# Timescales of eddy activity in the Southern Ocean

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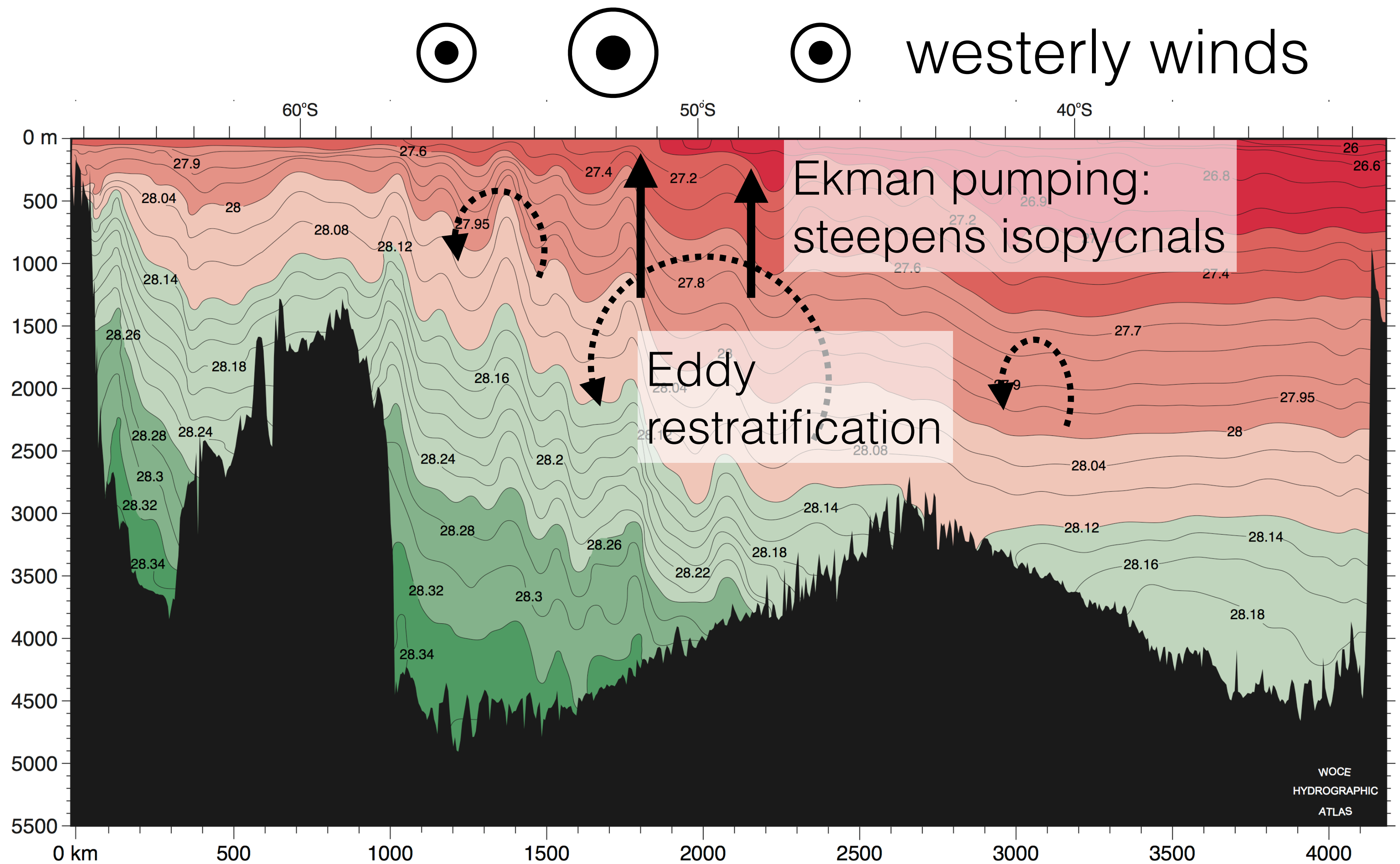
**& Ryan P. Abernathey**
Columbia University in the City of New York

FESD Annual Meeting
June 07, 2016

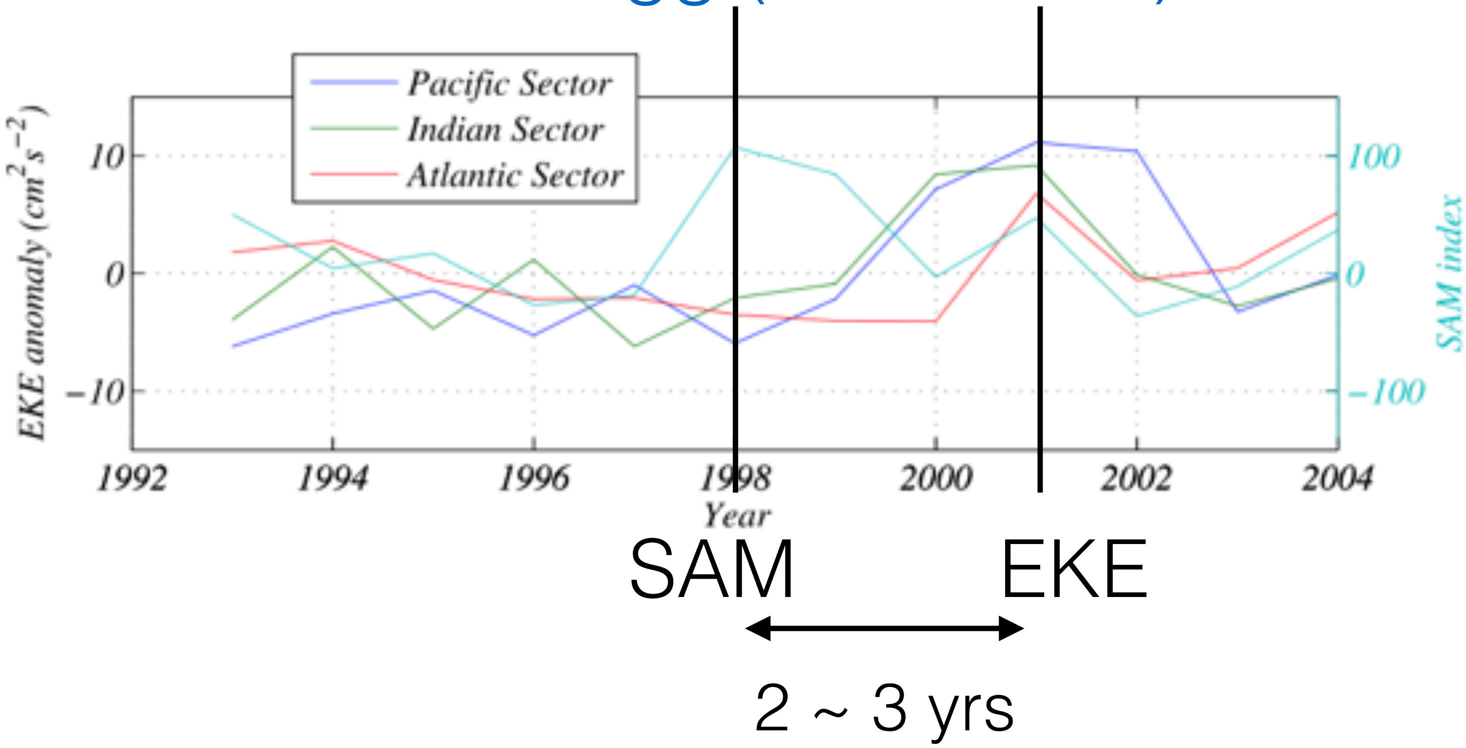
# Southern Ocean Momentum Balance




Neutral Density

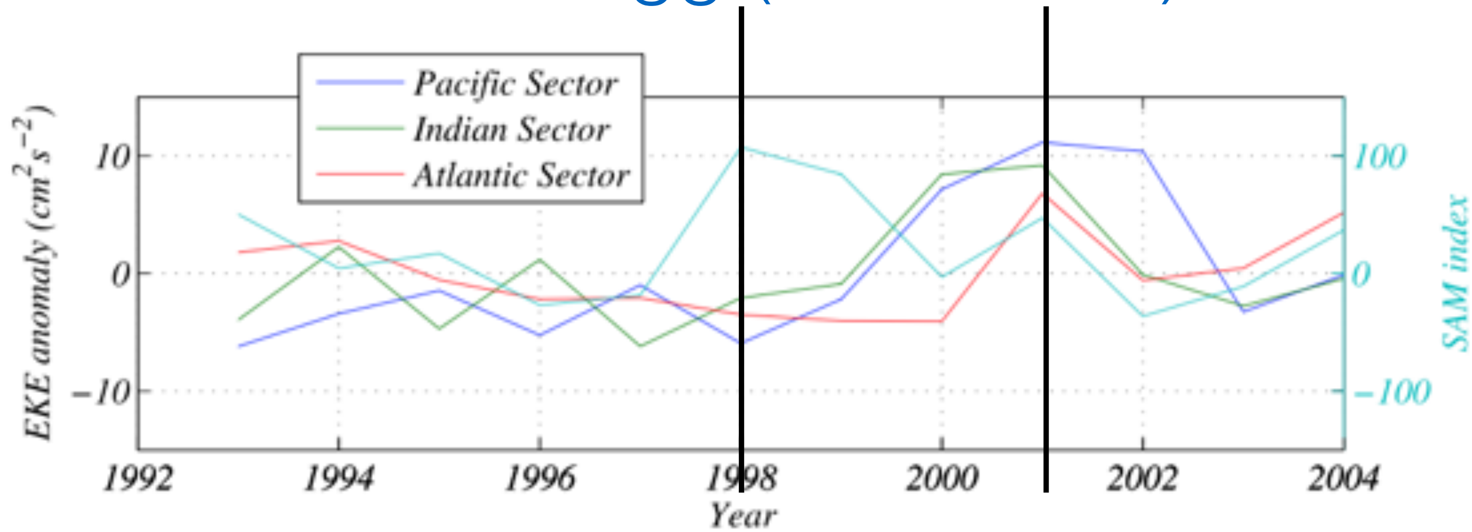
Existing Theoretical Framework (Gill et. al. 1974, Marshall & Speer, 2012; Hallberg & Gnanadesikan, 2006; Abernathey & Cessi, 2014): Competition between **wind** driven upwelling and baroclinic **eddies** determines **mean isopycnal slope, ACC transport,** and **MOC**

# Meredith & Hogg (2006, GRL)




Wind Stress —> **APE** —> **EKE**

Meredith & Hogg (2006, GRL)



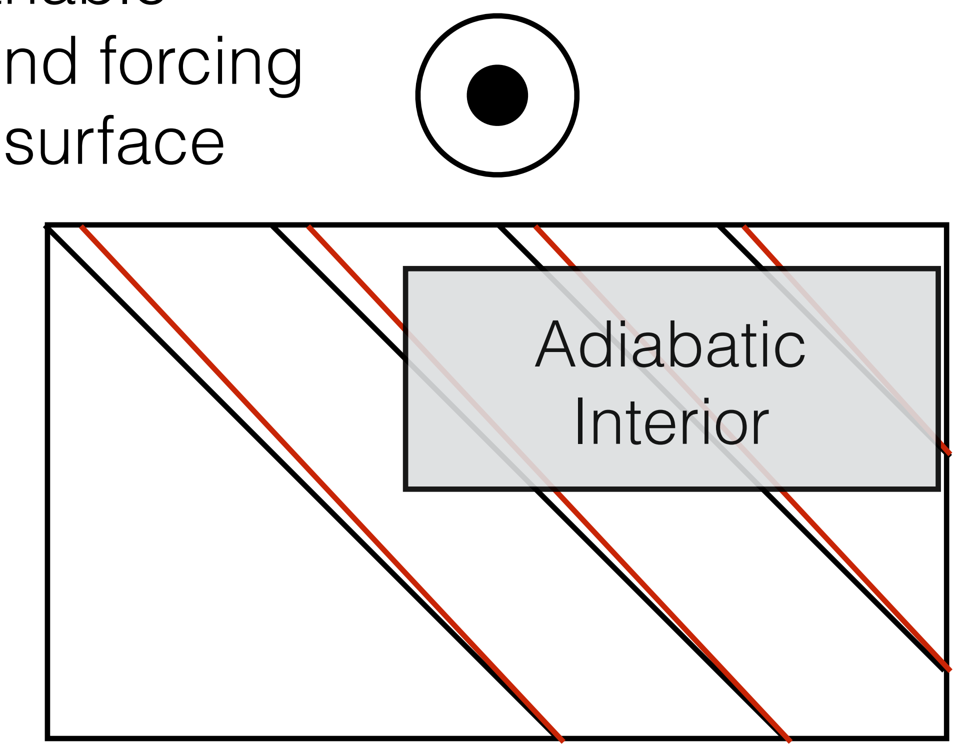

SAM EKE

2 ~ 3 yrs

Wind Stress —> **APE** —> **EKE**

# **Simple model:**
channel SO

Variable
Wind forcing
at surface



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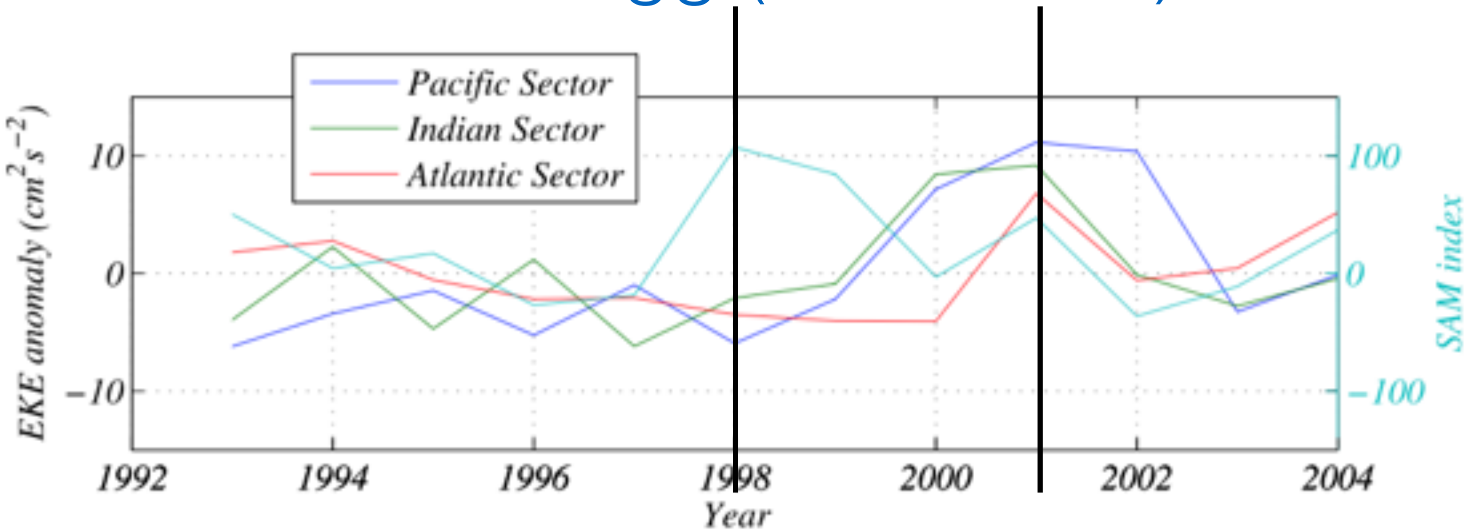


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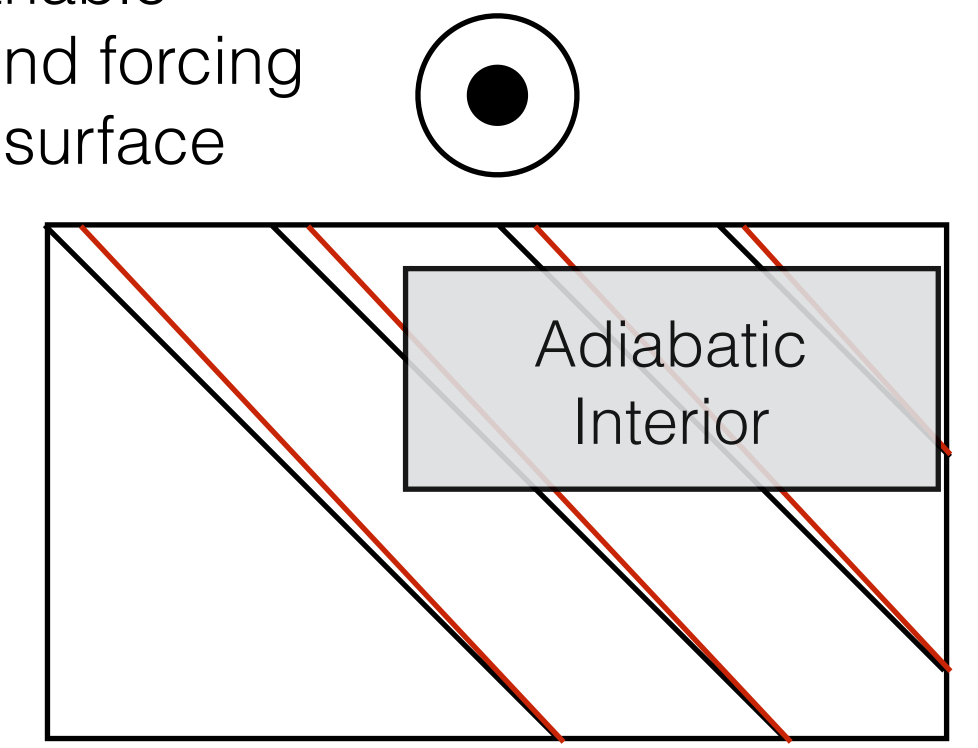


