The energy transports and the mid-latitudinal general circulation of the atmosphere

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Outline

- Energy sources, sinks and exchanges in the atmosphere;
- Lorenz Energy Cycle: the “work” made by mid-latitudinal eddies;
- Enthalpy and dry/moist static energy;
- The role of eddies at different scales;
- Extreme transports: why they are relevant;
- Preferred weather regimes for extreme heat transports;

Global-scale Energy Exchanges in the Atmosphere

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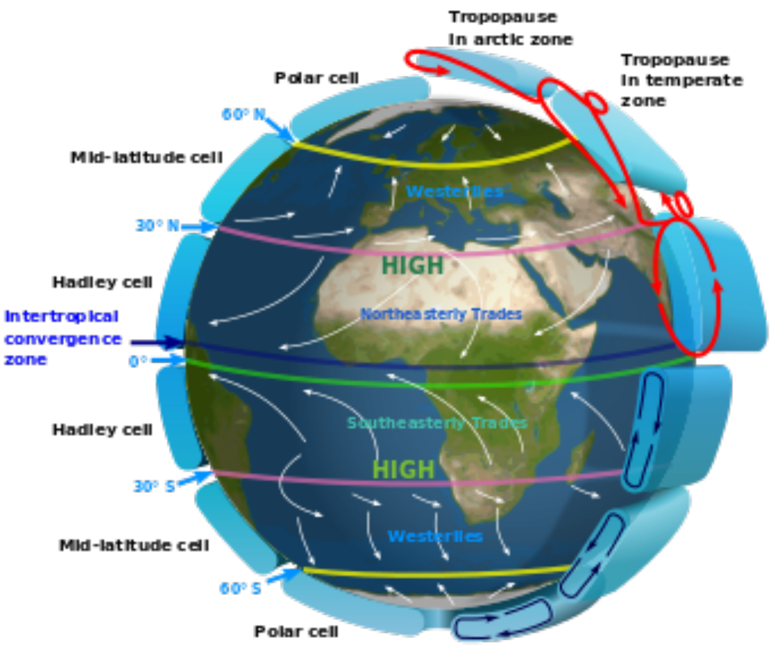
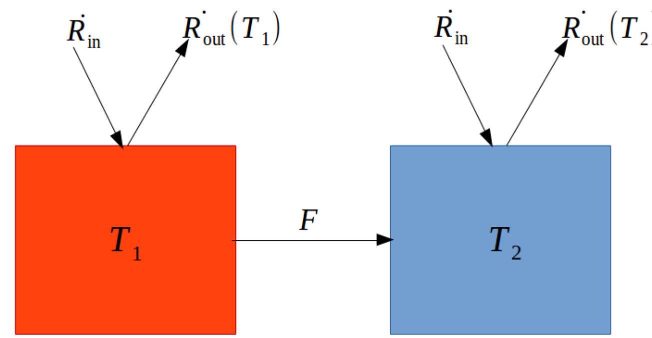


(Wikipedia)



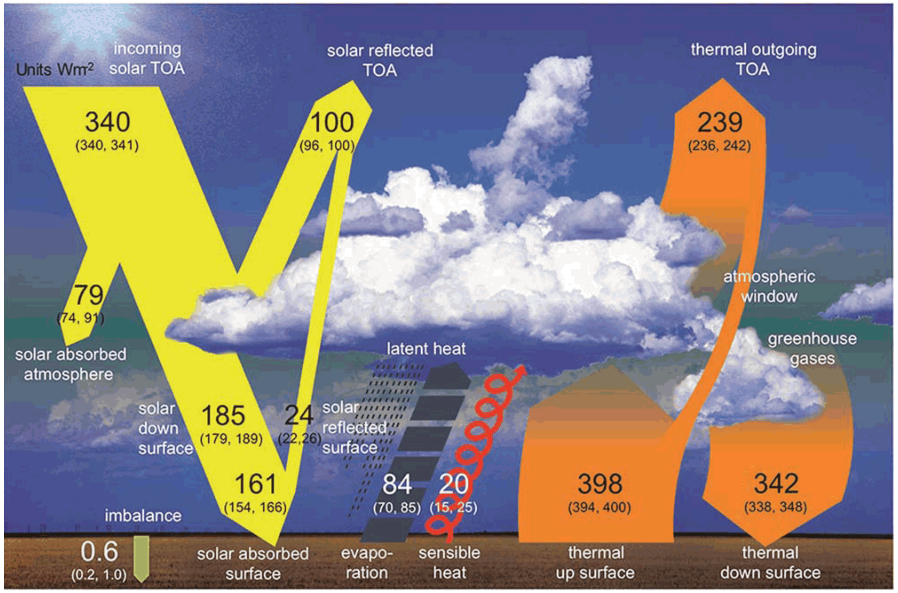
(adapted from Ambaum, 2010)

Global-scale Energy Exchanges in the Atmosphere

(100%)

(3%)

(97%)



(Wild et al., 2013)

Top of the Atmosphere

$$\langle \overline{B}_t \rangle = \langle \overline{S}_t \rangle - \langle \overline{L}_t \rangle \approx 0$$

Atmosphere

$$\langle B_a \rangle = \langle B_t \rangle - \langle B_s \rangle$$

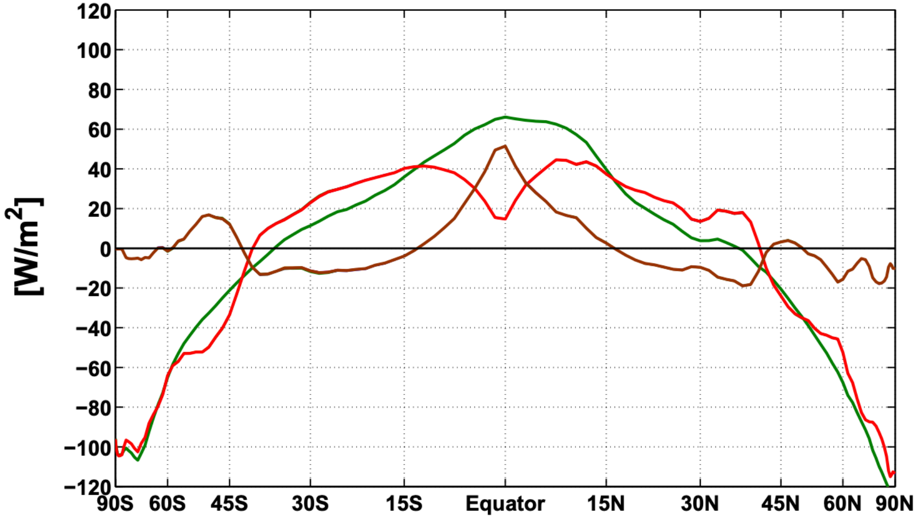
Surface

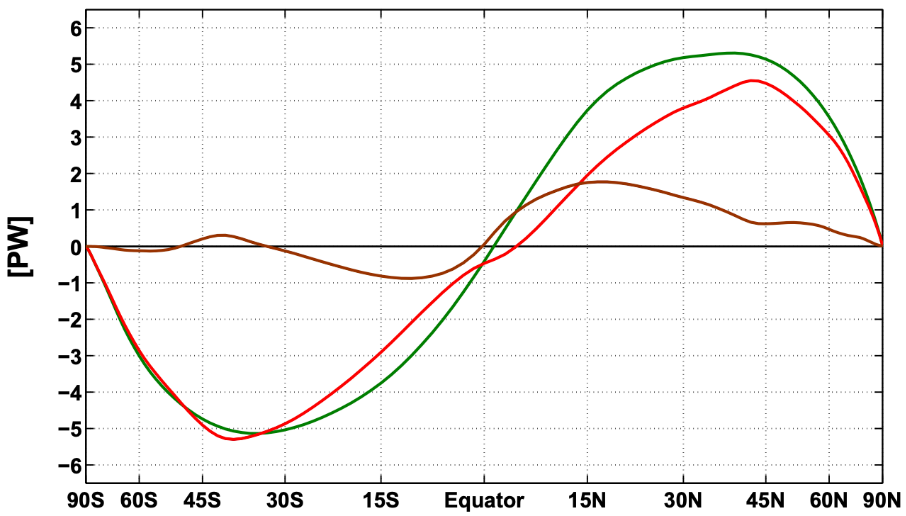
$$\langle B_s \rangle = \langle S_s \rangle - \langle L_s \rangle - \langle H_L \rangle - \langle H_S \rangle$$

S: shortwave, L: longwave
t: TOA, a: atmosphere, s: surface
HL: latent heat flux, HS: sensible heat flux

Global-scale Energy Exchanges in the Atmosphere

Green: TOA, Red: Atmosphere, Brown: Surface





$$\overline{B_t(\varphi)} = \nabla \cdot T_t(\varphi)$$
$$\overline{B_a(\varphi)} = \nabla \cdot T_a(\varphi)$$
$$\overline{B_s(\varphi)} = \nabla \cdot T_o(\varphi)$$

(Lembo et al. 2017)

