The importance of theoretical tools as guidance for turbulence measurements in the Atmospheric Boundary Layer

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Thanks

For inviting me here.

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Intersection of surface flux measurement interests

Many scientific communities have interest in surface fluxes:

Meteorologists Because they need the surface boundary conditions for weather and climate,

Hydrologists Because evapotranspiration is a missing link in Hydrology,

Ecologists Because NEE and GPP are key variables to understand ecosystems,

Agronomists Because evapotranspiration is essential for crop productivity,

Environmental Engineers Because of air pollution,

etc.

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Turbulence measurements in the ABL can bring important contributions to many fields

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Examples drawn from contributions to the field (based on my personal experience).

Atmospheric Turbulence

Different approaches

- **Theoretical** The ABL is a "natural laboratory" for turbulent flows because of the very high Reynolds numbers.
- **Applied** Boundary-Layer Meteorology has important applications in may fields, as we have seen (Weather prediction, Climate Simulation, Agronomy, Ecology, Hydrology, Air Pollution, etc.).

Above: The Chaitén Eruption in Chile, (O Globo Newspaper, May 07 2008)

An optimistic view of atmospheric turbulence, c. 1970

(Monin and Yaglom, 1971, v. 1, p. 22):
The fact is, that the atmosphere, which von Kármán himself (1934) called "a giant laboratory for 'turbulence research,' " possesses *very valuable properties* which make it especially suitable for the verification of the deductions of modern statistical theory. We have already observed that atmospheric motion is usually characterized by *far larger Reynolds numbers* than flows created in the laboratory, and therefore is far more convenient for investigating specific laws relating to the case of very large Re. Moreover, the geometrical conditions of atmospheric turbulence (namely, the conditions of a two-dimensional flow in a half-space bounded by a rigid wall, …*where in many cases the "wall" may be considered as plane and homogeneous; …*) *are simpler than in most laboratory experiments*. The *only additional complication*, which arises on transition from laboratory to atmosphere, is the necessity of taking into account *the thermal stratification…*

But

(And this is a list of but a few of the problems that remain)

- There are flows with lower Reynolds numbers under stable conditions (laminar?)
- Horizontal inhomogeneity (land cover changes), topographical effects.
- Vertical inhomogeneity (what is the effect of the transport terms in the 2$^{\underline{\text{nd}}}$-order equations?)
- Non-stationarity and the difficulty of taking representative time averages.
- The increasing role of more and more scalars, such as CO_2, CH_4, N_2O, O_3, VOC*s*, etc., and the need to "partition" CO_2 into respiration and photosynthesis, and H_2O into transpiration and evaporation, etc..

Fundamental progress (a little history)

This is a personal choice of favorites! Many works will be (unfairly) left out

- Reynolds (1895) The first derivation of the TKE: the birth of the statistical approach to turbulence (following Maxwell (1867), but much earlier than Einstein (1905)'s paper on Brownian motion.
- Richardson (1920) The birth of the Richardson number
- Kolmogorov (1941) The K41 Theory: $E_e(k) = \alpha_e \epsilon_e^{2/3} k^{-5/3}$, microscales
- Kolmogorov (1941 1991) The 4/5 law: $\overline{[u(x_1 + r_1) - u(x_1)]^3} = -\frac{4}{5}\epsilon_e r_1$
- Obukhov (1946 1971) The Monin-Obukhov Similarity Theory (MOST)
- Obukhov (1949), Corrsin (1951) The scalar spectrum
- Batchelor (1959) The Batchelor microscale

Kolmogorov's theory and MOST together

Stewart and Townsend (1951), Grant *et al.* (1962), Gibson and Schwarz (1963), Wyngaard and Coté (1972); Kaimal *et al.* (1972)

$$nC_{wa}(n)/\overline{wa} = \mathscr{A}(\mathscr{B}f)/[1 + (\mathscr{B}f)^{7/3}], \qquad \mathscr{B} = \mathscr{B}(\zeta)$$

