Energetics of the Ocean Surface at Low Frequencies in GFDL's CM2-O Model Hierarchy.

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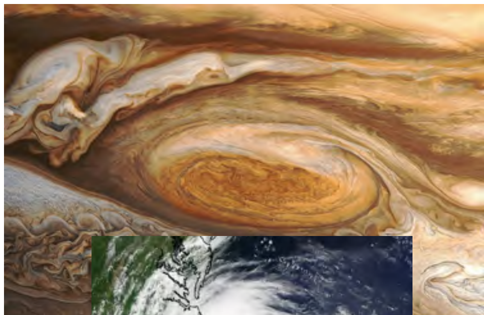
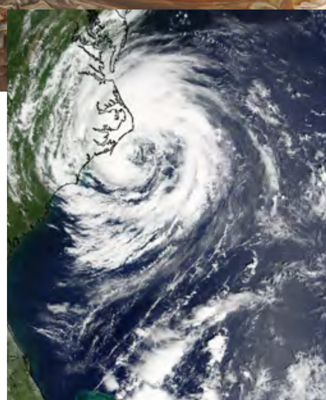
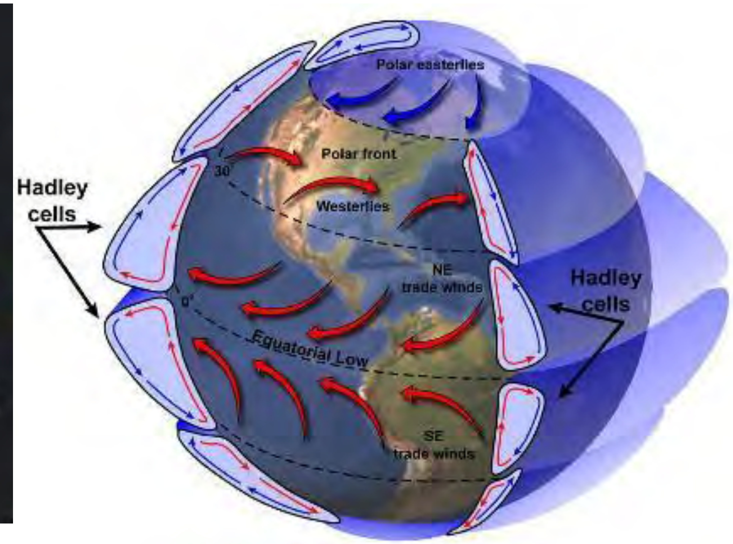
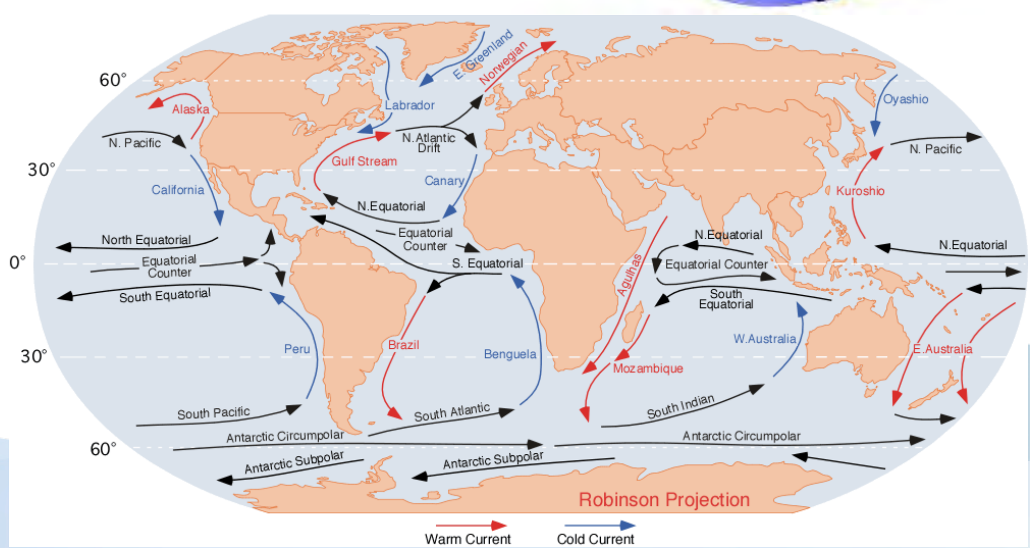
From Eddies to Climate

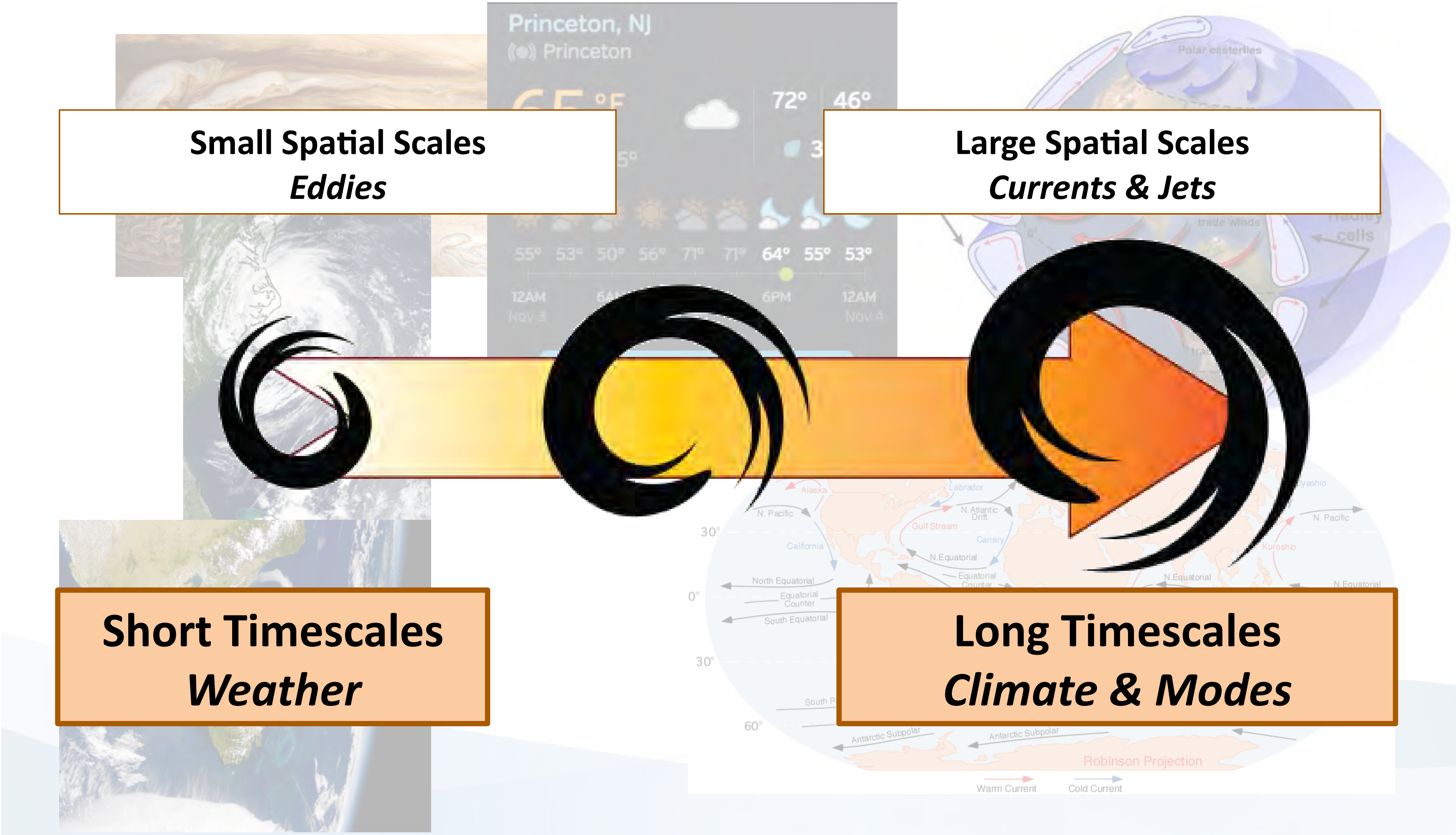








From Eddies to Climate



Small Spatial Scales
Eddies

Large Spatial Scales
Currents & Jets

Short Timescales
Weather

Long Timescales
Climate & Modes

GFDL CM2-O Model Suite

- Hierarchy of fully coupled GCMs with three horizontal ocean resolutions
  - Constant 1990 radiative forcing
  - 20 years analyzed

CM2-1deg	CM2.5	CM2.6
1.0° Ocean 50 vertical levels + 0.33° Equatorial waveguide + Mesoscale eddy param. for tracer budgets (Dunne et al 2012)	**0.25° Ocean** 50 vertical levels - No mesoscale eddy parameterization in tracer equations	**0.10° Ocean** 50 vertical levels -No mesoscale eddy parameterization in tracer equations
50km Atmosphere Identical Land + Sea Ice configurations (Delworth et al. 2012)	50km Atmosphere Identical Land + Sea Ice configurations (Delworth et al. 2012)	50km Atmosphere Identical Land + Sea Ice configurations (Delworth et al. 2012)

Griffies et al 2015

Additional Project with CM2-0

- CM2.5 Development
  - Delworth et al. 2012 (J. Climate)
- Climate Sensitivity
  - Winton et al. 2014 (GRL)
- Ocean heat drift
  - Griffies et al. 2015 (J. Climate)
- Cross frontal transport in Southern Ocean
  - Doufour et al. 2015 (JPO)
- Northwest Atlantic shelf warming
  - Saba et al. 2015 (JGR-Oceans)
- Agulhas mass transport
  - Biastoch et al. 2015 (Nature Communications)
- Patterns of heat uptake in Southern Ocean
  - Morrison et al. 2015 (Accepted to J. Climate)

- Plus more to be submitted!

