Interaction between large scales and temperature fluctuations during the 2003 heat wave

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Outline

1. The question

Context of blocking

Problem: – each blocking is unique

– unravel the mechanisms of genesis, persistence and dissipation of each blocking

2. Methodology:

First principles + Triple decomposition framework

– time derivatives of temperature variance

– highlight the interactions between large (quasi-periodic) scales and small-scale statistics during the 2003 heat wave

3. Results

Data analysis (2^{nd}- and 3^{rd}-order moments), summer 2003, ERA5

1. Context – I. The general context of climate

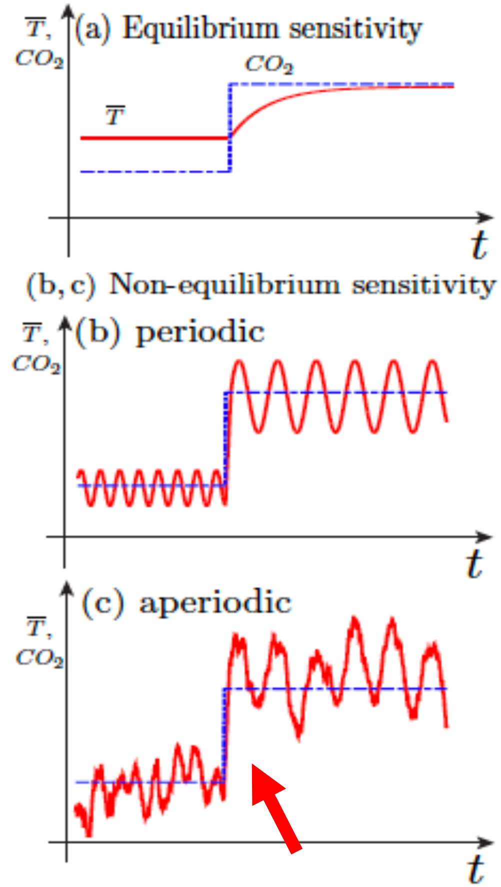
Climate and Its Sensitivity

Let's say CO_2 doubles:

How will "climate" change?

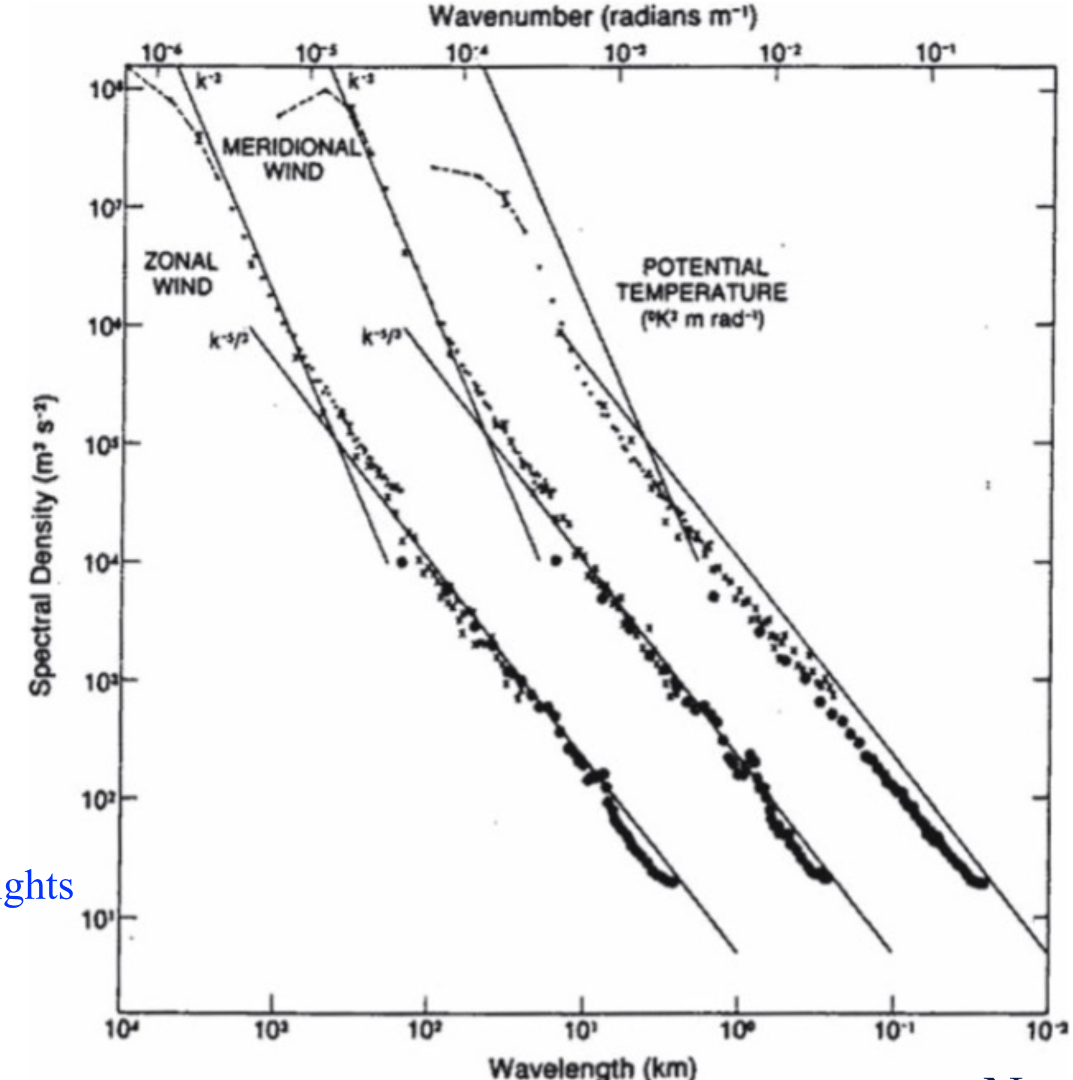
1. Climate is in stable equilibrium (fixed point); if so, mean temperature will just shift gradually to its new equilibrium value.
2. Climate is purely periodic; if so, mean temperature will (maybe) shift gradually to its new equilibrium value. But how will the period, amplitude and phase of the limit cycle change?
3. And how about some "real stuff" now: chaotic + random?

Ghil (in *Encycl. Global Environmental Change*, 2002)



Jump of fluctuations and statistics:
Need for d/dt (M_n)
Here: n = 2, focus on production

