WAVES TO WEATHER

DFG Collaborative Research Center 165

The Atmospheric Mesoscale

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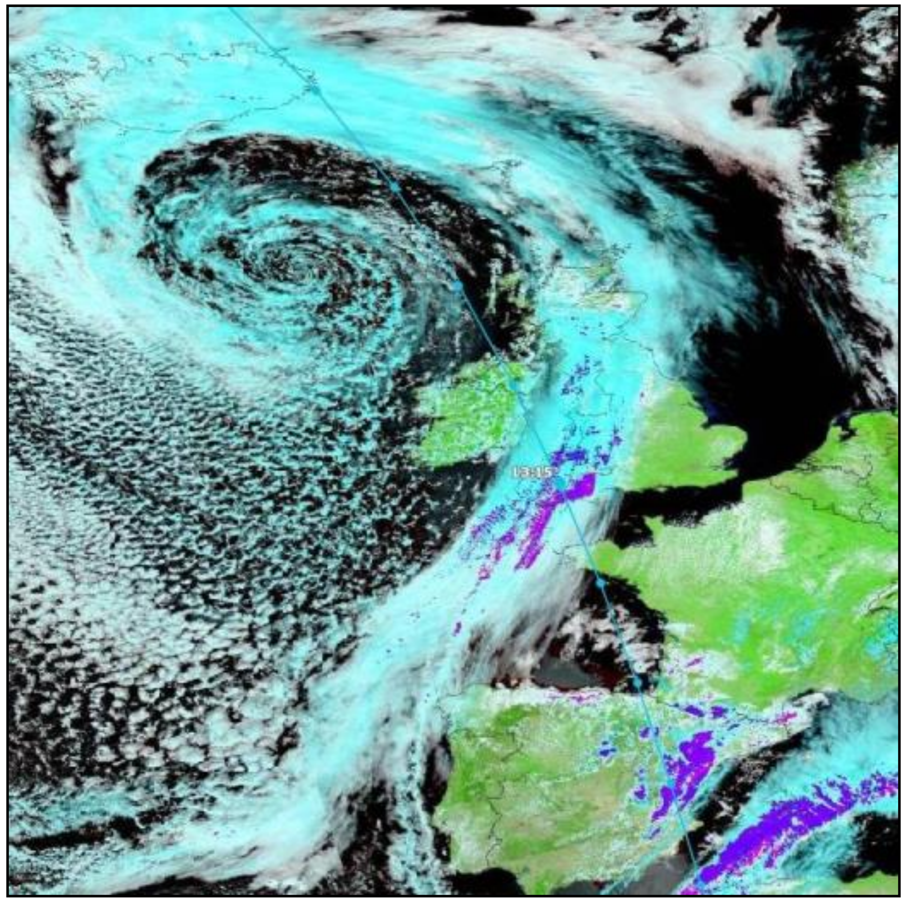
WAVES TO WEATHER

The mesoscale gap

Synoptic	Mesoscale	Convective
1000 km	100 km	10 km
100 hr	10 hr	1 hr



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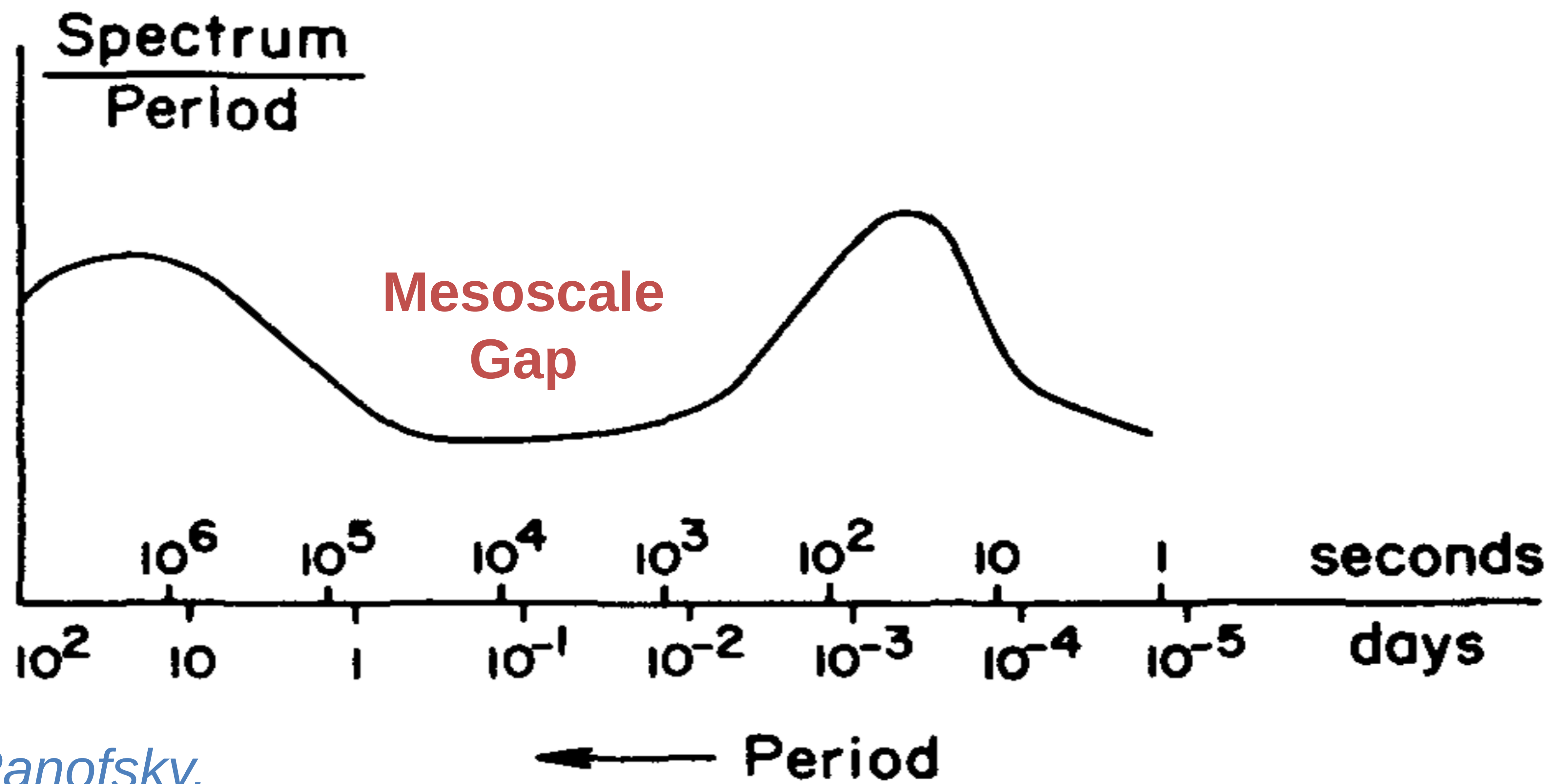
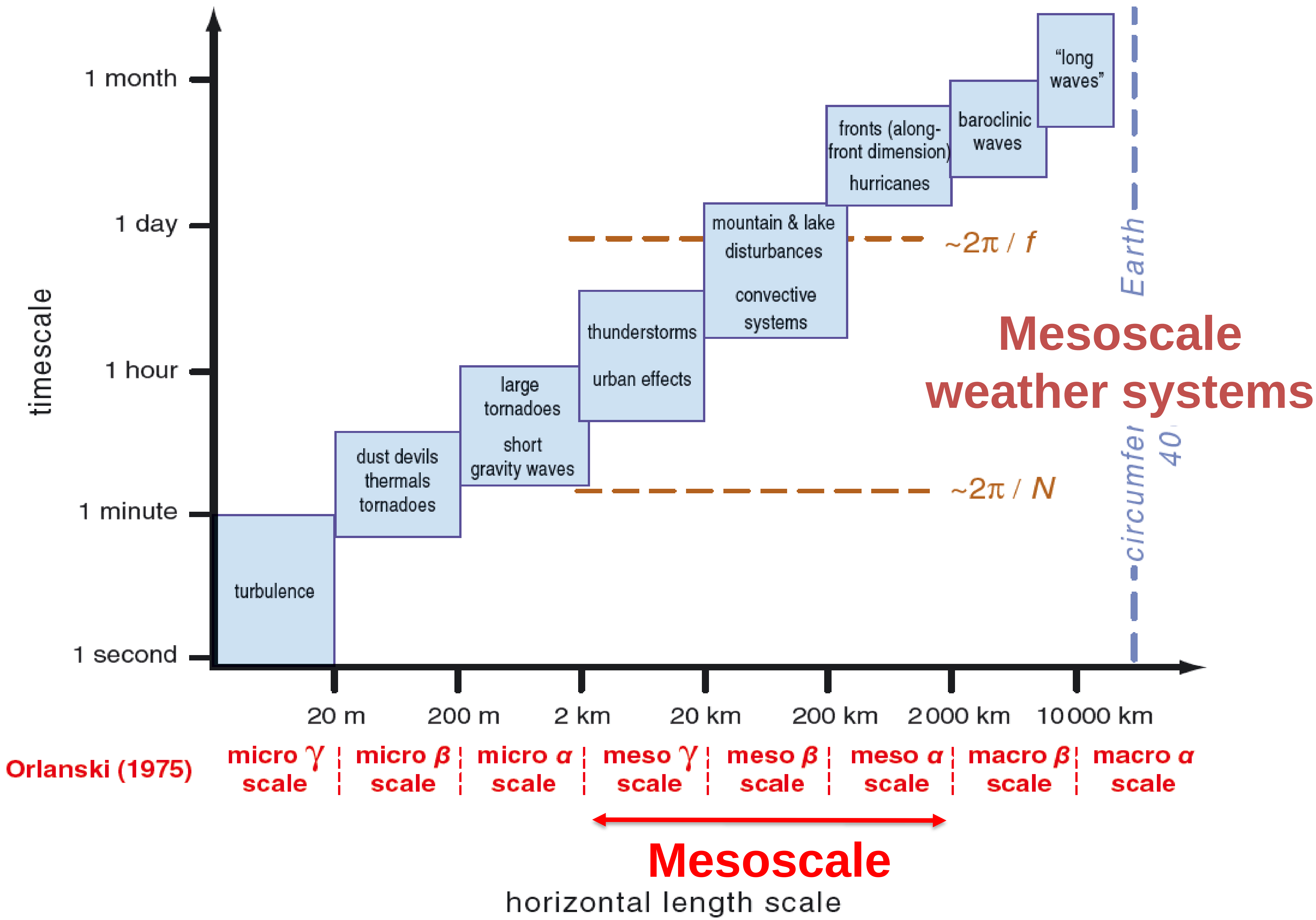


