Seasonality and Scale-dependence of Oceanic Energy Transfers

with investigations into strain- and vorticity-dominated regions

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Methods: Data and Geography

- NEMO analysis/forecast, global, 1/4 degree, 1 Jan 2016 - 31 Dec 2020

  This study has been conducted using E.U. Copernicus Marine Service Information: GLOBAL_ANALYSISFORECAST_PHY_CPL_001_015

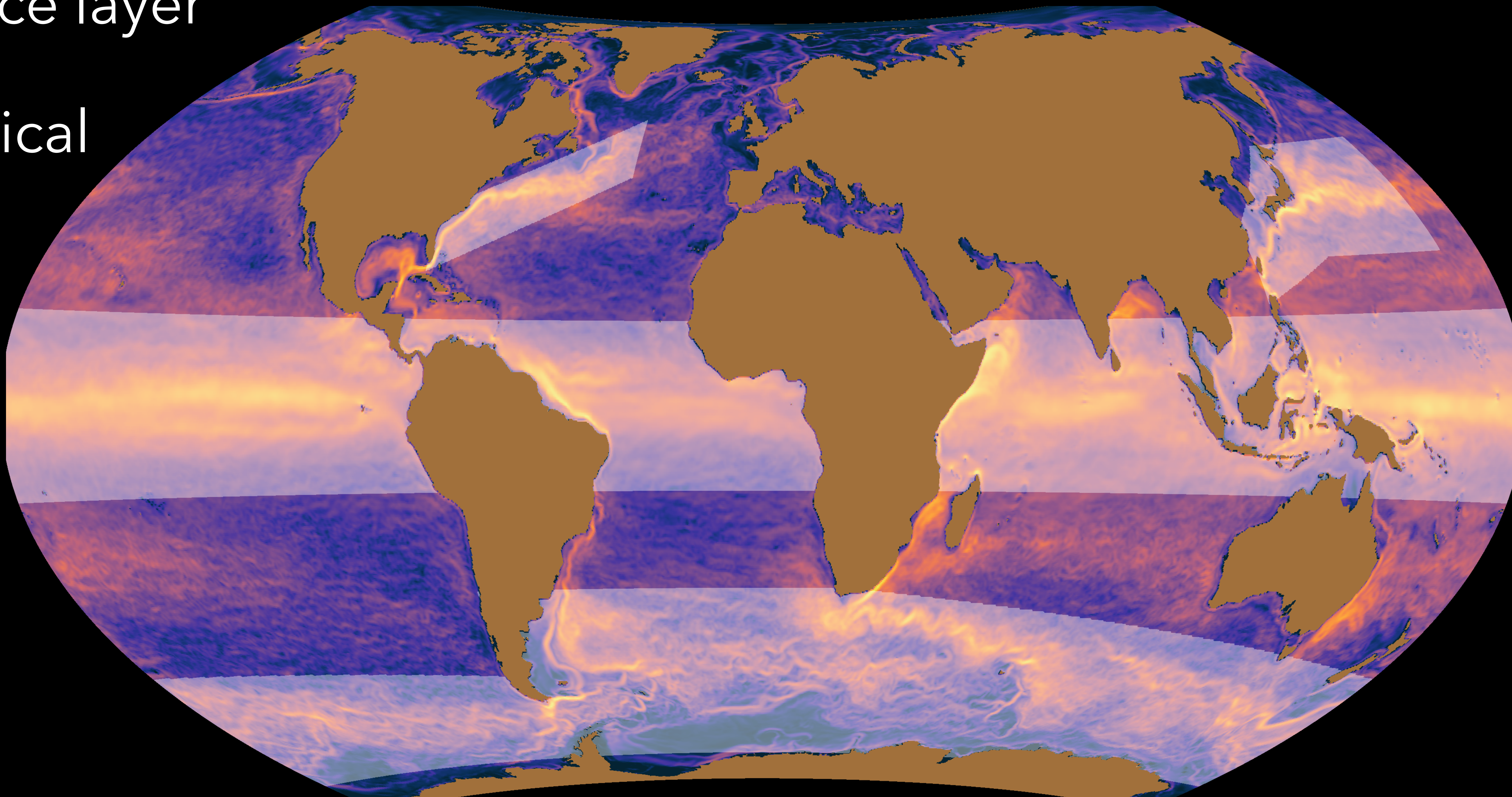
  Weakly coupled ocean-atmosphere

  Assimilation / forecast

  - Only considering surface layer

- Averages over geographical regions of interest

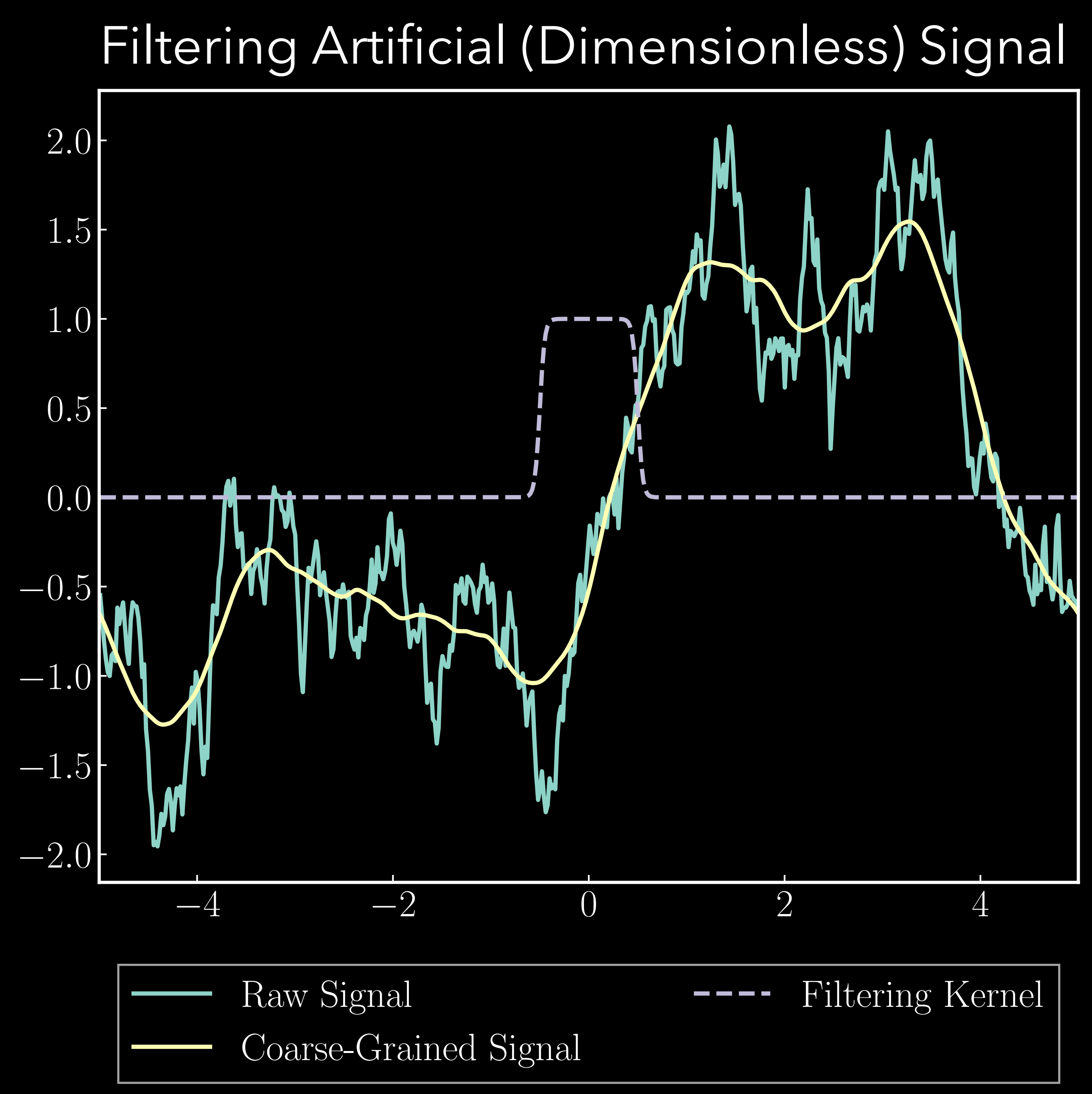
- Land treated as zero velocity ocean

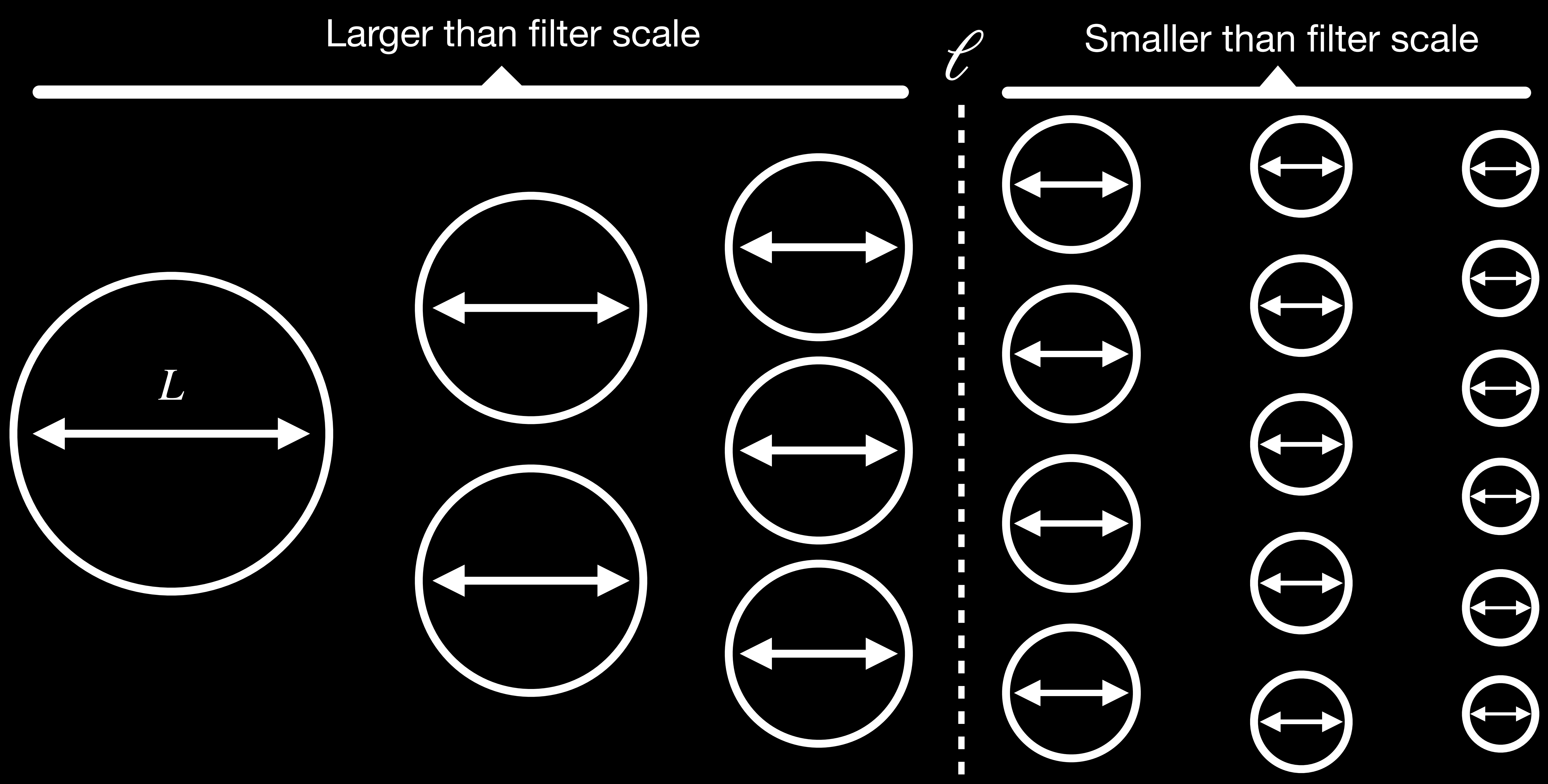


Methods: Coarse-graining

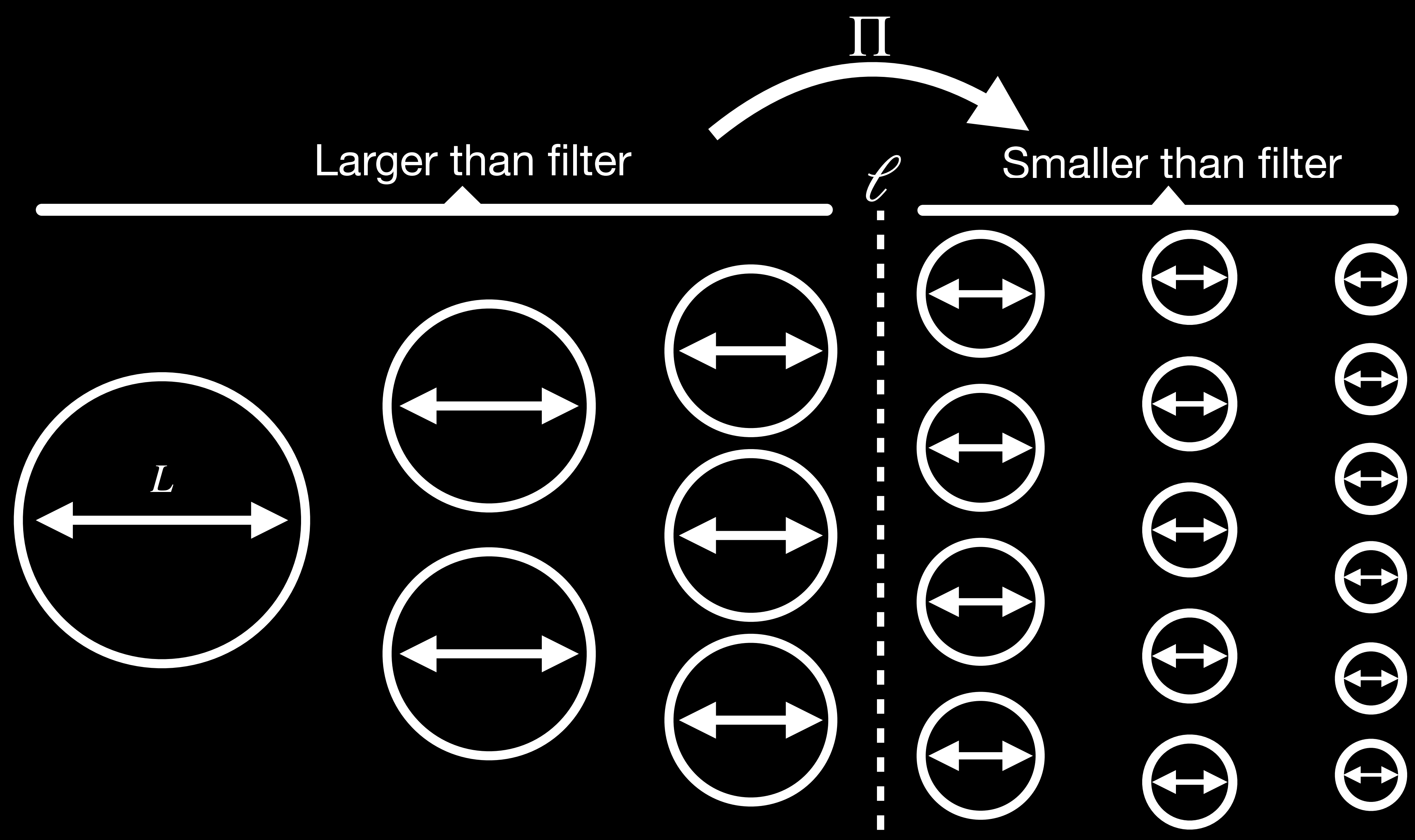
- Choose a length scale (in metres), and smooth / blur the fields. Essentially a locally weighted average in space