1. Context – II. Scales: MacroTurbulence

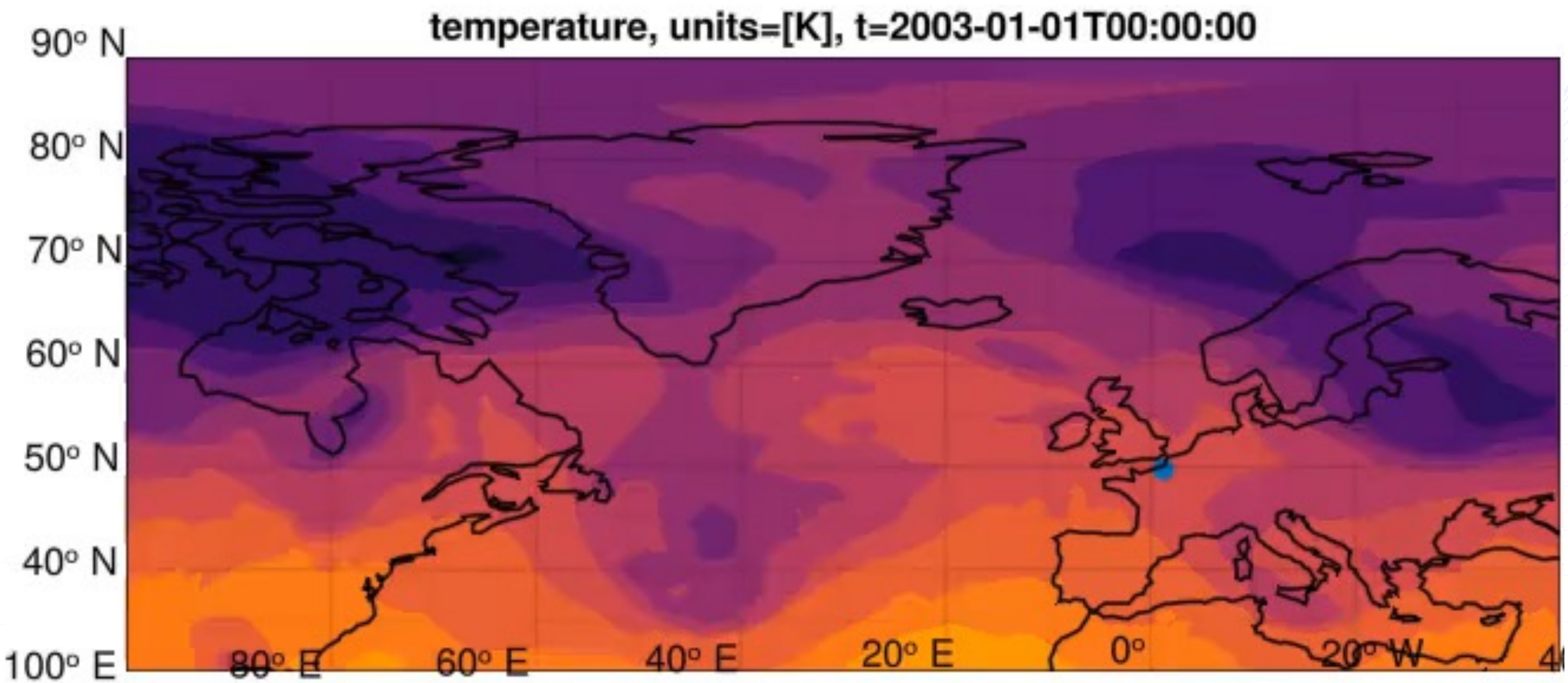


- Obs. from commercial flights
- 9–12km altitude

Nastrom & Gage (1985)

All scales are present: different scalings, reflecting different physical mechanisms

1. Context – III. Blocking vs. heat waves, summer 2003



Hourly 500 hPa Temperature time series for 1 Jan. – 31 Dec. 2003

All scales are present: The MacroTurbulence

The approach. Phase averages

Triple decomposition [3]: $\beta = \overline{\beta} + \widetilde{\beta} + \beta'$

Phase-average: $\langle \beta \rangle = \overline{\beta} + \widetilde{\beta}$

Phase-averaged Strain: $\langle S \rangle = \overline{S} + \widetilde{S} = \frac{1}{2}\left(\frac{\partial \langle U \rangle}{\partial y} + \frac{\partial \langle V \rangle}{\partial x}\right)$

[3] Reynolds and Hussain 1972

Thiesset and Danaila, J. Fluid Mech. 2013,2014, 2020
Bouha, PhD thesis, 2016
Barbano et al., Bdry. Layer Met., 2022
Finnigan and Einaudi…

2. Methodology – II. Transport equations

2.1. *Transport equations for* TT, $\overline{\tilde{\theta}\tilde{\theta}}$ *and* $\overline{\theta'\theta'}$

The starting point is the heat transport equation

$$\frac{\partial \Theta}{\partial t} + U_j \frac{\partial \Theta}{\partial x_j} = \kappa \frac{\partial}{\partial x_j} \frac{\partial \Theta}{\partial x_j} \tag{2.1}$$

Following the triple decomposition of Reynolds & Hussain (1972), the velocity and temperature can be written as

$$\Theta = T + \tilde{\theta} + \theta' \tag{2.2a}$$

$$U_j = \overline{U}_j + \tilde{u}_j + u'_j \tag{2.2b}$$

Substituting (2.2) into (2.1), and then phase averaging, we obtain

$$\frac{\partial \tilde{\theta}}{\partial t} + \overline{U}_j \frac{\partial T}{\partial x_j} + \overline{U}_j \frac{\partial \tilde{\theta}}{\partial x_j} + \tilde{u}_j \frac{\partial T}{\partial x_j} + \tilde{u}_j \frac{\partial \tilde{\theta}}{\partial x_j} + \left\langle u'_j \frac{\partial \theta'}{\partial x_j} \right\rangle = \kappa \frac{\partial}{\partial x_j} \frac{\partial (T + \tilde{\theta})}{\partial x_j} \tag{2.3}$$

The time average of (2.3) gives the equation for the mean temperature field:

$$\overline{U}_j \frac{\partial T}{\partial x_j} + \overline{\tilde{u}_j \frac{\partial \tilde{\theta}}{\partial x_j}} + \overline{u'_j \frac{\partial \theta'}{\partial x_j}} = \kappa \frac{\partial}{\partial x_j} \frac{\partial T}{\partial x_j} \tag{2.4}$$

2. Methodology – III. Transport equations

The transport equation for $\theta'\theta'$ is

$$\frac{\partial \frac{1}{2}\overline{\theta'\theta'}}{\partial t} + \overline{U}_j \frac{\partial \frac{1}{2}\overline{\theta'\theta'}}{\partial x_j} + \frac{\partial \frac{1}{2}\overline{\tilde{u}_j \langle \theta'\theta' \rangle}}{\partial x_j} + \overline{\theta' u'_j}\frac{\partial T}{\partial x_j} +$$

$$\overline{\langle \theta' u'_j \rangle \frac{\partial \tilde{\theta}}{\partial x_j}} + \frac{\partial \frac{1}{2} \overline{u'_j\theta'\theta'}}{\partial x_j} = \kappa \frac{\partial}{\partial x_j}\frac{\partial \frac{1}{2}\overline{\theta'\theta'}}{\partial x_j} - \kappa \overline{\frac{\partial\theta'}{\partial x_j}\frac{\partial\theta'}{\partial x_j}}$$

$$\frac{\partial \frac{1}{2} \overline{\tilde\theta\tilde\theta}}{\partial t} + \overline{U}_j \frac{\partial \frac{1}{2}\overline{\tilde\theta\tilde\theta}}{\partial x_j} + \overline{\tilde\theta\tilde u_j}\frac{\partial T}{\partial x_j} + \frac{\partial \frac{1}{2} \overline{\tilde\theta\tilde\theta\tilde u_j}}{\partial x_j} +$$

$$\frac{\partial \overline{\tilde\theta\langle\theta' u'_j\rangle}}{\partial x_j} - \langle\theta'u'_j\rangle\frac{\partial\tilde\theta}{\partial x_j} = \kappa\frac{\partial}{\partial x_j}\frac{\partial\frac{1}{2}\overline{\tilde\theta\tilde\theta}}{\partial x_j} - \kappa\overline{\frac{\partial\tilde\theta}{\partial x_j}\frac{\partial\tilde\theta}{\partial x_j}}$$

3. Results – I: August 2003

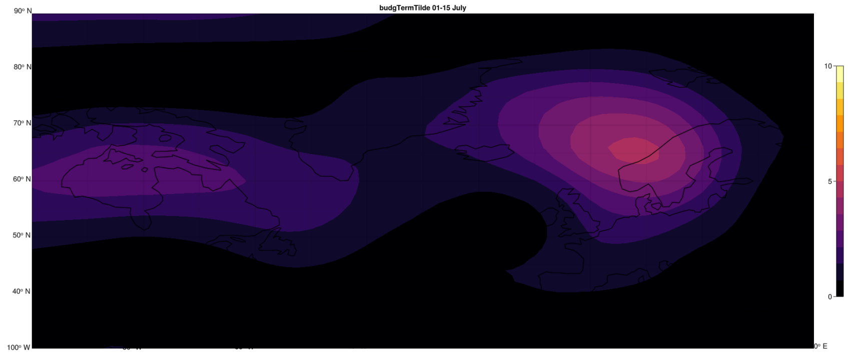
Here, we show:

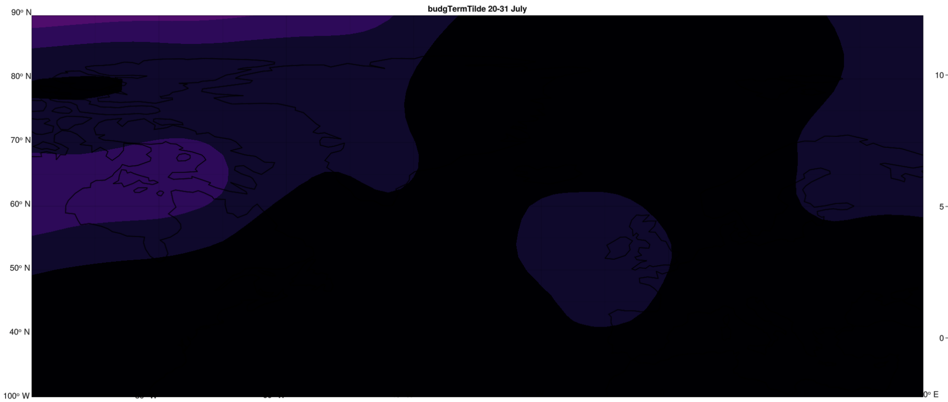
Decomposition EMD space-time (Huang)

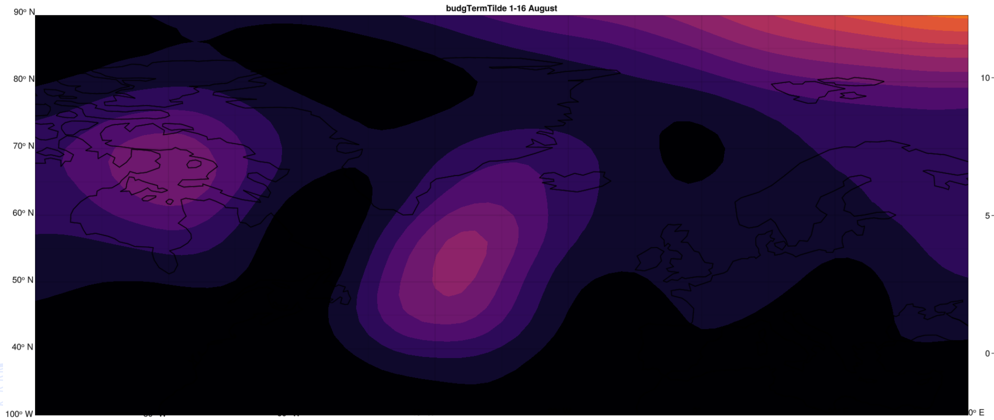
One-point statistics

Variance (CM, RM)
Production terms (CM and RM), Advection, ….

3. Results: Variance of CM temperature, periods 1, 2 and 3

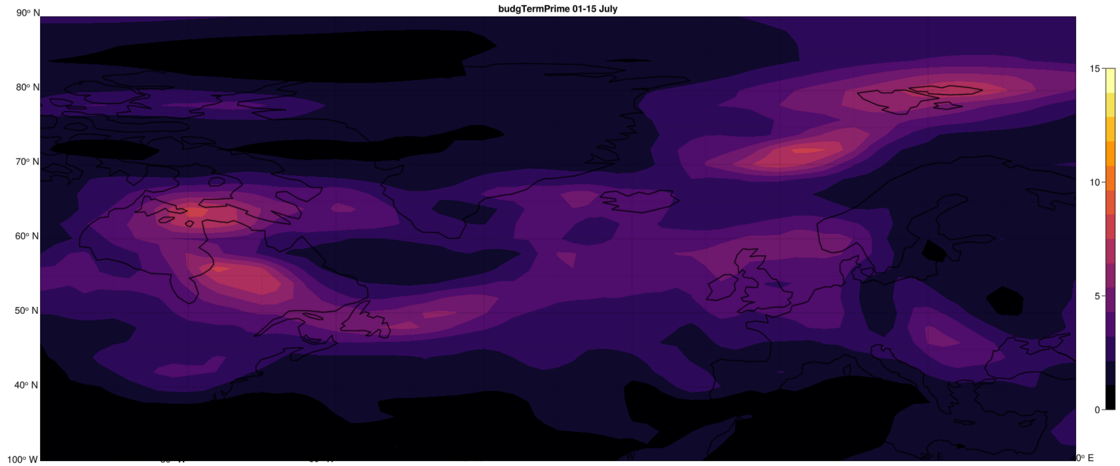


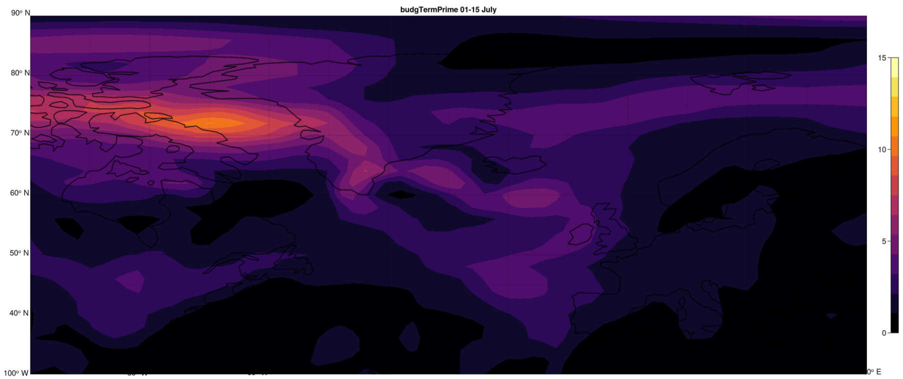


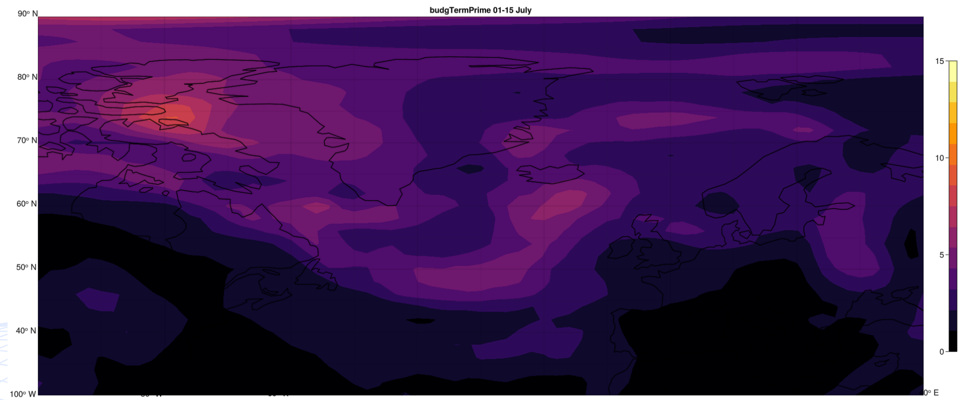


Less and less fluctuations for Europe (both CM and RM)