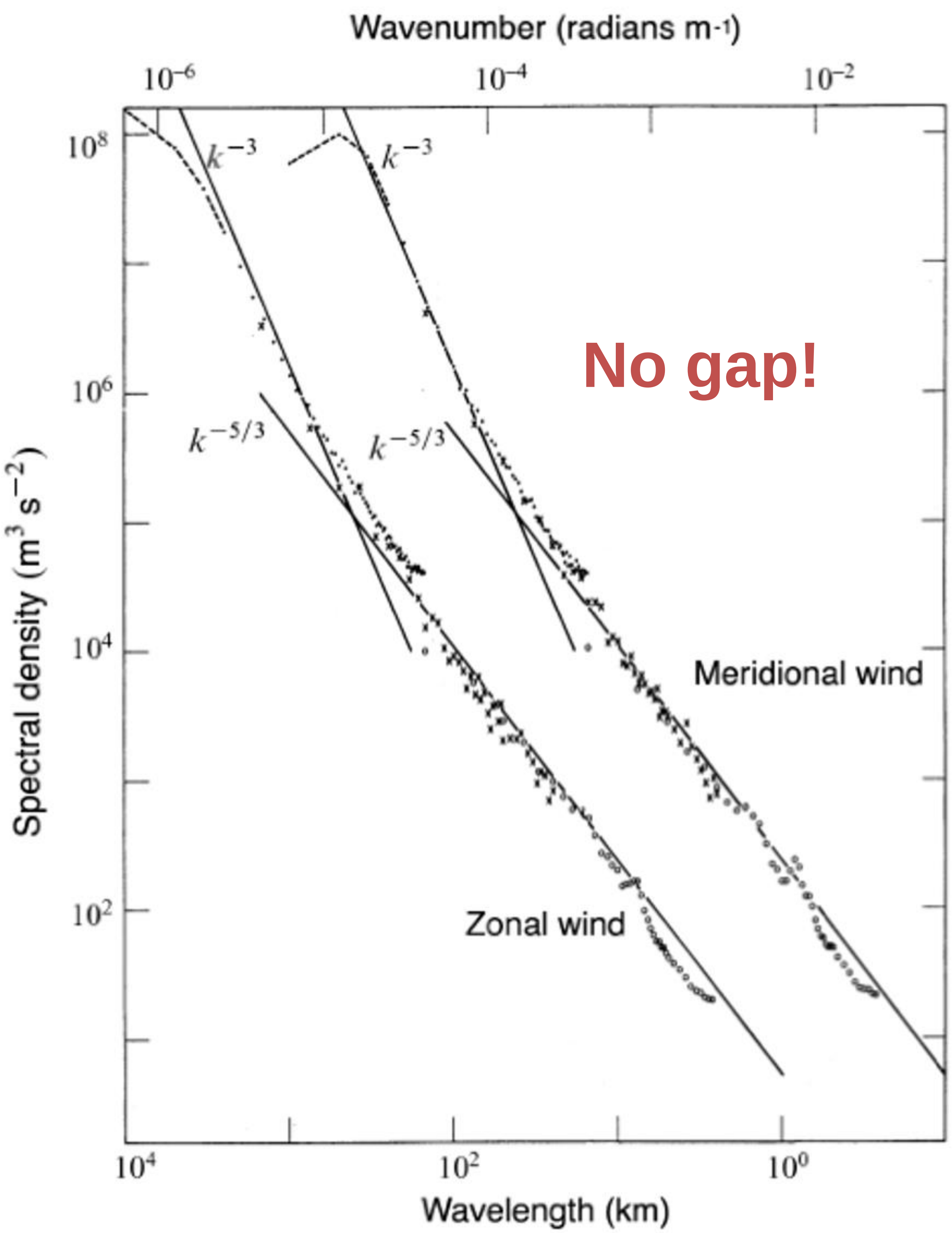
(Fiedler and Panofsky, BAMS 1970)

Mesoscale weather phenomena



(Markowski, "Mesoscale Meteorology in Midlatitudes" 2010)

Observed kinetic energy spectrum

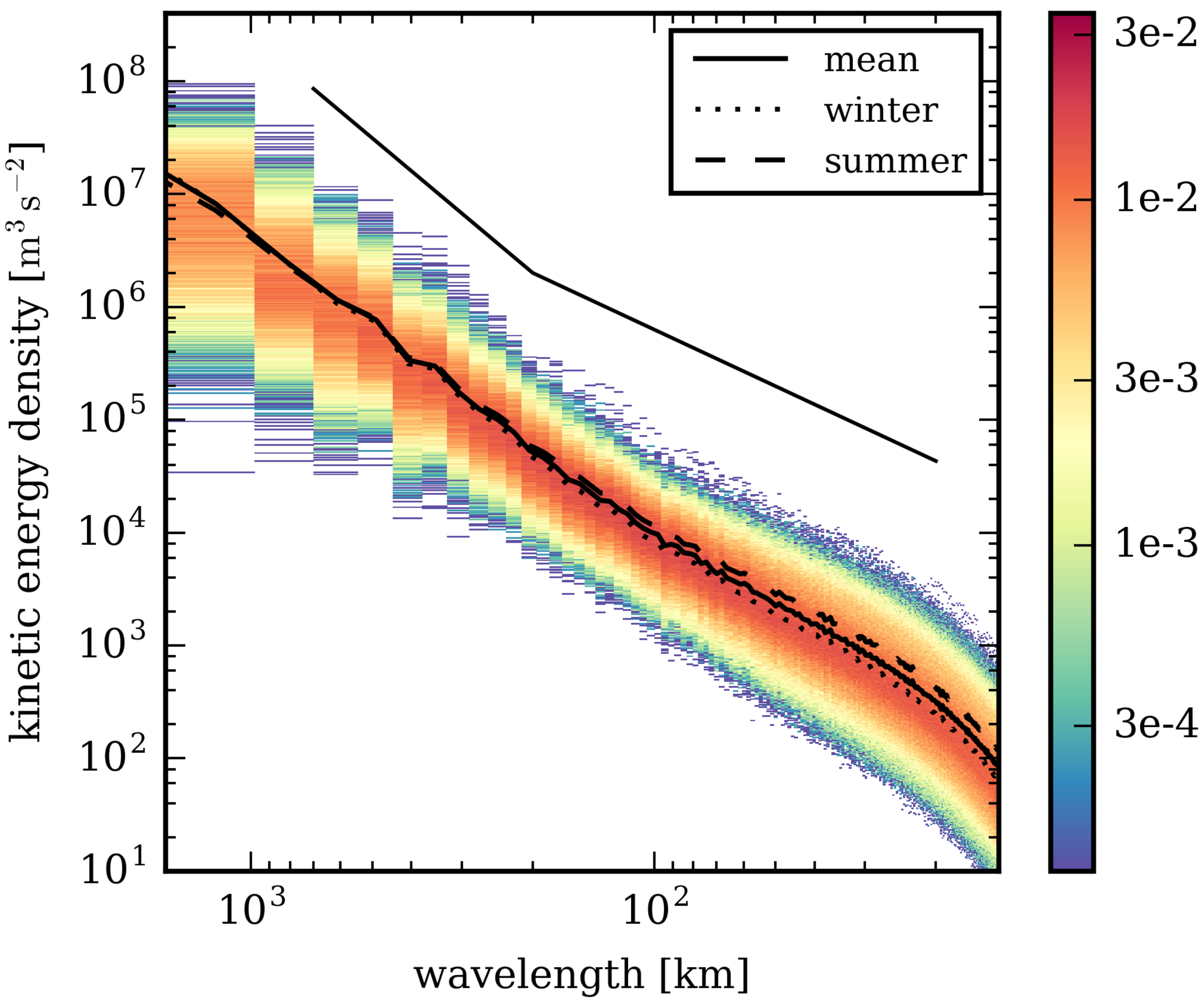


Kinetic energy spectrum observed from commercial aircraft (Global Atmospheric Sampling Program; *Nastrom et al 1984*)

“Universal” shape
***k*$^{-3}$ power law** – QG enstrophy cascade
***k*$^{-5/3}$ power law** – upscale cascade, *or* downscale cascade, *or* orography, *or* gravity wave saturation, *or* …?

