Ambient Turbulence and Canopy Wave Generation by Kelvin-Helmholtz Instability

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Questions?
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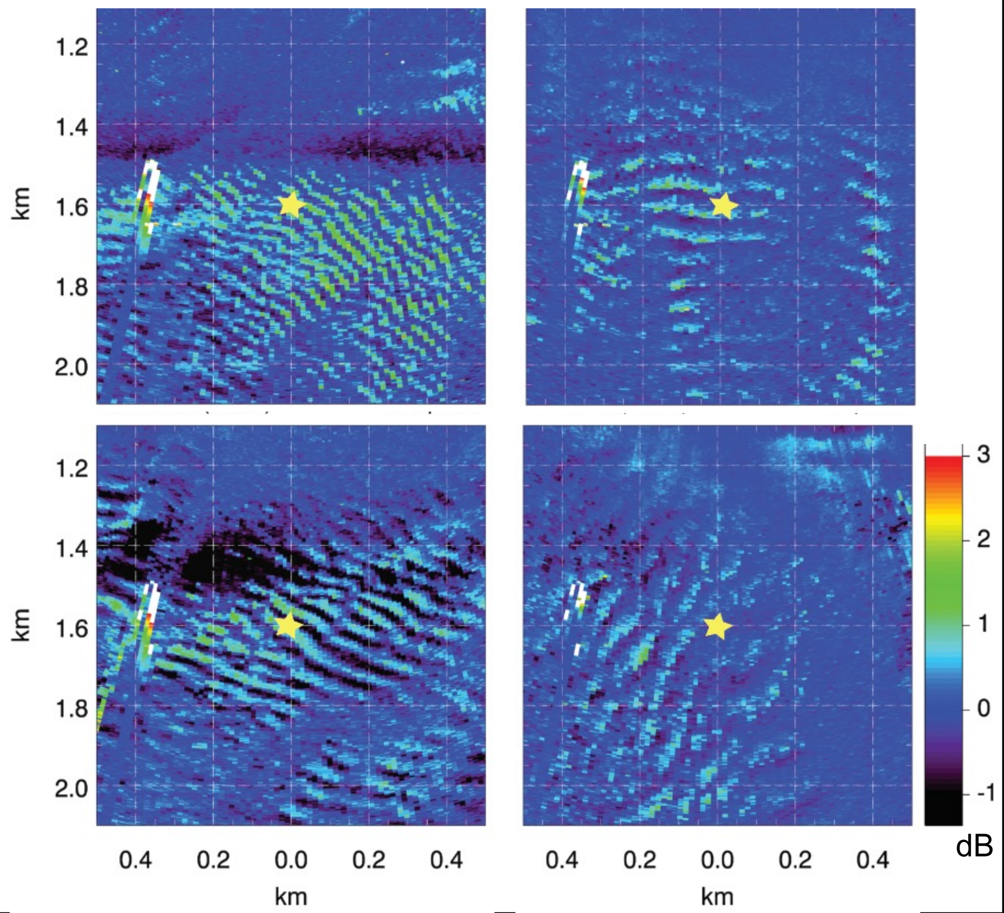
Introduction

We test the hypothesis that internal waves observed in flow over forest canopies are generated by Kelvin-Helmholtz instability.

- Waves were observed at night, under stably stratified and weak wind conditions, with a horizontally scanning aerosol lidar and an instrumented tower.
- Lidar images determine the time, wavelength and phase propagation velocity of each episode.
- Tower data provide vertical profiles of background velocity and buoyancy just before each wave event. Profiles are input to an extended Taylor-Goldstein equation to predict phase velocity, wavelength and period of the fastest-growing linear instability.
- Observed wavelengths are longer than predicted by the Taylor-Goldstein theory, typically by a factor of two. That discrepancy is removed when the theory is extended to account for the effects of ambient, small-scale turbulence.

Fig. 1 Canopy waves observed by the REAL during CHATS. The star in the middle of each panel indicates the position of the 30-m tower from which *in situ* data were obtained.