Ocean Eddies, Kinetic Energy, and Frequency

- Can nonlinearity drive energy between frequencies in an analogous manner to the **inverse cascade** in wavenumber space?
  - High frequency to low frequency?

Ocean Eddies, Kinetic Energy, and Frequency

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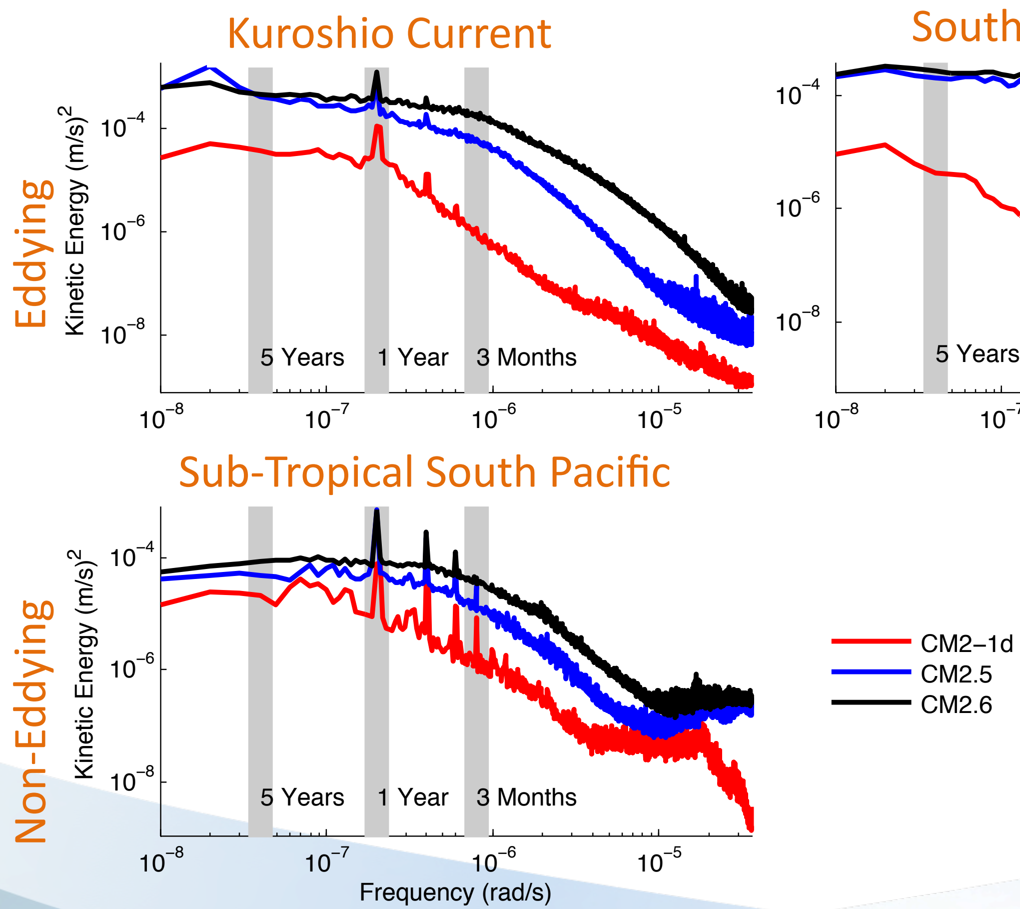
  - High frequency to low frequency?
- Is variability **internally or externally driven**?
  - Eddy-eddy interaction or externally wind driven?

Ocean Eddies, Kinetic Energy, and Frequency

- Can nonlinearity drive energy between frequencies in an analogous manner to the inverse cascade in wavenumber space?
  - High frequency to low frequency?
- Is variability internally or externally driven?
  - Eddy-eddy interaction or externally wind driven?
- How does **model resolution** influence the energy budget at **low frequencies**?
  - Do resolved eddies at high frequencies change energy contributions to low frequencies?

Energy in Frequency Across Models



- Basin averaged 20 year geostrophic kinetic energy spectrum
- Highest energy in eddying regions of higher resolution model
- CM2.6 and CM2.5 similar behavior, significantly different than CM2-1d

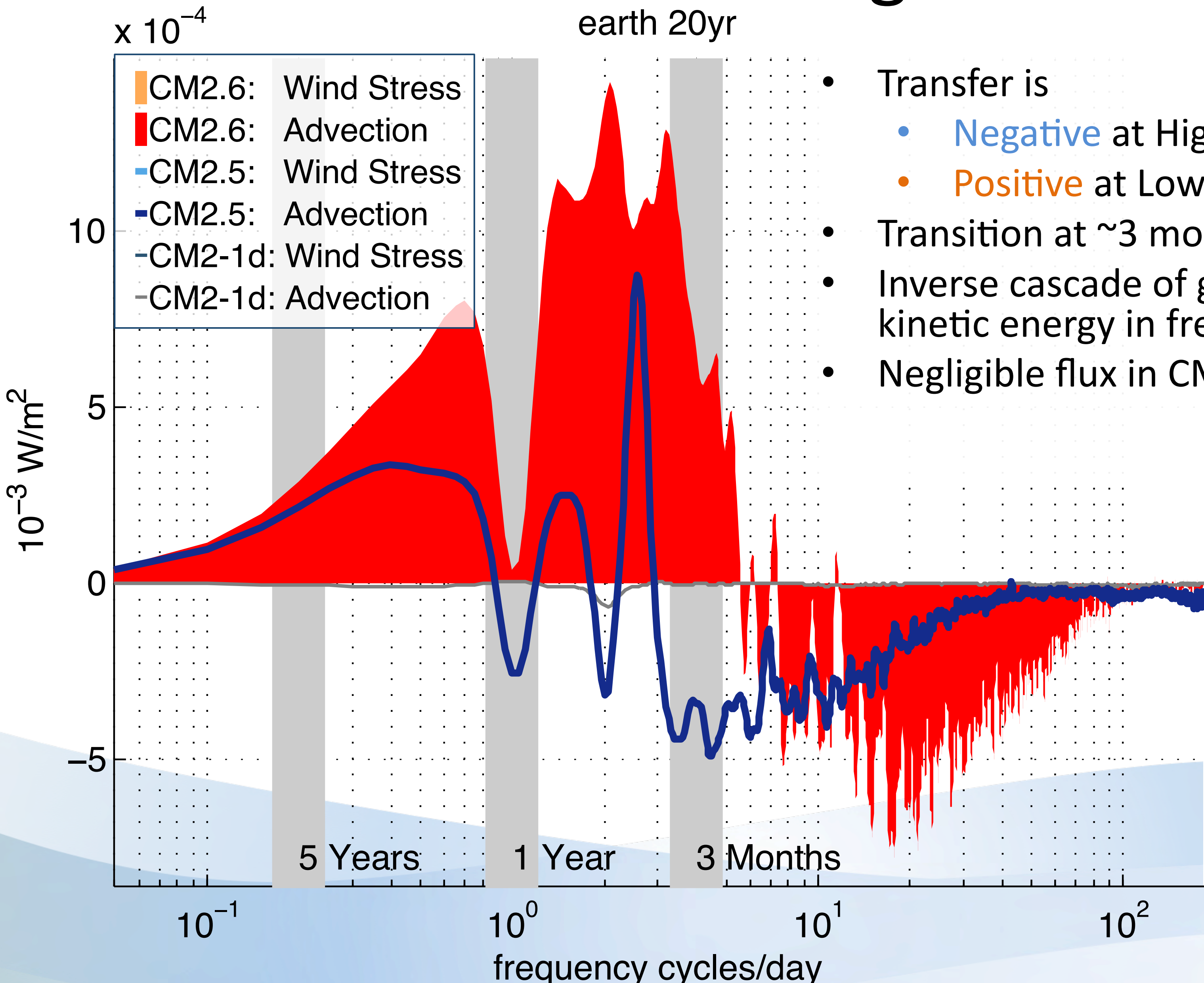
Transfer Equations

- Geostrophic kinetic energy equation, simplified:

$$\frac{\partial \mathrm{KE}}{\partial t} = -\boxed{(\rho H)\,\vec{u}\cdot\nabla\vec{u}} + \boxed{\vec{u}\cdot\vec{\tau}} + \mathrm{PE}_{con} + \mathrm{Drag} + \mathrm{Adtl.\ \ Sources}$$

