# Effect of energy injection on jet-waves-random interactions across scales, case study: 2003 western Europe summer heat wave

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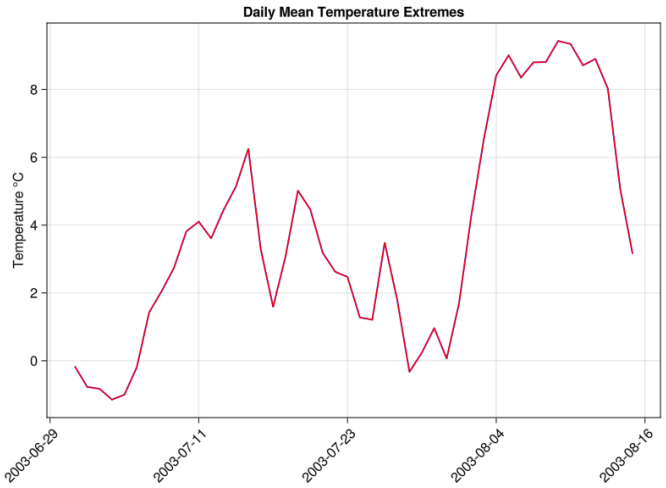
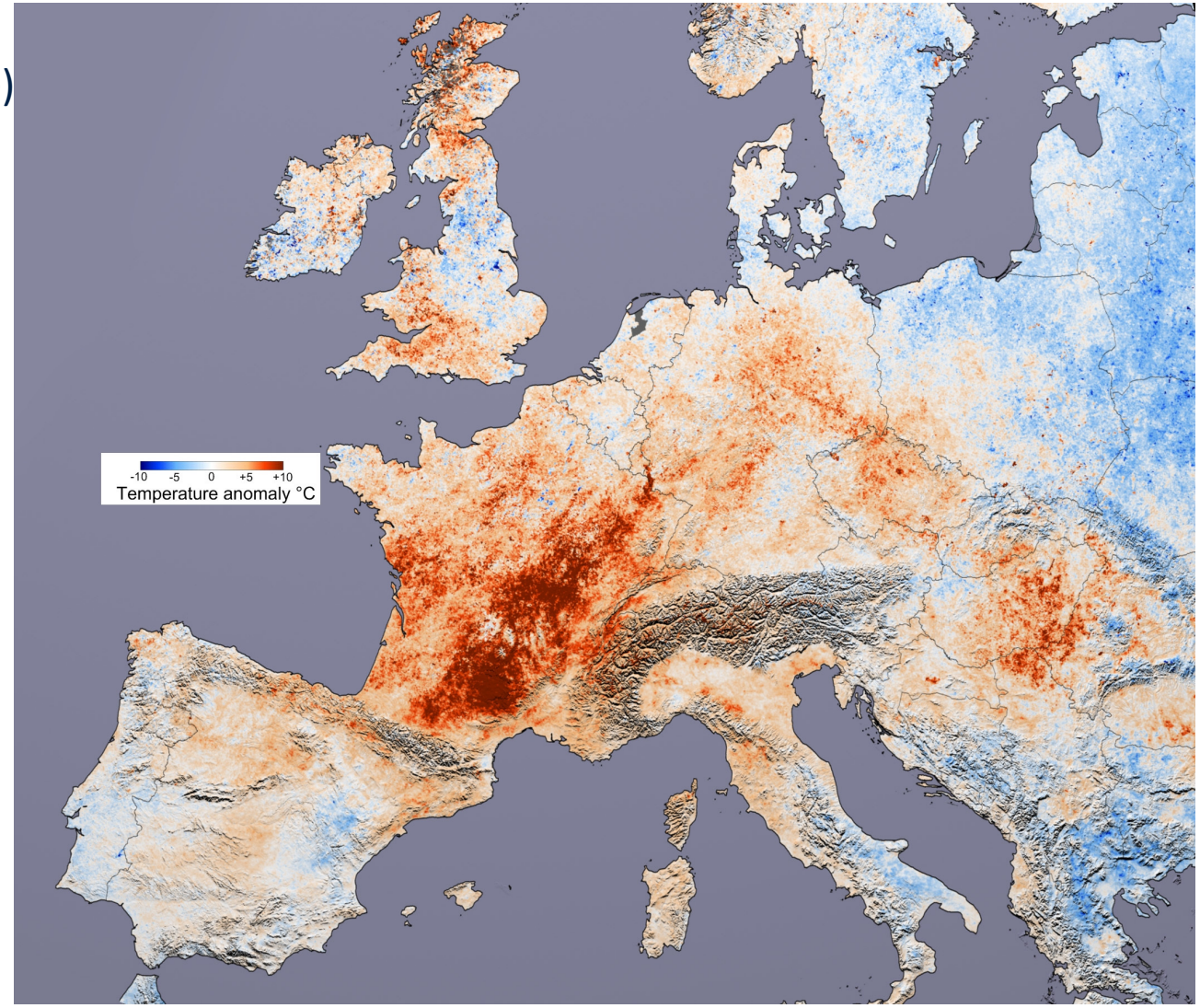
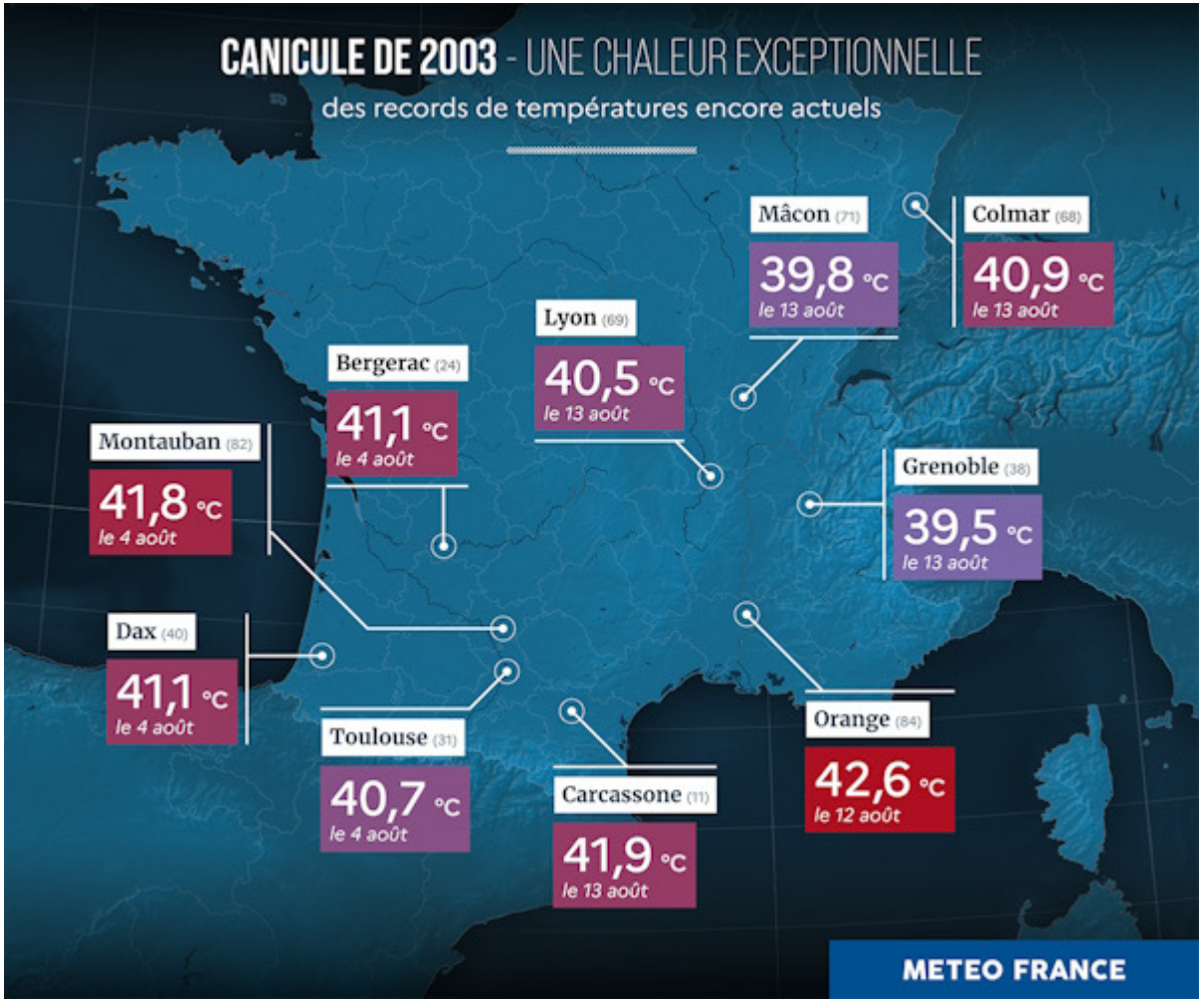
# Outline

