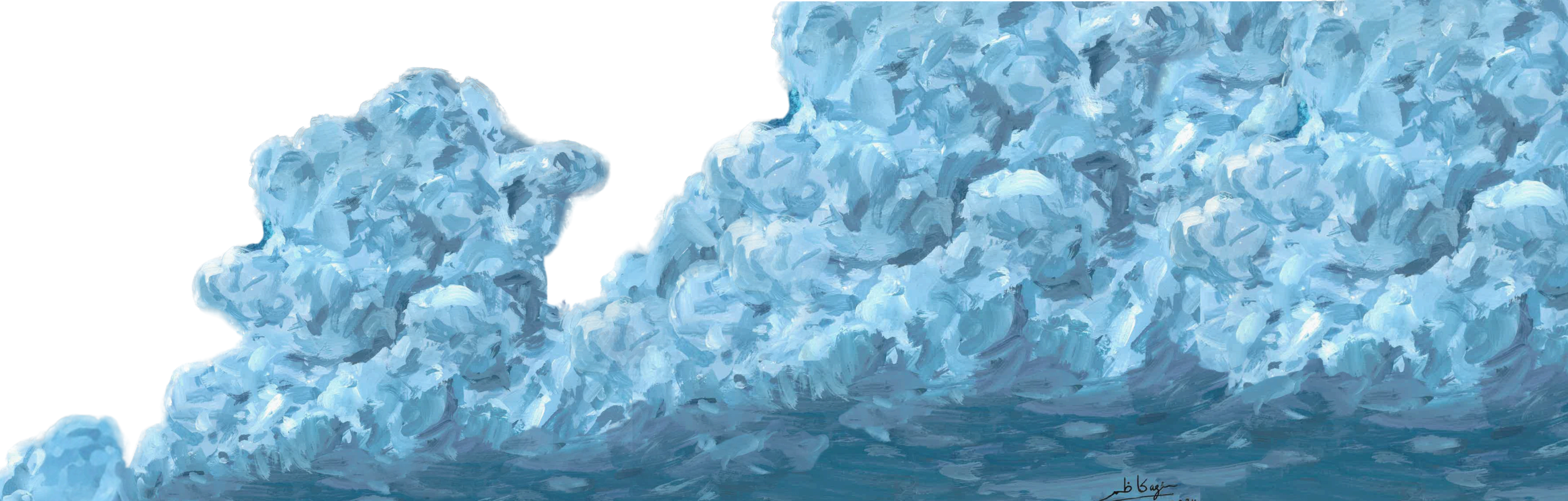
CRIANN SCIENCE DAY

SCALE BY SCALE

TURBULENCE APPROACH TO THE ATMOSPHERE

Temperature, Moisture and Wind statistics during a Heatwave

Sayeed K., Blervacq C., Massei N., Danaila L.
M2C – Morphodynamique continentale et côtière – UMR 6143



OBJECTIVES

- *Characterize the Atmosphere Across Scales*

Investigate atmospheric dynamics from Planetary to microscale using GCM, convection permitting models, Reanalyses, observations and DNS.

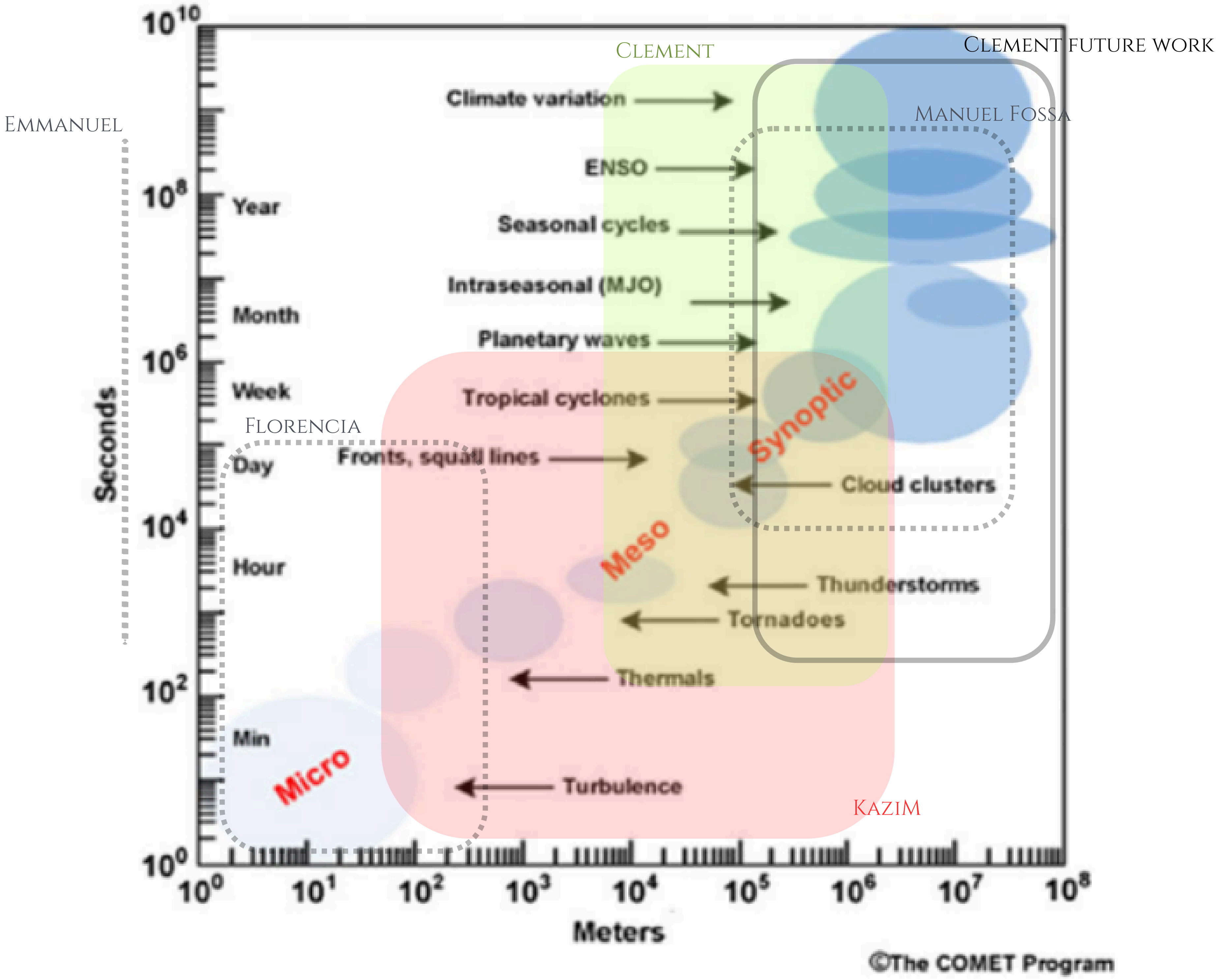
- *Apply Turbulence-Based Statistical Frameworks*

- *Incorporate all Physically Relevant Terms*

Beyond simplified assumptions in theory by including processes such as stratification, shear, non-stationarity, coriolis in the scale analysis.