## Simple model:
Energy pathway

wind power input

Conversion term

Drag term

$$\frac{d(APE)}{dt} = W - C$$

$$\frac{d(EKE)}{dt} = C - D$$

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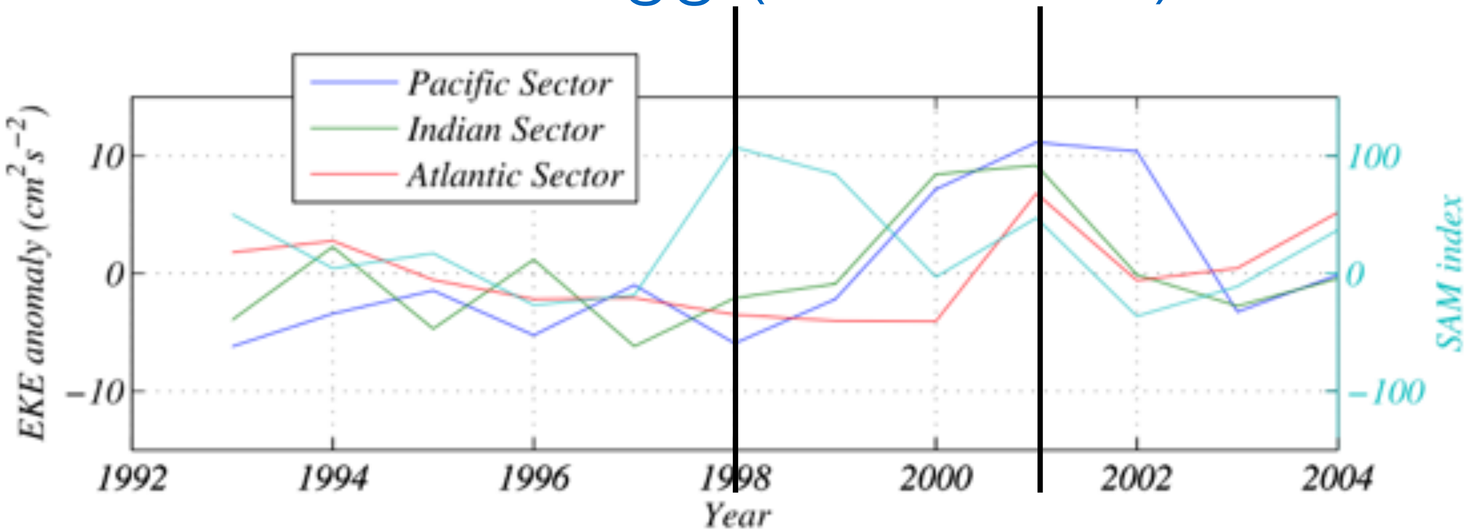


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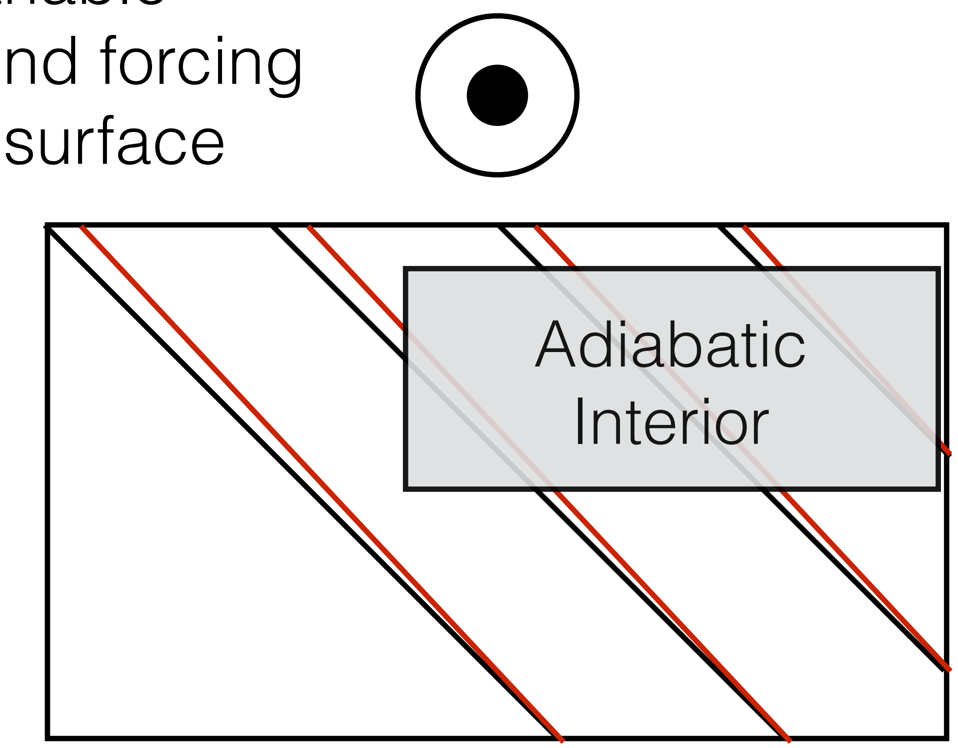


## Simple model:
Energy pathway

$$\frac{d(APE)}{dt} = W - C$$

$$\frac{d(EKE)}{dt} = C - D$$

wind power input (W)

Conversion term (C)

Drag term (D)

$$C = -\iiint_{dV} \overline{w'b'}$$

$$\sim -K_{GM}\frac{(\nabla b)^2}{N^2}$$

# Simple model: w/o Eddy feedback

$$\frac{dP(t)}{dt} = f(t) - cP(t)$$

GM type closure

$$\frac{dK(t)}{dt} = cP(t) - rK(t)$$

linear bottom drag

**Transfer Function**

$$f = \hat{f}e^{i\omega t} = \left|\hat{f}\right| e^{i\omega t + \phi_f}$$

$$P = \hat{P}e^{i\omega t} = \left|\hat{P}\right| e^{i\omega t + \phi_P}$$

$$K = \hat{K}e^{i\omega t} = \left|\hat{K}\right| e^{i\omega t + \phi_K}$$

$$c \sim \frac{K_{GM}}{L_y^2} \approx 10^{-9}\ s^{-1}$$ (~3 years !)

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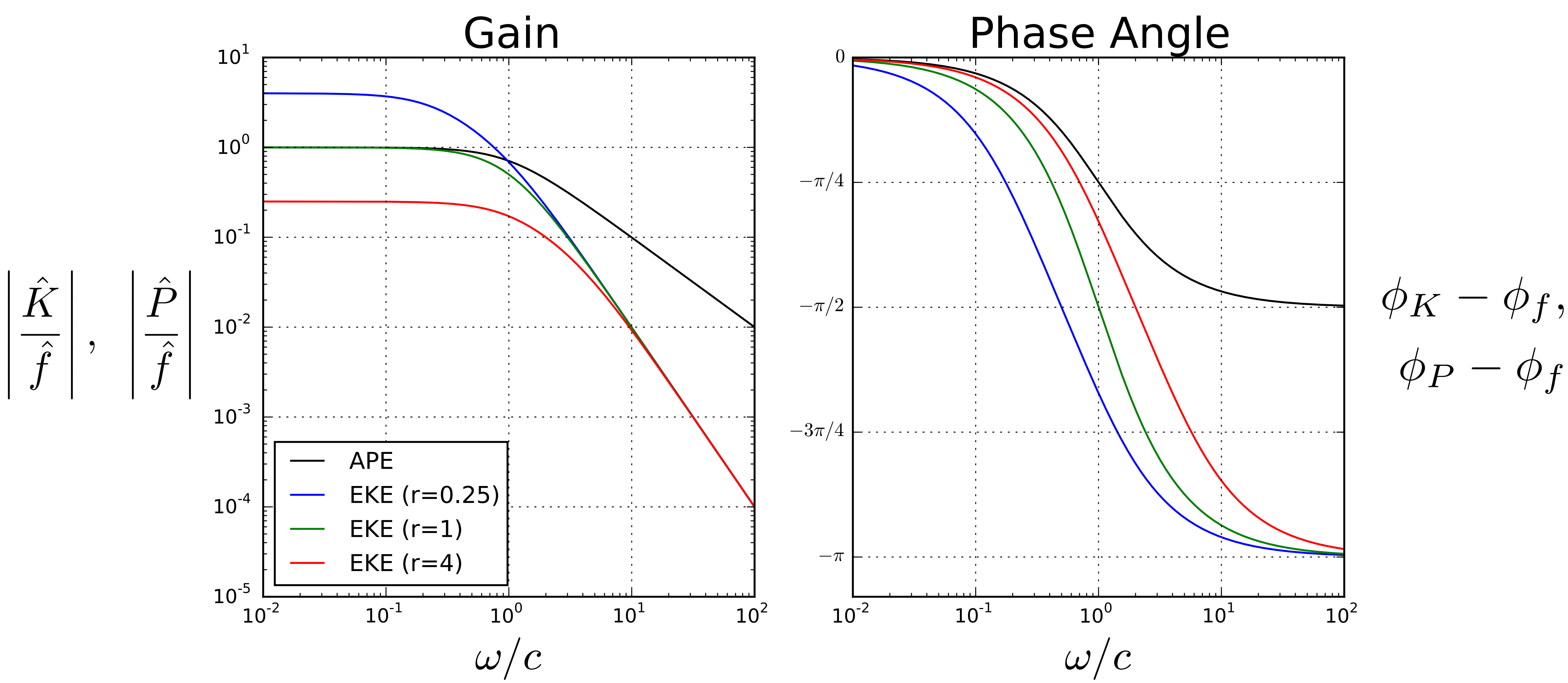


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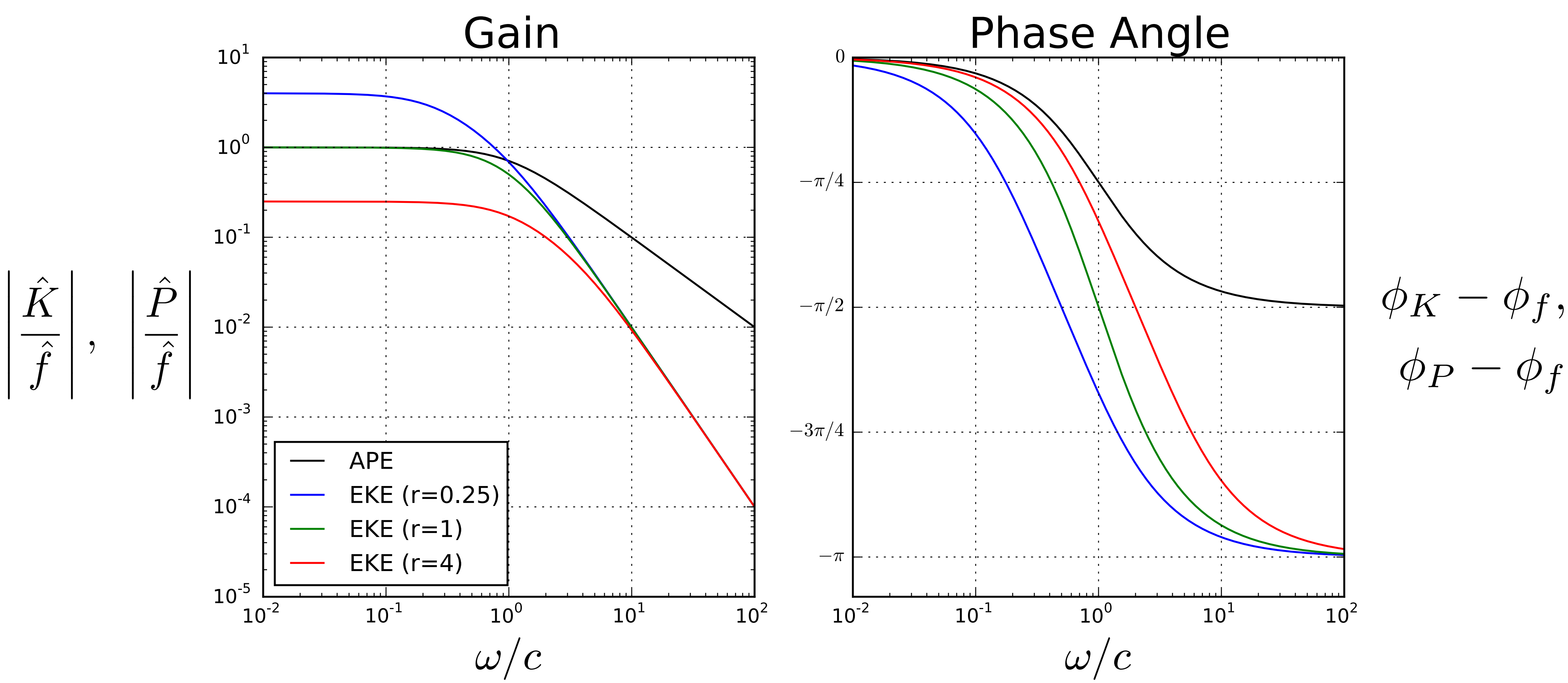

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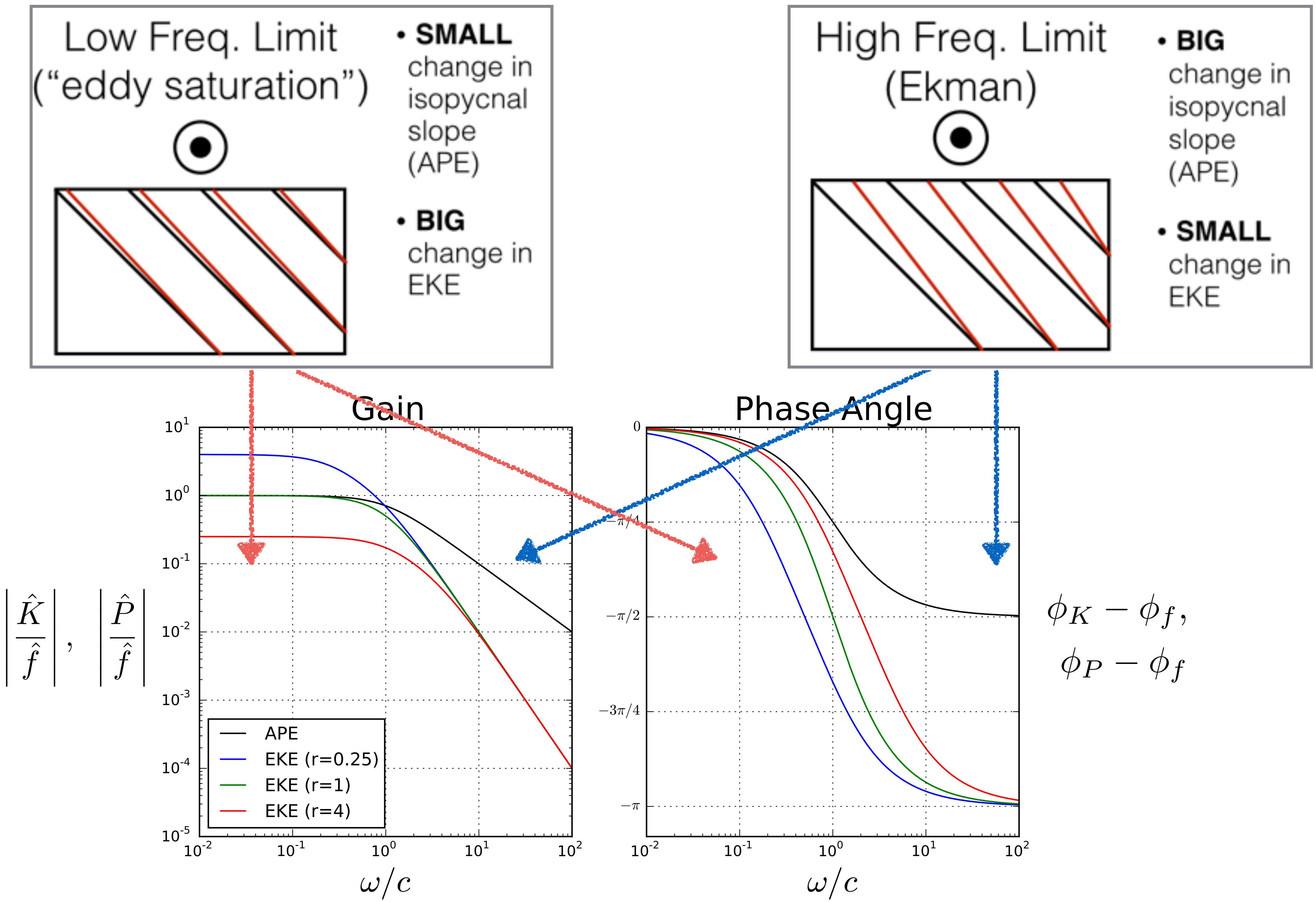

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*Sinha & Abernathey (submitted to JPO)*

# Simple model

## w/o Eddy feedback

$$\frac{dP(t)}{dt} = f(t) - cP(t)$$

$$\frac{dK(t)}{dt} = cP(t) - rK(t)$$

## with Eddy feedback

based on mixing length arguments

$$\frac{dP}{dt} = f - kPK^{\alpha}$$

$$\frac{dK}{dt} = kPK^{\alpha} - r_1 K^{\beta}$$

general bottom drag

linearize and solve for

$$\frac{dP'}{dt} = f' - c_1 P' - c_2 K'$$

$$\frac{dK'}{dt} = c_1 P' + c_2 K' - rK'$$

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# Simple model

## w/o Eddy feedback

$$\frac{dP(t)}{dt} = f(t) - cP(t)$$

$$\frac{dK(t)}{dt} = cP(t) - rK(t)$$

Same as c,
(eddy mixing coeff)

Two conversion terms : $c_1, \ c_2$

New term,
(eddy feedback)