The Lorenz Energy Cycle: energy conversions in the atmosphere

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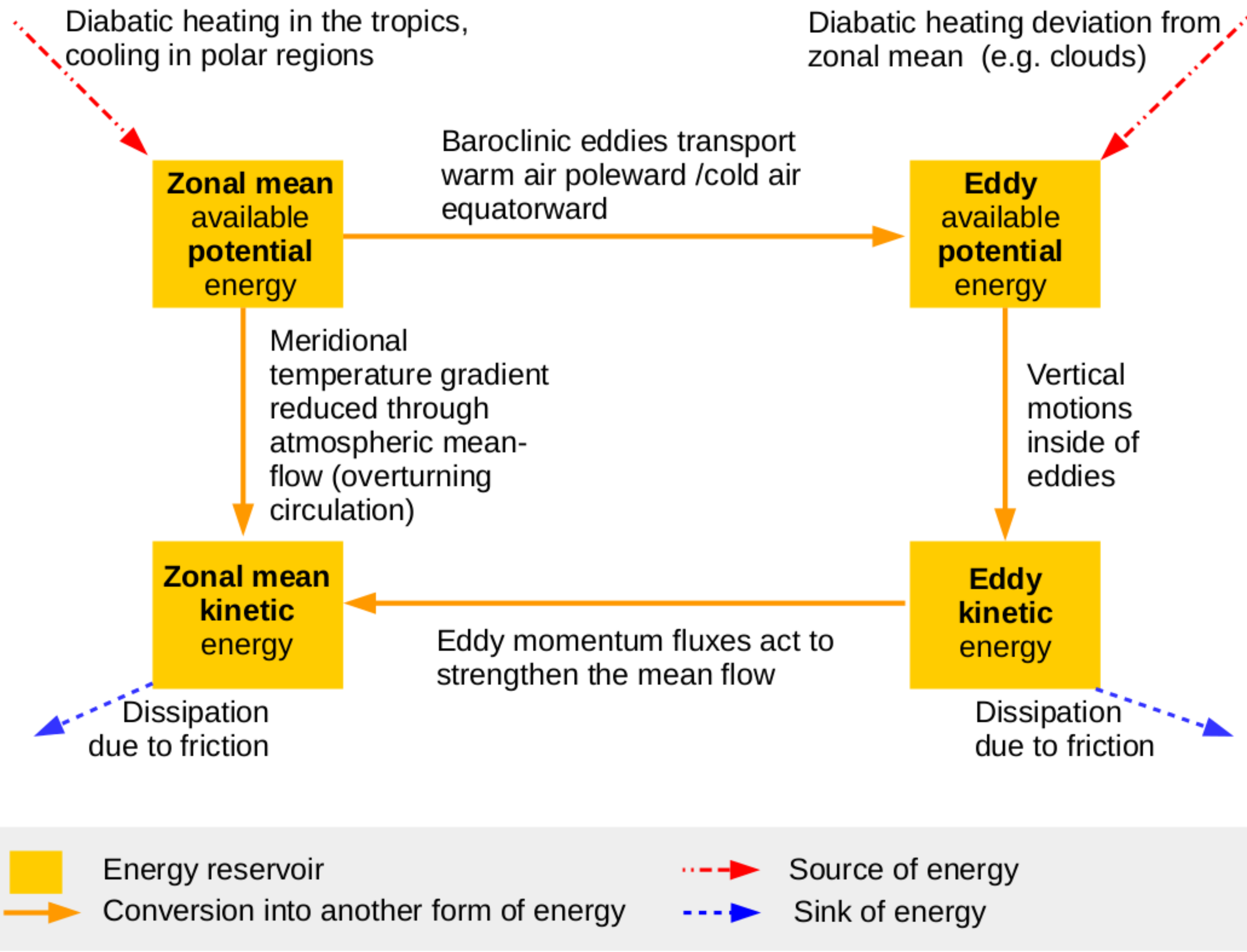
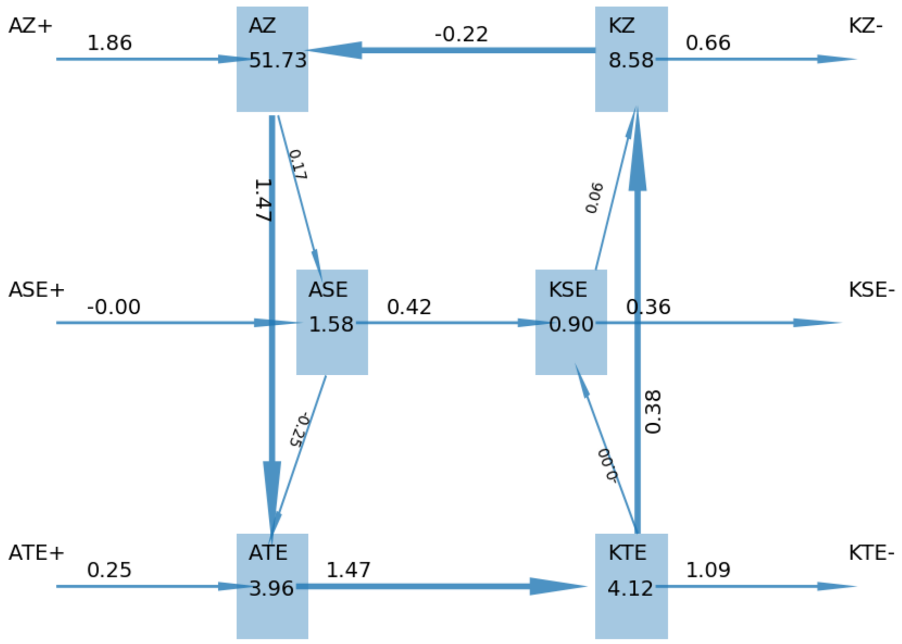


(Wikipedia)

The Lorenz Energy Cycle: energy conversions in the atmosphere

$$\frac{d}{dt}A = G(A_Z) + G(A_E) - C(A_Z, K_Z) - C(A_E, K_E)$$

$$\frac{d}{dt}K = C(K_Z, A_Z) + C(A_E, K_E) - D(K_Z) - D(K_E)$$



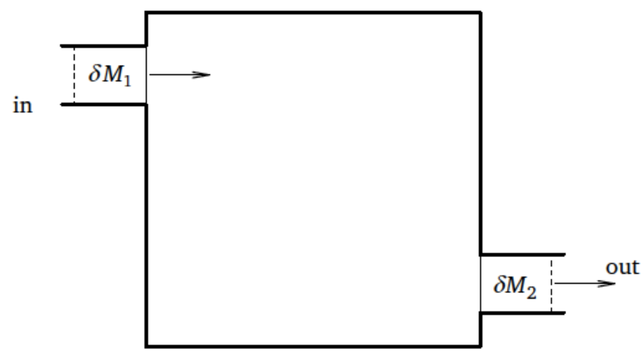
(Lembo et al. 2019)

The Lorenz Energy Cycle: energy conversions in the atmosphere

Definition of enthalpy:

$$h = u + pv$$
$$H = U + pV$$

Suppose a mass δM₁ flows in a domain and a mass δM₁ flows out.

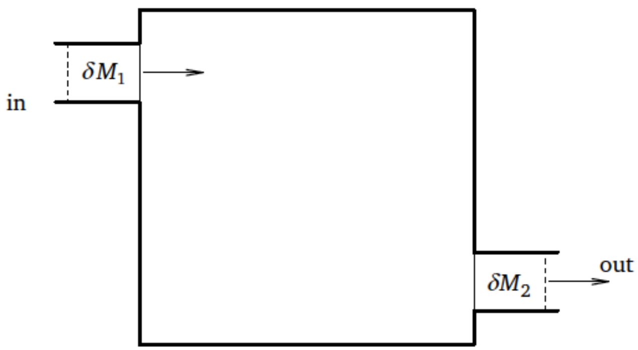


(Ambaum, 2010)

The masses δM_i have internal energy: $U_i = \delta M_i u_i$ and an amount of work $p_i \delta V_i$ will be accomplished on the domain to let the mass δM_i in:

$$\delta U = \delta M_1 (u_1 + p_1 v_1) - \delta M_2 (u_2 + p_2 v_2) = \delta M_1 h_1 - \delta M_2 h_2$$

The Lorenz Energy Cycle: energy conversions in the atmosphere



(Ambaum, 2010)

Generalizing to infinitesimal domains and considering mass flowing in the 3 directions:

$$\frac{dU}{dt} = -\int_A \rho \mathbf{U} h \cdot \hat{\mathbf{n}} dA'$$

where we replace the mass δM with: $\rho \mathbf{U} dA$ $\quad \mathbf{U} = \left(\frac{dx}{dt}, \frac{dy}{dt}, \frac{dz}{dt}\right)$

Using the Gauss' theorem: $\frac{d\rho u}{dt} = -\nabla \cdot (\rho \mathbf{U} h)$ —> An enthalpy flux!

The differential of the enthalpy of a dry air particle is written:

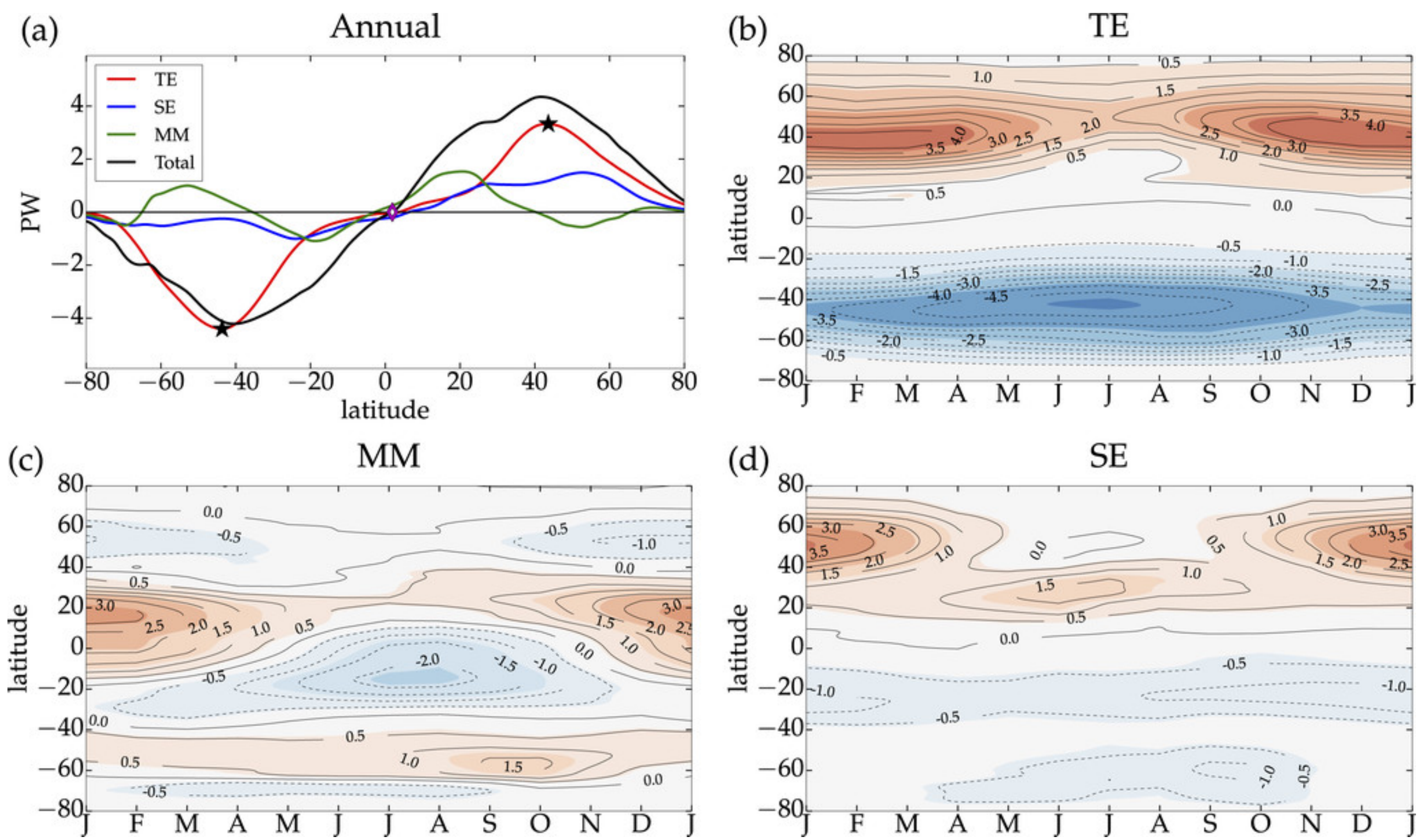
$$dh = Td\sigma + vdp$$

Enthalpy is generalized to be proportional to dry static energy (DSE):