- Can extract large-scale and small-scale kinetic energy as a function of space, time, and chosen length scale





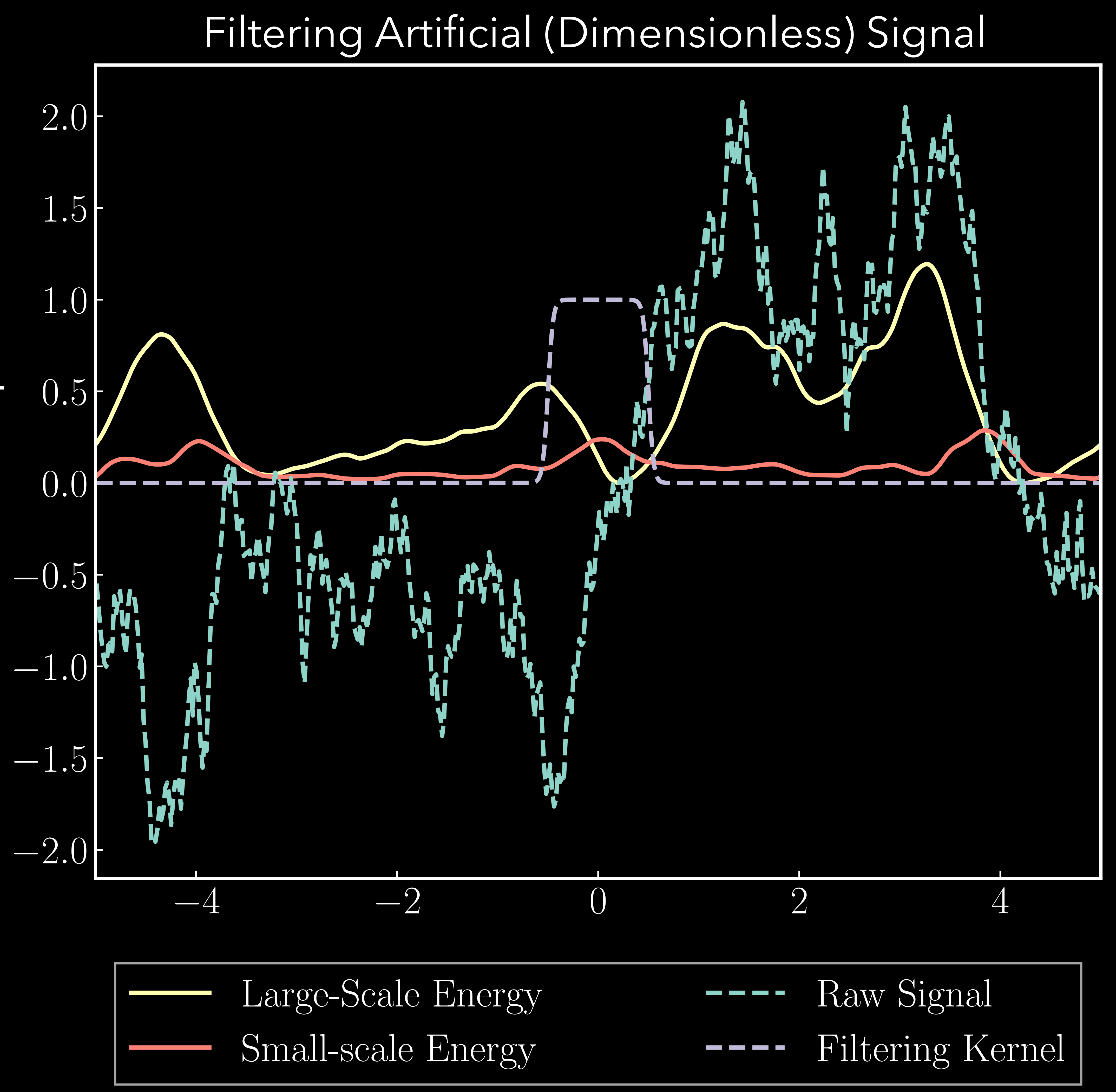
Methods: Definitions



- **Coarse velocities:** $\overline{u}, \overline{v}$
- **Large-scale KE:** $\mathrm{cKE} = \mathrm{KE}(\overline{\mathrm{u}}, \overline{\mathrm{v}}) = \frac{1}{2}\rho_0 \left(\overline{u}^2 + \overline{v}^2\right)$
- **Small-scale KE:** $\mathrm{fKE} = \overline{\mathrm{KE}(u, v)} - \mathrm{KE}(\overline{u}, \overline{v}) = \frac{1}{2}\rho_0 \overline{\left(u^2 + v^2\right)} - \frac{1}{2}\rho_0 \left(\overline{u}^2 + \overline{v}^2\right)$
- **Energy transfer across scales:** $\Pi = \rho_0 \times \underbrace{\frac{1}{2}\left(\overline{u}_{i,j} + \overline{u}_{j,i}\right)}_{\text{Large-scale strain}} \times \underbrace{\left(\overline{u_i u_j} - \overline{u}_i \overline{u}_j\right)}_{\text{Small-scale stress}}$
- **Okubo-Weiss:** $\mathrm{OW} = s_n^2 + s_s^2 - \omega^2 = \left(S_{11} - S_{22}\right)^2 + \left(S_{12} + S_{21}\right)^2 - \omega^2$ where $S_{ij} = \frac{1}{2}\left(\overline{u}_{i,j} + \overline{u}_{j,i}\right)$

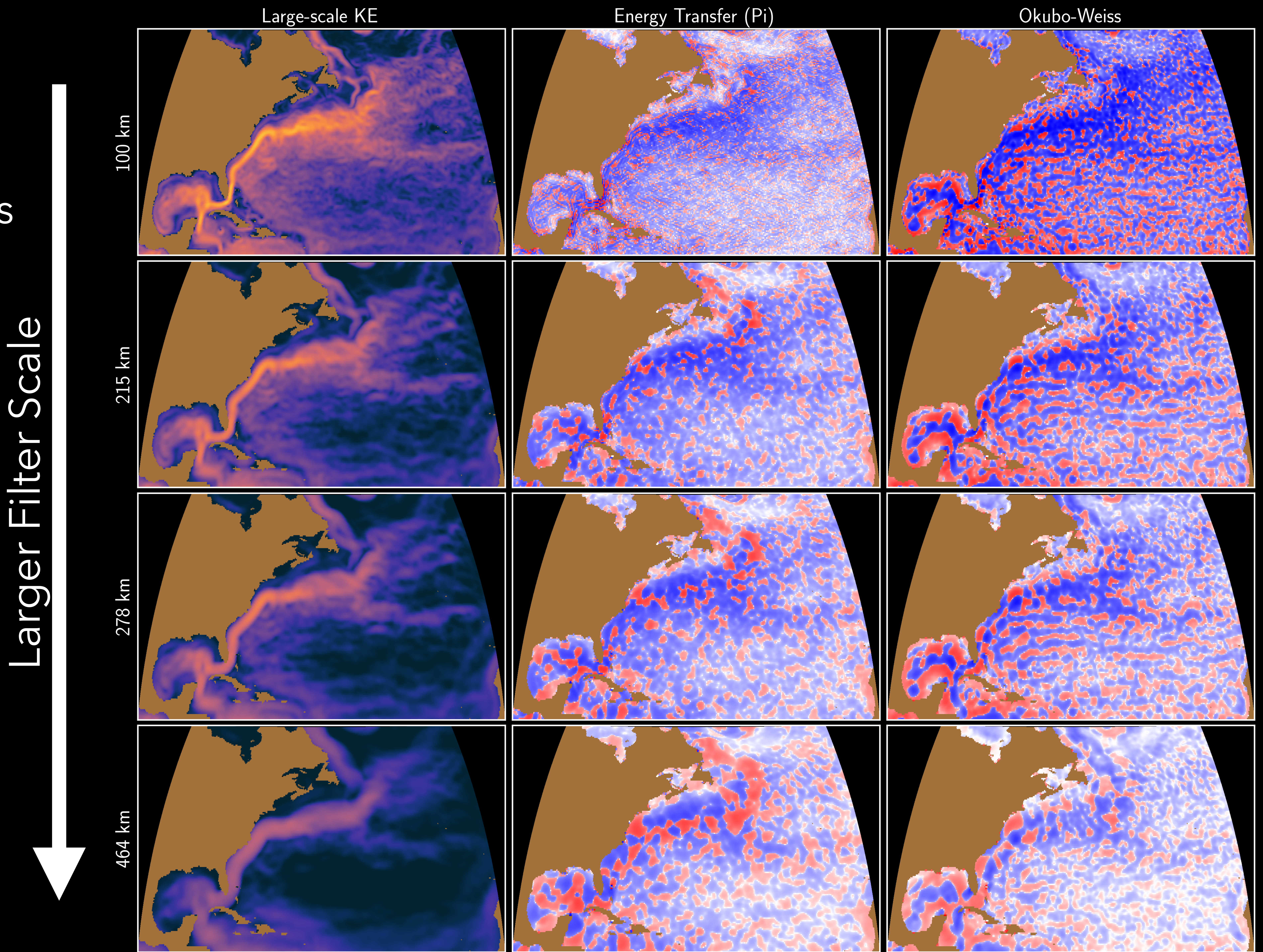
Methods: Definitions

- **Large-scale KE:** Energy at scales larger than the filter scale
- **Small-scale KE:** Energy at scales smaller than the filter scale
- **Energy transfer across scales (Pi):** Positive indicates direct cascade, negative indicates inverse / upscale cascade
- **Okubo-Weiss:** Positive indicates strain-dominated, negative indicates vortex dominated



What do these variables (qualitatively) look like on ocean data?

- One-year averages
- Negative Pi indicates inverse / upscale energy transfer
- Negative Okubo-Weiss indicates vortex dominated (positive to strain dominated)
- Colour bars are consistent within each column



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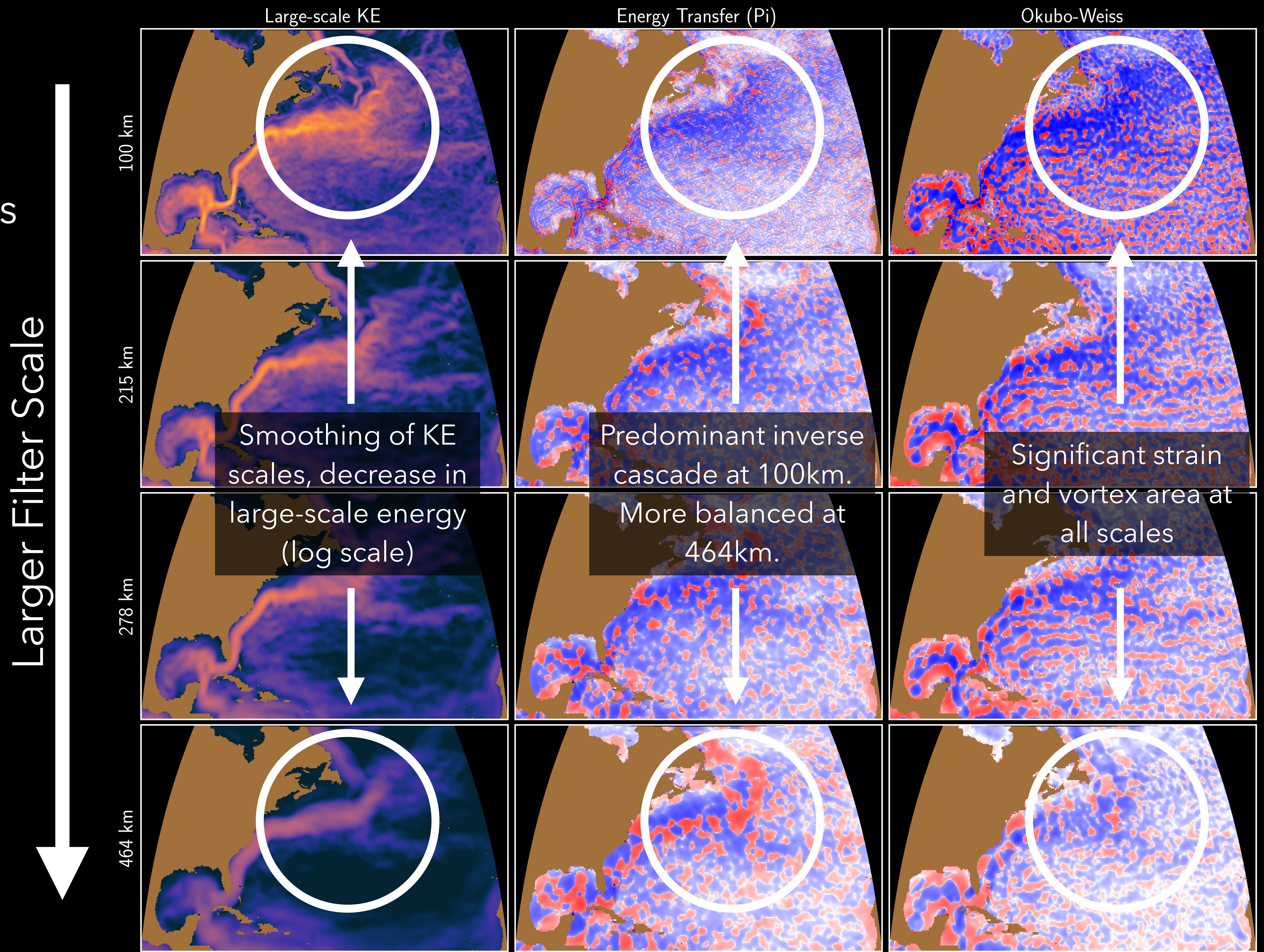