3. Results: Variance of RM temperature, periods 1, 2 and 3

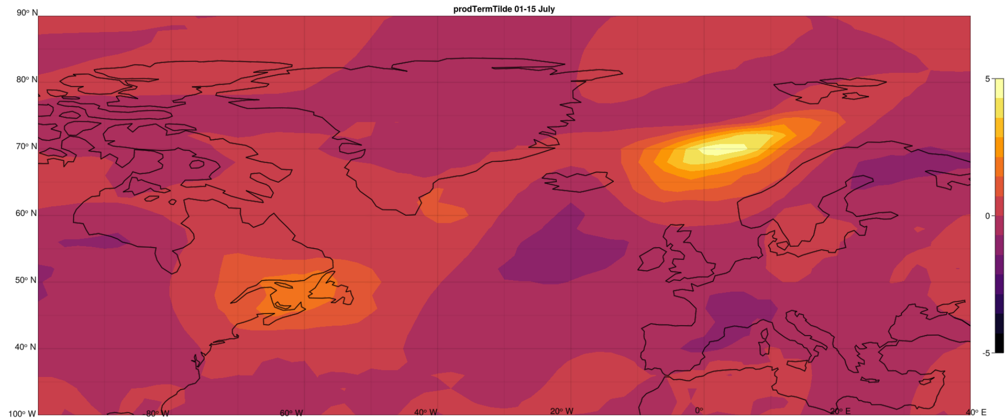


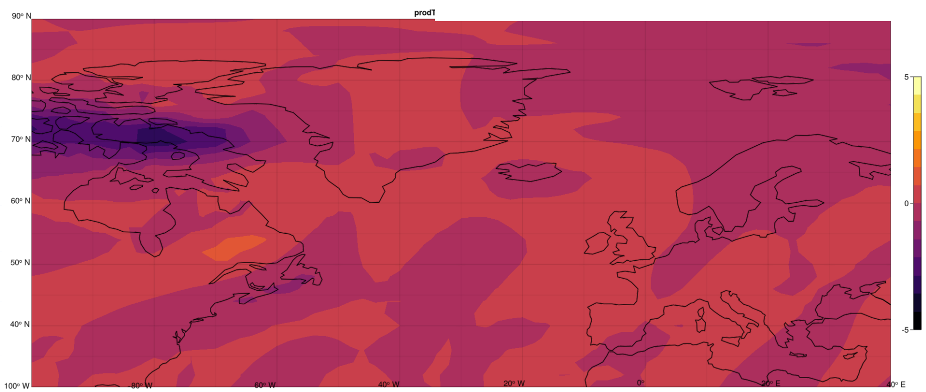


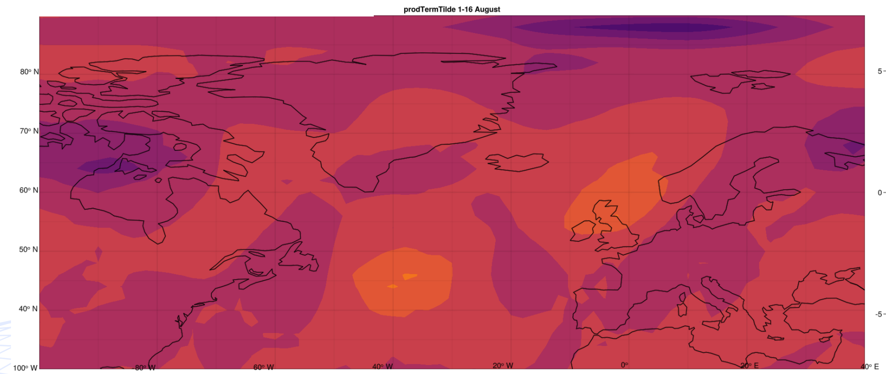


Less and less fluctuations for Europe (both CM and RM)

3. Results: Production of Coherent for 3 periods

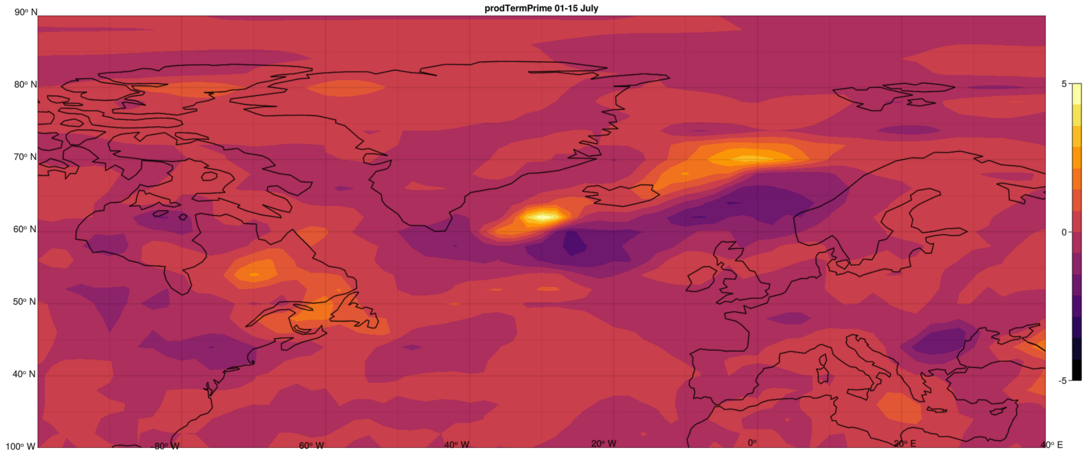


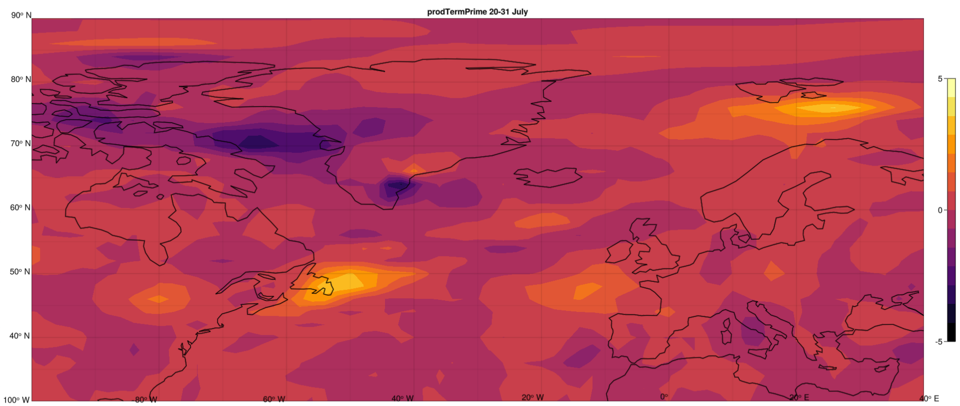


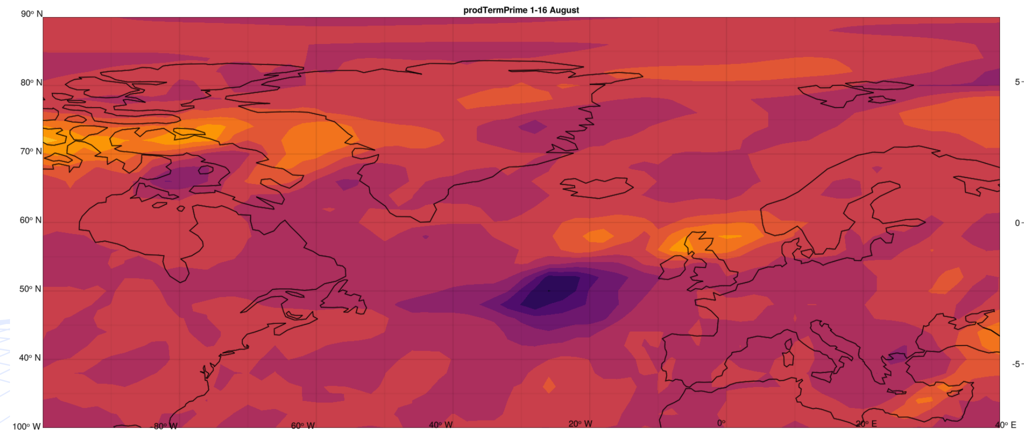


Production which is both positive and negative (sink-like)
Smaller and smaller (absolute) values of the production towards August