$$\eta = h + gz = c_p T + gz \sim DSE$$

The Lorenz Energy Cycle: energy conversions in the atmosphere

Moist static energy (MSE): $H = L_v q + c_p T + gz$



(Barpanda and Shaw, 2017)

The role of mid-latitudinal waves

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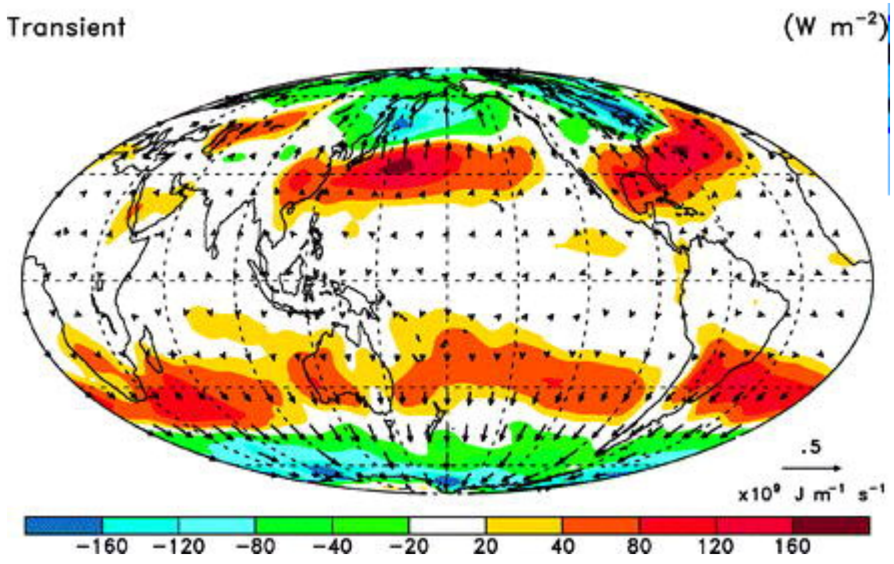


Annual mean divergent energy transport (vectors) and divergence (colours; Trenberth and Stepaniak, 2003)

- In the extratropics the energy transports are carried out by baroclinic eddies.
- Storm tracks emerge very clearly as “organized baroclinic transients”.
- Heat transport by the quasi-stationary waves is substantial, espec. in the Northern Hemisphere winter.

The role of mid-latitudinal waves

- **The computation of atmospheric energy results from the combination of dry static, moist static and kinetic component:**

$$E = c_p T + gz + Lq + \frac{1}{2}\mathbf{v}^2$$

- **The zonal integrated total meridional energy transport is thus:**

$$vE(\phi) = \oint_0^{p_s} vE \frac{dp}{g} dx$$

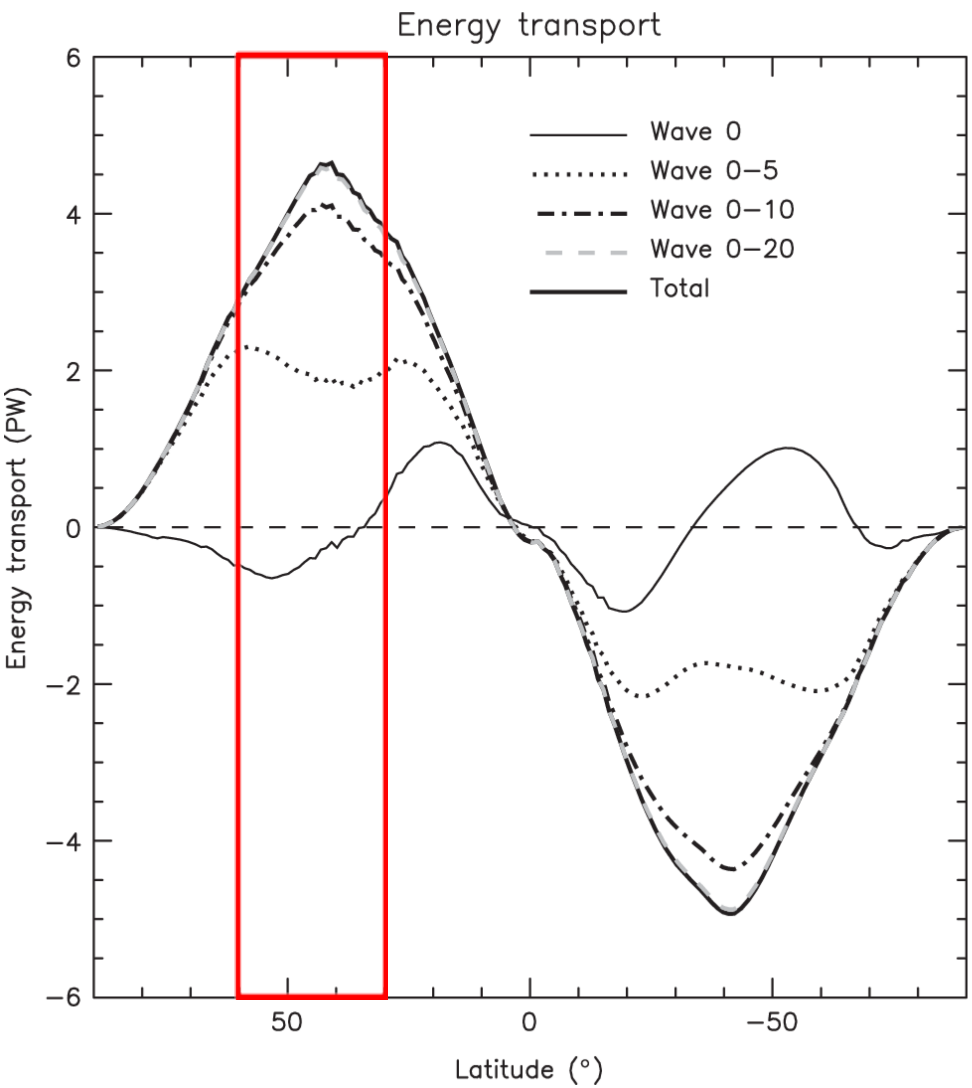
- **The Fourier coefficients (a, b) are separately computed for meridional velocity and energy at every level, so that the heat transport carried by wavenumber k is retrieved as:**

$$\begin{cases} \hat{\mathscr{F}}_0(\phi) = D \int_{p_s}^{0} \frac{1}{4} a_0^v a_0^E \frac{dp}{g} \\ \hat{\mathscr{F}}_k(\phi) = D \int_{p_s}^{0} \frac{1}{2} (a_k^v a_k^E + b_k^v b_k^E) \frac{dp}{g} \end{cases}$$

$$a_k^{\Psi}(t, \phi) = \frac{2}{D} \int \Psi(t, \phi, \lambda) \cos\left(\frac{k 2\pi\lambda}{d}\right) d\lambda$$

$$b_k^{\Psi}(t, \phi) = \frac{2}{D} \int \Psi(t, \phi, \lambda) \sin\left(\frac{k 2\pi\lambda}{d}\right) d\lambda$$

The role of mid-latitudinal waves



(Graversen and Burtu, 2016)

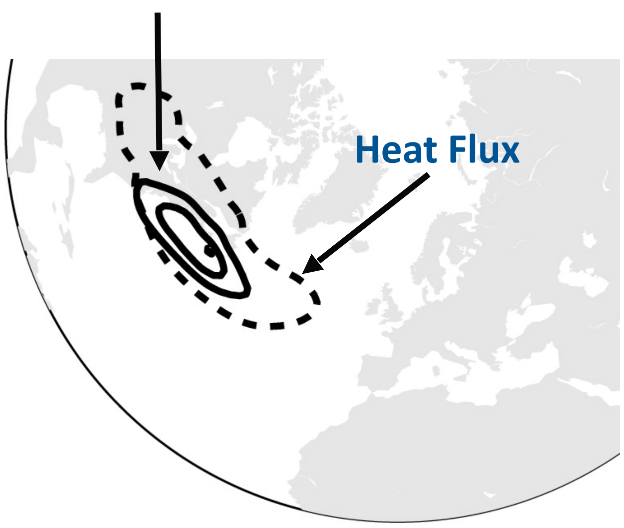
In the NH mid-latitudes (30-60) the first 10 wavenumbers contribute to nearly all the transport:

- Wave 0 (zonal mean): slightly negative;
- Waves 1-5 (planetary waves): contributes nearly half of the transport;
- Waves 6-10 (synoptic waves): set the peak location and strength of the transport;

