

# Interannual co-variability of gravity waves, vertical wind shear and turbulence in the lowermost stratosphere over the North Atlantic

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## Introduction

The tropopause separates the well-mixed troposphere from the stably stratified stratosphere and can be defined through various definitions. At mid-latitudes a distinct chemical transition layer is evident from trace gas observations (e.g., Hoor et al. 2004). This transition layer is formed by frequent occurrence of vertical shear which leads to a turbulence in the tropopause region (Kaluza et al. 2021, 2022). In consequent studies, the focus has shifted towards the contribution of small-scale (unbalanced) dynamics which are often associated with gravity waves (Umbarkar and Kunkel, 2025; Umbarkar et al., 2026). An open question is, however, can this GWs contribute to the formation and maintenance of Extratropical transition layer (ExTL) and thereby to the large-scale processes in the extratropics? This study investigates the critical role of GWs in enhancing vertical wind shear and facilitating turbulent mixing in the LMS, thereby contributing to the formation of the ExTL.

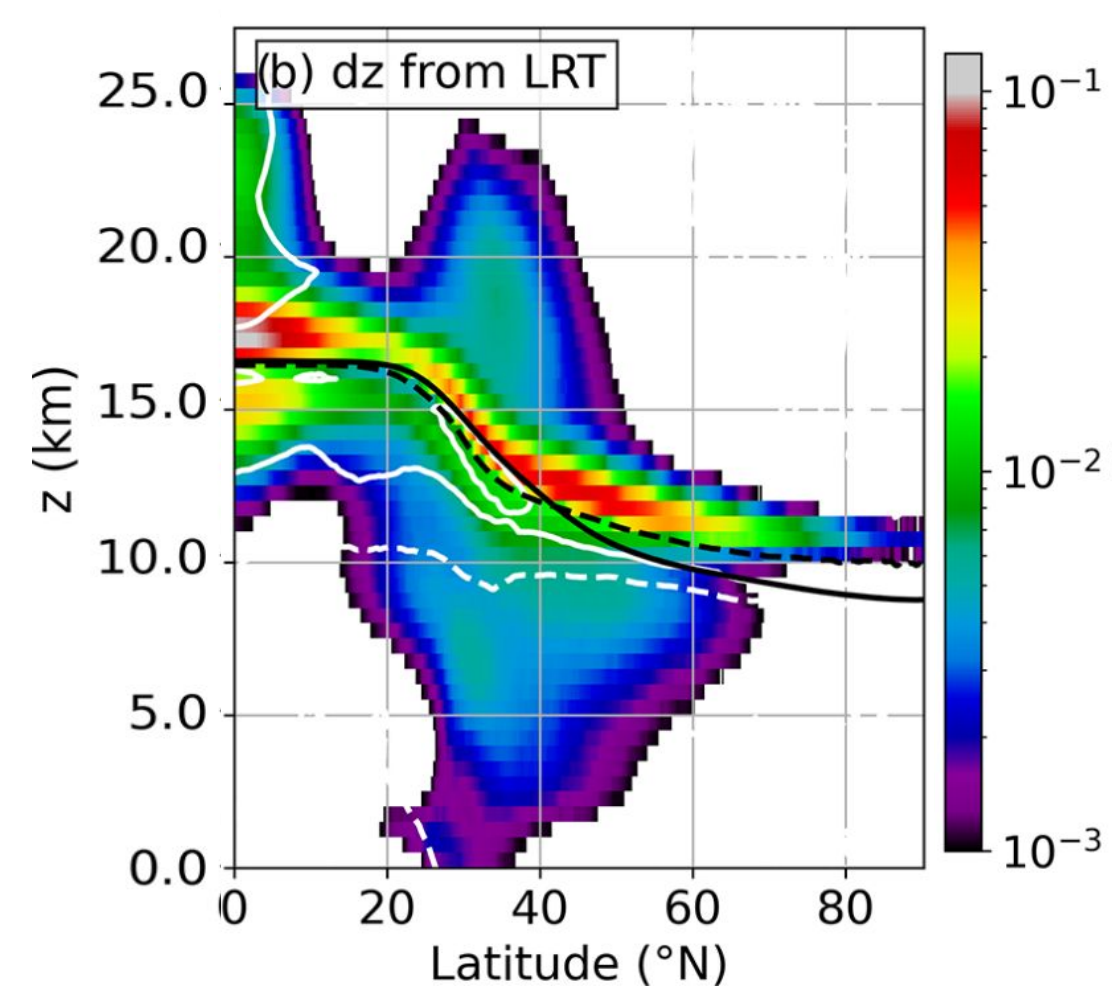


Fig. 1: A 10-year ERA5 climatology from Kaluza et al. 2021 showing tropopause shear layer w.r.t. occurrence frequency distribution of strong vertical wind shear

### Central Question:

**Can small-scale GWs persistently alter the tropopause shear layer, be attributed to the ExTL dynamics and thereby to the large-scale processes?**

## Methodology & Study Region

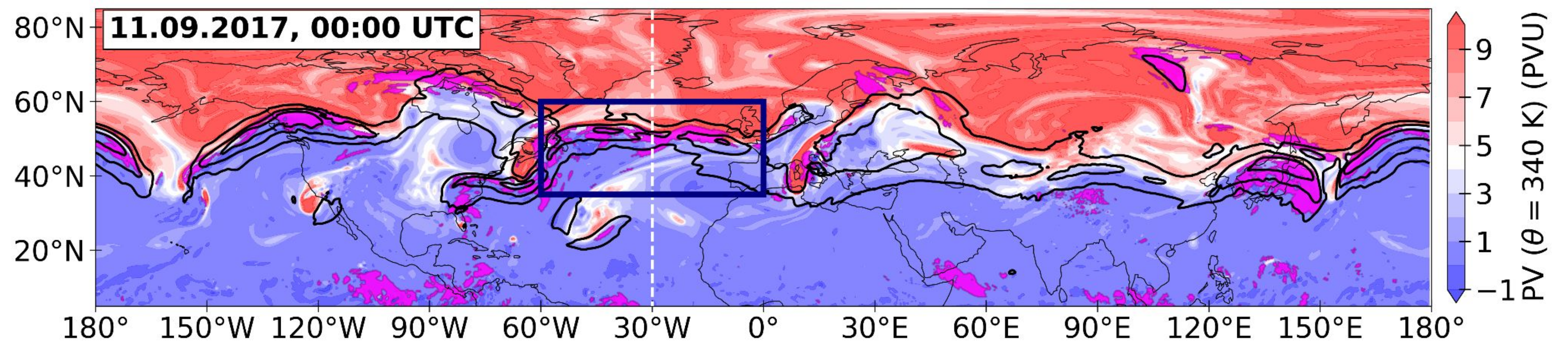


Fig. 2: Potential vorticity (PV) at  $\Theta = 340$  K over the Northern Hemisphere on 11 September 2017, 00:00 UTC. Black lines show contours of the horizontal wind  $\geq 30$  m s<sup>-1</sup>. Magenta shaded areas represent regions of  $S^2 \geq 4 \times 10^{-4}$  s<sup>-2</sup>, between 3.5 PVU dynamical tropopause and 1.5 km above.