## with Eddy feedback

based on
mixing length arguments

$$\frac{dP}{dt} = f - kPK^{\alpha}$$

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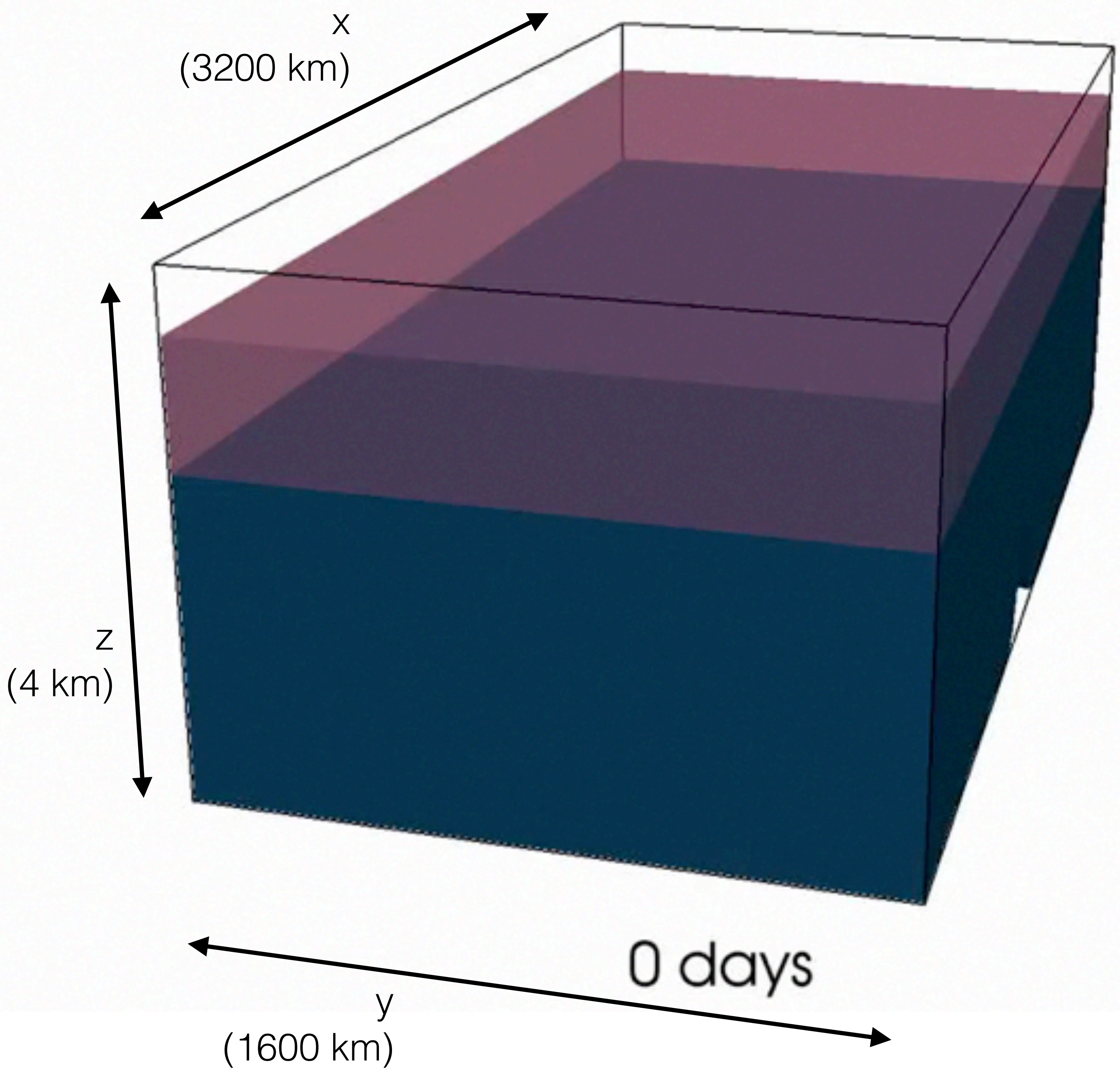
# Isopycnal GOLD model:

(Hallberg & Gnanadesikan, 2001, 2006; Howard et al. 2015)




- Reduced gravity model
- 4 km horizontal resolution
- Three isopycnal layers
- Wind forcing only

**Seven experiments**

- Steady sinusoidal wind jet (0.2 N/m^2)
- plus oscillations +/- (0.1 N/m^2), 0.25, 0.5,1, 2, 4, 8 year periods

**Diagnostics**

- EKE
- APE
- Wind Energy input

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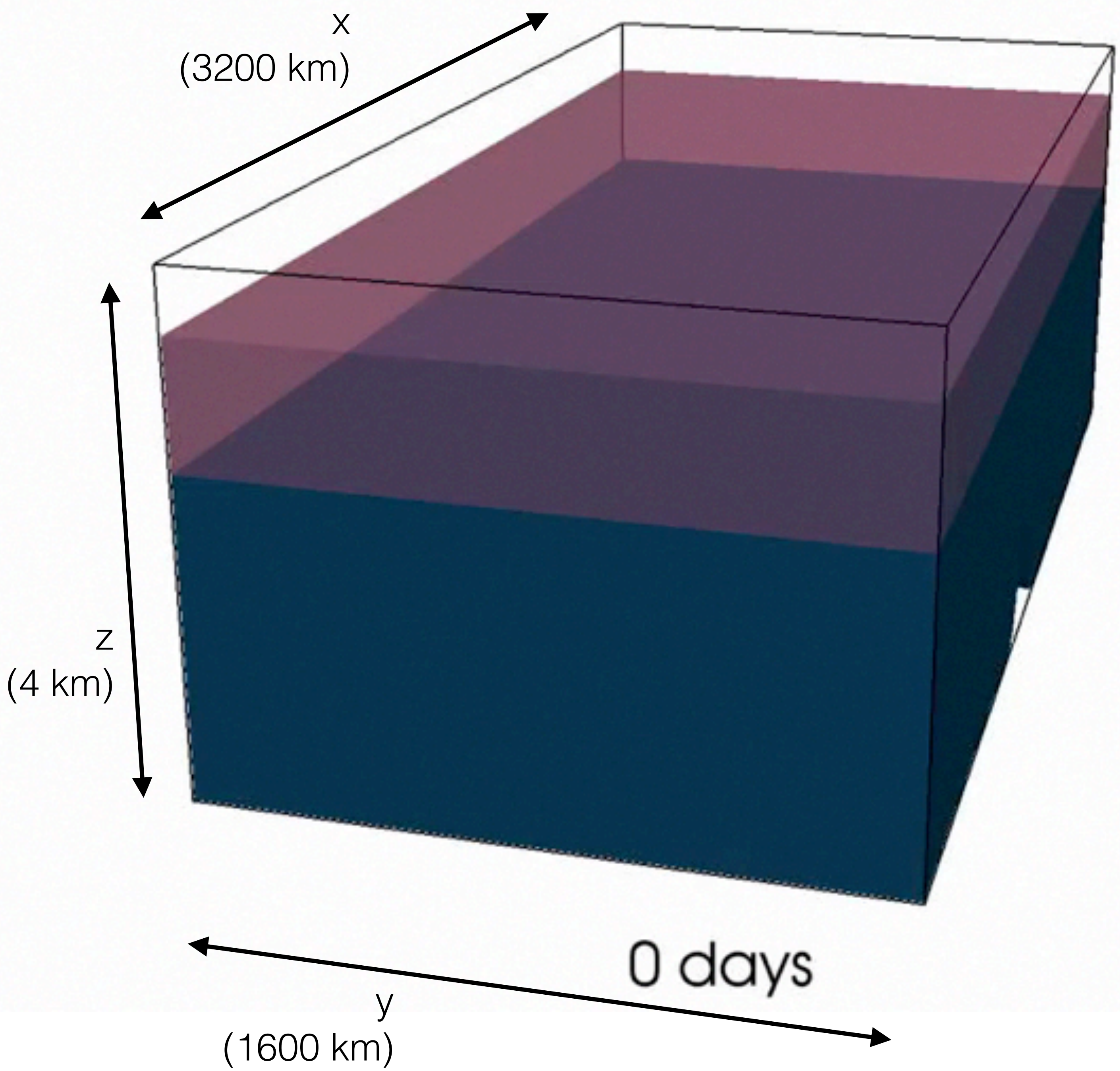


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**Diagnostics**

- EKE
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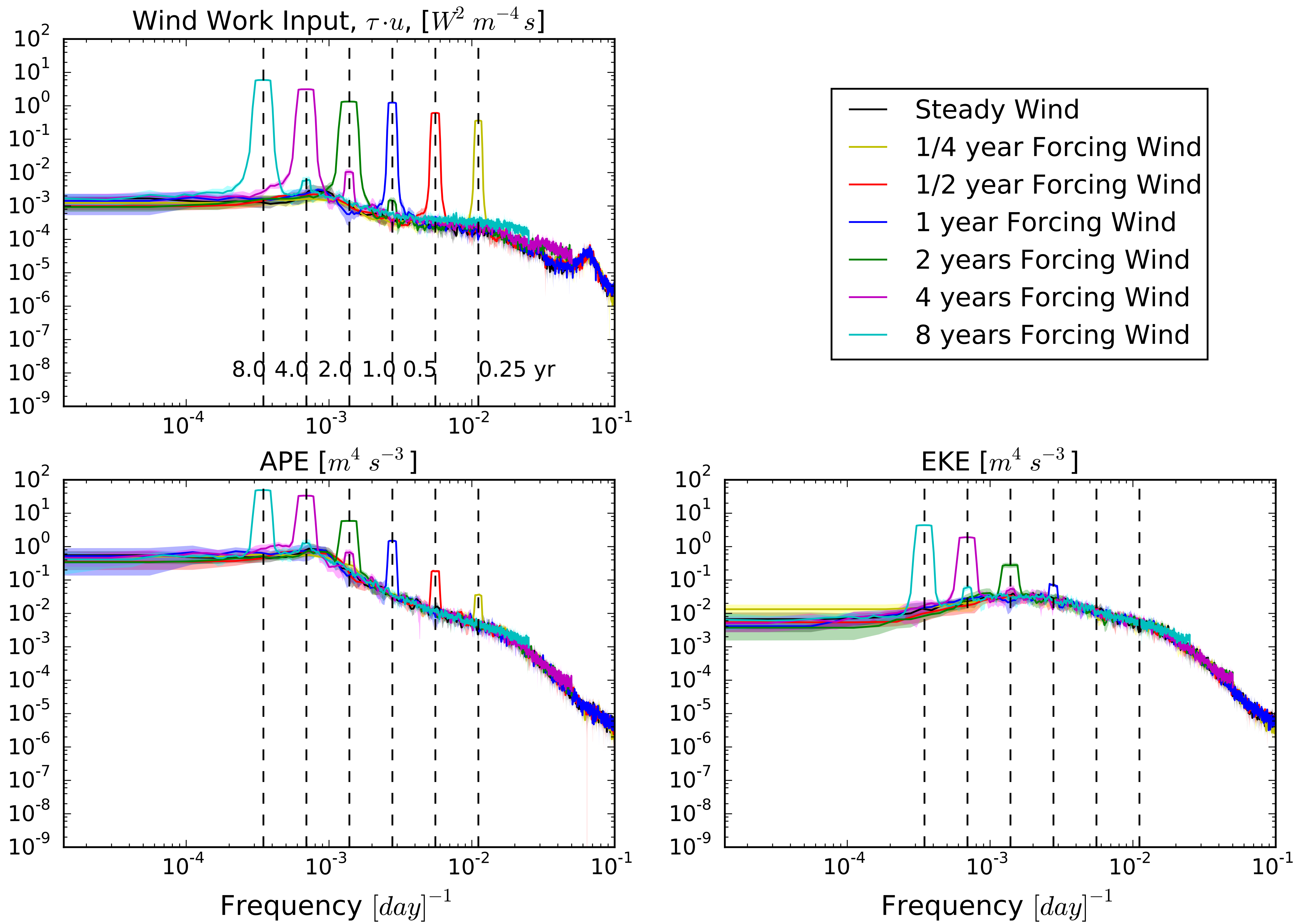
- Wind Energy input

*Sinha & Abernathey (submitted to JPO)*

# Spectral Analysis

energy input:
same power,
different
frequency

response:
different
amplitudes

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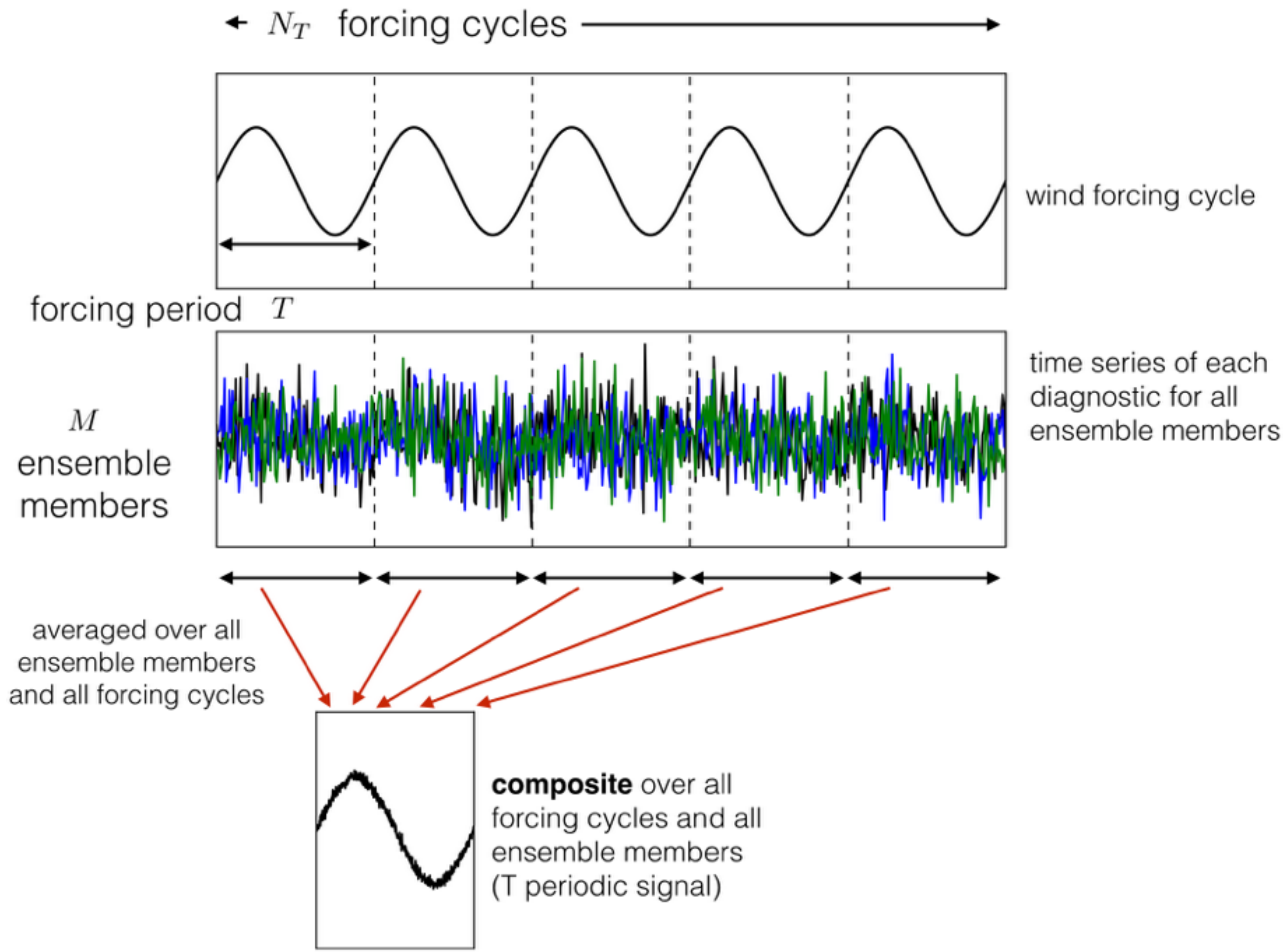
# Composite Analysis



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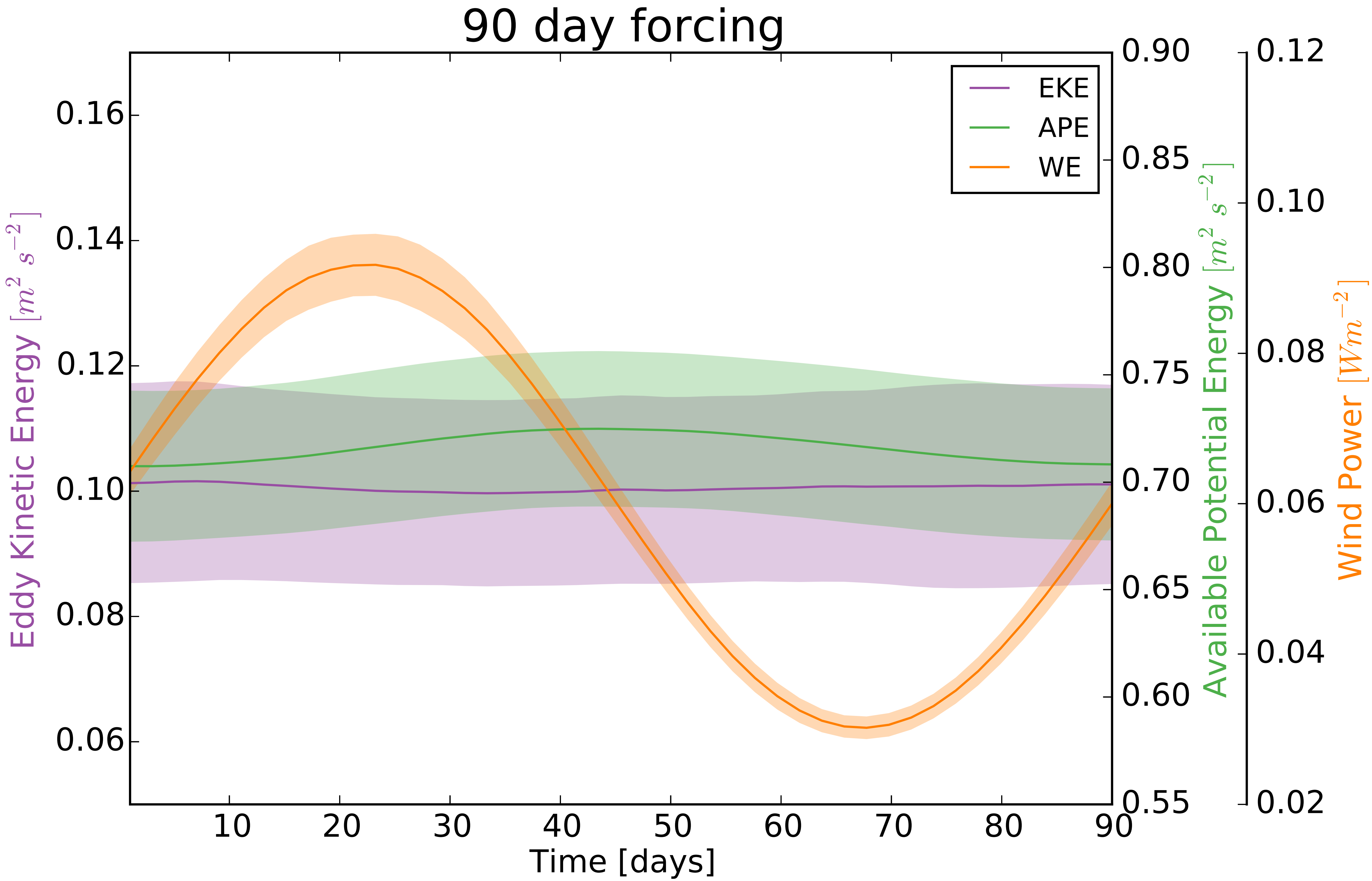