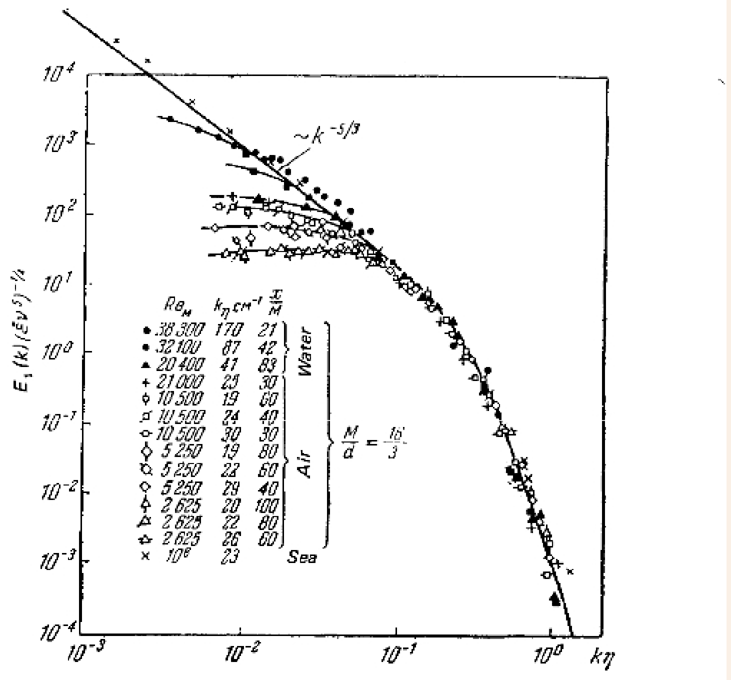


Fig. 75 Normalized longitudinal velocity spectrum, according to different authors. The measurements in water are due to Gibson and Schwarz, in air–Stewart and Townsend, and in the sea–Grant, Stewart, and Moilliet.

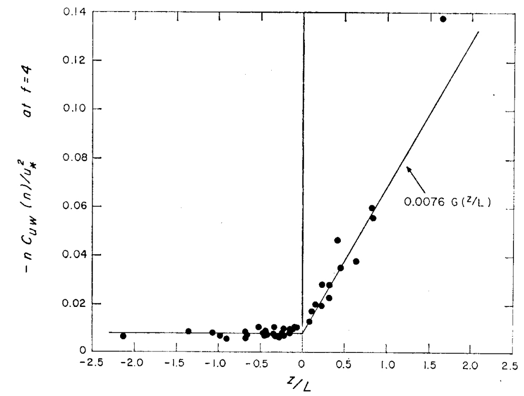


Figure 10. Normalized logarithmic *uw* cospectral estimates at $f = 4$ compared with empirical formula in Eq. (12).