- *Quantify Variability and Extremes*

Capture the variability and tails—crucial for predicting extreme weather and rare events in the rapidly changing climate.



Co-ordinates and equations

Cartesian

$$\partial_t u_i + u_j \partial_{X_j} u_i + \alpha \partial_{X_i} p + \delta_{i3} g = -\partial_{X_j} (\overline{u_i' u j'}) + f_{u_i}$$

$$\partial_t \theta_m + u_j \partial_{X_j} \theta_m = \partial_{X_j} (\overline{u_j' \theta_m'}) + f_{\theta_m}$$

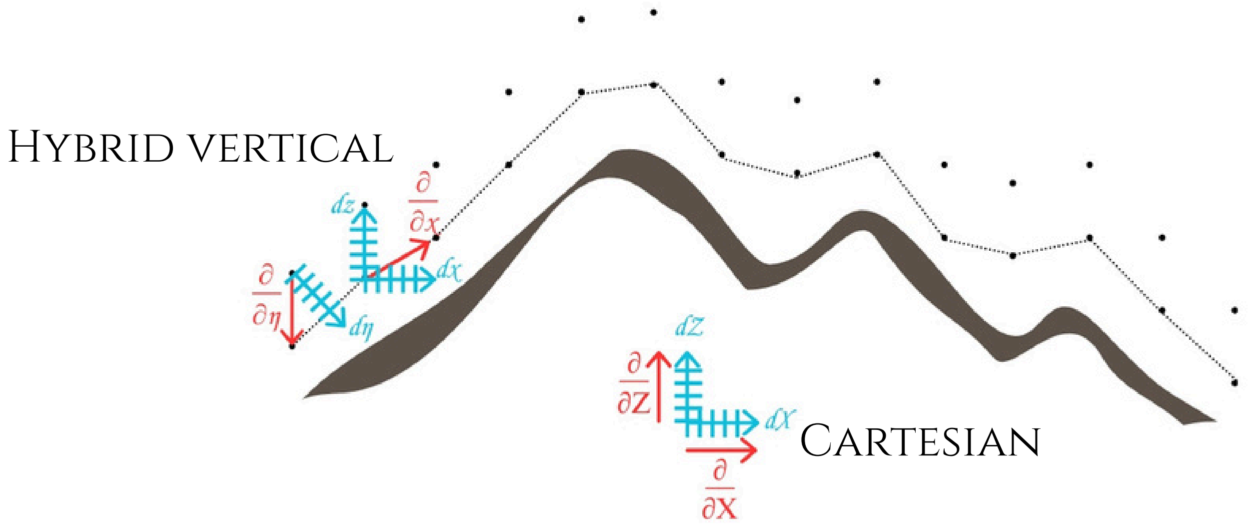
$$\partial_t q_m + u_j \partial_{X_j} q_m = \partial_{X_j} (\overline{u_j' q_m'}) + f_{q_m}$$

$$\partial_t \rho_d + \partial_{X_j} (\rho_d u_j) = 0$$

u_i : resolved velocity in i direction
p : resolved pressure
g : gravitational constant
f : resolved additioanl forces
α: inverse of resolved air density
ρ_d: resolved density of dry air
θ_m: resolved moist potential temperature
(temperature if air parcel is brought to the ground and all latent heat in moisture is released)
q_m: resolved water species concentration
_' : unresolved quantity of variable

Hybrid vertical

$$\mathbf{V} = \mu \mathbf{v} = (U, V, W), \quad \Omega = \mu \dot{\eta}, \quad \Theta = \mu \theta.$$



$$J = \frac{\partial(t,x,y,z)}{\partial(t,x,y,\eta)} = \begin{pmatrix} \frac{\partial t}{\partial t} & \frac{\partial t}{\partial x} & \frac{\partial t}{\partial y} & \frac{\partial t}{\partial \eta} \\ \frac{\partial x}{\partial t} & \frac{\partial x}{\partial x} & \frac{\partial x}{\partial y} & \frac{\partial x}{\partial \eta} \\ \frac{\partial y}{\partial t} & \frac{\partial y}{\partial x} & \frac{\partial y}{\partial y} & \frac{\partial y}{\partial \eta} \\ \frac{\partial z}{\partial t} & \frac{\partial z}{\partial x} & \frac{\partial z}{\partial y} & \frac{\partial z}{\partial \eta} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ z_t & z_x & z_y & \frac{-\alpha_d \mu_d}{g} \end{pmatrix}$$

$$J^{-1} = \frac{\partial(t,x,y,\eta)}{\partial(t,x,y,z)} = \begin{pmatrix} \frac{\partial t}{\partial t} & \frac{\partial t}{\partial x} & \frac{\partial t}{\partial y} & \frac{\partial t}{\partial z} \\ \frac{\partial x}{\partial t} & \frac{\partial x}{\partial x} & \frac{\partial x}{\partial y} & \frac{\partial x}{\partial z} \\ \frac{\partial y}{\partial t} & \frac{\partial y}{\partial x} & \frac{\partial y}{\partial y} & \frac{\partial y}{\partial z} \\ \frac{\partial \eta}{\partial t} & \frac{\partial \eta}{\partial x} & \frac{\partial \eta}{\partial y} & \frac{\partial \eta}{\partial z} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \frac{g z_t}{\alpha_d \mu_d} & \frac{g z_x}{\alpha_d \mu_d} & \frac{g z_y}{\alpha_d \mu_d} & \frac{g}{-\alpha_d \mu_d} \end{pmatrix}$$

$$|J| = \frac{-\alpha_d \mu_d}{g}$$

$$\mu_d = -g \rho_d |J|$$

Co-ordinates and equations

Cartesian

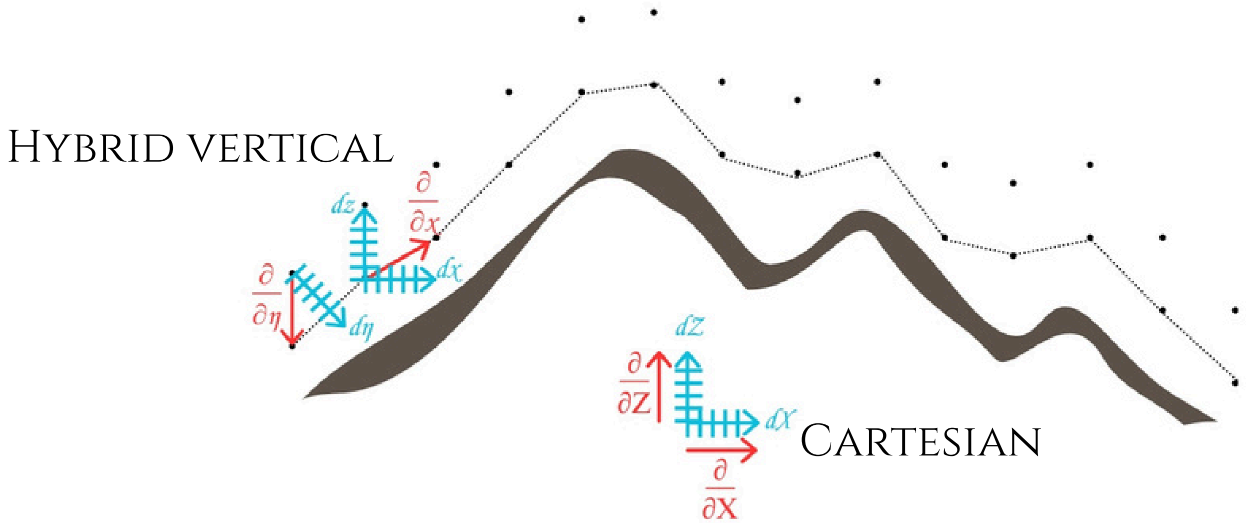
$$\partial_t u_i + u_j \partial_{X_j} u_i + \alpha \partial_{X_i} p + \delta_{i3} g = -\partial_{X_j} (\overline{u_i' u_j'}) + f_{u_i}$$