3. Results: Production of Random for 3 periods



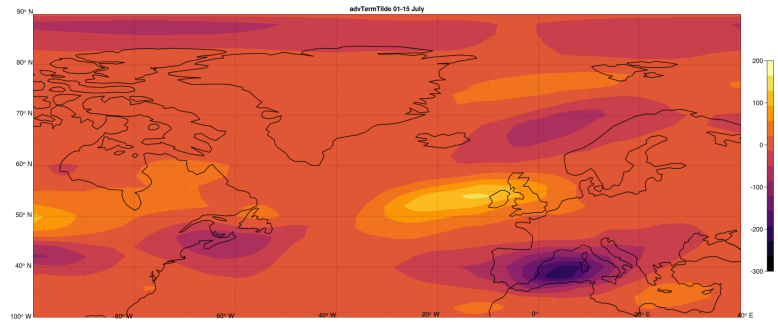


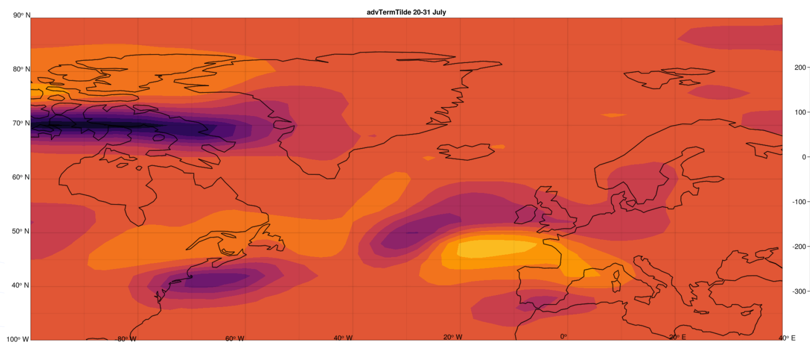


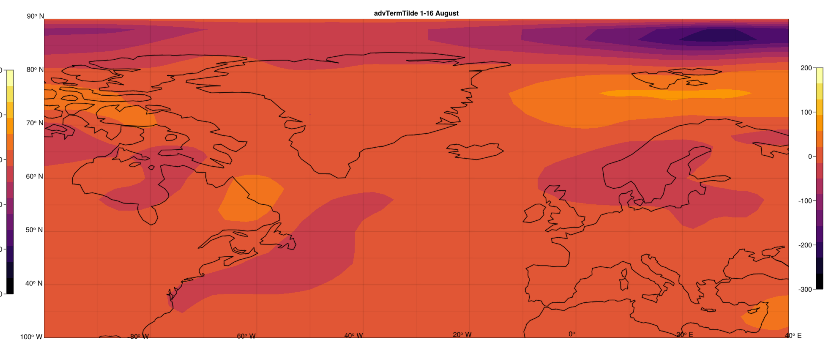
Larger values and more rapid dynamics for RM

Production which is both positive and negative (sink-like)

3. Results: Advection of Coherent motion

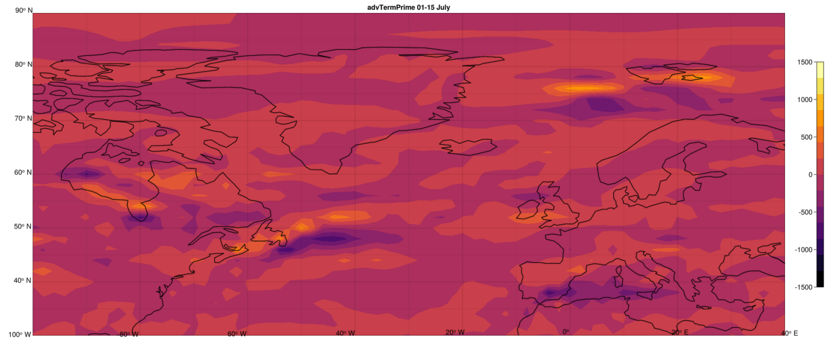


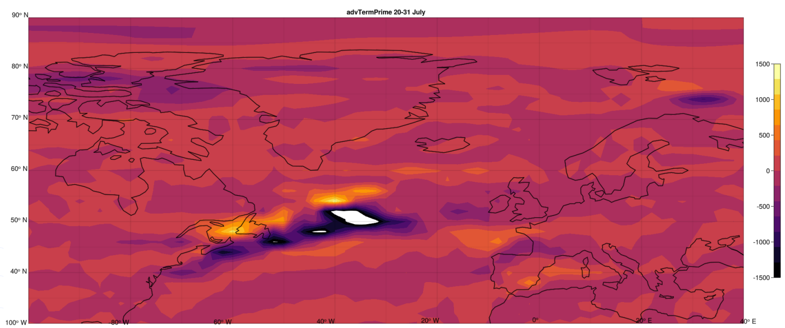


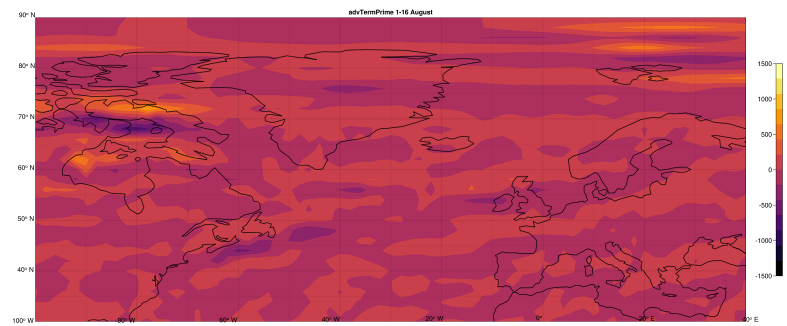


Smaller and smaller values towards August
Spatial extent of the motions CM

3. Results: Advection of Random motion







Smaller and smaller values towards August
Spatial extent of the motion, reduced over small scales

4. Conclusions

Key results

-Decomposition of the motion in CM and RM (EMD)

-Transport equations for CM and RM of temperature at 500 hPa

-Production term, both positive and negative (sink)

- Both 2nd- and 3rd-order structure functions disagree with Nastrom & Lindborg observations (difference in altitude and the use of Taylor hypothesis).

3. Results

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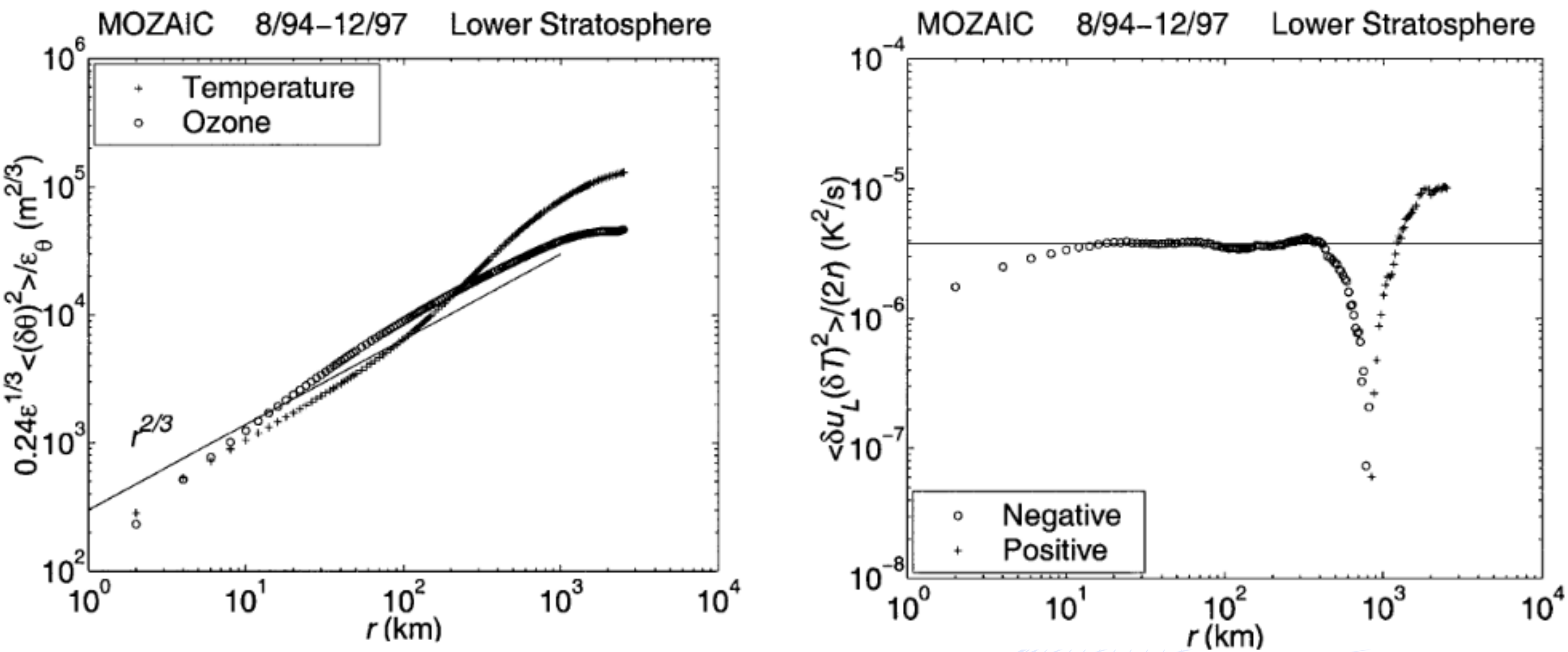
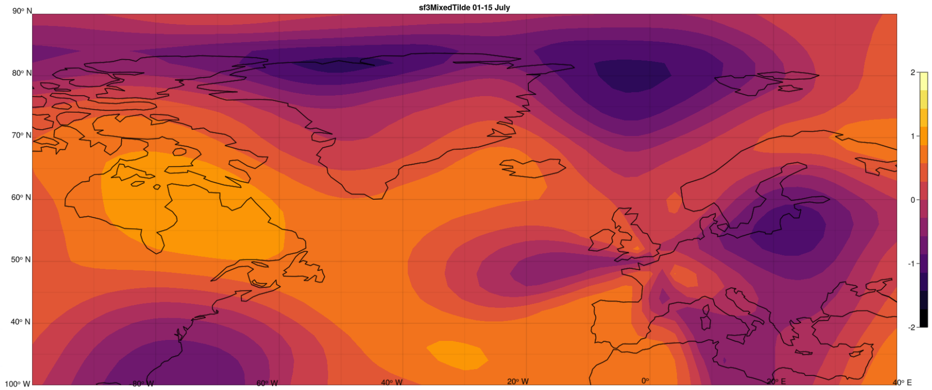