KH Instability theory

Normal mode perturbation

$$w'(x,y,z,t) = \mathrm{Real}[\ \hat{w}(z)\ e^{\sigma t + \imath(kx+\ell y)}\ ]$$

applied to background wind $U(z)$ and buoyancy $B(z)$:

$$\sigma \begin{bmatrix} \nabla^2 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{w} \\ \hat{b} \end{bmatrix} = \begin{bmatrix} -\imath kU\nabla^2 + \imath k \frac{d^2U}{dz^2} + T_w + V_w & -k^2 \\ -\frac{dB}{dz} & -\imath kU + T_b + V_b \end{bmatrix} \begin{bmatrix} \hat{w} \\ \hat{b} \end{bmatrix}$$

where: $\nabla^2 = \frac{d^2}{dz^2} - k^2$

Vegetation effects (Lee 1997):

$$V_w = -C_d \frac{d}{dz}\left[L_f|U|\frac{d}{dz}\right] + k^2 C_d L_f |U|; \quad V_b = -C_h L_f |U|.$$

L_f = leaf fraction

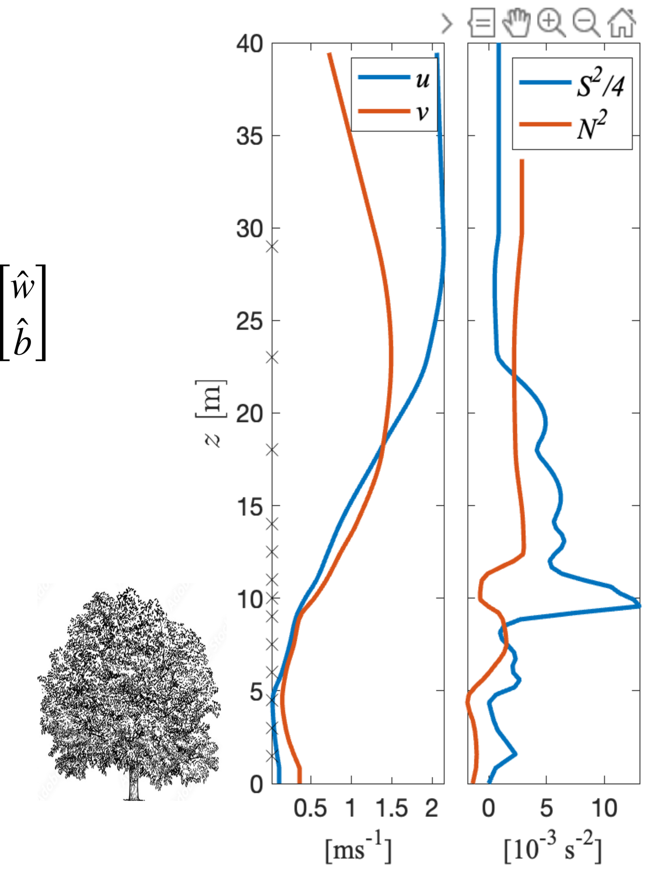
Ambient turbulence effects:

$$T_w = A\nabla^4; \quad T_b = K\nabla^2$$

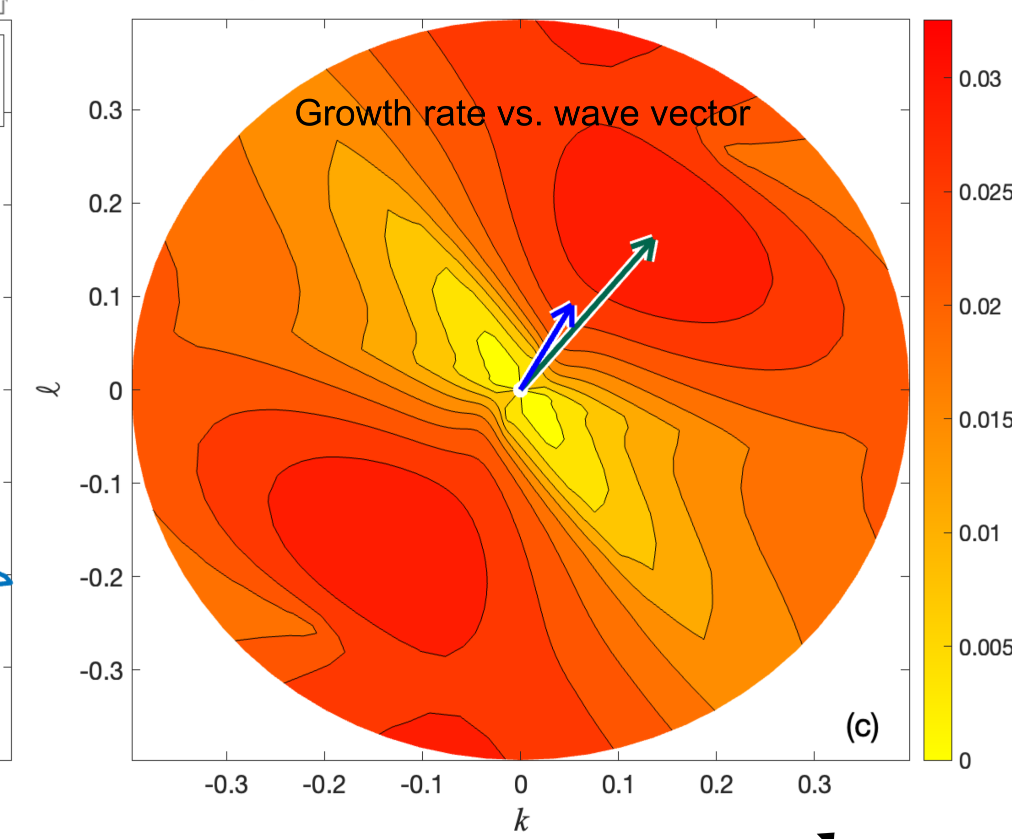
A = uniform eddy viscosity

K = uniform eddy diffusivity

Sample episode



Taylor-Goldstein model: $T = V = 0$



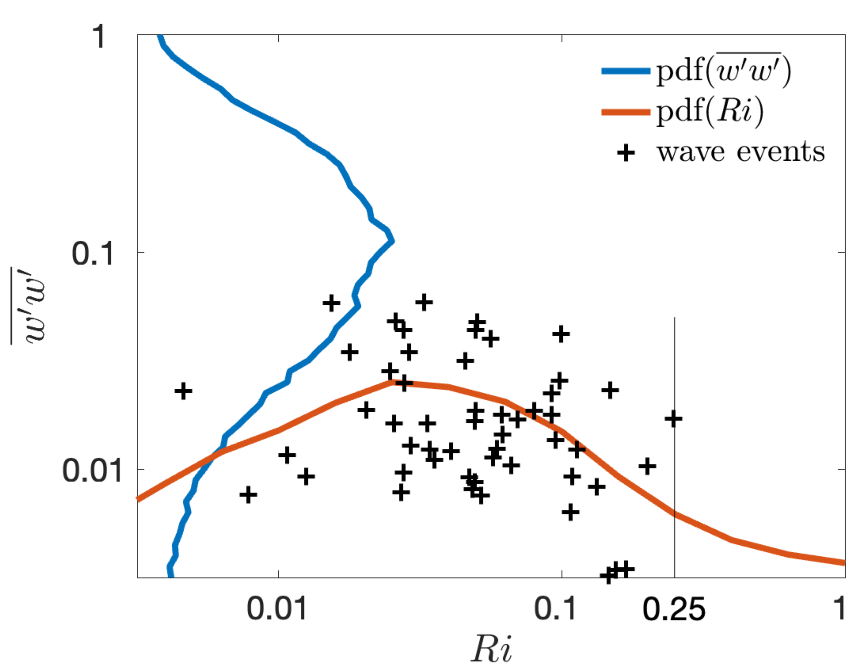
Just above treetop height:

- Strong shear
- Weak stratification

Fastest-growing KH mode:

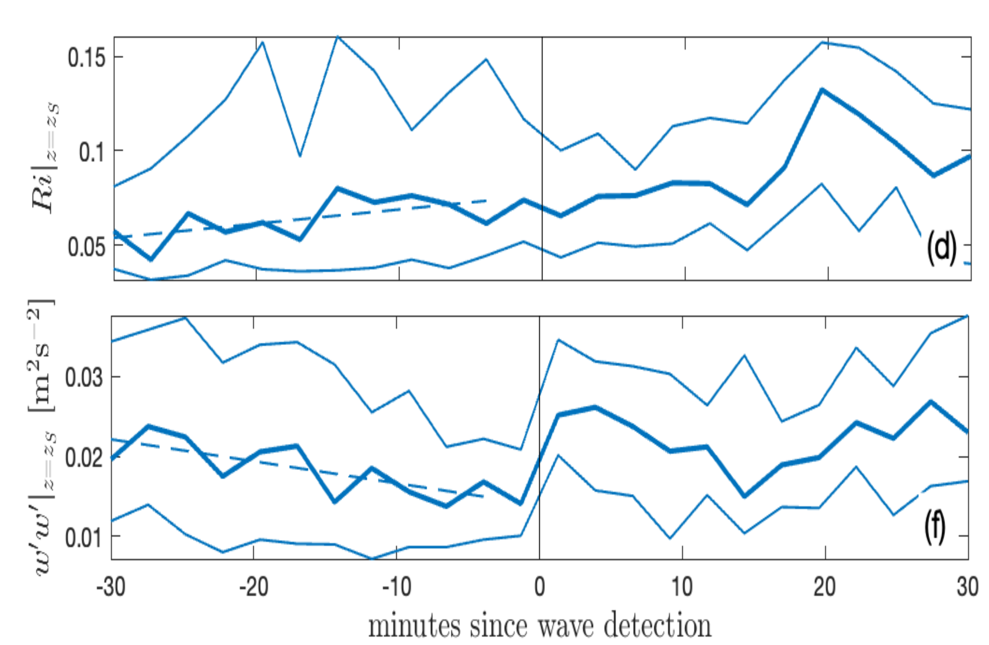
- Direction matches observation
- But wavelength too short by half.