- Highest death toll (40 000 in France)
- Up to 12°C higher than average



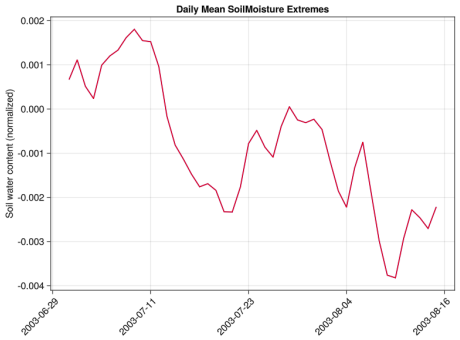



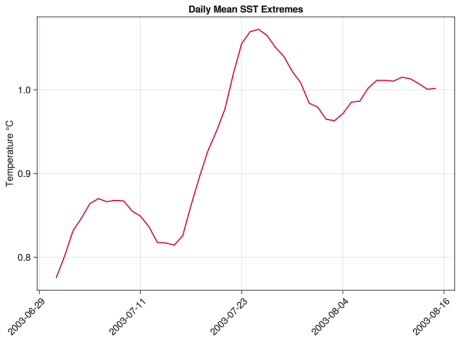
# Outline

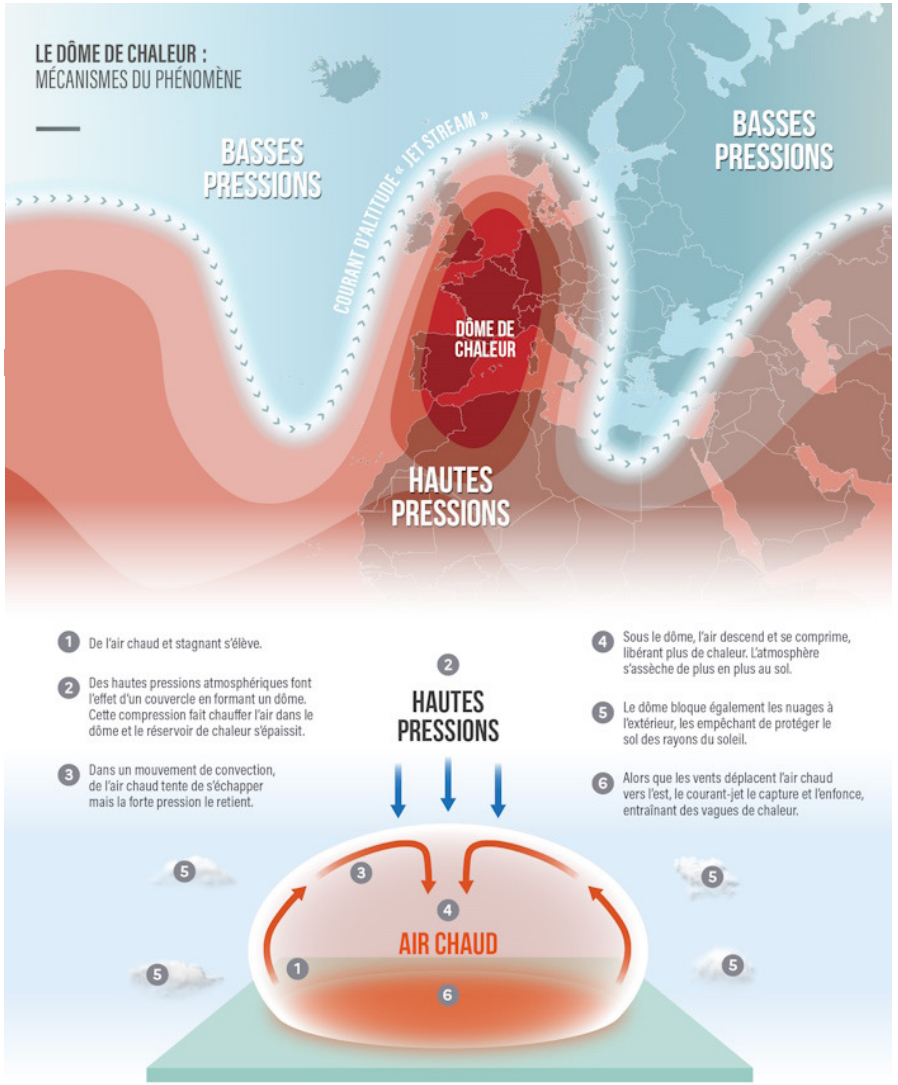

CANICULE DE 2003 - UNE CHALEUR EXCEPTIONNELLE
des records de températures encore actuels
Mâcon (71)
39,8 °C
le 13 août
Colmar (68)
40,9 °C
le 13 août
Lyon (69)
40,5 °C
le 13 août
Bergerac (24)
41,1 °C
le 4 août
Montauban (82)
41,8 °C
le 4 août
Grenoble (38)
39,5 °C
le 13 août
Dax (40)
41,1 °C
le 4 août
Toulouse (31)
40,7 °C
le 4 août
Carcassone (11)
41,9 °C
le 13 août
Orange (84)
42,6 °C
le 12 août
METEO FRANCE

# How it is explained so far:

- Pre-existing conditions:
  - Blocking
  - Soil moisture deficit
  - Sea surface temperatures



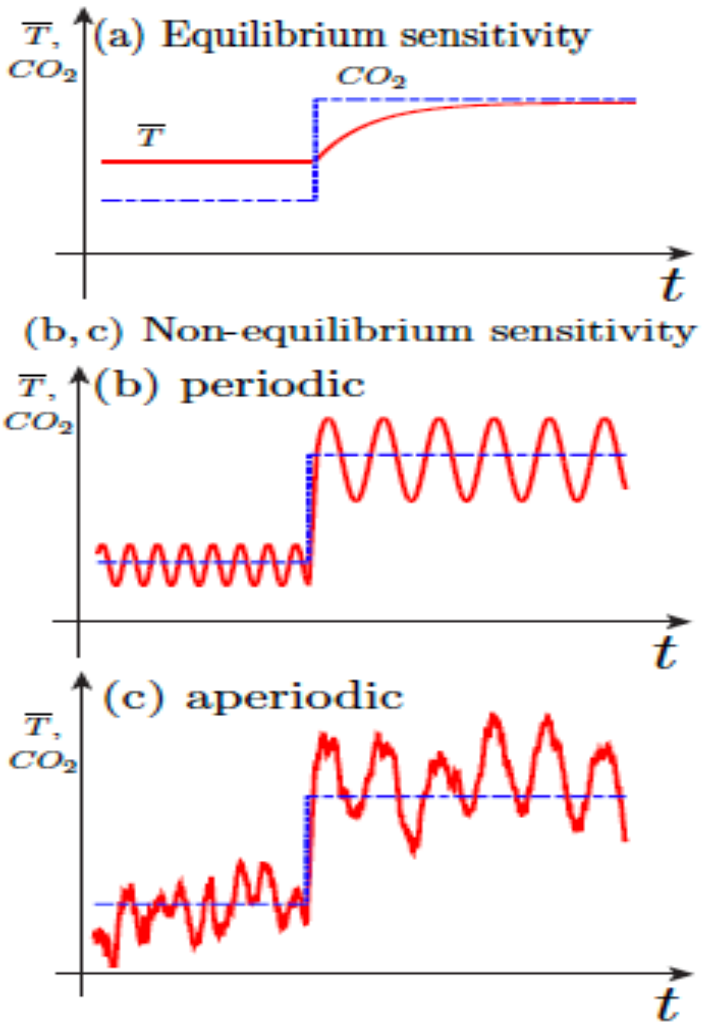



# It leaves several questions unanswered: I

**Energy injection** ( greenhouse gases , forcing) at a given scale

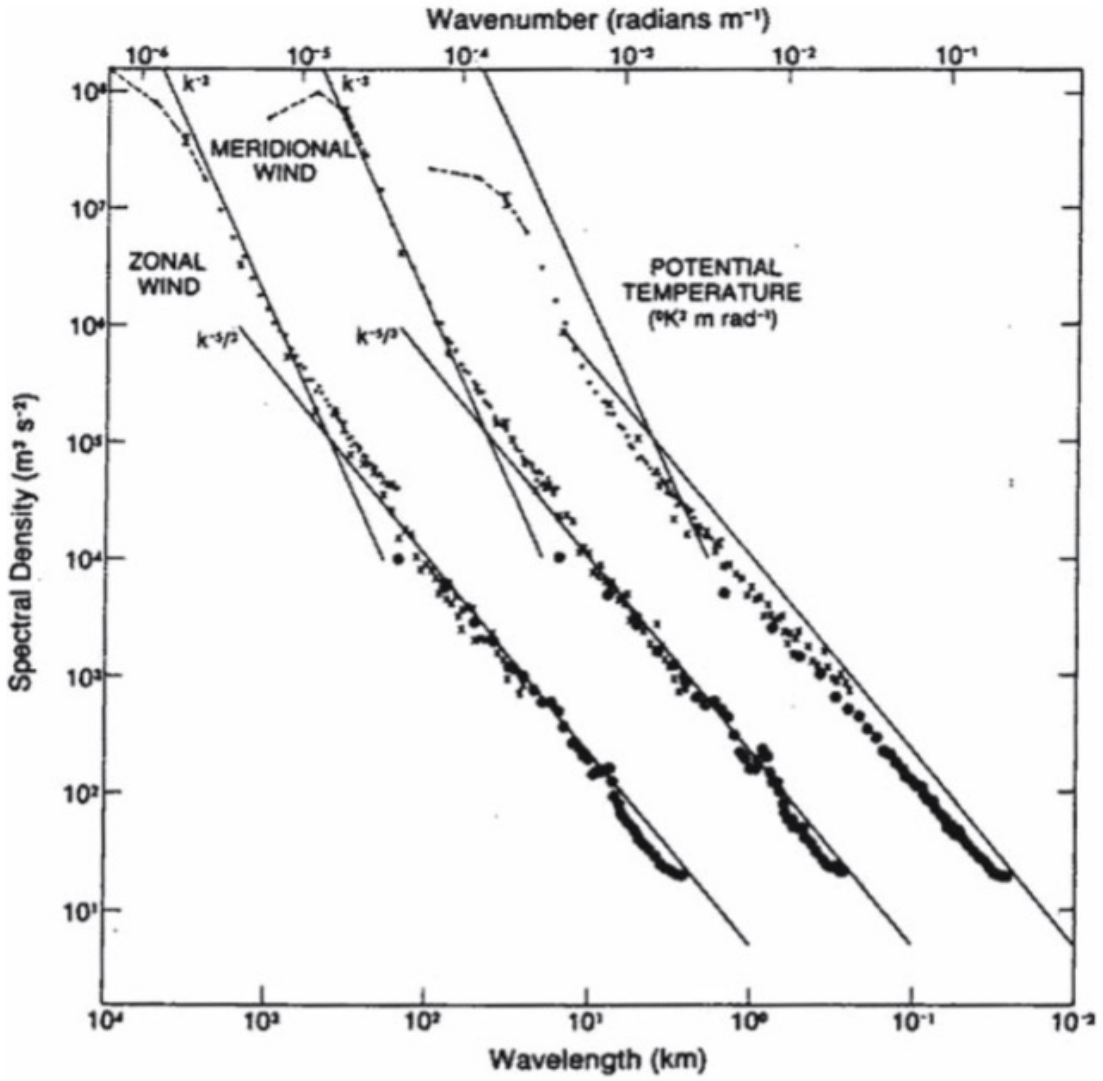
**=> mean** ( jet ) **, coherent** ( Waves ) **and random** ( eddies ) **fluctuations**