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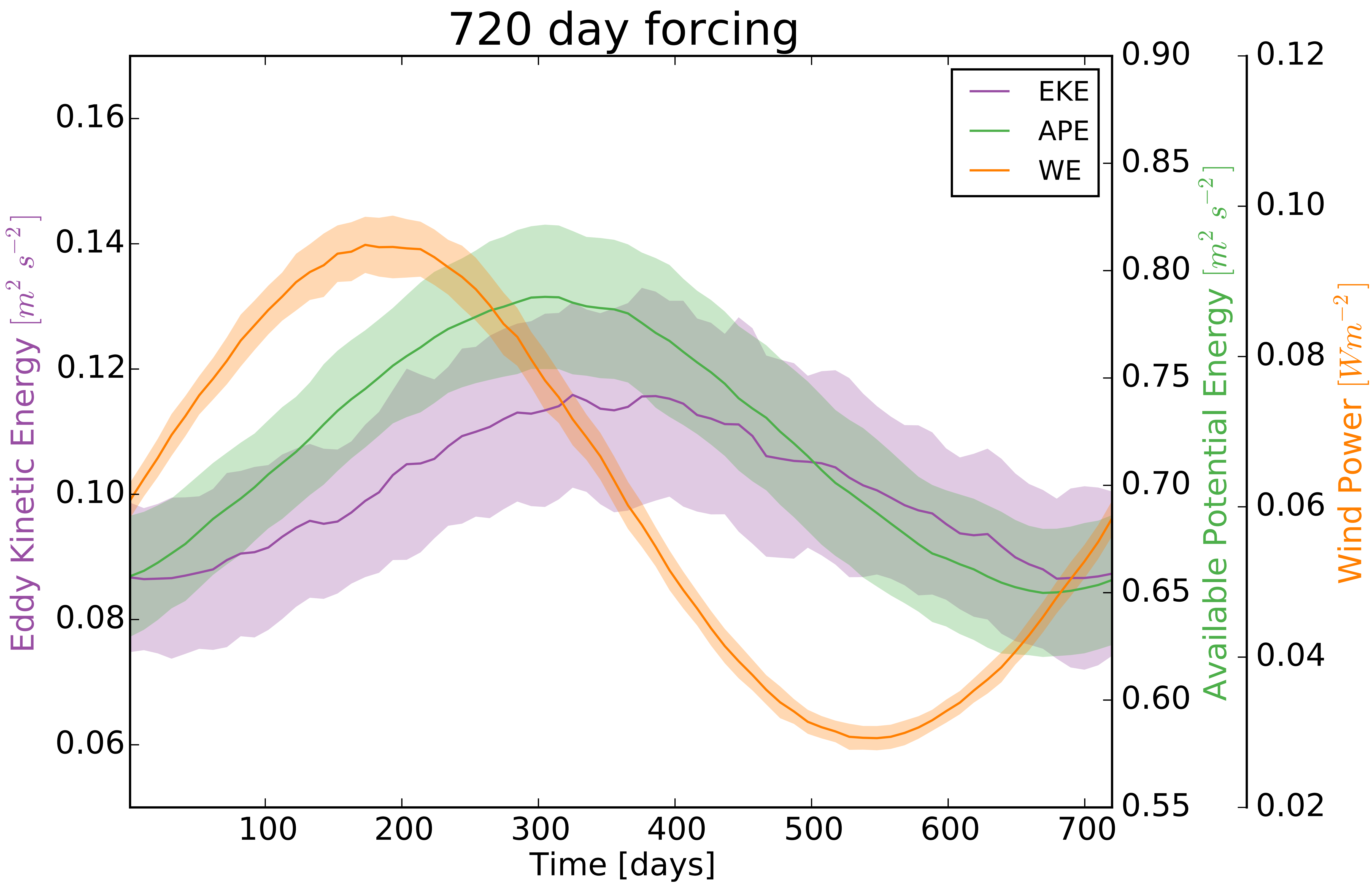


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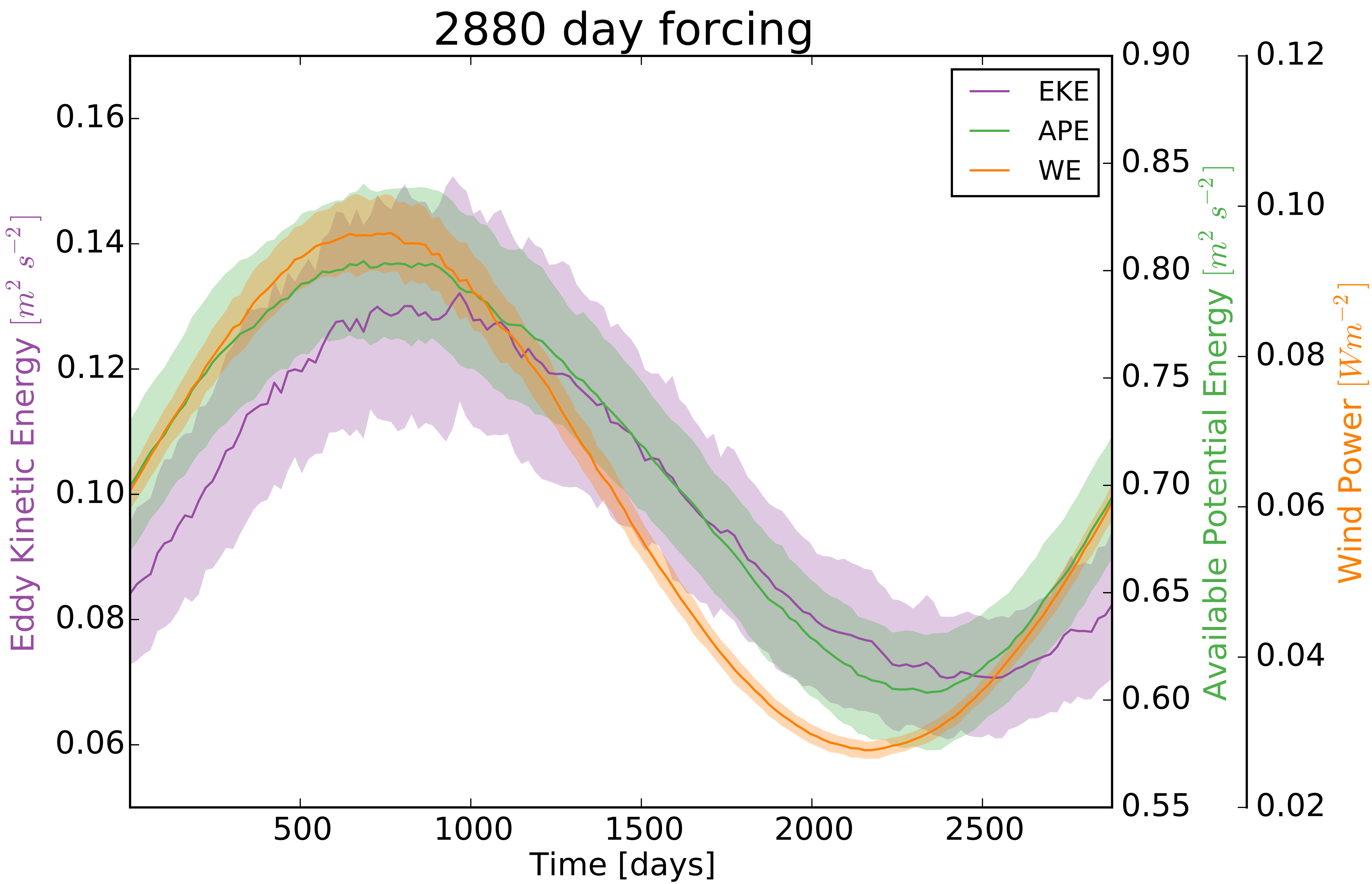


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# Compare Analytic & Numerical Model

$$\frac{dP'}{dt} = f' - c_1 P' - c_2 K'$$
$$\frac{dK'}{dt} = c_1 P' + c_2 K' - rK'$$

**weak eddy feedback**

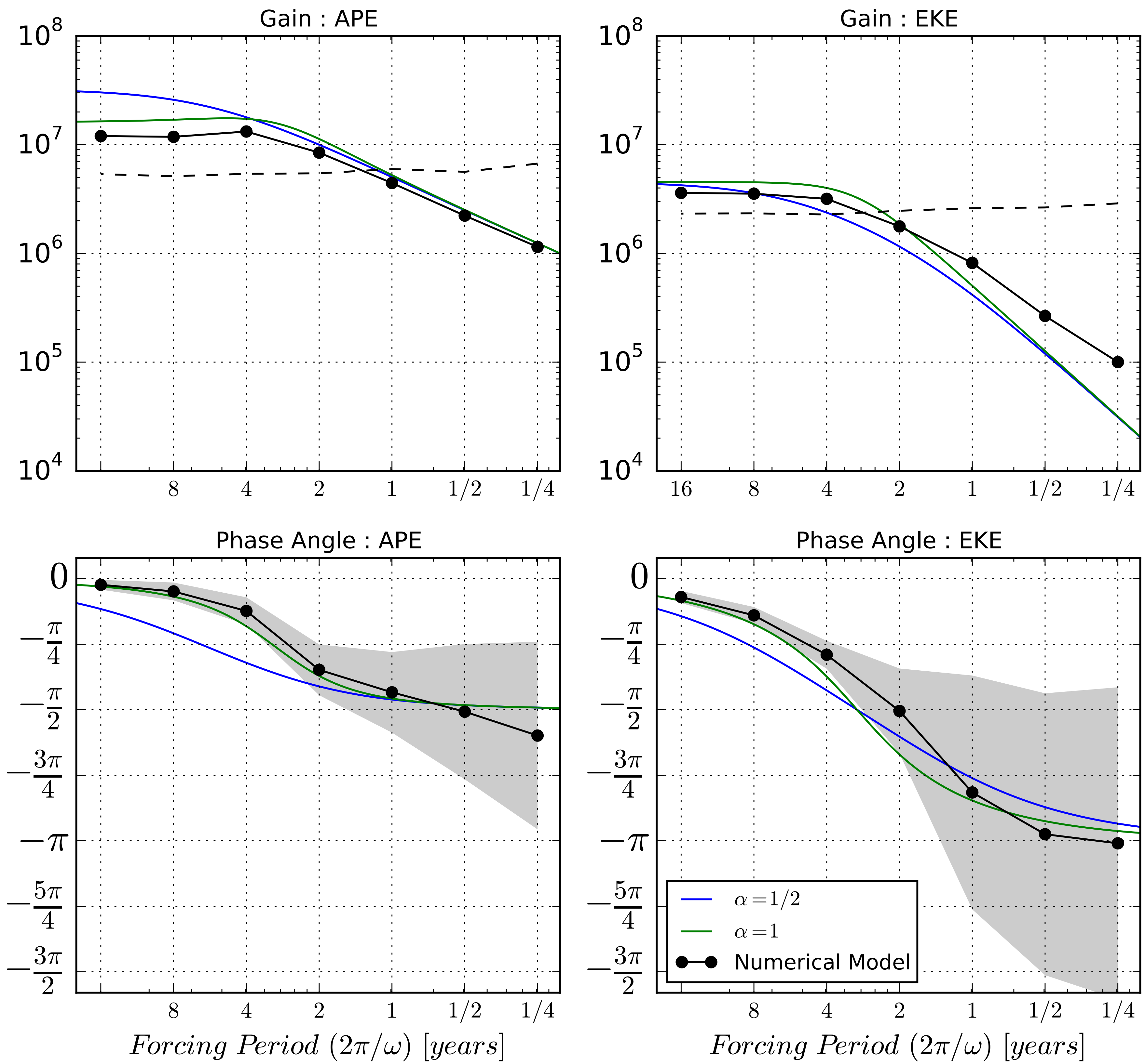
$c_1 = \overline{f}/\overline{P};\ c_2 = \overline{f}/\overline{2K}$

~560 days ~157 days

**strong eddy feedback**

$c_1 = \overline{f}/\overline{P};\ c_2 = \overline{f}/\overline{K}$

~560 days ~78 days

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# Summary

- Two limits : **Fast** vs **Slow** - **Transient response** to **changing winds**

- **Analytical model**: Energy Budget - **wind power, APE, EKE**
  - with and without **eddy feedback**

- smooth **transfer function**, complex **phase** and **amplitude** response to changing winds: **Regime shift**

- **Numerical simulations** with idealized model

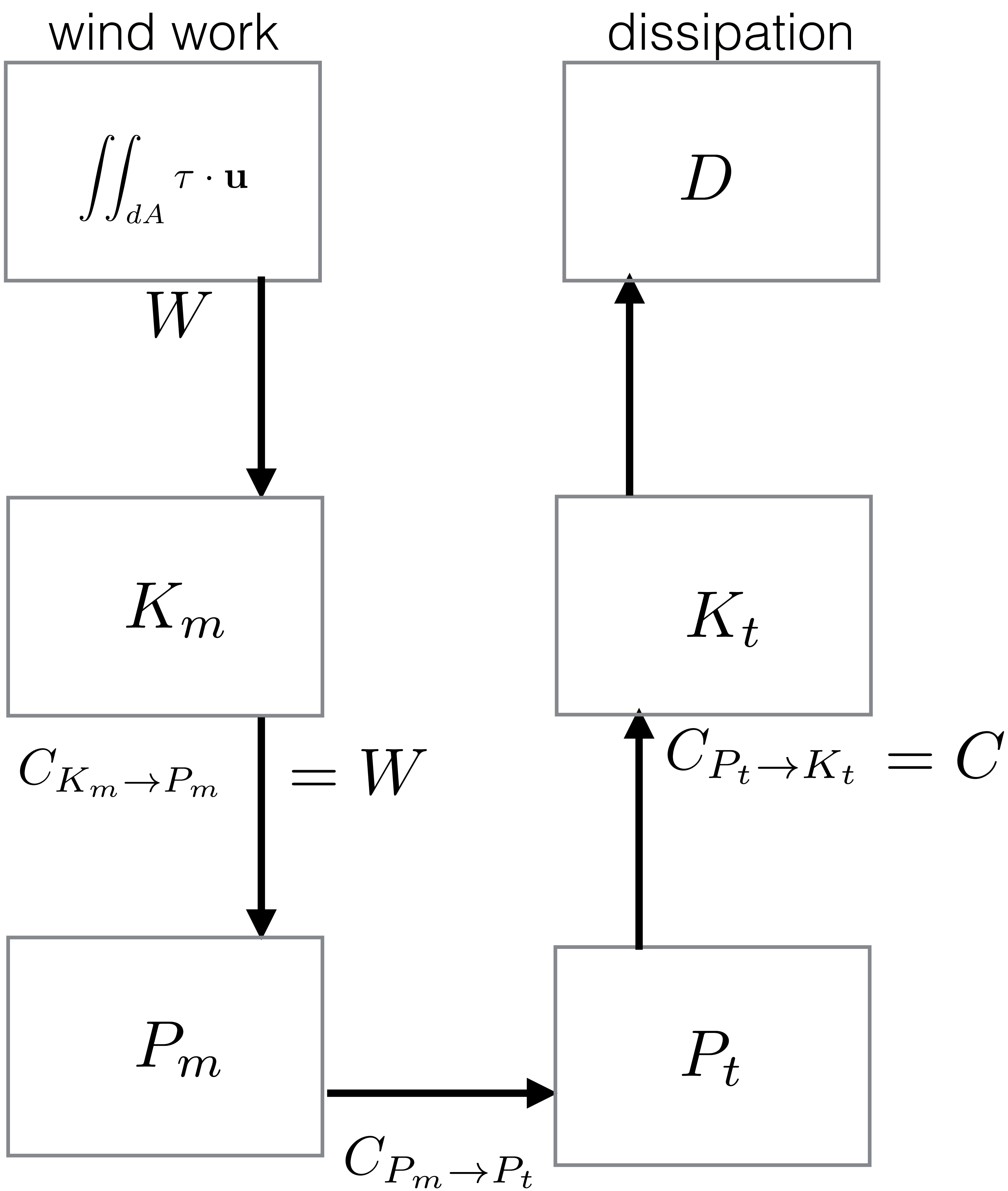
- **mechanistic description** of the **eddy equilibration** process with **purely dynamic forcing**

# Discussions

- Eddy **generation** and **dissipation** - **non-local in time**
- Eddy **memory effect** - Time dependent **eddy parameterization**
- Used in conjunction with multiple timescale response to **thermodynamic forcing** (Ferreira et al 2014 )(sea ice, ozone depletion etc.) - more **complete** theory for SO response, **baroclinic eddy equilibration**

Thank you.