$$\partial_t \theta_m + u_j \partial_{X_j} \theta_m = \partial_{X_j} (\overline{u_j' \theta_m'}) + f_{\theta_m}$$

$$\partial_t q_m + u_j \partial_{X_j} q_m = \partial_{X_j} (\overline{u_j' q_m'}) + f_{q_m}$$

$$\partial_t \rho_d + \partial_{X_j} (\rho_d u_j) = 0$$

u_i : resolved velocity in i direction
p : resolved pressure
g : gravitational constant
f : resolved additioanl forces
α: inverse of resolved air density
ρ_d: resolved density of dry air
θ_m: resolved moist potential temperature
(temperature if air parcel is brought to the ground and all latent heat in moisture is released)
q_m: resolved water species concentration
_' : unresolved quantity of variable



Hybrid vertical

$$\mathbf{V} = \mu \mathbf{v} = (U, V, W), \quad \Omega = \mu \dot{\eta}, \quad \Theta = \mu \theta.$$

What goes here?

$$\partial_t U + (\nabla \cdot \mathbf{V} u) + \mu_d \alpha \partial_x p + (\alpha / \alpha_d) \partial_\eta p \partial_x \phi = F_U$$

$$\partial_t V + (\nabla \cdot \mathbf{V} v) + \mu_d \alpha \partial_y p + (\alpha / \alpha_d) \partial_\eta p \partial_y \phi = F_V$$

$$\partial_t W + (\nabla \cdot \mathbf{V} w) - g[(\alpha / \alpha_d) \partial_\eta p - \mu_d] = F_W$$

Turbulent mixing, coriolis, surface fluxes

$$\partial_t \Theta_m + (\nabla \cdot \mathbf{V} \theta_m) = F_{\Theta_m}$$

Turbulent, radiative, surface fluxes

$$\partial_t \mu_d + (\nabla \cdot \mathbf{V}) = 0$$

ϕ : geopotential (ϕ=gz)

$$\partial_t \phi + \mu_d^{-1} [(\mathbf{V} \cdot \nabla \phi) - gW] = 0$$

$$\partial_t Q_m + (\nabla \cdot \mathbf{V} q_m) = F_{Q_m}$$

Turbulent, surface fluxes, microphysical exhanges, precipitation

$$J = \frac{\partial(t,x,y,z)}{\partial(t,x,y,\eta)} = \begin{pmatrix} \frac{\partial t}{\partial t} & \frac{\partial t}{\partial x} & \frac{\partial t}{\partial y} & \frac{\partial t}{\partial \eta} \\ \frac{\partial x}{\partial t} & \frac{\partial x}{\partial x} & \frac{\partial x}{\partial y} & \frac{\partial x}{\partial \eta} \\ \frac{\partial y}{\partial t} & \frac{\partial y}{\partial x} & \frac{\partial y}{\partial y} & \frac{\partial y}{\partial \eta} \\ \frac{\partial z}{\partial t} & \frac{\partial z}{\partial x} & \frac{\partial z}{\partial y} & \frac{\partial z}{\partial \eta} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ z_t & z_x & z_y & \frac{-\alpha_d \mu_d}{g} \end{pmatrix}$$

$$J^{-1} = \frac{\partial(t,x,y,\eta)}{\partial(t,x,y,z)} = \begin{pmatrix} \frac{\partial t}{\partial t} & \frac{\partial t}{\partial x} & \frac{\partial t}{\partial y} & \frac{\partial t}{\partial z} \\ \frac{\partial x}{\partial t} & \frac{\partial x}{\partial x} & \frac{\partial x}{\partial y} & \frac{\partial x}{\partial z} \\ \frac{\partial y}{\partial t} & \frac{\partial y}{\partial x} & \frac{\partial y}{\partial y} & \frac{\partial y}{\partial z} \\ \frac{\partial \eta}{\partial t} & \frac{\partial \eta}{\partial x} & \frac{\partial \eta}{\partial y} & \frac{\partial \eta}{\partial z} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \frac{g z_t}{\alpha_d \mu_d} & \frac{g z_x}{\alpha_d \mu_d} & \frac{g z_y}{\alpha_d \mu_d} & \frac{g}{-\alpha_d \mu_d} \end{pmatrix}$$

$$|J| = \frac{-\alpha_d \mu_d}{g}$$

$$\mu_d = -g \rho_d |J|$$

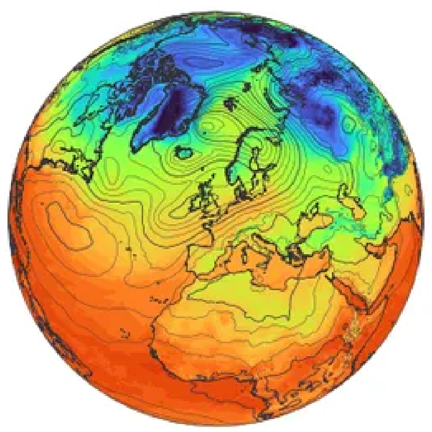
MORE ON THE MODEL

Governing equations

$$\partial_t U + (\nabla \cdot \mathbf{V} u) + \mu_d \alpha \partial_x p + (\alpha/\alpha_d)\partial_\eta p \partial_x \phi = \boxed{F_U}$$
$$\partial_t V + (\nabla \cdot \mathbf{V} v) + \mu_d \alpha \partial_y p + (\alpha/\alpha_d)\partial_\eta p \partial_y \phi = F_V$$
$$\partial_t W + (\nabla \cdot \mathbf{V} w) - g[(\alpha/\alpha_d)\partial_\eta p - \mu_d] = F_W$$
$$\partial_t \Theta_m + (\nabla \cdot \mathbf{V} \theta_m) = F_{\Theta_m}$$
$$\partial_t \mu_d + (\nabla \cdot \mathbf{V}) = 0$$
$$\partial_t \phi + \mu_d^{-1}[(\mathbf{V} \cdot \nabla \phi) - gW] = 0$$
$$\partial_t Q_m + (\nabla \cdot \mathbf{V} q_m) = \boxed{F_{Q_m}}$$
$$p = p_0(R_d \theta / p_0 \alpha)^\gamma.$$