Michael Ghil 2019

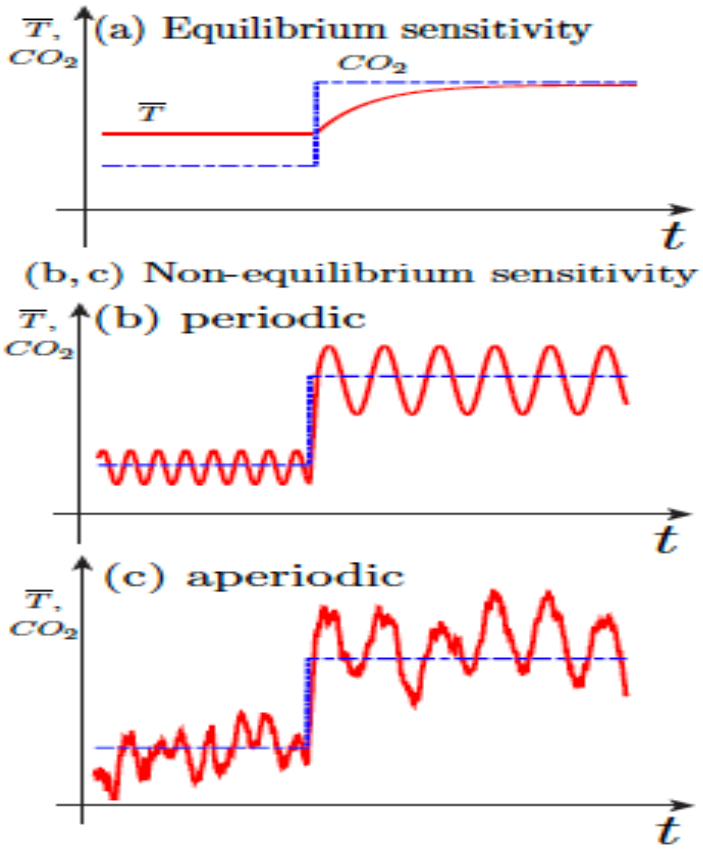
# It leaves several questions unanswered: II

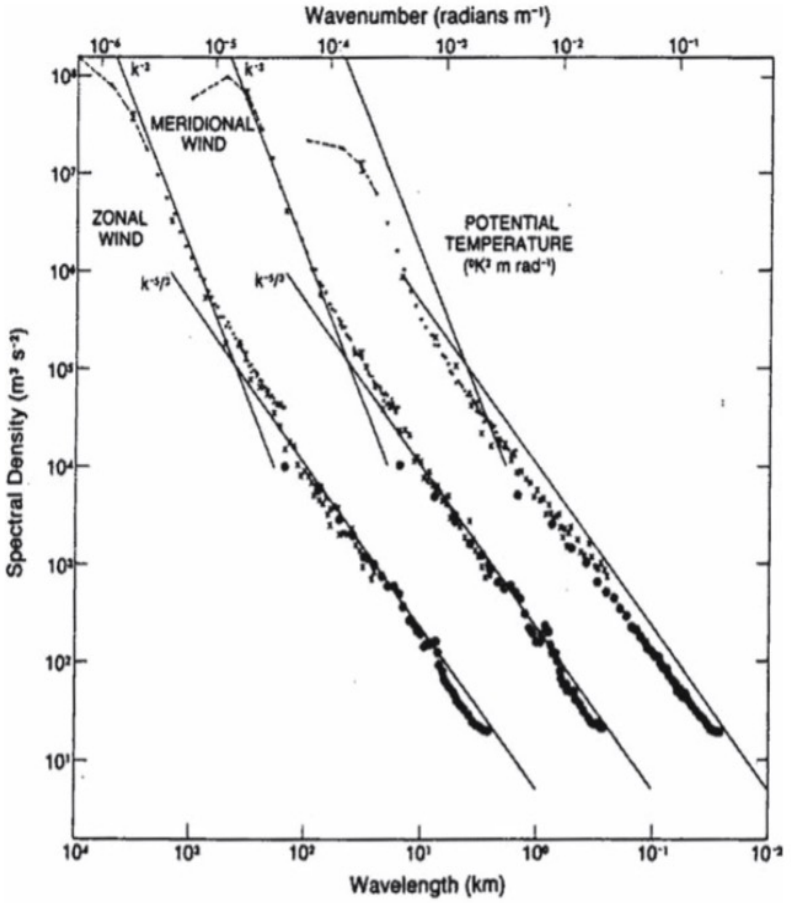
Energy travels **across scales**




Nastrom and Gage, 1985

# Question to be answered:

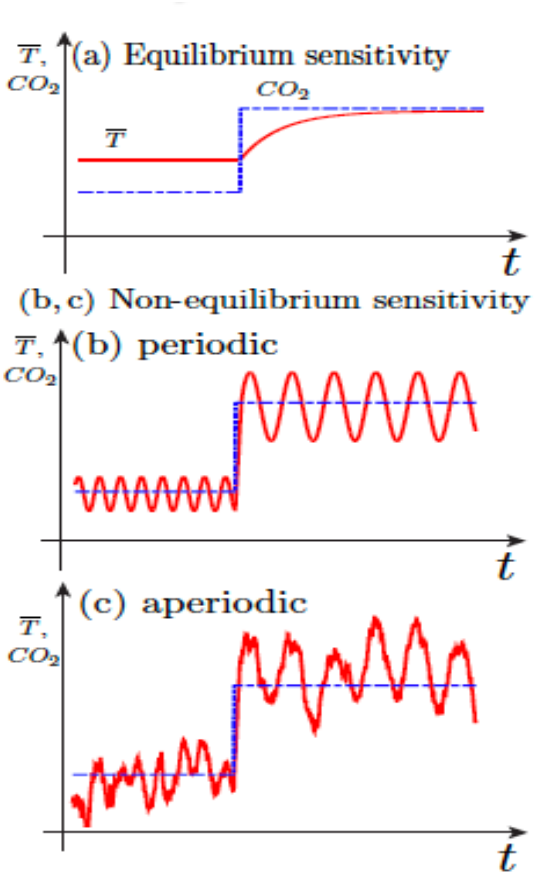



What are the **respective parts of mean, coherent and random atmospheric fluctuations**, and their **transfer across scales**, and how did the they trigger the summer 2003 **blocking event**?

# Methodology I: Triple Decomposition

Temperature = Mean (**jet stream**) + coherent (**Rossby & Gravity Waves**) + random (**Eddies**)




$$T = \overline{T} + \tilde{T} + T'$$

# Methodology I: Triple Decomposition

Currently used Methods:

- Empirical Method Decomposition and Variants ( **EMD** )
  - Limitations: No mathematical theory, time scale based, mixing of modes

- **Fourier transform** and Variants:
  - Limitations: Assumes strict periodicity, time scale based , linear interactions

- **Wavelet** based
  - time scale based, linear interactions.

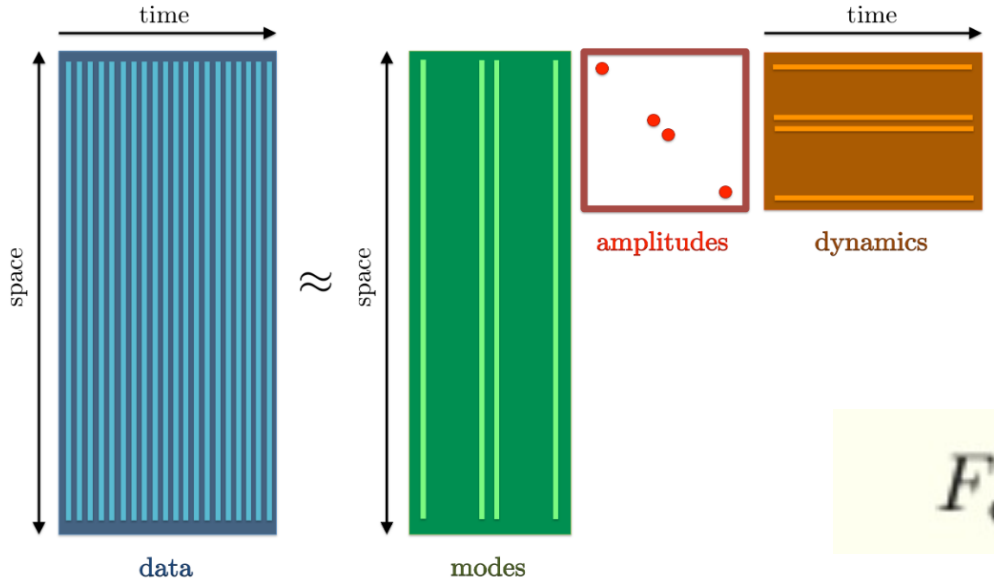
Decomposition method used: **Sparsity-promoting Dynamic Mode Decomposition** ( Jovanovic et al. 2014 )

- based on spatiotemporal dynamics = > Non linear spatiotemoral interactions are taken into account

# Methodology I: Triple Decomposition

Decomposition method used: **Sparsity-promoting Dynamic Mode Decomposition** ( Jovanovic et al. 2014 )

