(Views on) Advancing turbulence closure models under stable stratification

Thorsten Mauritsen

Max Planck Institut für Meteorologie
Hamburg, Deutschland

The Knowledge Gap

MO: Weak diffusion

Strong diffusion:

- Reduce surface cold bias
- Improve cyclone life-cycle

The Knowledge Gap

Observations ⟷ NWP Models (IFS?)

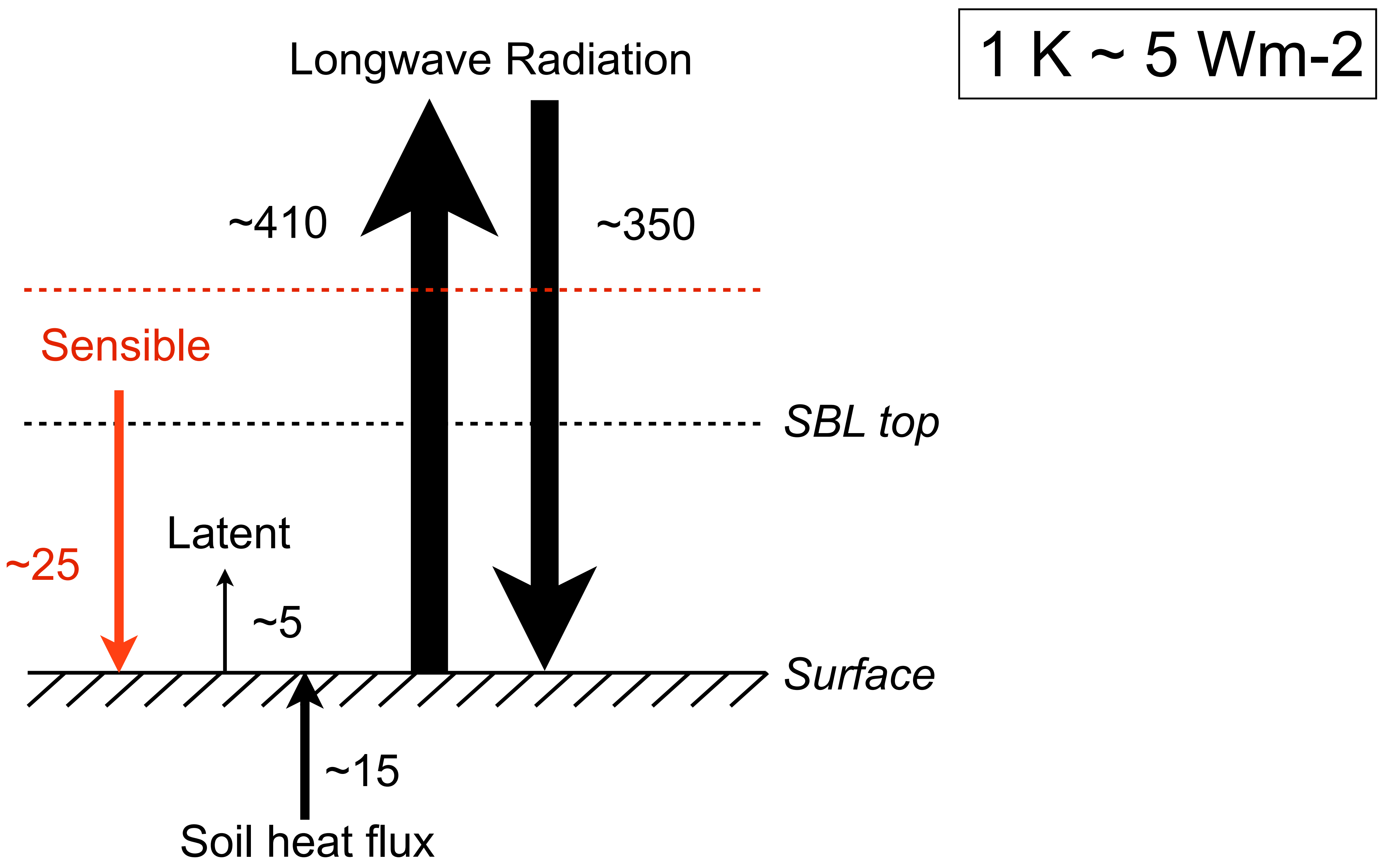
MO: Weak diffusion

Strong diffusion:

- Reduce surface cold bias
- Improve cyclone life-cycle

- Problems in observations?
- Missing processes?
- Compensating errors?

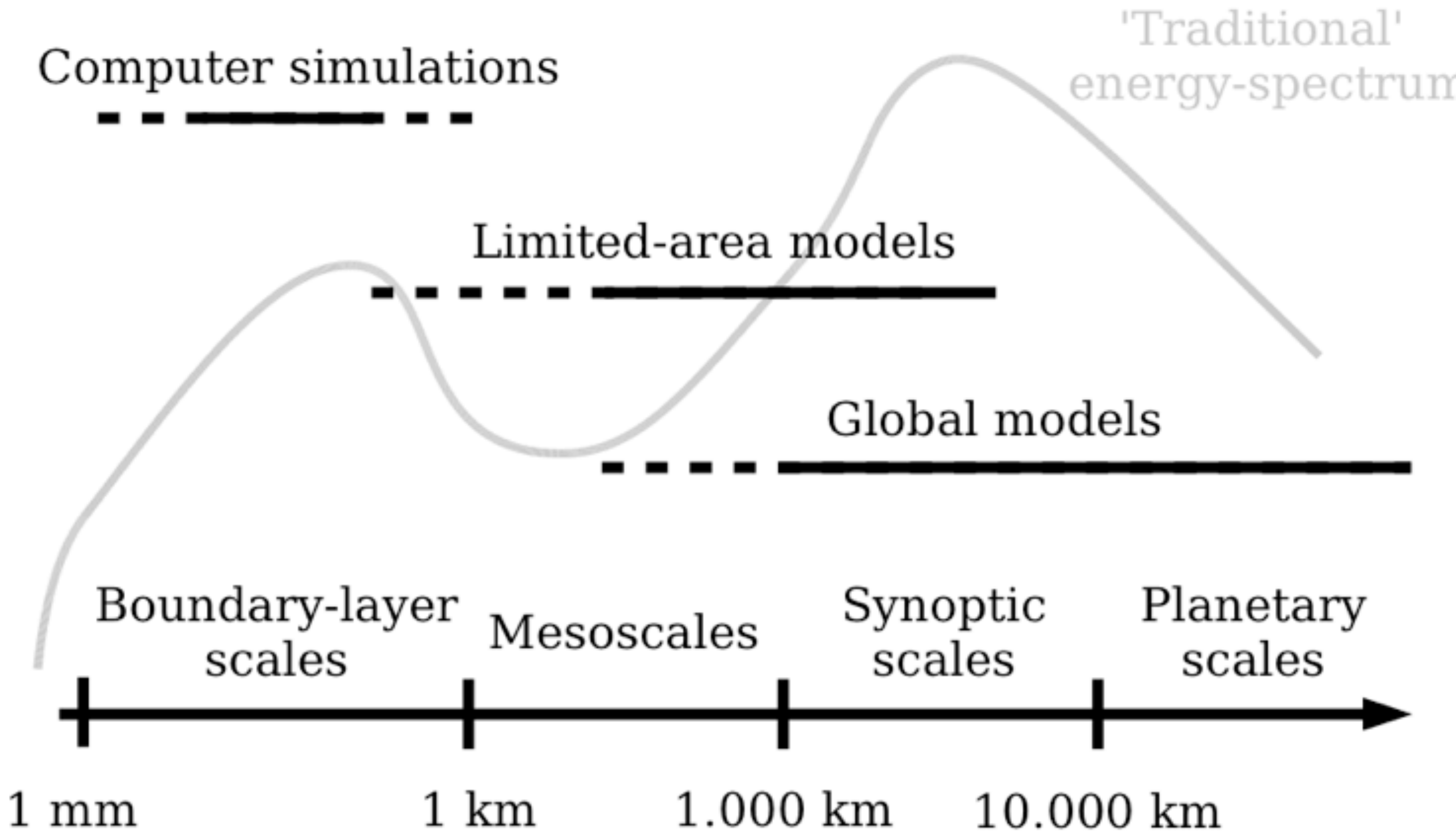
What determines the night-time surface temperature?



Observations are from GABLS3 by Fred Bosveld

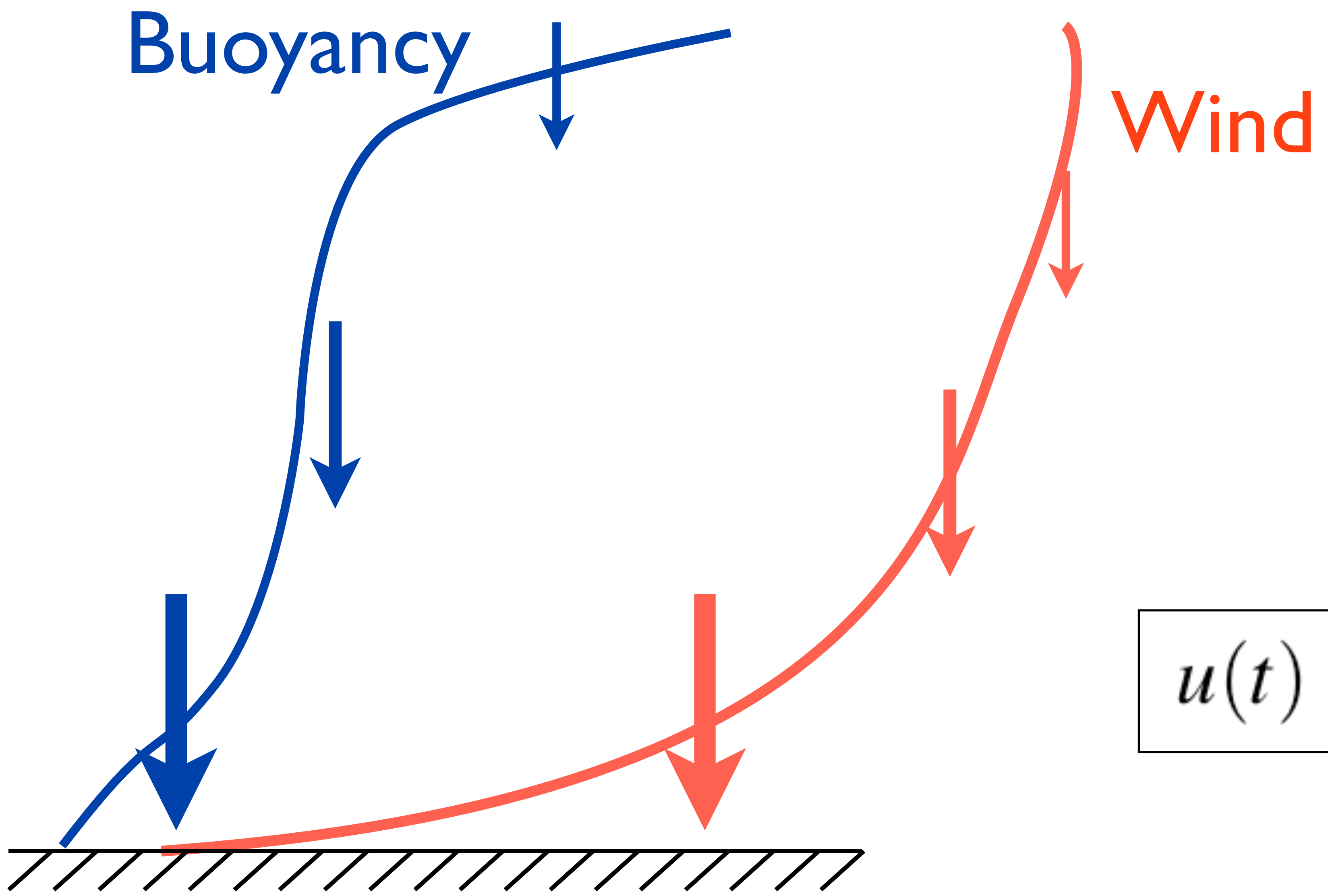
The Problem

$$u(t) = \overline{u} + u(t)',$$



The Problem

Given a mean flow, what are the vertical fluxes?