# Simple model: Energy pathway



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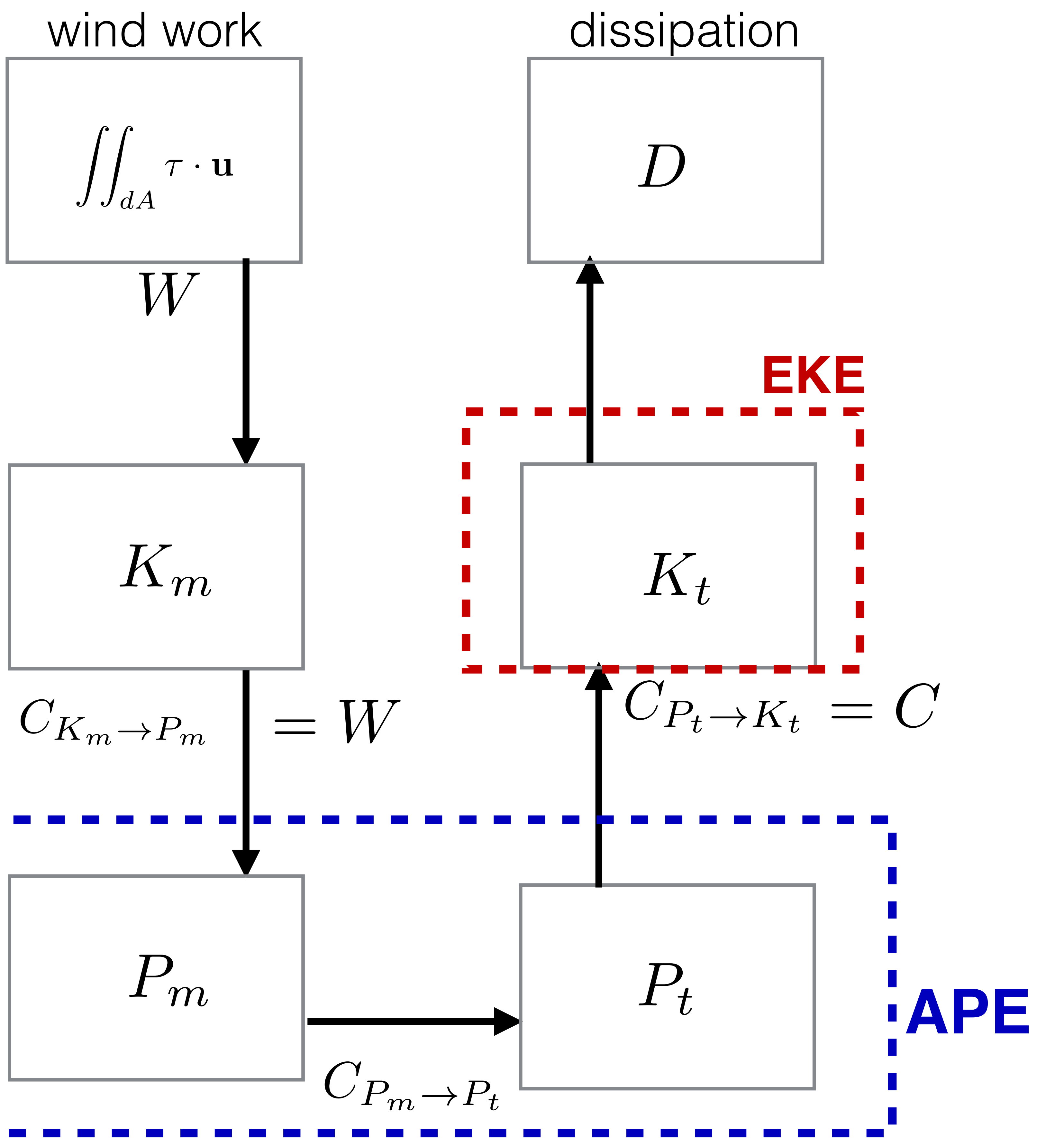

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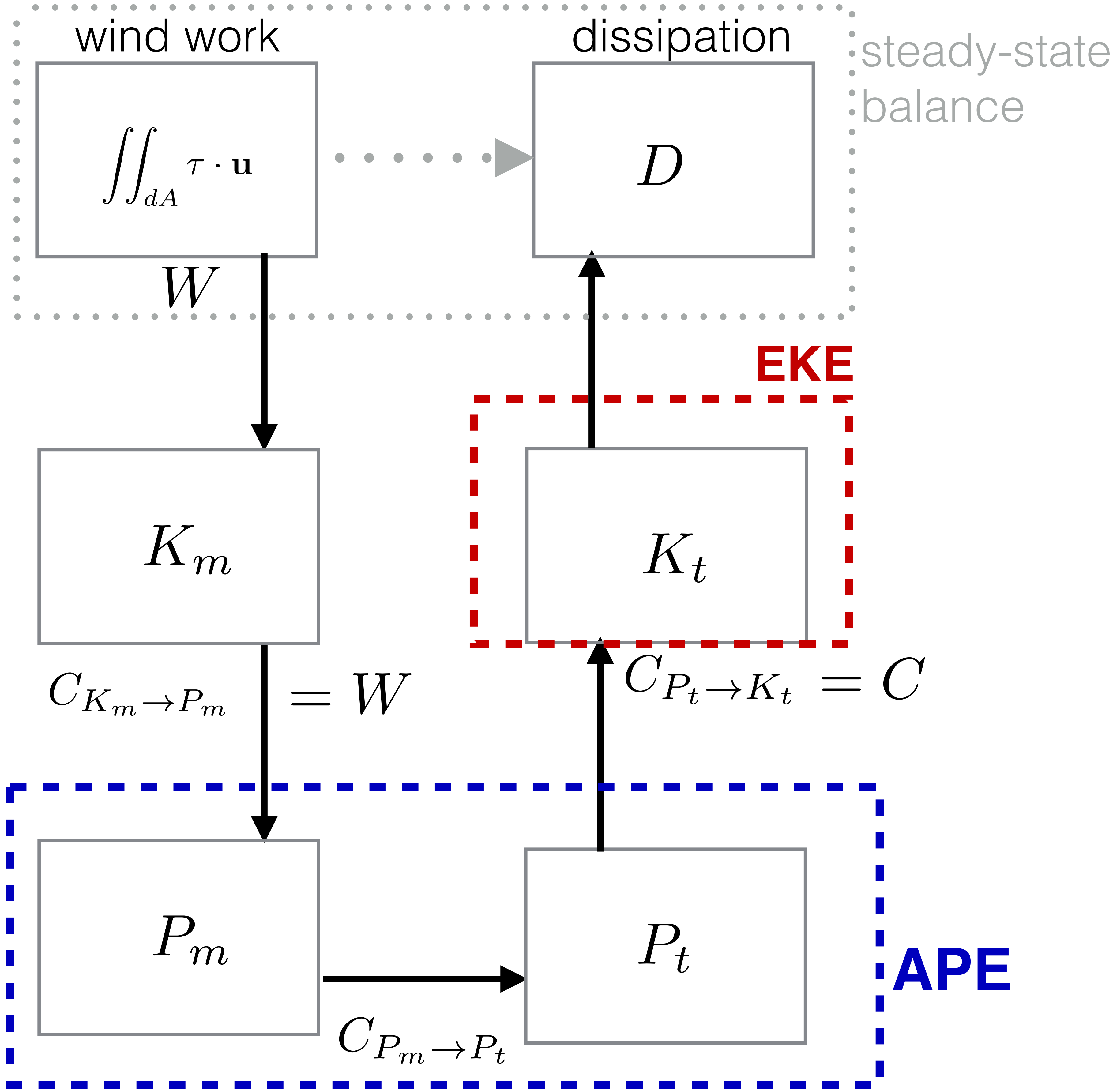

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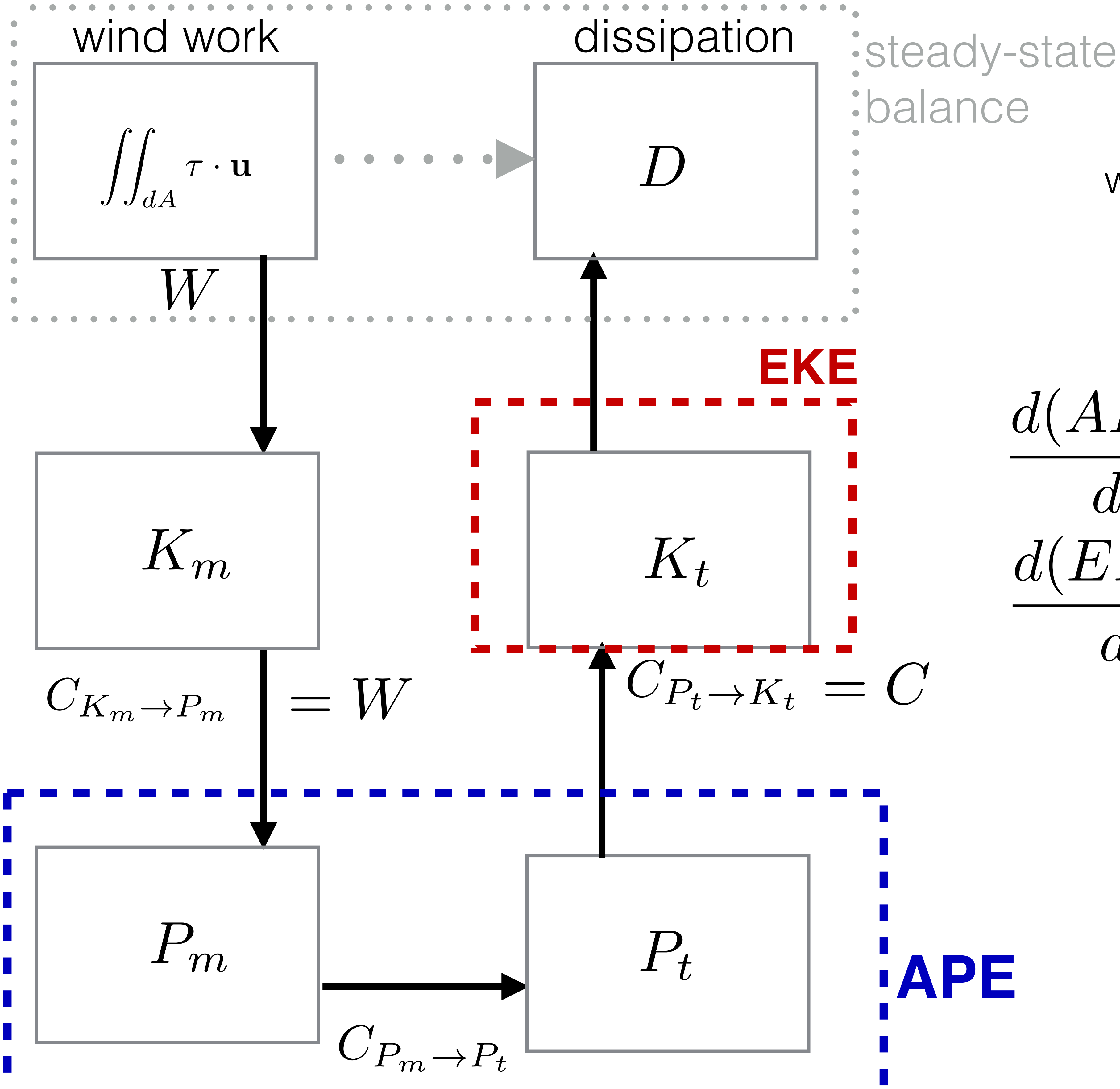


wind power input

Conversion term

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Drag term

# Appendix

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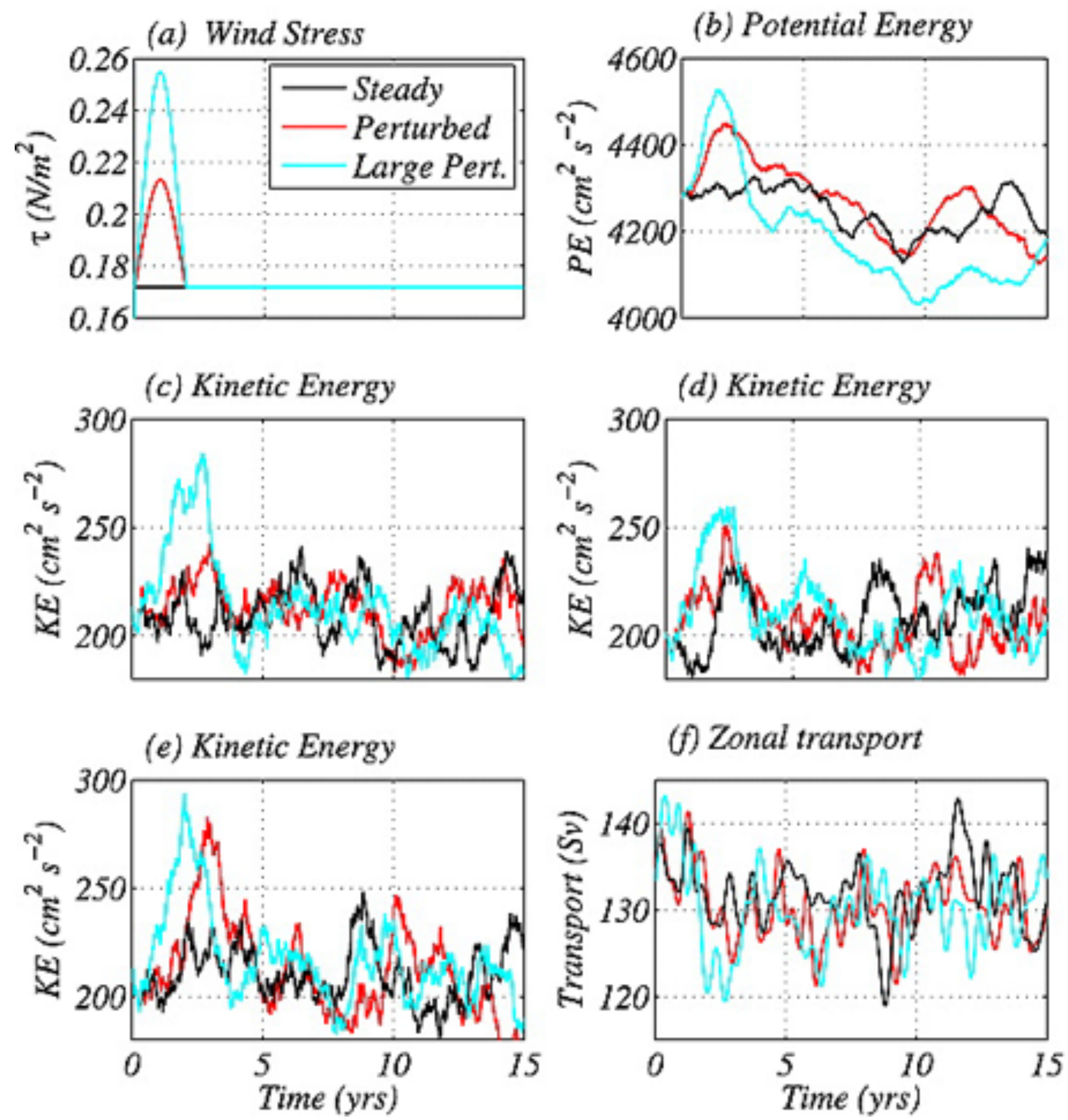

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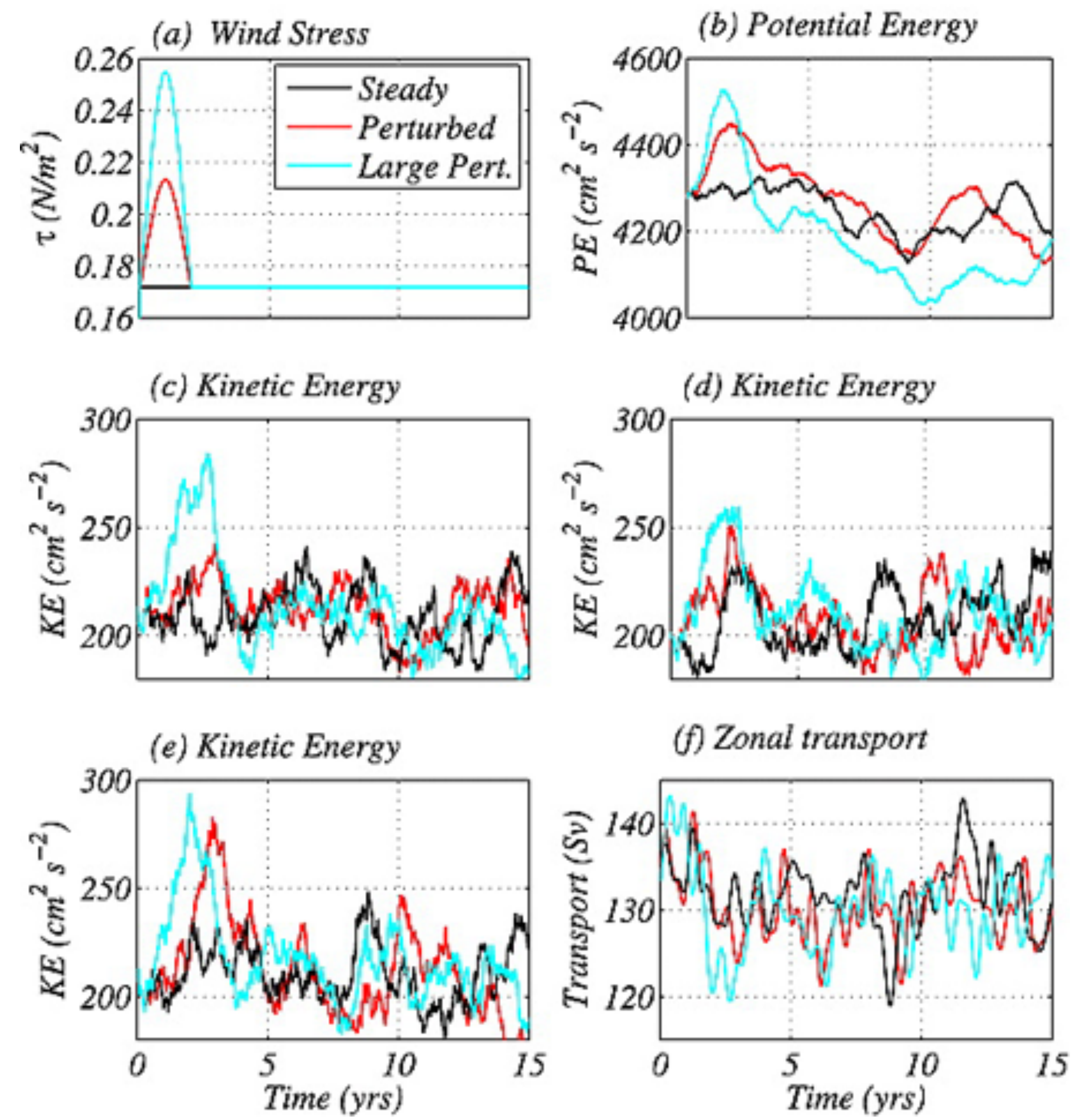