GW induced absolute momentum flux

$$\rho \sqrt{(\overline{u'w'})^2 + (\overline{v'w'})^2}$$

Vertical shear perturbations

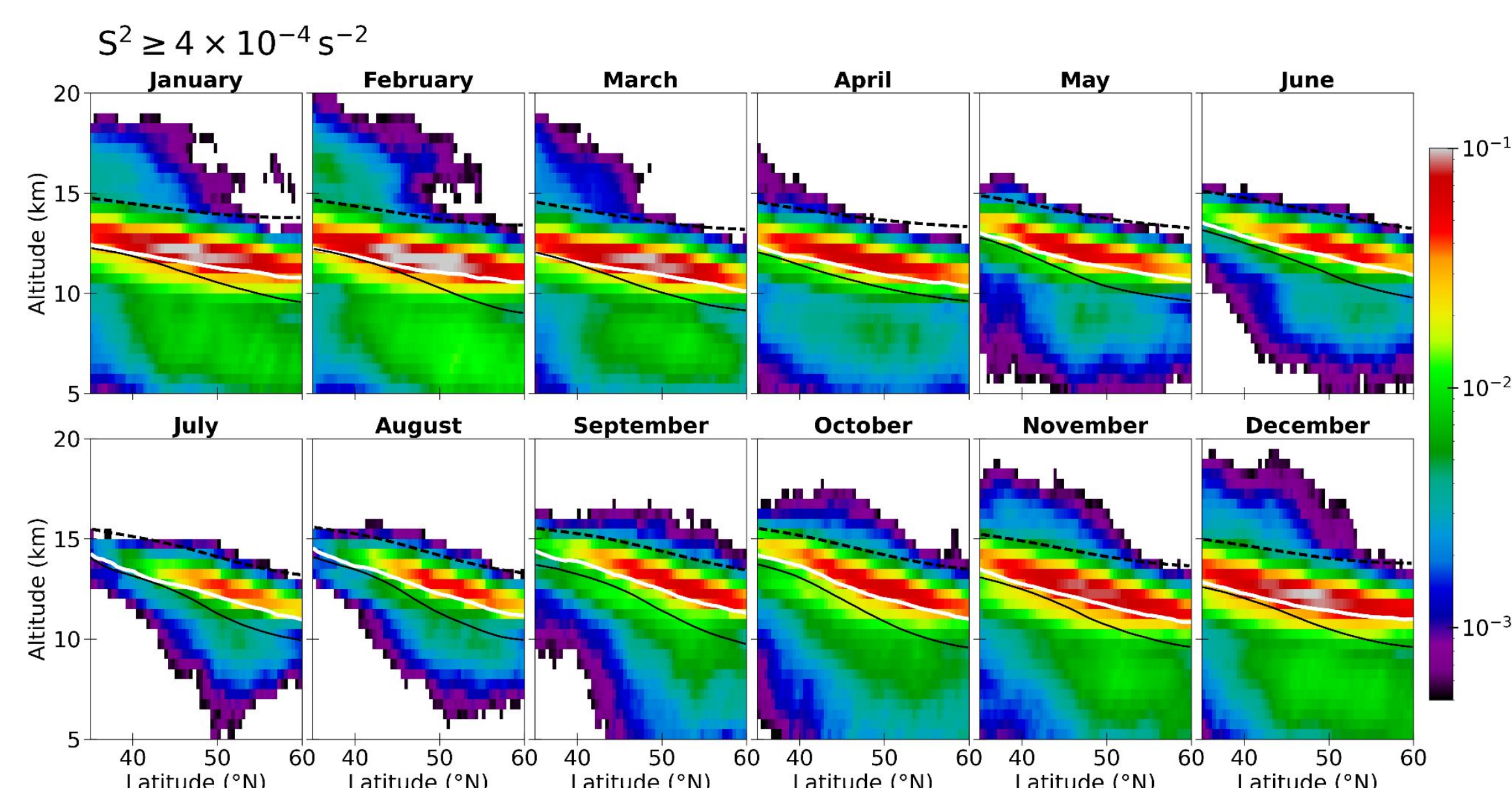
$$\left(\frac{\partial u'}{\partial z}\right)^2 + \left(\frac{\partial v'}{\partial z}\right)^2$$

... where  $\rho$  = density,  $u', v', w'$  = zonal, meridional and vertical velocity perturbations  
Overbar denotes the low-pass filtering of the quadratic quantities

ERA5 reanalysis data: T639 (~31 km), 137 levels from surface to 0.01 hPa, hourly resolution, 10 years climatology from 1 January 2016 to 31 December 2025