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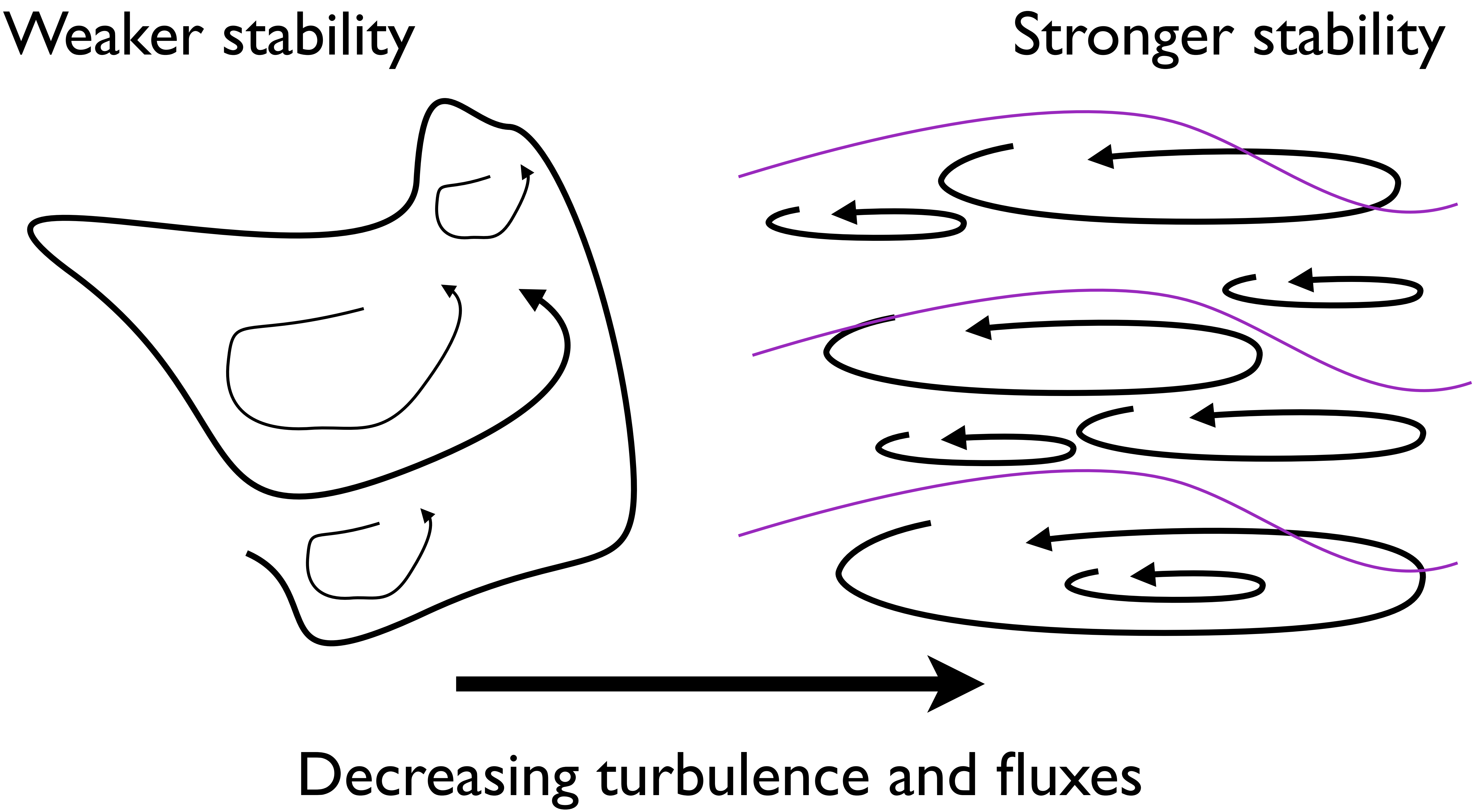
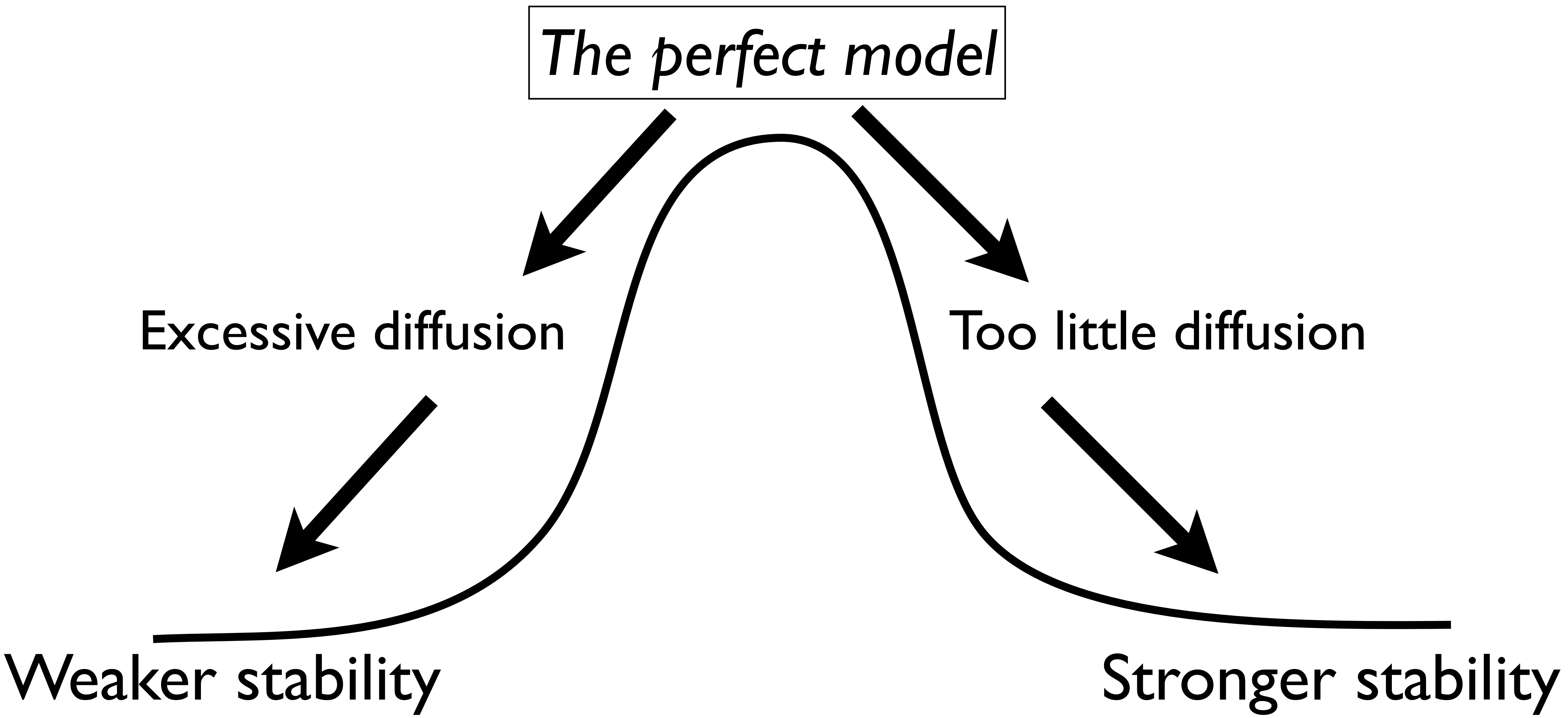
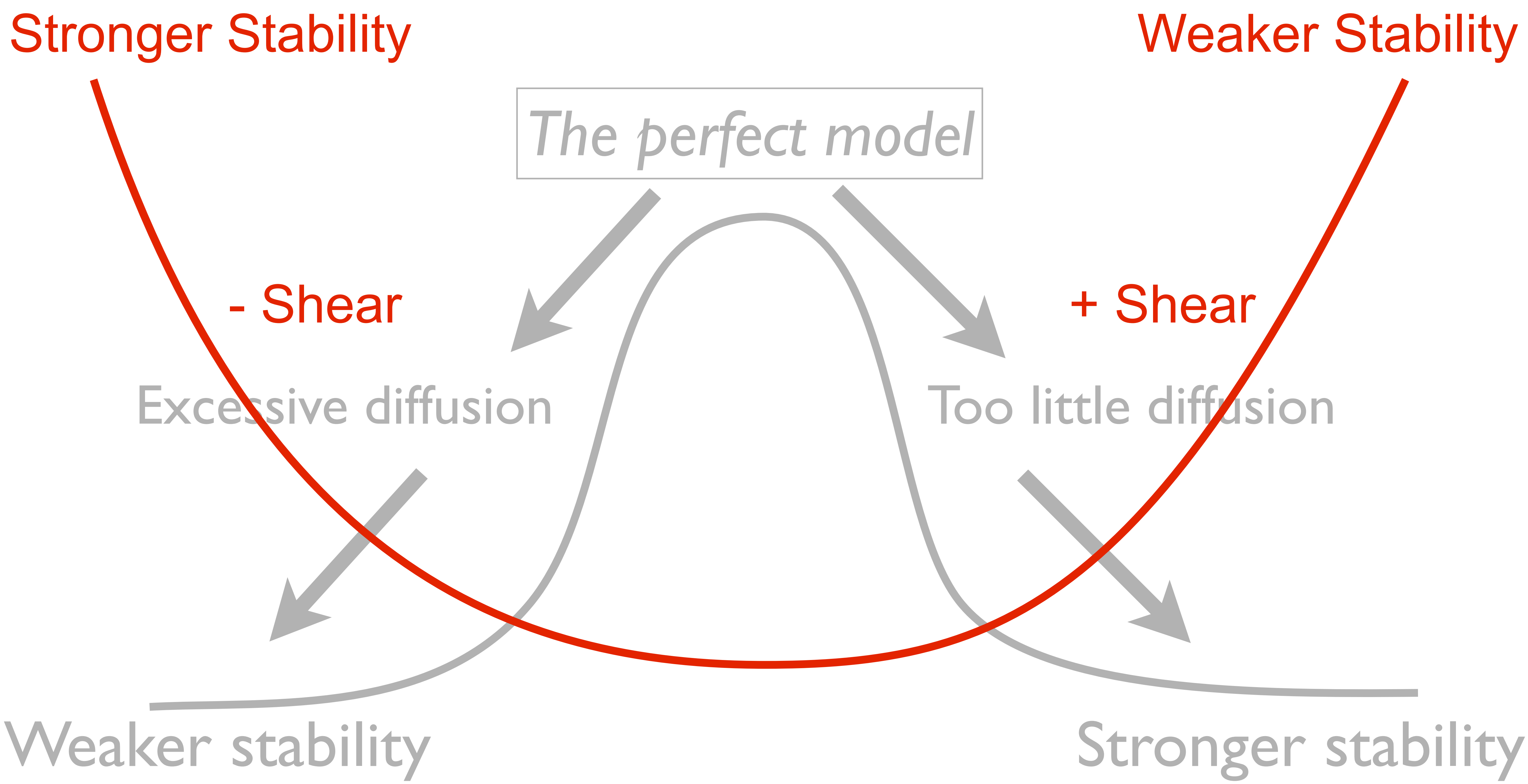

Weaker stability
Stronger stability
Decreasing turbulence and fluxes

The Problem

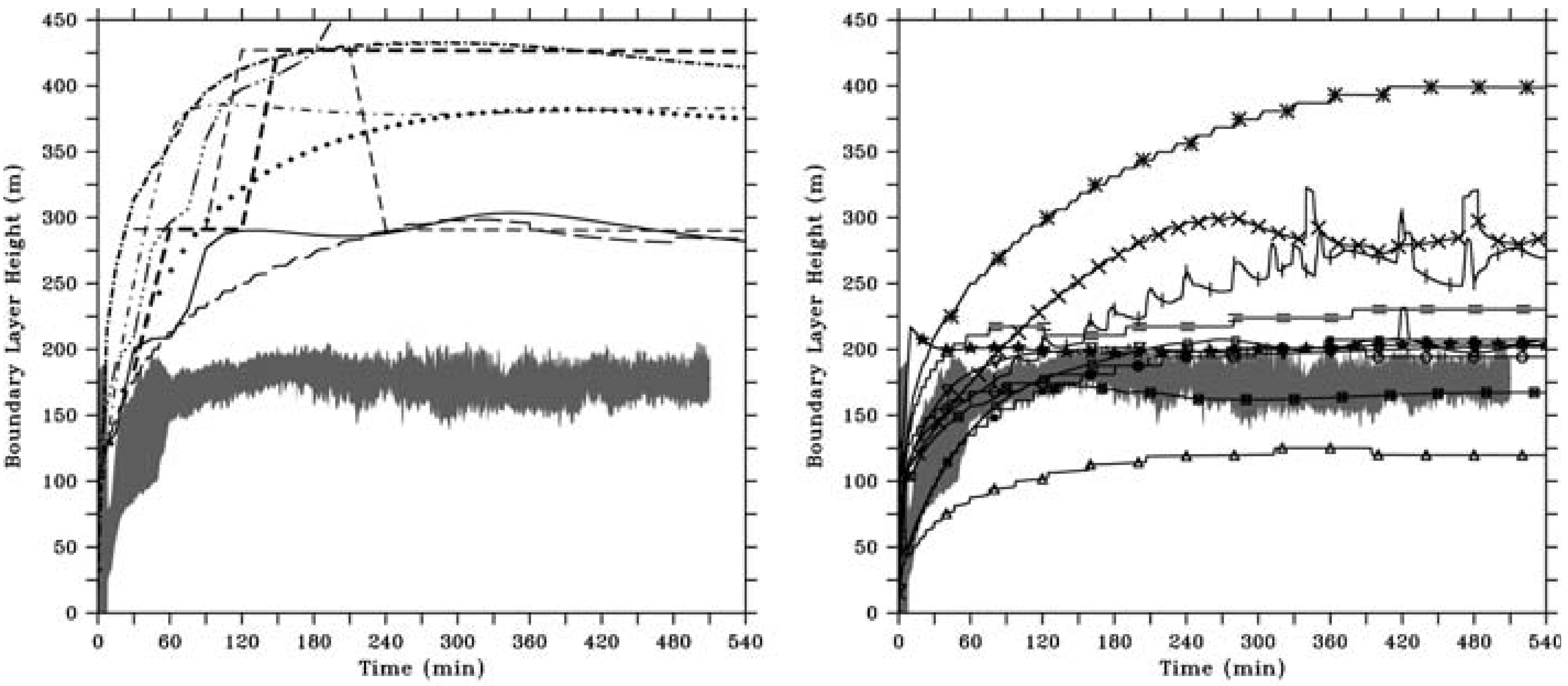

The perfect model
Excessive diffusion
Too little diffusion
Weaker stability
Stronger stability

The Problem



Stronger Stability
Weaker Stability
The perfect model
- Shear
+ Shear
Excessive diffusion
Too little diffusion
Weaker stability
Stronger stability

The Problem



From Cuxart et al. (2006)

The Solution

$$K = f\,l^2 S$$

Shear (1/s)
- *given*

Mixing length (m)
- *'magic'*

Non-dimensional Stability functions
- *similarity theory + measurement, or ad-hoc*

The Solution

We seek similarity in turbulent flows along two routes:

$$\frac{z}{L} = \frac{gkz}{\theta} \cdot \frac{-\overline{w'\theta'}}{\tau^{3/2}},$$