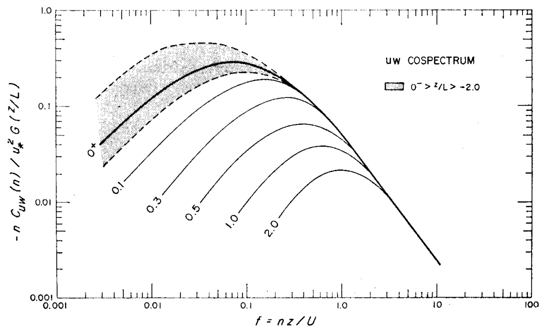
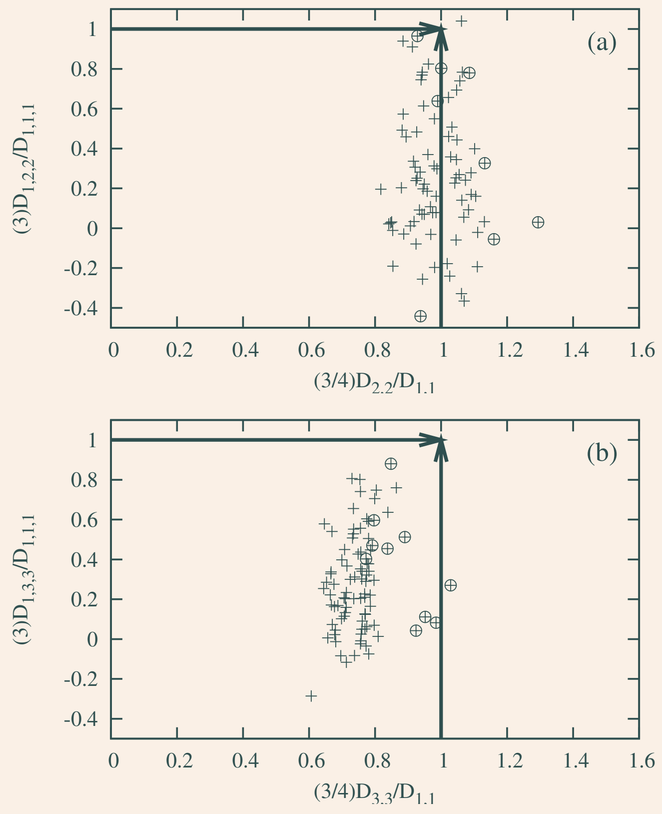
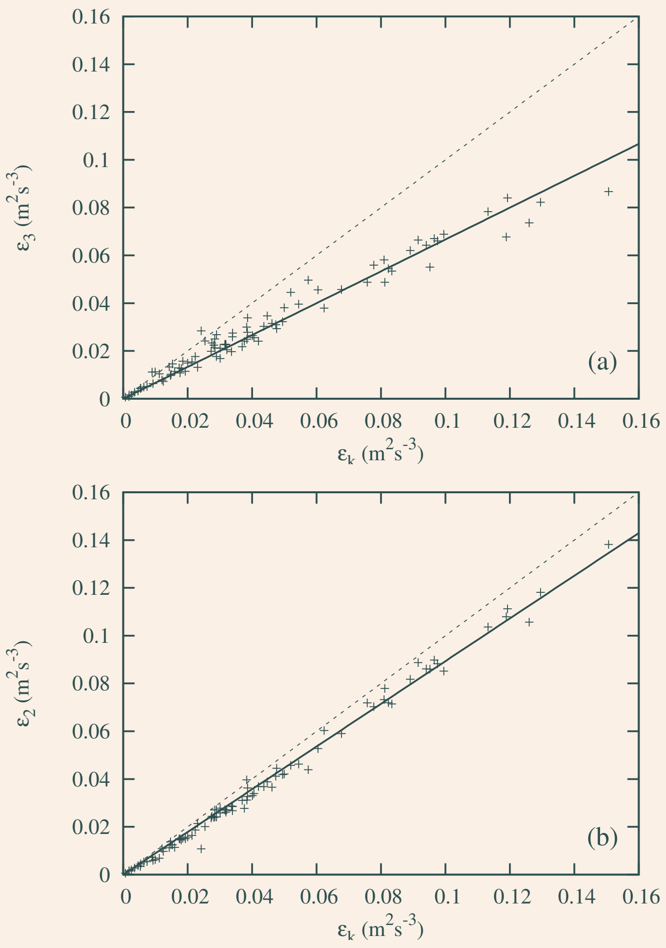


Figure 11. Generalized *uw* cospectrum for z/L values ranging from $+2{\cdot}0$ to $-2{\cdot}0$.

But some questions are only partially answered to this day

Isotropy of structure functions in K41 and rate of dissipation of TKE (Chamecki and Dias, 2004): the 4/5 law.





Further things to do

- (**very difficult**) Make progress towards directly measuring

$$\epsilon_e \approx \nu \overline{\frac{\partial u'_i}{\partial x_k}\frac{\partial u'_i}{\partial x_k}}$$

- Understand deviations from the idealized 4/5 law conditions (Danaila *et al.*, 2001):

$$-\overline{(\Delta u'_1)^3} + 6\nu \frac{\mathrm{d}\overline{(\Delta u'_1)^2}}{\mathrm{d}r} + \frac{6}{r^4}\int_0^r y^4 \left[-\frac{\partial \overline{u'_3 (\Delta u'_1)^2}}{\partial x_3}\right] \mathrm{d}y = \frac{4}{5}\epsilon_e r$$