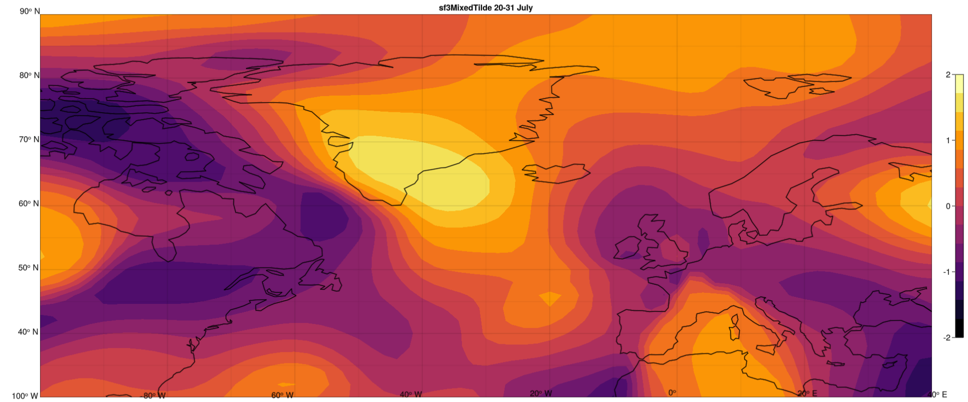
- Obs from commercial flights
- 9-12km altitude
- Temperature derived from velocity via Taylor hypothesis

(Linborg and Cho, 2000)

3. Results

Third-order mixed Structure functions for July 2003 (left) and August 2003 (right)



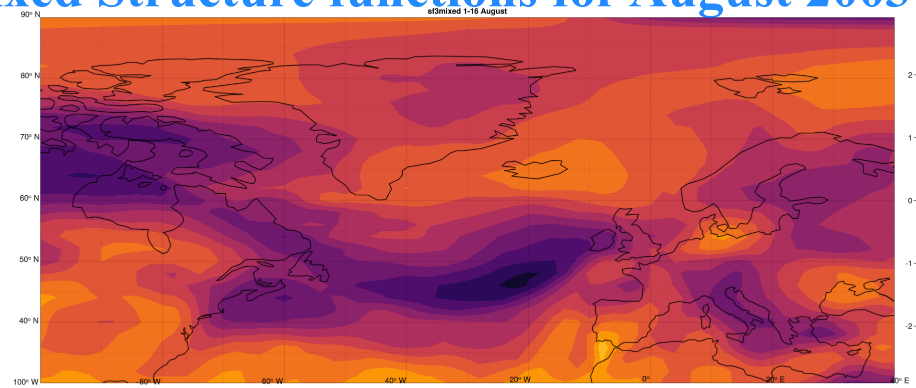


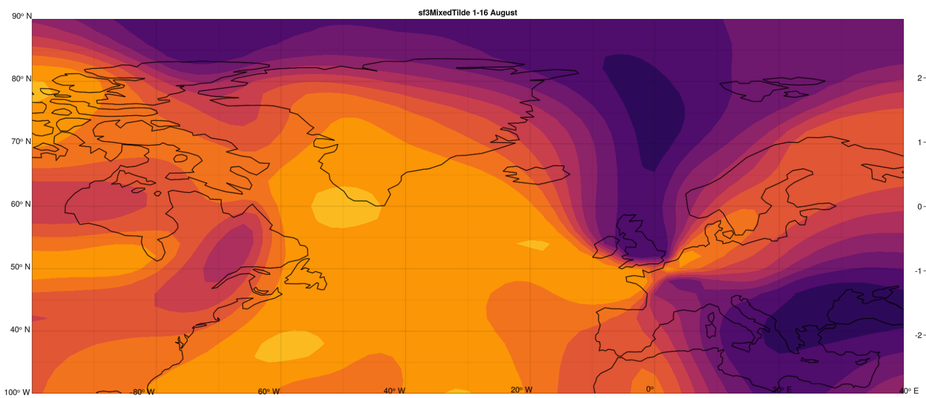
3. Results

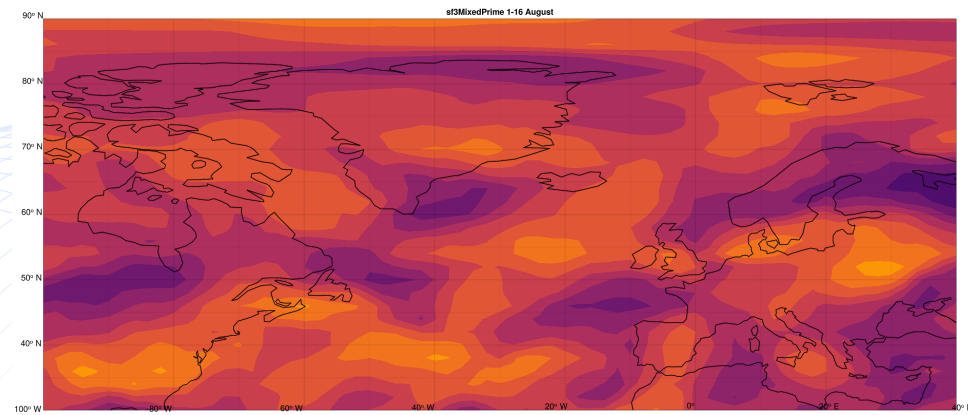
Third-order mixed Structure functions for August 2003

3. Results

Third-order mixed Structure functions for August 2003







2. Methodology – IV. Transport equations => Reserve Slides

$$\frac{\overline{D\delta\tilde{\theta}^2}}{Dt} + \frac{\partial}{\partial X_\alpha}\left[\overline{\sum \tilde{u}_\alpha \delta\tilde{\theta}^2} + 2\overline{\left\langle \sum u'_\alpha \delta\theta' \right\rangle \delta\tilde{\theta}}\right] + 2\overline{\delta\tilde{u}_\alpha \delta\tilde{\theta}}\frac{\partial T}{\partial x_\alpha}$$
$$-\overline{\left\langle \sum u'_\alpha \delta\theta' \right\rangle \frac{\partial}{\partial X_\alpha}\delta\tilde{\theta}} + \frac{\partial}{\partial r_\alpha}\overline{\delta\tilde{u}_\alpha \delta\tilde{\theta}^2} + \overline{2\delta\tilde{\theta}\frac{\partial}{\partial r_\alpha}\left\langle \delta u'_\alpha \delta\theta' \right\rangle}$$
$$-\kappa\left[\left(2\frac{\partial^2}{\partial r_\alpha^2} + \frac{1}{2}\frac{\partial^2}{\partial X_\alpha^2}\right)\overline{\delta\tilde{\theta}^2}\right] = -2\sum$$

$$\frac{\overline{D\delta\theta'^2}}{Dt} + \frac{\partial}{\partial X_\alpha}\left[\overline{\sum u'_\alpha \delta\theta'^2} + \overline{\sum \tilde{u}_\alpha \left\langle \delta\theta'^2 \right\rangle}\right] + \overline{\left\langle \sum u'_\alpha \delta\theta' \right\rangle \frac{\partial}{\partial X_\alpha}\delta\tilde{\theta}}$$
$$+2\overline{\delta u'_\alpha \delta\theta'}\frac{\partial T}{\partial x_\alpha} + \frac{\partial}{\partial r_\alpha}\left(\overline{\left\langle \delta u'_\alpha \delta\theta'^2 \right\rangle} + \overline{\delta\tilde{u}_\alpha \left\langle \delta\theta'^2 \right\rangle}\right)$$
$$-\kappa\left[\left(2\frac{\partial^2}{\partial r_\alpha^2} + \frac{1}{2}\frac{\partial^2}{\partial X_\alpha^2}\right)\overline{\delta\theta'^2}\right] = -2\sum$$