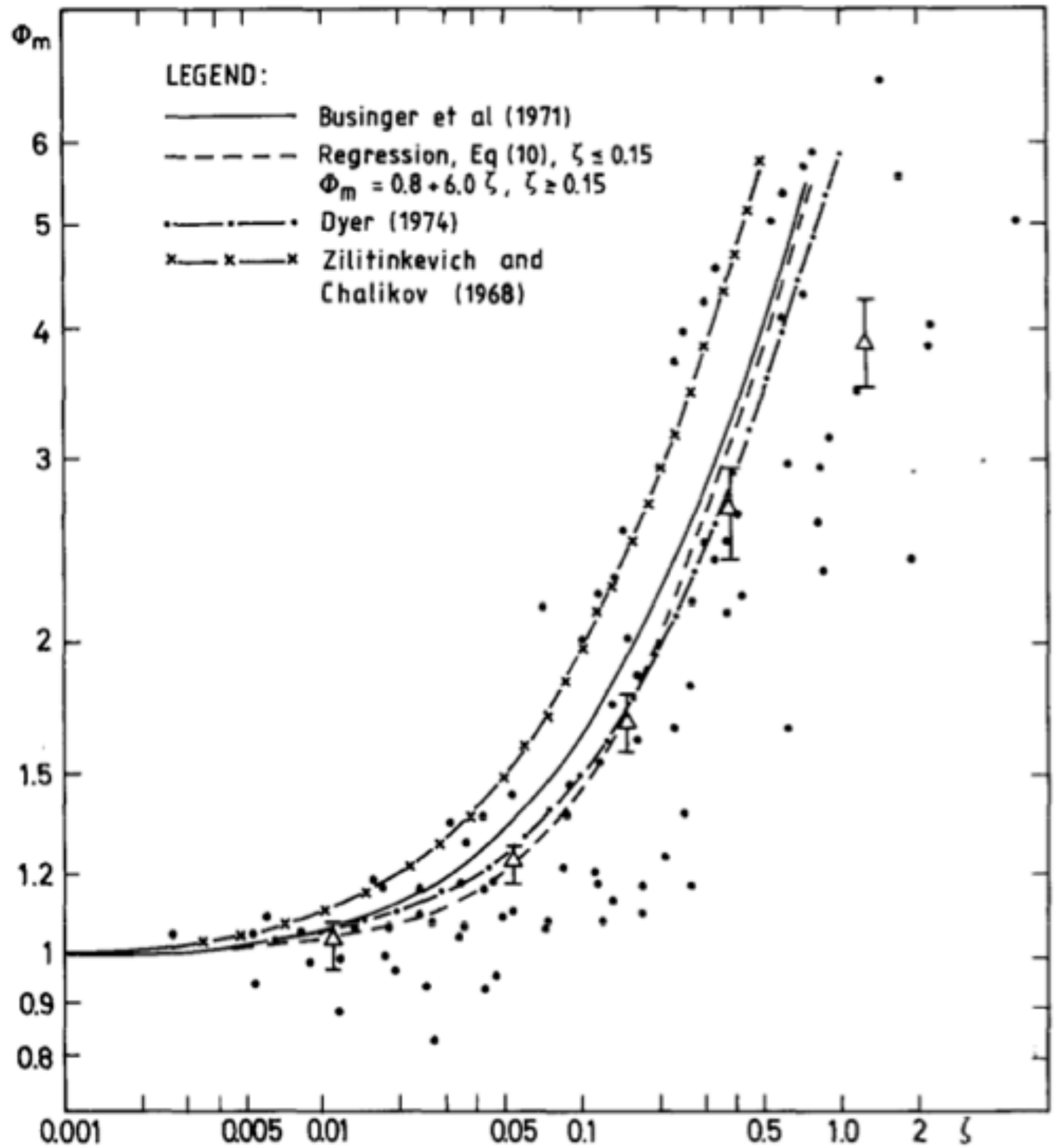
Flux-based

$$Ri \equiv N^2/S^2$$

Gradient-based

MO and Self-correlation

$$\frac{\partial \bar{u}}{\partial z}\frac{kz}{u_*} = \phi_m(z/L),$$



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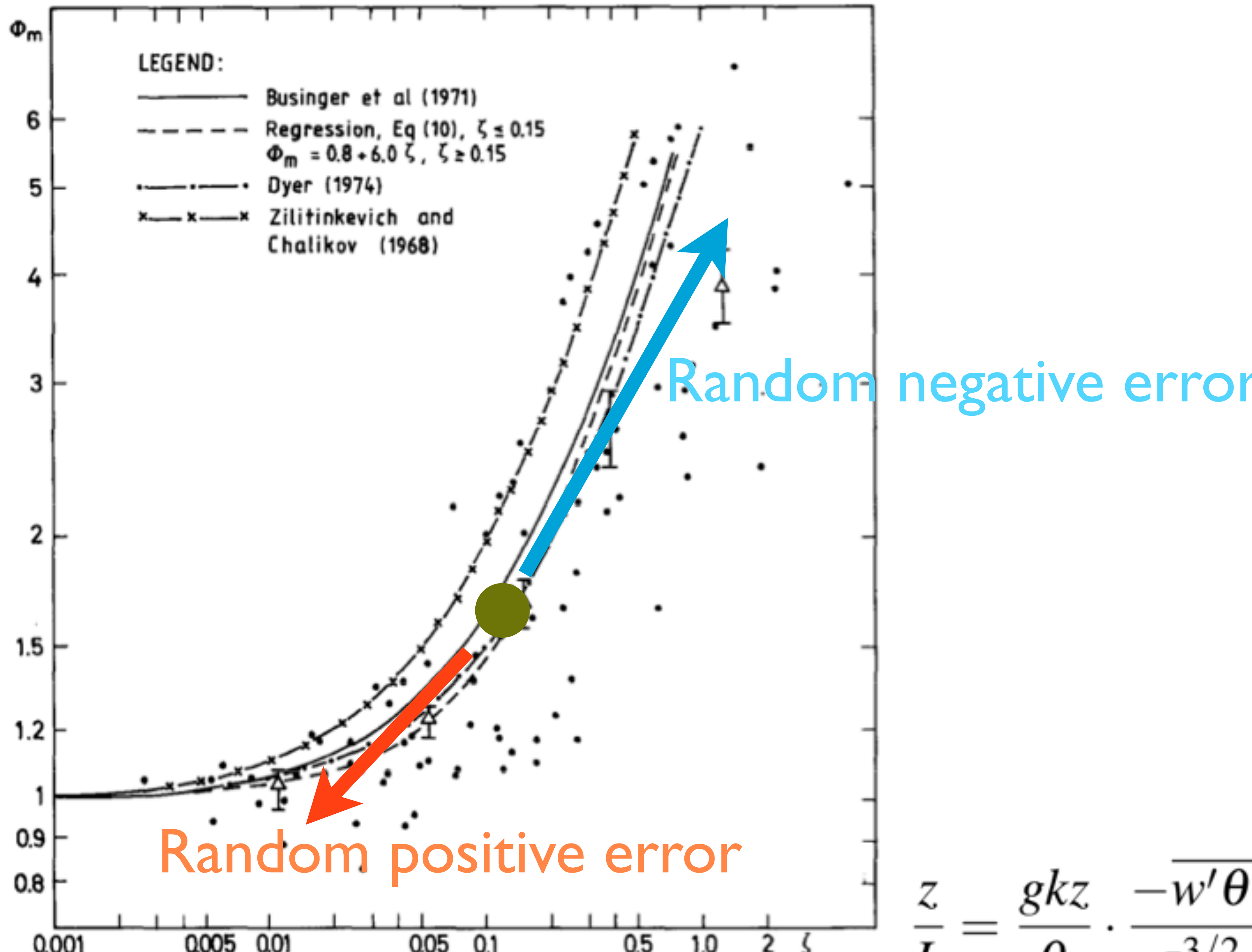

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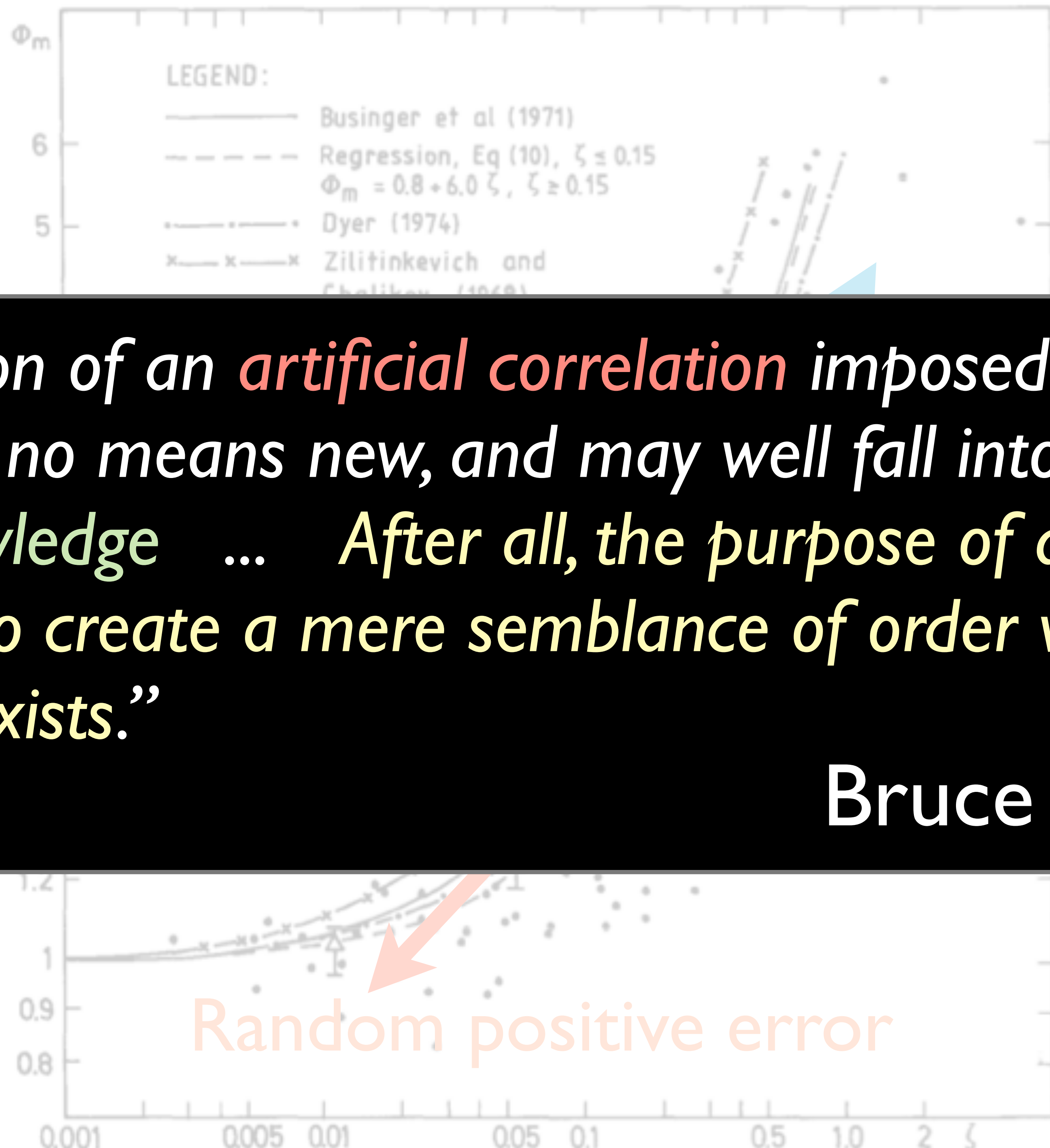


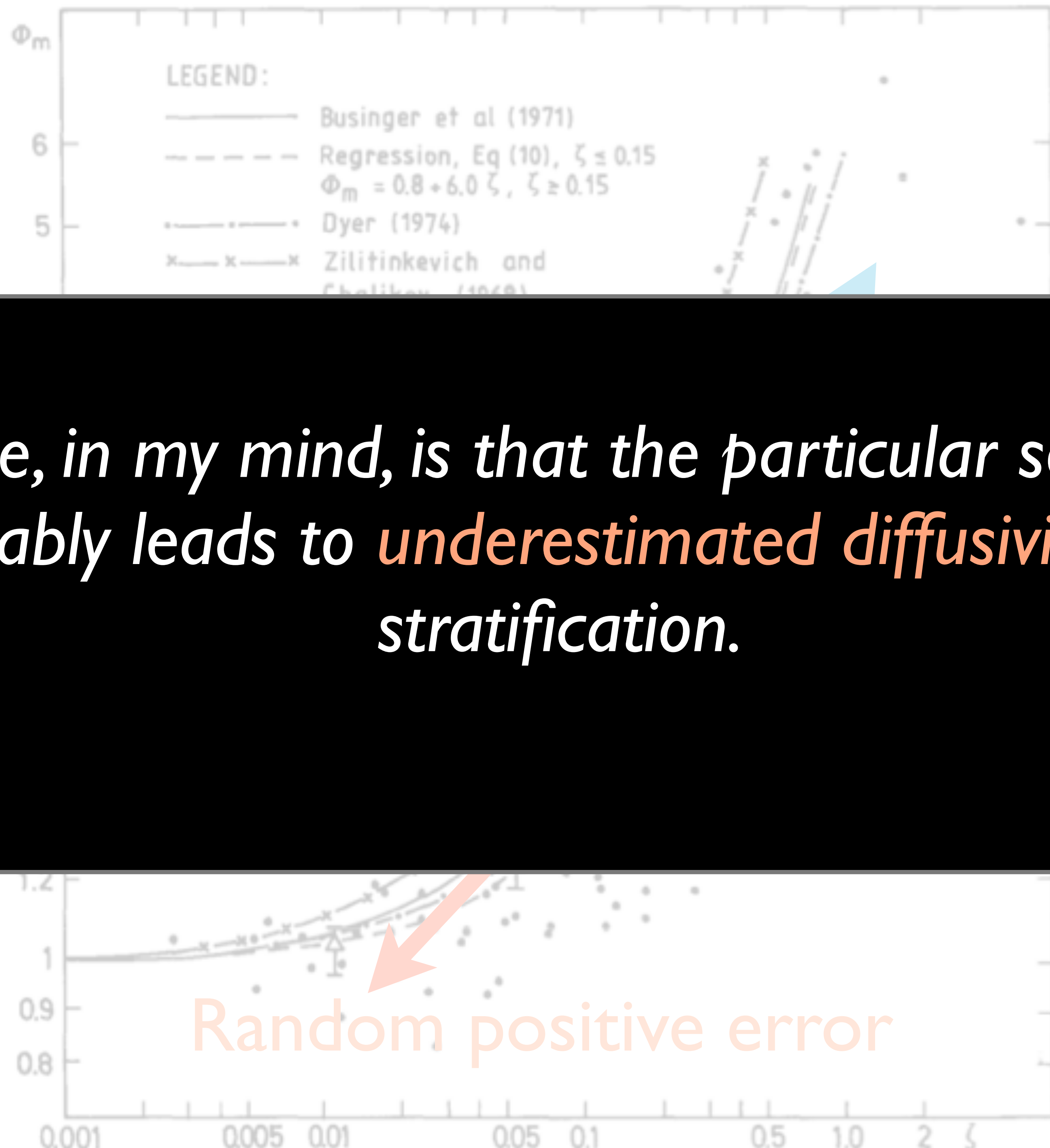
"The suggestion of an artificial correlation imposed by analysis methods is by no means new, and may well fall into the category of common knowledge ... After all, the purpose of any analysis is certainly not to create a mere semblance of order where only randomness exists."

Bruce Hicks (1978)

$$\frac{z}{L} = \frac{gkz}{\theta}\cdot\frac{-\overline{w'\theta'}}{\tau^{3/2}},$$

MO and Self-correlation

$$\frac{\partial \bar{u}}{\partial z}\frac{kz}{u_*} = \phi_m(z/L)\,,$$



What is worse, in my mind, is that the particular self-correlation in MO unavoidably leads to underestimated diffusivity under stable stratification.

$$\frac{z}{L} = \frac{gkz}{\theta}\cdot\frac{-\overline{w'\theta'}}{\tau^{3/2}}\,,$$

Critical Richardson Number?

TKE:

$$\underset{\text{Storage}}{\frac{DE_k}{Dt}} = \underset{\text{Shear}}{\tau \cdot \mathbf{S}} \underset{\text{Buoyancy}}{+\frac{g}{\theta} \cdot \overline{w'\theta'}} \underset{\text{Dissipation}}{-\varepsilon} \underset{\text{Transport}}{-\frac{\partial F_k}{\partial z}},$$

Richardson (1920)

Critical Richardson Number?