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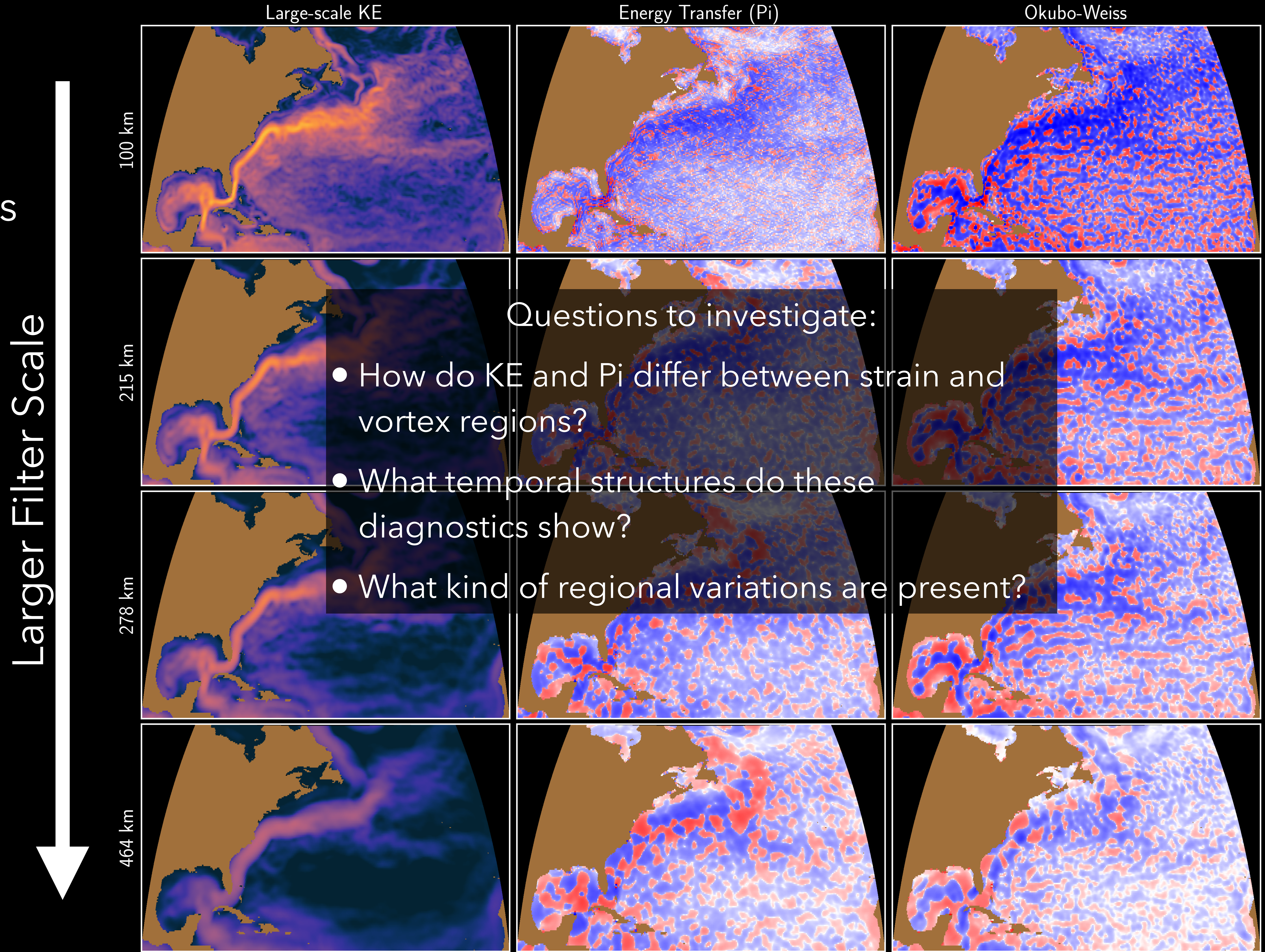


Questions to investigate:

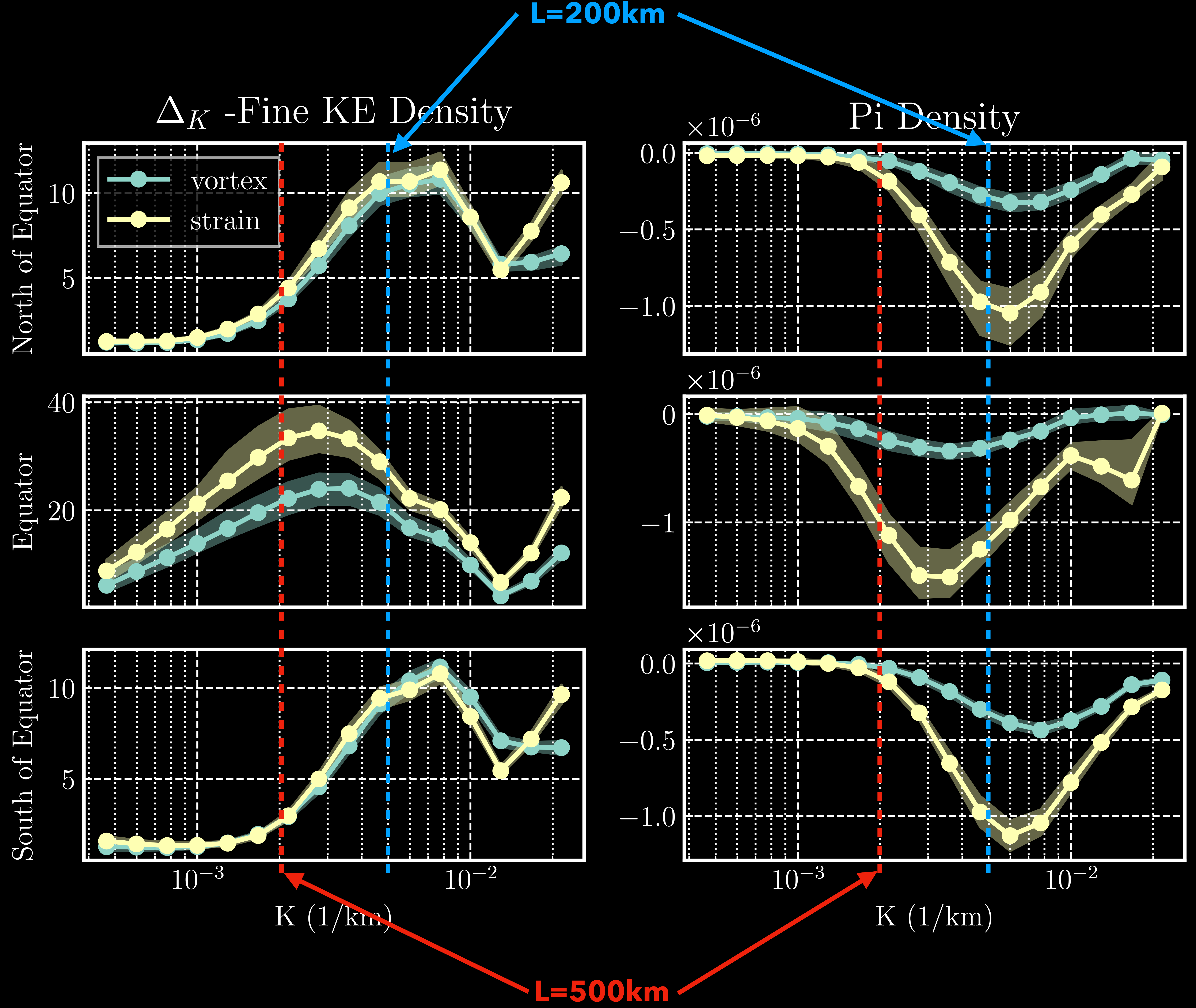
- How do KE and Pi differ between strain and vortex regions?
- What temporal structures do these diagnostics show?
- What kind of regional variations are present?

First, for reference,
the time and space
averaged quantities

Sadek, M., & Aluie, H. (2018). Extracting the spectrum of a flow by spatial filtering. *Physical Review Fluids*

First, for reference, the time and space averaged quantities

- KE and cascade peak around ~170km outside of equator and ~300km in equatorial band
- Qualitatively similar spectra between strain and vortex regions
- Energy minimum around 80km
  Suggestions on cause?



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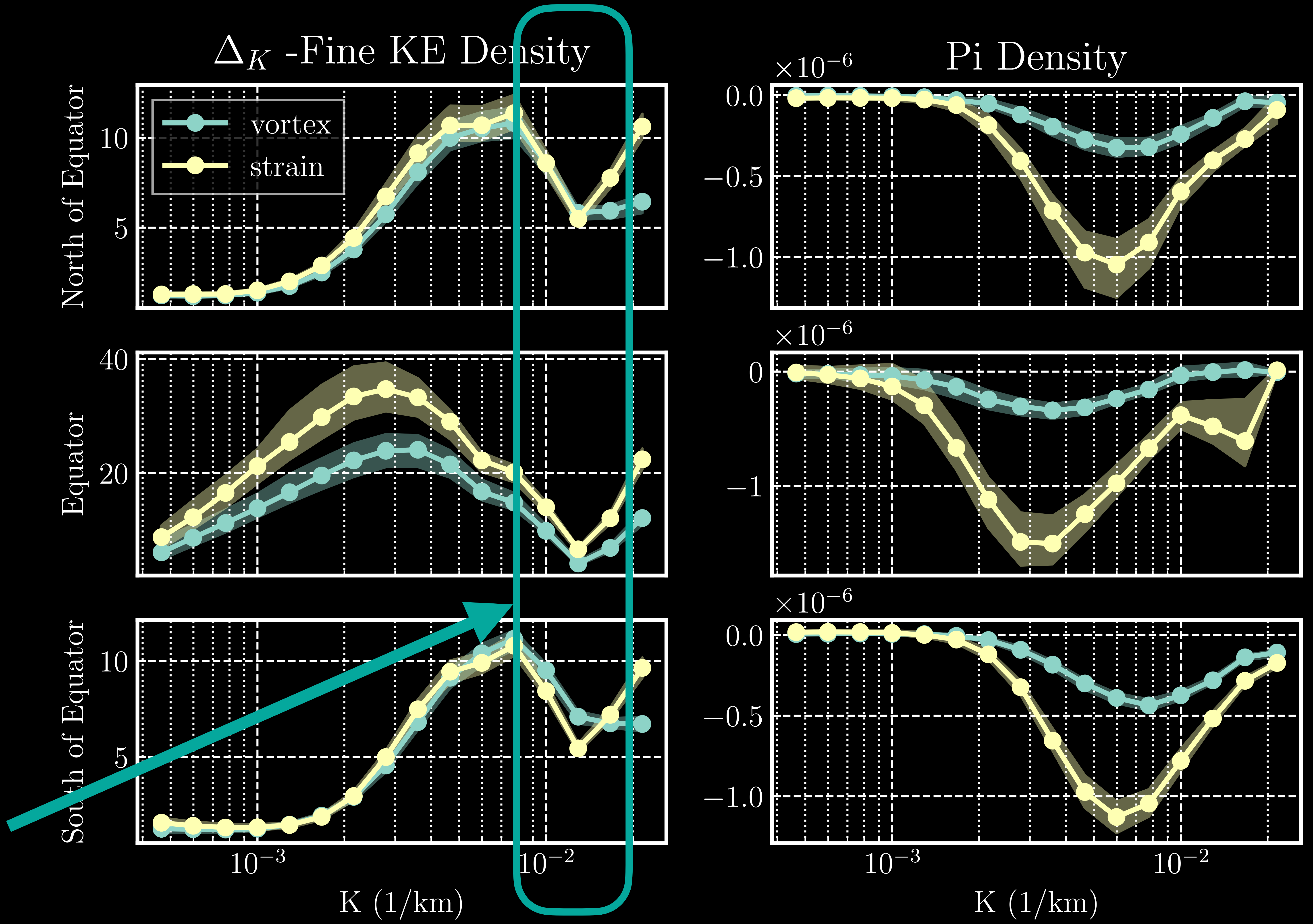
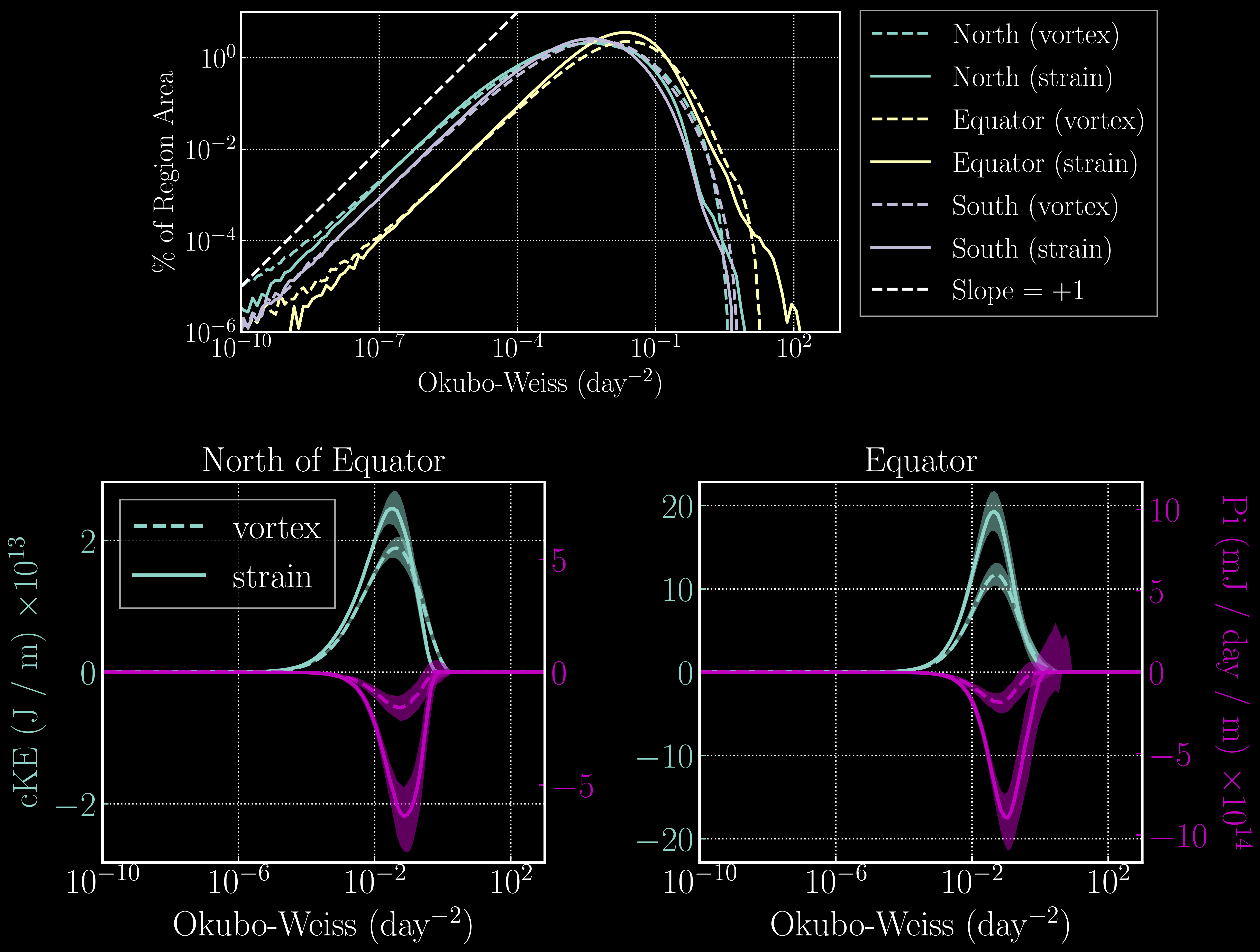


Partition into Strain vs Vortex Regions

Is it a sound partition?