Background conditions



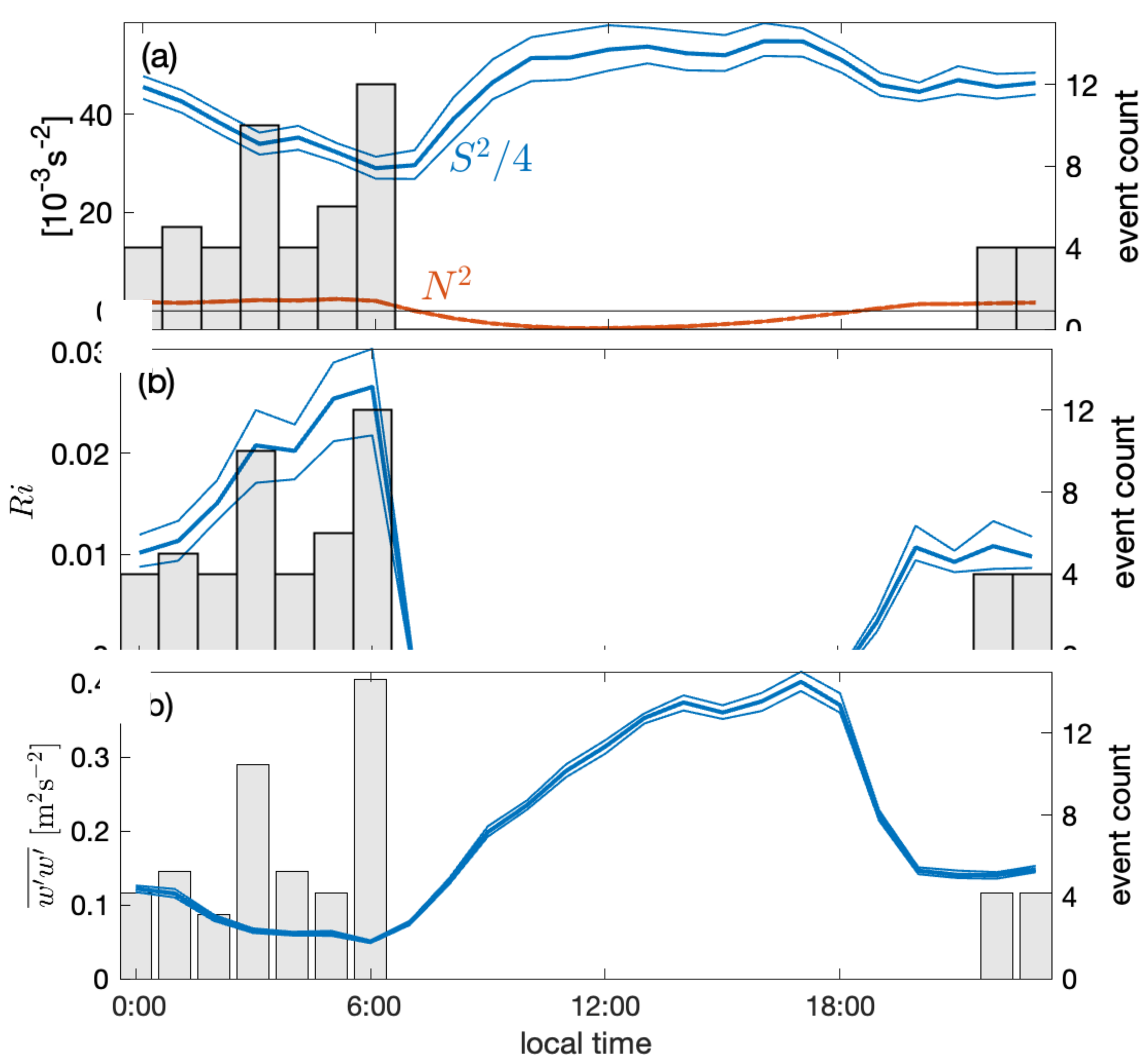
Waves emerge when surface layer is:

- Weakly sheared: Richardson number Ri is slightly larger than usual but < 0.25.
- Calm: Vertical velocity variance $\overline{w'w'}$ is smaller than usual.



Events are preceded by:

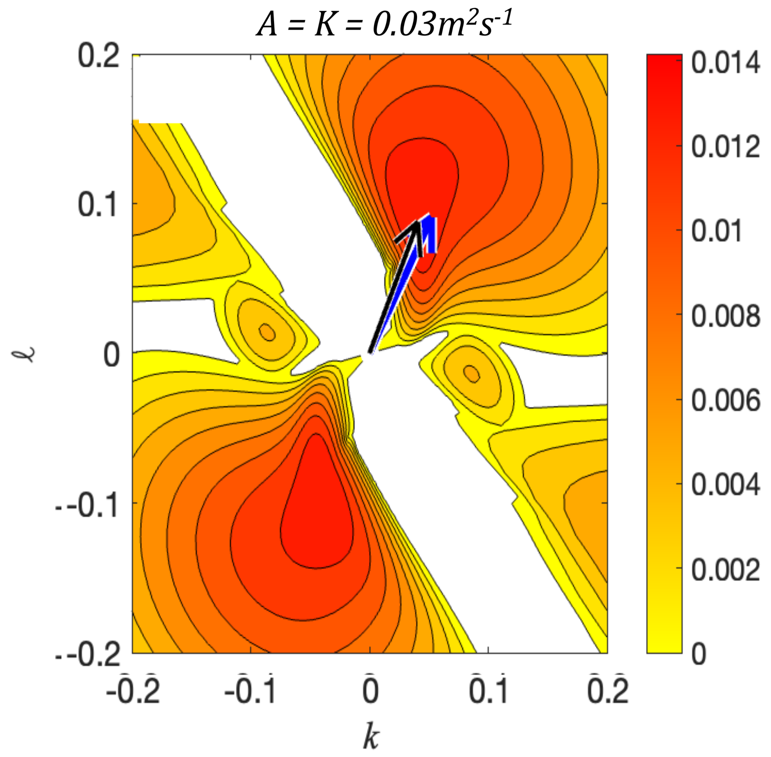
- increasing Ri,
- decreasing $w'w'$.