TKE:

$$\frac{DE_k}{Dt} = \tau \cdot \mathbf{S} + \frac{g}{\theta} \cdot \overline{w'\theta'} - \varepsilon - \frac{\partial F_k}{\partial z},$$

Storage	Shear	Buoyancy	Dissipation	Transport

Ignore transport, and consider the sign of the Storage term for low levels of turbulence when Dissipation is still negligible. Turbulence will then grow whenever:

$$\tau \cdot \mathbf{S} > -\frac{g}{\theta} \cdot \overline{w'\theta'}.$$

$$\frac{K_m}{K_h} > \frac{N^2}{S^2}.$$

$$Pr > Ri.$$

$$\tau = K_m \mathbf{S}$$

$$\overline{w'\theta'} = -K_h \frac{\partial \theta}{\partial z}$$

$$Pr \equiv K_m / K_h$$

$$Ri \equiv N^2 / S^2$$

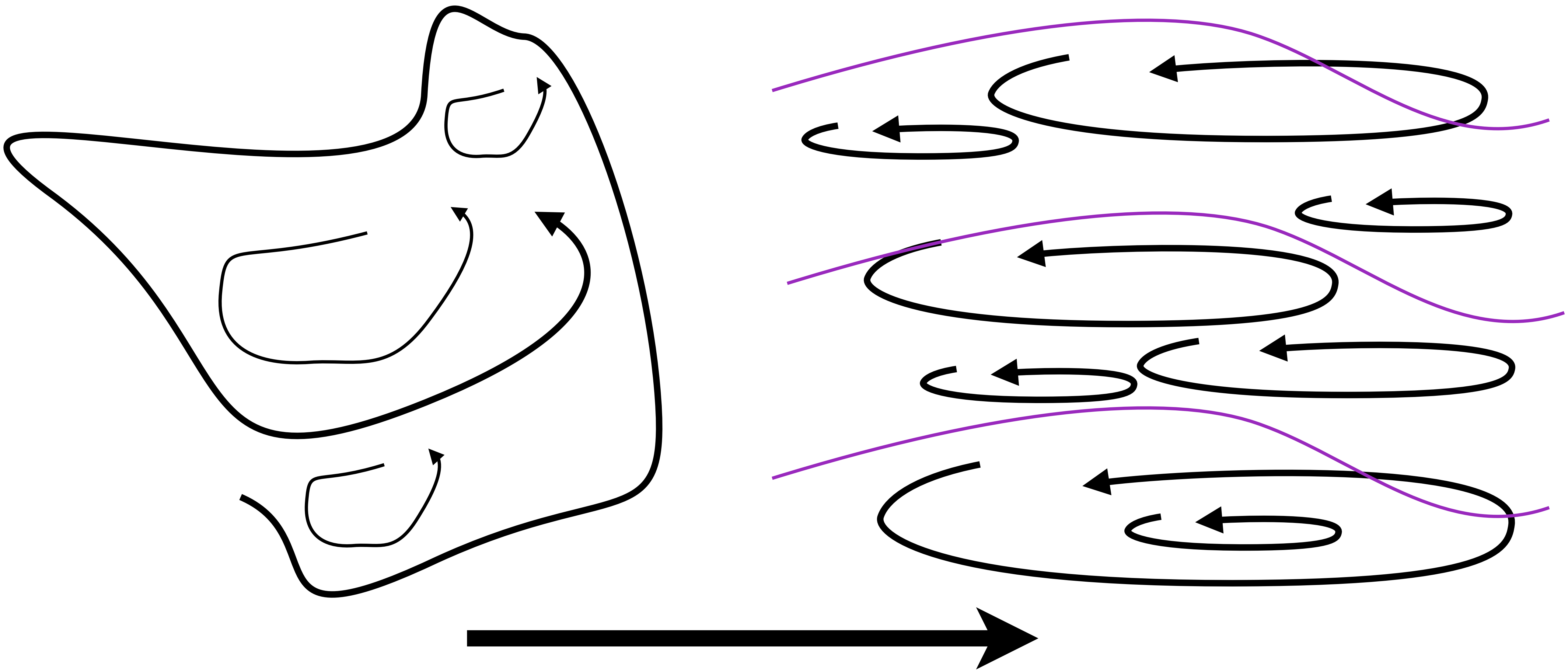
Unfortunately, Richardson then assumed Km = Kh = 1 and made his famous conclusion.

Richardson (1920)

The Problem

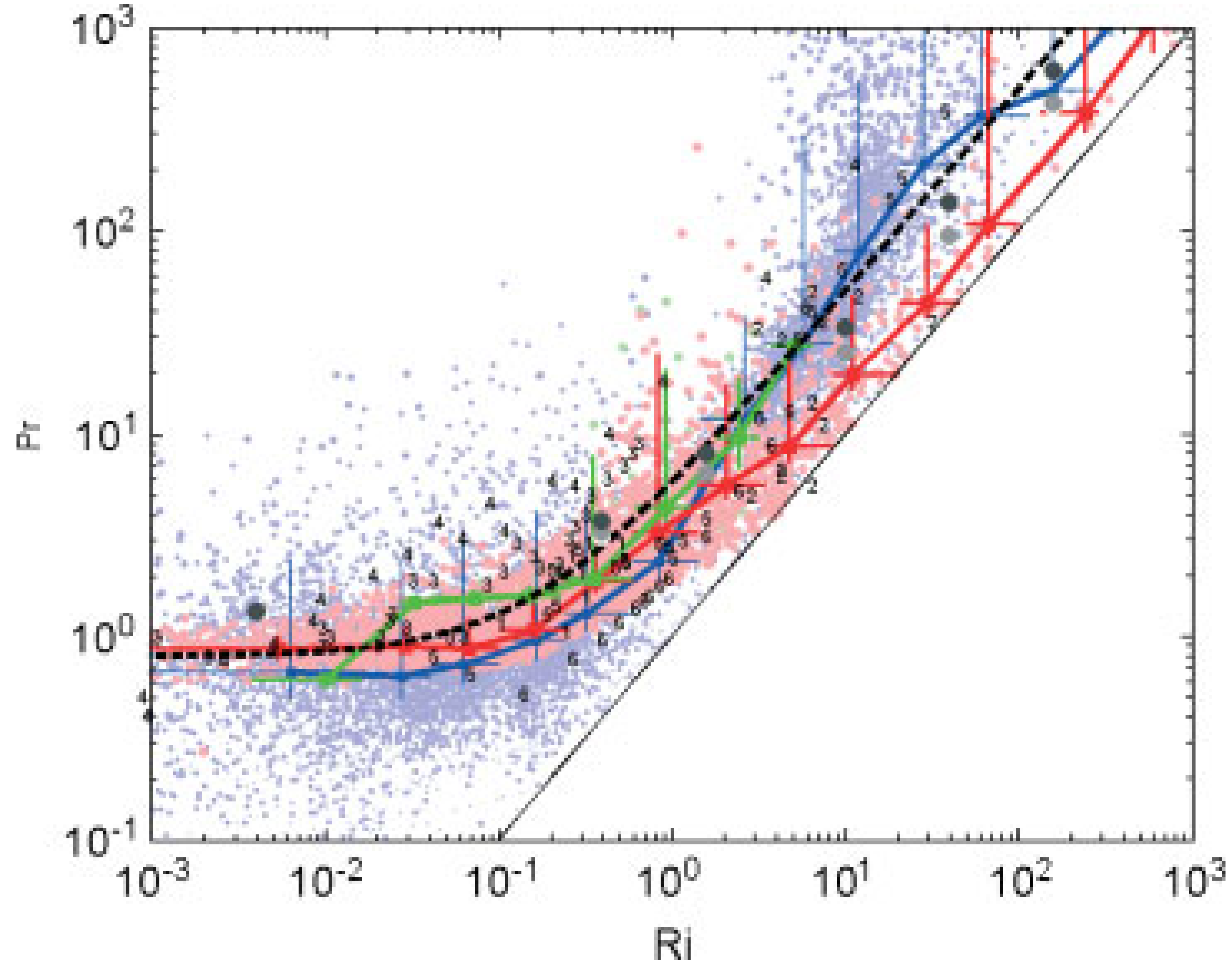
Weaker stability

Stronger stability



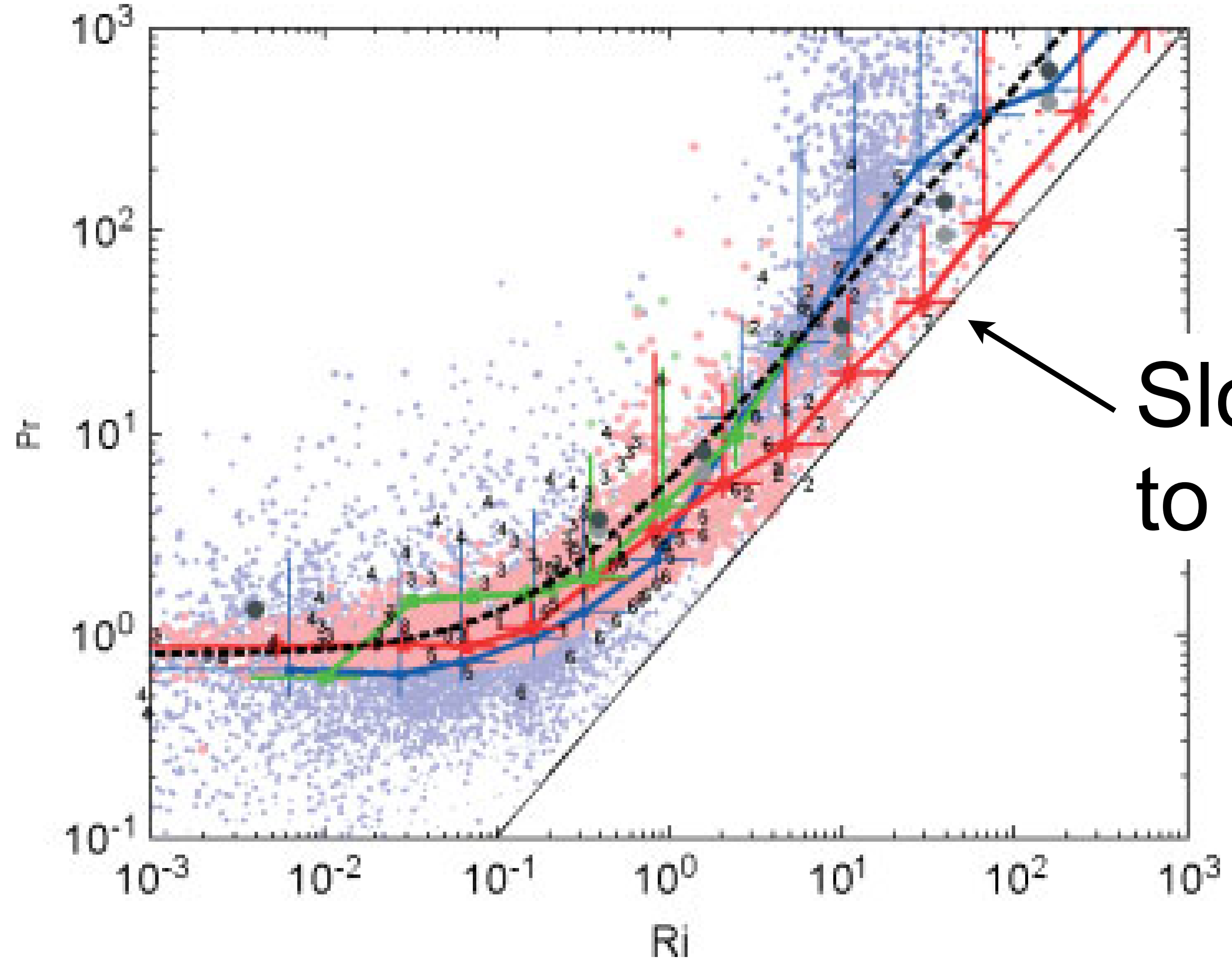
Decreasing turbulence and fluxes

Prandtl number (Pr)



Zilitinkevich et al. (2008)

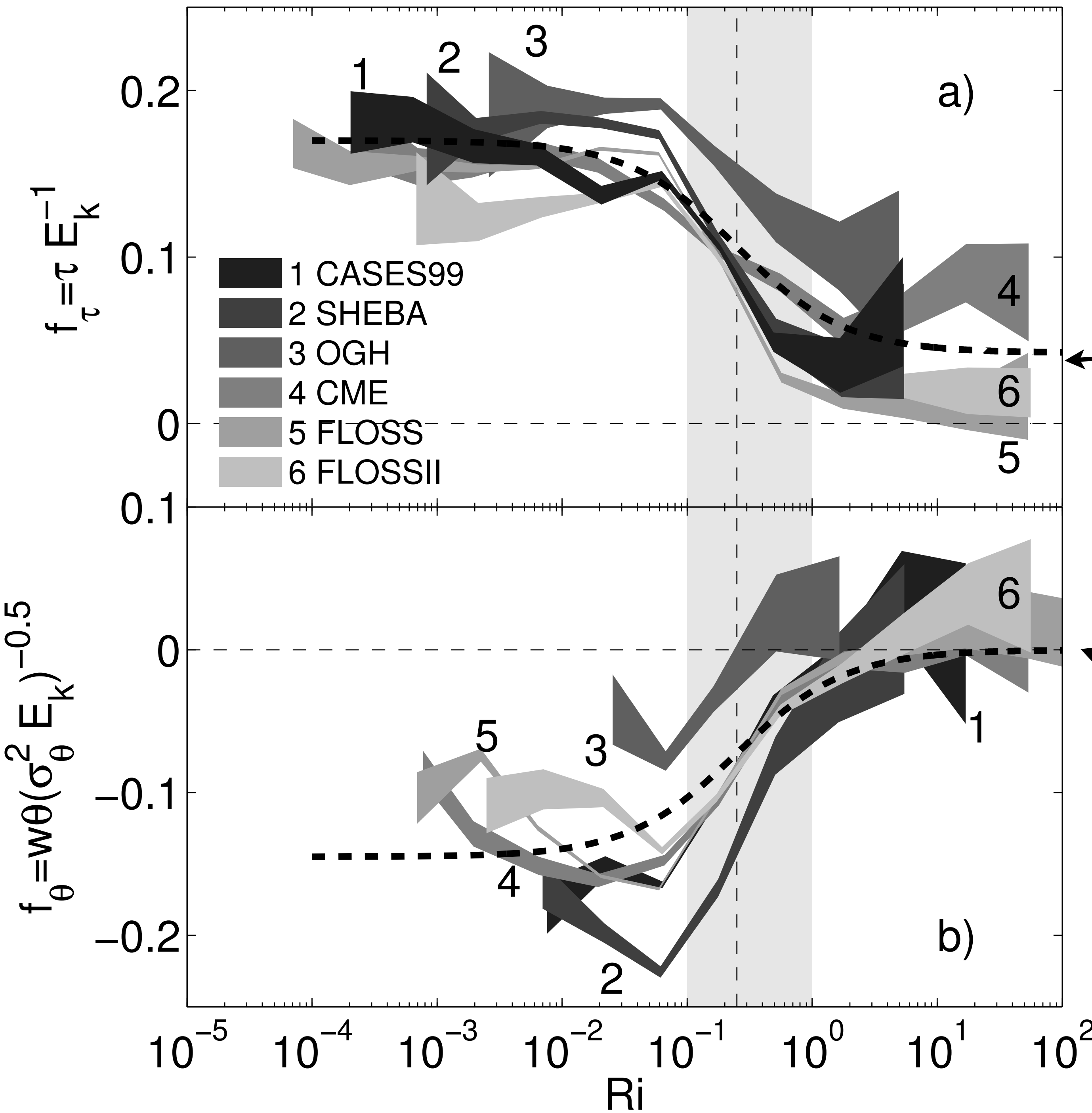
Prandtl number (Pr)



Slope could be due to self-correlation!