- Transfers obtained via cross spectrum analysis (Arbic et al. 2014)
  - Transfers are the product of two spectral fields, such as
    - Advective ("Nonlinear") Term: $T_A = -\Re\left[\widehat{(\rho H\vec{u})}\cdot\widehat{(\vec{u}\cdot\nabla\vec{u})}^*\right]$
    - Wind Stress Term: $T_W = \Re\left[\hat{\vec{u}}\cdot\widehat{\vec{\tau}}^*\right]$
- This spectral transfer diagnostic has been used in previous works including:
  - *Hayashi (1980)*, Salmon (1978, 1980), Hua and Haidvogel (1986), Larichev and Held (1995), LaCase (1996)

Global Average



- Transfer is
  - Negative at High Frequency
  - Positive at Low Frequency
- Transition at ~3 months
- Inverse cascade of geostrophic kinetic energy in frequency
- Negligible flux in CM2-1d

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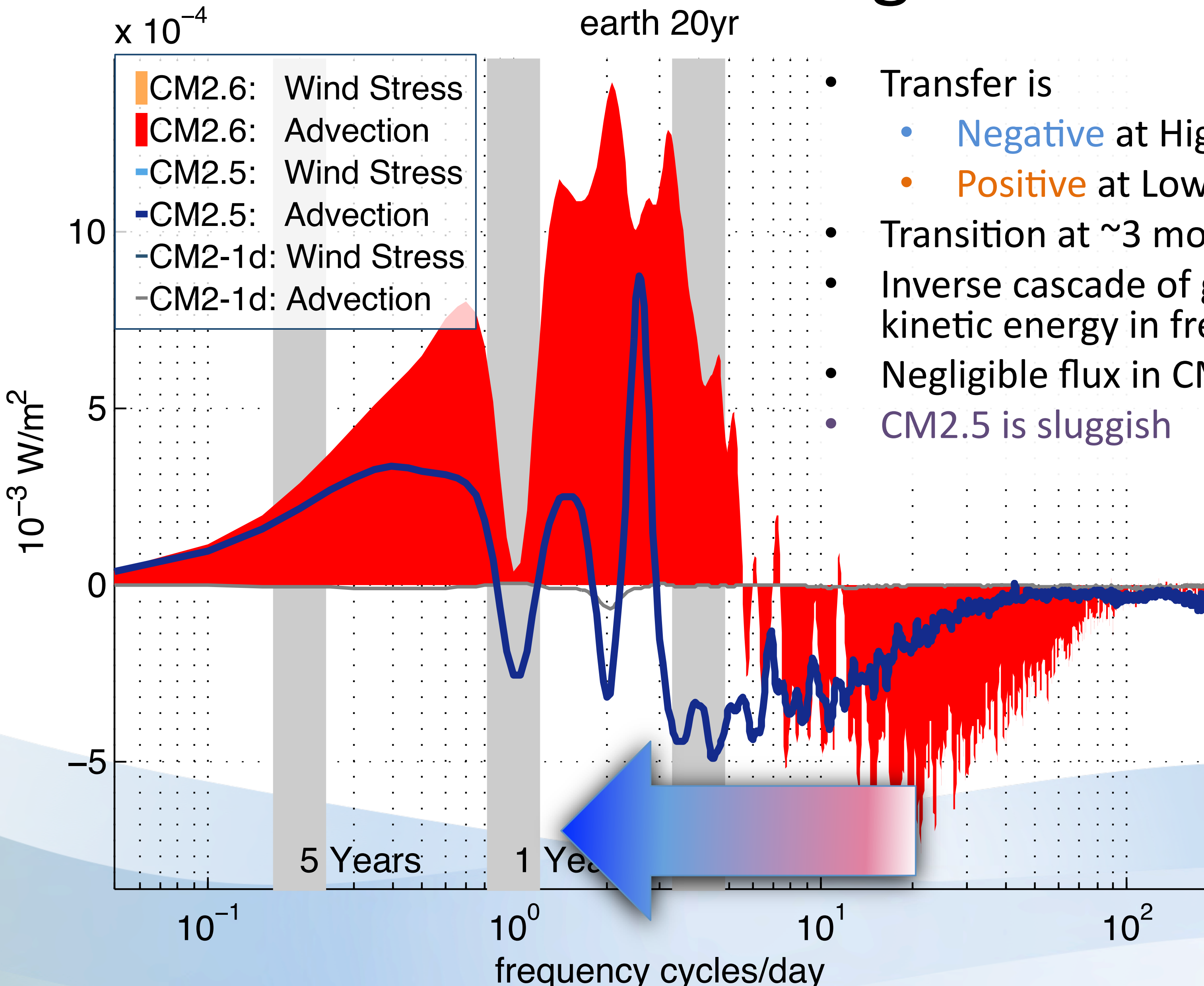

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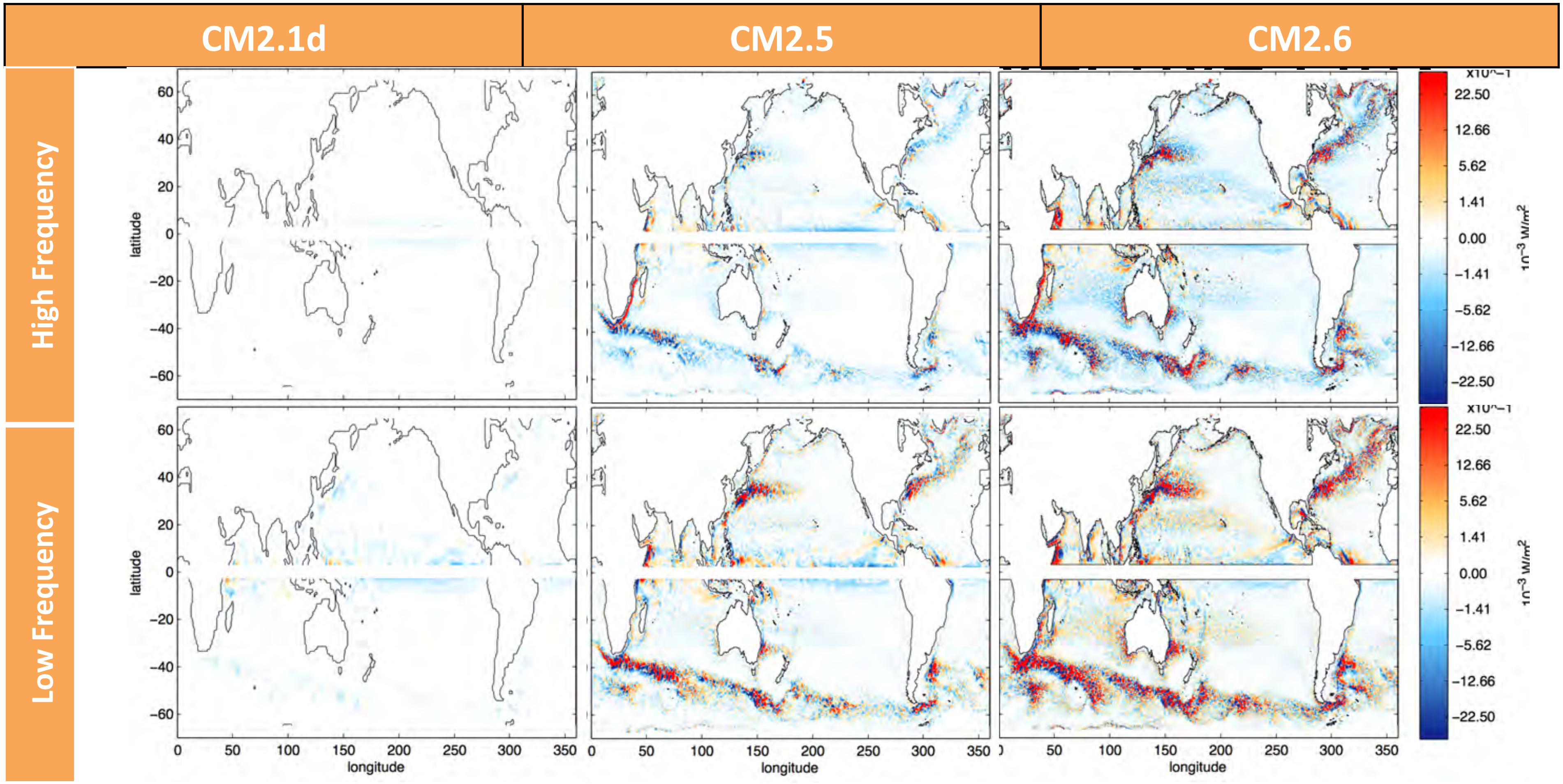
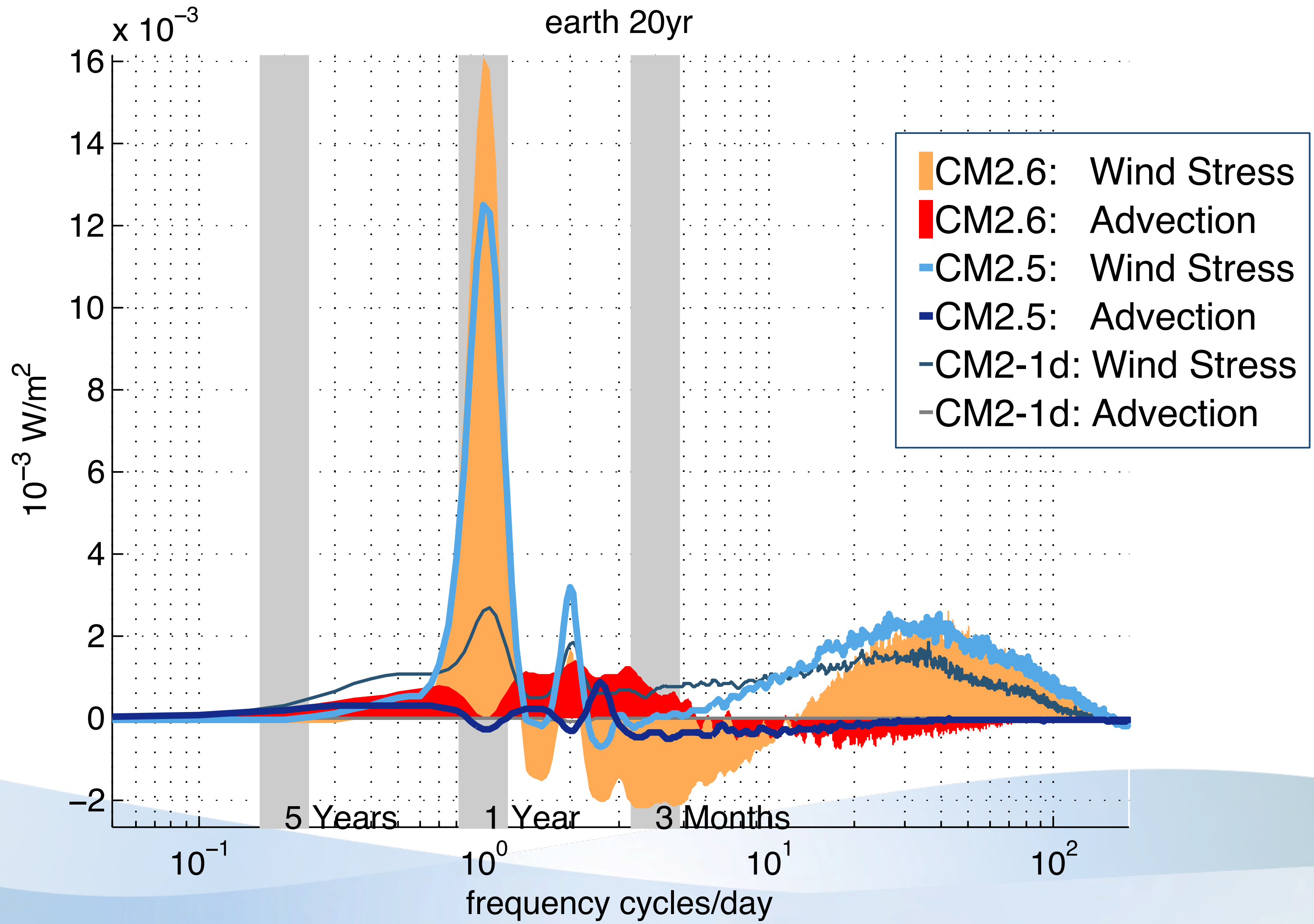
- CM2.5 is sluggish