Strain vs Vortex Regions

- 215km filter scale
- slope ≈ 1 in area distribution
  Suggestions on cause / implications?
- cKE and Pi localized in Okubo-Weiss



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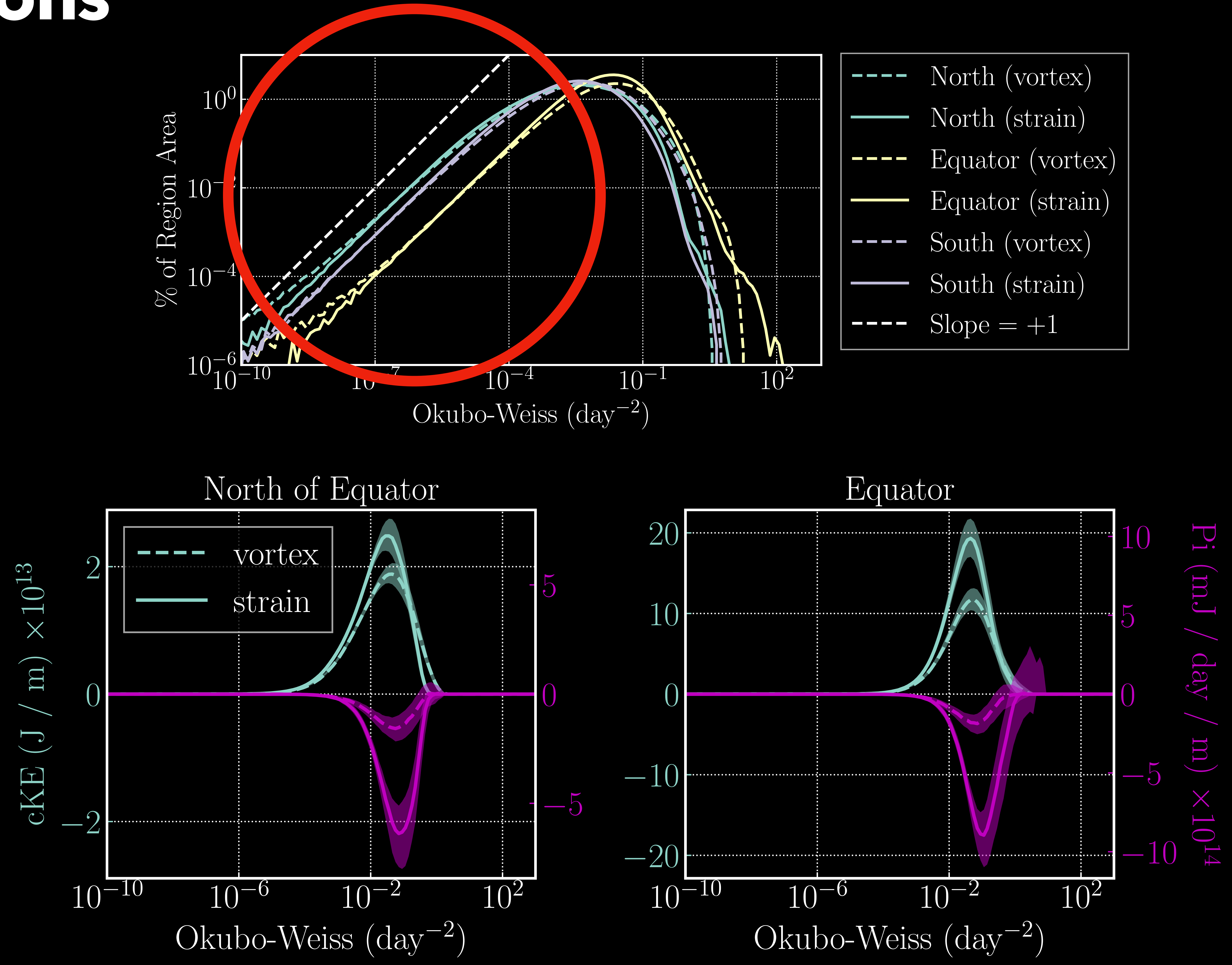

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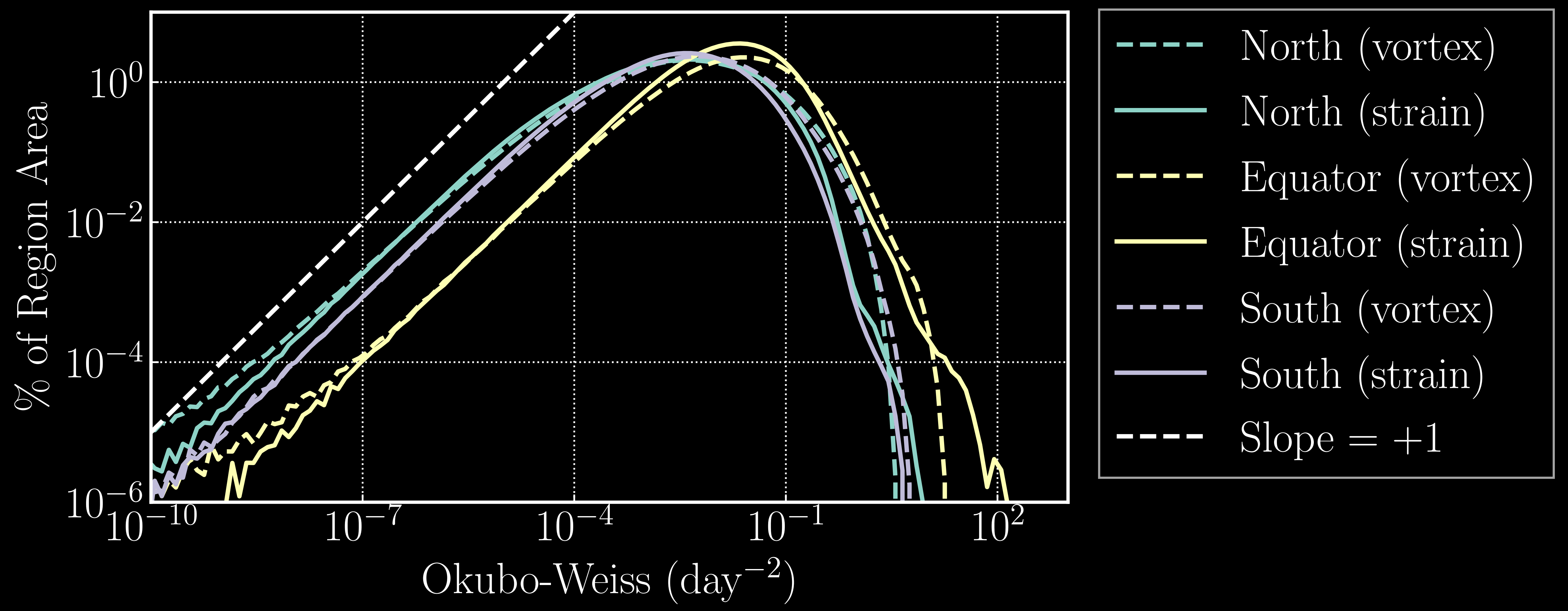
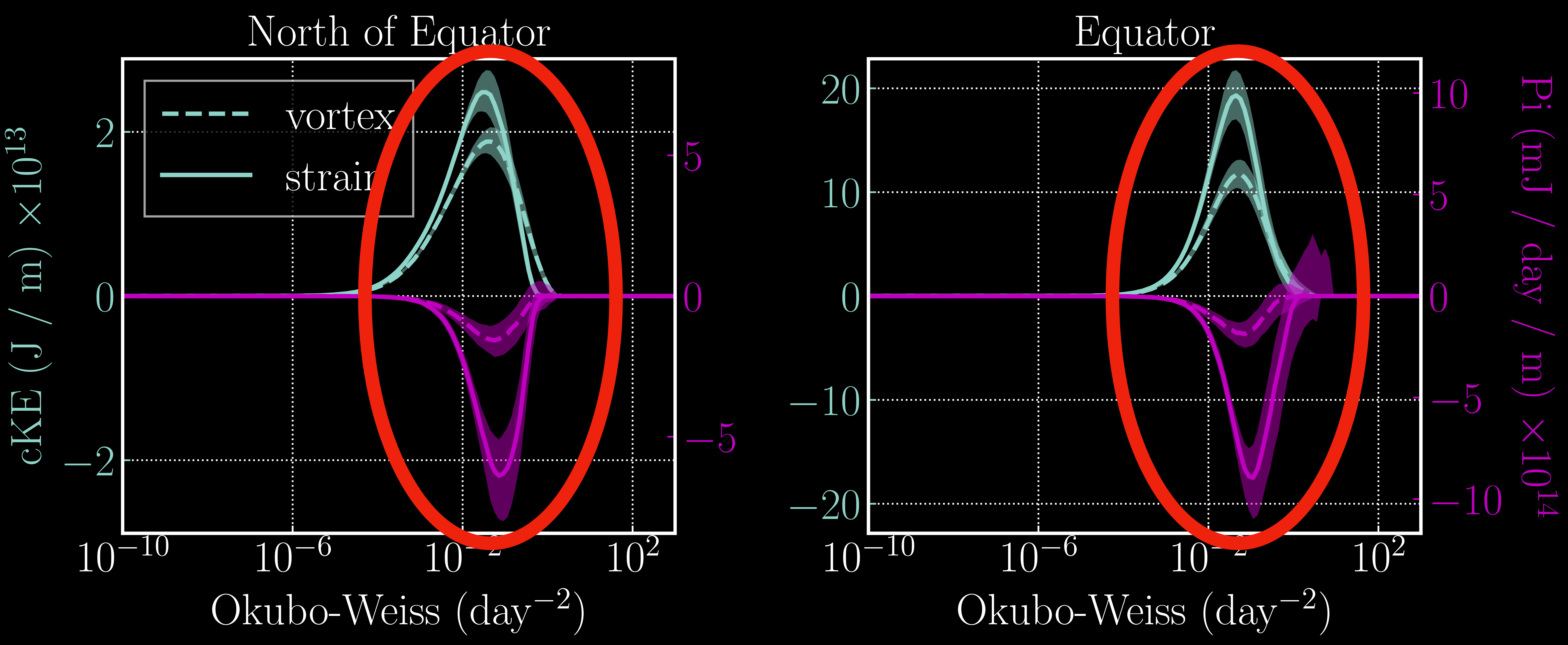
So not unreasonable to use Okubo-Weiss to partition space





Partition into Strain vs Vortex Regions

What % of KE, Pi are in strain region?

Scale-dependence?

Strain vs Vortex Regions

Field Partitioning

- Proportion of Pi, fKE, cKE in strain (Okuko-Weiss > 0) regions as a function of scale
- Majority of cascade (Pi) occurs in straining regions, across all scales
  - Also observed in 2-D experiments and rotating turbulence
    - (enstrophy) Rivera, M. K., Aluie, H., & Ecke, R. E. (2014). The direct enstrophy cascade of two-dimensional soap film flows. *Physics of Fluids*
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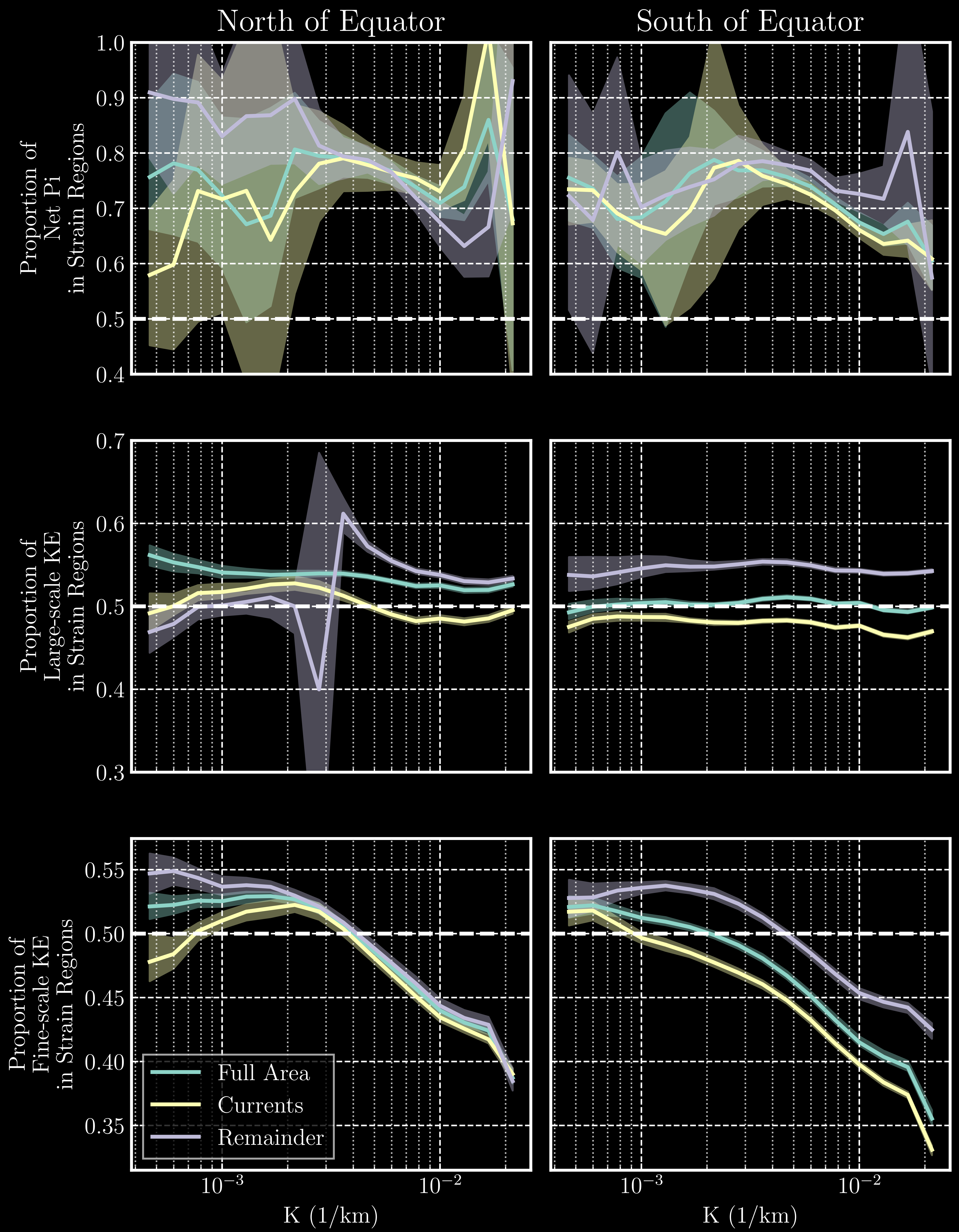
- Energy is roughly at parity between strain and vortex regions (esp. larger than 200km)