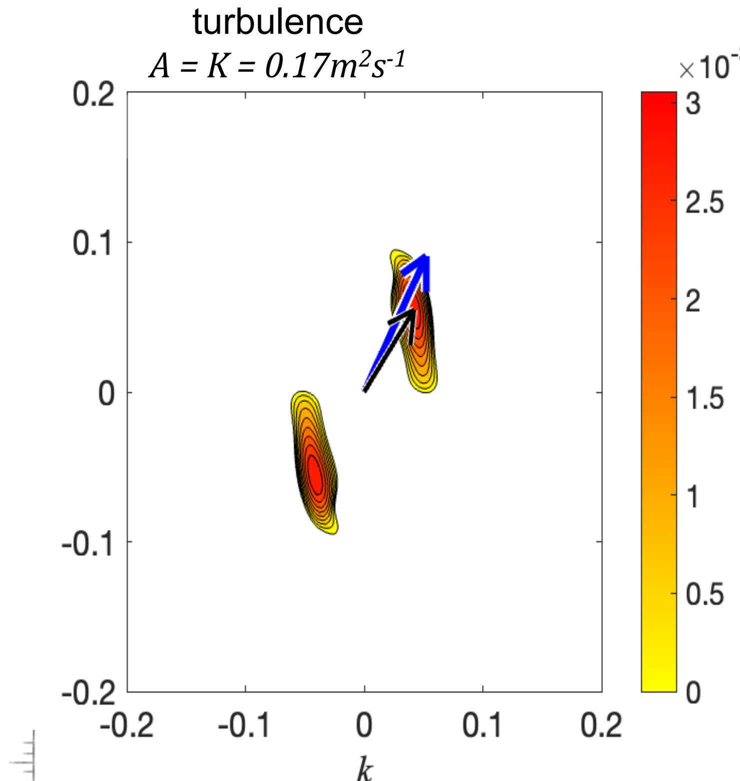
Calm, weakly sheared conditions conducive to wave growth are most common just before sunrise.