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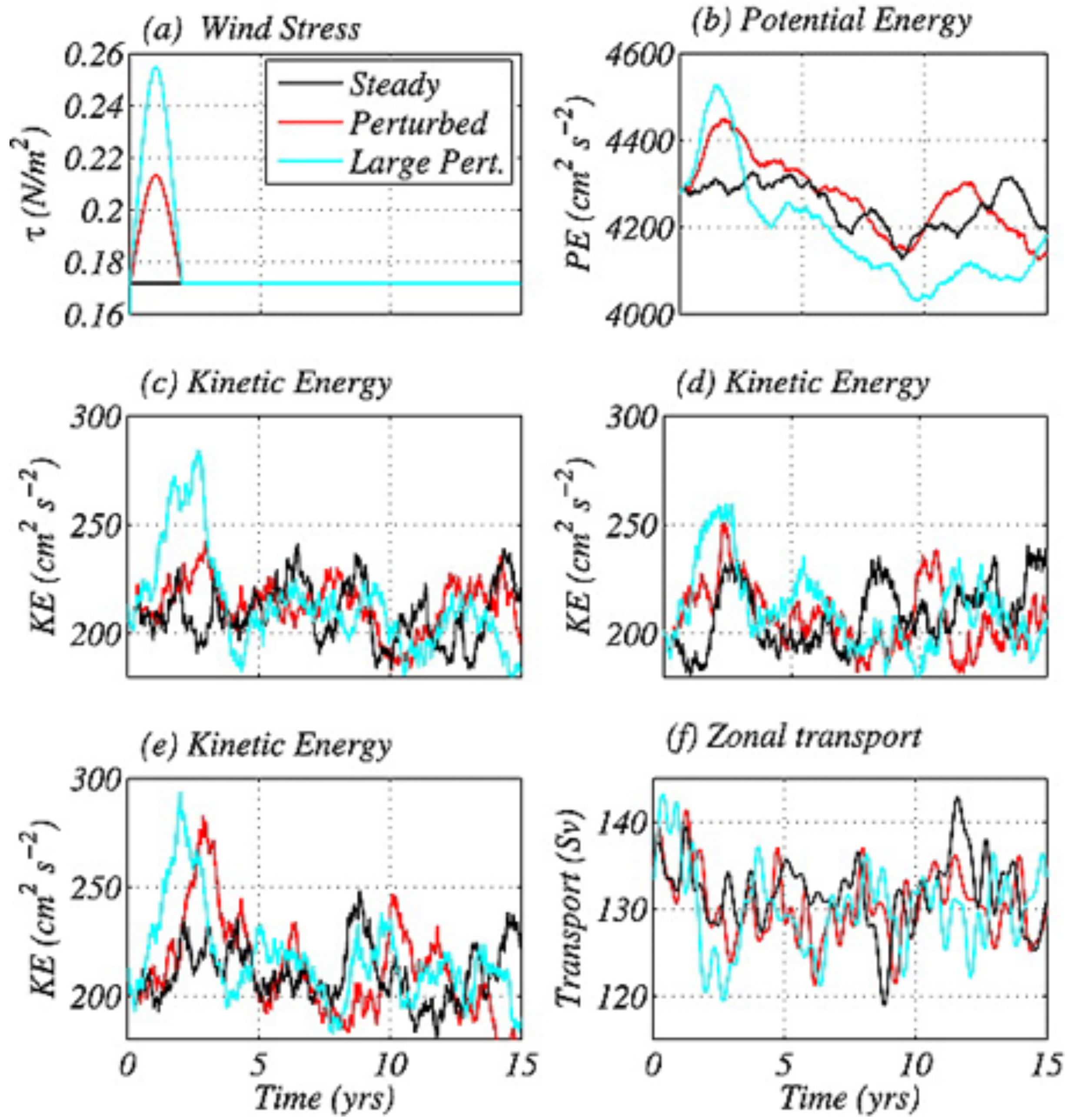


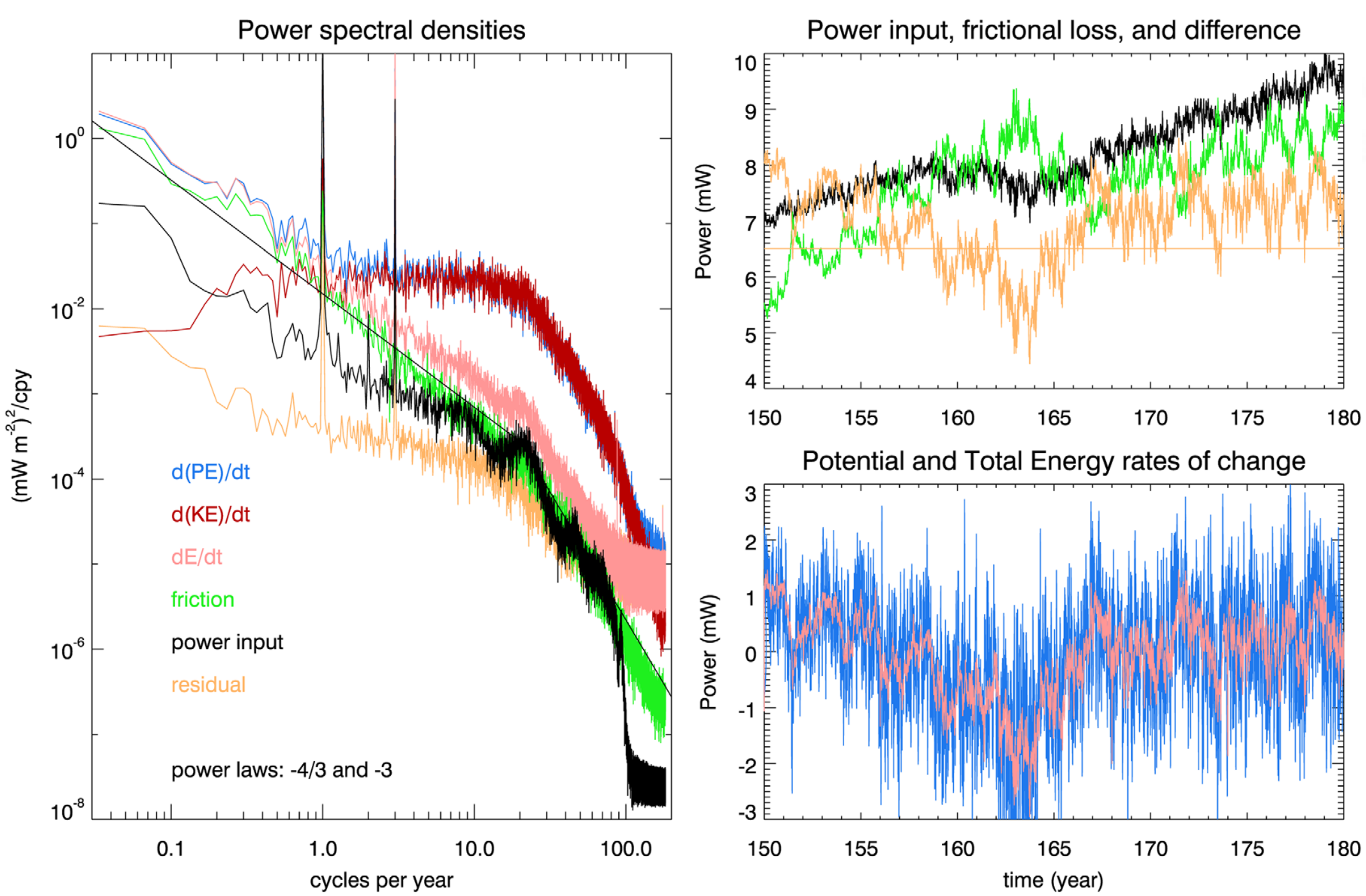

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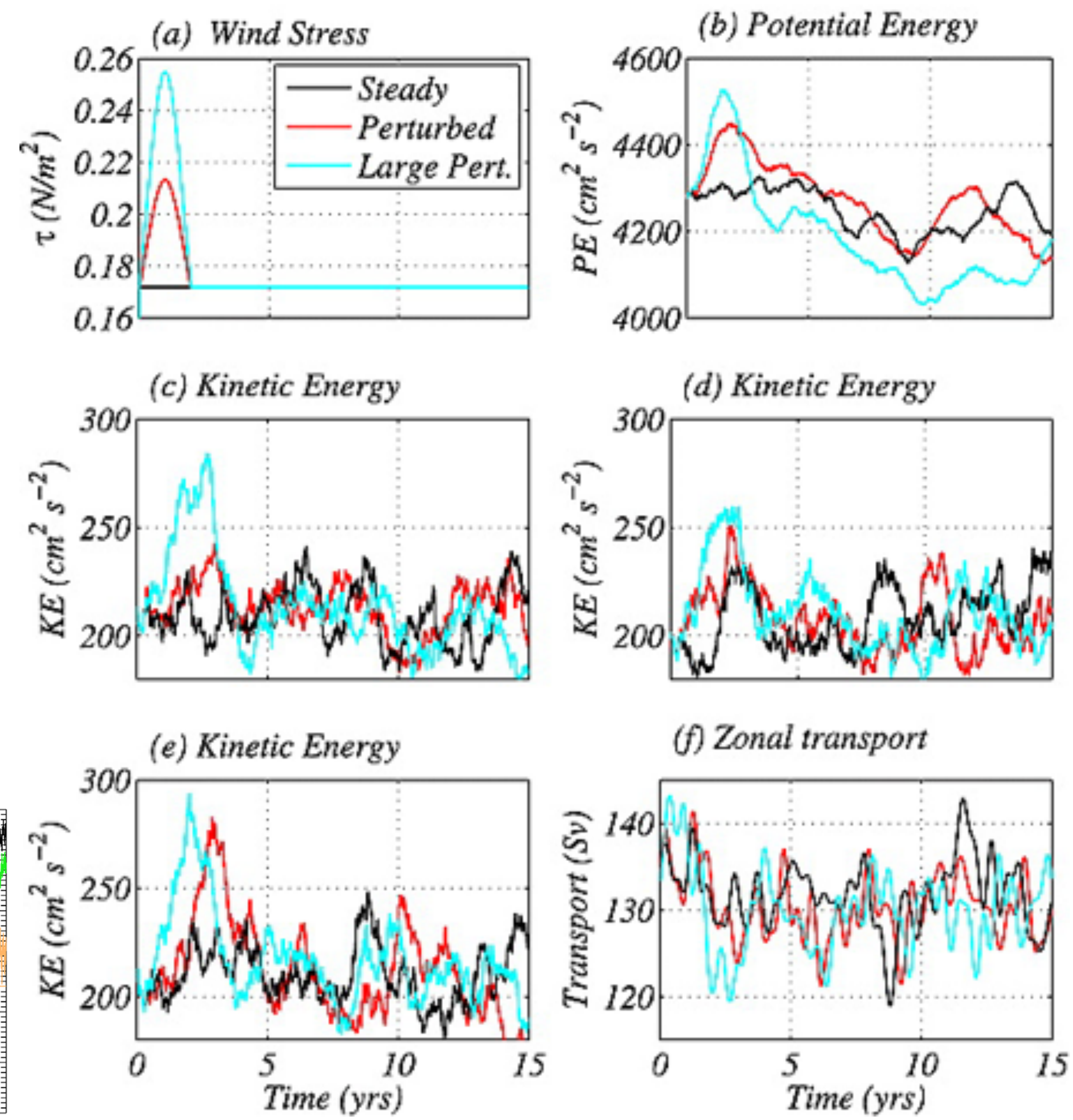