Large model-based data set

Kinetic energy spectrum
at 10 km



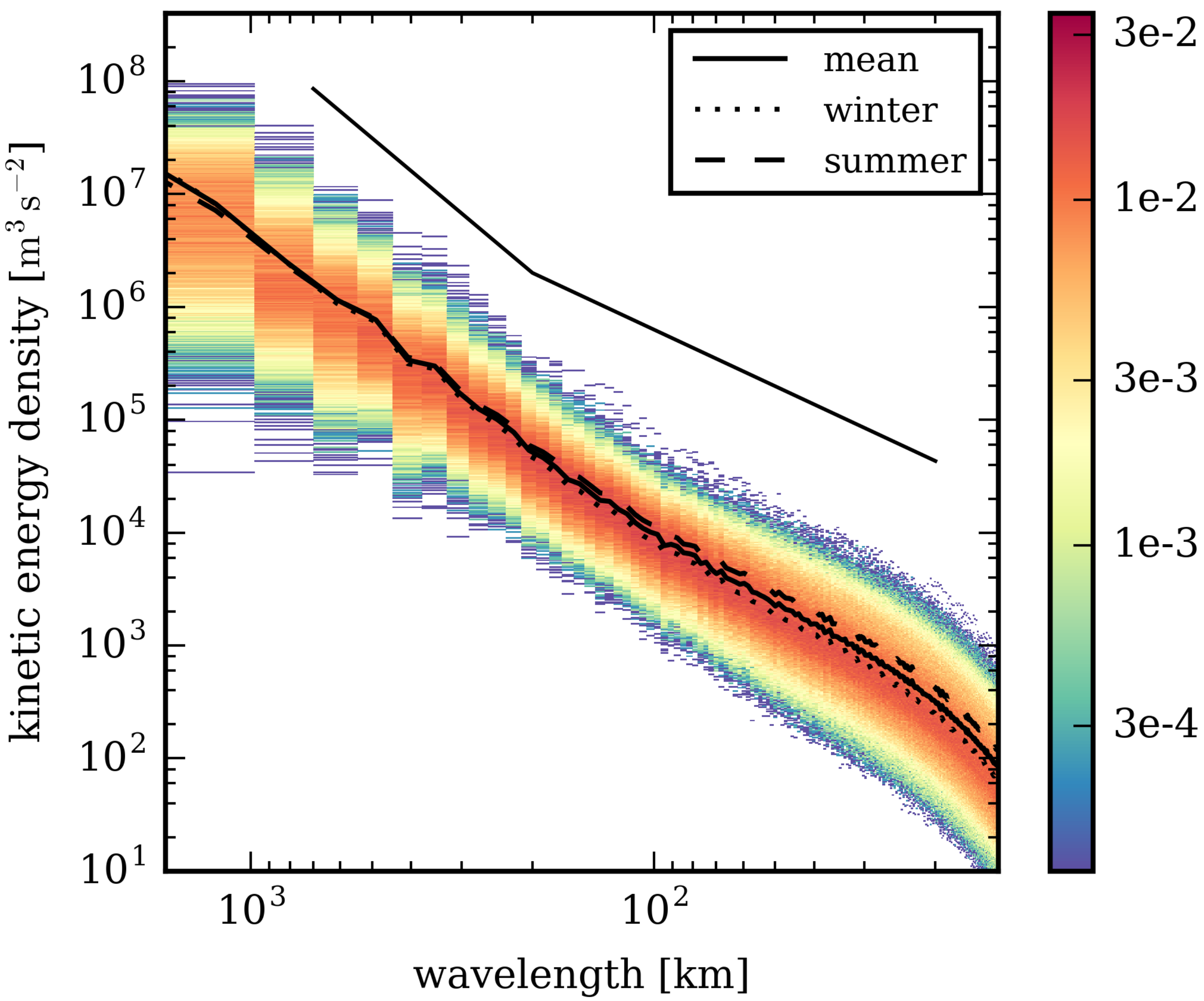
COSMO-DE operational analysis

- Nudging to radar and conventional data
- Horizontal resolution: 2.8 km
- Domain: 1200x1300 km, centred over Germany
- 3 years (2014-2016), at 3 hourly intervals

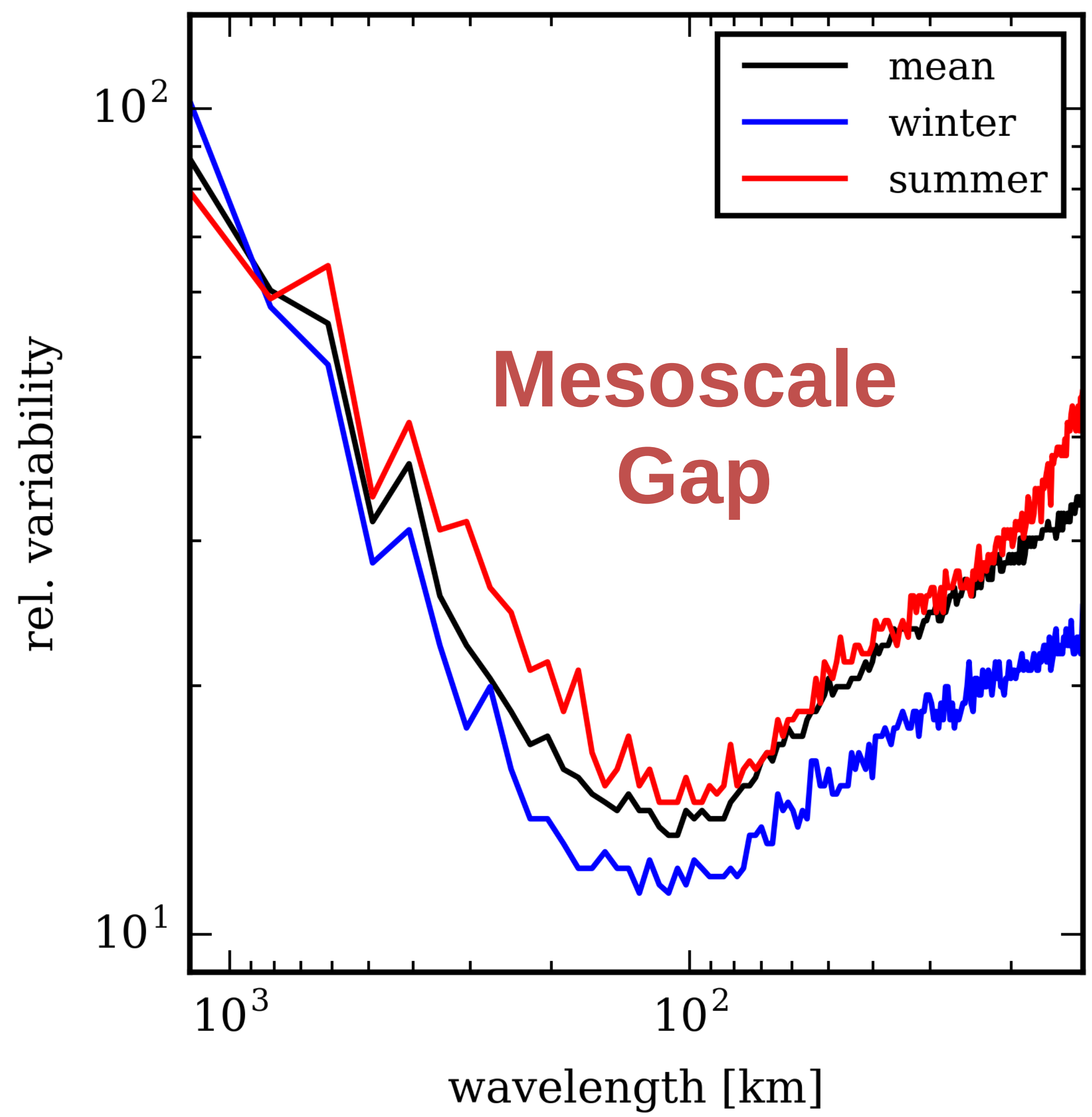
(Selz, Bierdel and Craig JAS 2018, submitted)