Global Geostrophic Advective Flux

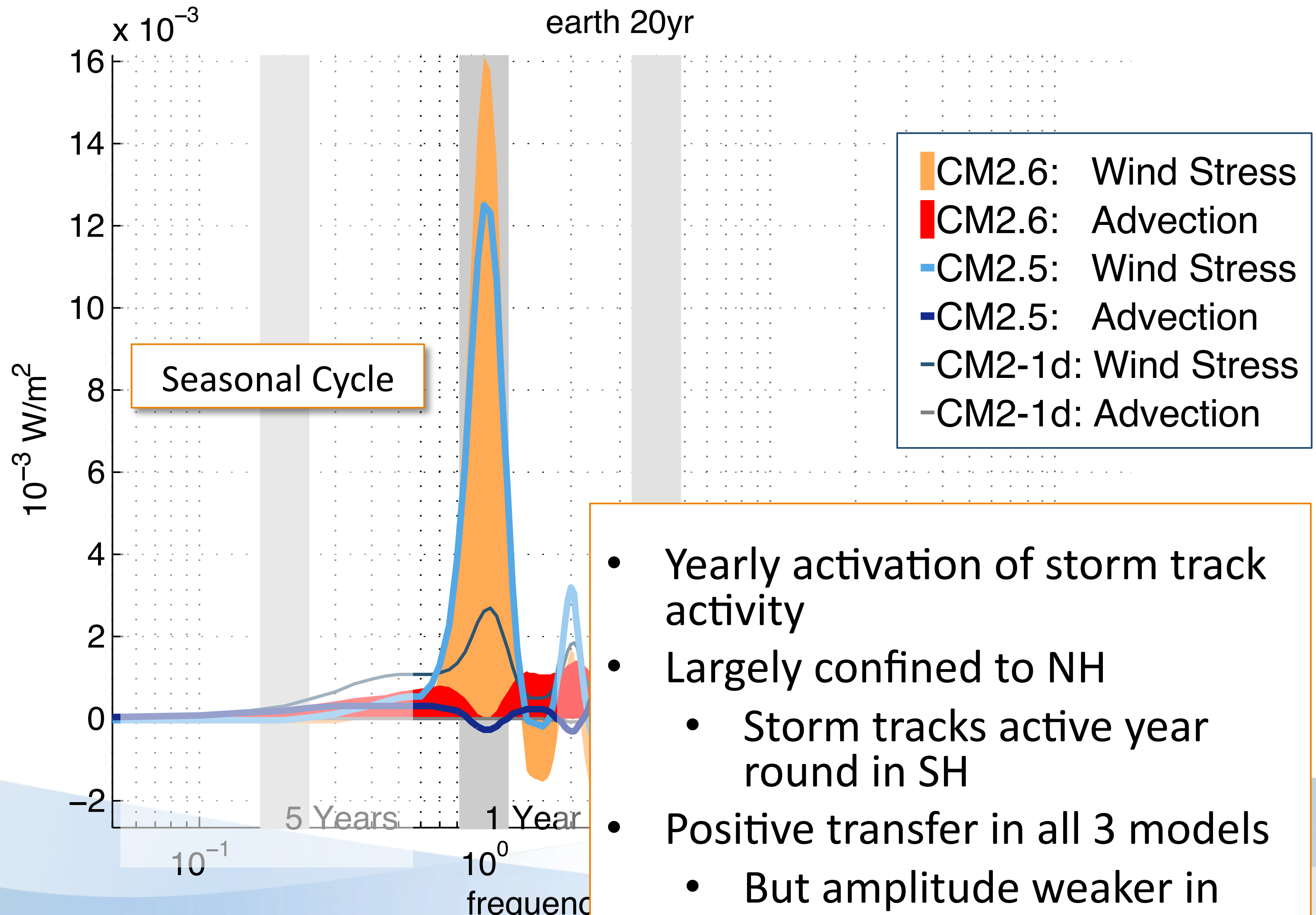


- Very little activity in CM2-1d
  - Unable to represent eddy fields except in the very near tropics
  - Boundary currents only appear at low frequencies
- Positive Flux at Low/Negative at High
  - Consistent in CM2.5 and CM2.6
- CM2.6 capturing high frequency fluxes
  - More energetic overall