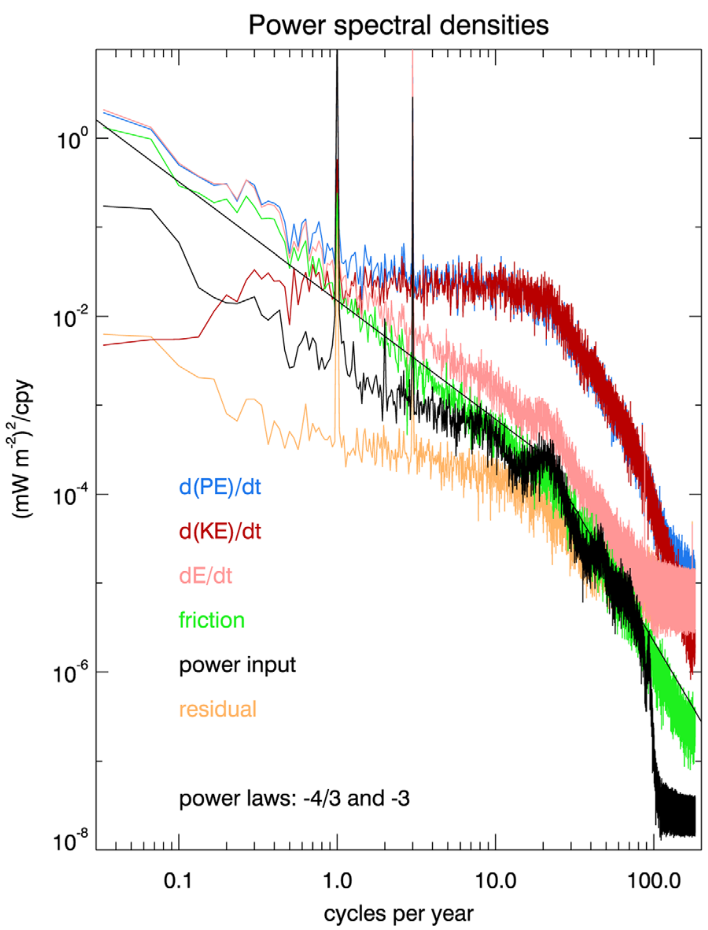


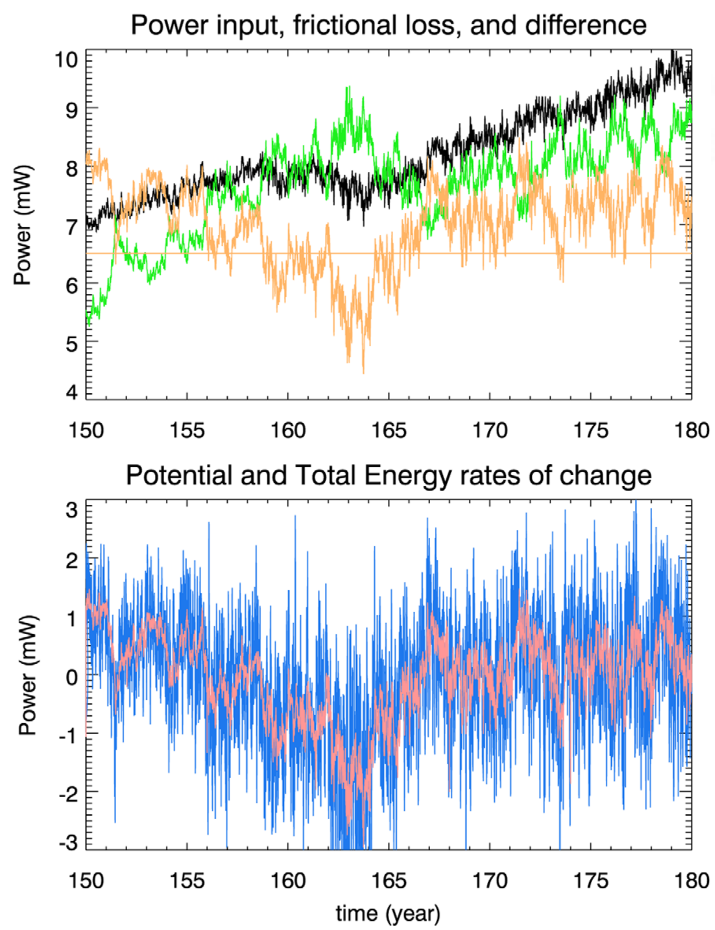


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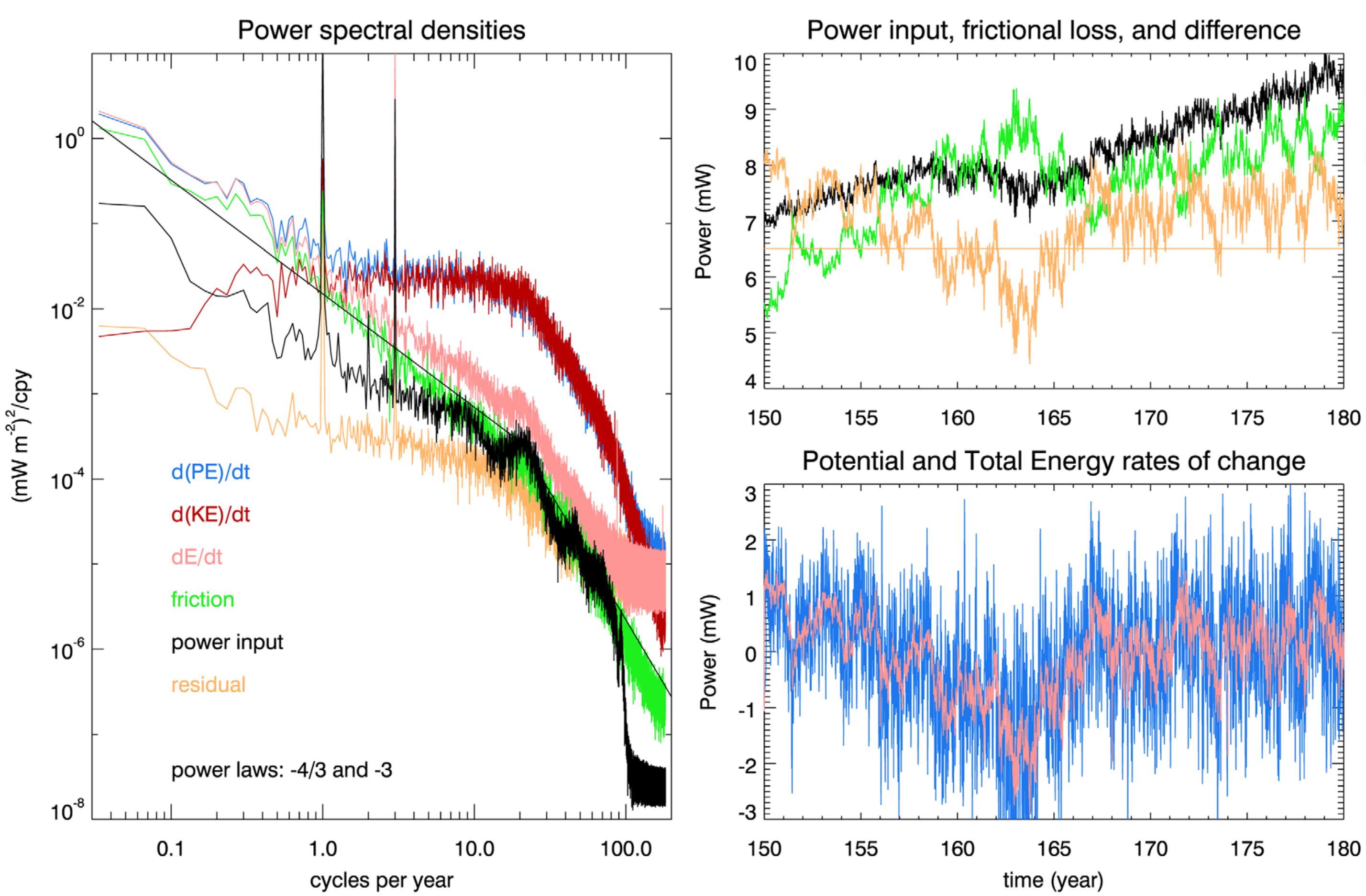
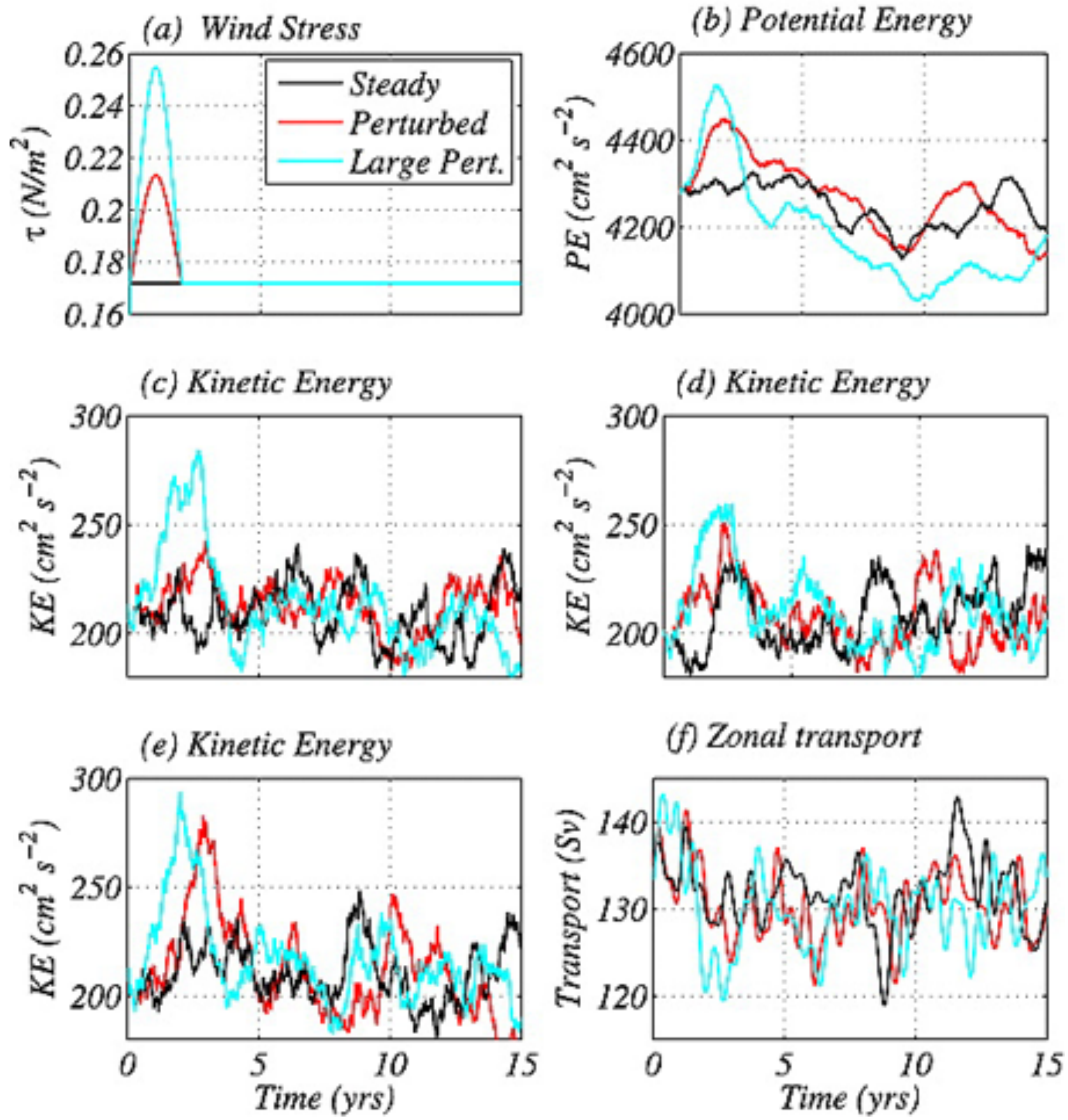
$$W + B_{ML} = \frac{d}{dt}(PE) + \frac{d}{dt}(KE) + D + V$$

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- **Treguier et. al. (2010):** response to increase in SAM in eddy permitting model

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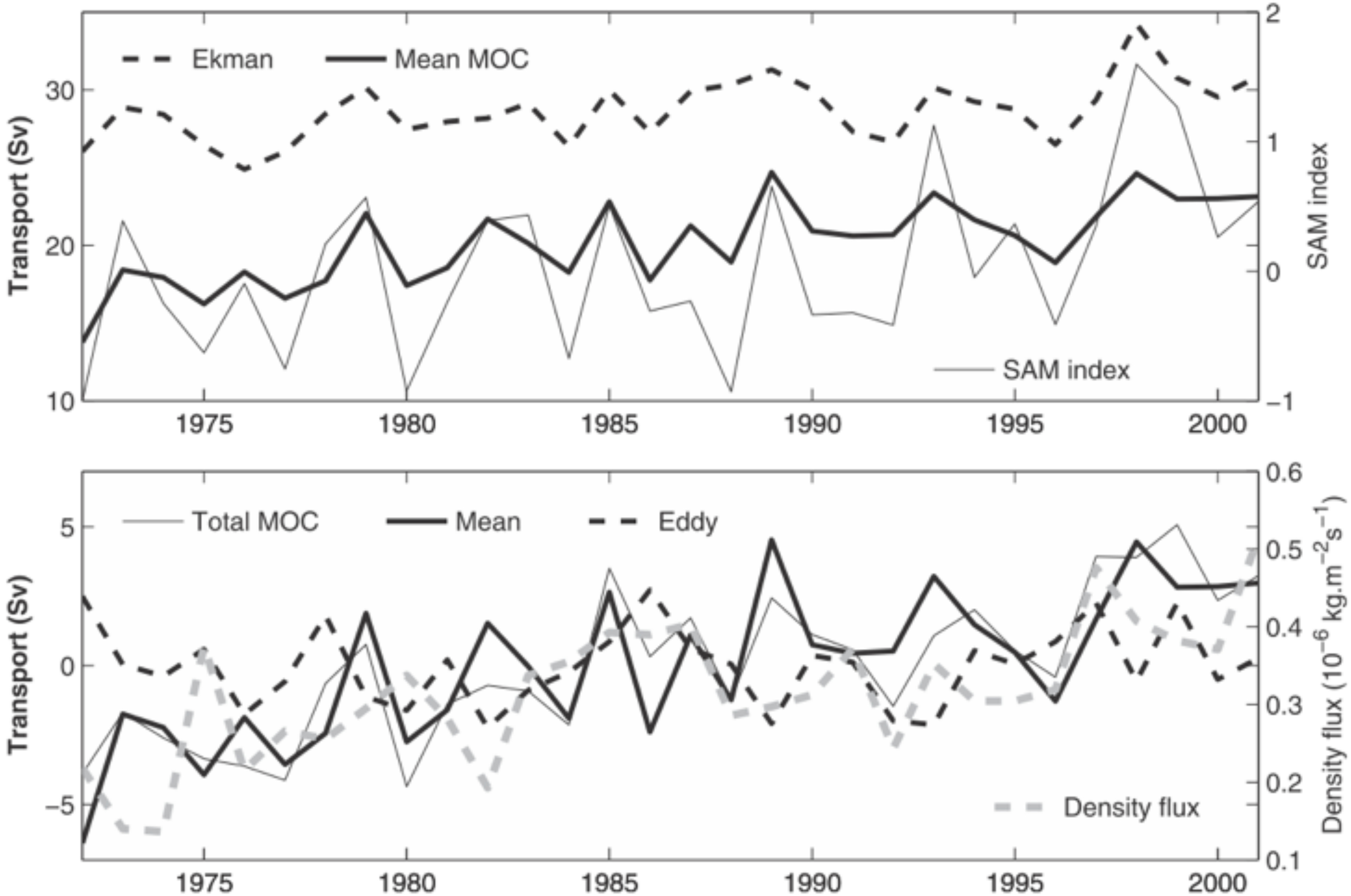
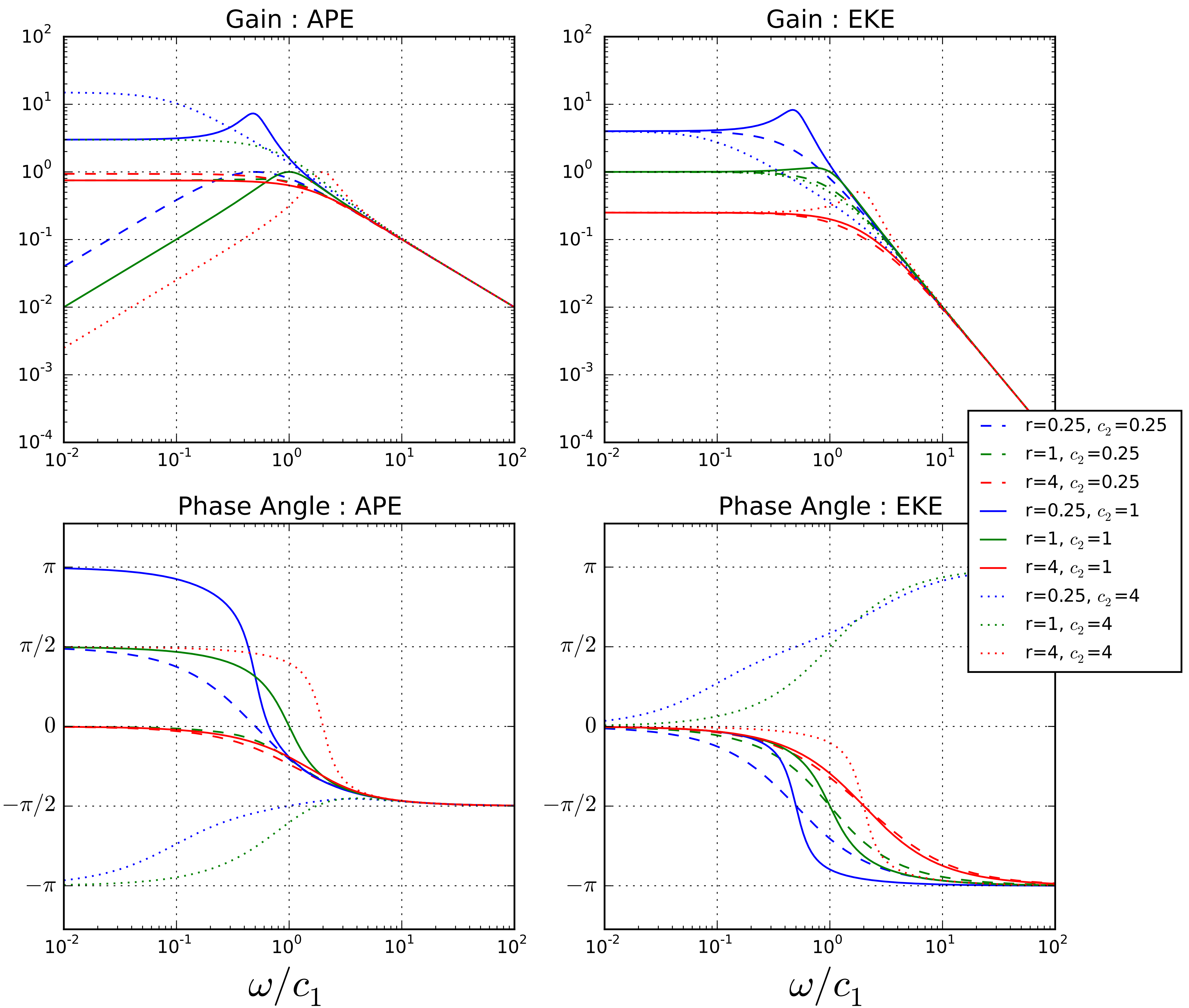
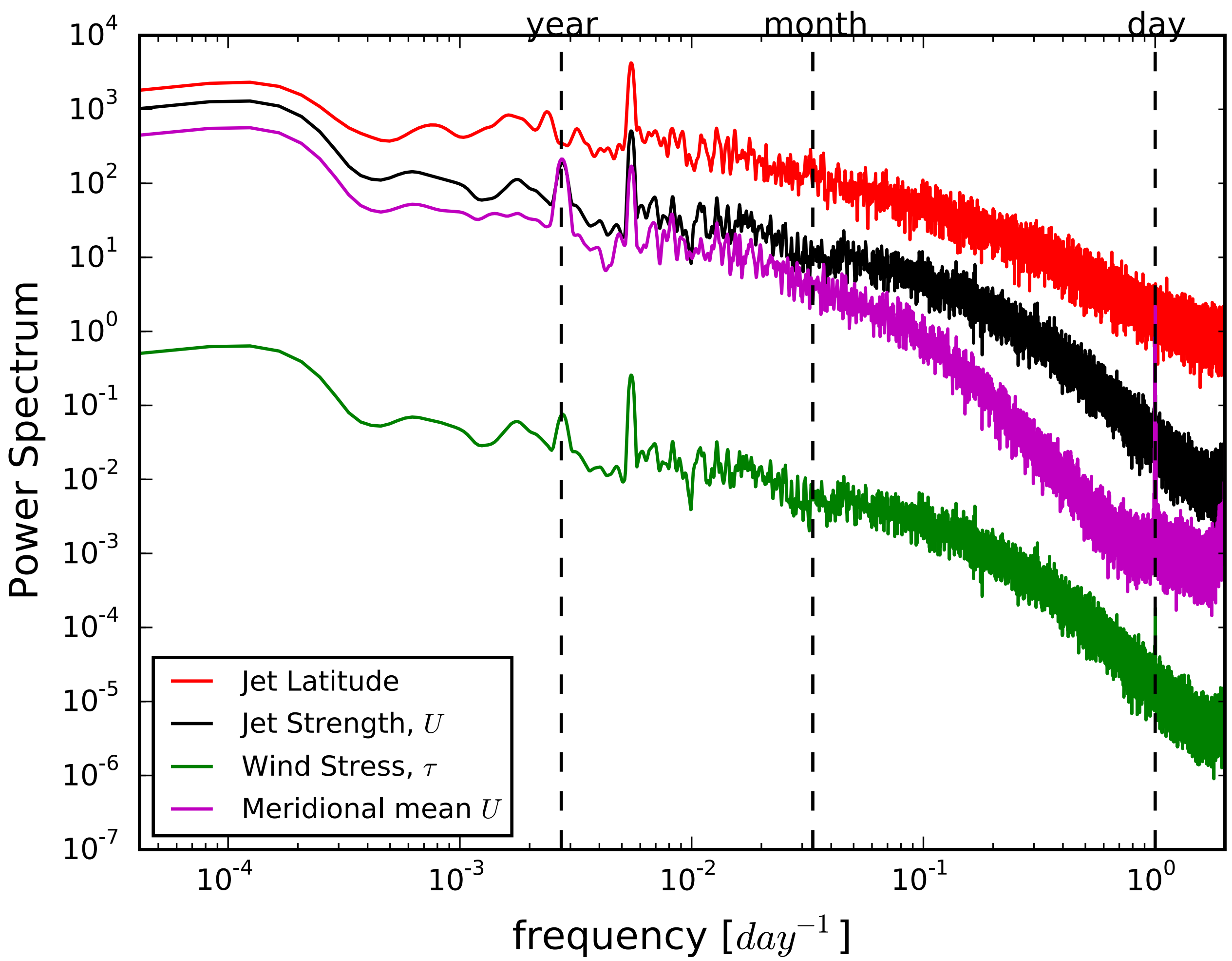