Initial conditions + Boundaries D00, D01

ERA5 Reanalysis



0.25°x0.25°
(~30km x 30km in midlatitudes)

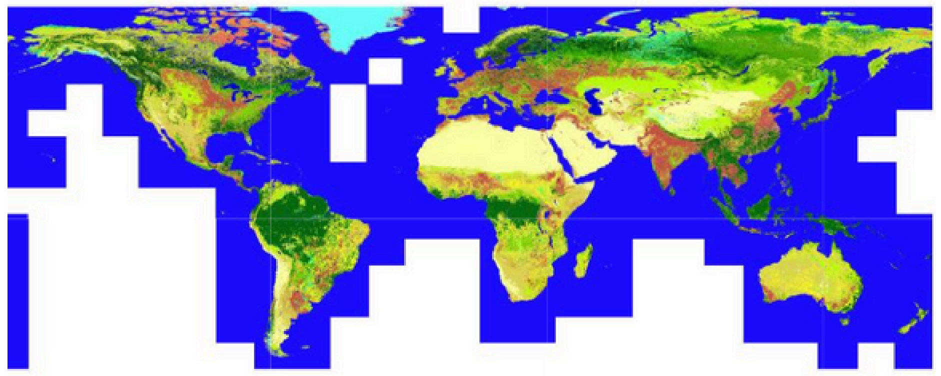
Preprocessed and interpolated on grid via WRF preprocessing System.

PROGRAMME OF THE EUROPEAN UNION · Copernicus · Climate Change Service · IMPLEMENTED BY ECMWF

Geographic data

CGLC-Modis-LCZ

(100m reloution)
32 land/surface types



+ Radiative Physics(RRTM)
+ Microphysical interaction across species (Thompson Scheme)
+ Land surface exchanges using Monin Obukhov similarity
+ Land model physics (Noah MP)
+ additional physics models
(1.5 order Hybrid TKE mixing model, etc.)

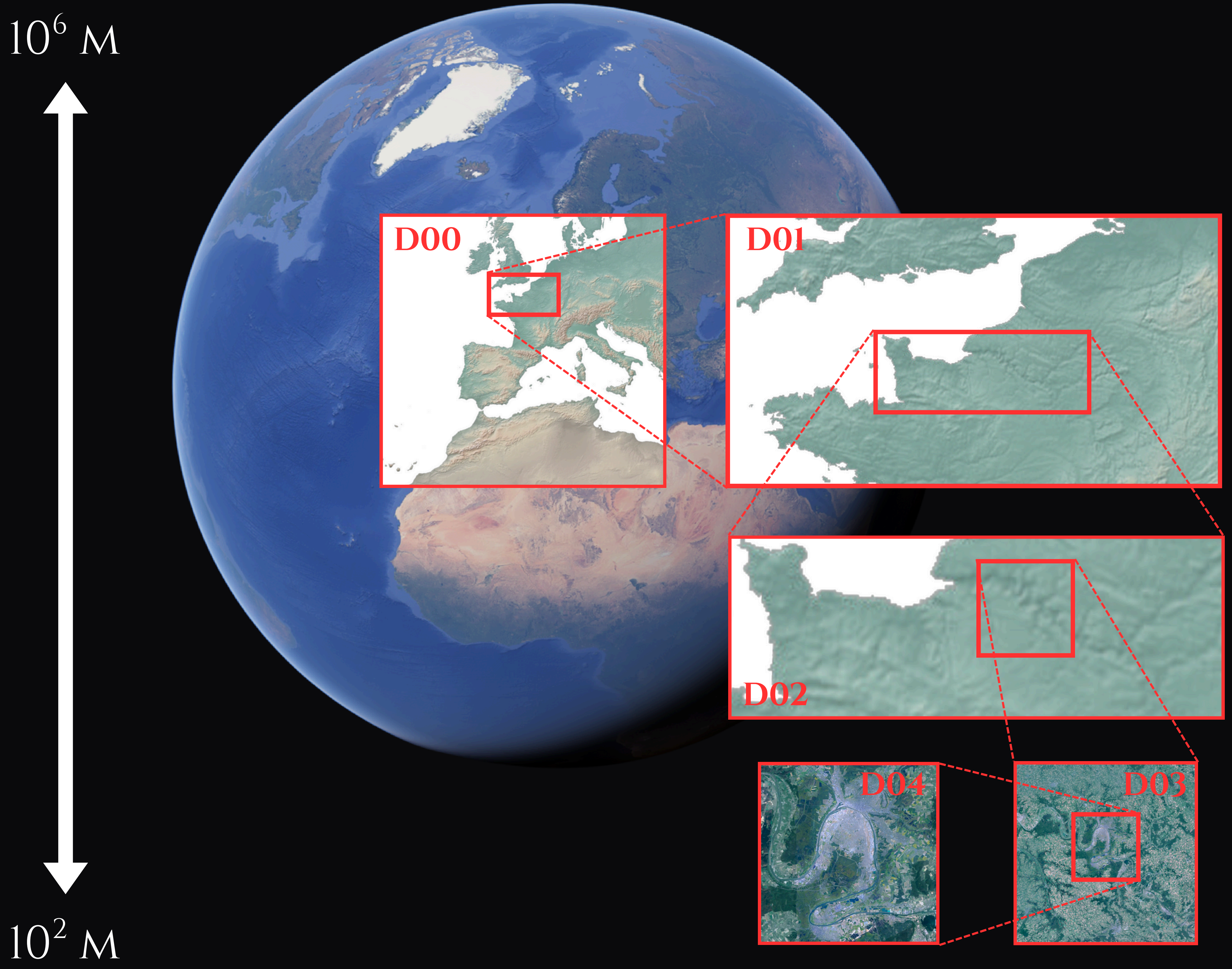
Domain 0:
3600km x 3450km
15km horizontal grid

Domain 1:
880km x 500km
5km horizontal grid

Domain 2:
375km x 140km
1km horizontal grid

Domain 3:
70km x 70km
200m horizontal grid

Domain 4:
23km x 23km
67m horizontal grid



Domain 0:
3600km x 3450km x 12km
15km horizontal grid

vertical resolution: 10m - 250m
Grid points: 240x230x52
No. Time steps: 10^4 (60s each)

Domain 1:
880km x 500km x 12km
5km horizontal grid

vertical resolution: 10m - 200m
Grid points: 176x100x75
No. Time steps: 3×10^4(20s each)

Domain 2:
375km x 140km x 12km
1km horizontal grid

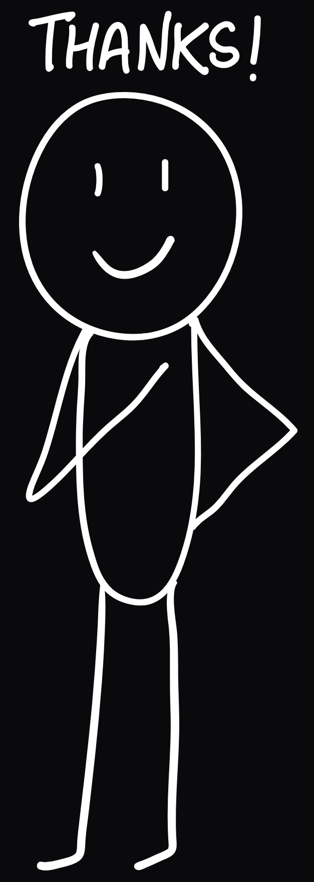
vertical resolution: 10m - 200m
Grid points: 375x140x75
No. Time steps: 1.5×10^5(4s each)