Beyond mean values…

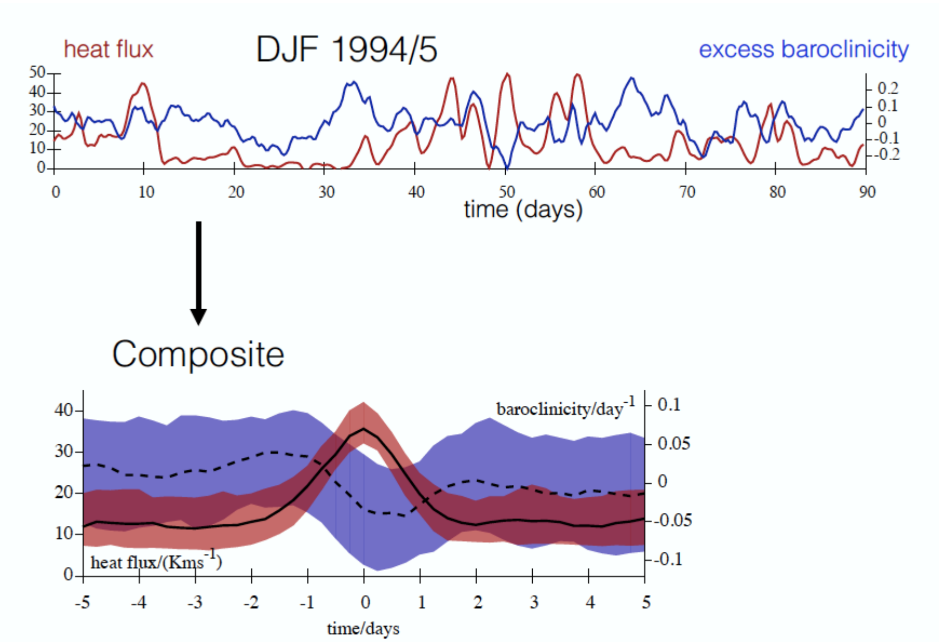
Beyond mean values… A nonlinear oscillator

In the N. Atlantic: approximate collocation of the baroclinicity and eddy transports:



(Novak et al., 2015)

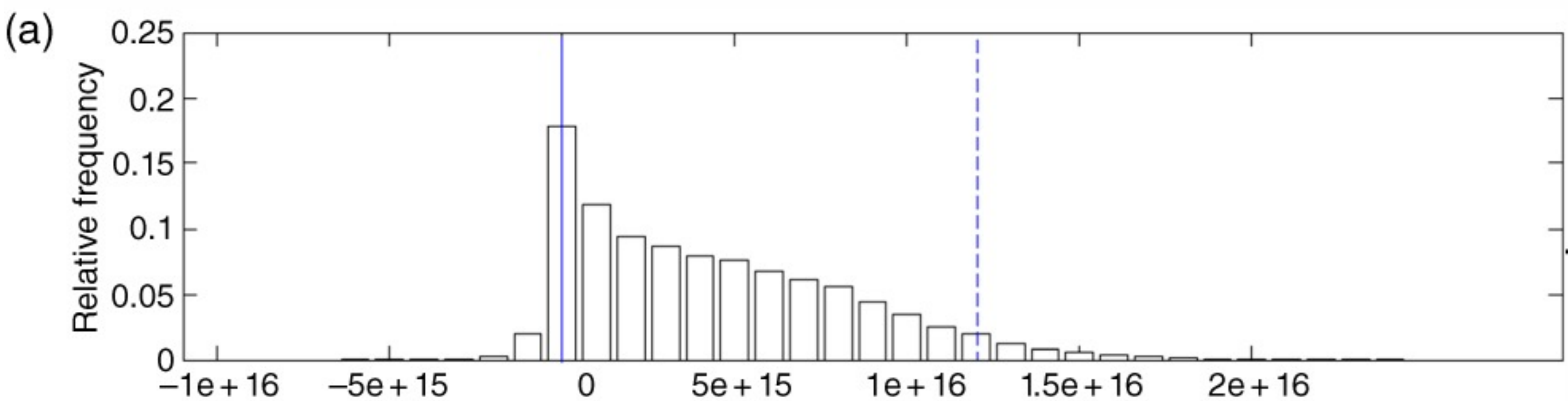
Nonlinear oscillator model: displays some salient features that can be seen in observations. Firstly, the heat flux does not appear to be uniform in time, or even uniformly random, but comes in bursts of activity.



(Ambaum and Novak, 2014)

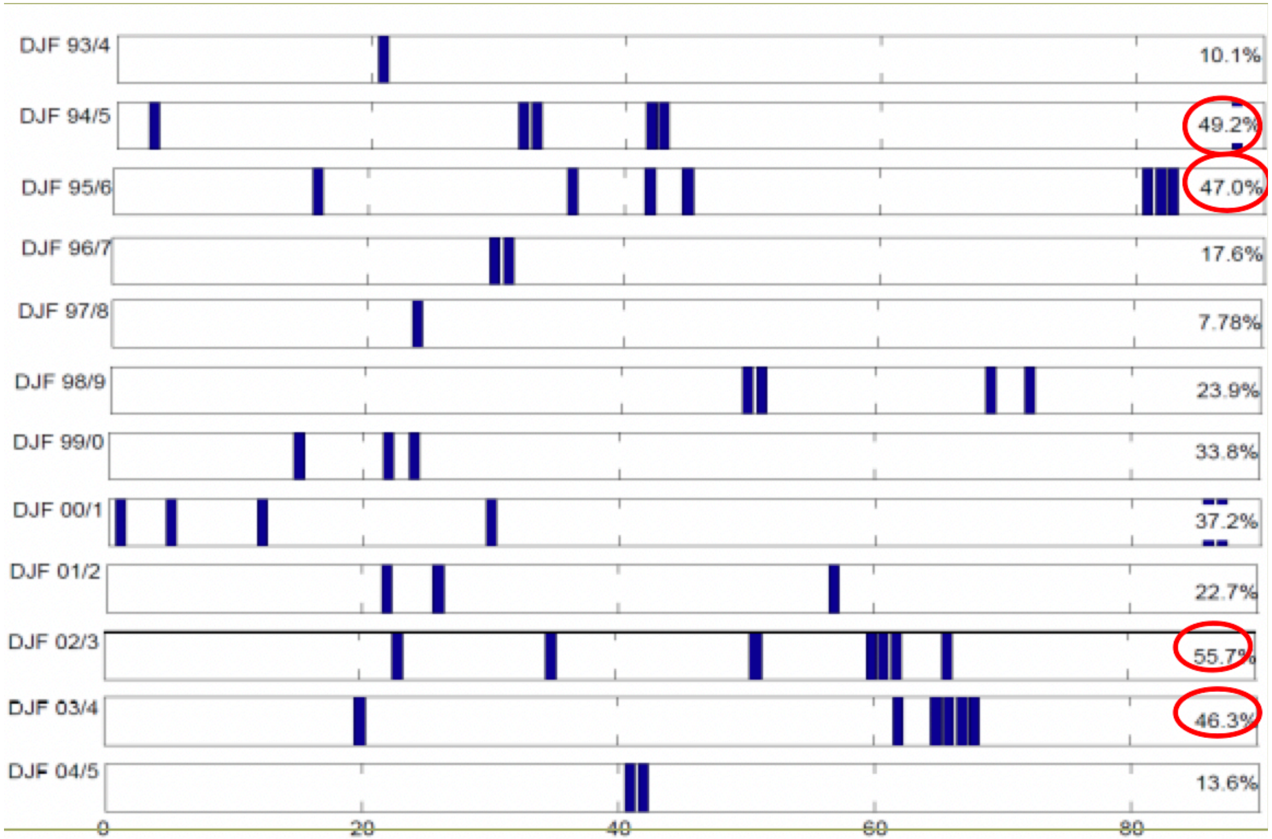
Beyond mean values… The role of extremes

Zonally integrated eddy transport at 45N, during DJF:



(Messori et al., 2013)

Beyond mean values… The role of extremes



(Messori and Czaja 2013)

A few sporadic events can make up to 56% of the total poleward transport related to eddies in a season!

Beyond mean values… The role of extremes

k=1-5 (“planetary”) and k=6-10 (“synoptic”) are the main contributors to the mean transport. How do they contribute to extremes?