- Based on POD but with spatiotemporal conjugate Matrix
- Autonomous dynamical system: The next snapshot can be extracted from the previous
- SPDMD is an inter-snapshot SVD decomposition




$$\Psi_0 = \begin{bmatrix} \psi_0 & \psi_1 & \cdots & \psi_{N-1} \end{bmatrix} \in \mathbf{C}^{M\times N}$$

$$\Psi_1 = \begin{bmatrix} \psi_1 & \psi_2 & \cdots & \psi_{N} \end{bmatrix} \in \mathbf{C}^{M\times N}$$

$$\psi_{t+1} = A\,\psi_t, \quad t = \{0,\ldots,N-1\}$$

$$A = U\,F\,U^*.$$

$$F_{\mathrm{dmd}} = U^*\,\Psi_1\,V\,\Sigma^{-1}$$

# Methodology I: Data

ERA5 Reanalysis: 06/01/2003-08/31/2003

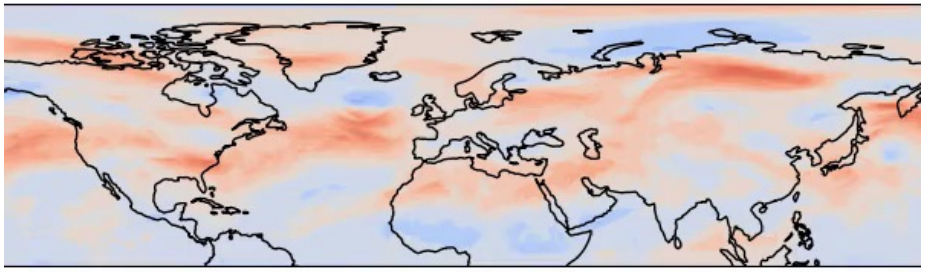
- Hourly time step
- Northern hemisphere @ 0.25° by 0.25° resolution (~30km)
- Three pressure levels: 200hPa (~9km height), 500hPa (~5km height), 850 hPa (~2km height)
- Variables used in computations (Total, Mean, Coherent, Random) : Temperature, Zonal Wind, Meridional Wind, TOA Net Thermal radiation, atmosphere gases/clouds feedback climate kernels

We will show computations mostly at the 500hPa pressure level because it represents a good approximation of both upper tropopause and near-surface flows.

# Methodology I: Triple Decomposition

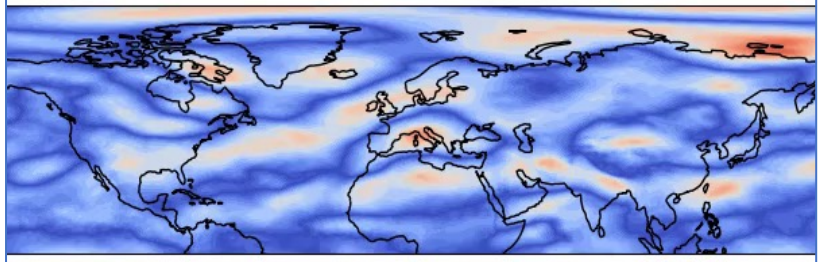
Temperature

2003/06/01/01/00



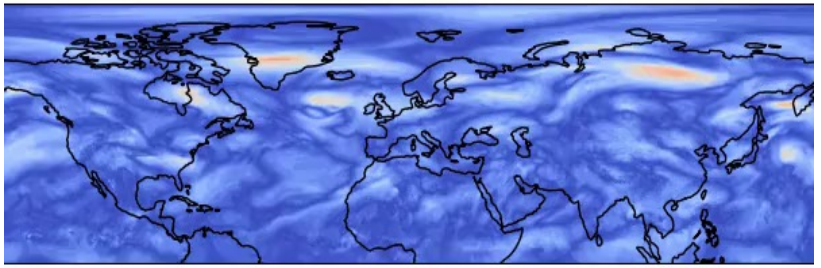
Coherent T

2003/06/01/01/00



Random T

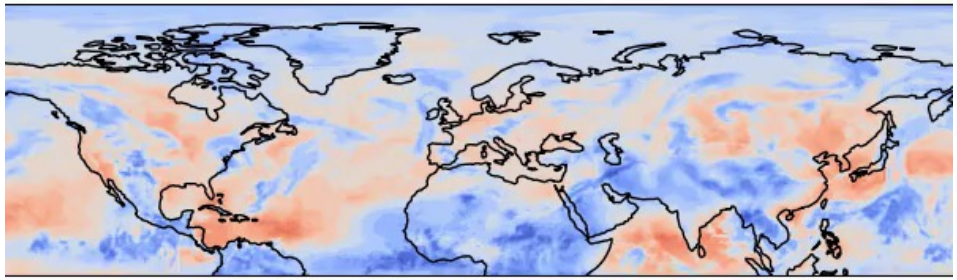
2003/06/01/01/00



# Methodology I: Energy injection and Forcing

Net Thermal radiation @ 500hPa

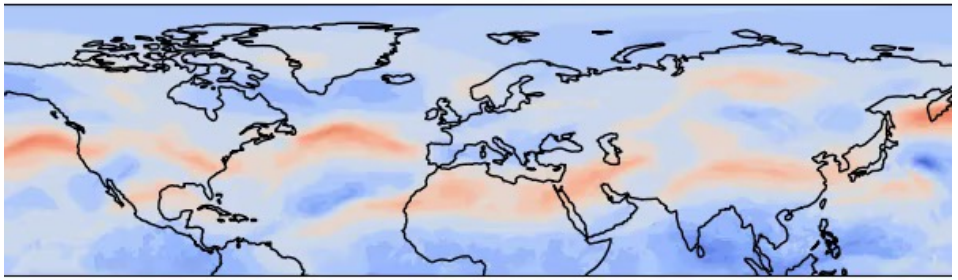
2003/06/01/01/00



(red colors => net thermal radiation deficit )

Temperature @ 200 Hpa

2003/06/01/01/00



- Deficit progressively stagnates and increases over the Middle East and North of the Himalayan Range
- => Excess energy heats the atmosphere around those locations

- The Jet steam progressively breaks East of those areas
- => Large stagnating eddies appear West of Europe

# Methodology I: Decomposed Variance

Coherent T Variance

2003/06/01/01/00

Random T Variance

2003/06/01/01/00

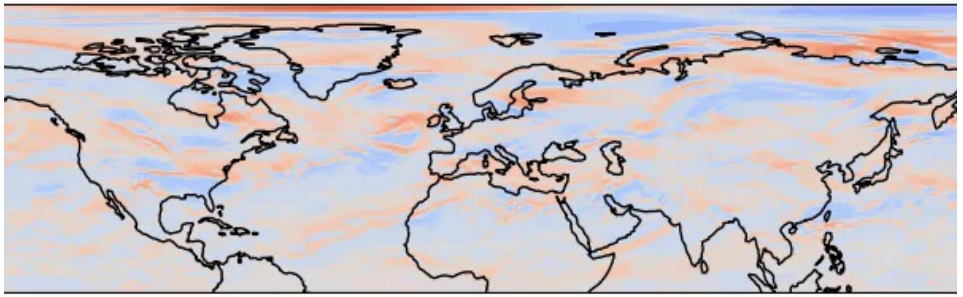
(white/red colors => high T Variance )

- Coherent T Variance decreases over western Europe is correlated with sudden increase in variance North Eurasia and East Asian Seas

- Random T Variance progressively bypasses West Europe around beginning of July
- Large mixing occurs in Eurasia at the same Time

# Methodology I: Decomposed  Variance Production

Coherent T Variance production
(due to mean T gradients)
2003/06/01/01/00



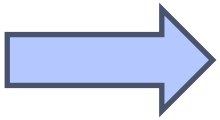
Random T Variance Production
(due to mean and coherent T gradients)
2003/06/01/01/00

(white/red colors => positive Prod / blue colors = negative Prod )

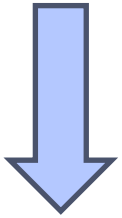
- Coherent T Variance progressively decreases west of Europe but increases in Eurasia at the same time.
- Random T Variance Prod stays about the same intensity but stockpiles on the western Europe continent before bypassing it.
- Eurasian Random Prod occurs at large spatial scale over Siberia

# Methodology I: Temptative explanation

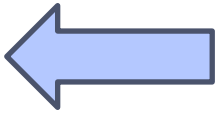
Net radiation Deficit Middle-East/North of Himalyan Range



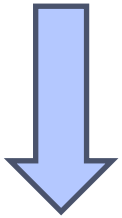
Increase in the poleward temperature advection around those longitudes



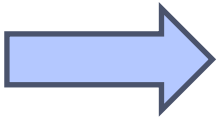
Rossby Wave Break West of this poleward advection