Domain 3:
70km x 70km x 12km
200m horizontal grid

vertical resolution: 10m - 200m
Grid points: 350x350x75
No. Time steps: 6×10^5(1s each)

Domain 4:
23km x 23km x 12km
67m horizontal grid

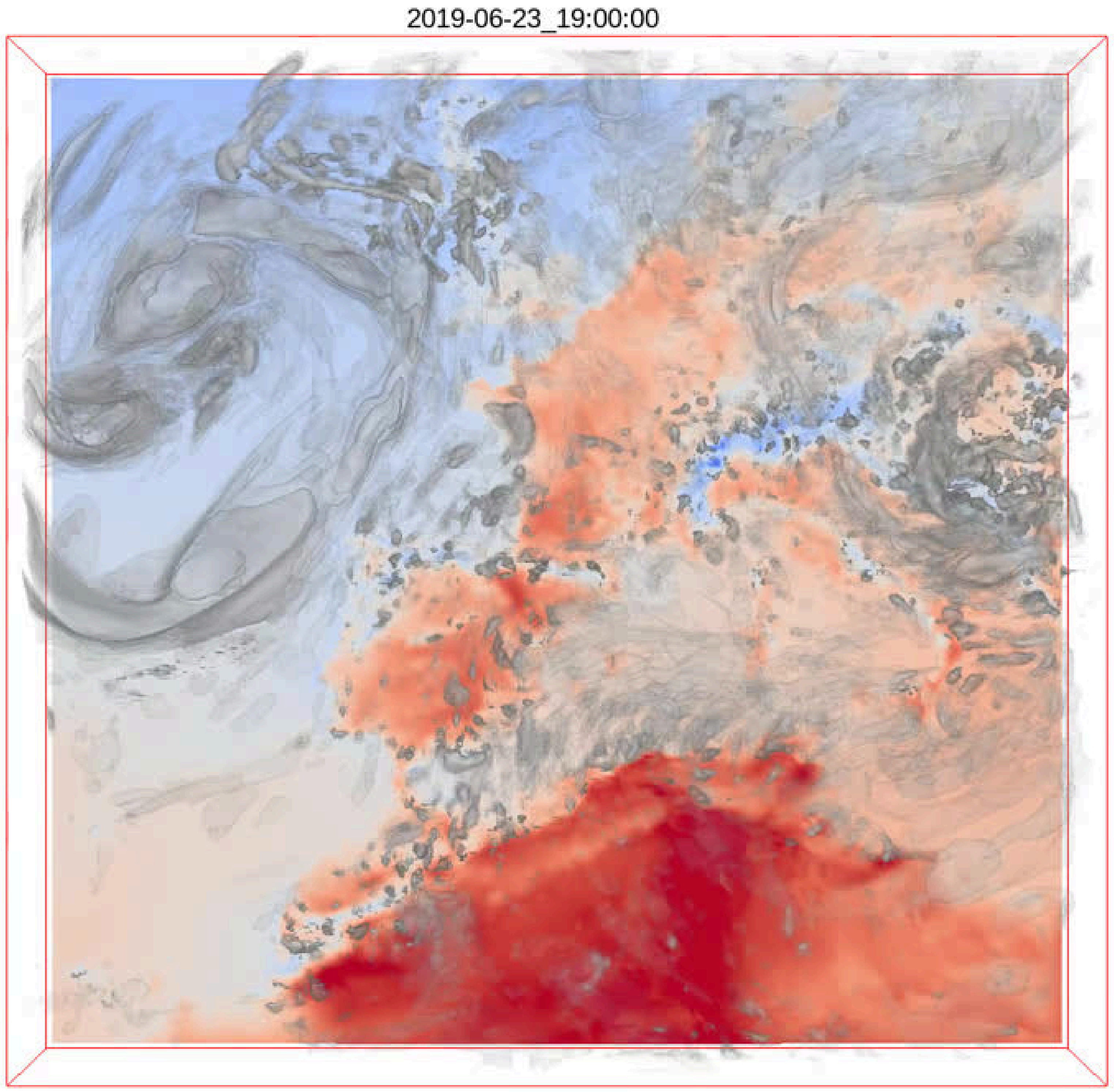
vertical resolution: 5m - 100m
Grid points: 350x350x150
No. Time steps: 5×10^6(1/8 s each)