Zilitinkevich et al. (2008)

Prandtl number increase?



Stress is non-zero

Heat flux tends to zero

Mauritsen and Svensson (2007)

Total turbulent energy

TKE:

$$\frac{DE_k}{Dt} = \boldsymbol{\tau} \cdot \mathbf{S} + \beta \overline{w\theta} - \epsilon - \frac{\partial F_k}{\partial z}$$

TTE:

$$\boxed{\frac{DE}{Dt} = \boldsymbol{\tau} \cdot \mathbf{S} - \gamma - \frac{\partial F_E}{\partial z}}$$

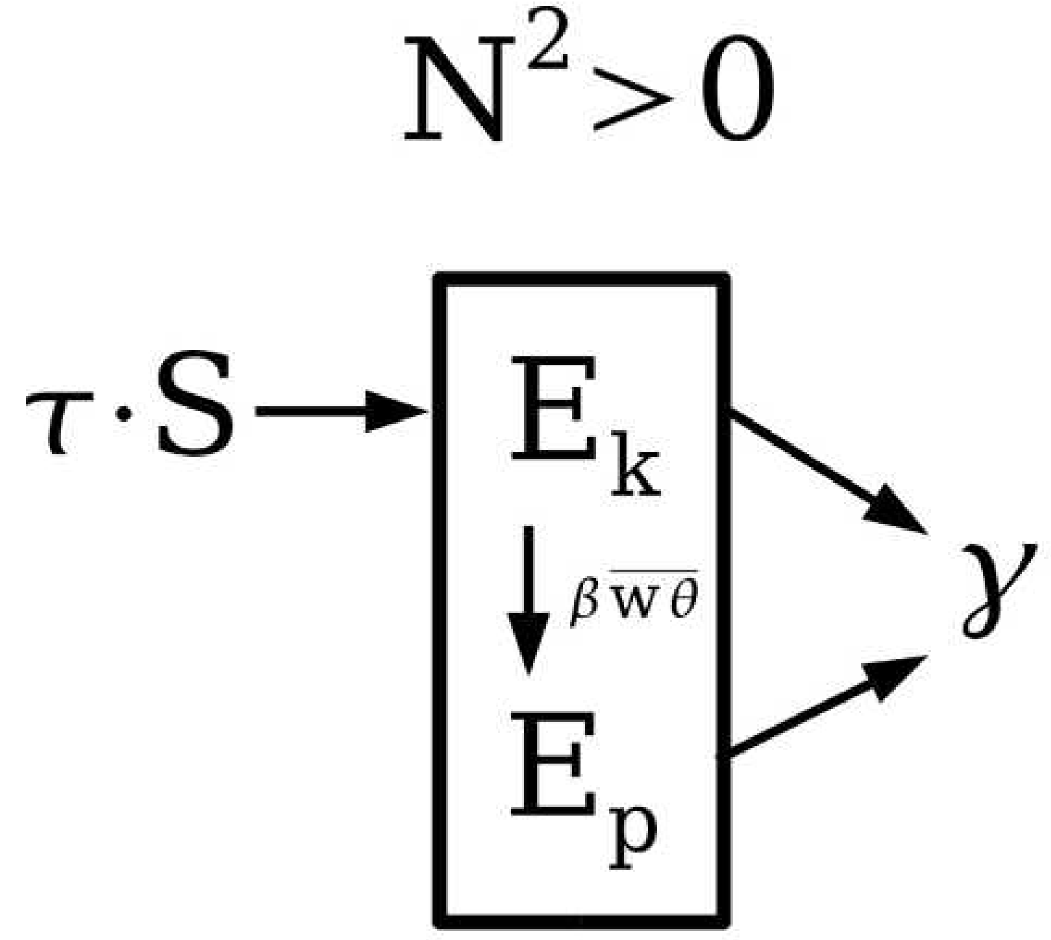
Ri > 0

TPE:

$$\frac{DE_p}{Dt} = \beta |\overline{w\theta}| - \frac{\beta^2}{|N^2|} \left(\phi + \frac{\partial F_\theta}{\partial z} \right). \quad E_p = \frac{1}{2} \sigma_\theta^2 \frac{\beta^2}{|N^2|},$$

From Mauritsen et al. (2007)

Total turbulent energy



From Mauritsen et al. (2007)

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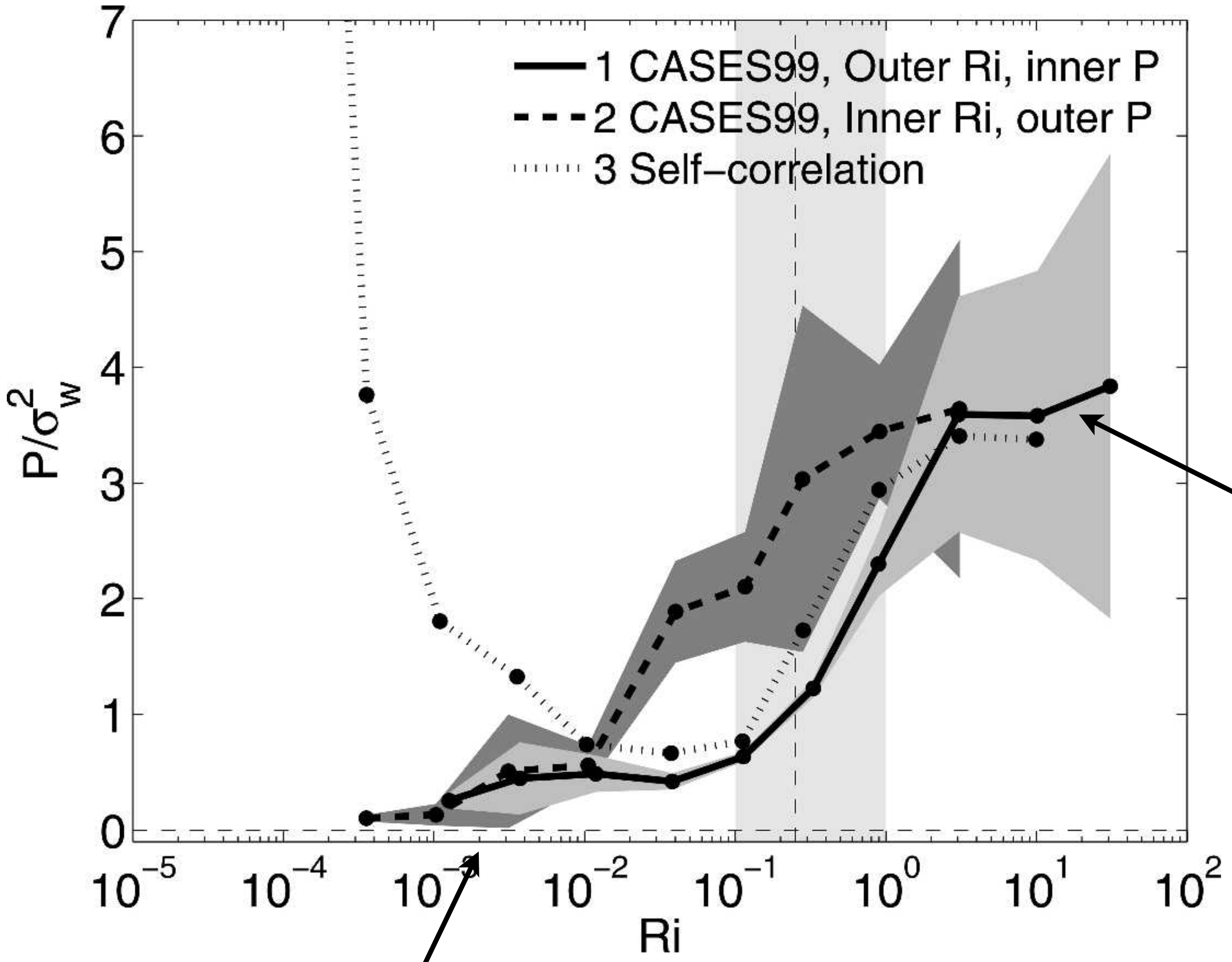
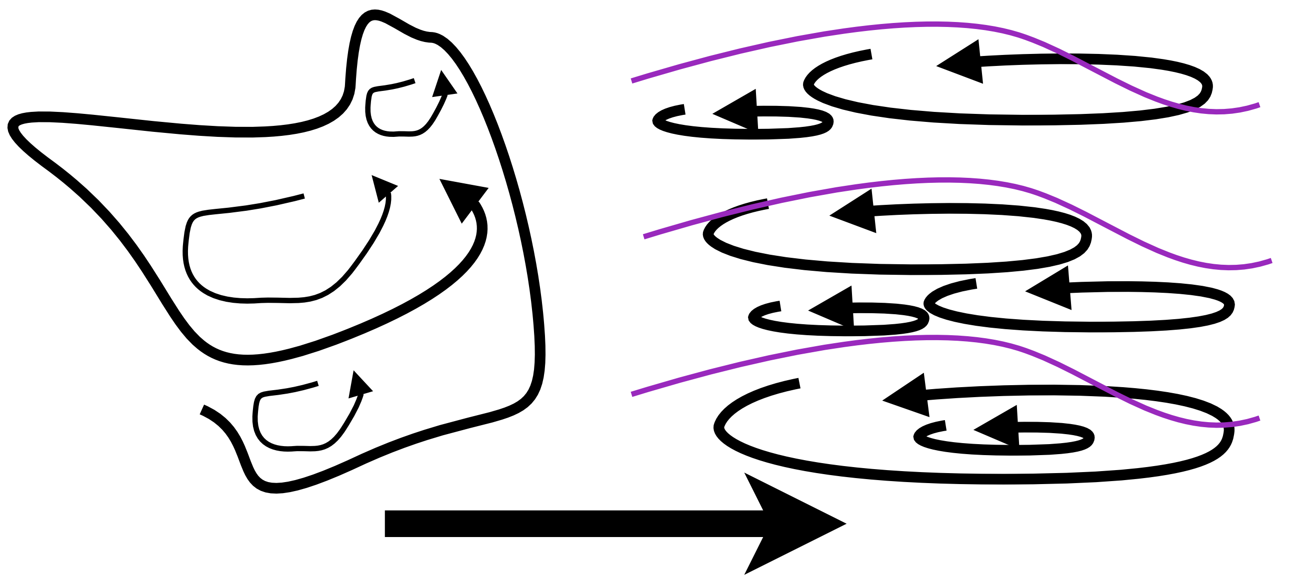


TPE about half TKE

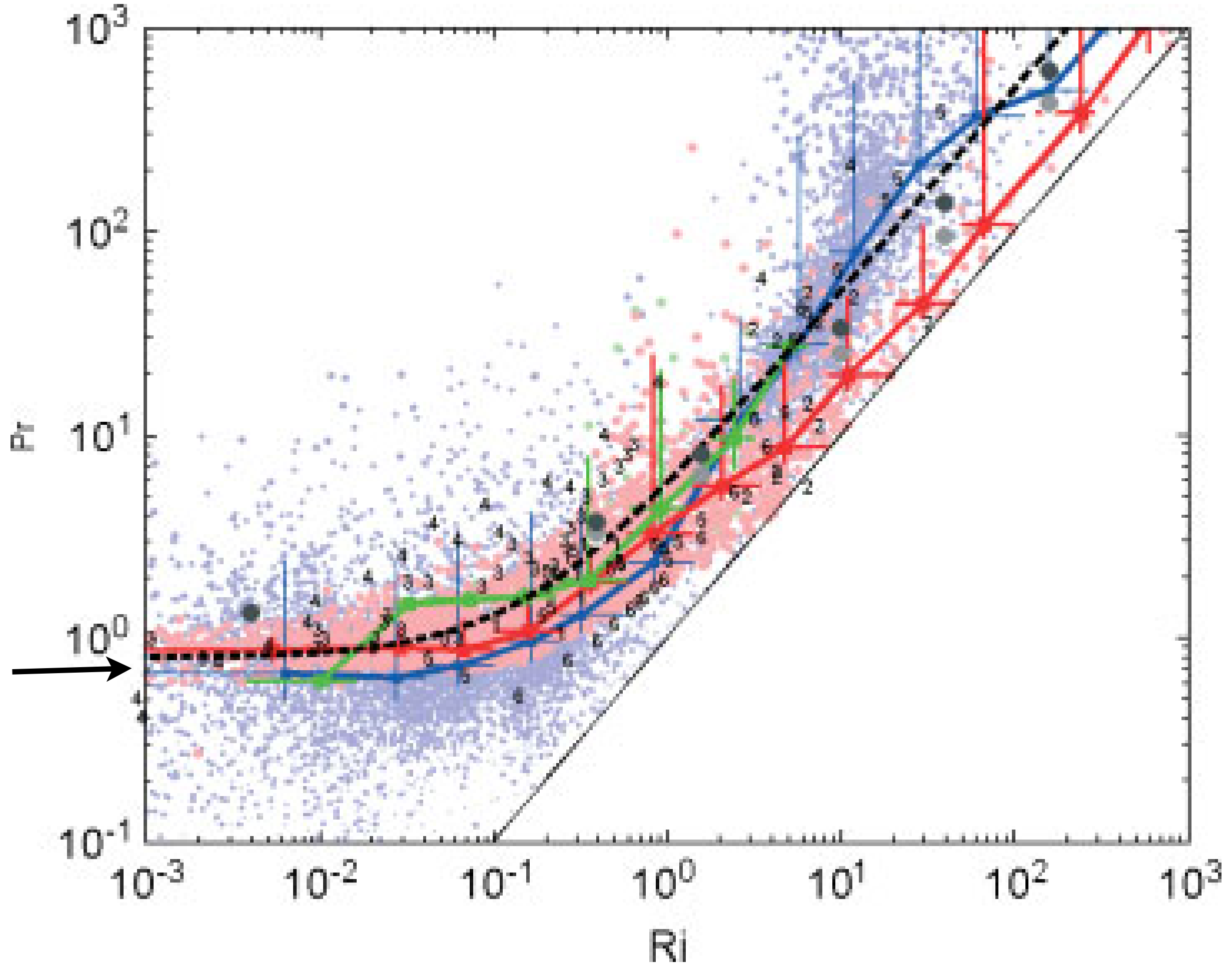
TPE near zero



From Mauritsen and Svensson (2007)