Large eddies appear both on the North West Side, and the North East-Side



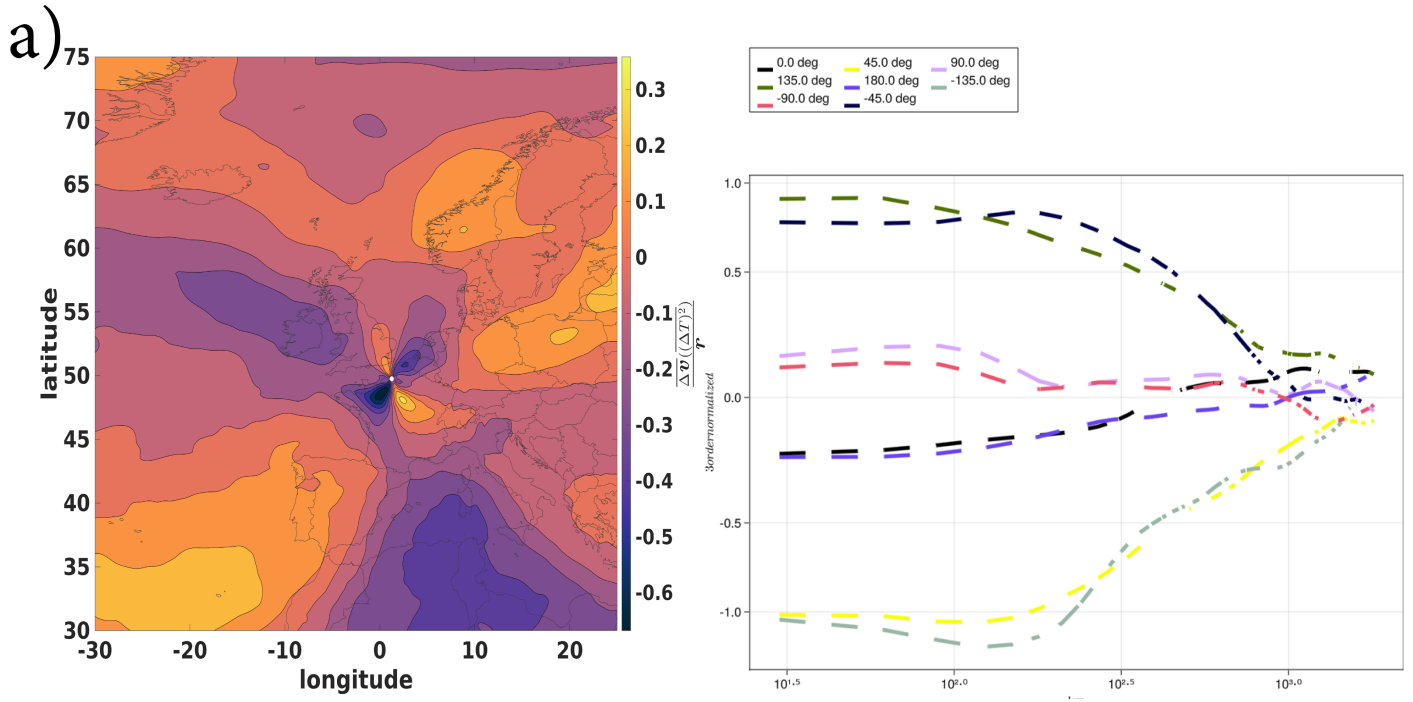
France is sandwiched between those two sides with hot air coming from south and no westerlies due to wave breaking



**Blocking Event**

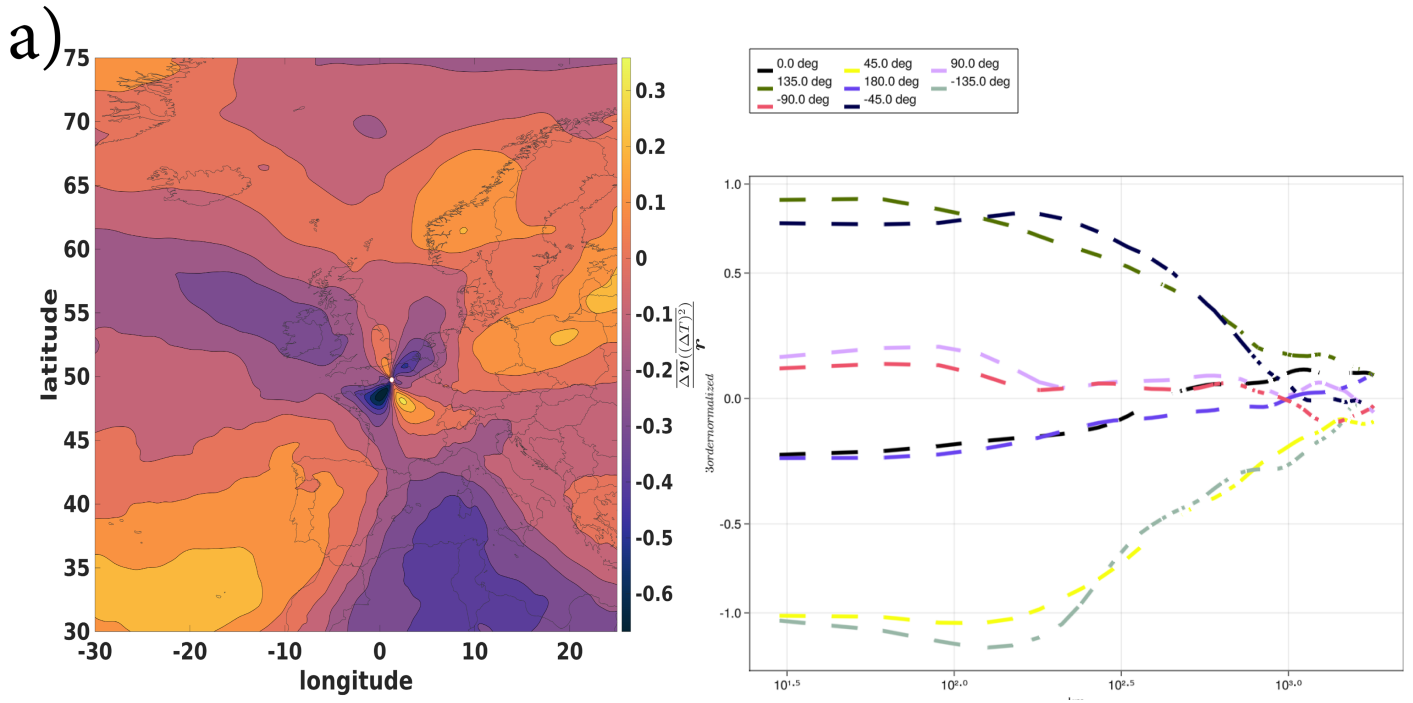
# Methodology II: Energy Transfer Across Scales

Temperature Variance Cascade (August 2003 average)




- Left: Energy cascade direction around Rouen ( blue colors: direct/Yellow: inverse)
- Right: Energy cascade direction in selected direction from Rouen ( dash lines: direct/ dotted lines: inverse)

# Methodology II: Energy Transfer Across Scales




For random fluctuations:

- **Direct cascade** => Eddies break into smaller eddies
- **Inverse cascade** => Eddies merge into larger eddies

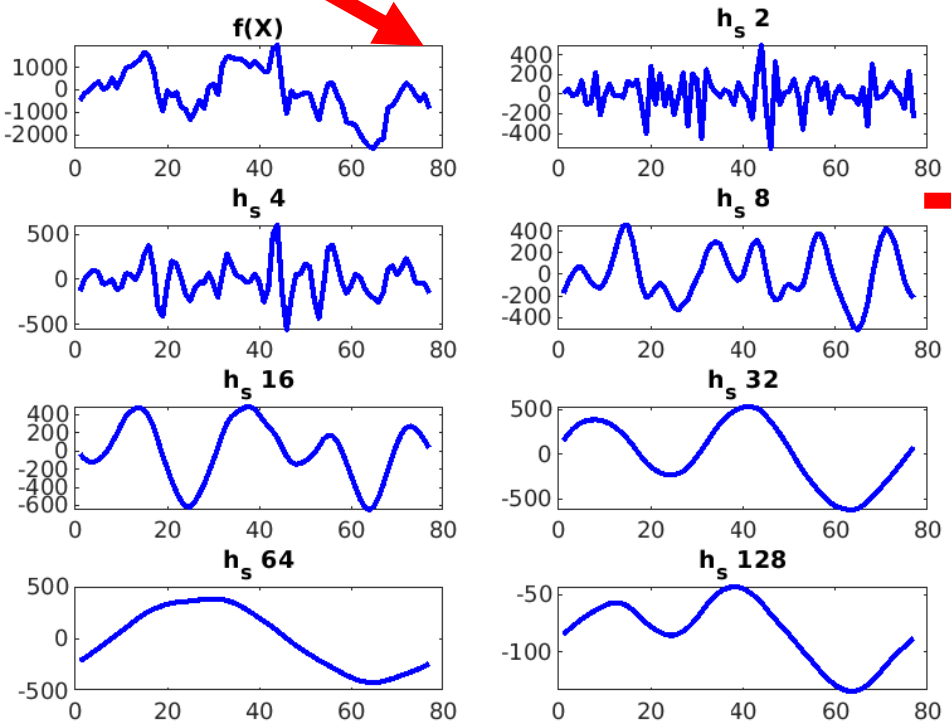
This butterfly shape may be due to alternating eddies bypassing Europe on the north, and coming from the south, creating eddies stretching which forces surrounding eddies to either merge and break.