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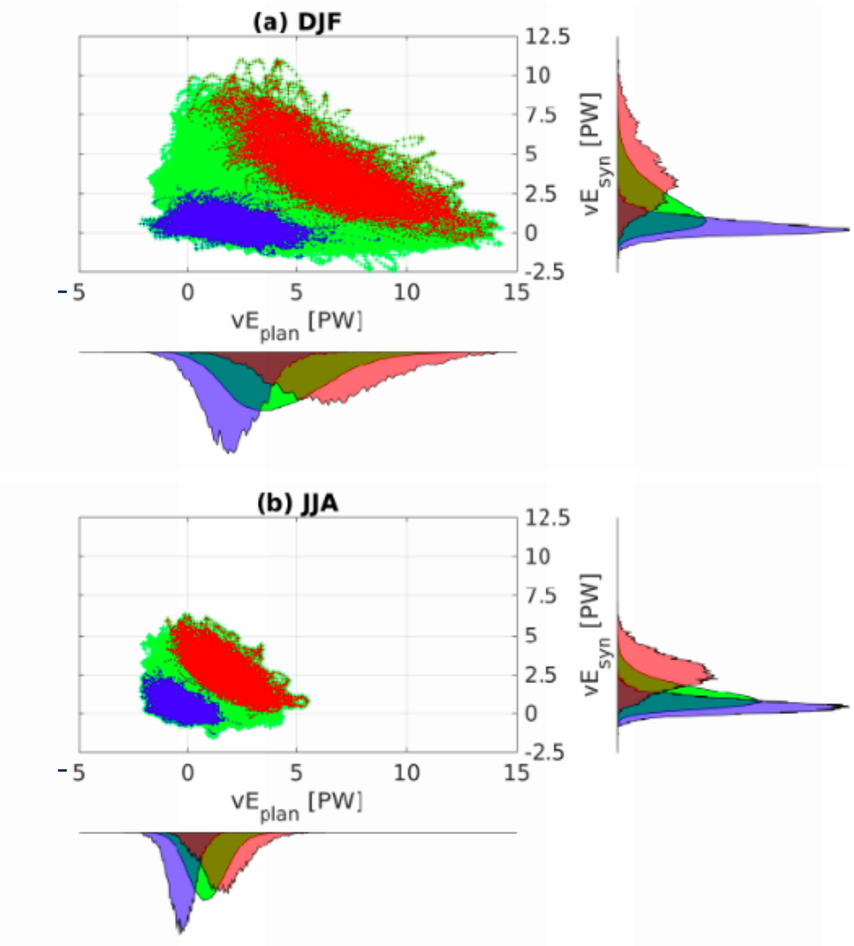
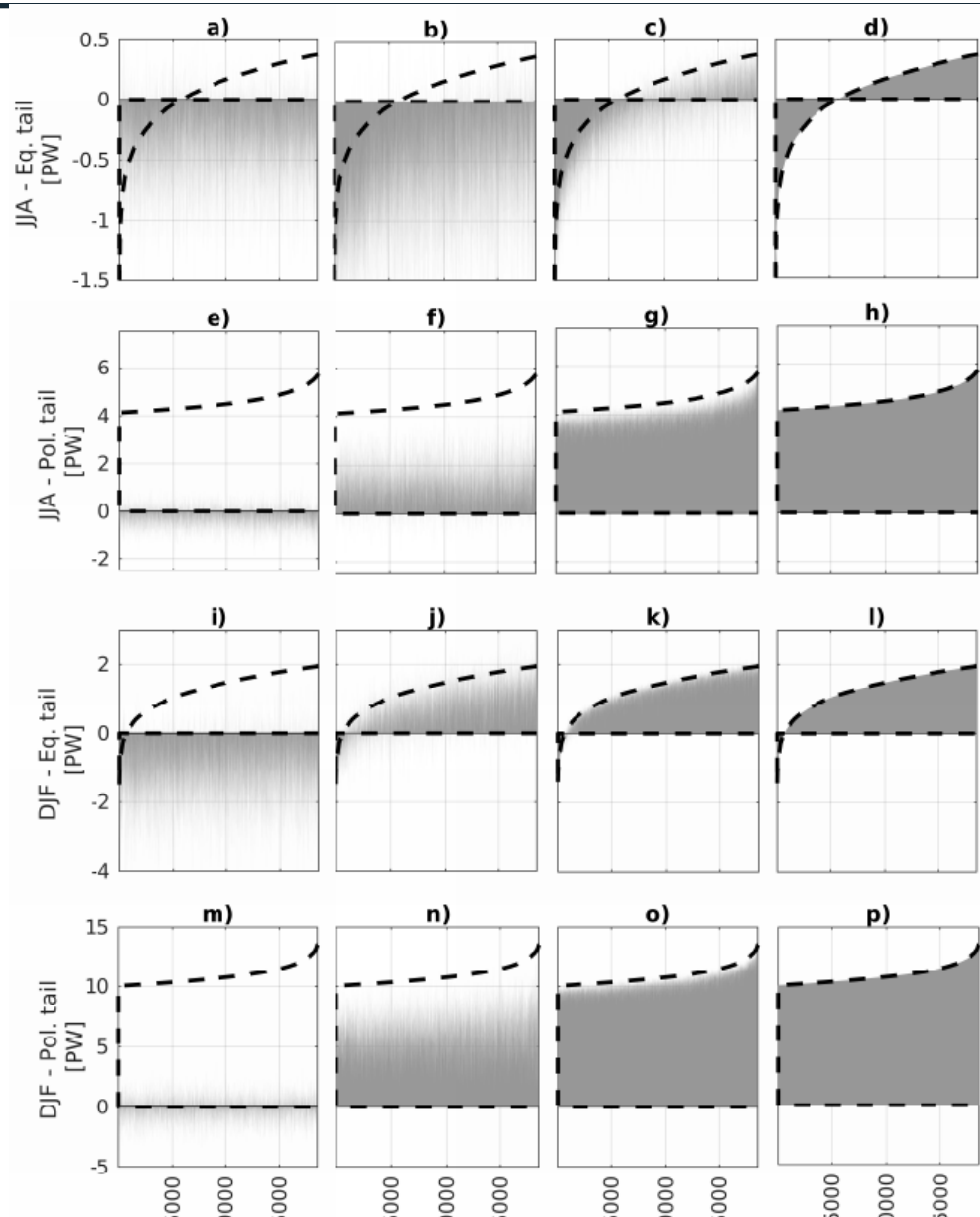
Beyond mean values… The role of extremes

k=1-5 (“planetary”) and k=6-10 (“synoptic”) are the mean contributors to the mean transport. How do they contribute to extremes?

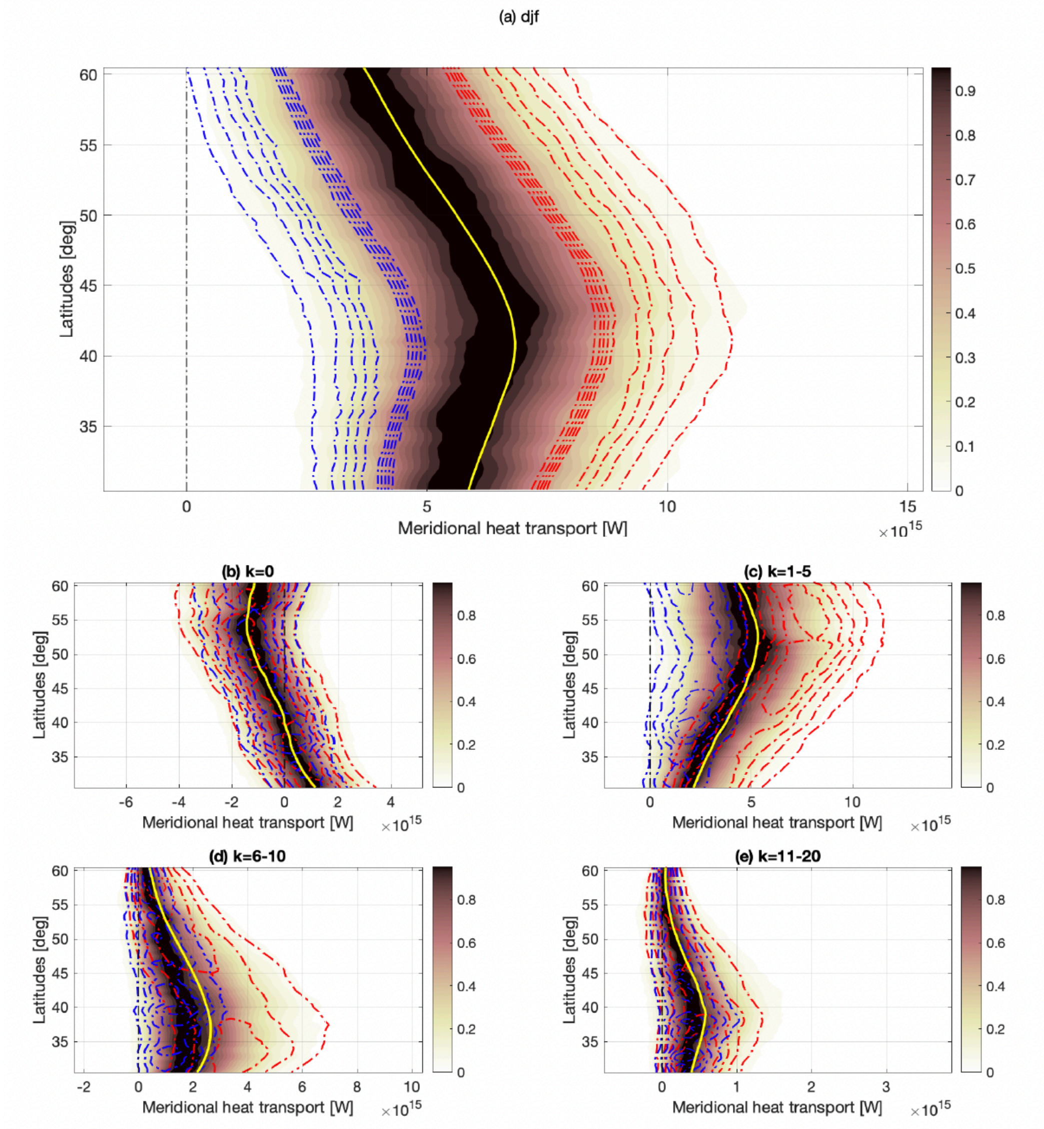


- **Are the synoptic and planetary scale anti-correlated in the extremes? Possibly, particularly for poleward extremes!**
- **Poleward extremes have a larger skewness, especially for the synoptic component;**
- **The situation is more confused for eqw. extremes, especially in JJA, where the planetary component is mostly negative!**

Beyond mean values… The role of extremes



Beyond mean values… The role of extremes



Let us switch to 2-D again.

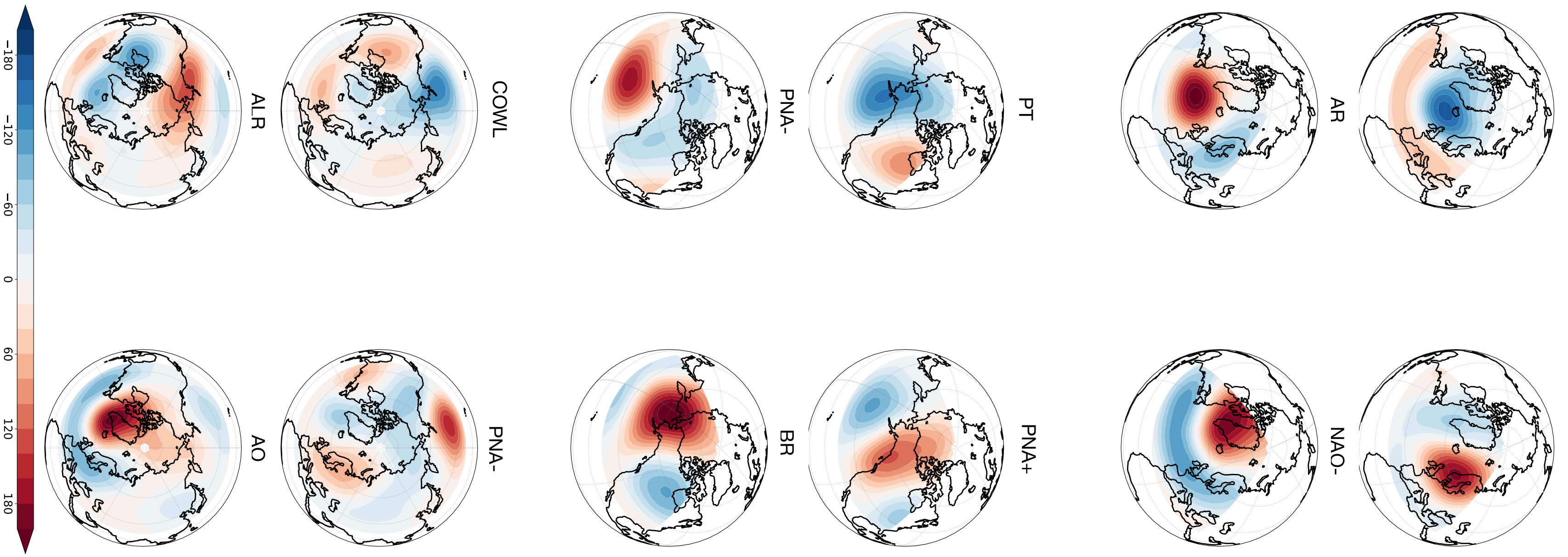
What about the dependency on latitudes?