- Extend analysis to scalars

Letting the equations talk

A systematic approach

- Try to start at the *governing equations*
- Make clear physical approximations
- Make good experiments
- Support your analysis with statistics

Example 1: the Brutsaert theory for the scalar roughness length

Problem: turbulence in the interfacial sublayer and how you parameterize the scalar flux Brutsaert (1965, 1975a,b).
Key: use Danckwerts (1951)'s surface renewal theory, but parameterize the renewal rate with the thickness of the interfacial (roughness) sublayer h. Also, match the top of the interfacial sublayer to the bottom of the inertial sublayer, eliminating $\overline{c_h}$.

$$
\begin{aligned}
s &\propto \left(u_*^3/(\nu\kappa(h-d_0)\right)^{1/2}\\
F &= \overline{\rho}\,(\nu_c s)^{1/2}\,(\overline{c_0}-\overline{c_h})\\
z_{0c} &= z_0 \exp\left[-\kappa\left(7.3\,\mathrm{Re}_0^{1/4}\,\mathrm{Sc}^{1/2} - 5\right)\right]\\
F &= \overline{\rho}\frac{\kappa^2}{\left[\ln\frac{z_a-d_0}{z_0}-\Psi_m(\zeta_a)\right]\left[\ln\frac{z_a-d_0}{z_{0c}}-\Psi_F(\zeta_a)\right]}\overline{u}_a(\overline{c_0}-\overline{c_a})
\end{aligned}
$$

Example 2: similarity of scalars

- If two scalars a and b are perfectly similar in the ABL, then $a' = kb'$.
- a' may be much easier to measure then b' $\Rightarrow$ get eddy diffusivities from a, apply to b.
- Perfect similarity is often assumed in applications. Examle: Model to partition the H_2O and CO_2 fluxes between evaporation and transpiration, and between respiration and photosynthesis (Scanlon and Sahu, 2008).

Dias and Brutsaert (1996):

$$
\begin{aligned}
-2\overline{w'a'}\frac{\partial \overline{a}}{\partial z} - \frac{\partial \overline{w'a'a'}}{\partial z} &= 2\epsilon_{aa},\\
-2\overline{w'b'}\frac{\partial \overline{b}}{\partial z} - \frac{\partial \overline{w'b'b'}}{\partial z} &= 2\epsilon_{bb},\\
-\overline{w'a'}\frac{\partial \overline{b}}{\partial z} - \overline{w'b'}\frac{\partial \overline{a}}{\partial z} - \frac{\partial \overline{w'a'b'}}{\partial z} &= 2\epsilon_{ab},
\end{aligned}
$$

If the transport terms can be neglected, this leads to

- Equality of the MOST dimensionless gradients for a and b,
- Perfect correlation bewteen the fluctuations, meaning $a' = kb'$.

With zero transport

$$\phi_H = \phi_{\epsilon_{\theta\theta}} \qquad \phi_E = \phi_{\epsilon_{qq}} \qquad \phi_H + \phi_E = 2\phi_{\epsilon_{\theta q}}$$

$$\frac{\epsilon^2_{\theta q}}{\epsilon_{\theta\theta}\epsilon_{qq}} = \frac{\left(\frac{\nu_\theta+\nu_q}{2}\right)^2 \left(\overline{\frac{\partial\theta'}{\partial x_k}\frac{\partial q'}{\partial x_k}}\right)^2}{\nu_\theta\nu_q \left(\overline{\frac{\partial\theta'}{\partial x_k}\frac{\partial\theta'}{\partial x_k}}\right)\left(\overline{\frac{\partial q'}{\partial x_k}\frac{\partial q'}{\partial x_k}}\right)} = \frac{\phi^2_{\epsilon_{\theta q}}}{\phi^2_{\epsilon_{\theta\theta}}\phi_{\epsilon_{qq}}} = 1.008 r^2_{\nabla\theta\nabla q} \approx r^2_{\nabla\theta\nabla q}$$

$$x + y = z, \qquad z^2 = r^2 x y \qquad \Rightarrow \frac{x}{z} = \frac{r^2 \pm \sqrt{r^4 - r^2}}{r^2} \Rightarrow x = y = z; \qquad r^2 = 1.$$

And

$$r^2_{\nabla\theta\nabla q} = 1 \;\Rightarrow\; r^2_{\theta q} = 1.$$

Production and vertical transport need to be investigated further, but mean scalar gradients need good calibration, and 3rd moments have large errors.