Global Average: Adding Wind Stress

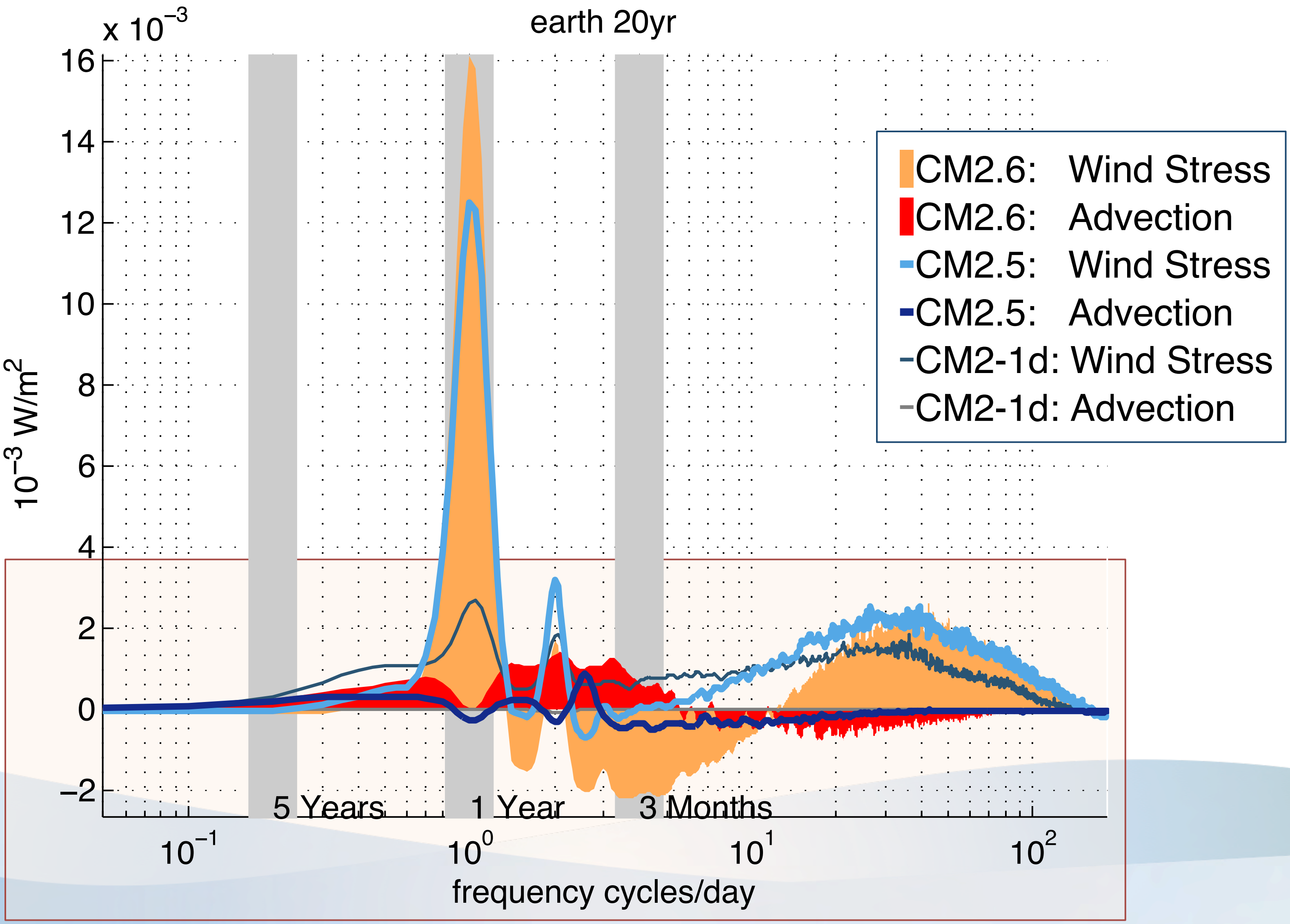


Global Average: Adding Wind Stress



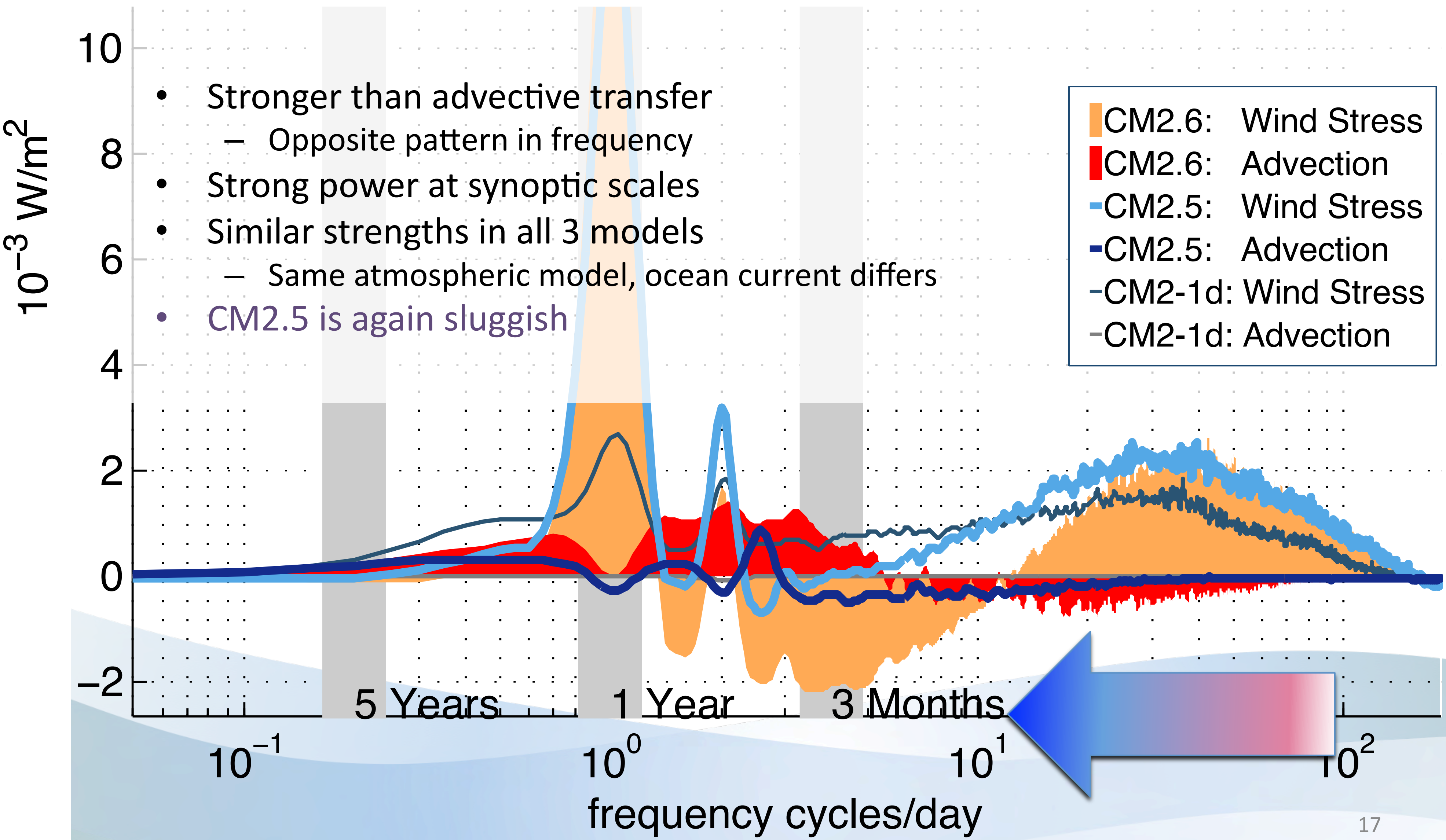
- Yearly activation of storm track activity
- Largely confined to NH
  - Storm tracks active year round in SH
- Positive transfer in all 3 models
  - But amplitude weaker in lower resolution