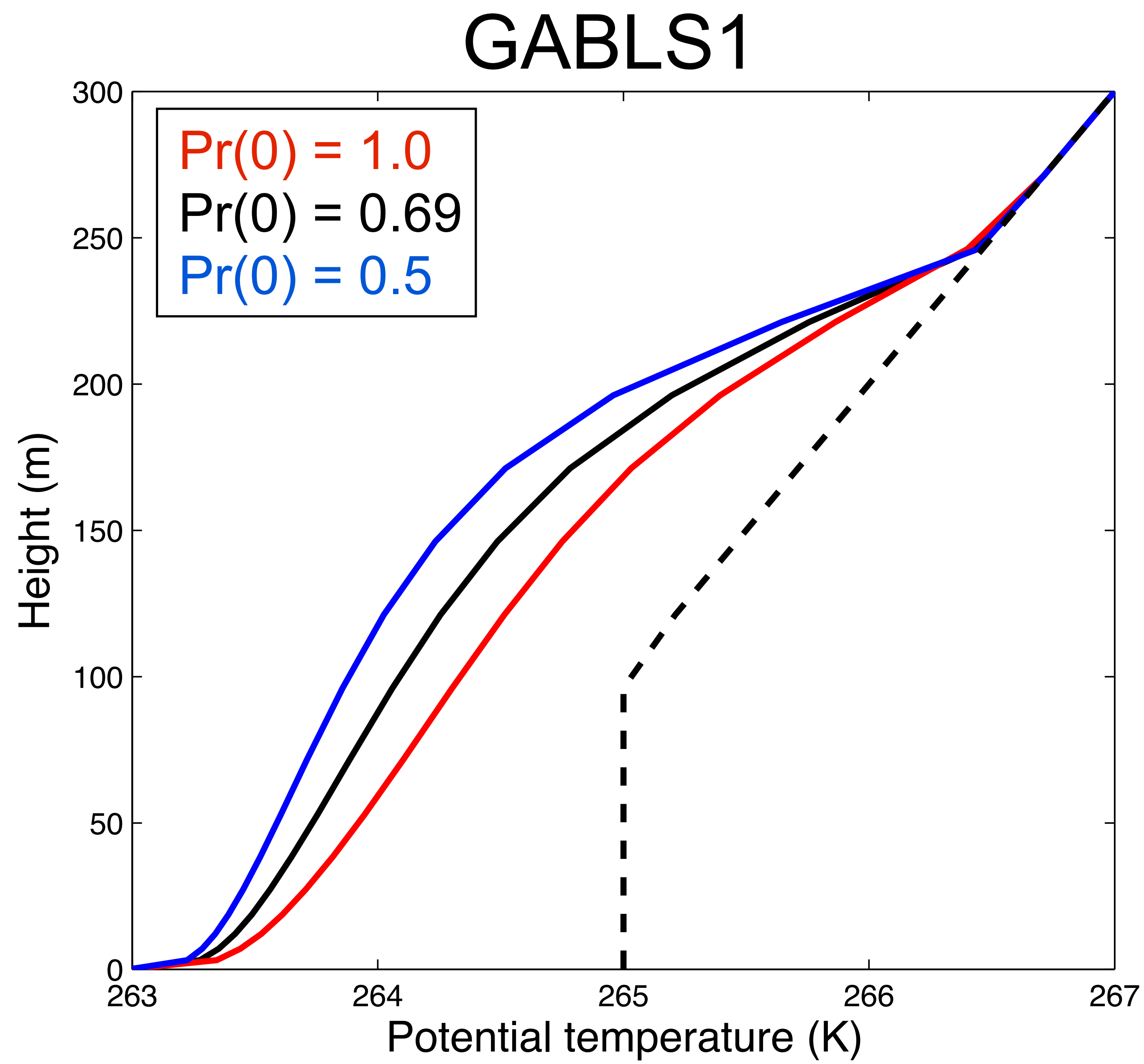
Neutral Prandtl number

Pr(0) below unity:



Zilitinkevich et al. (2008)

Pr(0): Carving more heat



Based on TTE model, Mauritsen et al. (2007)

Length-scales

$$K = f l^2 S$$

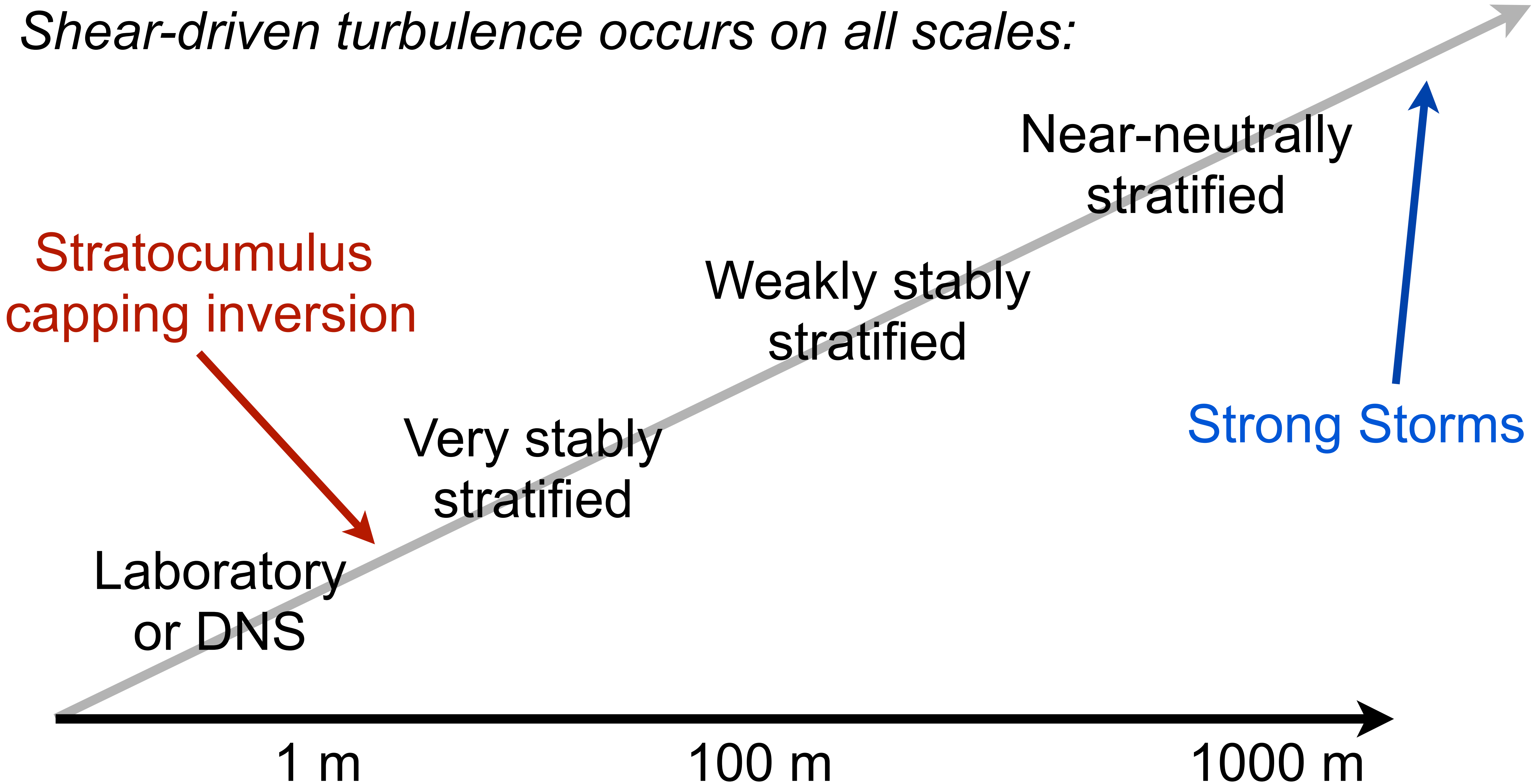
Shear (1/s)
- given

Length-scale (m)
- 'magic'

Non-dimensional Stability functions
- similarity theory + measurement

Length-scales

Shear-driven turbulence occurs on all scales:



... hence, a formulation may not contain dimensional parameters!

Length-scales

$$\frac{1}{l} = \frac{1}{kz} + \frac{f}{C_f\sqrt{\tau}} + \frac{N}{C_N\sqrt{\tau}},$$

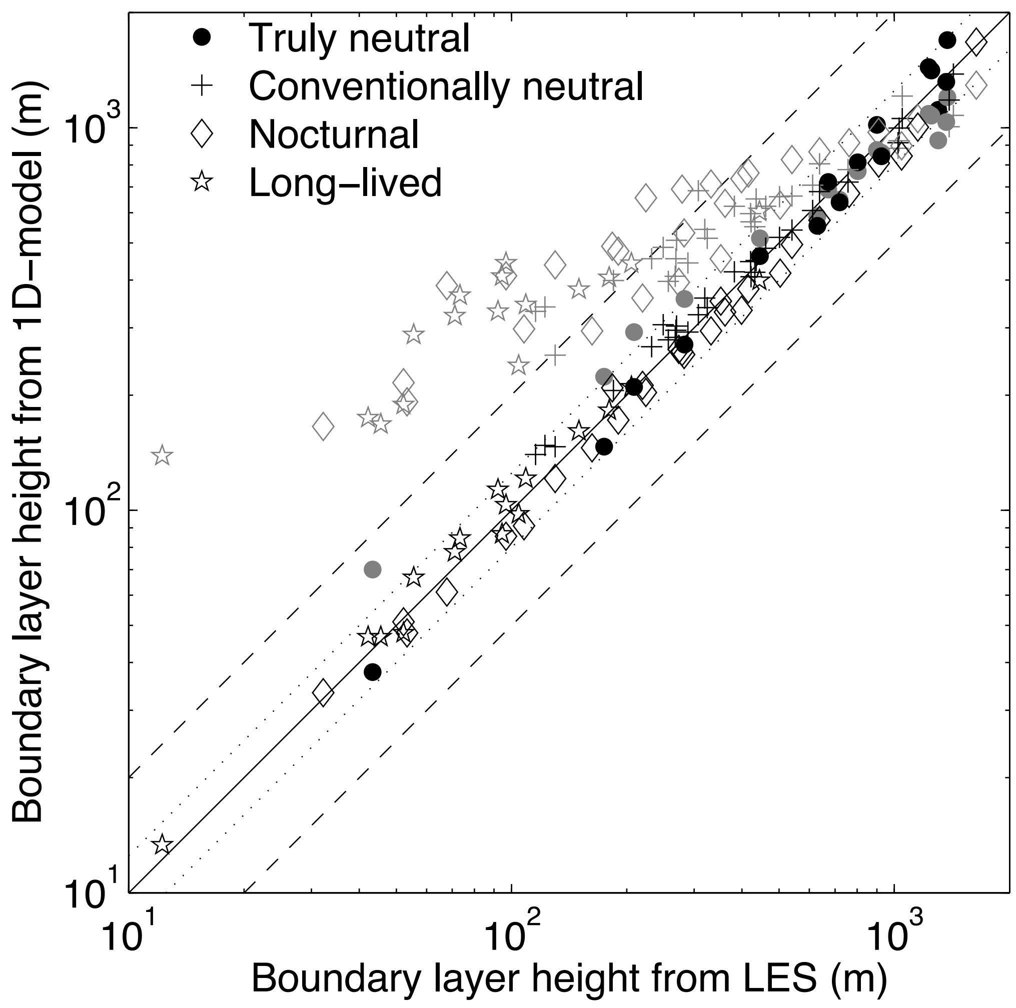
Wall-flow

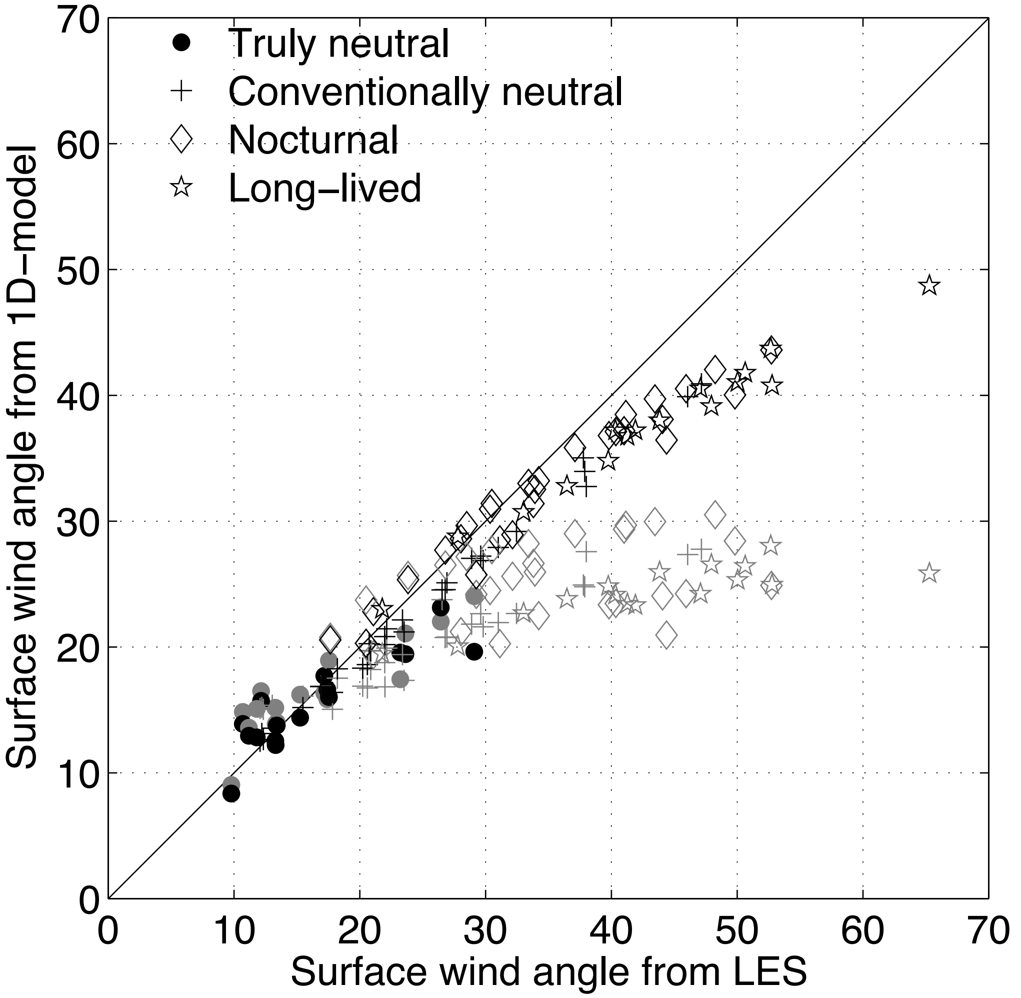
Rotation

Stratification

Rossby and Montgomery (1935), Blackadar (1962), Mauritsen et al. (2007)