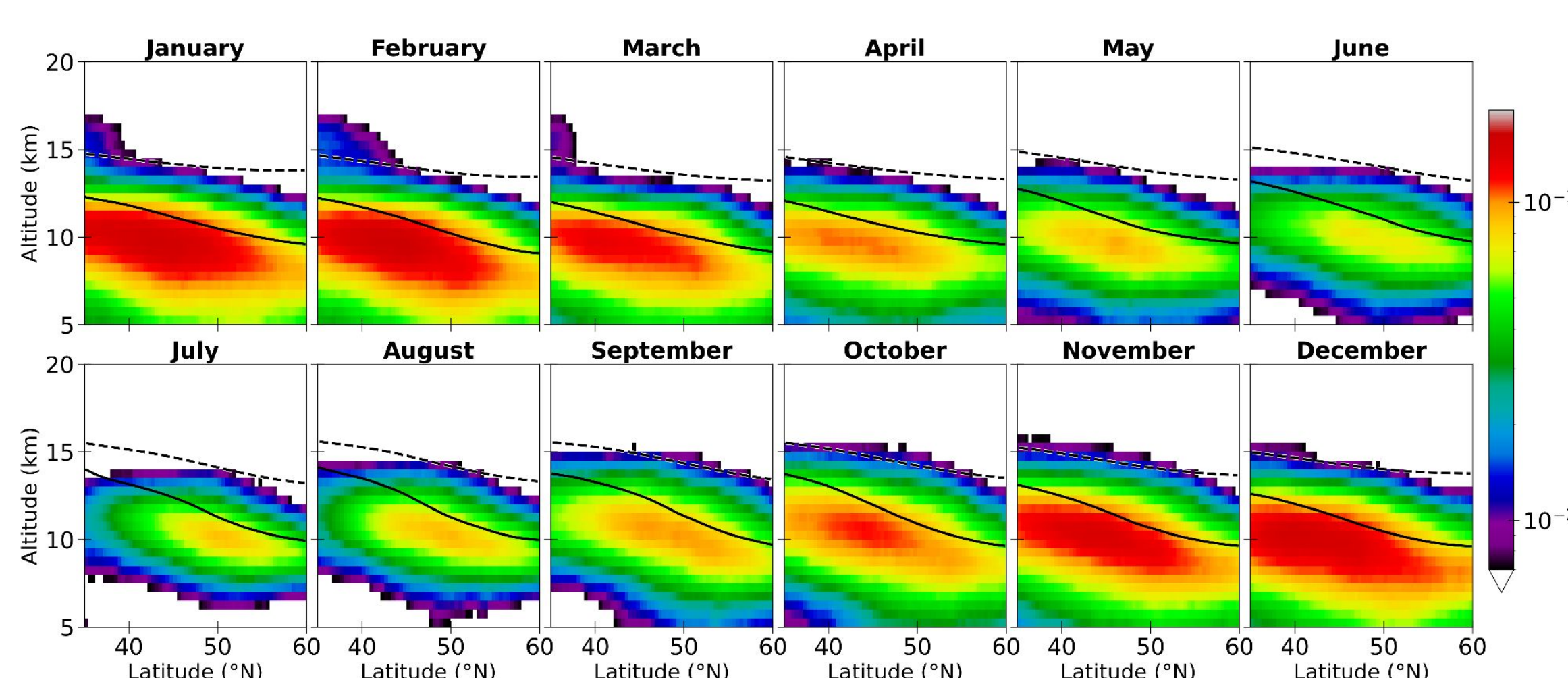
## On the co-occurrence of GWs and Tropopause shear layer in the extratropics

### • The Tropopause Shear Layer and turbulence occurrences



Left: Fig. 3: A 10-year ERA5 climatology showing (top) tropopause shear layer w.r.t. occurrence frequency distribution of strong vertical wind shear, and (bottom) layers of potential turbulence occurrences

The TSL exhibit an annual cycle with minimum (maximum) occurrences of the enhanced shear are found during summer (winter).



The vertical wind shear leads to low Richardson number above the tropopause where static stability (N²) gets large!