Example 3: the alignment between mean wind $\overline{\boldsymbol{u}}$ and Reynolds stress tensor $\boldsymbol{\tau}$

Problem (Bernardes and Dias, 2010): after rotation, $\overline{\boldsymbol{u}} = (\overline{u}, 0)$, $\boldsymbol{\tau} = \rho(\overline{u'w'}, \overline{v'w'})$ and $\overline{\boldsymbol{u}} \nparallel \boldsymbol{\tau}$.
So how do you calculate u_*:

$$u_* = [\overline{u'w'}^2 + \overline{v'w'}^2]^{1/4} \qquad \text{or} \qquad u_* = [-\overline{u'w'}]^{1/2}?$$

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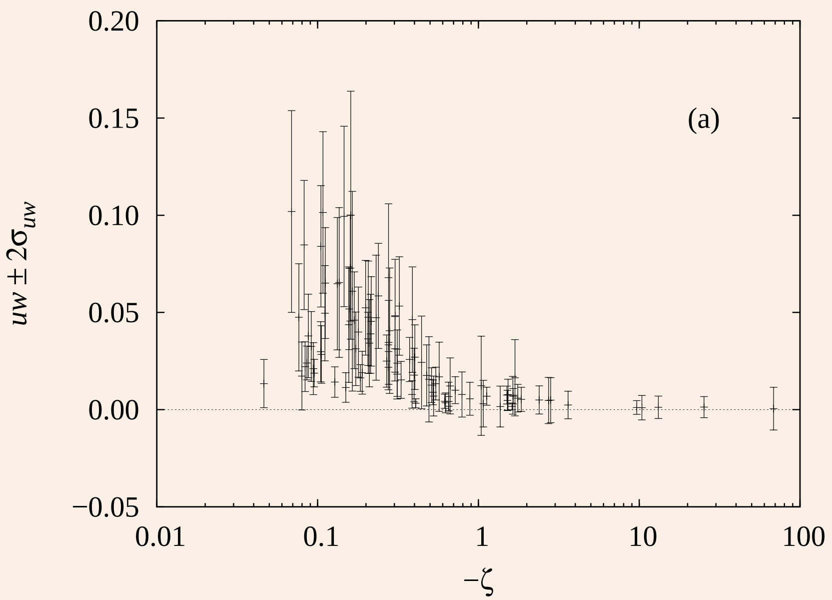

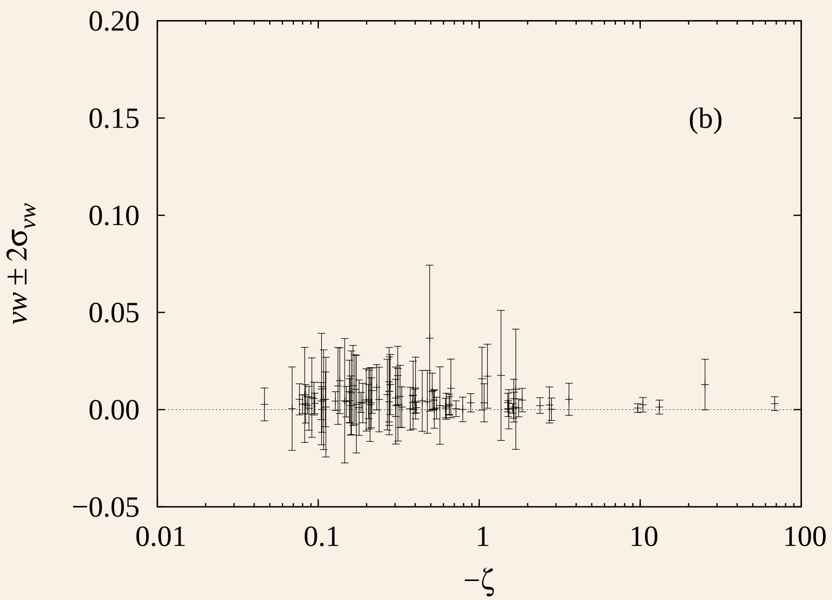

$-\zeta \gtrsim 1$: $\overline{u'w'}$ indistinguishable from 0

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But this is Wyngaard *et al.* (1971)'s prediction for local convection!