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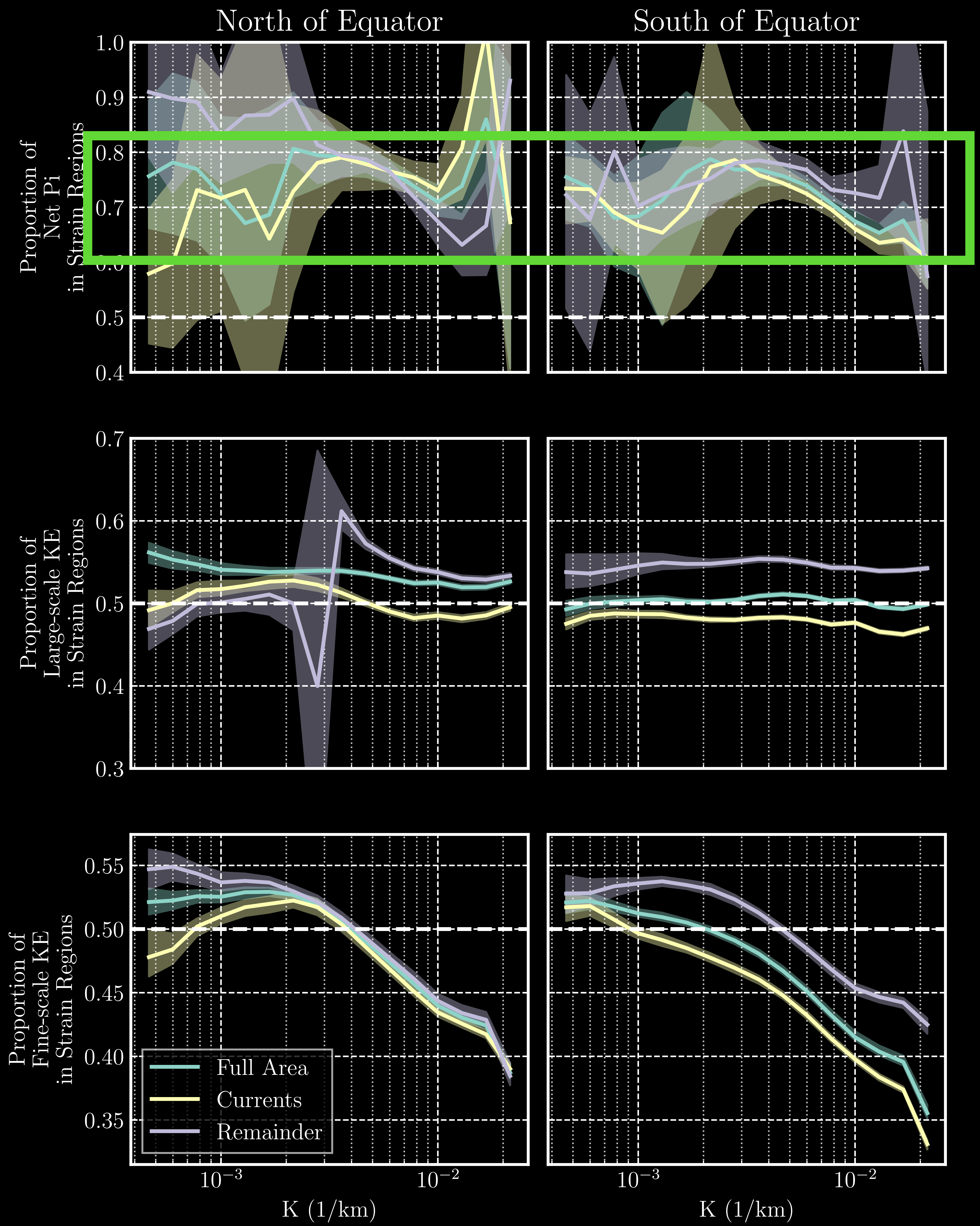

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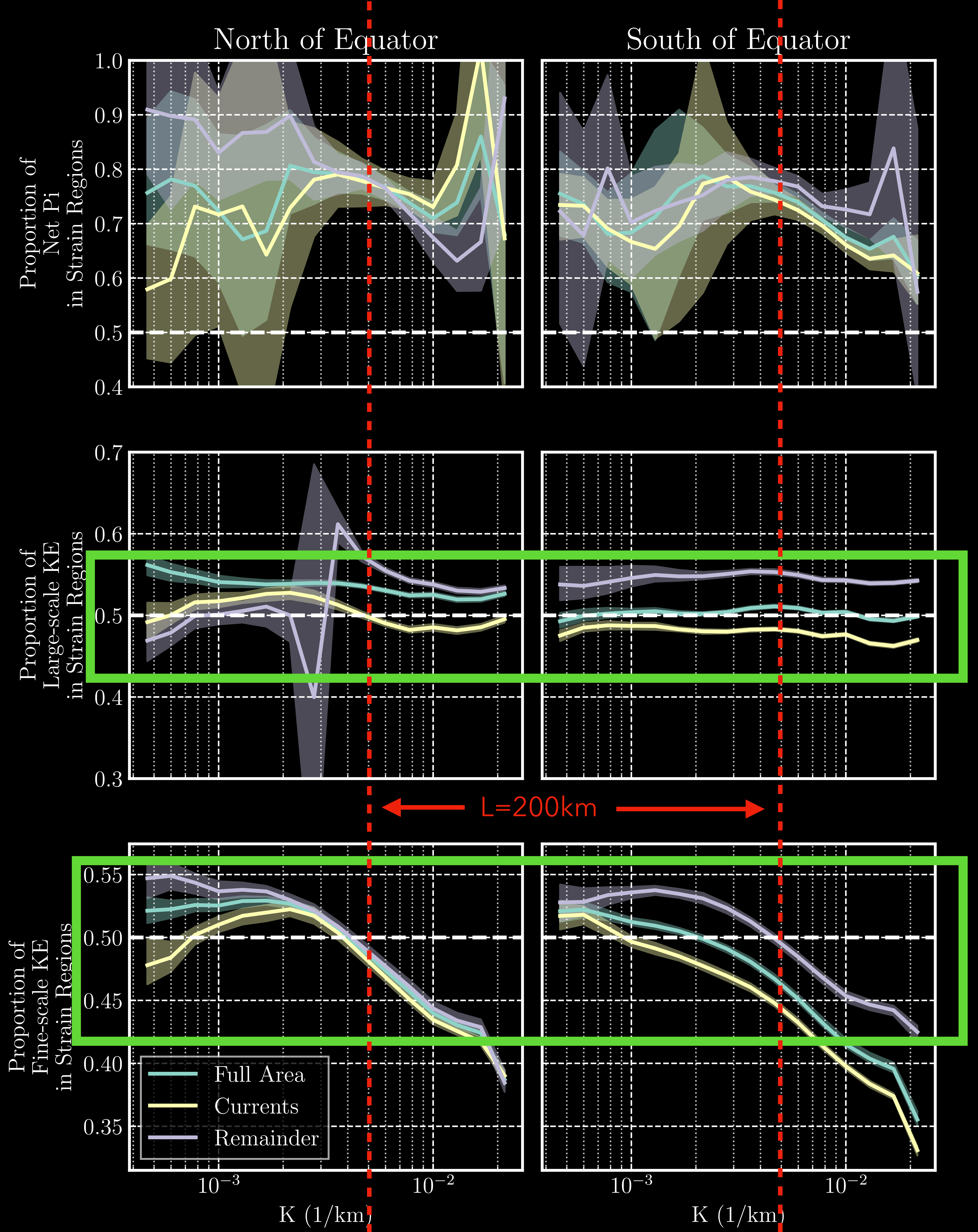


Partition into Strain vs Vortex Regions

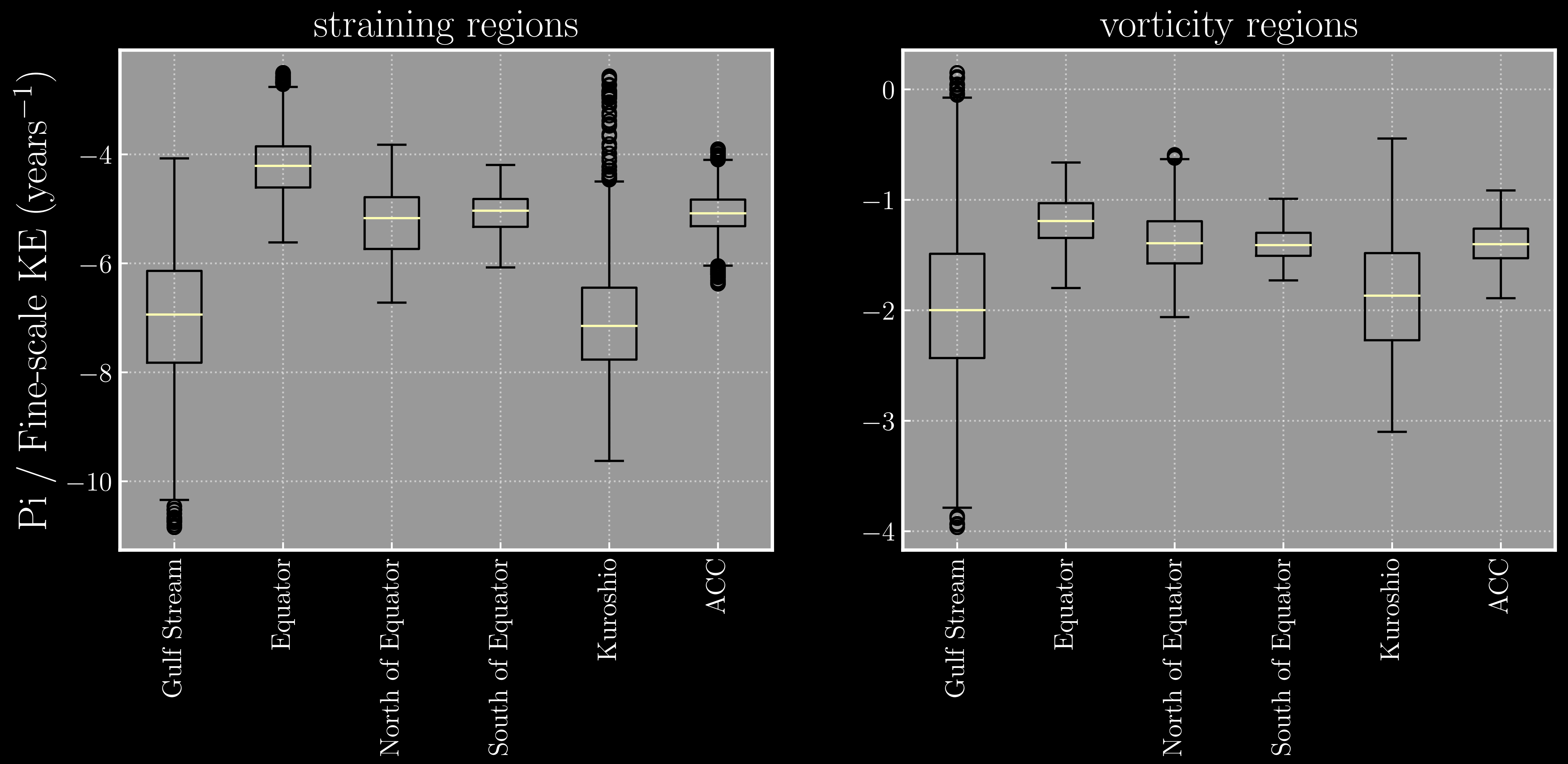
Relative strength of Pi to fKE?
('*cascade efficiency*')

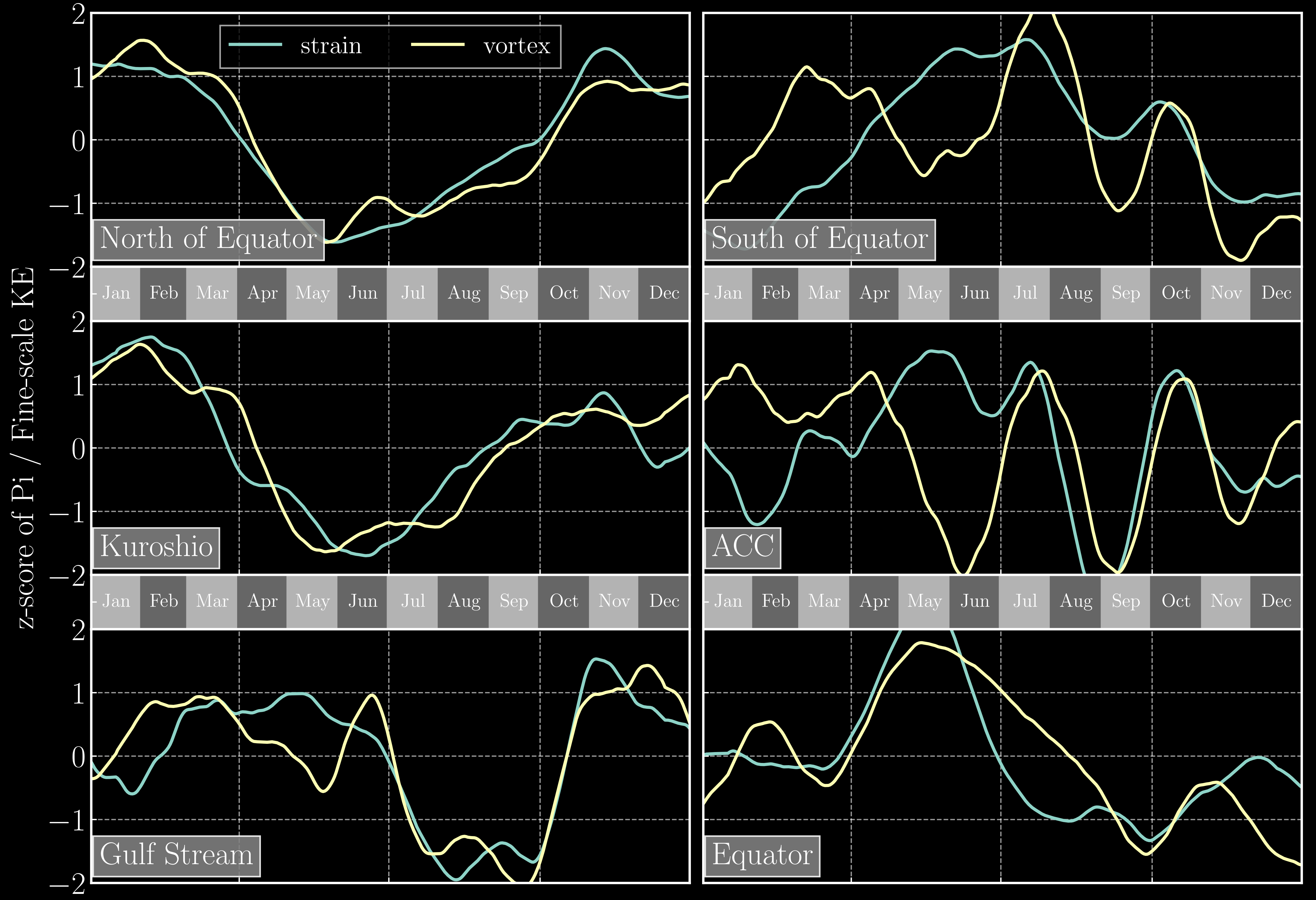
Any significant regional / seasonal structures?