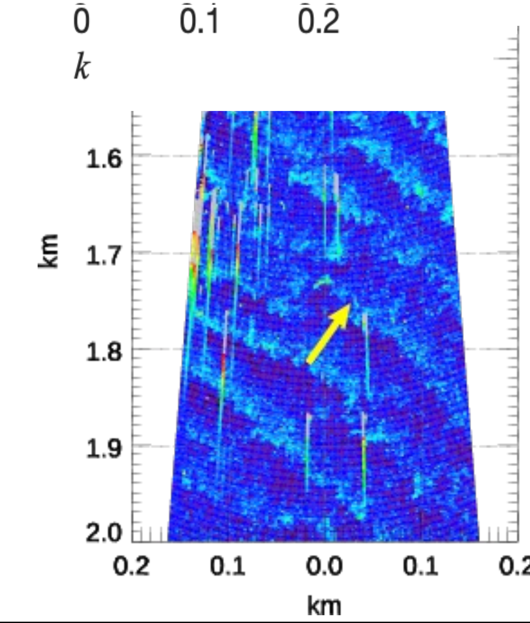
Ambient turbulence effects

Weak turbulence
$A = K = 0.03 m^2 s^{-1}$

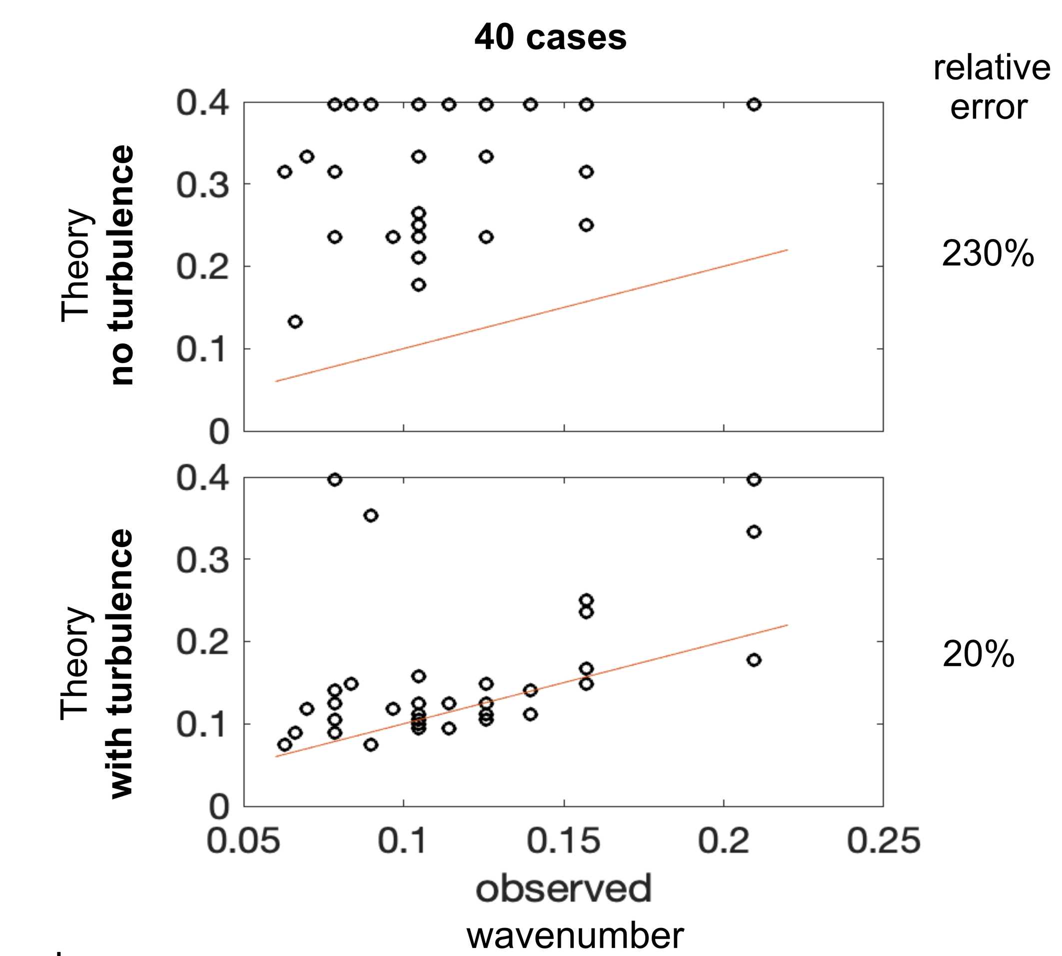


Strong turbulence
$A = K = 0.17 m^2 s^{-1}$





With turbulence, wavelength matches observations



Turbulence damps small scales
→ favors longer wavelengths.

(Vegetation effects are scale-independent,
→ have little effect on wavenumber.)

References

Lee X, 1997: Gravity waves in a forest: A linear analysis. *J Atmos Sci* 54:2574–2585.
Mayor SD, 2017: Observations of microscale internal gravity waves in very stable atmospheric boundary layers over an orchard canopy, *Agric. For Meteorol.* 244-245:136-150.
Smyth, WD, SD Mayor and Q Lian, 2022: The role of ambient turbulence in canopy wave generation by Kelvin-Helmholtz instability, *Boundary Layer Met.* (in review).

Conclusions

1. Canopy waves occur when ambient turbulence is weak enough to permit their growth. This state is often reached just before sunrise.
2. Canopy waves may be understood as KH billows only when the effects of ambient turbulence are accounted for.