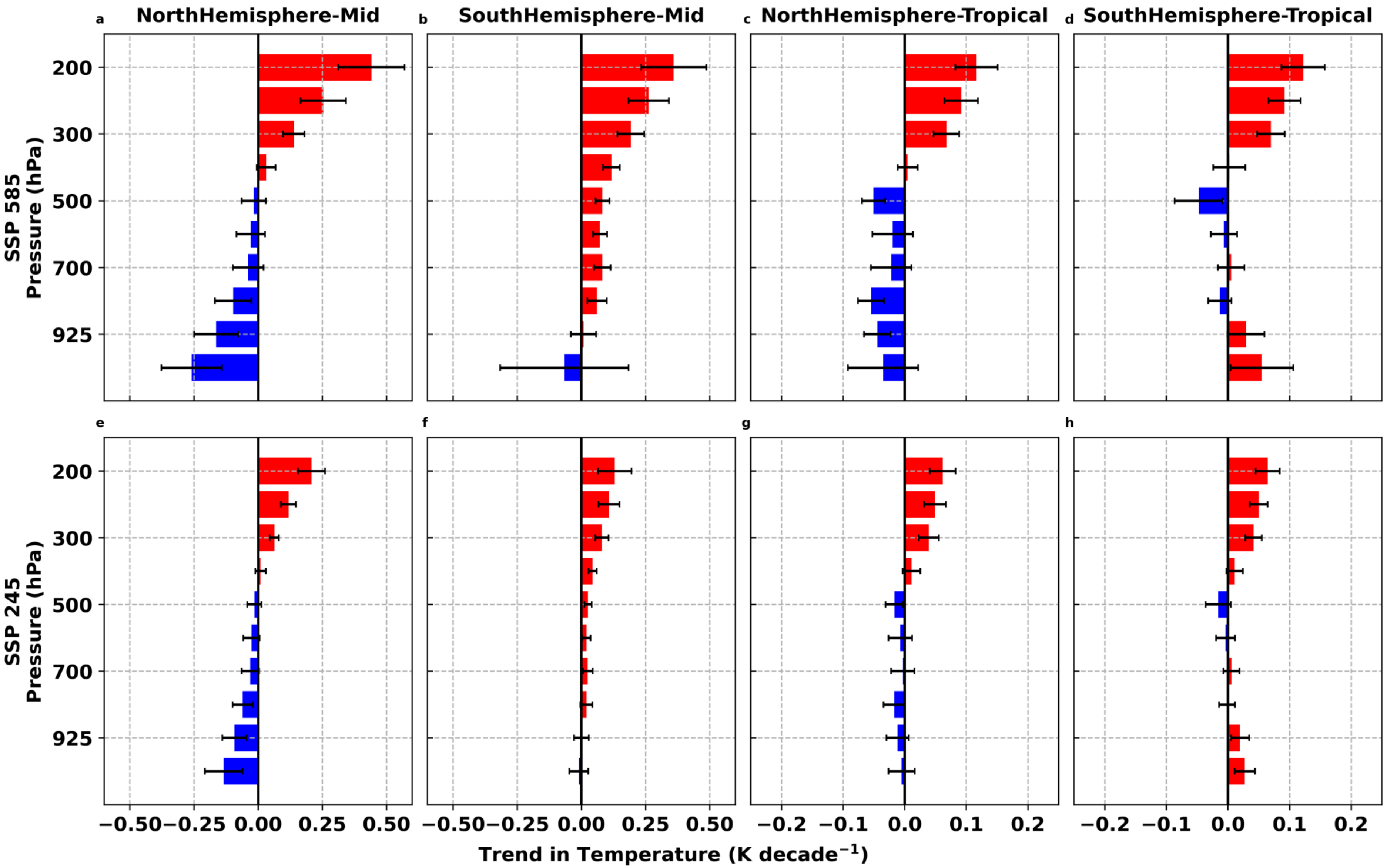
Ens mean of yearly mean trends

$$\text{Shear}_i = \frac{V_{i-1} - V_{i+1}}{z_{i-1} - z_{i+1}}$$

- **NH Mid-Latitudes:**
  - **Negative/Weak trends** in wind speed up to **~350 hPa**.
  - **Increase near 250 hPa** → stronger upper-level jets (Shaw & Miyawaki, 2024).
  - Vertical shear **rises significantly above 250 hPa**.
- **SH Mid-Latitudes:**
  - Continuous increase in wind speed & shear across all levels.