# Simple model with Eddy Feedback

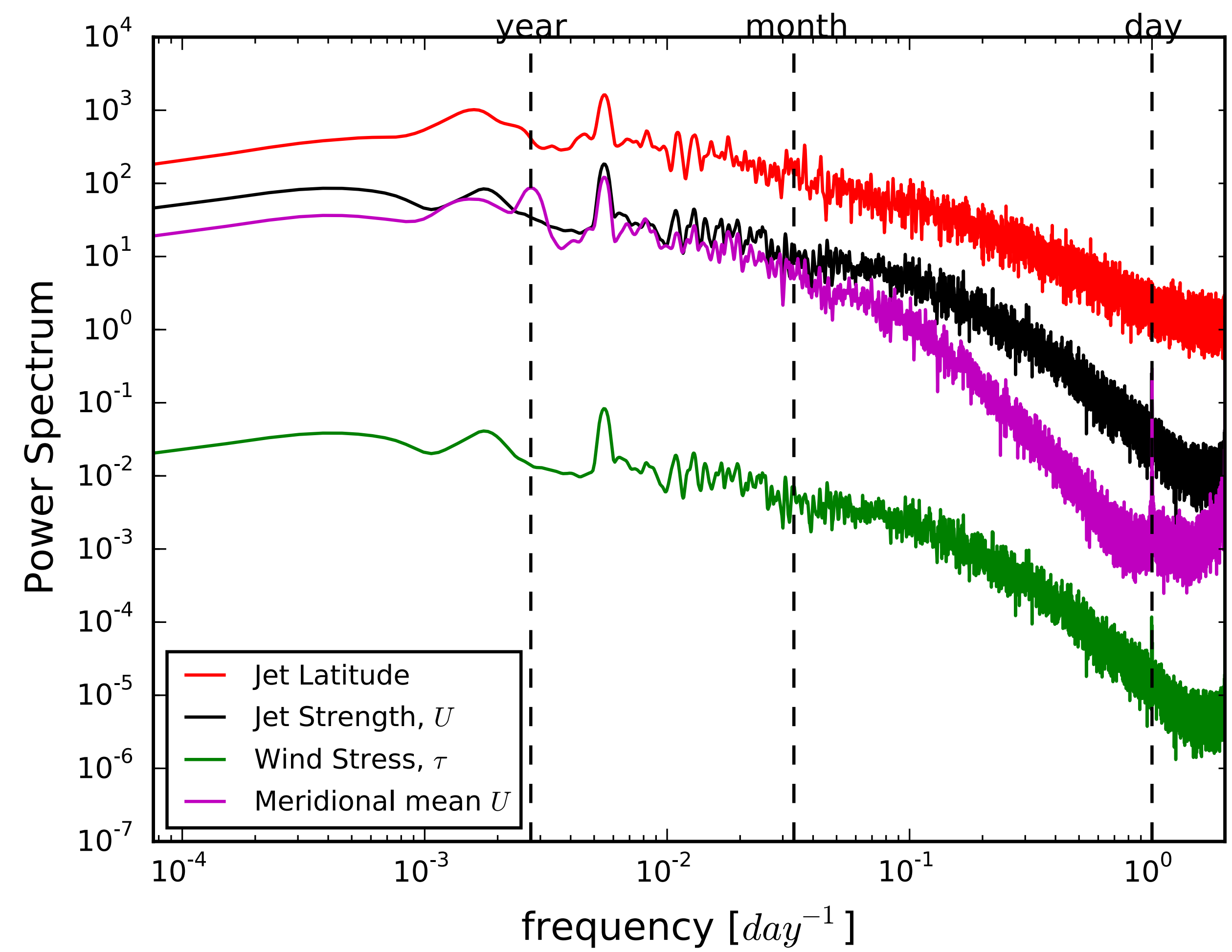


# Power Spectra of Winds

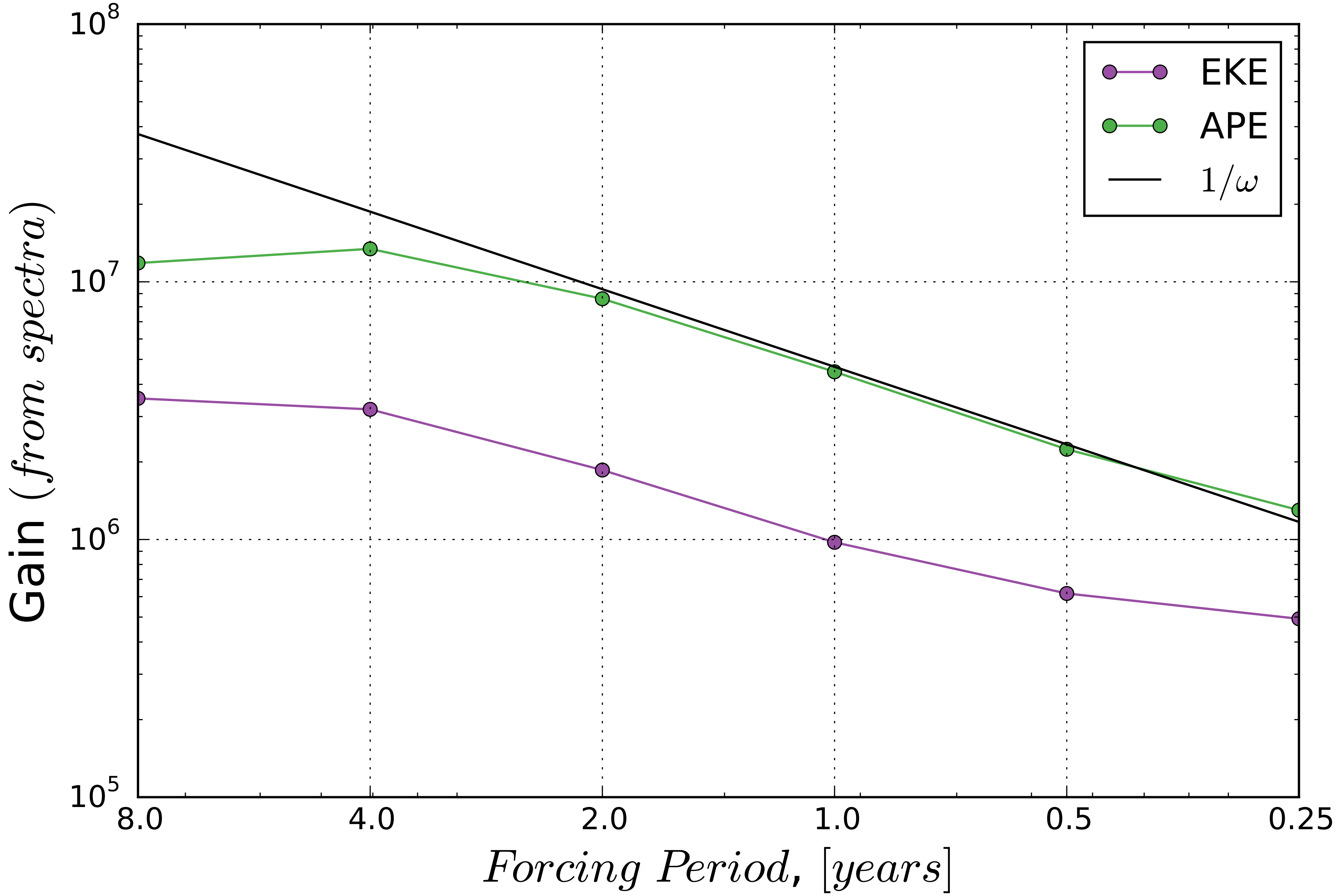
## NCAR Reanalysis



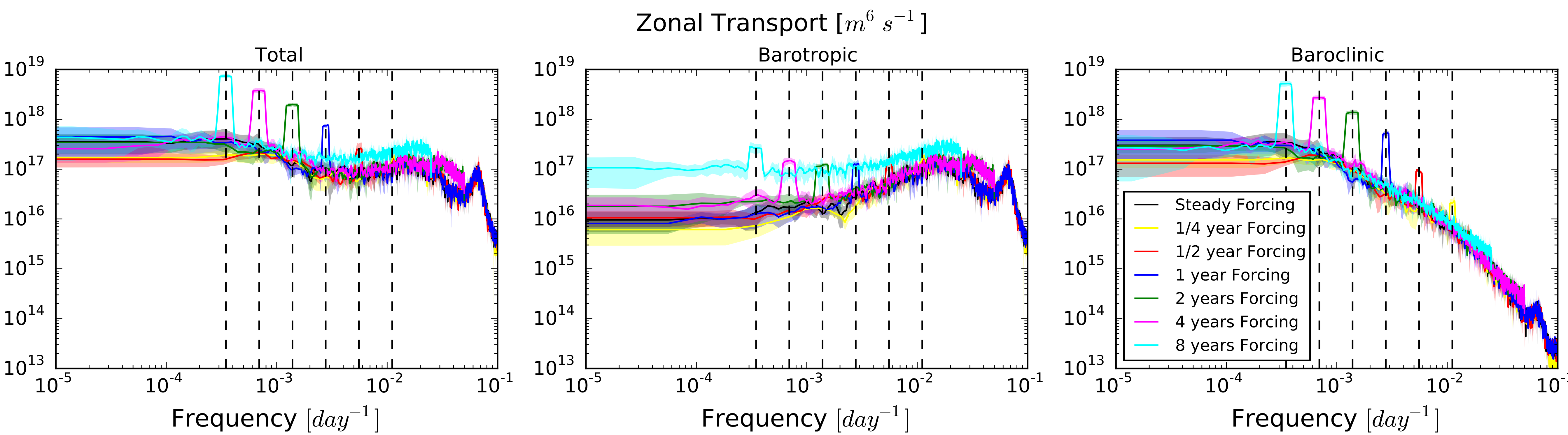

## ERA Interim



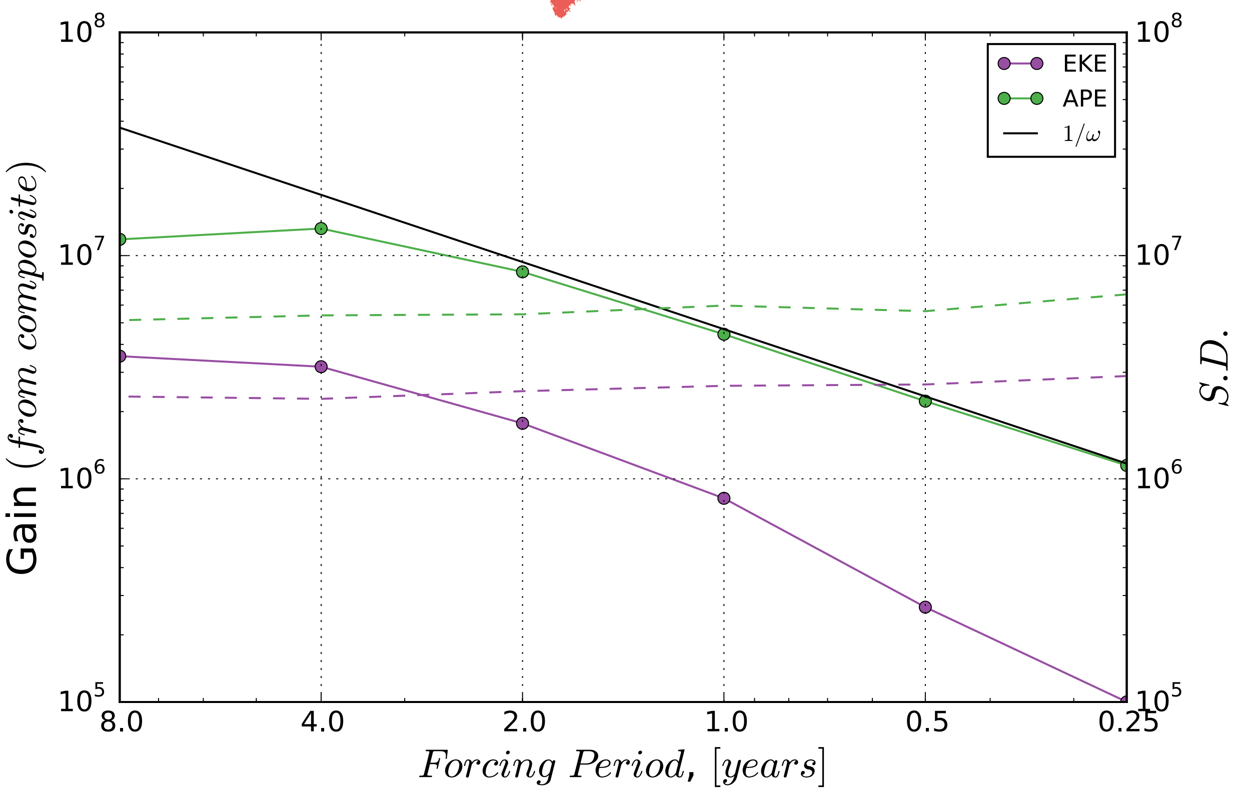
# Spectral
## Amplitude Response

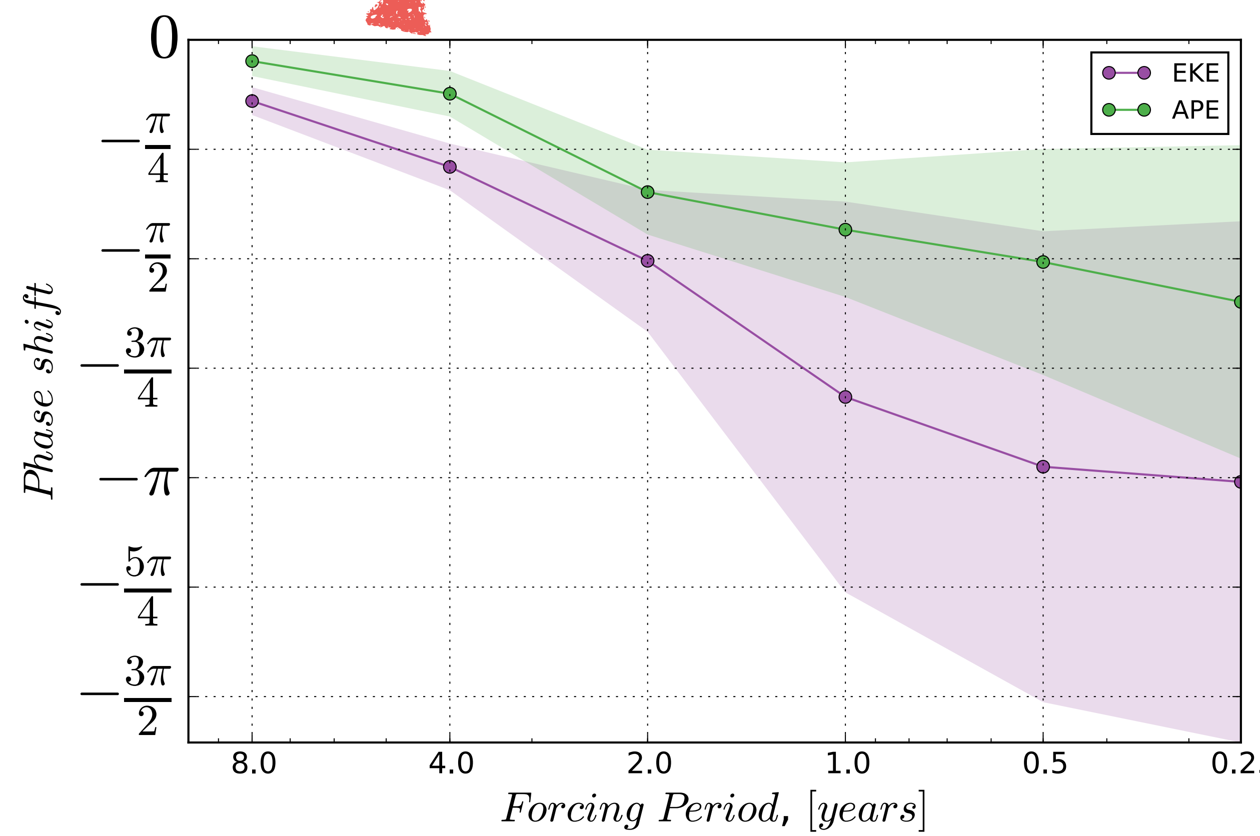


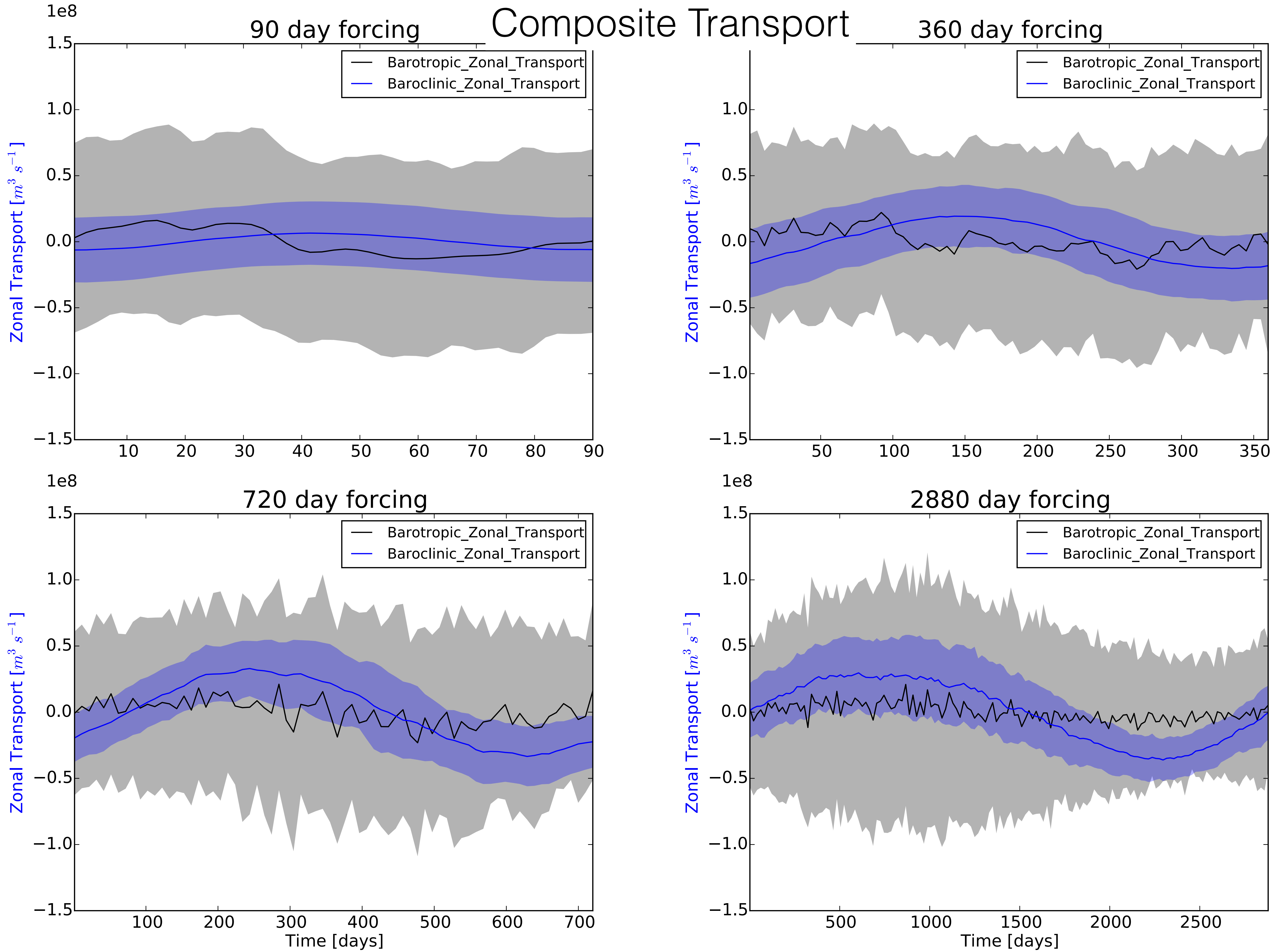
# Transport Spectra



# Amplitude and Phase from Composite




Composite Transport
90 day forcing
360 day forcing
720 day forcing
2880 day forcing
1e8
Barotropic_Zonal_Transport
Baroclinic_Zonal_Transport
Zonal Transport [$m^3\ s^{-1}$]
Time [days]