Variability of kinetic energy spectrum

Kinetic energy spectrum
at 10 km

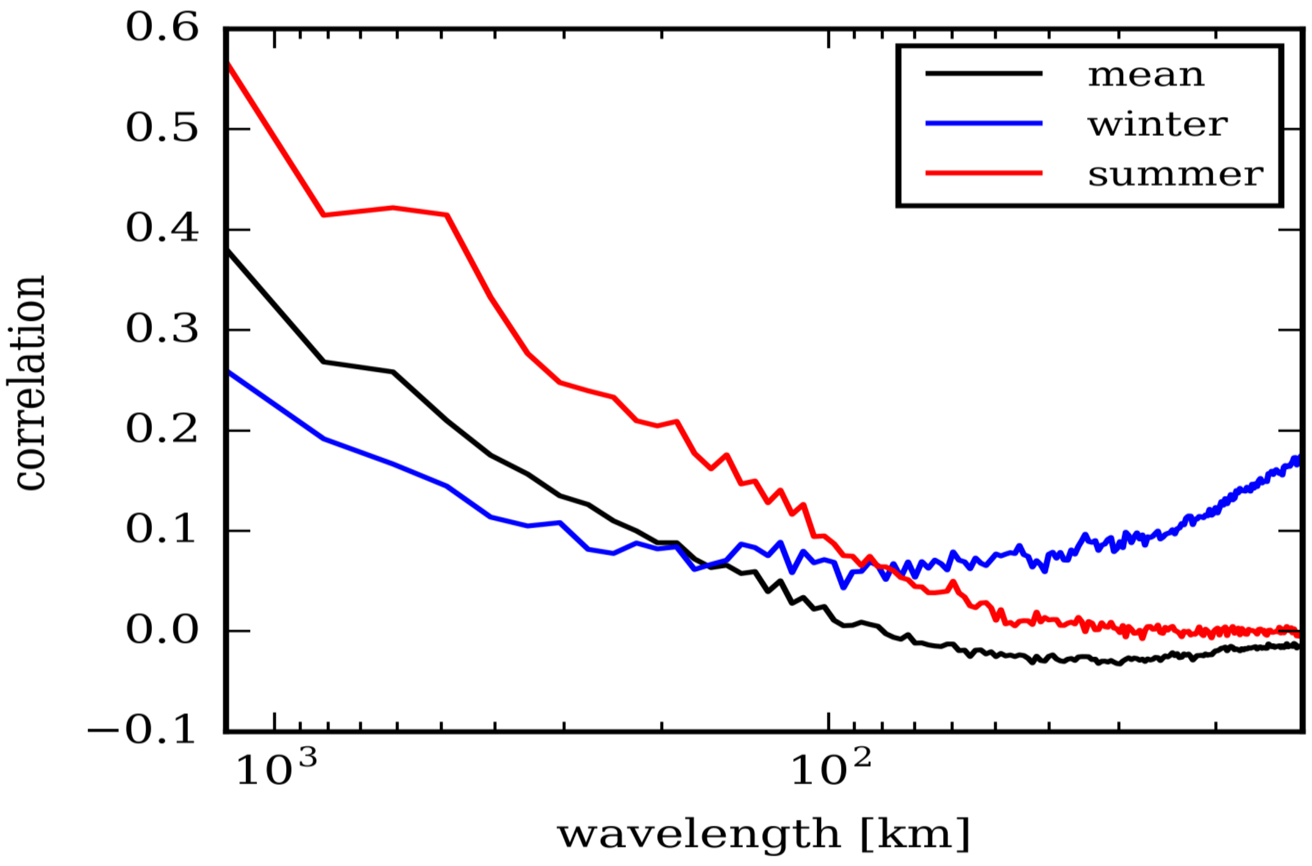


Relative variability of
kinetic energy spectrum

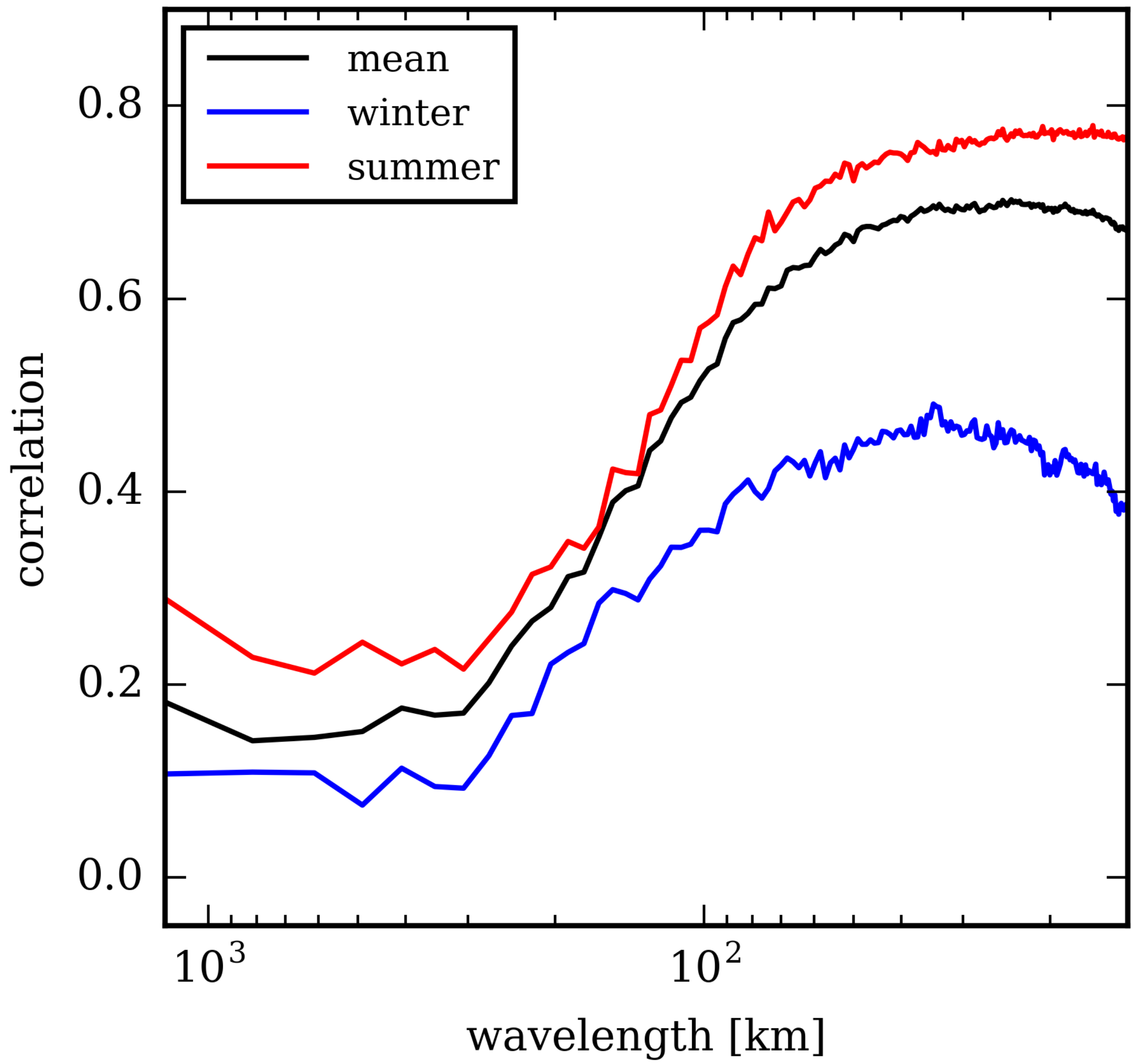


Correlations with kinetic energy