e. Meridional Temperature Gradient



Hemispheric asymmetry reflects contrasting meridional temp. gradients:

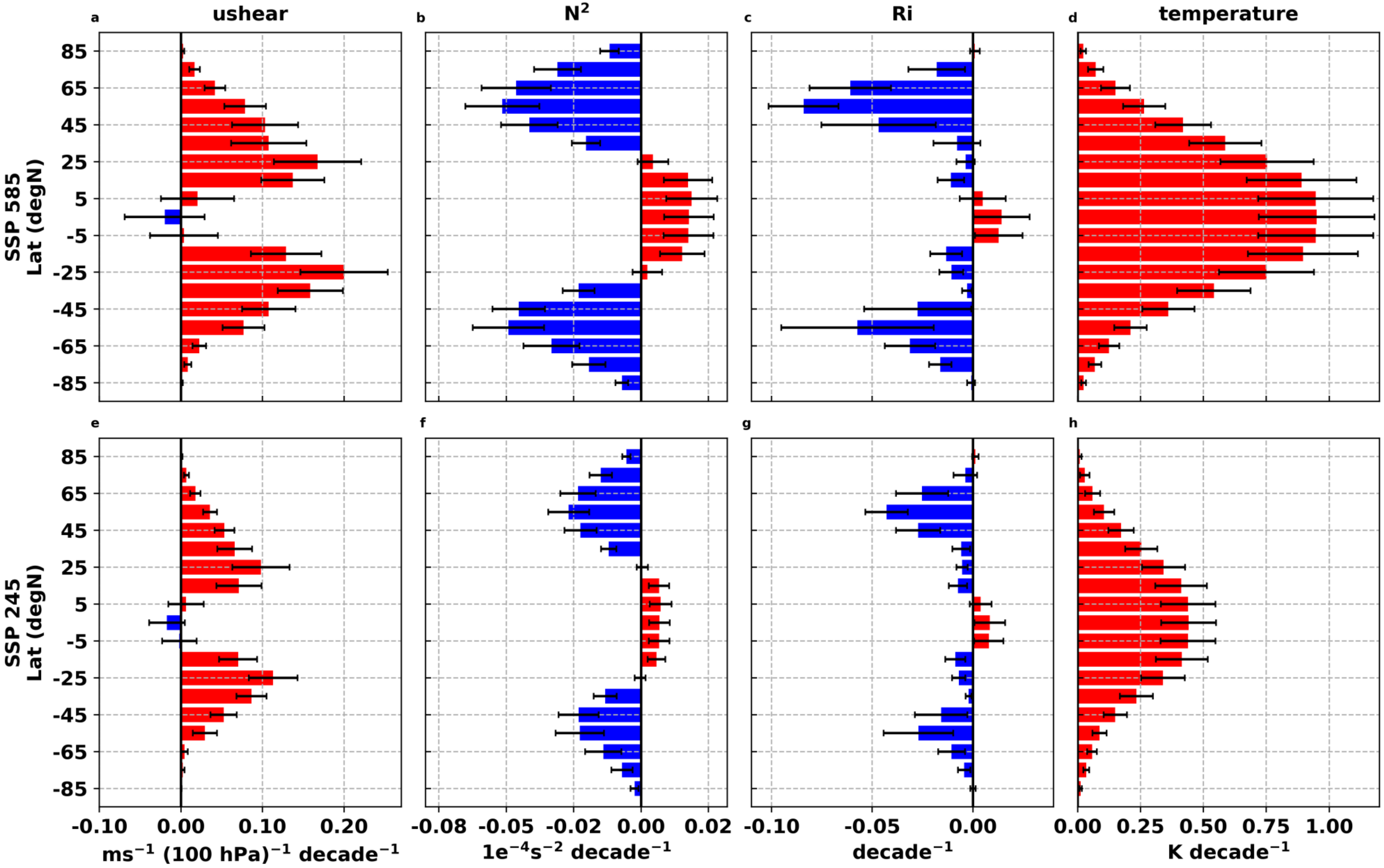
- **NH mid-lats**: Arctic amplification weakens low-level gradients but enhances upper-trop wind shear.
- **SH mid-lats**: Milder gradients, but widespread warming supports positive wind trends at both 200/300 hPa

Aligned with prior findings (Smith et al., 2019; Caporale et al., 2024).