Example 4: The reduced TKE budget

From Chamecki *et al.* (2018):

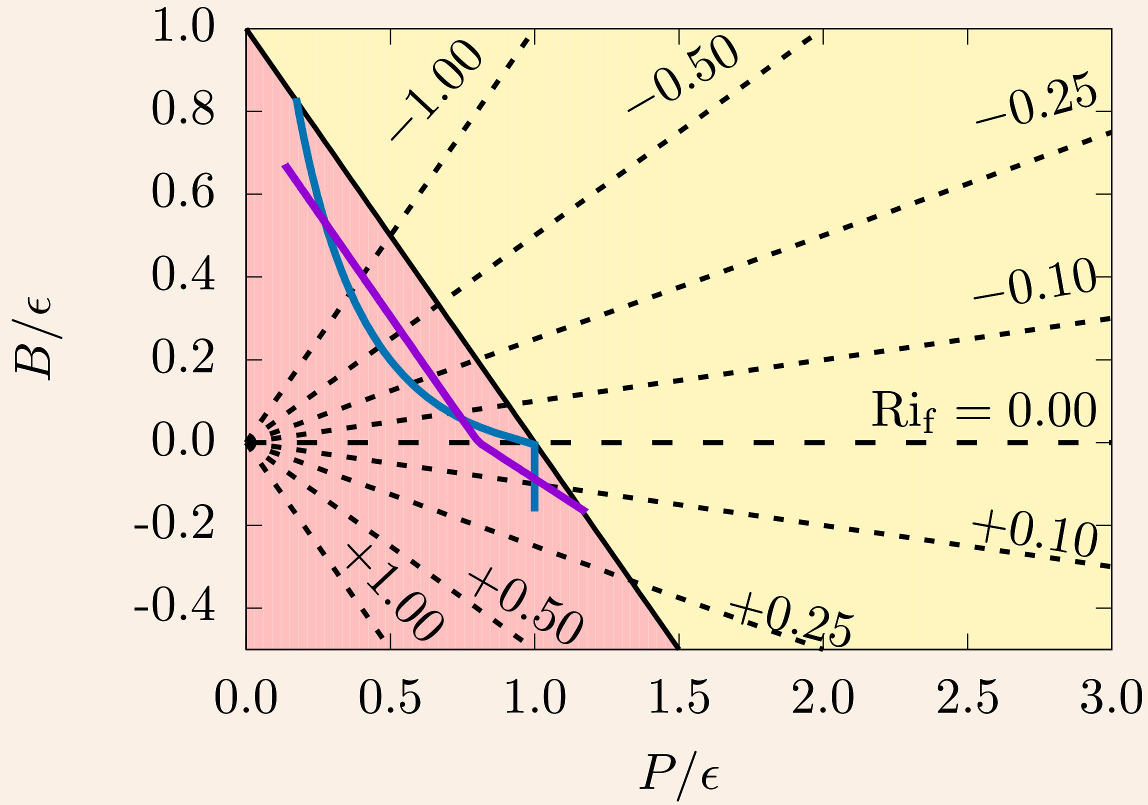
$$
\underbrace{-\overline{u'w'}\frac{\partial \overline{u}}{\partial z}}_{P} + \underbrace{\frac{g}{\overline{\theta}}\overline{w'\theta'}}_{B} - \epsilon_e = \underbrace{\frac{\partial \overline{e_k}}{\partial t} + \overline{u}\frac{\partial \overline{e_k}}{\partial x} + \frac{1}{\rho}\frac{\partial \overline{u_i' p'}}{\partial x_i} + \frac{\partial \overline{u_i' e_k'}}{\partial x_i}}_{R},
$$