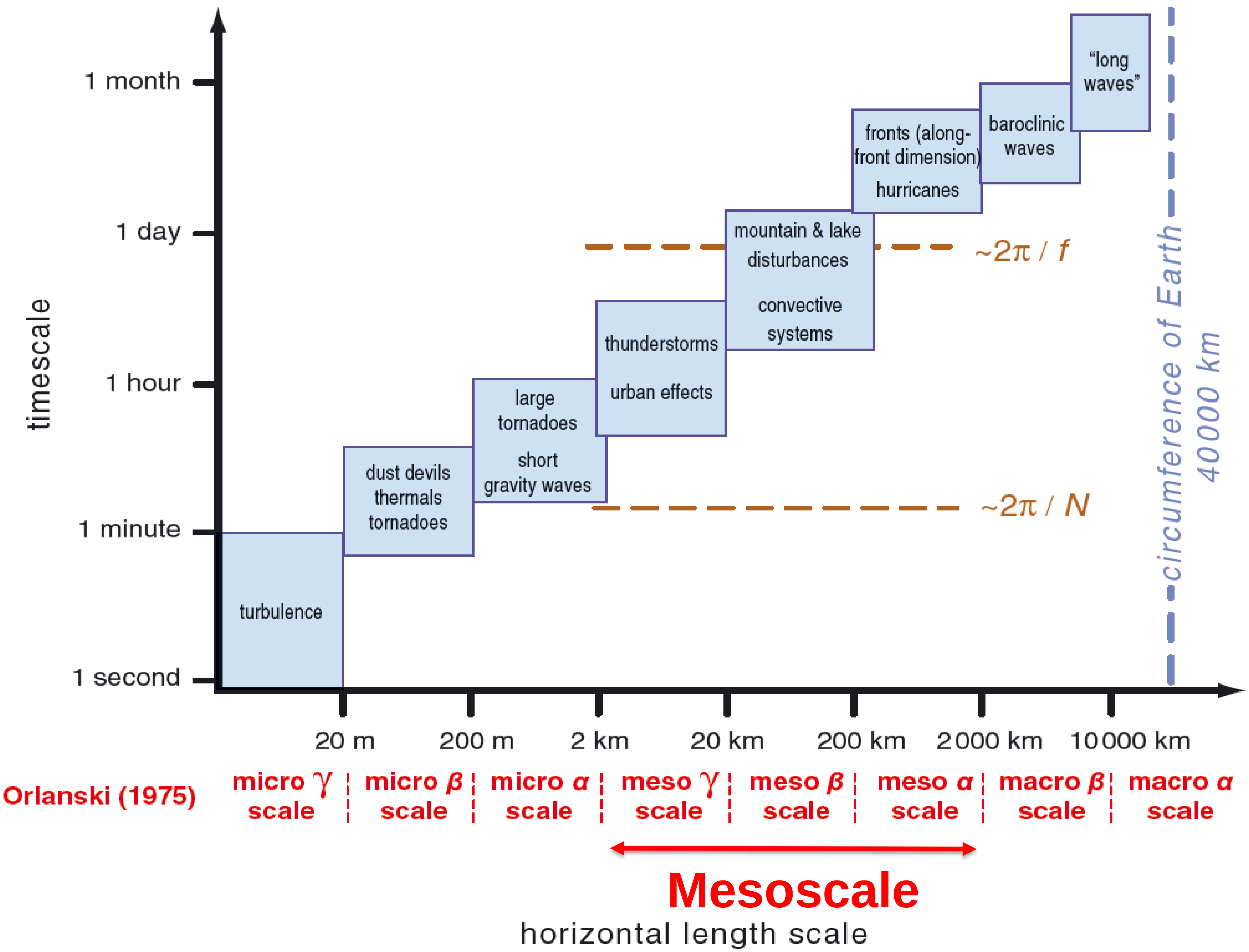
Correlation of kinetic energy with squared PV anomaly



Correlation of kinetic energy with precipitation

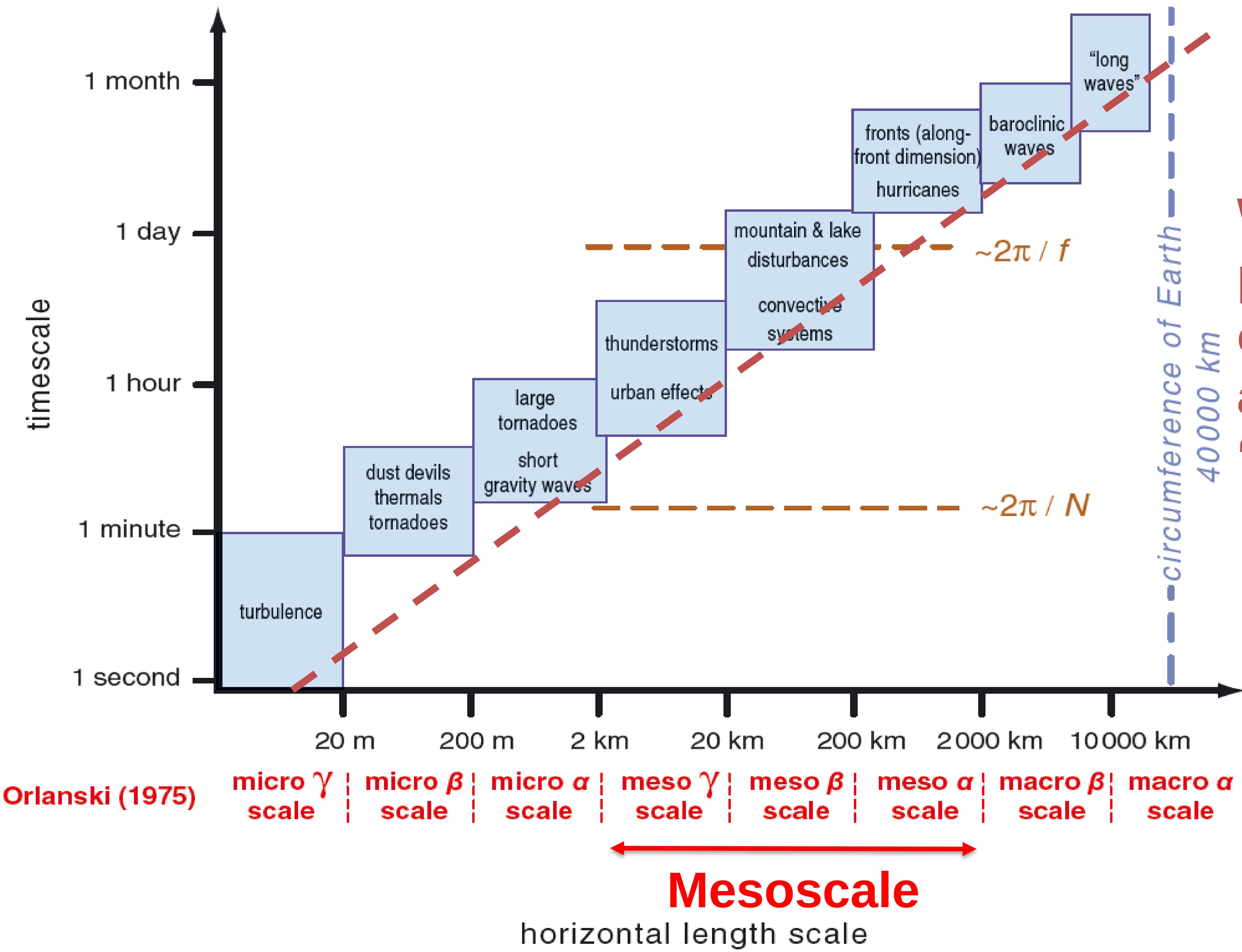


Mesoscale weather phenomena



(Markowski, "Mesoscale Meteorology in Midlatitudes" 2010)