### • GWs, shear and shear perturbations prone to potential turbulence: Coincidental or correlated?

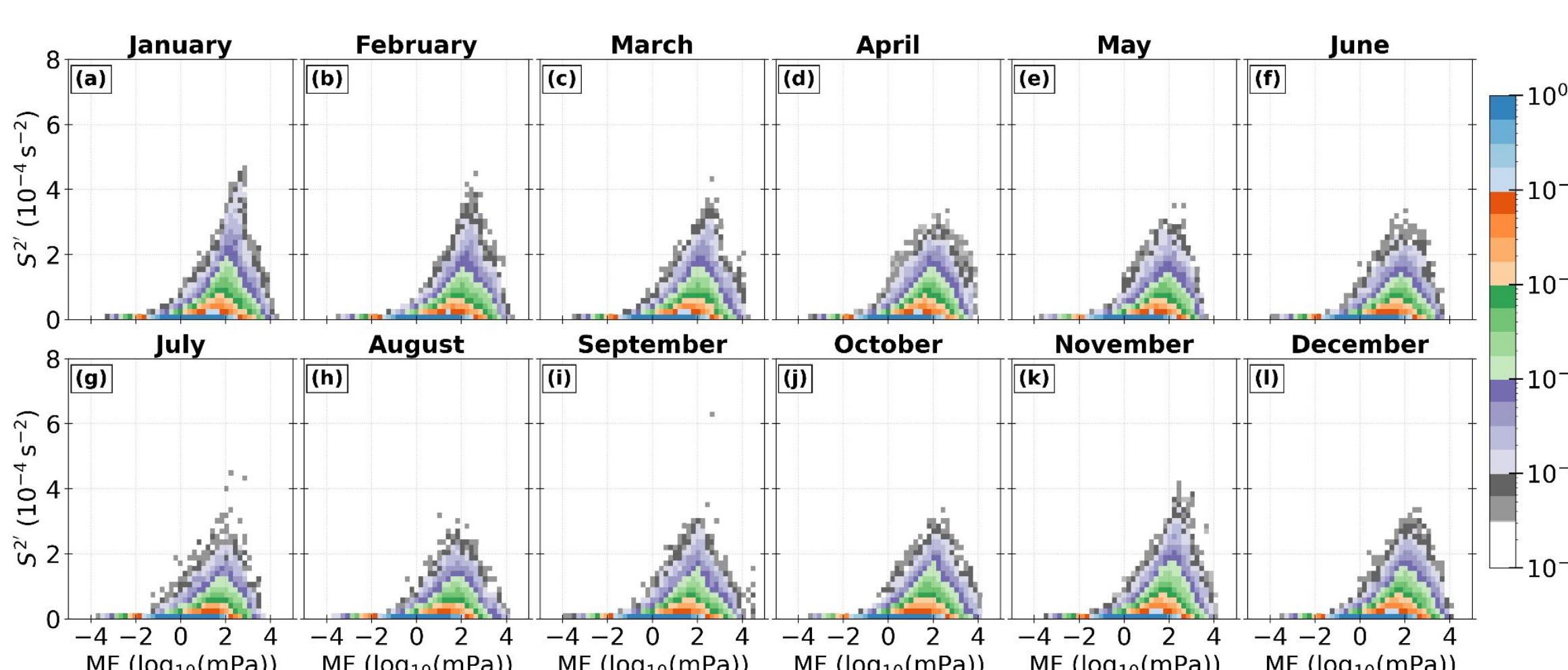
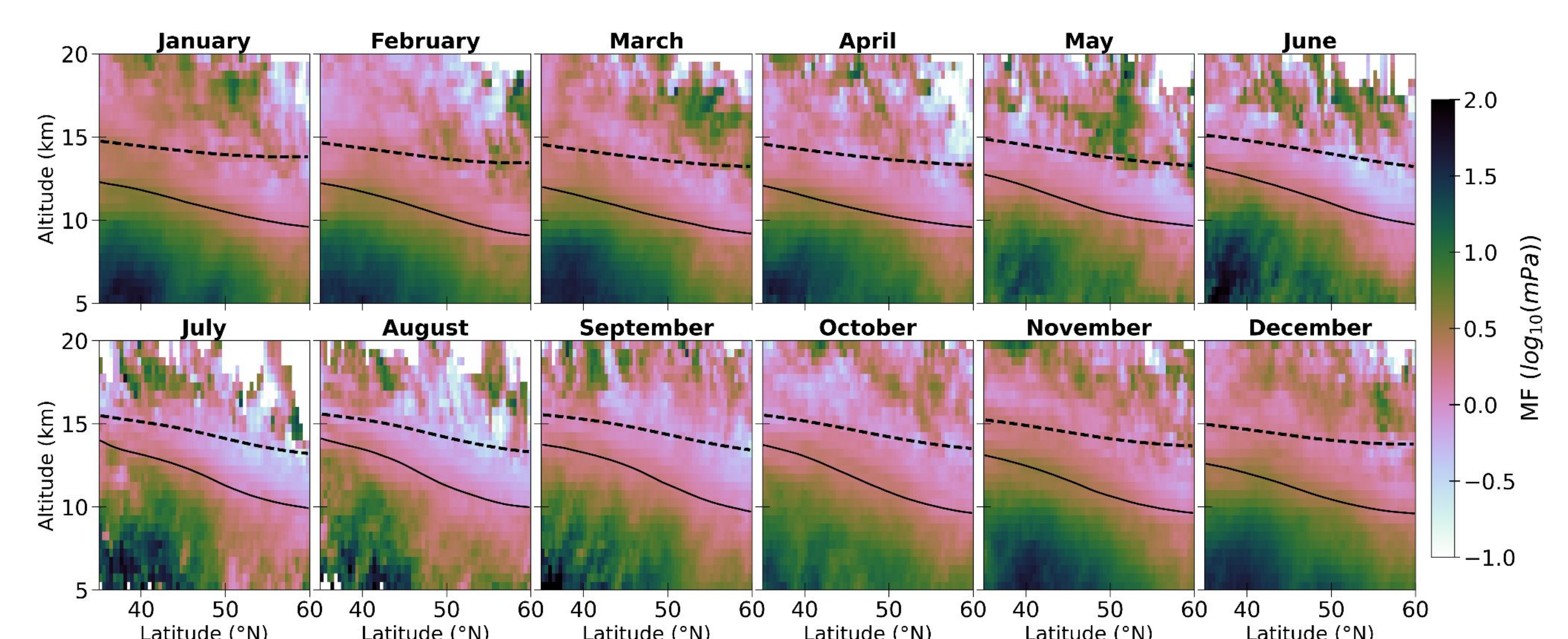
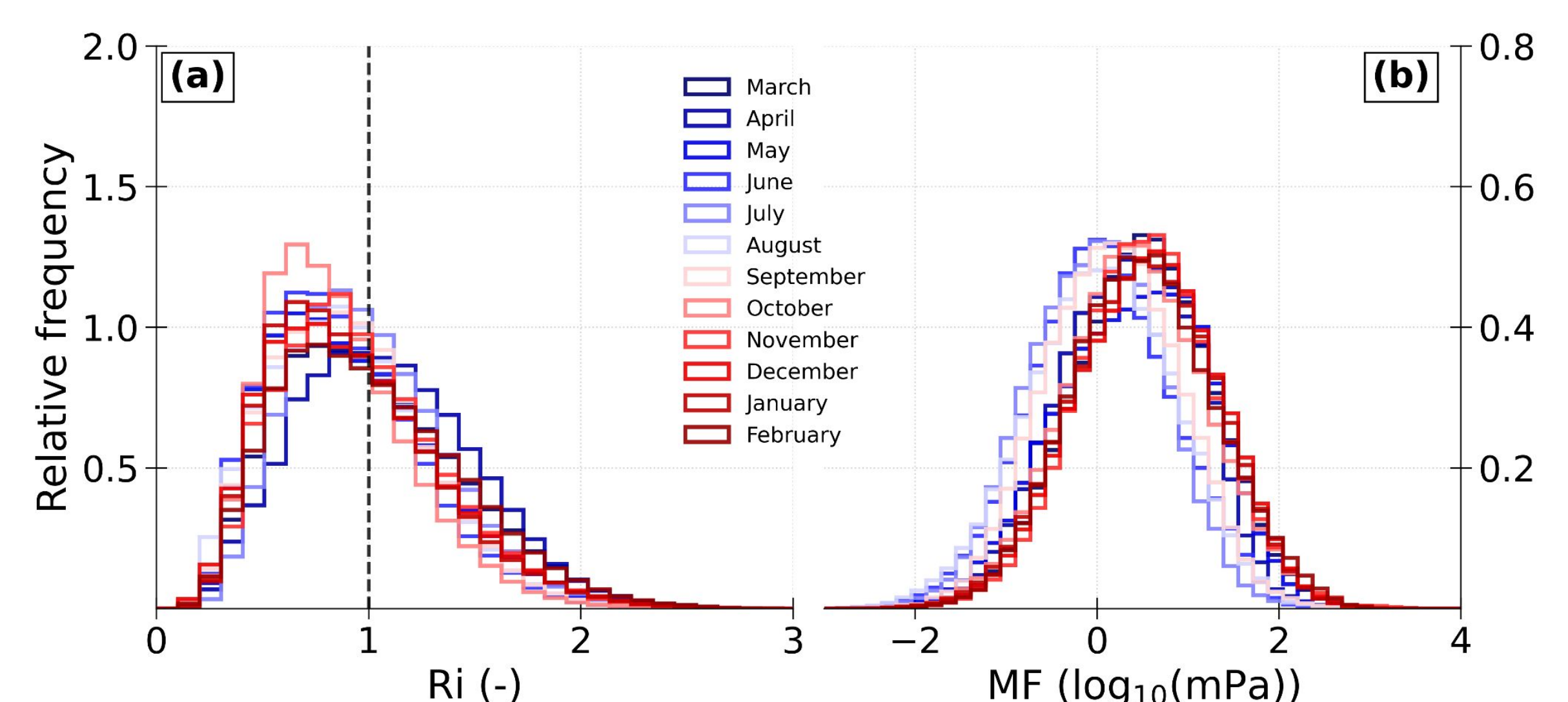