Global Average: Adding Wind Stress

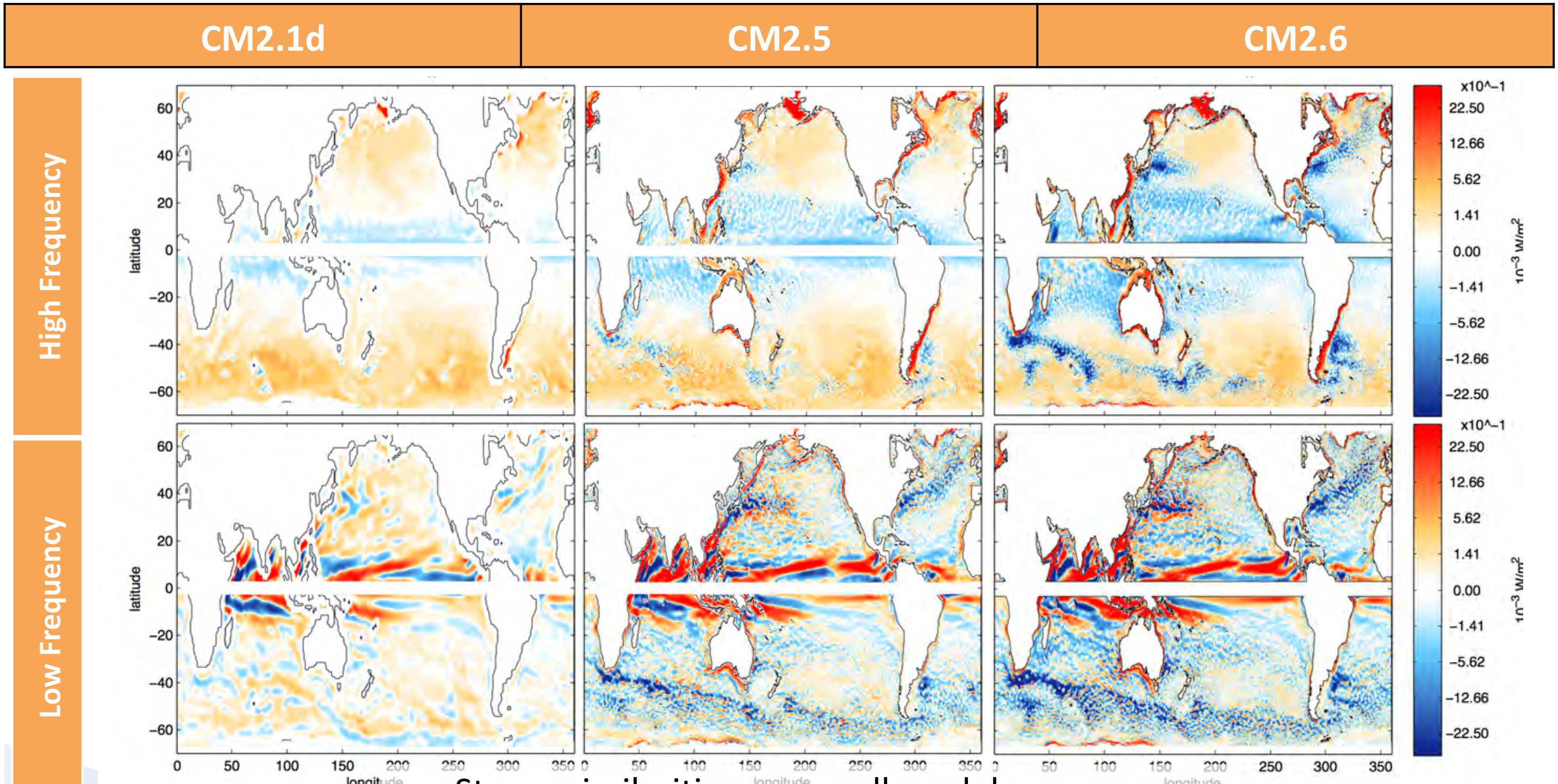


Global Average: Adding Wind Stress

- Stronger than advective transfer
  - Opposite pattern in frequency
- Strong power at synoptic scales
- Similar strengths in all 3 models
  - Same atmospheric model, ocean current differs
- CM2.5 is again sluggish



Global Wind Stress Flux



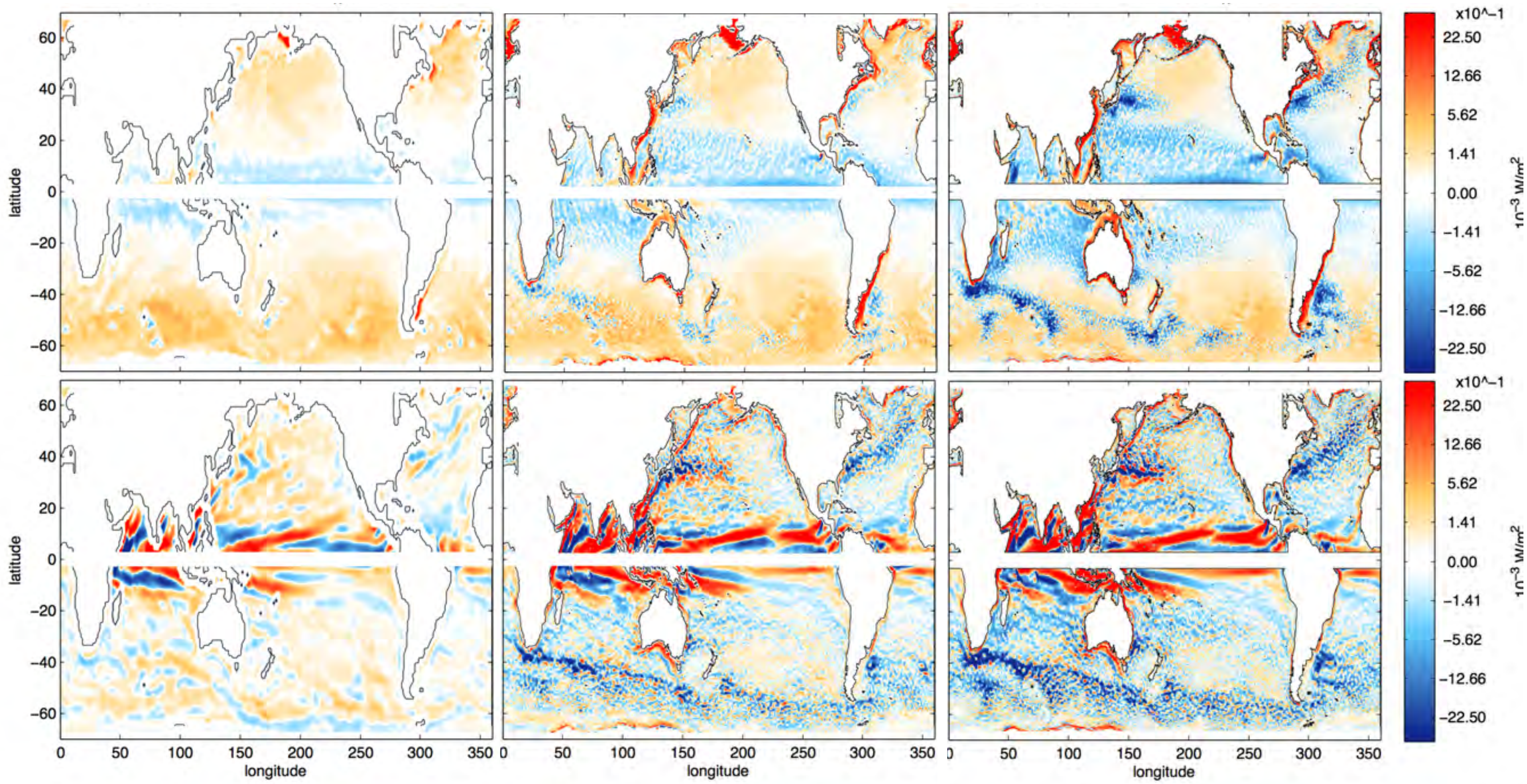
- Strong similarities across all models
  - Same atmosphere
  - Differences from ocean *u*
- Low Frequency Tropics
- High Frequency Storm Tracks/Westerlies

Global Wind Stress Flux

CM2.1d	CM2.5	CM2.6

High Frequency

Low Frequency



- Negative flux in eddying regions
    - Atmosphere damping eddies?
- Time Anomalous Fields
    - Small correction to largely positive wind power input due to time mean circulation

Eddies in the Ocean

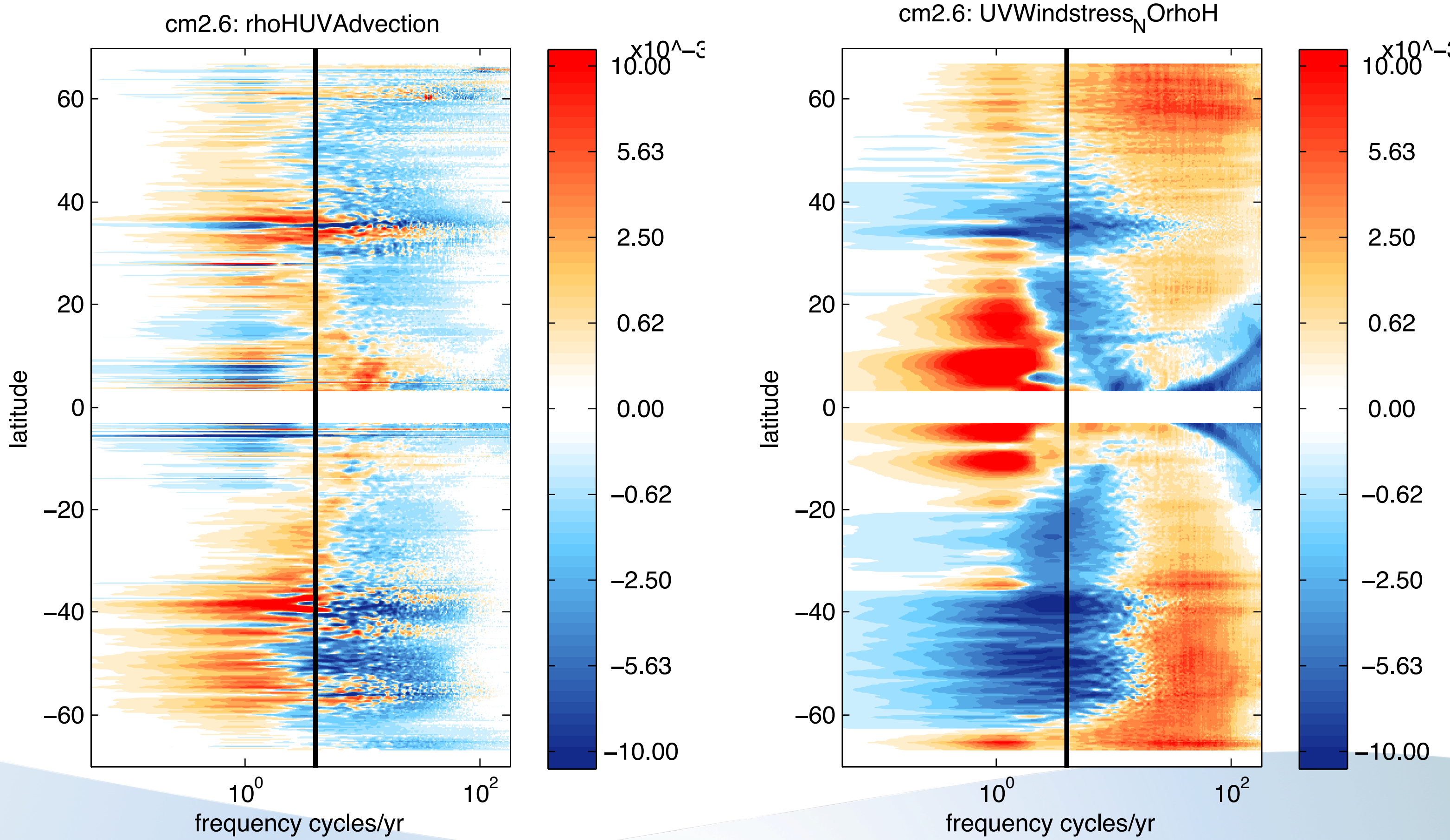
- **Advection transfer term** extracts geostrophic kinetic energy out of high frequencies and supplies it to low frequencies
  - Apparent in spatial average over eddying regions
- **Wind stress transfer term** is of similar, but often larger, magnitude than that of the advective transfer term
  - Strongest wind stress transfer at yearly and synoptic timescales