- **Mid latitudes: polar box [50 – 70 °N/S, -180 - 180 °E] – subtropical box [30 – 50 °N/S, -180 - 180 °E]**
- **Tropical latitudes: upper tropical box [15 – 30 °N/S, -180 - 180 °E] - lower tropical box [0 – 15 °N/S, -180 - 180 °E]**

f. Atmospheric Stability (N^2) and Ri @250 hPa

$$N^2 = \frac{g}{\theta}\frac{d\theta}{dz} \qquad \boldsymbol{Ri = \frac{N^2}{shear^2}}$$



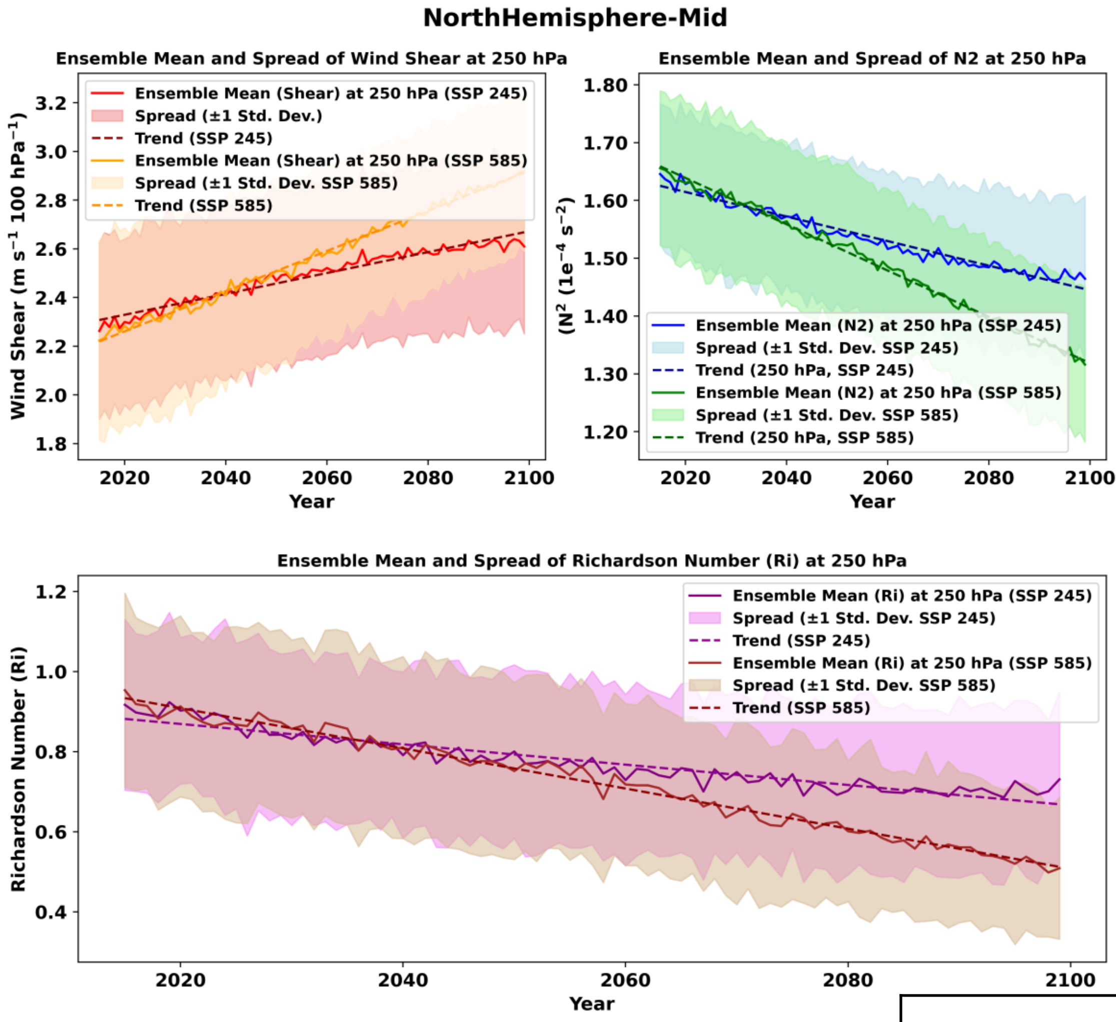
Low Ri (< 1/4) indicates atmospheric instability, promoting turbulence such as Clear Air Turbulence (CAT)