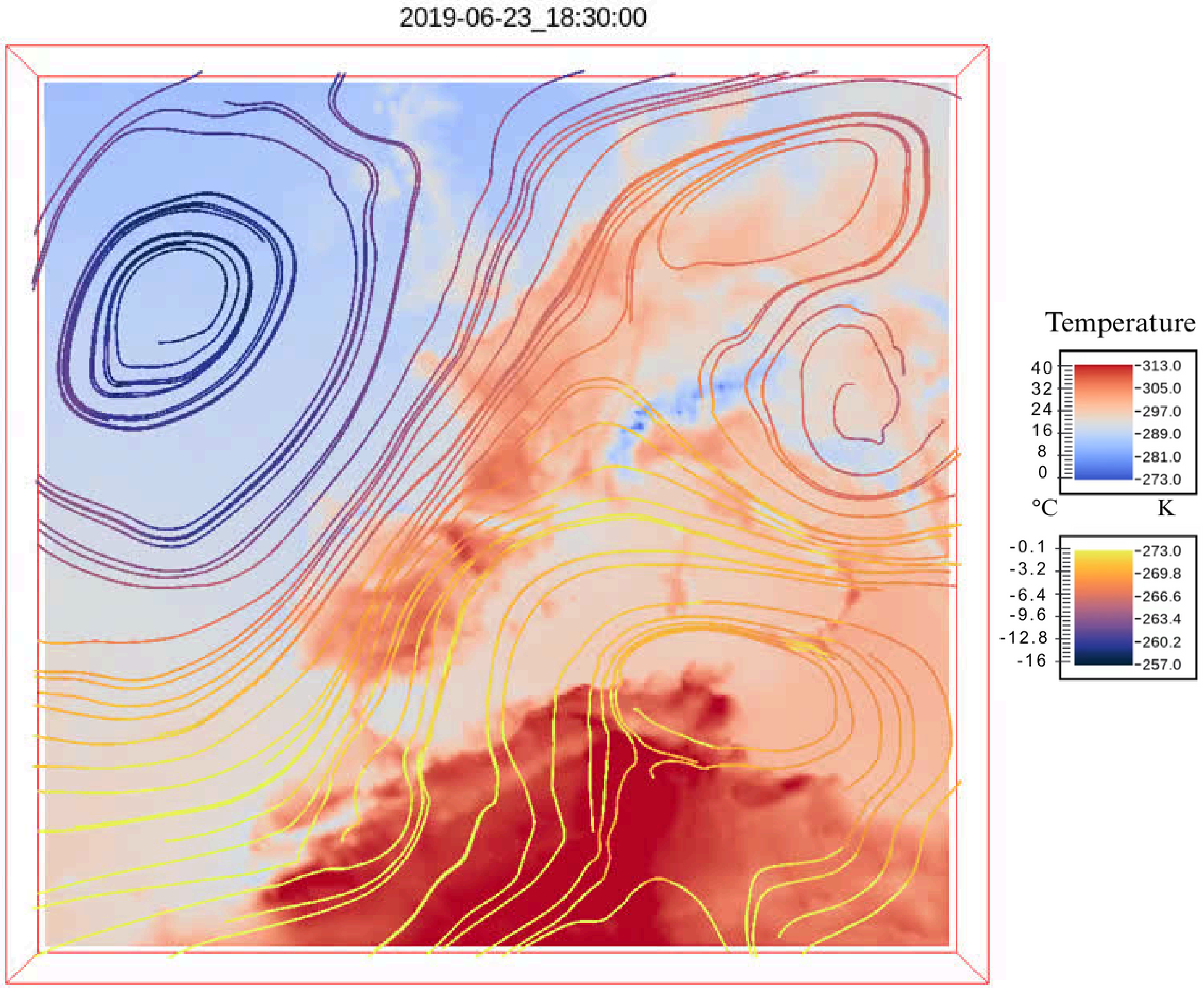


700,000 cpu hours
(~10^{20}FLOPs)

Simulation render Domain 0

Hot air travels north as big colder eddy pulls it

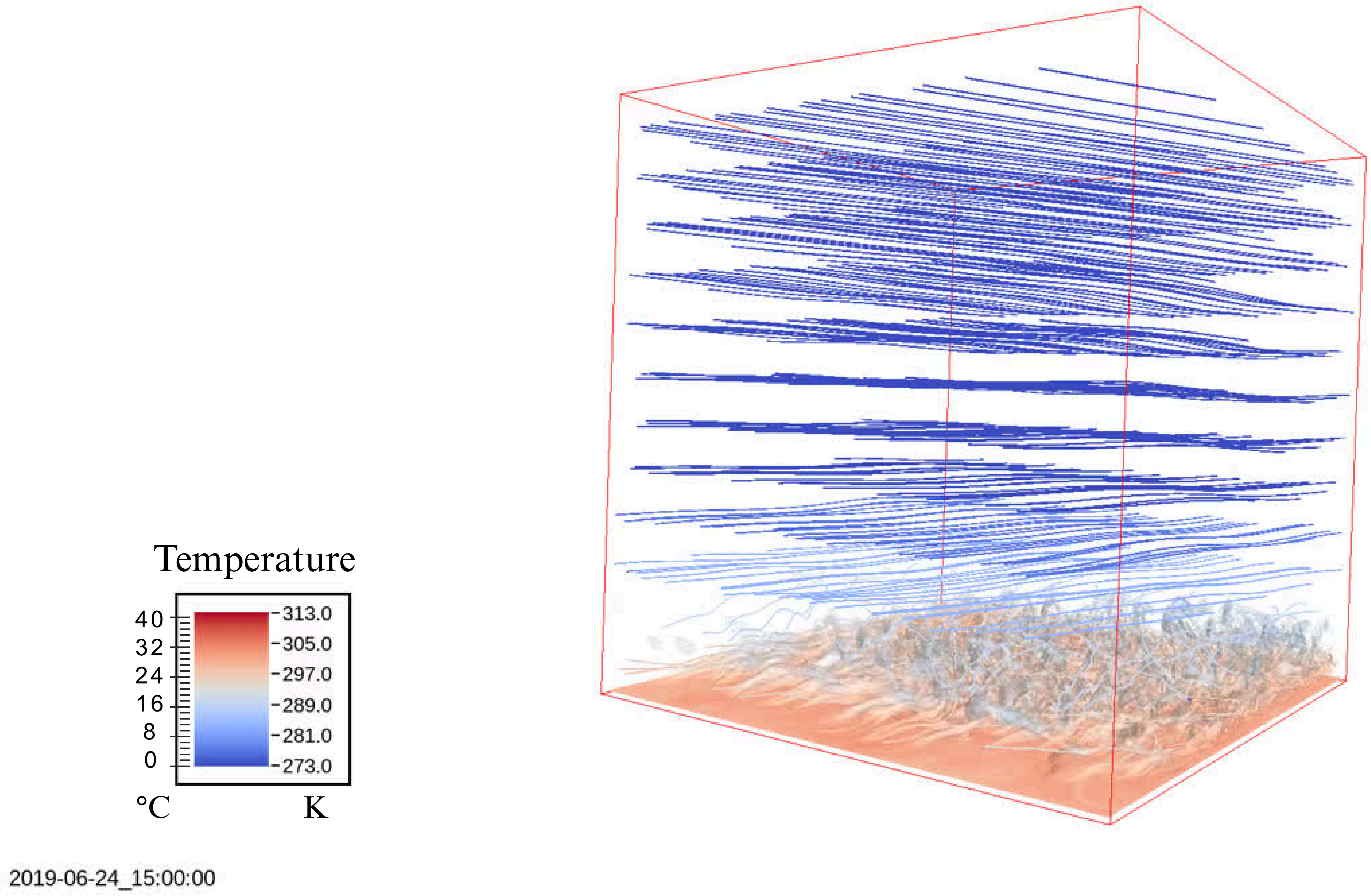




Temperature at 2m AGL(T2), Q-criterion isosurfaces   T2,Horizontal wind stramlines at 5 km ASL