Fig. 5: Relative occurrence frequency distribution of absolute GW momentum flux and vertical shear perturbation pairs in the LMS for  $0 \leq Ri \leq 1$  over the North Atlantic counted over ten years

### • Vertical distribution of GW momentum flux



Right: Fig. 4: Top: A 10-year ERA5 climatology showing (top) absolute GW momentum flux conditioned over the region of  $S^2 \geq 4 \times 10^{-4}$  s<sup>-2</sup> in the LMS. Bottom: Relative occurrence frequency distribution of (a) Ri associated with  $S^2 \geq S^2_c$  and (b) the logarithm of absolute momentum flux conditioned with  $0 \leq Ri \leq 1$  displayed in panel (a) in the LMS averaged over ten years from March (blue) February (red). The black dashed line in (a) represent  $Ri=1$ .



### Key takeaways:

- GW momentum fluxes and turbulence diagnostics reveal the distinct seasonality above the North Atlantic extratropical tropopause.
- The quasi-climatological distribution of GW activity and associated shear highlights that GW specifically play an important role in the formation and maintenance of the TSL.
- We provide statistical evidence that ERA5 resolved GW activity is associated with the small-scale component of enhanced shear and may contribute to the occurrence of dynamically unstable shear layers, and thereby, to conditions favorable for dynamic instability and clear-air turbulence generation in the LMS.

**GW-induced shear is a key driver of upper troposphere lower stratosphere transport and mixing, hence could play a crucial role in the modulation of the extratropical transition layer!**

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