# Summary

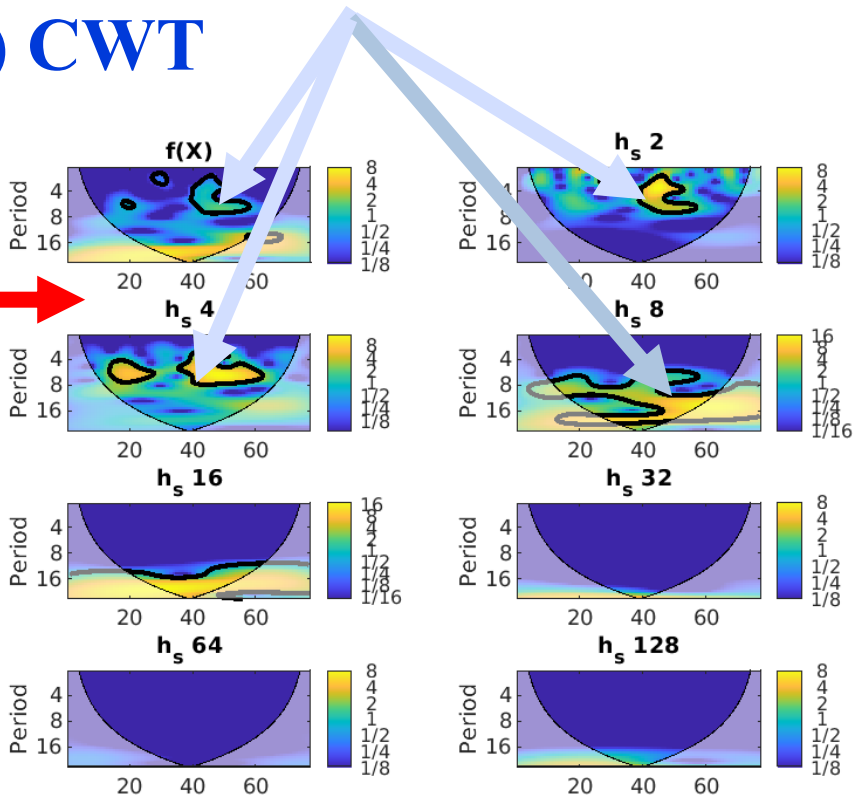
ご清聴ありがとうございました。

# 3) Separation

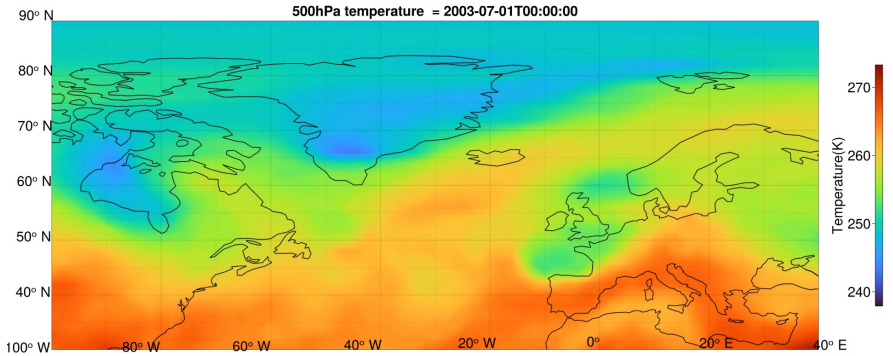
## 1) MRA




## 2) CWT



# 1. Context. Blocking during the 2003 summer heat wave

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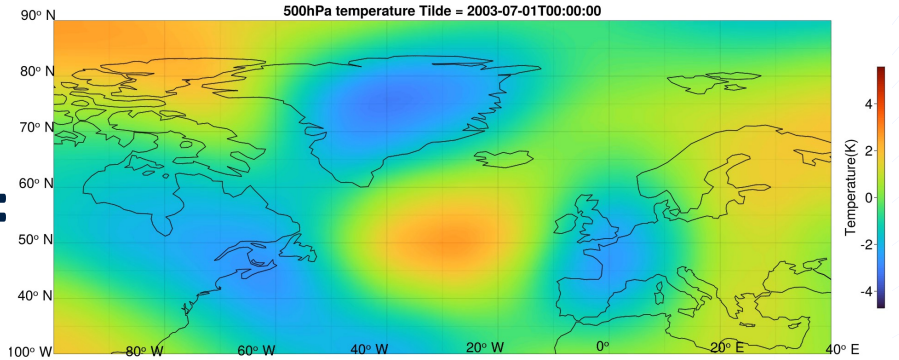


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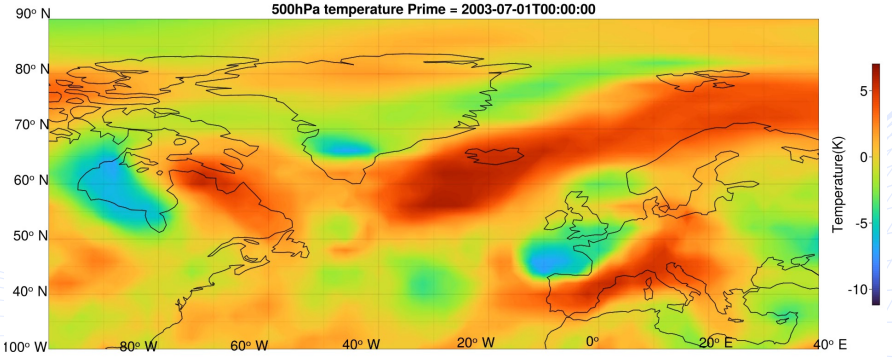
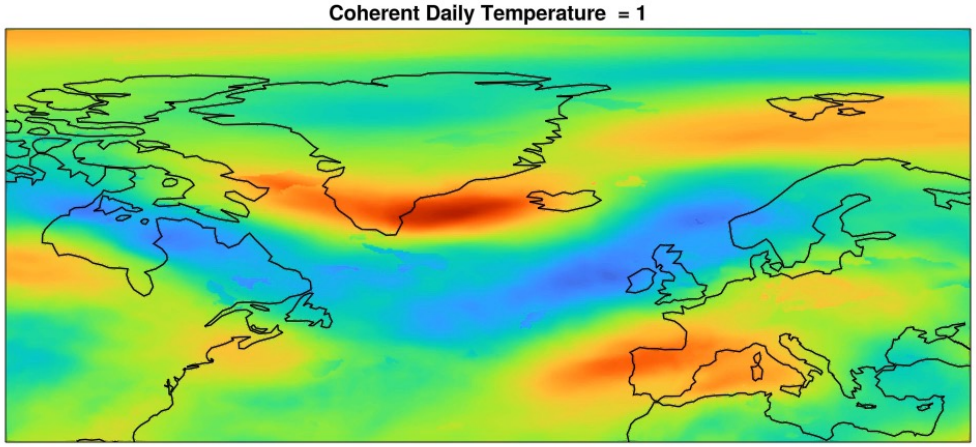
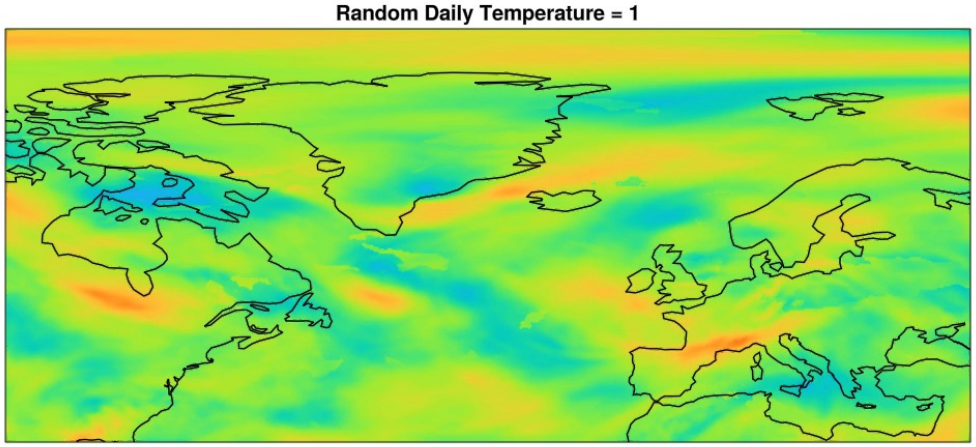