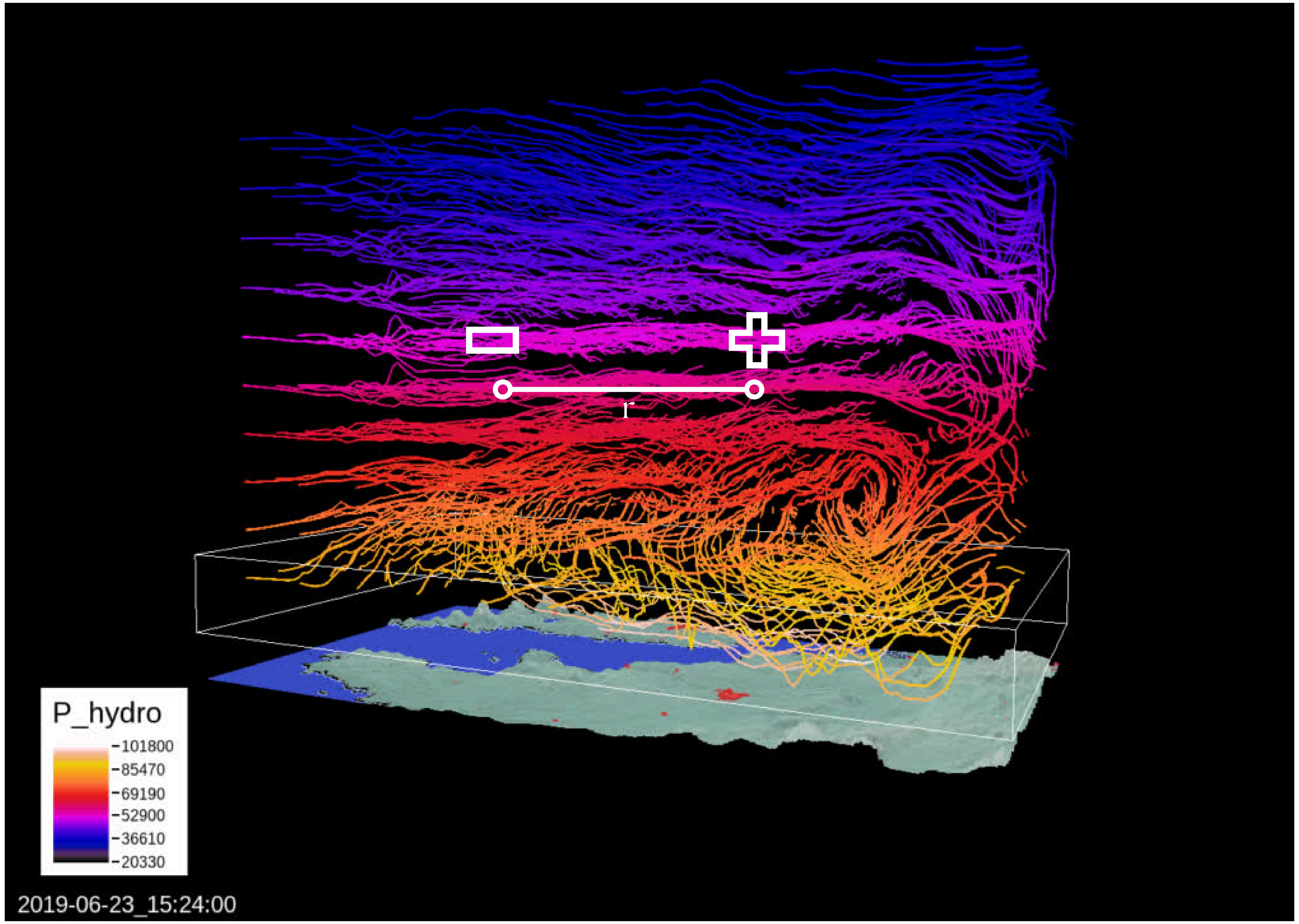
Simulation render Domain 4

featuring: Hairpin vortices, Unstable and Stable Atmosphere, Ekman layer



HOW TO ANALYSE SCALE BY SCALE?

Two points separated by 'r'



$$\delta f = f^{+} - f^{-}$$

$+$

$$\partial_t u_i^+ + u_j^+ \partial_{X_j^+} u_i^+ = -\alpha^+ \partial_{X_i^+} p^+ - \delta_{i3} g + f^+_{u_i cor} + \partial_{X_j^+}(K^+_{j'} \partial_{X_j^+} u_i^+) + f^+_{u_i+}$$

$$\partial_t \theta_m^+ + u_j^+ \partial_{X_j^+} \theta_m^+ = \frac{1}{\mu_d}(\partial_{X_j^+}(\mu_d K^+_{j'} \partial_{X_j^+}(\theta_m^+)) + f^+_{\theta_m+}$$

$-$

$$\partial_t u_i^- + u_j^- \partial_{X_j^-} u_i^- = -\alpha^- \partial_{X_i^-} p^- - \delta_{i3} g + f^-_{u_i cor} + \partial_{X_j^-}(K^-_{j'} \partial_{X_j^-} u_i^-) + f^-_{u_i-}$$

$$\partial_t \theta_m^- + u_j^- \partial_{X_j^-} \theta_m^- = \frac{1}{\mu_d}(\partial_{X_j^-}(\mu_d K^-_{j'} \partial_{X_j^-}(\theta_m^-)) + f^-_{\theta_m-}$$

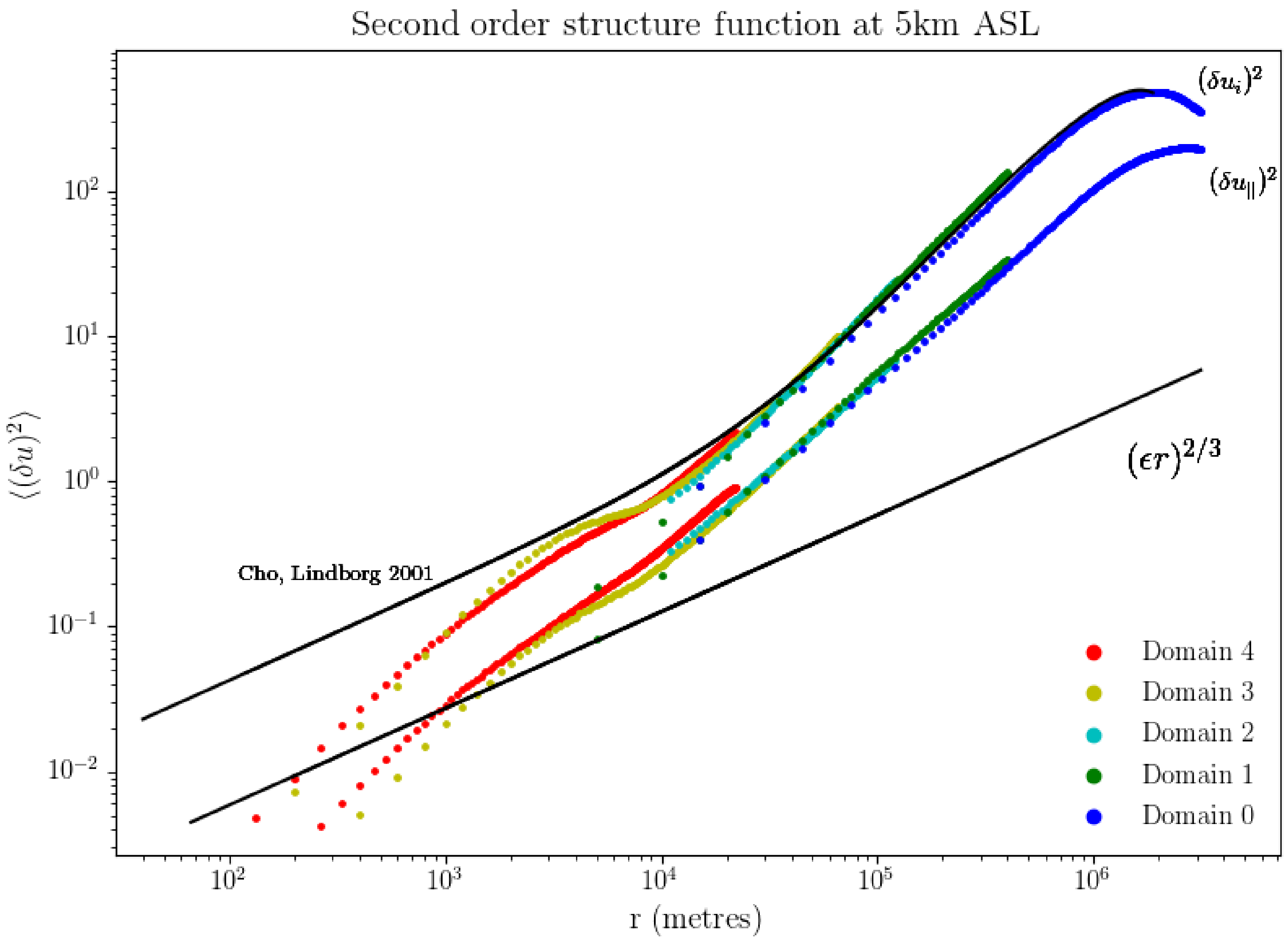
$\delta u \cdot \delta f\,(r)$ ⟶ covariance (r)

$(\delta u)^2(r)$ ⟶ variance (r)

etc.