- Transfer source/sink centers shifted to lower frequencies in CM2.5 compared to CM2.6
- Very little advective transfer in CM2-1d
  - CM2-1d is wind driven
- Strong regional dependence
  - Advection term primarily active in eddying regions
  - Wind stress tendencies strongly dependent on mean wind circulation

Hierarchy and Climate

- Eddy interaction across spatial and temporal scales is one of the fundamental questions in climate science
- Increasing interest in the role of eddies in the large scale field parallels ever increasing model resolution
  - Inclusion of eddies can directly change not only the characteristic spatial scale of ocean dynamics, but may also impact the characteristic time scales
- Simplified models are still necessary to understand fundamental dynamics in both atmospheres and oceans
  - This study, for instance, will benefit from an ongoing work utilizing an idealized, geostrophic coupled model with graduate student Paige Martin

CM2.5 compared to CM2.6: Transition Period



Negative Wind Stress Transfer?

- One of the most curious points coming from this analysis is that the wind stress appears to extract kinetic energy, particularly at high frequencies within eddying regions
- Does this mean the ocean is forcing the atmosphere at these locations?
  - Not necessarily. Transfers don't indicate where energy is going or coming from in terms of the energy budget (KE -> PE?)
- How should the sign of this term be interpreted?

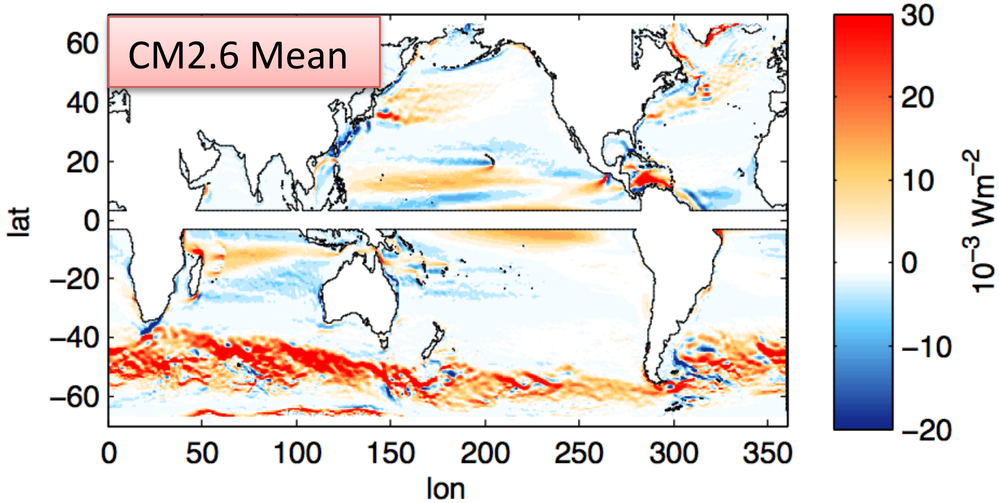
Negative Wind Stress Transfer?

- One important point to make is that this spectral transfer diagnostic involves the detrending and de-meaning of the wind stress field
  - We have removed the effect of the time mean winds, which is the greatest contribution to energy input into the ocean

- Parseval's Theorem: A physical check

$$\sum_{\omega_{\min}}^{\omega_{\max}} T_{a,b}(\omega) = \sum_{\omega_{\min}}^{\omega_{\max}} \Re\left[\hat{a}(\omega)\hat{b}^*(\omega)\right] = \overline{a(t)b(t)}^t$$

Mean Global Wind Stress Input



von Storch et al. (2007)
1/10° Coupled Model

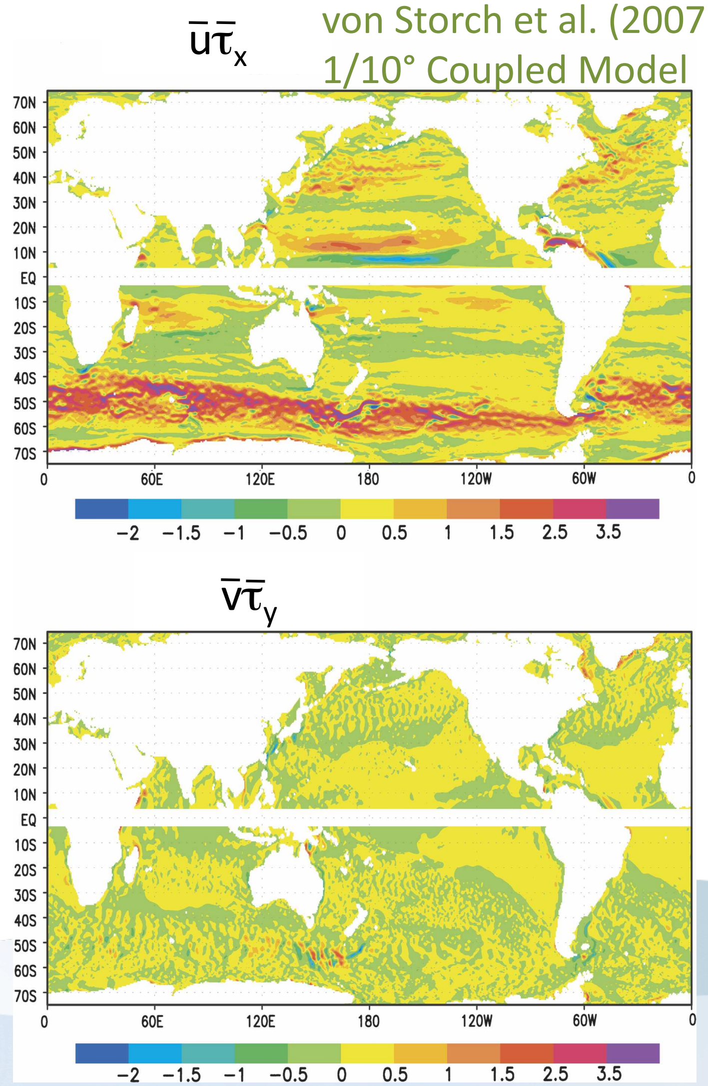
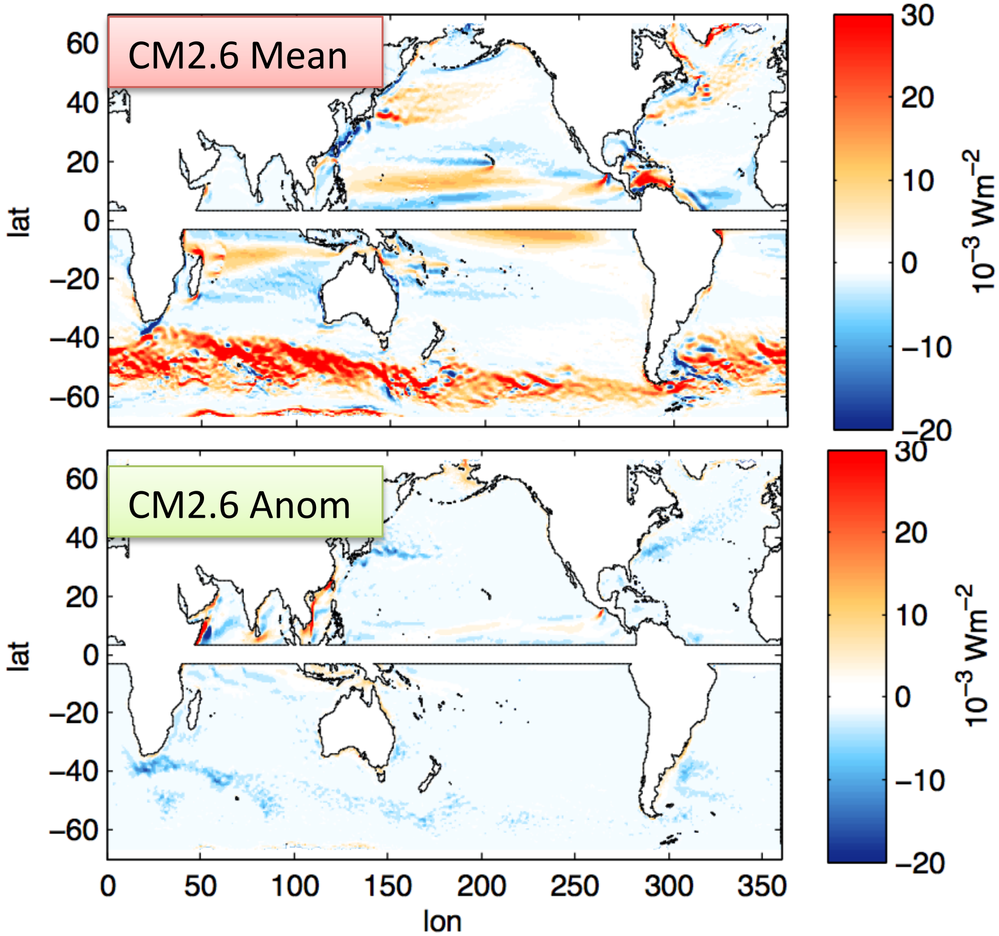