Strain vs Vortex Regions

Cascade Efficiency

- Filter scale = 215km
- Efficiency greater in strain regions and in Gulf Stream & Kuroshio
- Gulf Stream and Kuroshio show substantial variation
- Efficiency increases in (local) winter
  - (negative z-score indicates greater magnitude of efficiency)
  - seasonal trends from 5-year average





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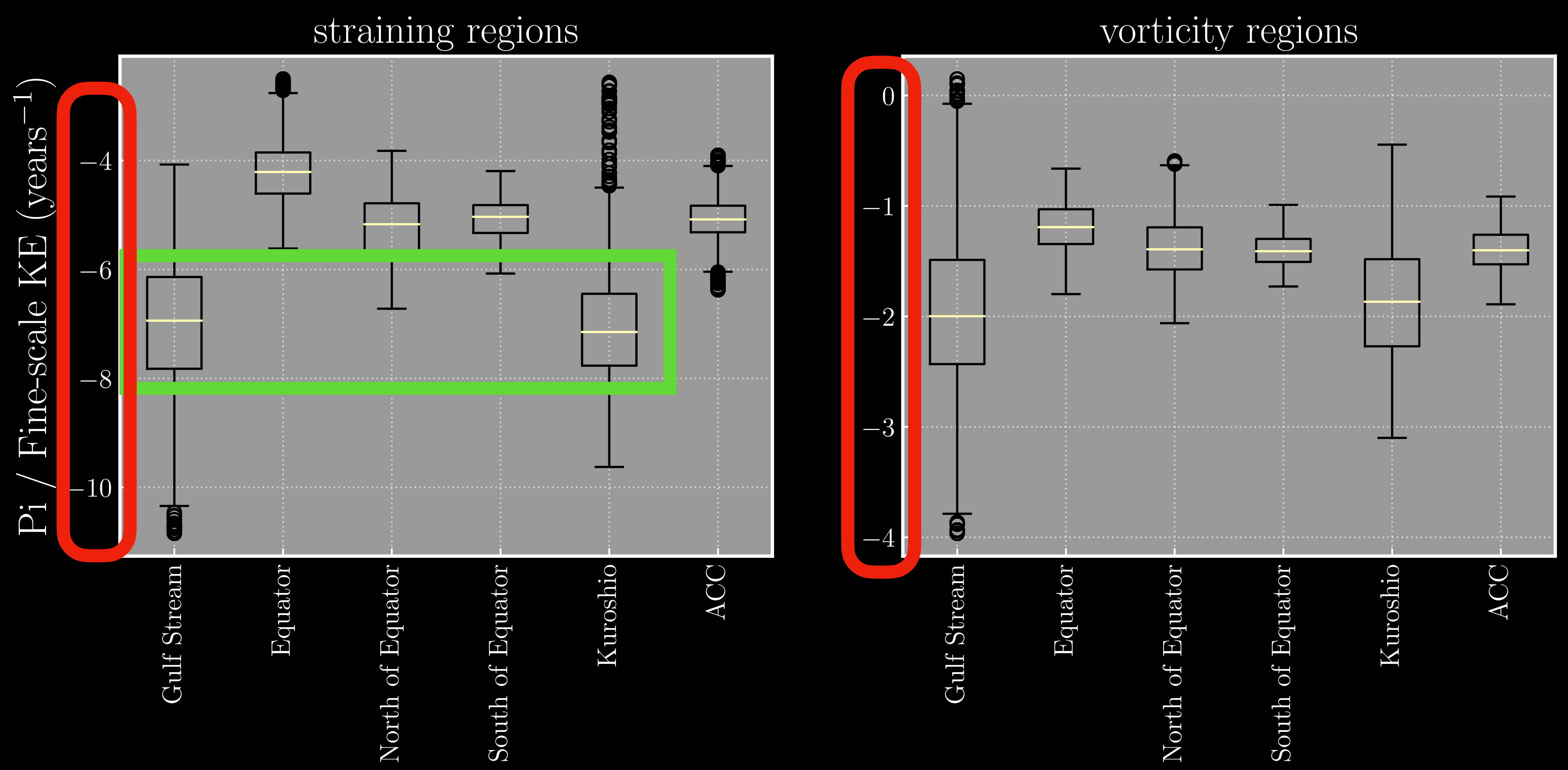

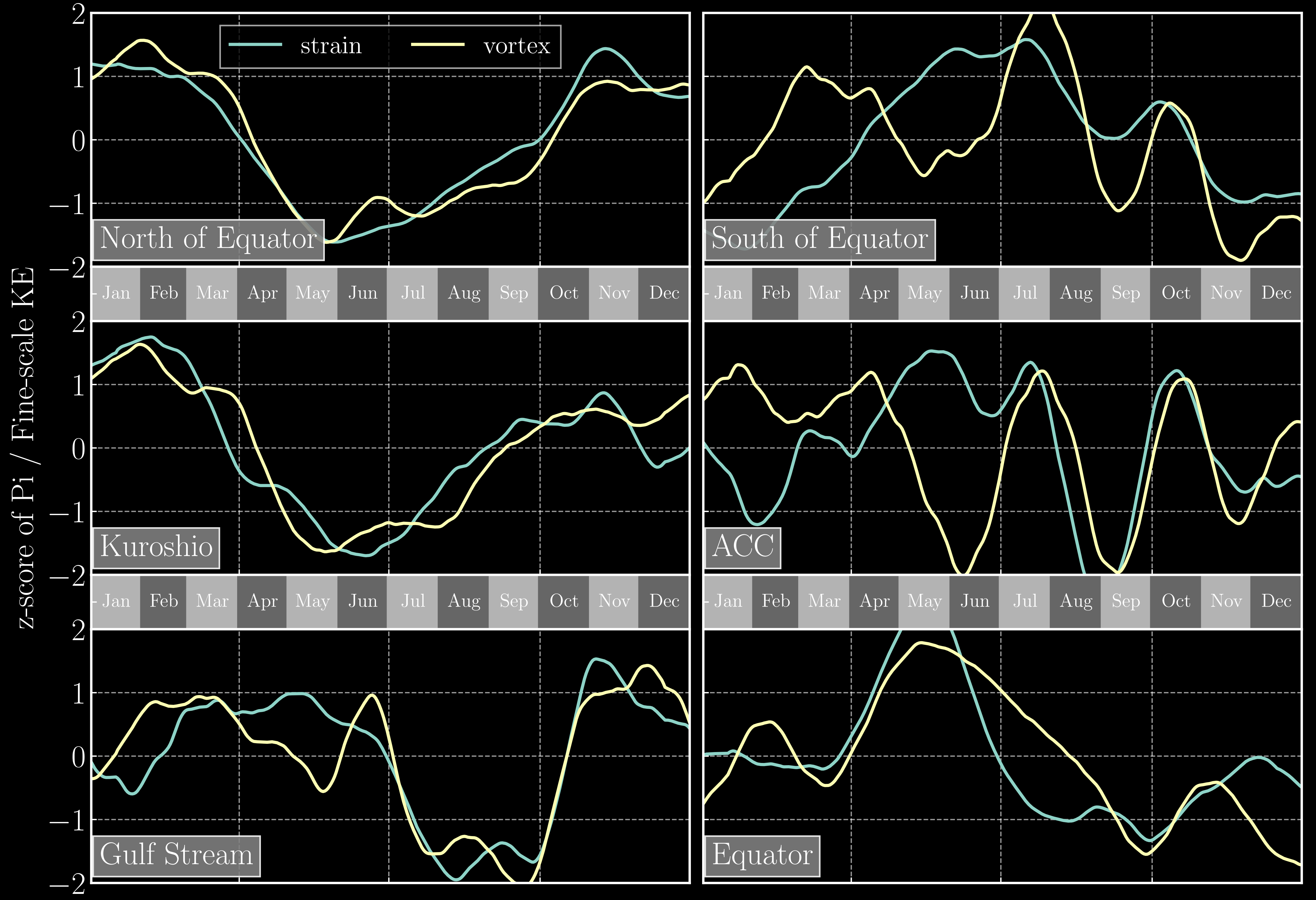

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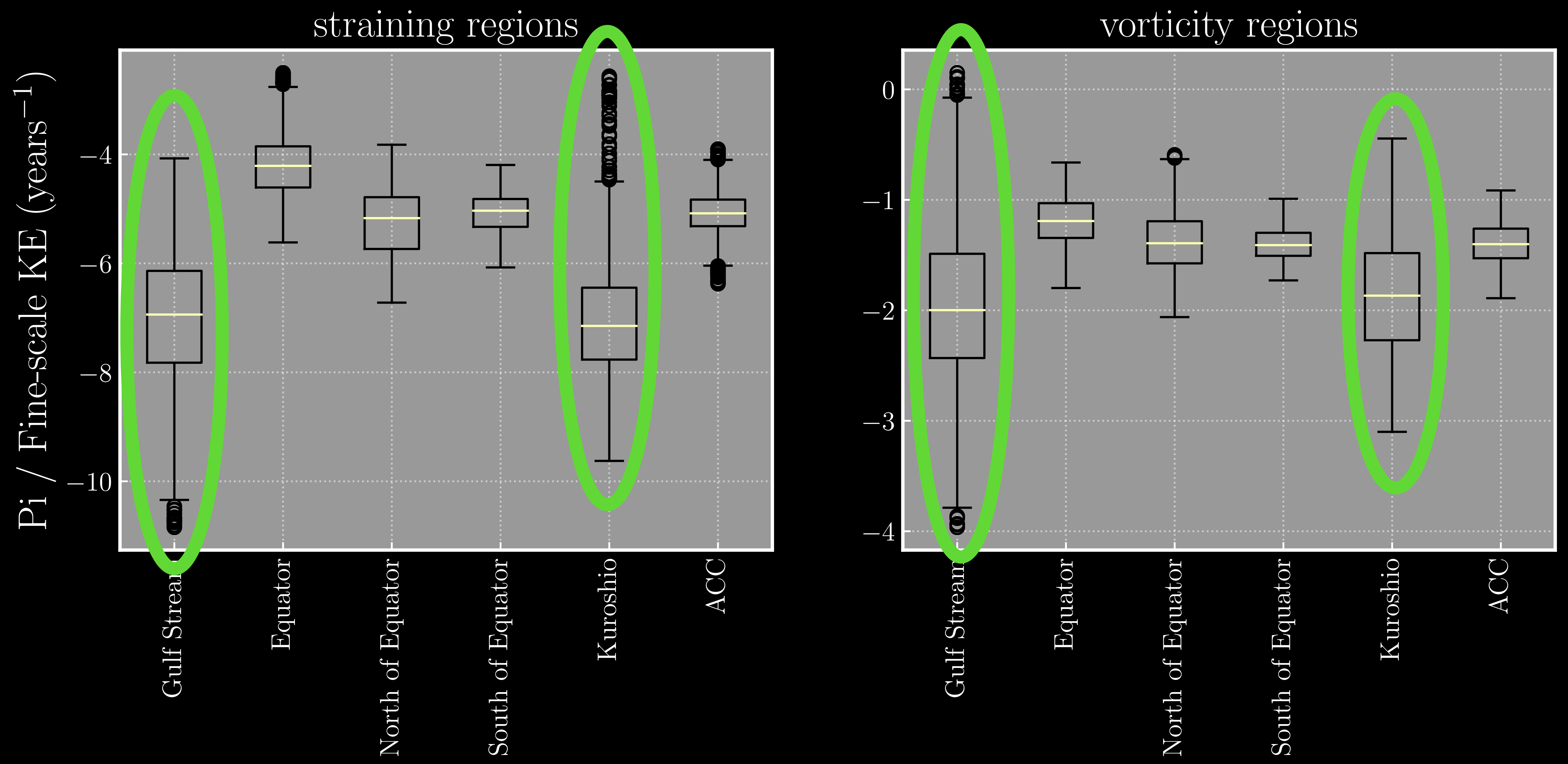