Mesoscale weather phenomena

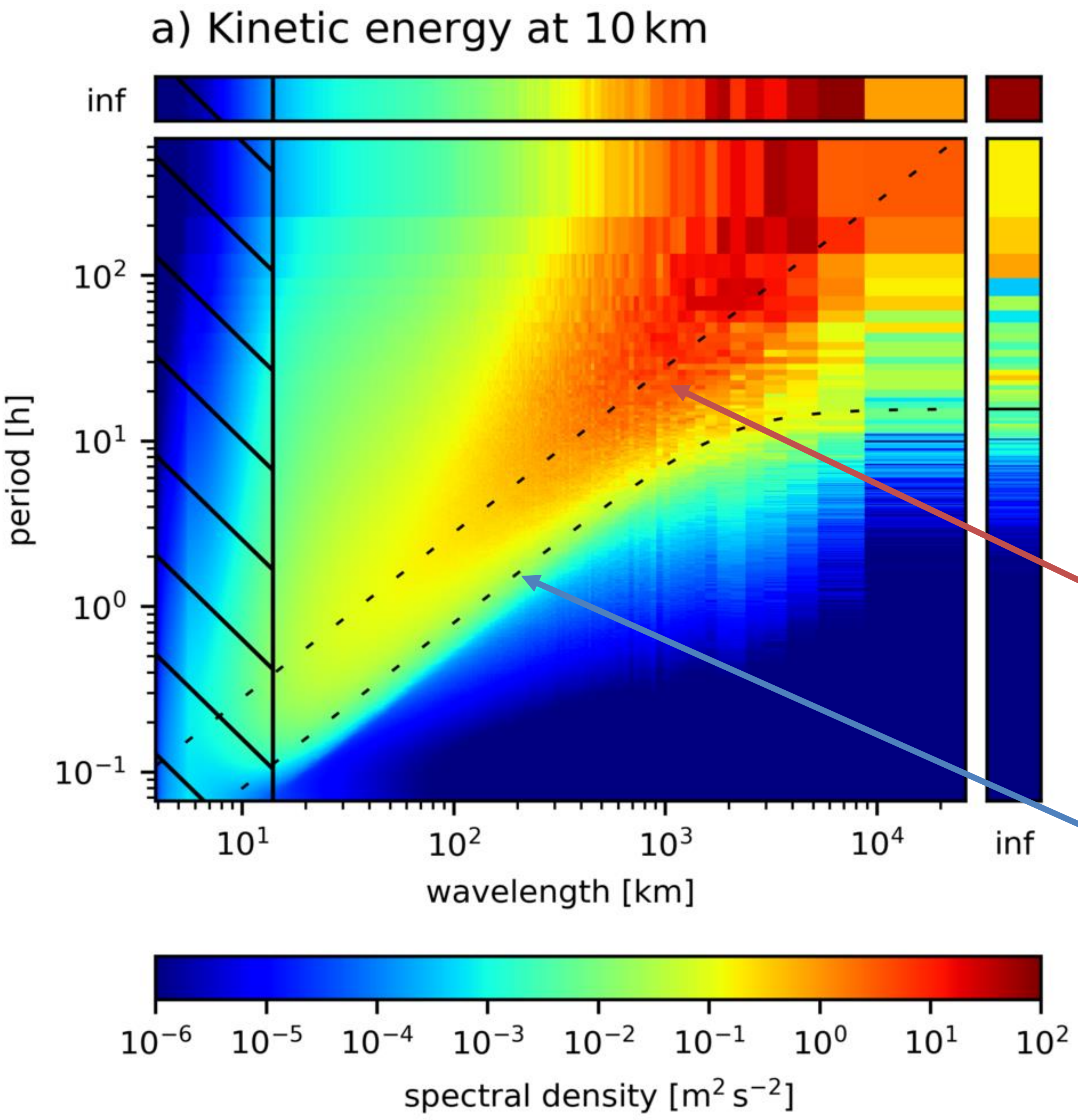


Constant speed
$v \sim 10$ ms^{-1}

Weather phenomena concentrated along "advective band"

(Markowski, "Mesoscale Meteorology in Midlatitudes" 2010)

Space-time energy spectrum



COSMO-DE simulation

- Horizontal resolution: 2.8 km
- Domain: 7000x4000 km, over Europe and N. Atlantic
- 7 days (from 28 May 2016) output at 2 min. intervals

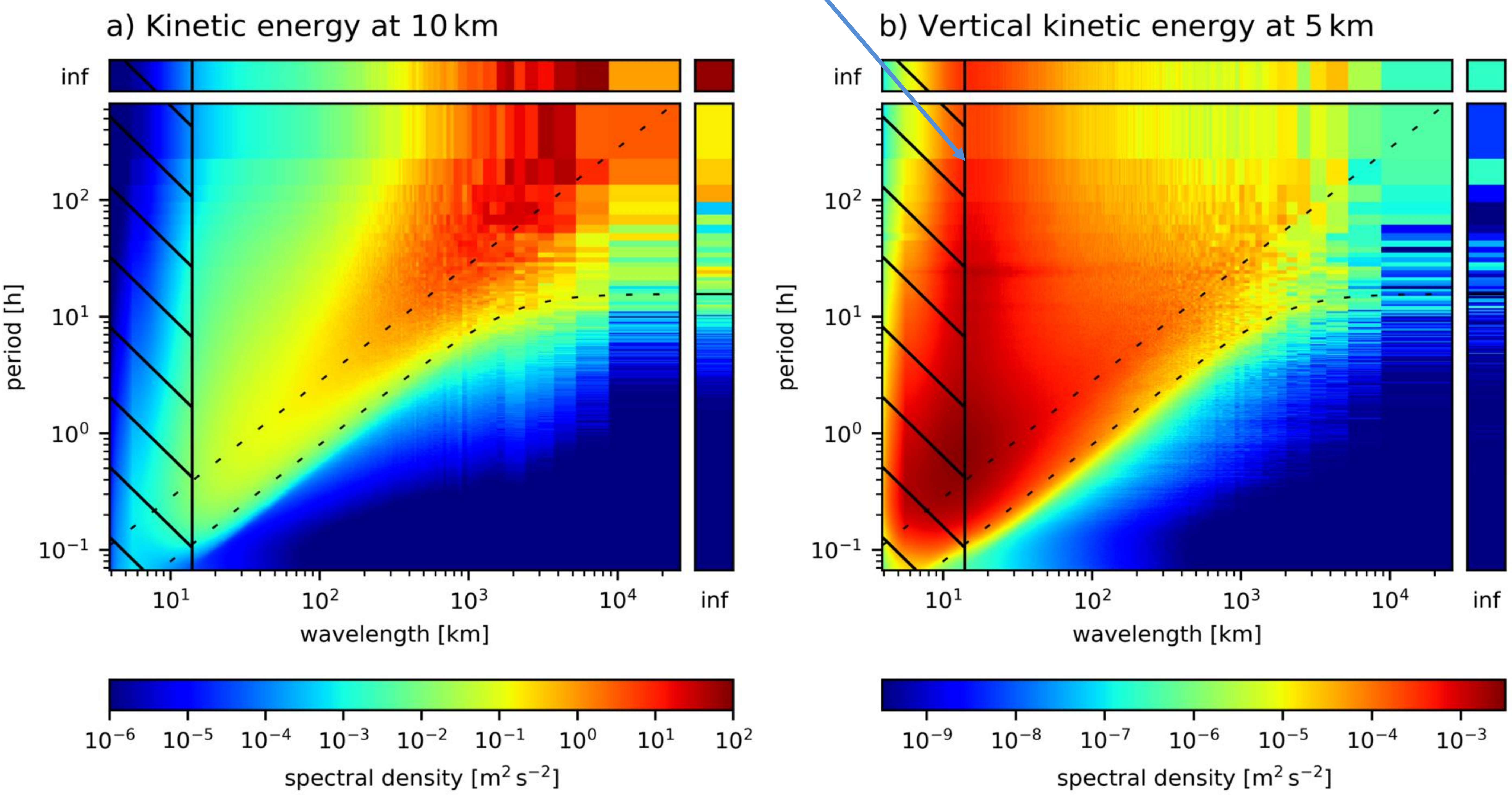
***v* ~ 10 ms^{-1}**
"advective band"

Inertia-gravity wave dispersion relation for gravest tropospheric mode

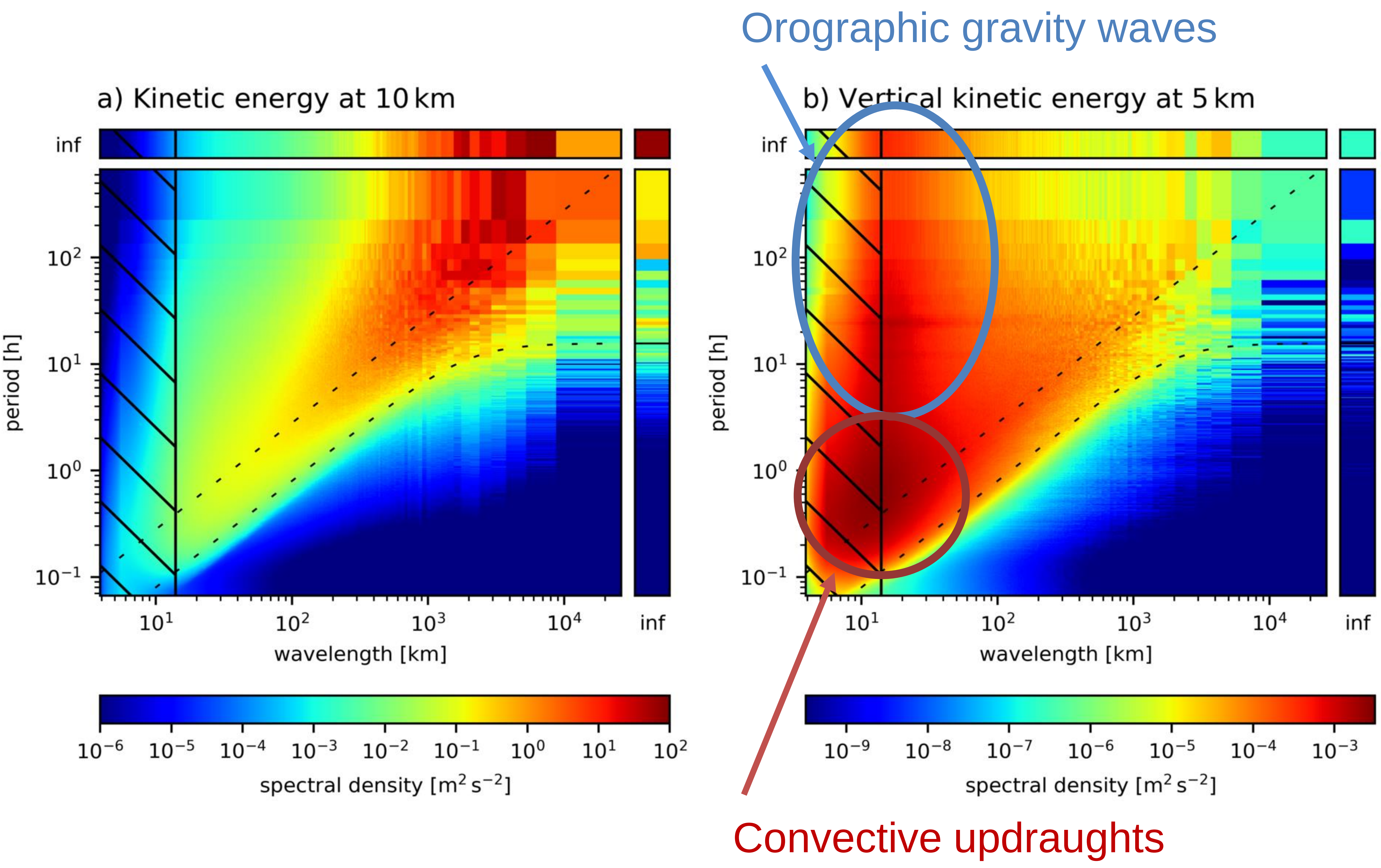
(Craig and Selz GRL 2018)