Length-scales





From Mauritsen et al. (2007)

Conclusions

- Modeling stably stratified turbulence is a simple, yet challenging task:
- *Tinkering* with MO is a perfectly valid approach to improving weather forecasts in the short- to medium term, however:
- I believe we *should* abandon MO in order to reduce the divide between observations and parameterizations, and that:
- An empirically-based approach *must* abandon MO, due to self-correlation that leads to an intrinsic underestimation of fluxes under stable stratification

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- An empirically-based approach *must* abandon MO, due to self-correlation that leads to an intrinsic underestimation of fluxes under stable stratification
- There is evidence that atmospheric turbulence occur at high Richardson numbers, and understanding this is closely linked to the behavior of the turbulent Prandtl number
- Using Total Turbulent Energy, rather than TKE, permits turbulence at large Ri
- Lower than unity Pr(0) allows ‘carving’ out more heat from the SBL, thereby alleviating part of the cold-bias
- Turbulent length-scale formulations should be based on physical scaling and contain only non-dimensional parameters

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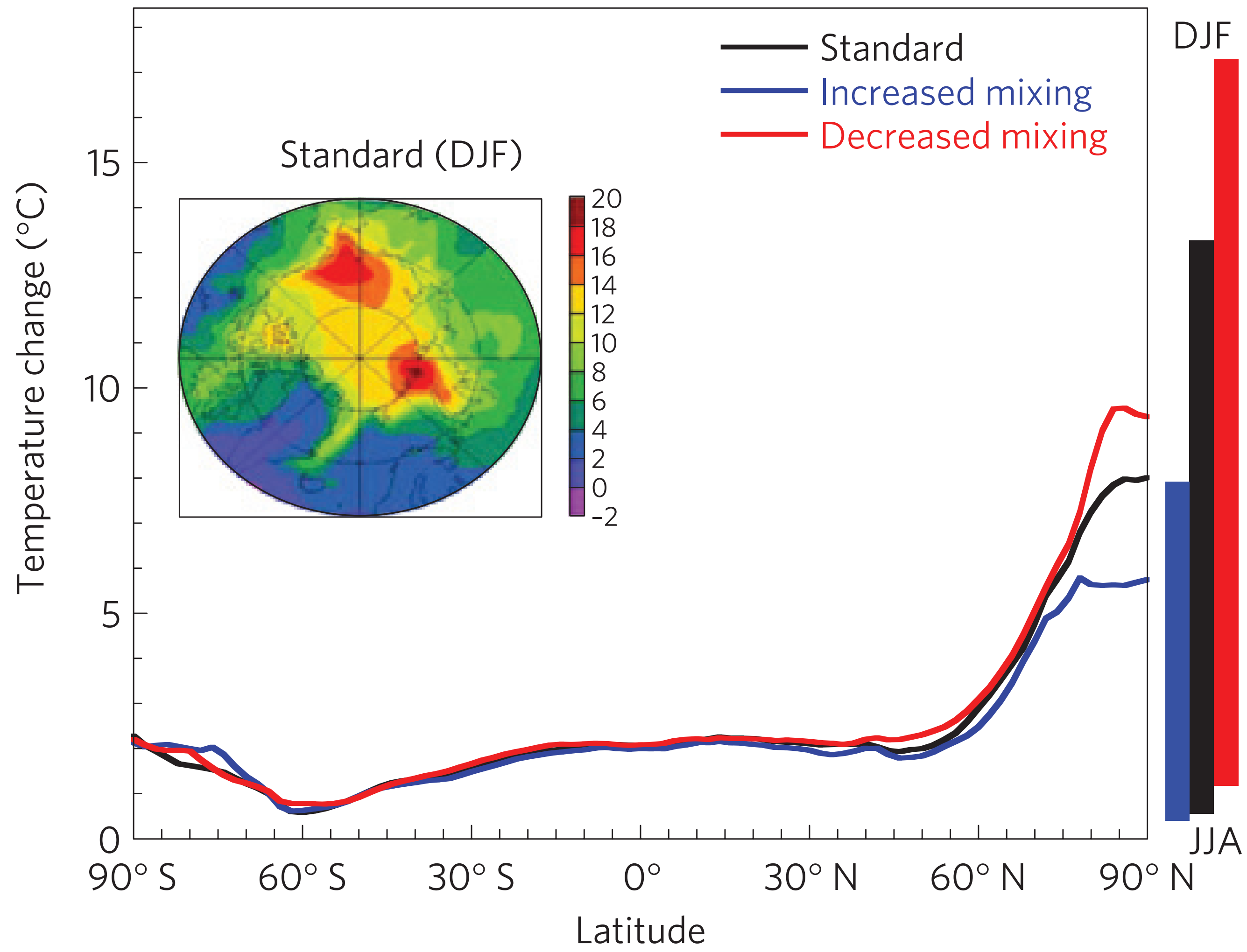
- Lower than unity Pr(0) allows 'carving' out more heat from the SBL, thereby alleviating part of the cold-bias
- Turbulent length-scale formulations should be based on physical scaling and contain only non-dimensional parameters
- A solution to the night-time cold-bias could be found in longwave radiation biases, e.g. due to water vapor, cloudiness, aerosol, surface emissivity, ***or,*** other processes, such as deep convection, gravity wave drag etc.

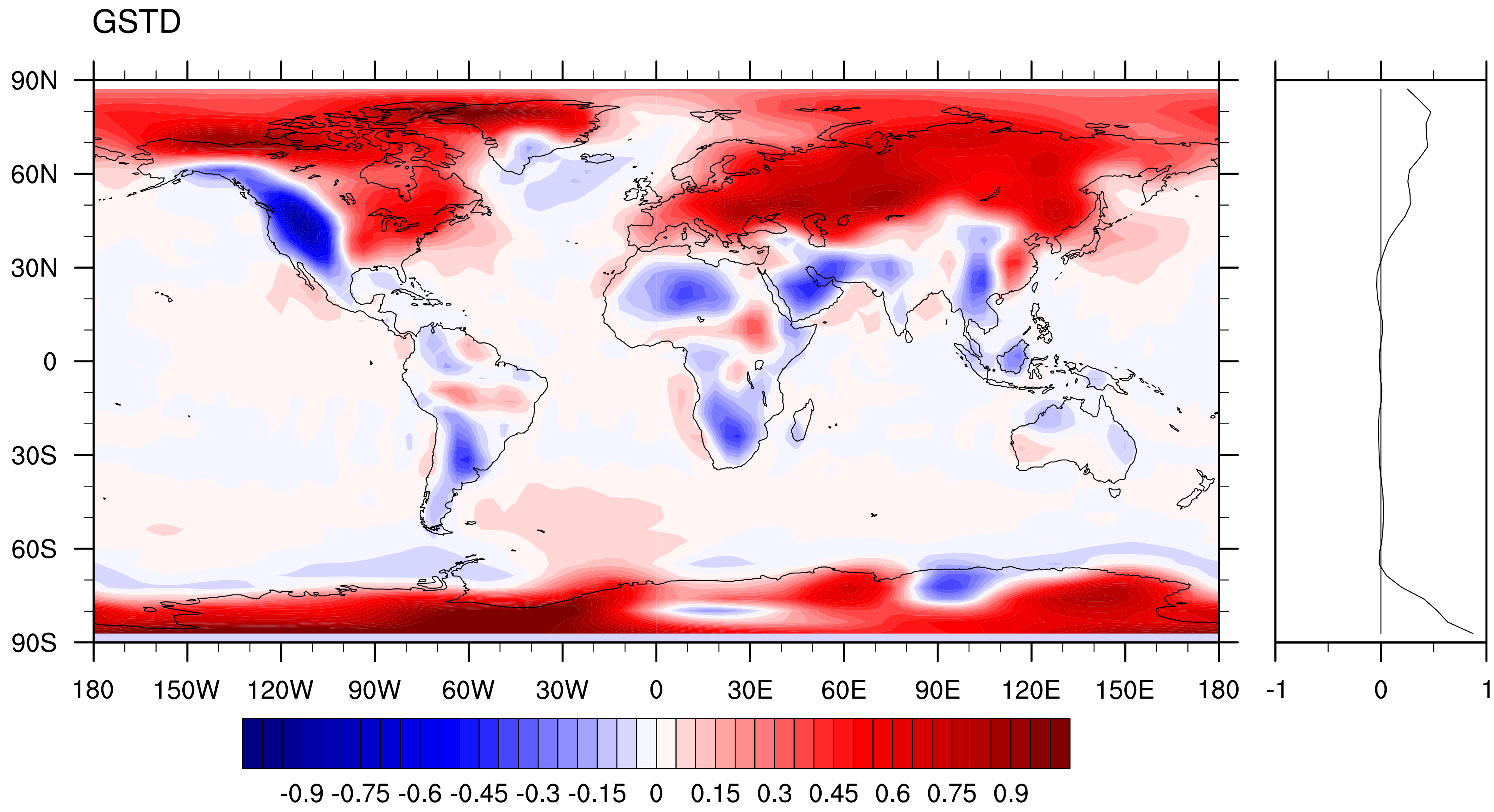
Arctic amplification and Turbulence



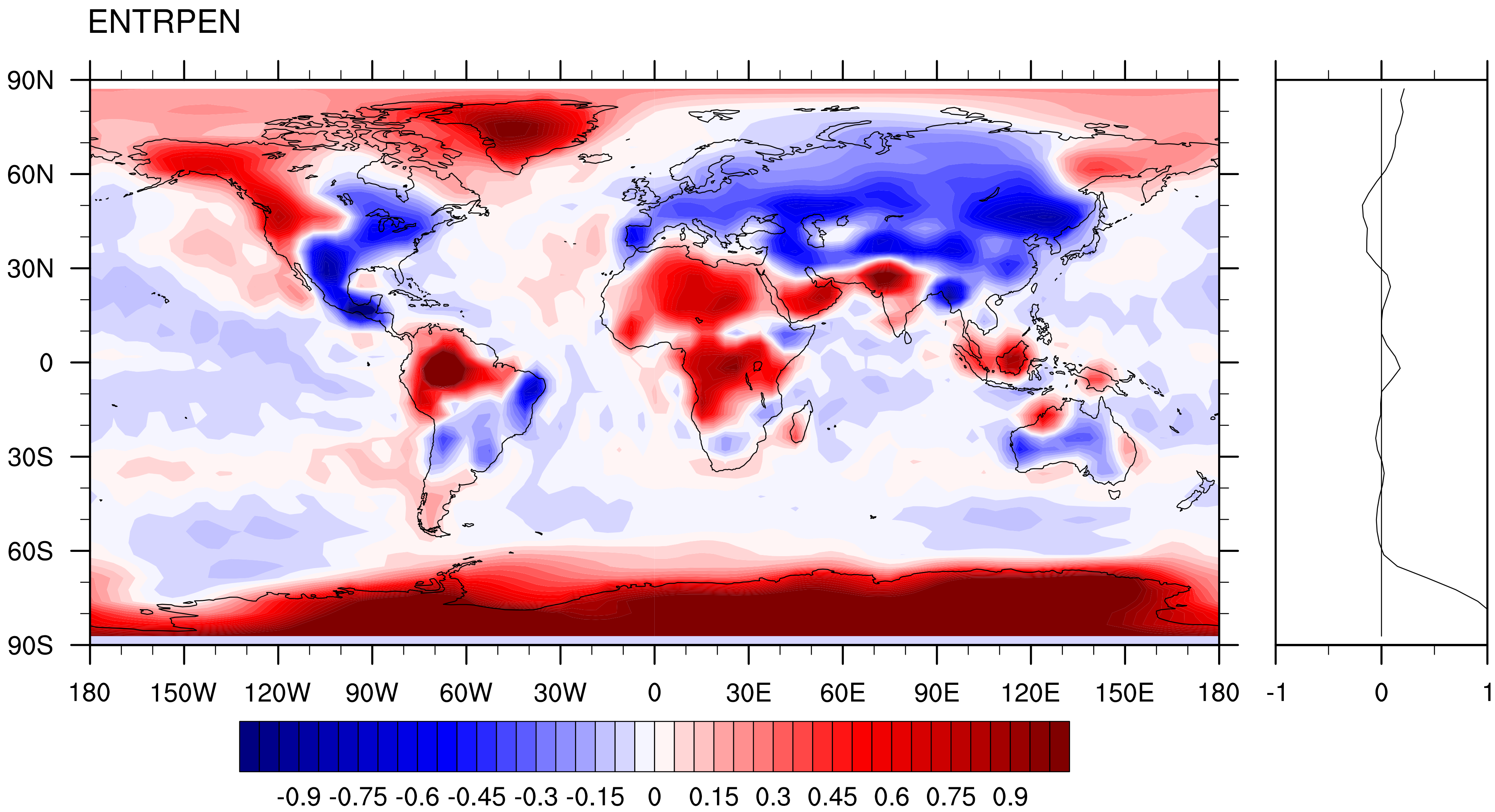
EC-EARTH: Yes
ECHAM 6.0: No

From Bintanje et al. (2011)