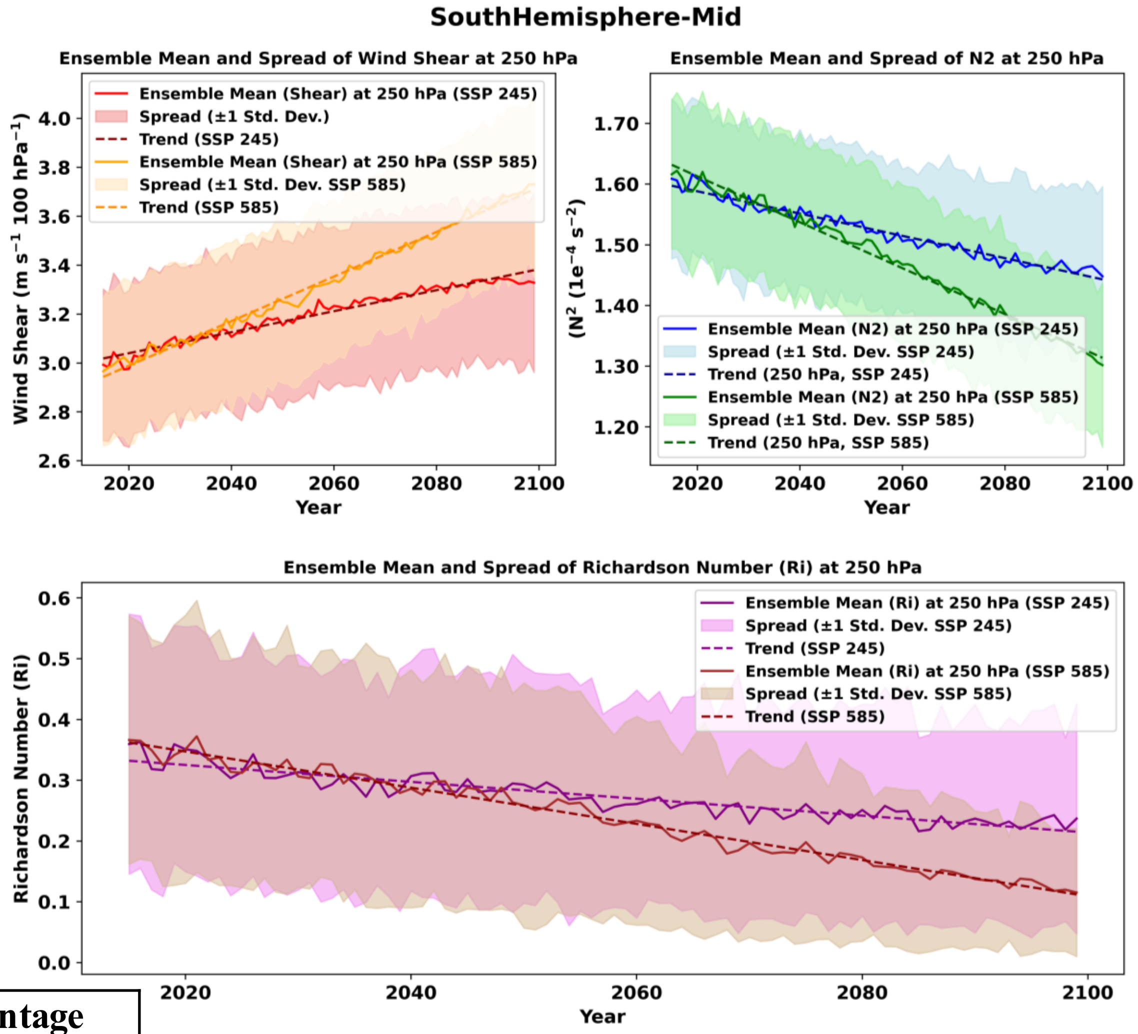
(Sharman & Pearson, 2017)

N^2 trend :

↑ in tropics: upper-trop warming >> sfc warming => increasing dθ/dz

↓ at 50–60°: near sfc warming >> aloft (< dθ/dz) , jet shift, tropopause rise *(Held & Soden 2006; Lu et al. 2008; Shaw et al. 2016)*