FIG. 1. Spatial distribution (10^{-3} W m^{-2}) of (a) $\overline{u_{g,\eta}}\,\overline{\tau_{s,x}}$ and (b) $\overline{v_{g,\eta}}\,\overline{\tau_{s,y}}$, where $u_{g,\eta}$ and $v_{g,\text{ets}}$ are zonal and meridional geostrophic velocities derived from the sea surface height and $\tau_{s,x}$ and $\tau_{s,y}$ are zonal and meridional wind stress. The equatorial region within ±3° is excluded from the calculation.

$$\overline{u\tau_x} + \overline{v\tau_y} = \overline{u}\,\overline{\tau_x} + \overline{v}\,\overline{\tau_y} + \overline{u'\tau_x'} + \overline{v'\tau_y'}$$

Time Varying Global Wind Stress Input



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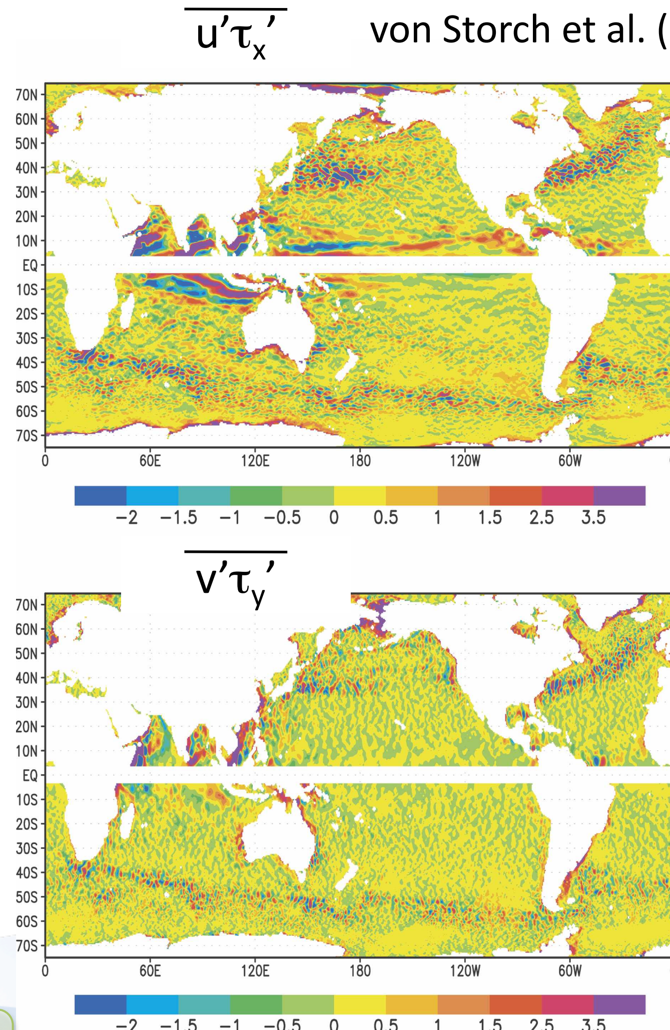
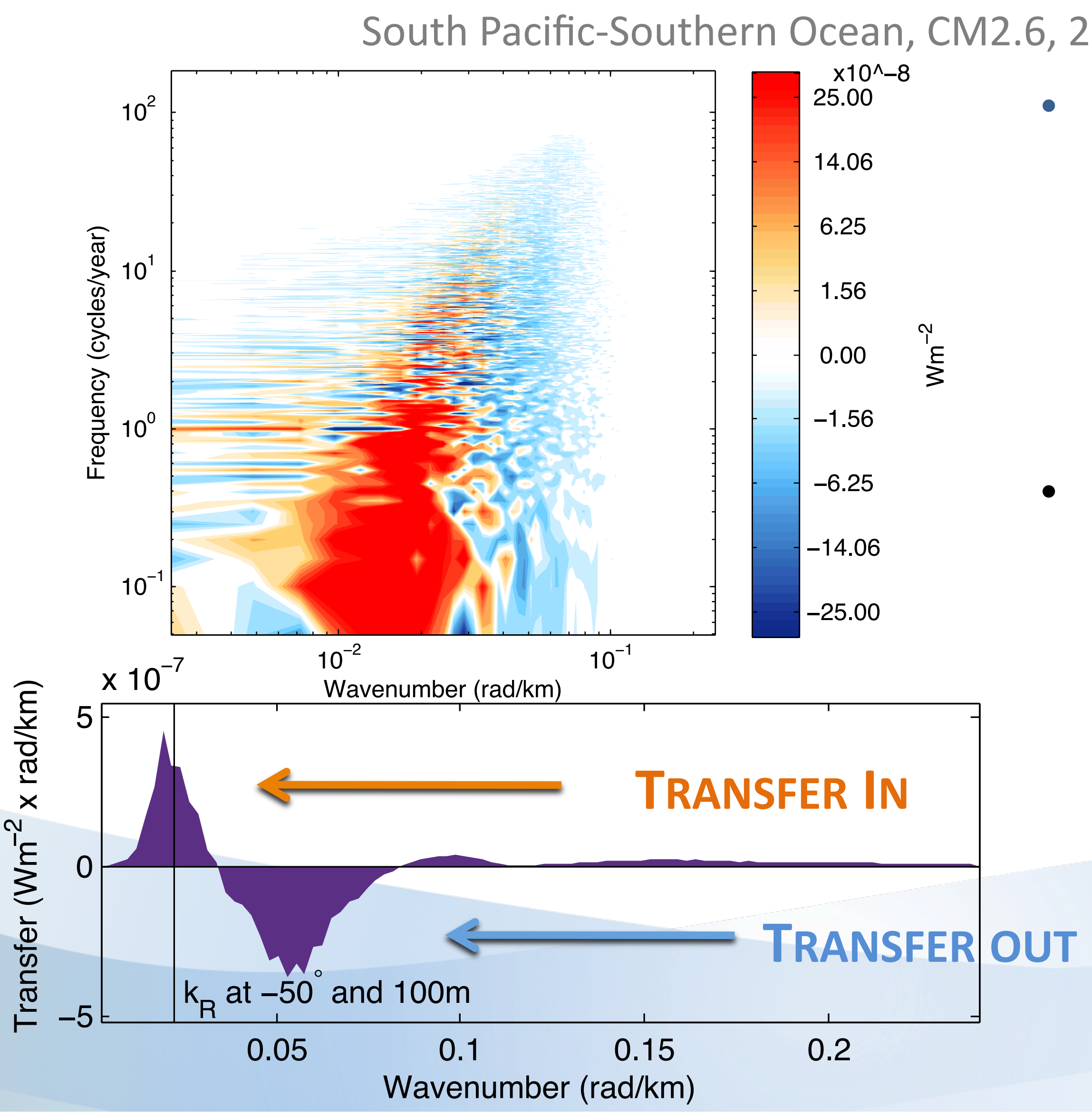


FIG. 2. As in Fig. 1, but for contributions from time-varying components (a) $\overline{u'_{g,\eta}\tau'_{s,x}}$ and (b) $\overline{v'_{g,\eta}\tau'_{s,y}}$.

$$\overline{u\tau_x} + \overline{v\tau_y} = \overline{u\tau_x} + \overline{v\tau_y} + \overline{u'\tau_x'} + \overline{v'\tau_y'}$$

Transfers in Wavenumber Space



- Negative (positive) transfers indicate sink (source) of energy at a given (k,ω) due to eddy-eddy interaction.
- Energy is extracted at small scales and supplied to large scales
  - A small amount of energy is supplied to very small scales.