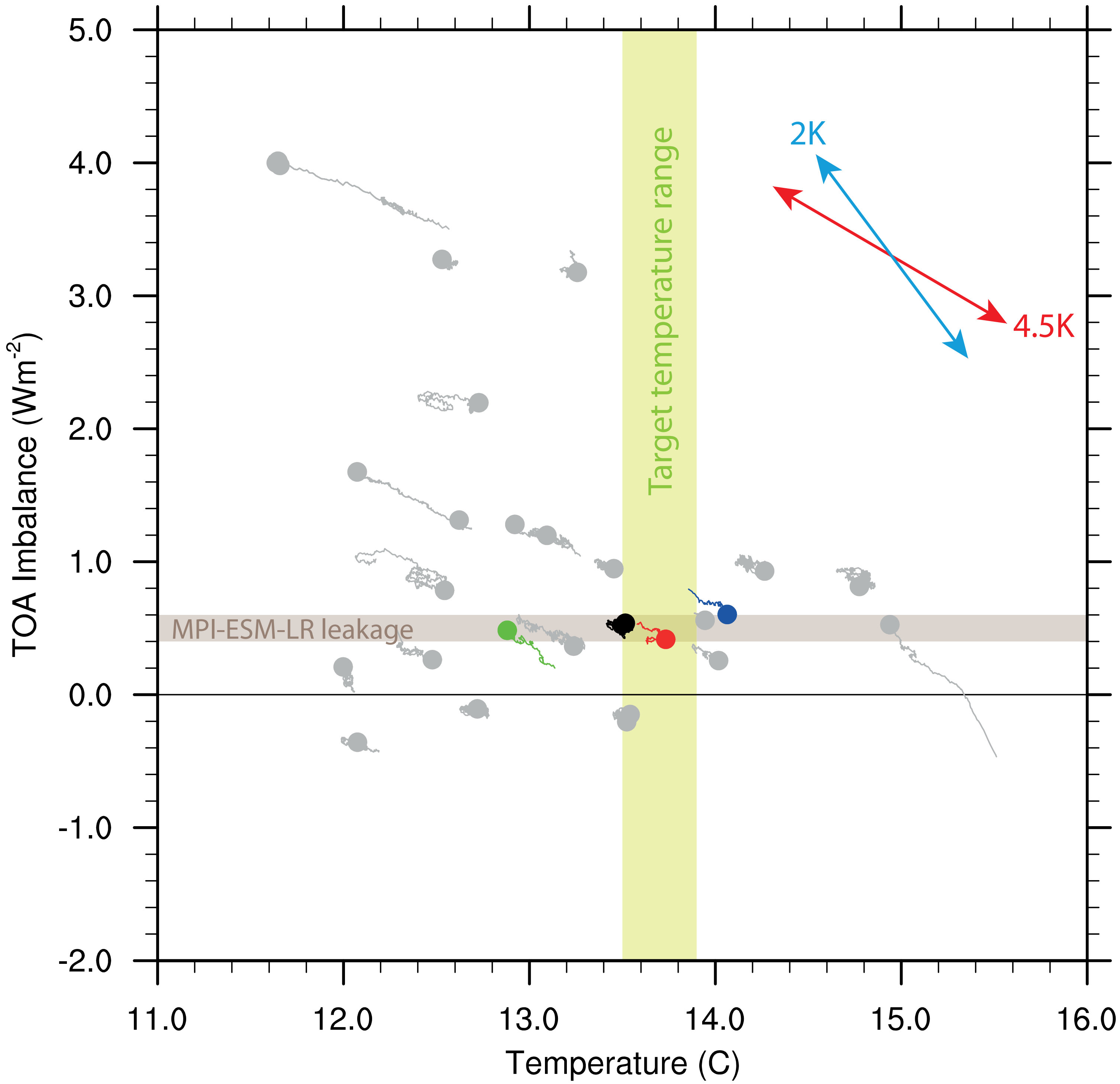
Gravity wave drag



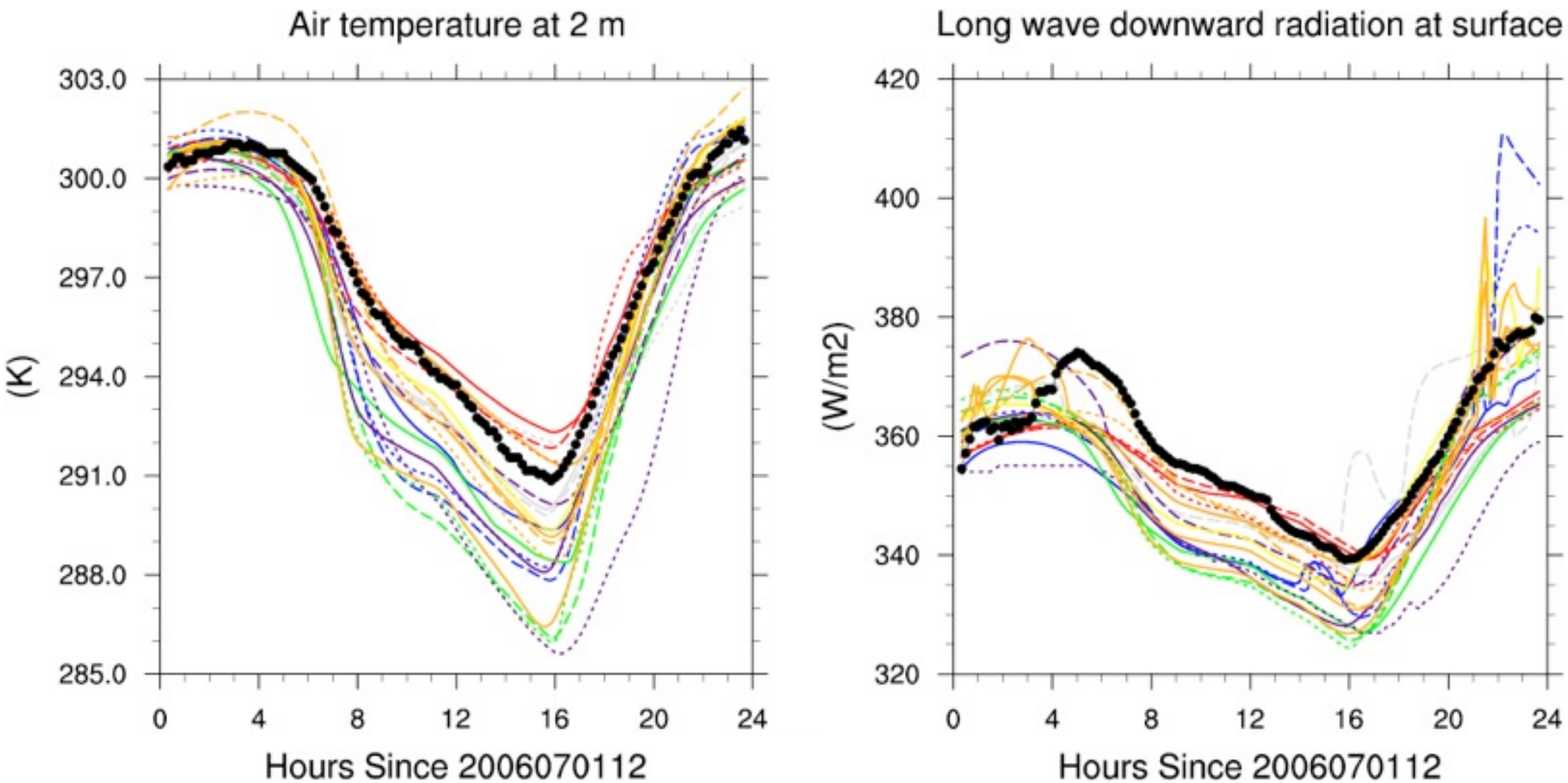
Deep convection



Climate drift

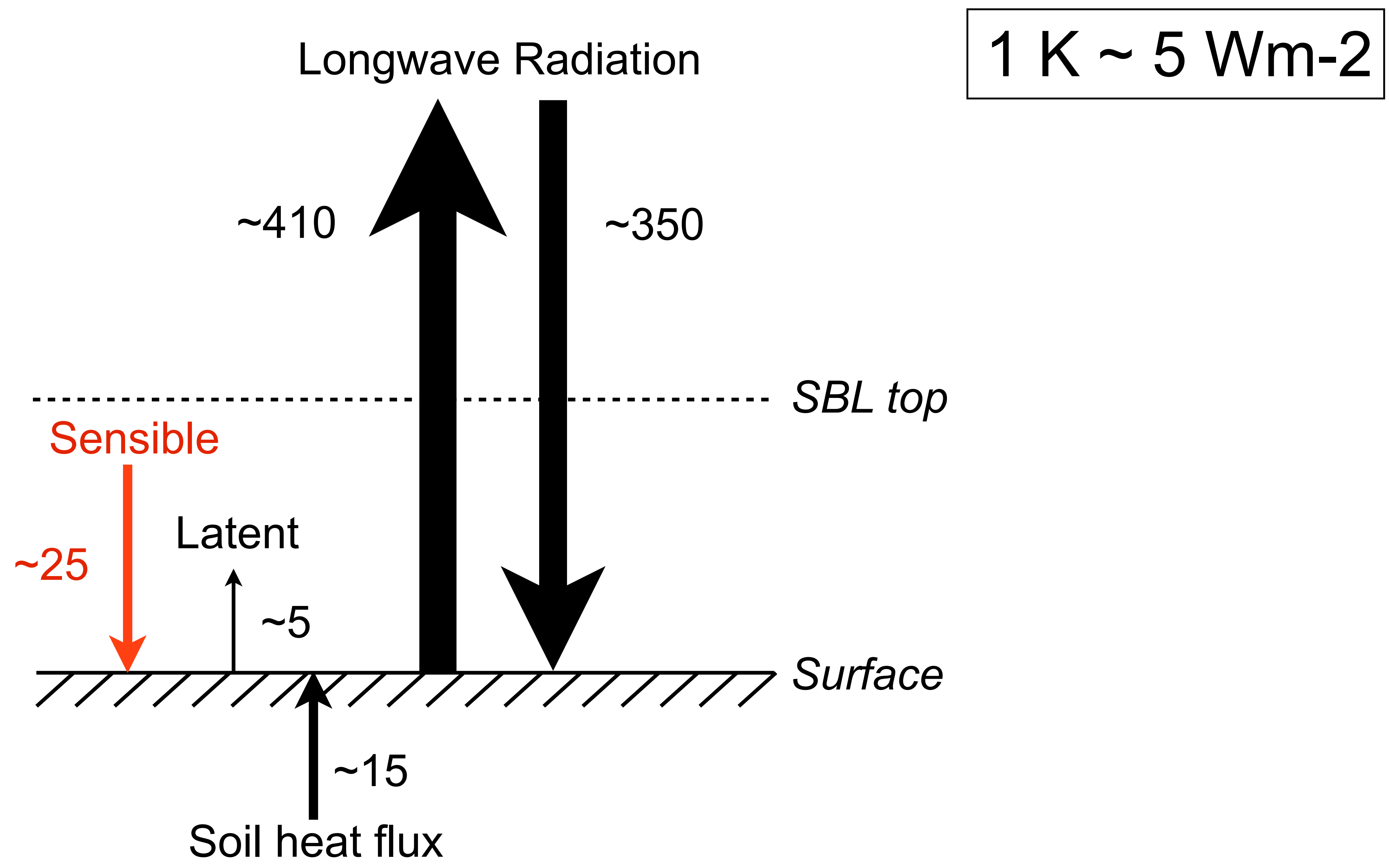


Longwave radiation bias?



Plots from GABLS3 by Fred Bosveld

What determines the night-time surface temperature?



Observations are from GABLS3

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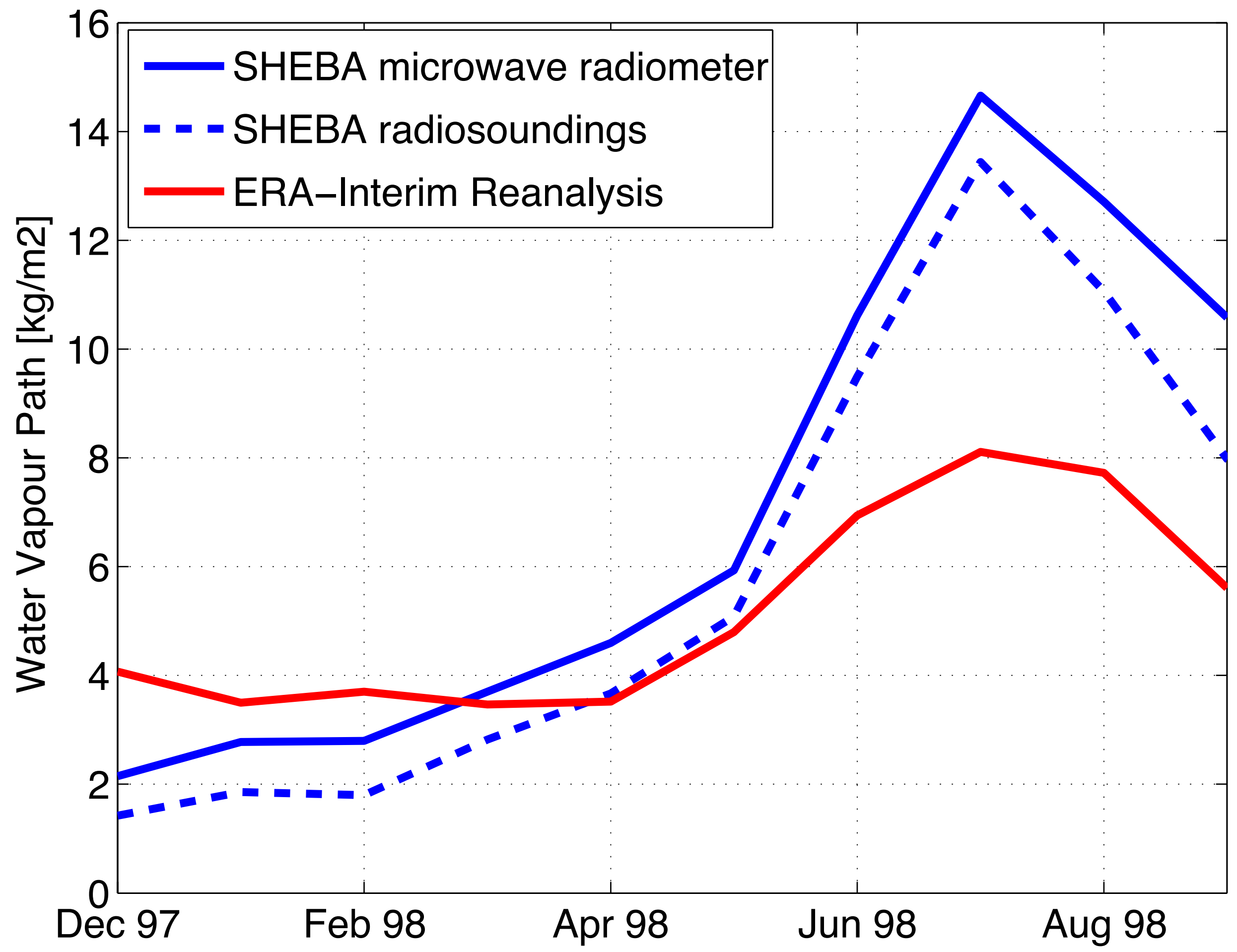

Zygmuntowska et al. (2012)