**Mean + CM/Waves + Eddies = Turbulence at all spatiotemporal scales**

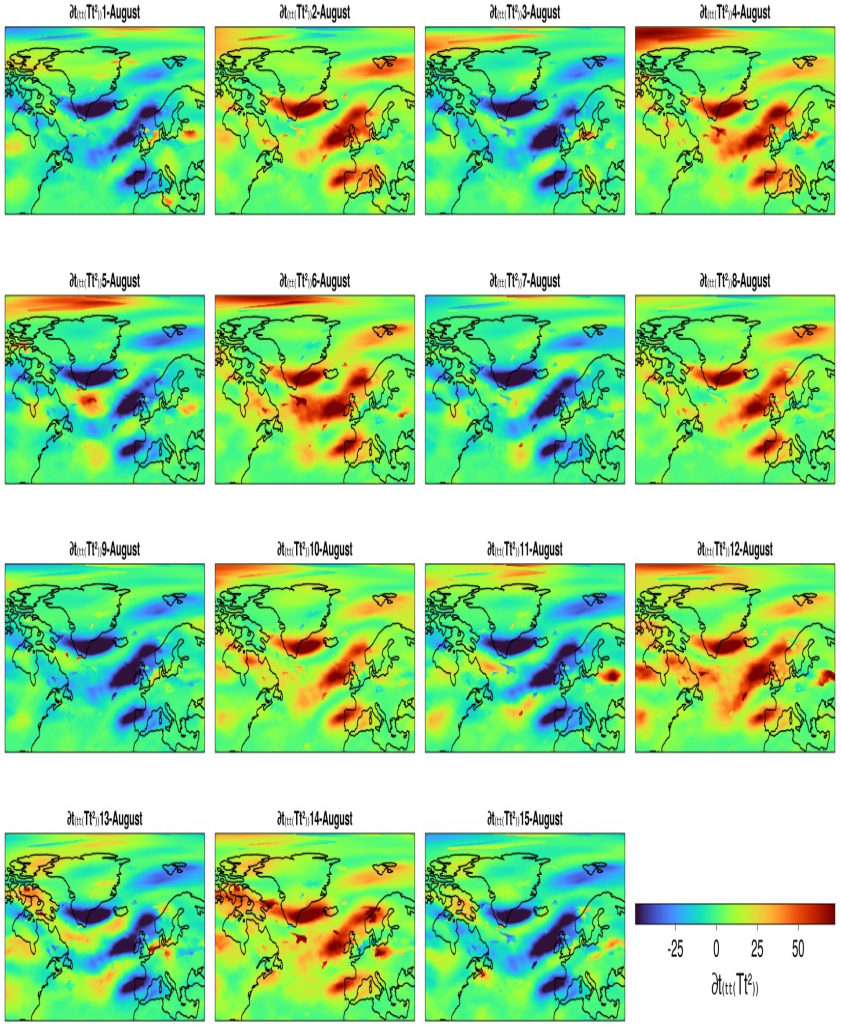
# 4) Sum



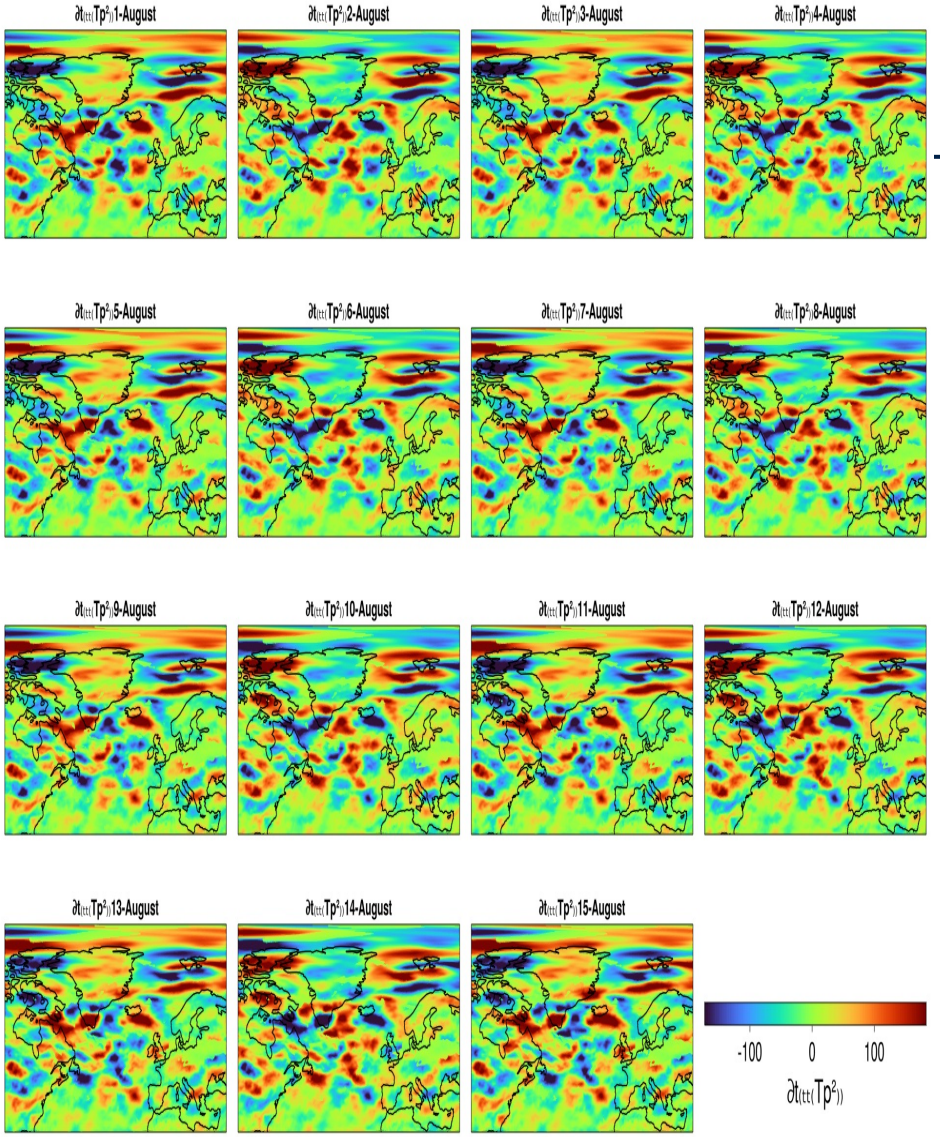



# Instantaneous 1-point temperature energy budget

## (1st – 16th August)

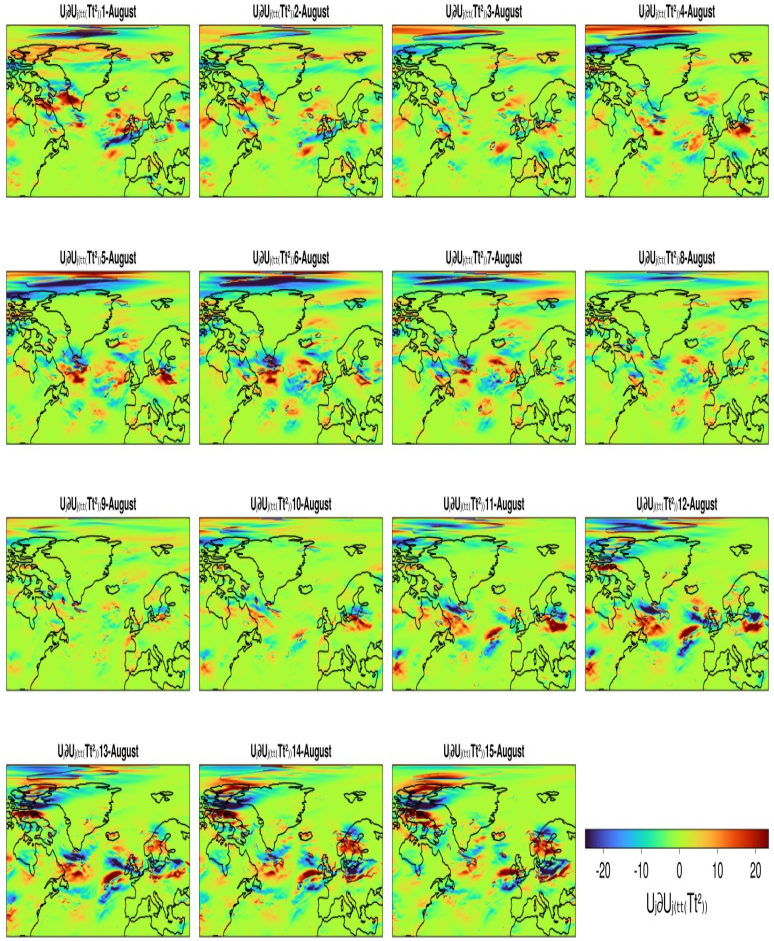



$\partial_t \tilde{T}^2$



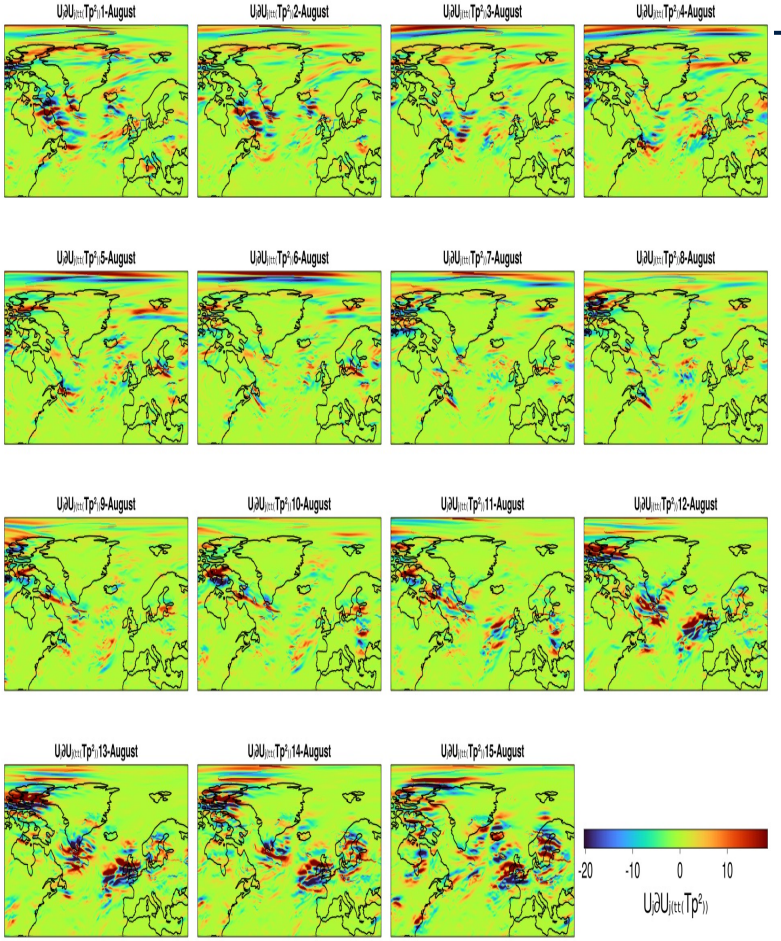

$\partial_t T'^2$

- **Stalled wave**
- **Random fluctuations trapped by stalled wave**
- **Small temperature fluctuations over France**