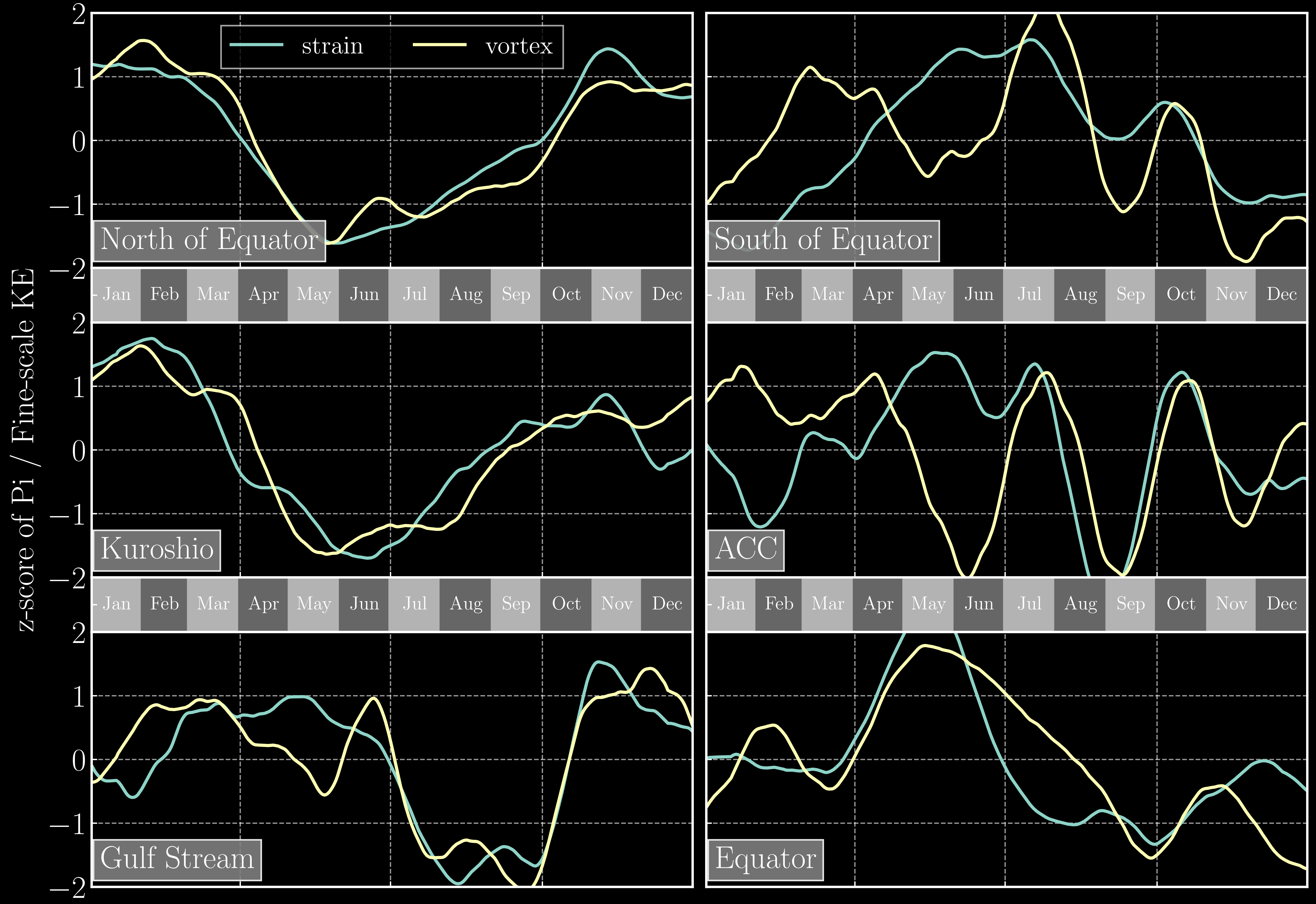

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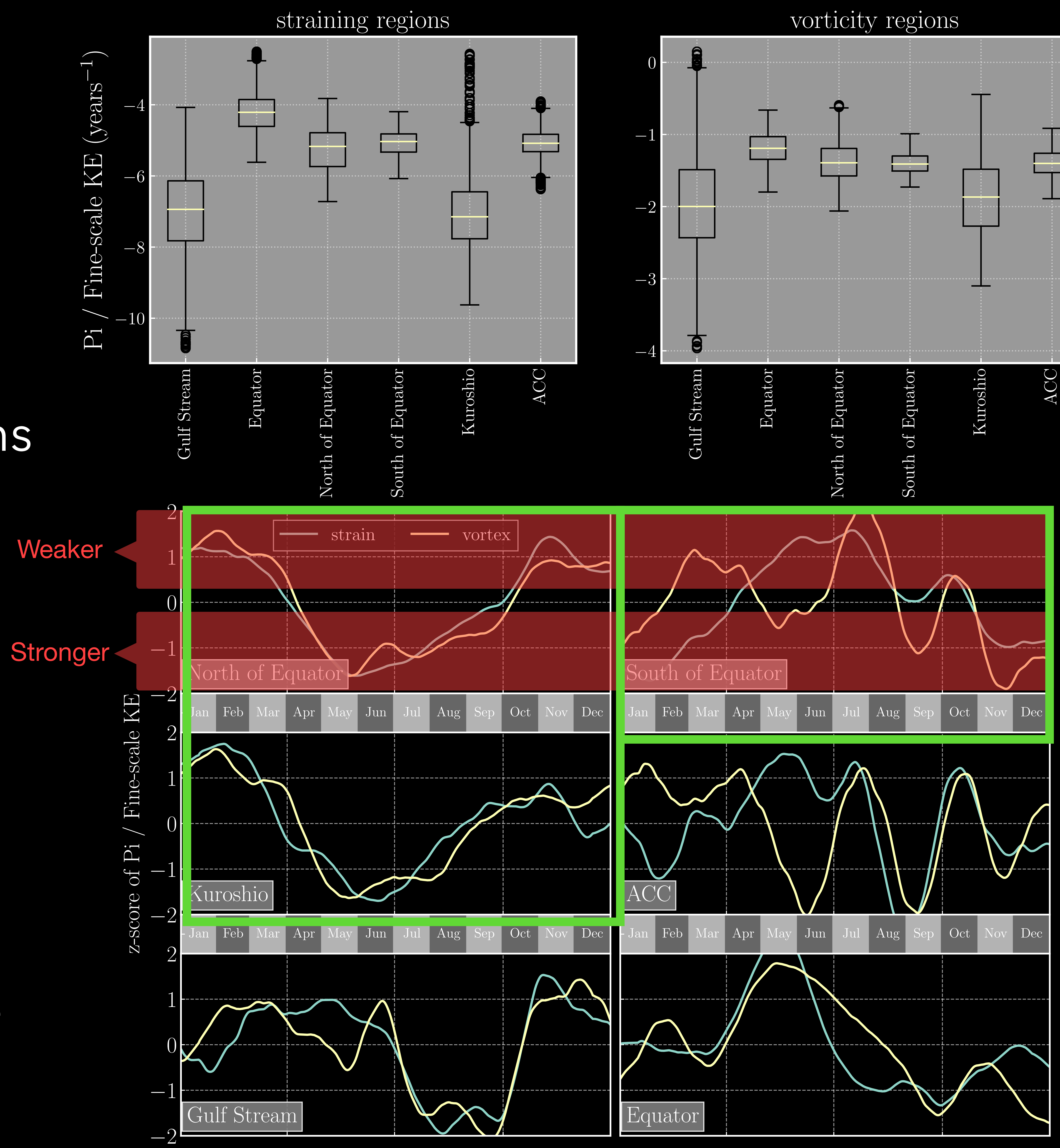
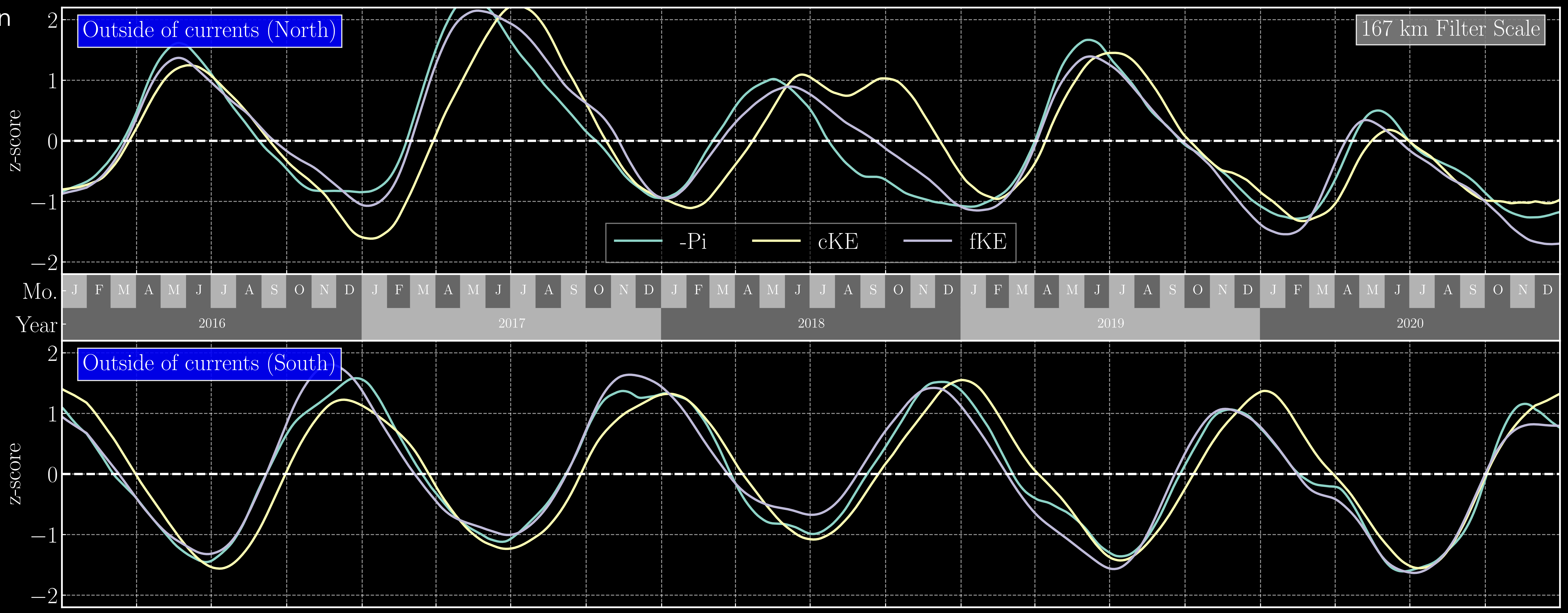


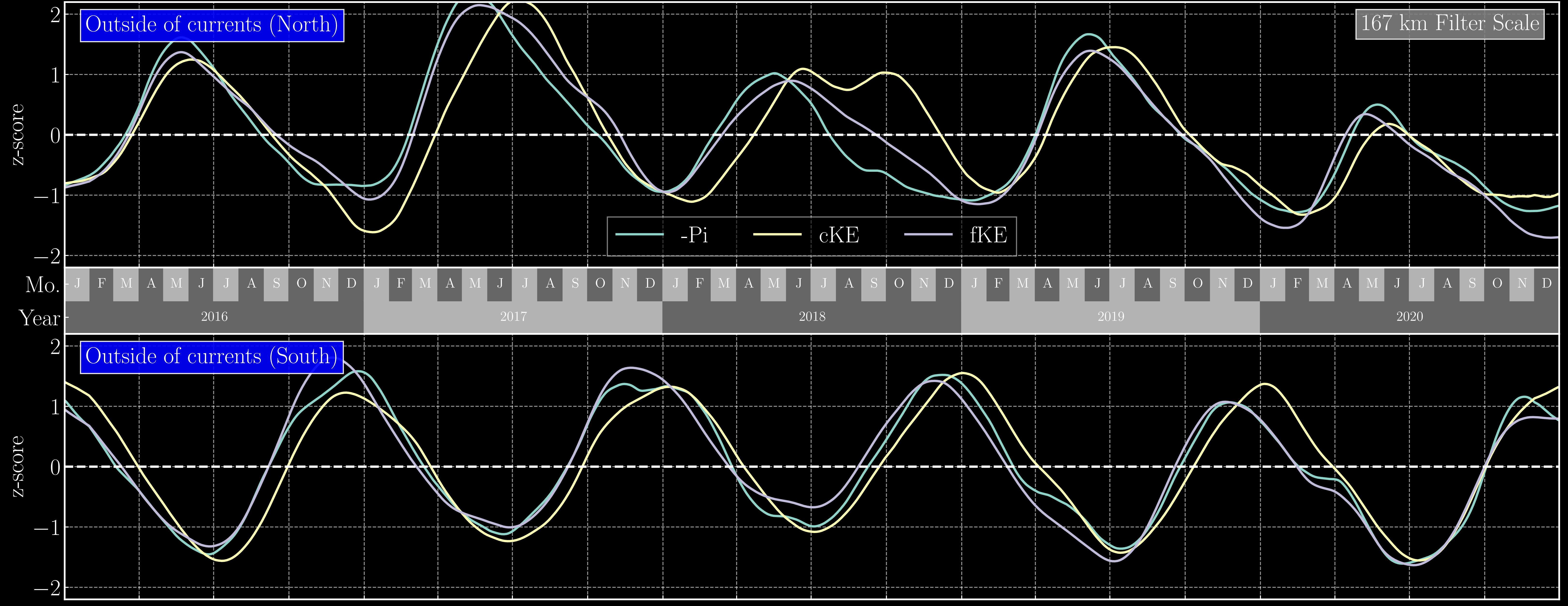
Comparing temporal signal between different length scales