Horizontal and vertical spectra

Effective resolution of model

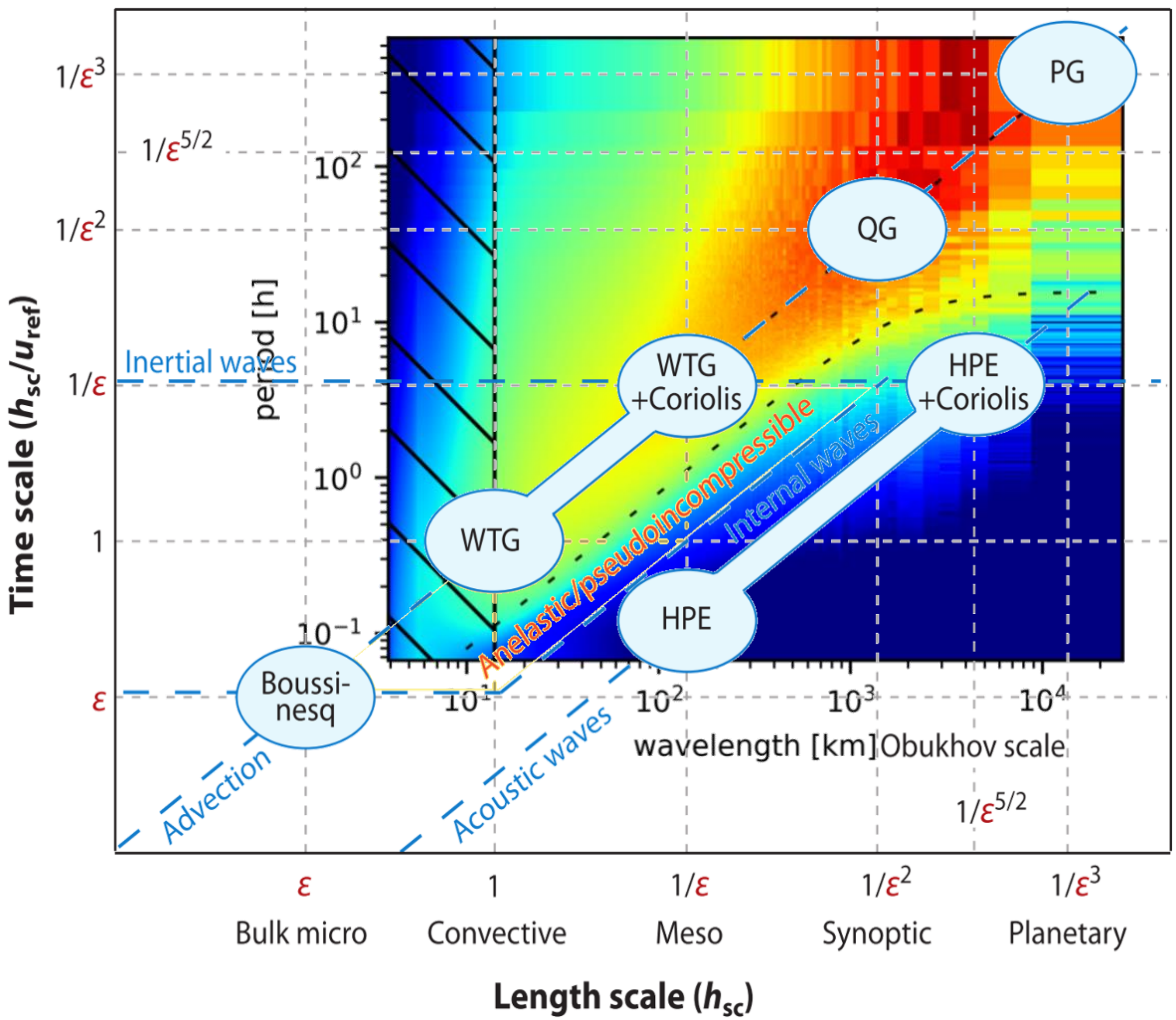


Horizontal and vertical spectra



Approximations for different regimes

Single-scale asymptotic regimes



Weak Temperature Gradient (WTG) approx.

- Expected for advective band on convective and mesoscale

$$w \partial_z \theta = Q$$

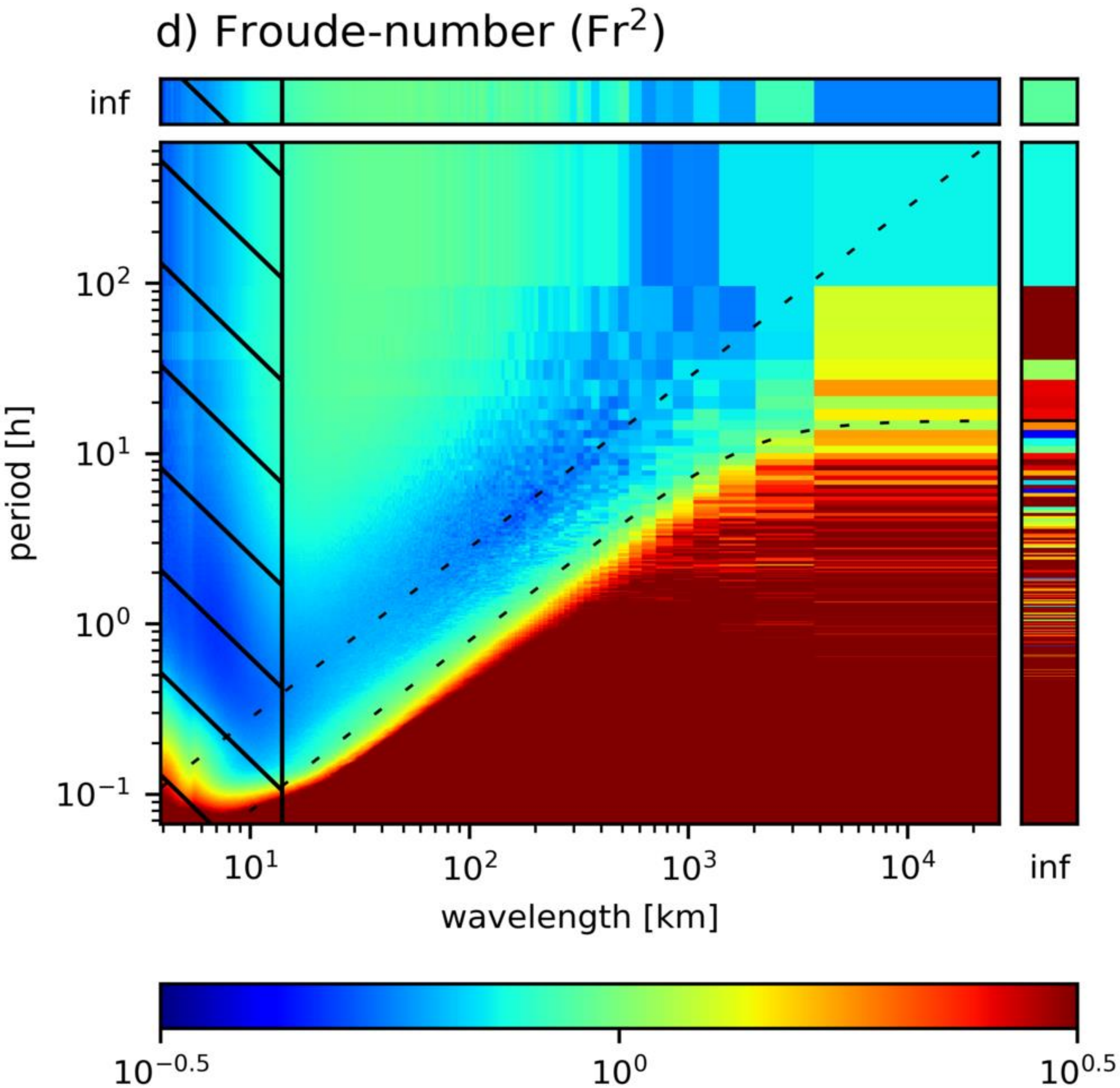
- Advective motions assumed slower than gravity waves

$$U \ll NH$$

- Often used for tropics

(Klein Ann. Rev. Fluid Mech. 2010)