“Projecting” extremes on weather regimes

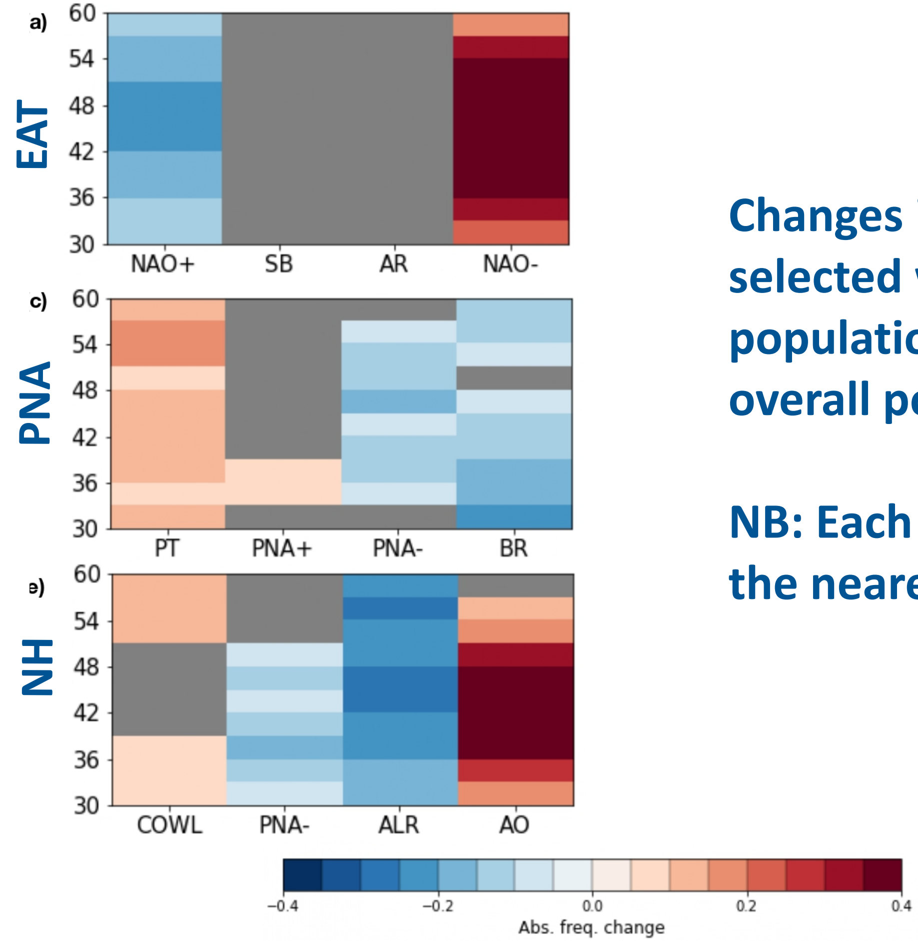
“Projecting” extremes on weather regimes

DJF Dominant weather regimes (k-means clustering algorithm)

Northern Hemisphere domain (NH) **Pacific-North America domain (PAC)** **Eastern-Atlantic domain (EAT)**



“Projecting” extremes on weather regimes

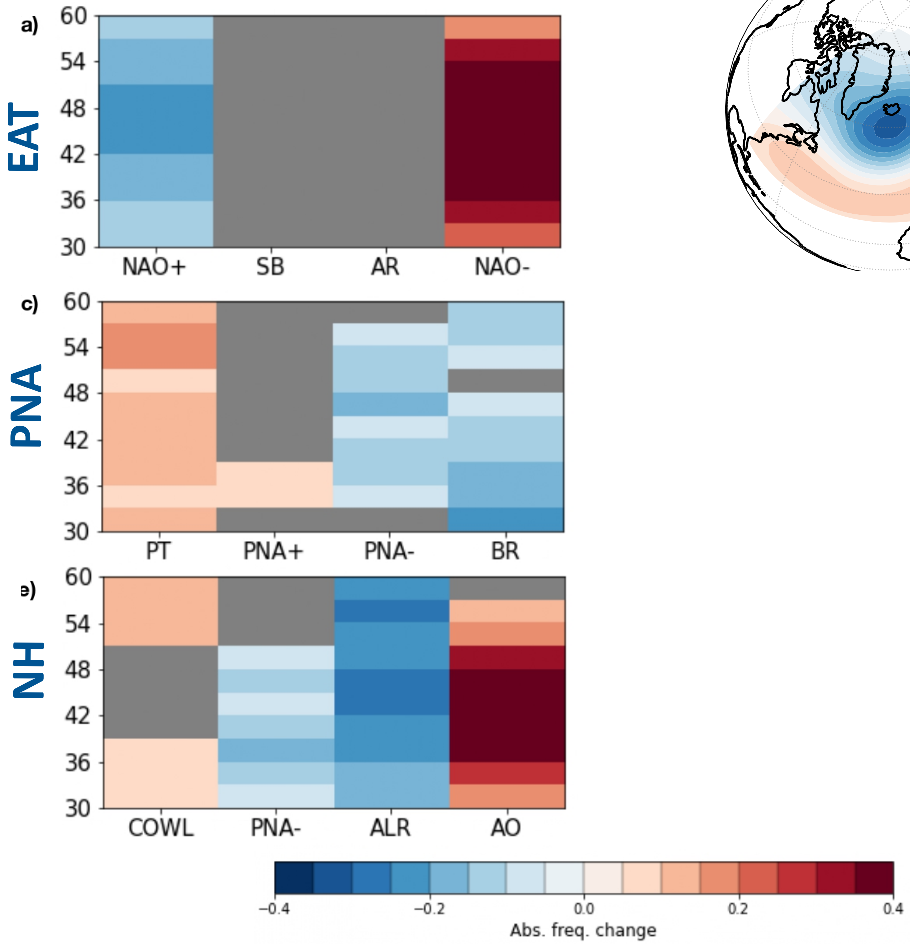


Poleward

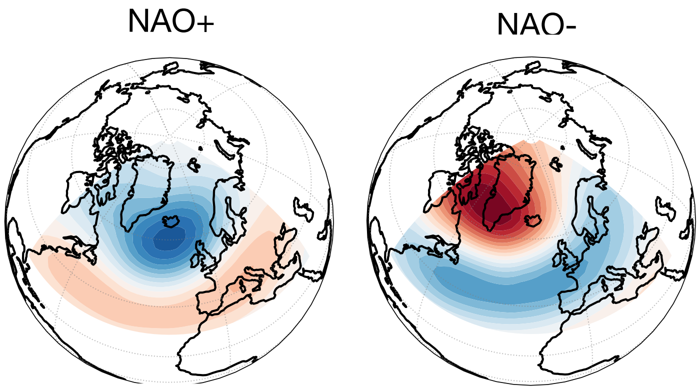
Changes in frequency of the selected weather regimes in the population of extremes, wrt. the overall population

NB: Each event is attributed to the nearest weather regime!

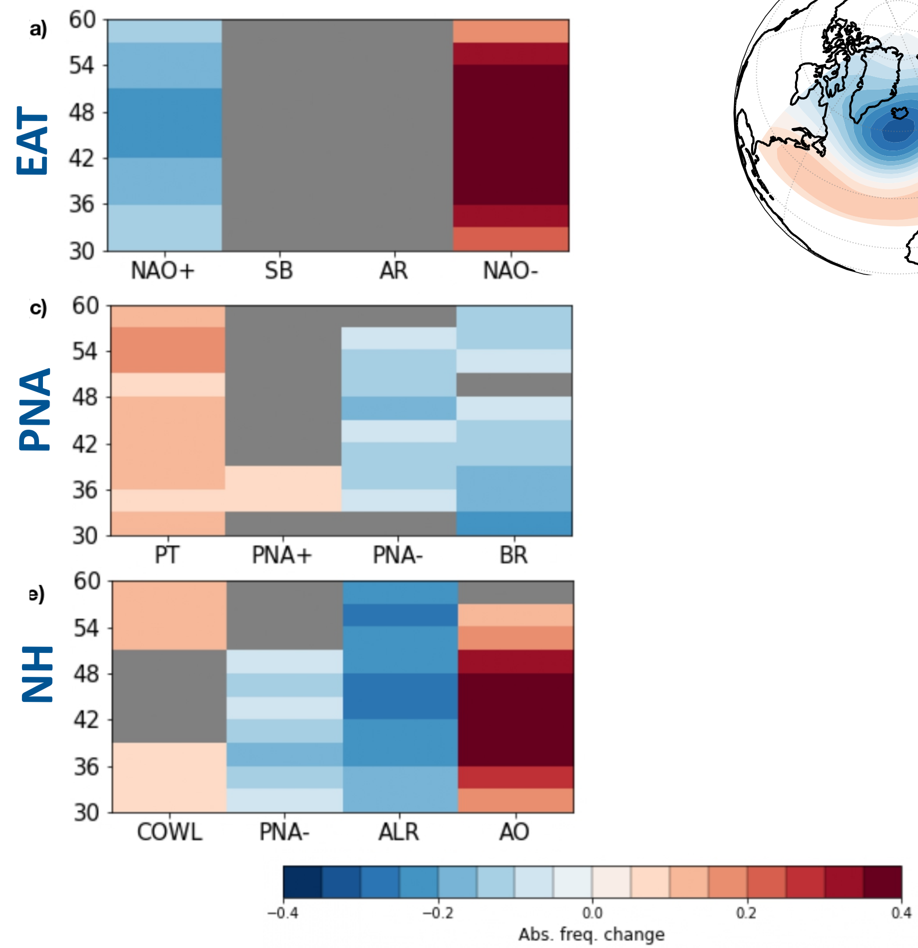
“Projecting” extremes on weather regimes