They indicate the additional forcing exerted by the CM on the random motion

Other terms are to be considered, accounting for the under-resolved scales! (ongoing work)

Operators allow for either 2D, or 3D turbulence to be tackled (ongoing work)

Considering the triple decomposition[2], $\theta = \bar{\theta} + \tilde{\theta} + \acute{\theta}$, $u_j = \overline{u_j} + \widetilde{u_j} + \acute{u_j}$. Where $\overline{...}$, $\widetilde{...}$ and $...\acute{}$ are respectivly the mean, the coherent and the random component.

Scale-by-scale scalar variance budget of CS and random field.

Energy budget of the Coherent motion

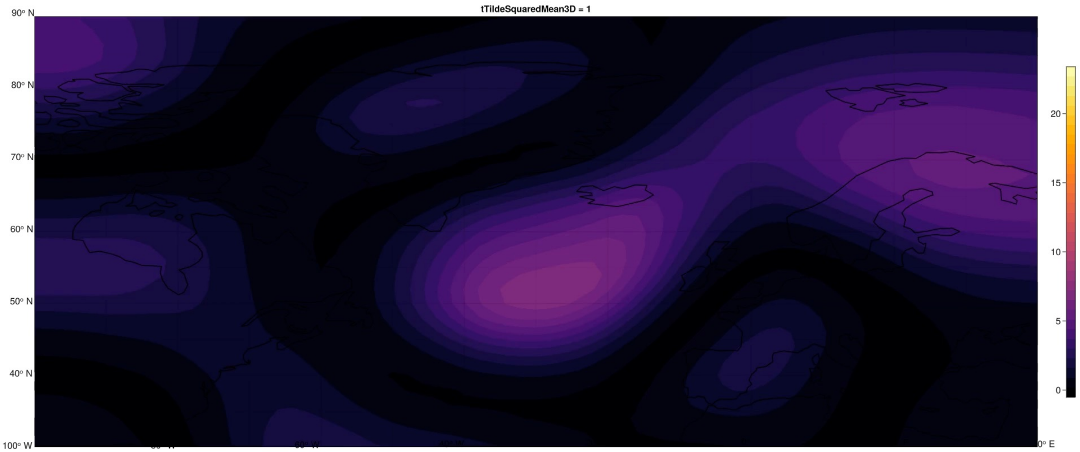
$$A_c + D_c + D_{cr} + P_{cm} - P_{cr} - V_c + \overline{2\delta\tilde{u}\frac{\partial}{\partial r_j}\langle\delta\acute{\theta}\ \delta\acute{\theta}\ \rangle} + \overline{\frac{\partial}{\partial r_j}\ \delta\tilde{u}(\delta\tilde{\theta})^2} = 2\,\overline{\widetilde{\chi^+}} + 2\,\bar{\tilde{\chi}}.$$

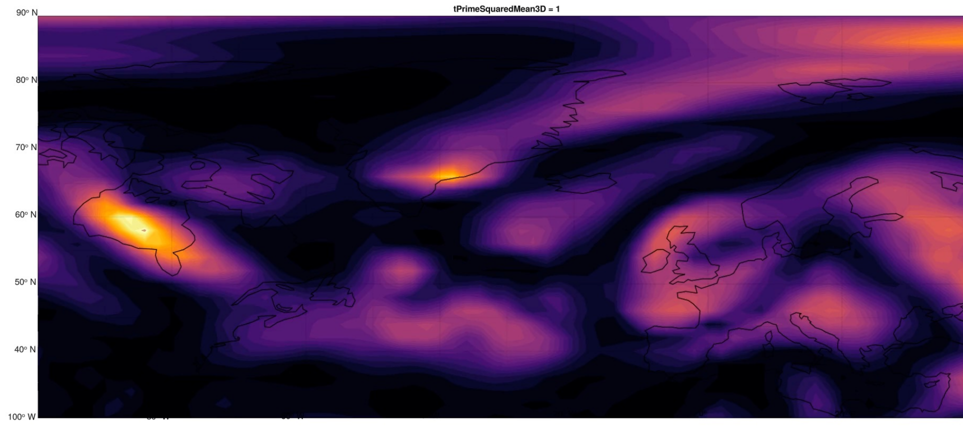
Energy budget of the random motion

$$A_r + D_r + D_{rc} + P_{rm} + P_{rc} - V_r - \overline{2\delta\tilde{u}\frac{\partial}{\partial r_j}\langle\delta\acute{\theta}\ \delta\acute{\theta}\ \rangle} - \overline{\frac{\partial}{\partial r_j}\ \delta\tilde{u}(\delta\acute{\theta}\ )^2} = 2\,\overline{\acute{\chi}^+} + 2\,\bar{\acute{\chi}}.$$

F. Thiesset, L. Danaila and R. A. Antonia, J. F. M. 2013, 2014
Alves Portela & C. Vassilicos, J.F.M. 2020
A. Cimarelli et al., J.F.M. 2023

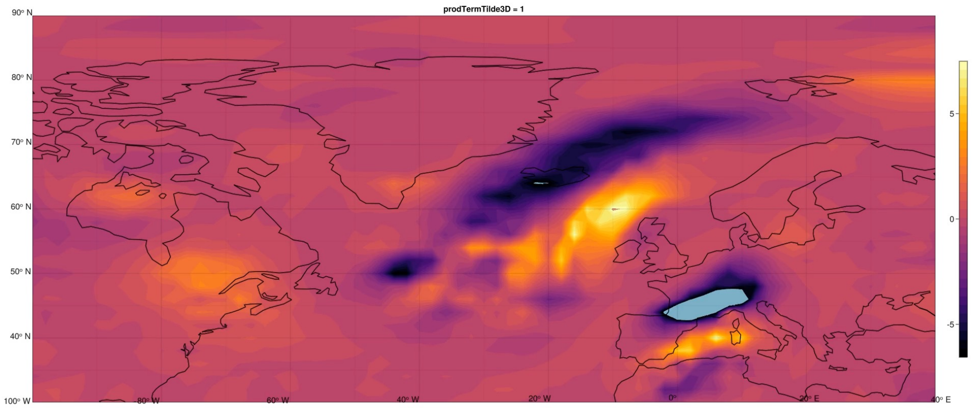
3. Results – II: Variance of Coherent vs. Random