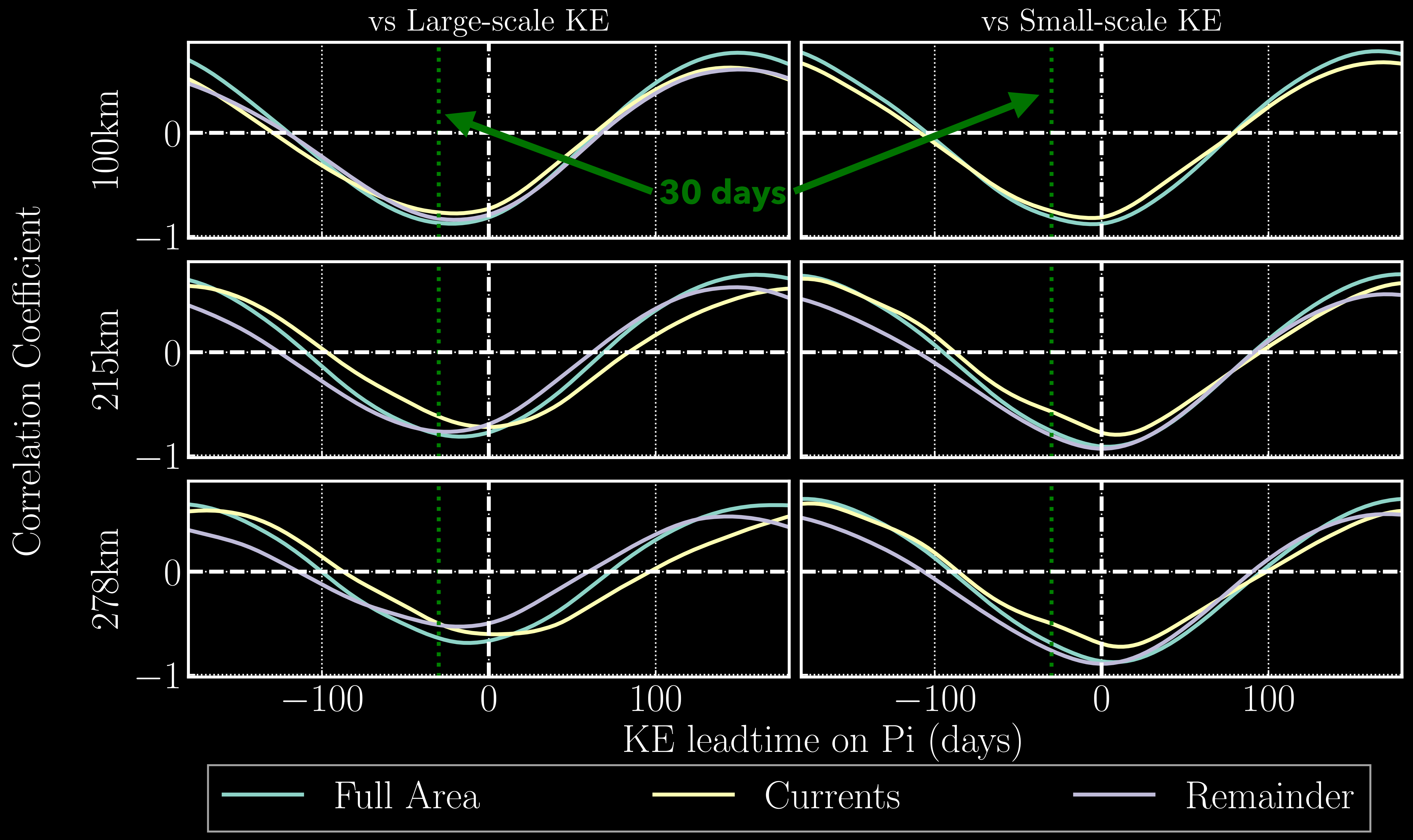
z-score ~ normalized deviation from the mean

- NEMO (right)
- AVISO (bottom)



- Measure correlation as a function of lag-time between large-scale KE and energy cascade
- Outside of equator, large-scale KE lags behind cascade by ~30 days at scales smaller than ~250km
- Lag most prominent outside of dominant currents



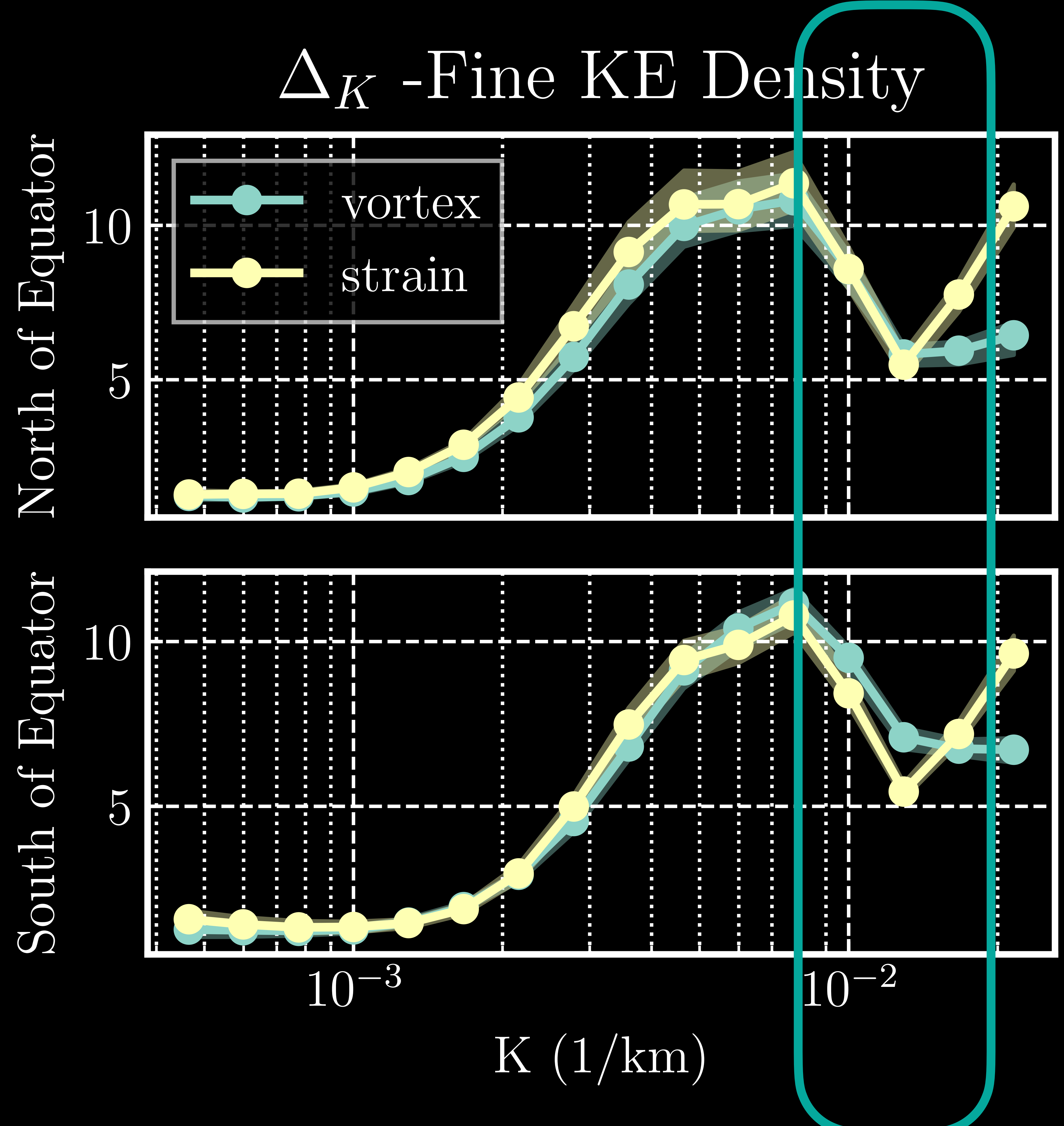


Conclusions

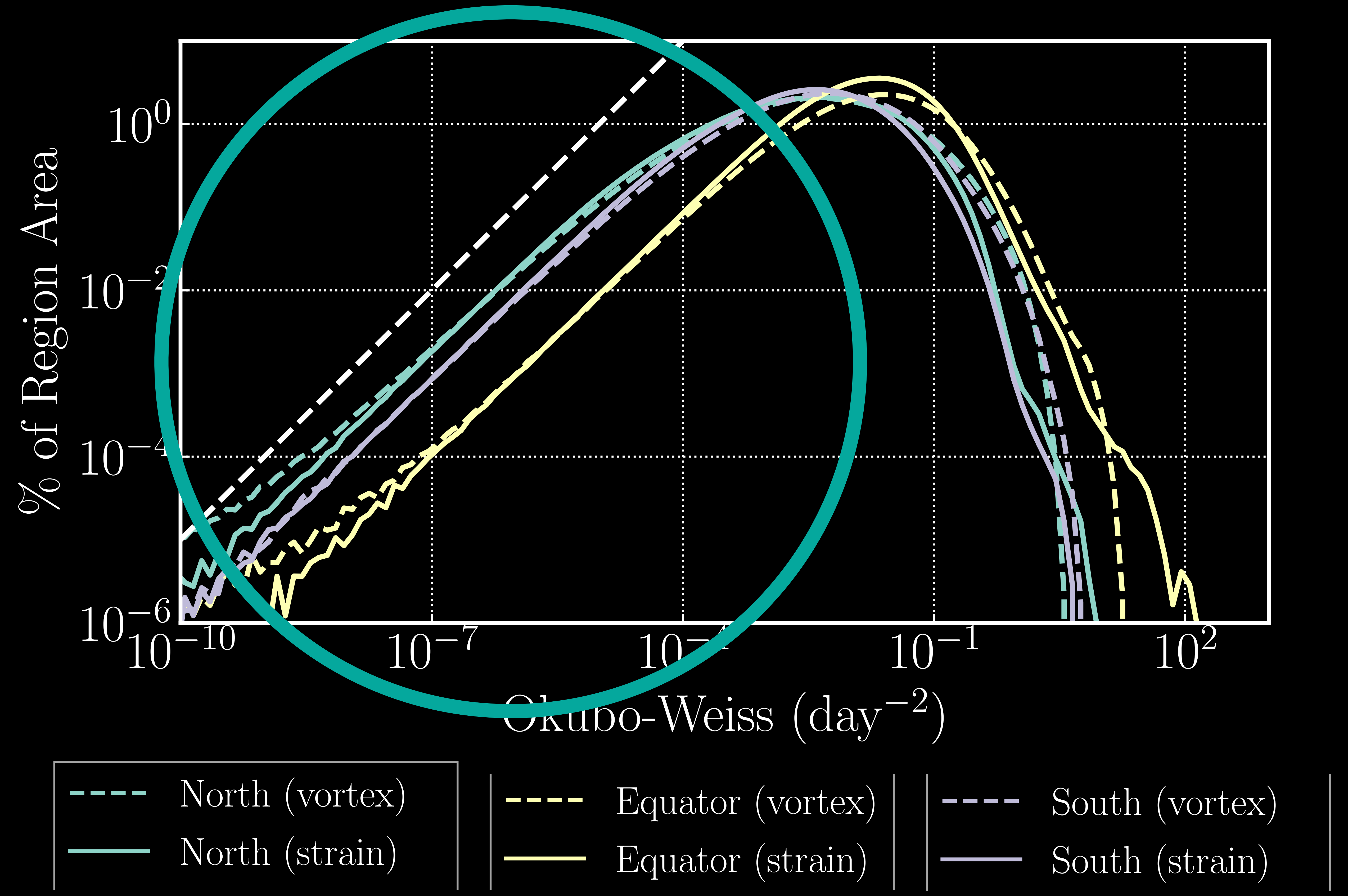
- Majority $(\approx 70\,\%)$ of net energy transfer occurs in strain-dominated regions
- Kinetic energy is roughly equally distributed between strain and vortex regions, with small scales tending towards vortex dominance
- Kuroshio and Gulf Stream have substantially stronger cascade efficiency (Pi / fKE) than other regions
  - Cascade efficiency tends to strengthen in (local) winter
- Outside of dominant currents, energy at scales larger than ~250 km lags behind the corresponding small scales and upscale cascade by ~30 days

Questions: Causes? Implications?

- Energy minimum around 80km?



- Log-log slope of ~1 when comparing area to Okubo-Weiss?



Extra slides

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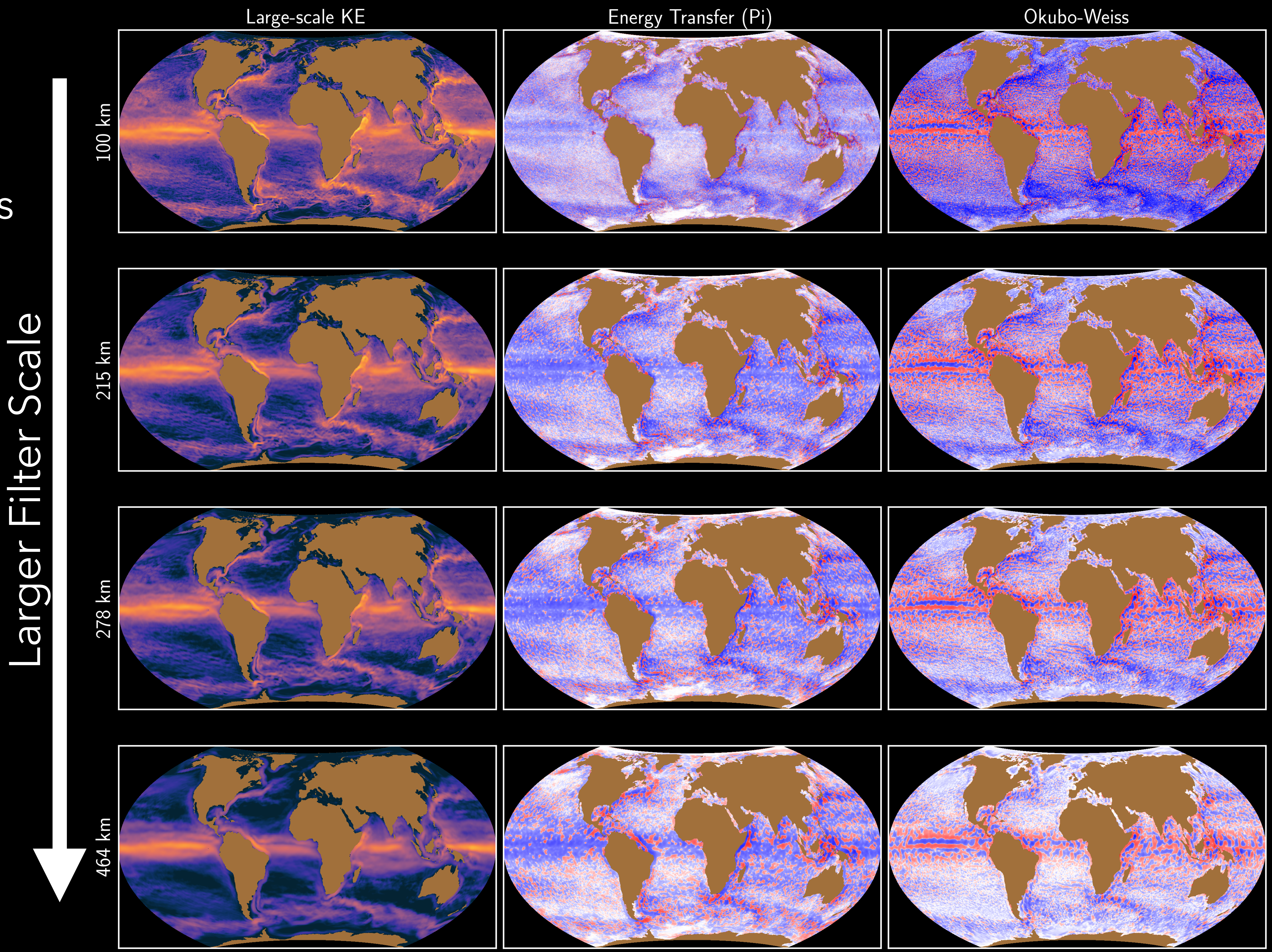

Strain vs Vortex Regions: Area Partitioning