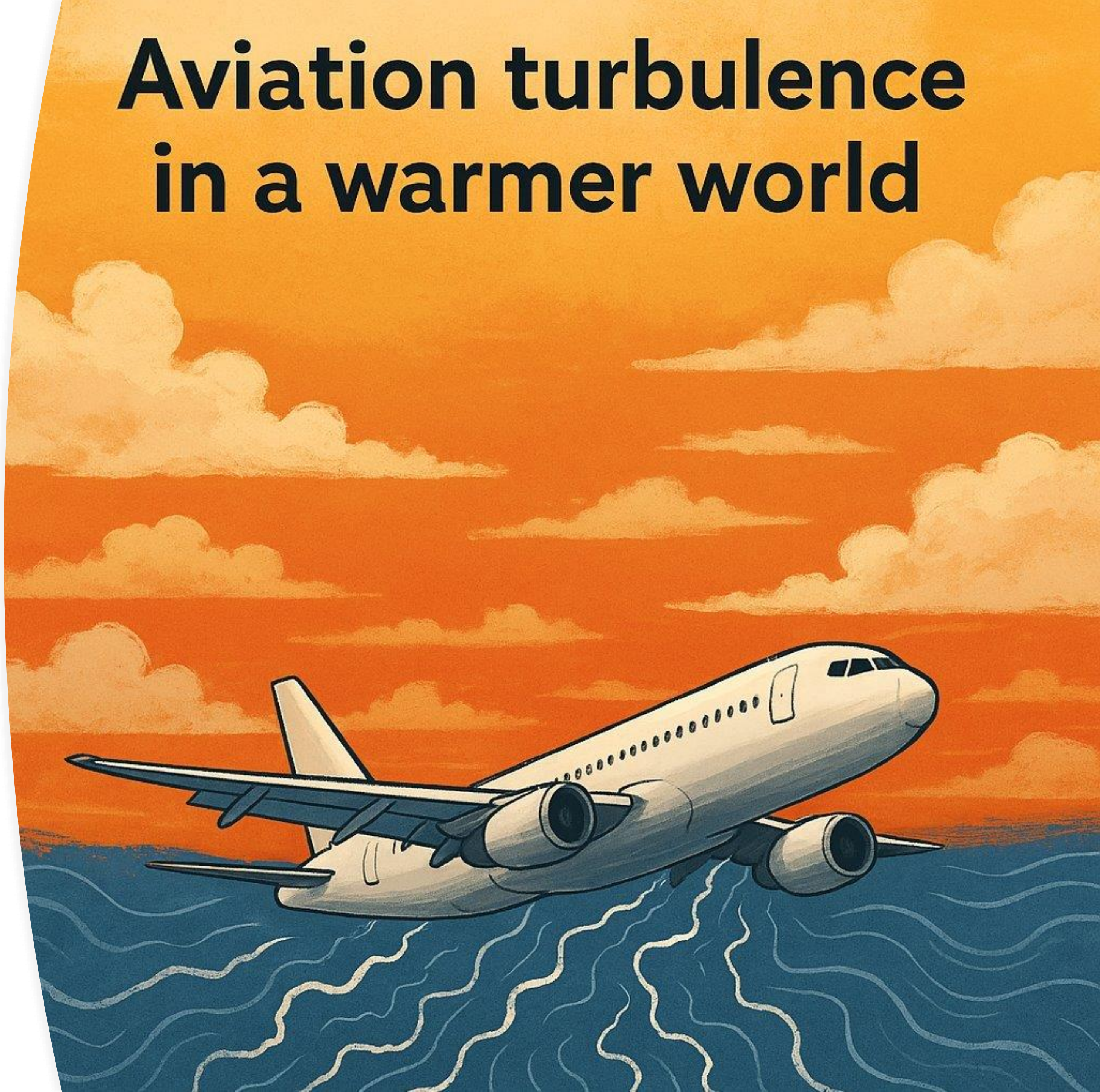
g. Time series and Trends of ushear, N^2 and Ri @250 hPa

	Percentage Change (%)	
Variable	NHM	SHM
Shear (SSP 245)	15	12
N2 (SSP 245)	-10	-9
Ri (SSP 245)	-24	-35
Shear (SSP 585)	31	26
N2 (SSP 585)	-20	-19
Ri (SSP 585)	-45	-69

These changes are indicative of large-scale atmospheric conditions becoming increasingly favorable for turbulence.