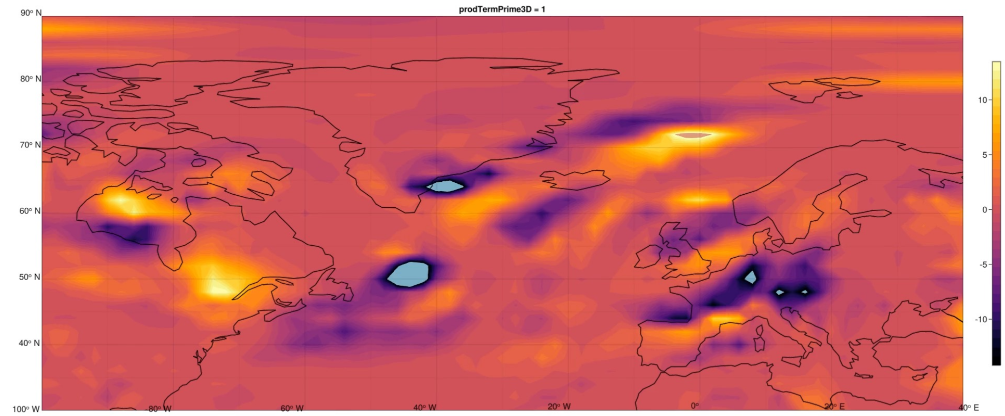




Larger values and more rapid dynamics for RM

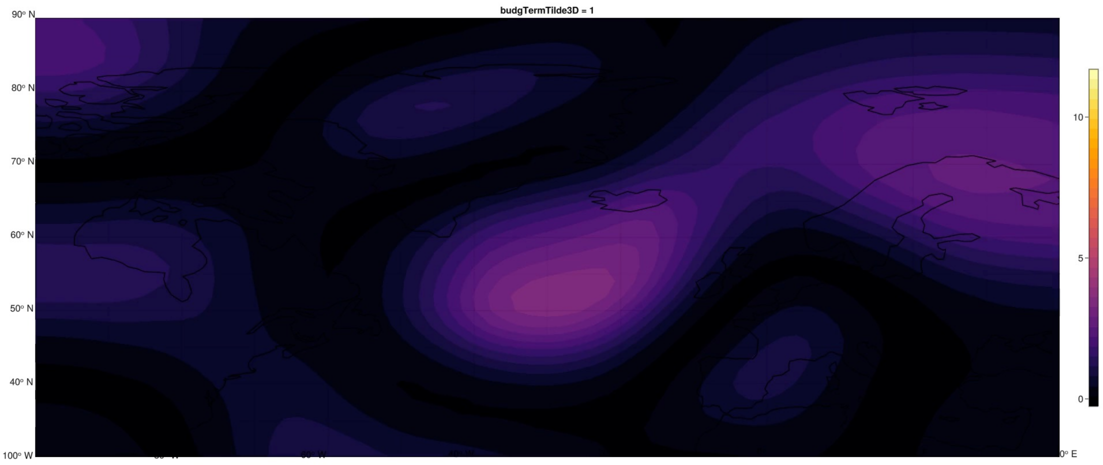
3. Results – III: Production of Coherent vs. Random

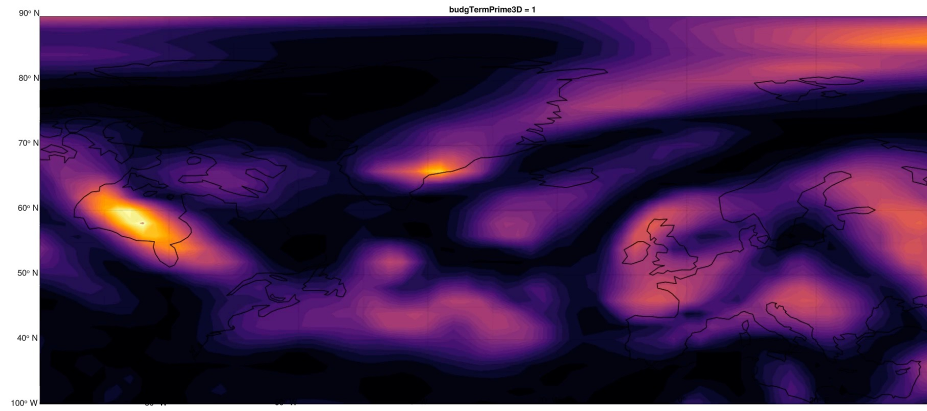




Larger values and more rapid dynamics for RM
Production which is both positive and negative (sink-like)

3. Results – IV: Temporal derivative Coherent vs. Random





Larger values and more rapid dynamics for RM

3. Results – V: Variance of Coherent vs. Random

Too many slides: pls. consider moving several to Reserve Slides!

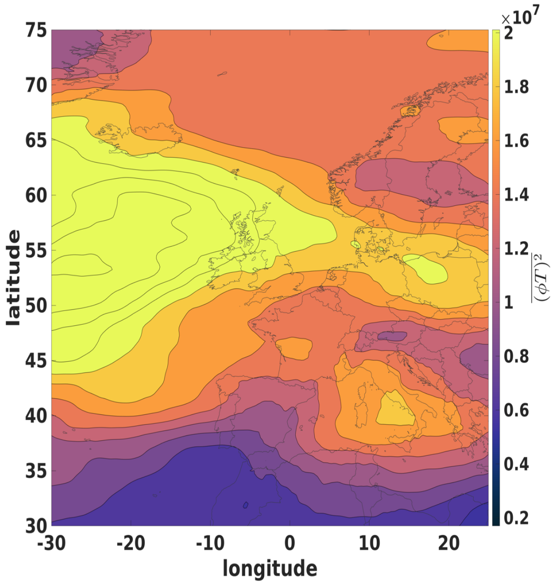
Max number ~ 12–15!!

Use larger type for visibility.

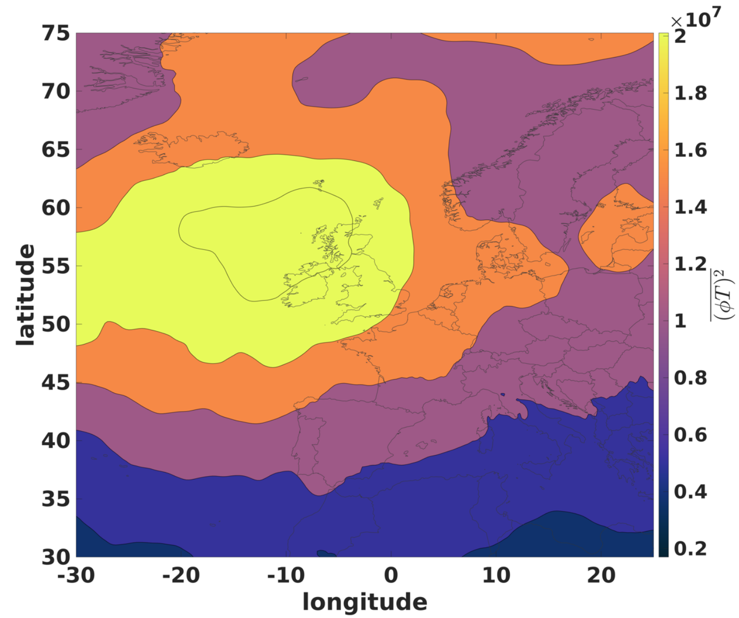
Larger values and more rapid dynamics for RM

2. Results – V. ERA5 data, summer 2003

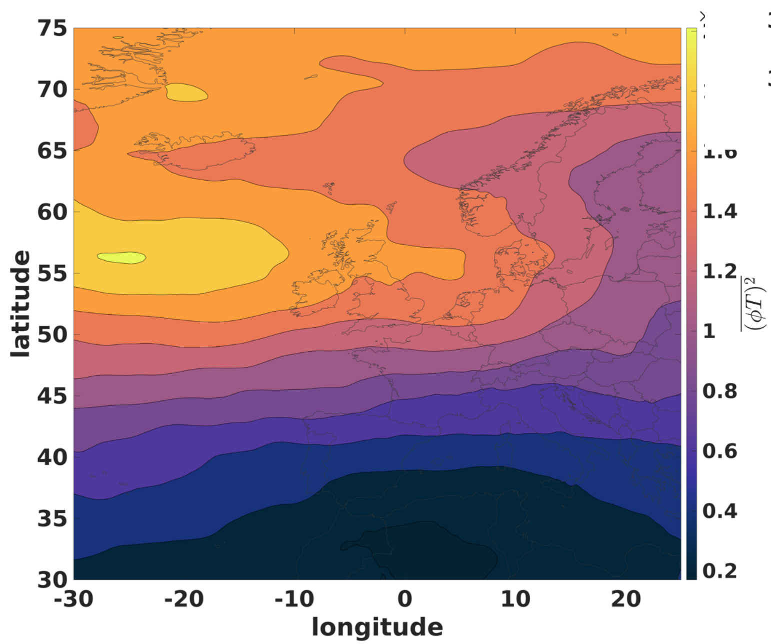
RMS of zonal velocity



RMS of meridional velocity



RMS of temperature fluctuations



Reserve slides