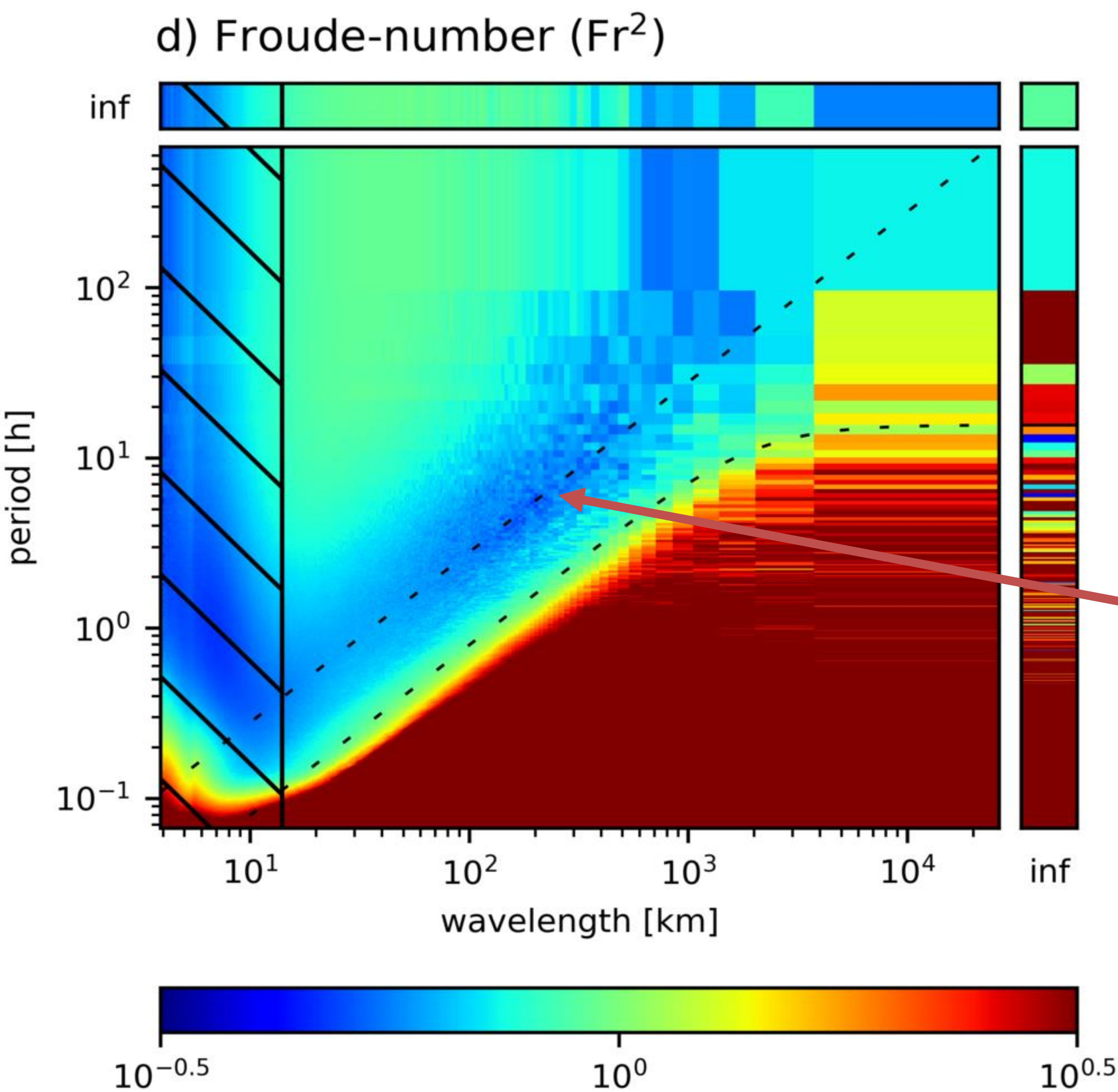
Validity of WTG approximation



Validity of WTG measured by:

$$Fr^2 \sim \left(\frac{U}{NH}\right)^2 \sim \frac{\partial_t \theta + \boldsymbol{v}_h \cdot \nabla_h \theta}{w \partial_z \theta}$$

Validity of WTG approximation



Validity of WTG measured by:

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$Fr^2 \sim 0.5$

Multiscale asymptotics I

Equations for the convective scale

Vertical velocity from heating (WTG approx.): $w^c \partial_z \bar{\theta} = Q^c$

Horizontal divergence from continuity: $\nabla_c \cdot \boldsymbol{v}_h^c = \frac{1}{\bar{\rho}} \partial_z (\bar{\rho} w^c)$

Dynamics from vertical component of vorticity equation:

$$\partial_{t_c} \zeta^c + \nabla_c \cdot (\boldsymbol{v}_h^c \zeta^c) \quad + \nabla_c \cdot (\boldsymbol{v}_h^m \zeta^c) \quad = \quad \nabla_c \cdot (w^c \boldsymbol{\zeta}_h^c)$$

2D ζ-conservation advection by $\boldsymbol{v}_h^m$ forcing from w^c

Application: Balance principle for convective-scale data assimilation

- Divergent wind given to leading order by heating
- Can damp “bad divergence“ (transient gravity waves) without supressing convection

Multiscale asymptotics II

Equations for the mesoscale

Non-divergent at leading order: $\nabla_m \cdot \boldsymbol{v}_h^c = 0$

WTG at second order: $\widetilde{w}^m \partial_z \bar{\theta} = Q^m$

Dynamics from vertical component of vorticity equation:

$$\partial_{t_m} \zeta^m + \nabla_m \cdot (\boldsymbol{v}_h^m \zeta^m) \quad + \nabla_m \cdot (\boldsymbol{v}_h^s \zeta^m) \quad + \nabla_m \cdot \left(\overline{\boldsymbol{v}_h^c \zeta^c} - \overline{w^c \boldsymbol{\zeta}_h^c} \right) = 0$$

2D ζ-conservation advection by $\boldsymbol{v}_h^s$ convective source

Preliminary result combining separate two-scale analyses

Application: Forcing of mesoscale by scale interactions

- 2D vorticity conservation couple in vertical by forcing from synoptic and mesoscales
- “Stratified turbulence“ with depth scale imposed by forcing terms

Multiscale asymptotics III

Equations for the synoptic scale

Geostrophic wind is non-divergent: $\nabla_s \cdot \boldsymbol{v}_h^s = 0$

Dynamics from QG potential vorticity equation:

$$\partial_{t_s} q^c + \nabla_s \cdot (\boldsymbol{v}_h^s q^s) + \nabla_s \cdot \left(\overline{\boldsymbol{v}_h^m \zeta^m} - \overline{\widetilde{w}^m \boldsymbol{\zeta}_h^m} \right) = \frac{f_0}{\bar{\rho}} \partial_z \left(\frac{\bar{\rho}}{\partial_z \bar{\theta}} Q^s \right)$$

q-conservation | mesoscale source | synoptic heating

Application: Mechanism for upscale impact of diabatic heating

- PV source due to forced mesoscale divergent wind – indirect effect of diabatic processes on smaller scales
- Projection of diabatic heating on synoptic scale is only direct effect of heating

Summary and implications

1. **Mesoscale gap in variability of kinetic energy spectrum**
2. **Kinetic energy is concentrated along an advective band**
3. **Leading order balance:**
   - Convective scale: Weak temperature gradient
   - Mesoscale: Forced stratified turbulence
   - Synoptic scale: Quasi-geostrophic
4. **Implications**
   - Balance principle for convective-scale data assimilation
   - Mesoscale motions forced by scale interactions
   - Mechanisms for upscale impact of diabatic heating on synoptic scale