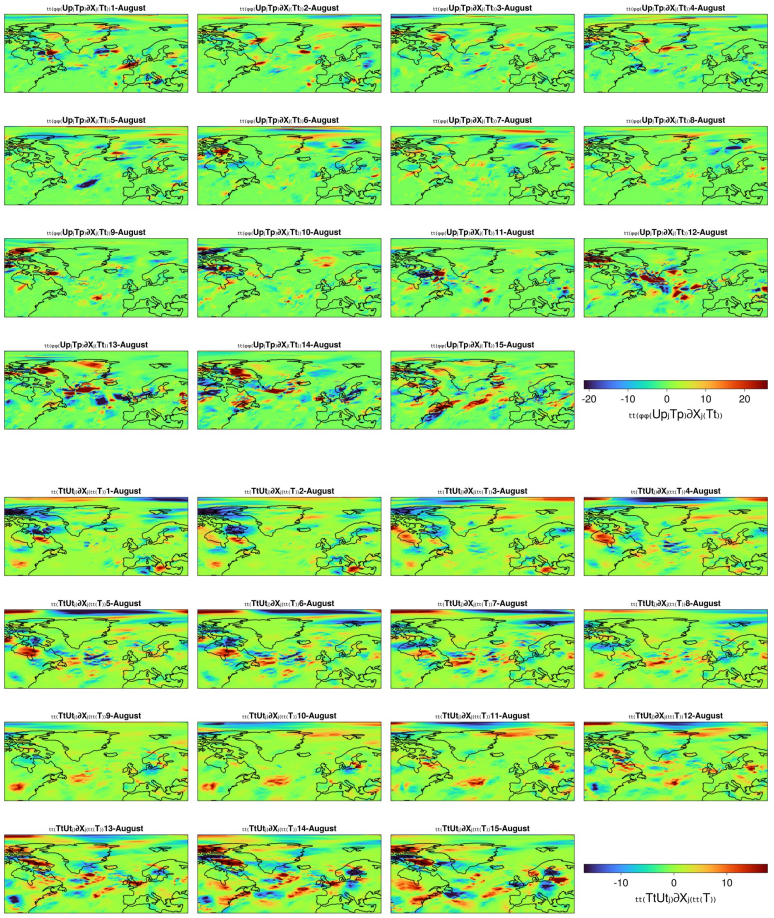

$\bar{U}\partial_x\tilde{T}^2$

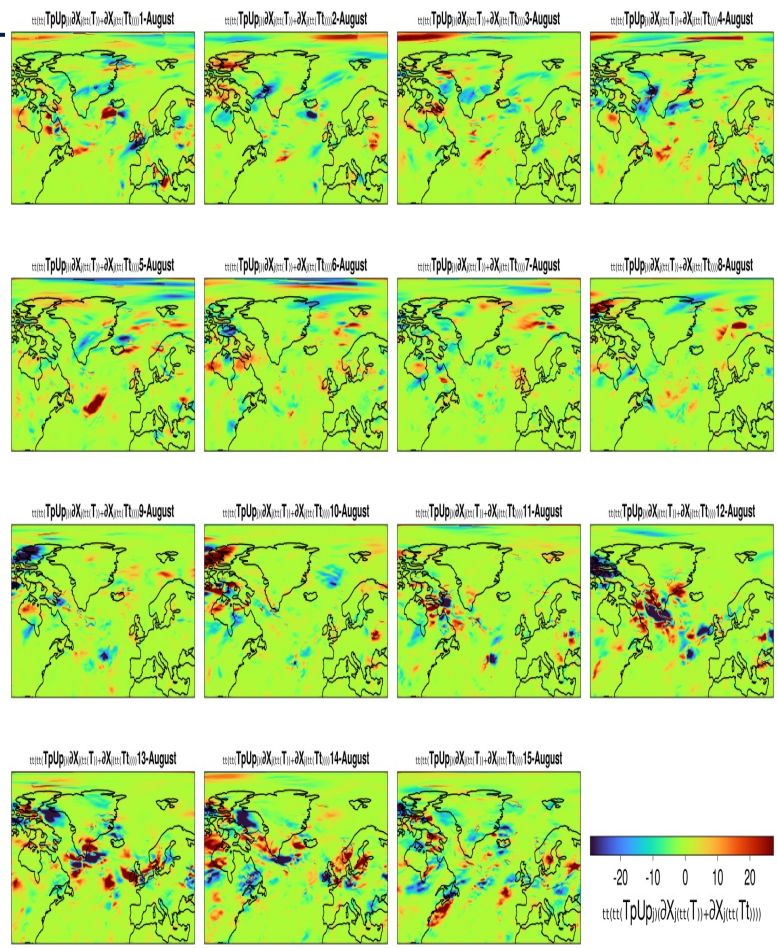
- *Transport confined to North Atlantic up to 10 August*




$\bar{U}\partial_x T'^2$

- Random fluctuations regain energy after coherent motions start again



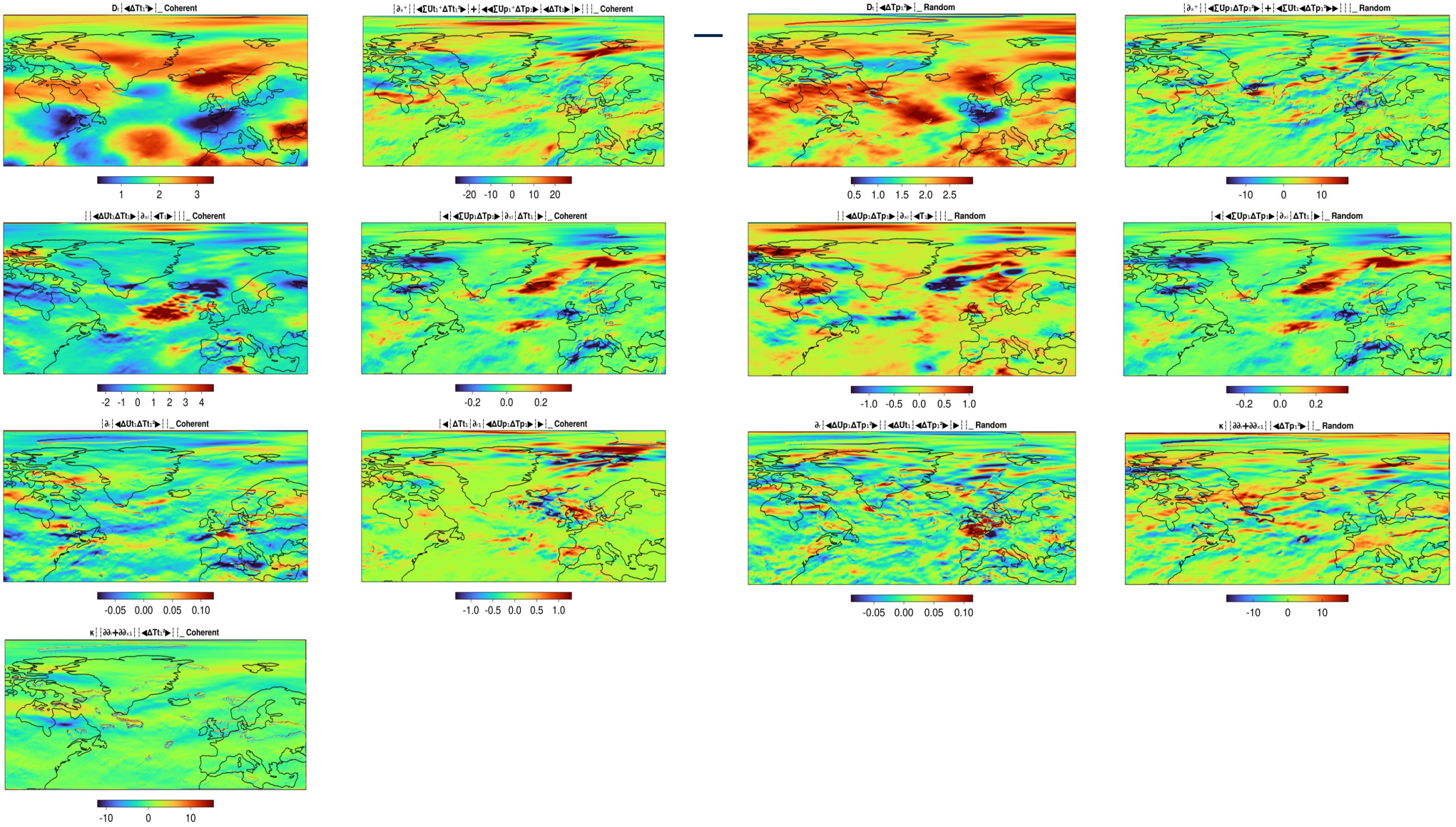




$\langle U'T' \rangle \partial_x \tilde{T} - \tilde{U}\tilde{T}\partial_x \bar{T}$

Production both positive and negative, moves eastward gets stuck then Starts again. Important production from exchanges with random from 11th

$T'U'[\partial_x \bar{T} + \partial_x \tilde{T}]$

- Production starts again as soon as coherent activity restarts


Dt⌈◀ΔTt1▶⌉_ Coherent
1 2 3
⌈∂x+⌈⌈◀[Σ]Ut1+ΔTt1▶⌉+⌈◀◀[Σ]Up1+ΔTp1▶⌈◀ΔTt1▶⌉▶⌉⌉⌉_ Coherent
-20 -10 0 10 20
Dt⌈◀ΔTp1▶⌉_ Random
0.5 1.0 1.5 2.0 2.5
⌈∂x+⌈⌈◀[Σ]Up1ΔTp1▶⌉+⌈◀[Σ]Ut1◀ΔTp1▶▶⌉⌉⌉_ Random
-10 0 10
⌈⌈◀ΔUt1ΔTt1▶⌈∂x⌉⌈◀T1▶⌉⌉⌉_ Coherent
-2 -1 0 1 2 3 4
⌈◀⌈◀[Σ]Up1ΔTp1▶⌈∂x⌉⌈ΔTt1⌉▶⌉_ Coherent
-0.2 0.0 0.2
⌈⌈◀ΔUp1ΔTp1▶⌈∂x⌉⌈◀T1▶⌉⌉⌉_ Random
-1.0 -0.5 0.0 0.5 1.0
⌈◀⌈◀[Σ]Up1ΔTp1▶⌈∂x⌉⌈ΔTt1⌉▶⌉_ Random
-0.2 0.0 0.2
⌈∂t⌈◀ΔUt1ΔTt1▶⌉⌉_ Coherent
-0.05 0.00 0.05 0.10
⌈◀⌈ΔTt1⌈∂t1⌈◀ΔUp1ΔTp1▶⌉▶⌉_ Coherent
-1.0 -0.5 0.0 0.5 1.0
∂t⌈◀ΔUp1ΔTp1▶⌉⌈◀ΔUt1⌈◀ΔTp1▶⌉▶⌉⌉_ Random
-0.05 0.00 0.05 0.10
κ⌈⌈∂∂+∂∂∂x1⌉⌈◀ΔTp1▶⌉⌉_ Random
-10 0 10
κ⌈⌈∂∂t+∂∂∂x1⌉⌈◀ΔTt1▶⌉⌉_ Coherent
-10 0 10