$$
\frac{P}{\epsilon_e} + \frac{B}{\epsilon_e} - 1 = \frac{R}{\epsilon_e}
$$

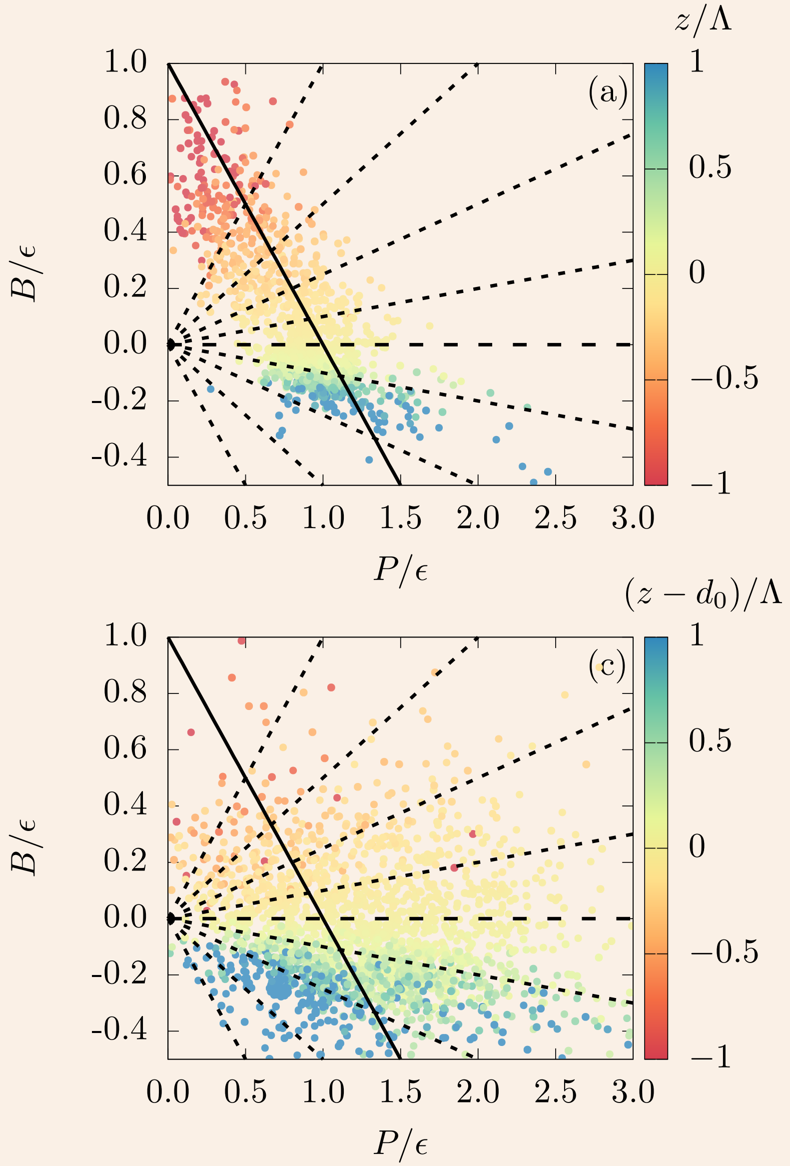
$$
\frac{P}{\epsilon_e} = \frac{\phi_m(\zeta)}{\phi_{\epsilon_e}(\zeta)},
$$

$$
\frac{B}{\epsilon_e} = -\frac{\zeta}{\phi_{\epsilon_e}},
$$

$$
\zeta = \zeta(\mathrm{Ri}_f).
$$



Data from AHATS (above) and GoAmazon (below)



Conclusions

A road to progress

- Understanding the “discarded” terms in MOST (time rate of change, advection, transport term, return to isotroy – see Freire *et al.* (2019)) is essential.
- Often much can be learned by starting from “ideal” conditions and “perturbing”.
- Better field measurements, and better models and theories, are always in need.

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Wrapping up:

- Progress requires universality.

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Thanks!

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