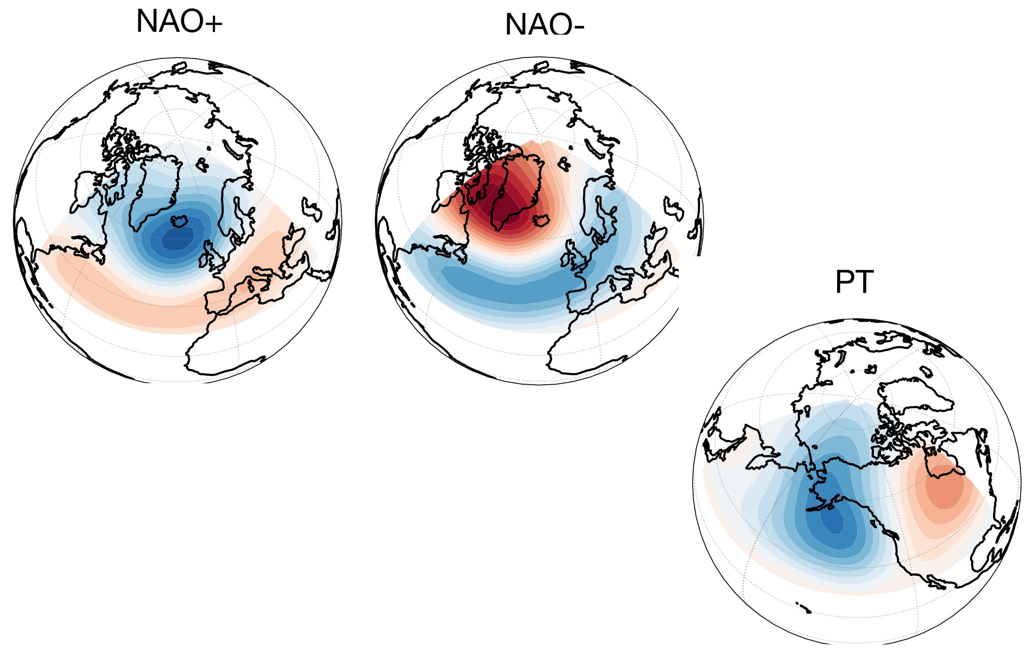


Poleward



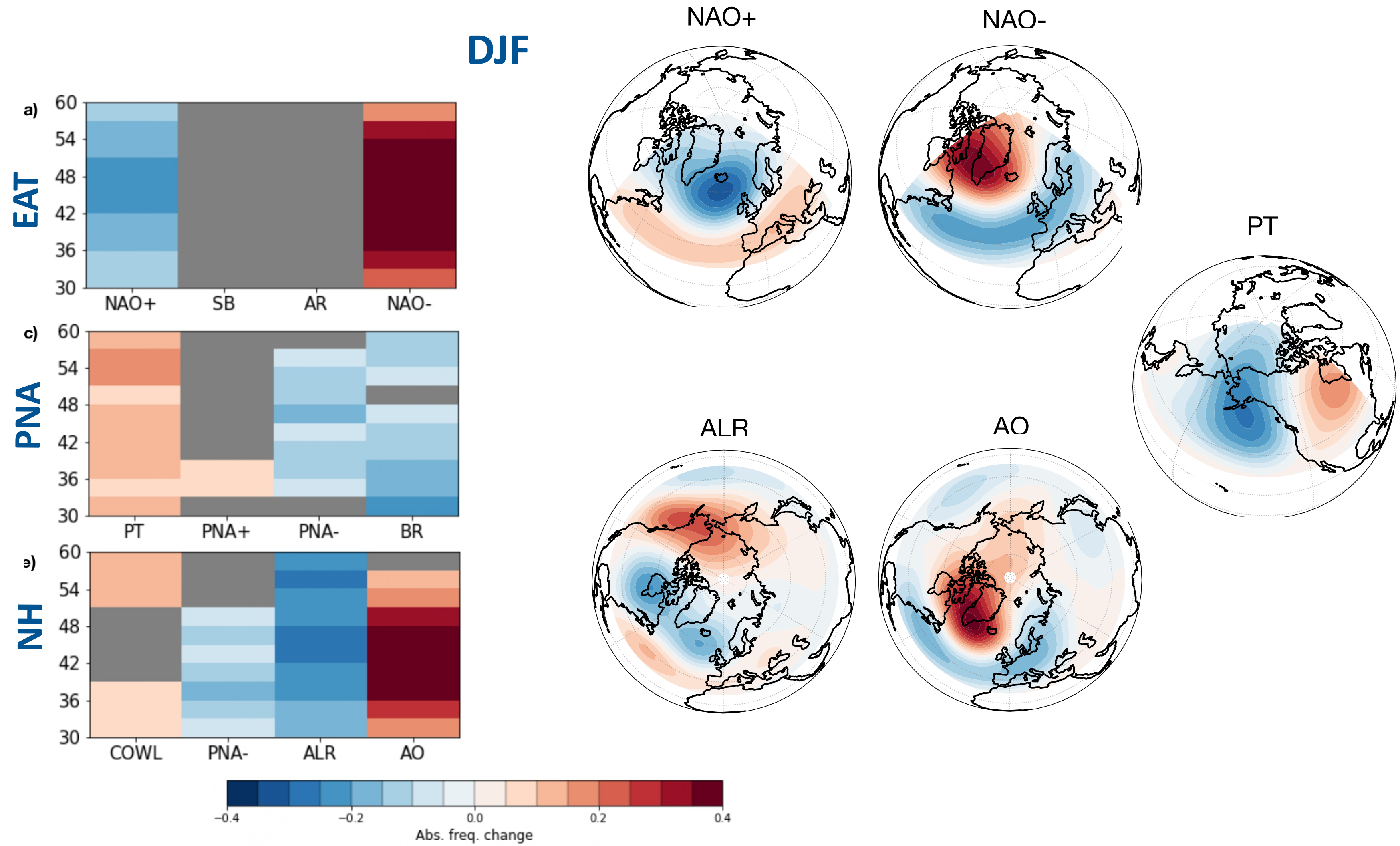
“Projecting” extremes on weather regimes





Poleward

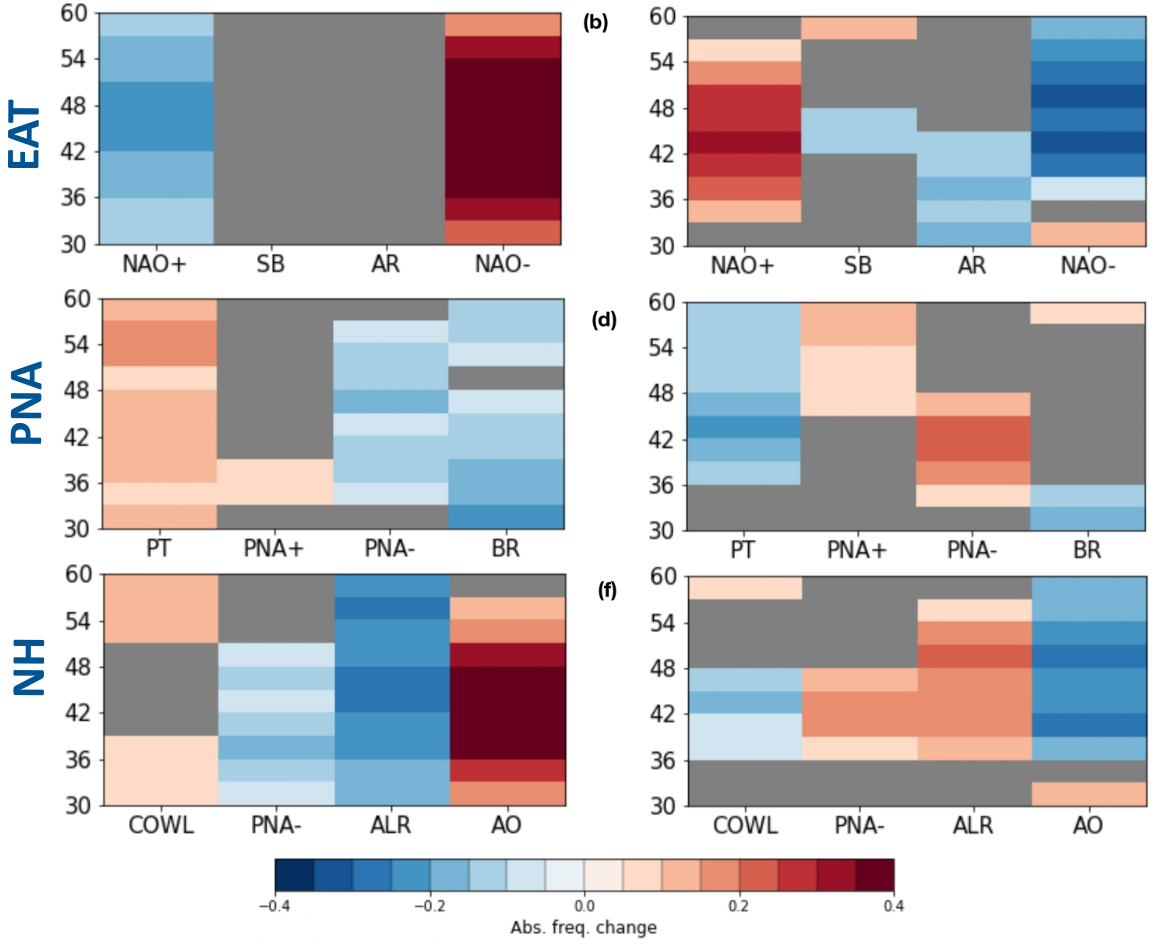
“Projecting” extremes on weather regimes



Poleward

“Projecting” extremes on weather regimes

DJF



Poleward **Equatorward**

Conclusions

(Some) take-home messages

- **The Lorenz Energy Cycle describes the reservoirs of Potential Energy due to differential diabatic heating across latitudes, how its transport by eddies in mid-latitudes is converted into kinetic energy and dissipated;**

- **Such poleward transport of mass and heat is conveniently understood as an enthalpy, or (moist) static energy flux;**

- **Eddies co-exist at a wide range of spatial (and temporal) scales, and are strongly non-linear, with extremes playing a very relevant role;**

- **Preferred weather regimes for meridional extreme heat transports are identified, promoting Atlantic high-latitude blockings and Pacific troughs;**

Thank You!