Summary & Discussion

- **Rising vertical wind shear** and **decreasing static stability (N^2)** suggest a **greater risk of clear-air turbulence (CAT)** under future climate scenarios.
- These changes, especially near **upper-level jet streams**, create more favorable conditions for turbulence (Sharman et al., 2014; Lee et al., 2023).
- **Smith et al. (2023)** confirm increasing CAT over the North Atlantic (1950–2050, multi-model study).
- While **CMIP6 resolution** limits turbulence representation, trends in **Ri, N^2, and shear** point to real aviation and climate risks.
- **Future work** needs **high-resolution models** or **downscaling** to resolve fine-scale turbulence processes and better assess climate impacts.



REFERENCES

Caporale, Guglielmo Maria and Gil-Alana, Luis A. and Carmona-González, Nieves, Polar Amplification: A Fractional Integration Analysis (2024). CESifo Working Paper No. 11073, Available at SSRN: https://ssrn.com/abstract=4803860 or http://dx.doi.org/10.2139/ssrn.4803860

Held, I. M., and B. J. Soden, 2006: Robust Responses of the Hydrological Cycle to Global Warming. J. Climate, 19, 5686–5699, https://doi.org/10.1175/JCLI3990.1

Huang, J., E. Bou-Zeid, and J. Golaz, 2013: Turbulence and Vertical Fluxes in the Stable Atmospheric Boundary Layer. Part II: A Novel Mixing-Length Model. J. Atmos. Sci., 70, 1528–1542, https://doi.org/10.1175/JAS-D-12-0168.1

Knox, J. A., 1997: Possible Mechanisms of Clear-Air Turbulence in Strongly Anticyclonic Flows. Mon. Wea. Rev., 125, 1251–1259, https://doi.org/10.1175/1520-0493(1997)125<1251:PMOCAT>2.0.CO;2

Lee, S. H., Williams, P. D., & Frame, T. H. A. (2019). Increased shear in the North Atlantic upper-level jet stream over the past four decades. Nature, 572(7769), 639–642.

Lee, J. H., Kim, J.-H., Sharman, R. D., Kim, J., & Son, S.-W. (2023). Climatology of Clear-Air Turbulence in upper troposphere and lower stratosphere in the Northern Hemisphere using ERA5 reanalysis data. Journal of Geophysical Research: Atmospheres, 128, e2022JD037679. https://doi.org/10.1029/2022JD037679

Lu, J., G. A. Vecchi, and T. Reichler (2007), Expansion of the Hadley cell under global warming, Geophys. Res. Lett., 34, L06805, doi:10.1029/2006GL028443

Lv, J., Wang, J., Chen, H., & Li, J. (2021). Projected increase in severe turbulence over North Atlantic flight routes. Environmental Research Letters, 16(9), 094026.

Shapiro, M. A. (1980). Turbulence and waves in the atmosphere. Annual Review of Fluid Mechanics, 12, 183–210.

Sharman, R.D., Cornman, L.B., Meymaris, G., Pearson, J., Farrar, T.: Description and derived climatologies of automated in situ eddy dissipation rate reports of atmospheric turbulence. J. Appl. Meteorol. Climatol. 53, 1416–1432 (2014)

Shaw, T. A., & Miyawaki, O. (2024). Fast upper-level jet stream winds get faster under climate change. Nat. Clim. Chang., 14, 61–67. https://doi.org/10.1038/s41558-023-01884-1

Shaw, T. A., Baldwin, M., Barnes, E. A., Caballero, R., Garfinkel, C. I., Hwang, Y.-T., ... & Voigt, A. (2016). Storm track processes and the opposing influences of climate change. Nature Geoscience, 9(9), 656–664. https://doi.org/10.1038/ngeo2783

Simpson, I. R. (2016). Climate change predicted to lengthen transatlantic travel times. *Environmental Research Letters, 11*(3), 031002. https://doi.org/10.1088/1748-9326/11/3/031002

Smith, I.H., Williams, P.D. & Schiemann, R. Clear-air turbulence trends over the North Atlantic in high-resolution climate models. Clim Dyn 61, 3063–3079 (2023). https://doi.org/10.1007/s00382-023-06694-x

Stohl, A., et al. (2003), Stratosphere-troposphere exchange: A review, and what we have learned from STACCATO, J. Geophys. Res., 108, 8516, doi:10.1029/2002JD002490, D12

Williams, P. D., & Joshi, M. M. (2013). Intensification of winter transatlantic aviation turbulence in response to climate change. Nature Climate Change, 3(7), 644–648.

Williams, P. D., 2017: Increased light, moderate, and severe clear-air turbulence in response to climate change. Adv. Atmos. Sci., 34(5), 576–586, doi:10.1007/s00376-017-6268-2