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- Graversen, R. G. and Burtu, M.: Arctic amplification enhanced by latent energy transport of atmospheric planetary waves, Quarterly Journal of the Royal Meteorological Society, 142, 2046–2054 (2016)
- Kim, Y. H. and Kim, M. K.: Examination of the global lorenz energy cycle using MERRA and NCEP-reanalysis 2, Clim. Dynam., 40, 1499–1513 (2013)
- Liang, M., Czaja, A., Graversen, R., and Tailleux, R.: Poleward energy transport: is the standard definition physically relevant at all time scales?, Climate Dynamics 2017 50:5, 50, 1785–1797 (2017)
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- **Lembo, V., Lunkeit, F., and Lucarini, V.: TheDiaTo (v1.0) – a new diagnostic tool for water, energy and entropy budgets in climate models, Geosci. Model Dev., 12, 3805–3834 (2020)**
- **Lembo, V., Fabiano, F., Galfi, V. M., Graversen, R., Lucarini, V., and Messori, G.: Meridional energy transport extremes and the general circulation of NH mid-latitudes: dominant weather regimes and preferred zonal wavenumbers, Weather Clim. Dynam. Discuss. (2021)**
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- Messori, G. and Czaja, A., On local and zonal pulses of atmospheric heat transport in reanalysis data. Q.J.R. Meteorol. Soc. (2015)
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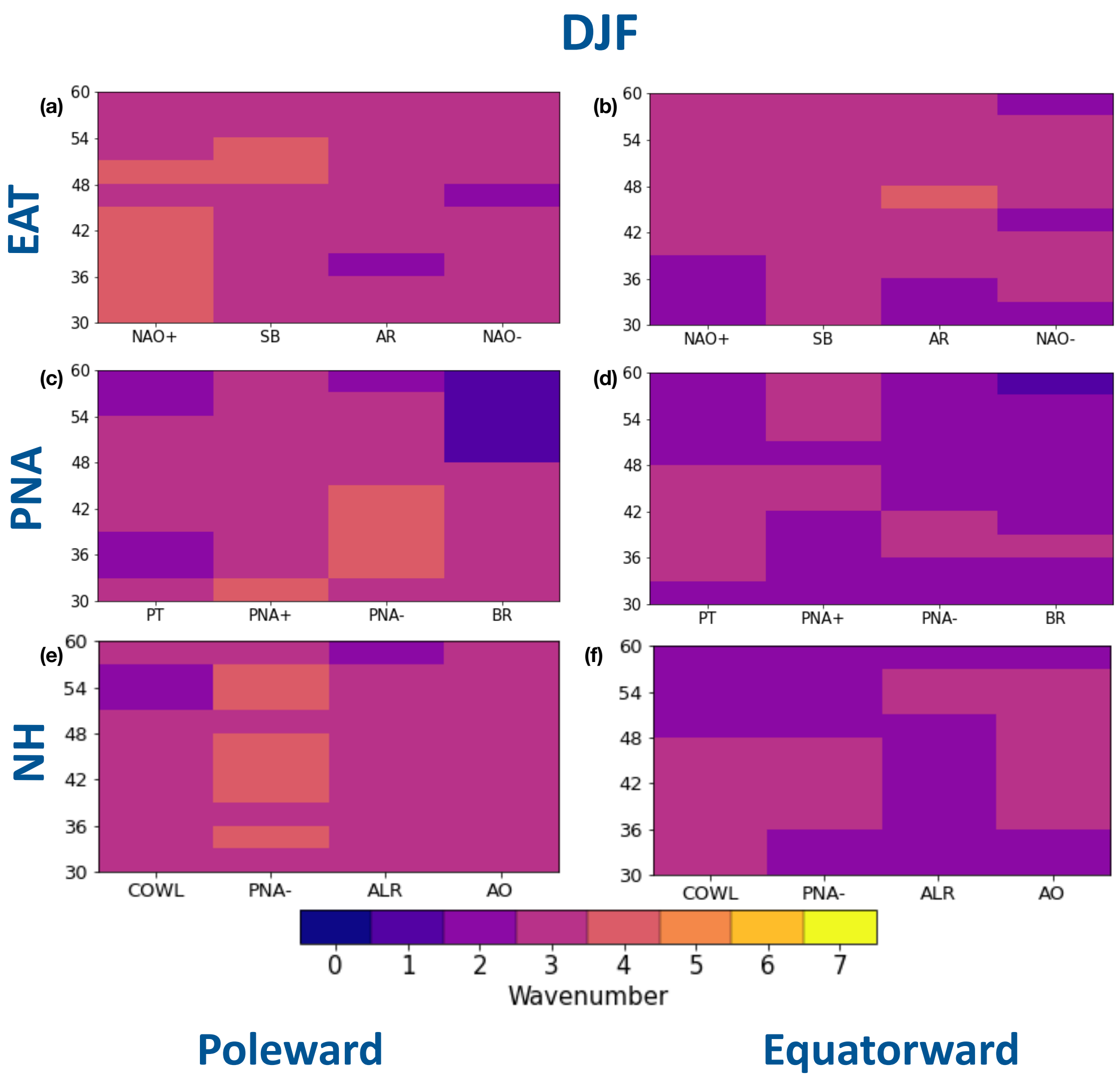
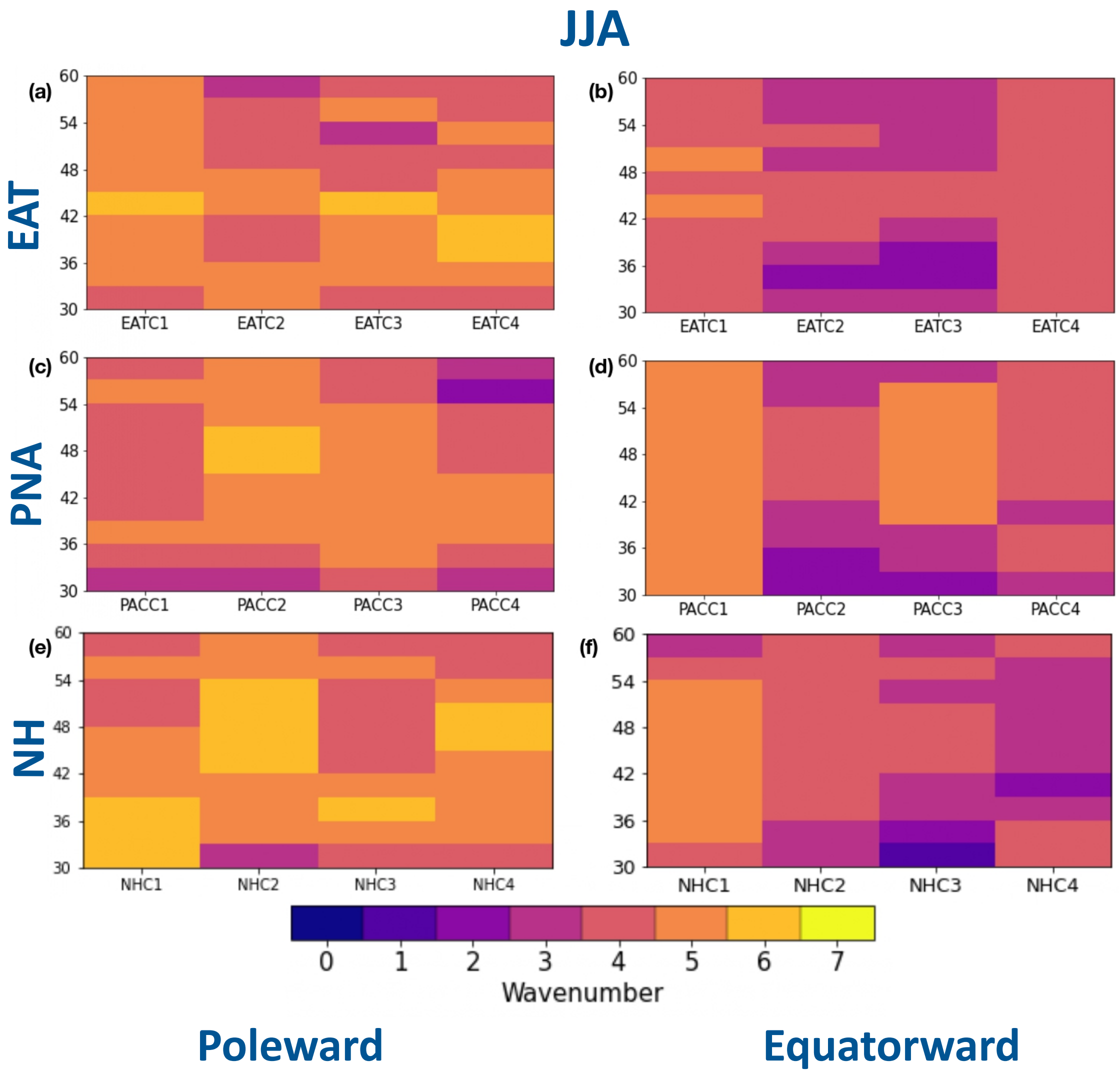
Additional slides

"Projecting" extremes on weather regimes



- Time averaged dominant wavenumbers sorted by weather regimes and latitude are shown;
- In the two tails of extremes k=2-4 dominates in almost any case;
- The composites (not shown) for equatorward and poleward extremes are reversed, indicating that no preferred wavenumbers emerge;

"Projecting" extremes on weather regimes



- Poleward extremes generally peak at higher wavenumbers than equatorward extremes;
- We complement here what shown before, suggesting that planetary scales overwhelm the synoptic scale transport in equatorward extremes;
- Poleward extremes peak at k=5-7, consistently with findings about concurrent heat waves;