SECOND ORDER VELOCITY STRUCTURE FUNCTION

Matching observations, for ‘spectrum in real space’



Horizontal velocity structure functions in the upper troposphere and lower stratosphere
1. Observations

John Y. N. Cho
Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts

Erik Lindborg
Department of Mechanics, Kungl Tekniska Högskolan, Stockholm, Sweden

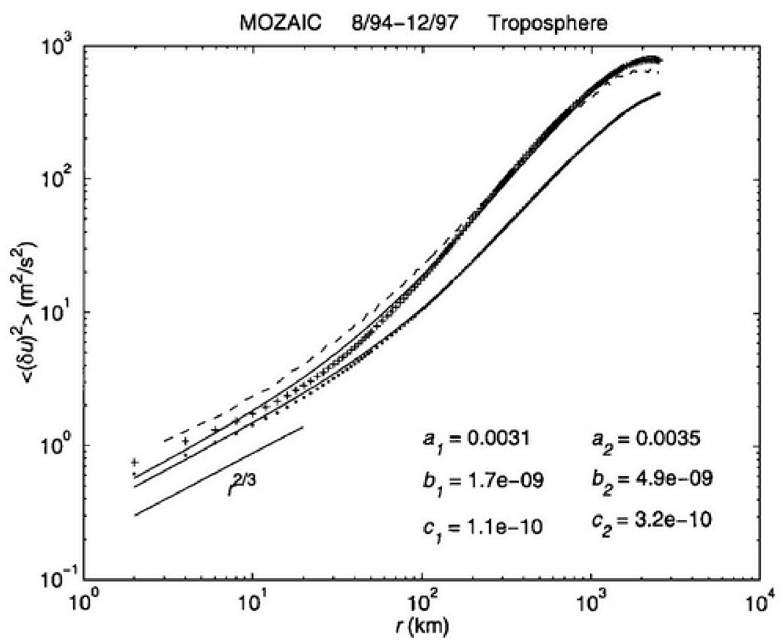
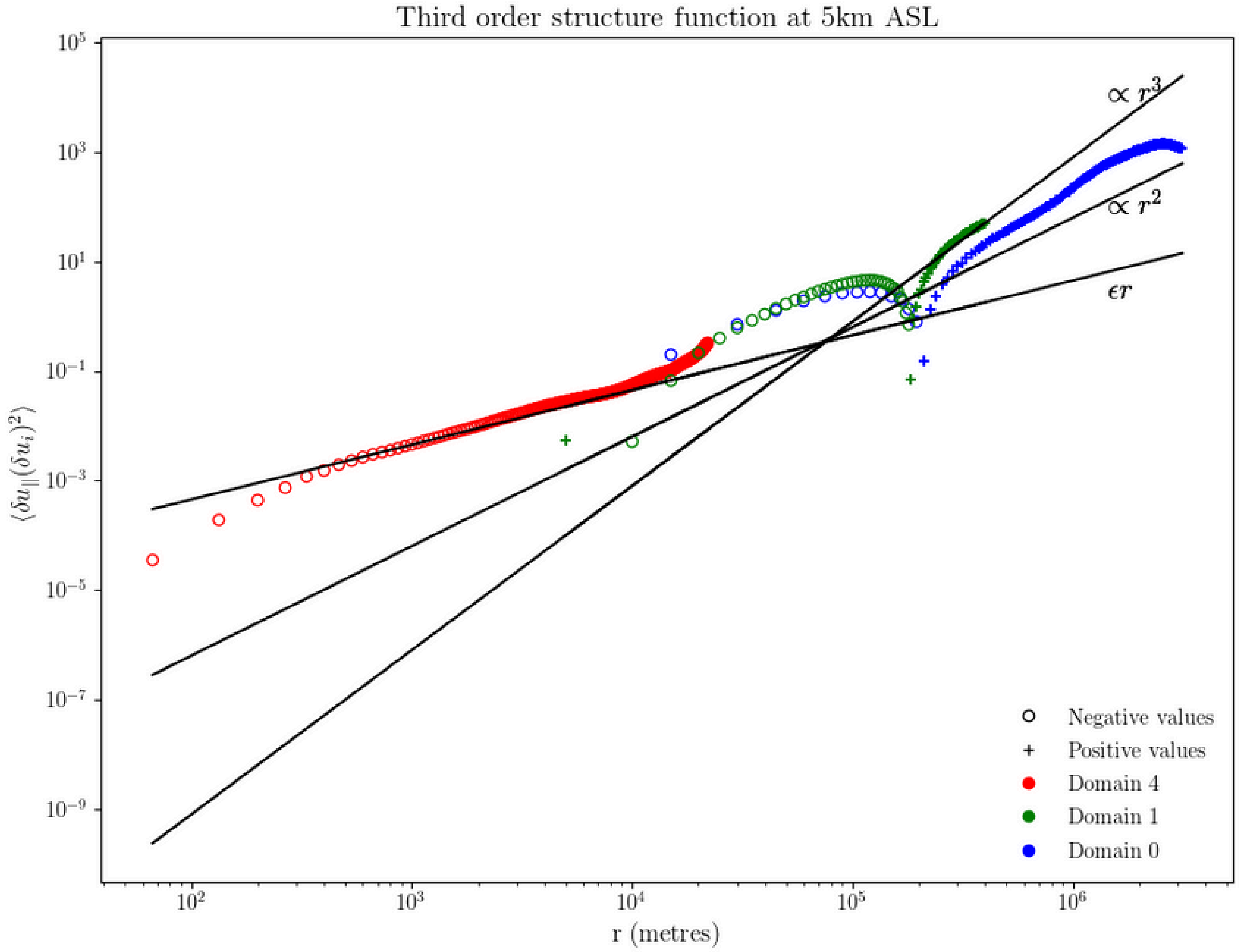


Figure 4. Second-order horizontal velocity structure functions for the longitudinal (dots) and transverse (crosses) components calculated for tropospheric data. The solid lines are nonlinear least squares fits to the theoretical functions; the values of the fitted parameters are displayed in the lower right-hand corner. The dashed line is the theoretical isotropic transverse function calculated from the measured longitudinal function.

THIRD ORDER VELOCITY STRUCTURE FUNCTION

How energy travels through length scales



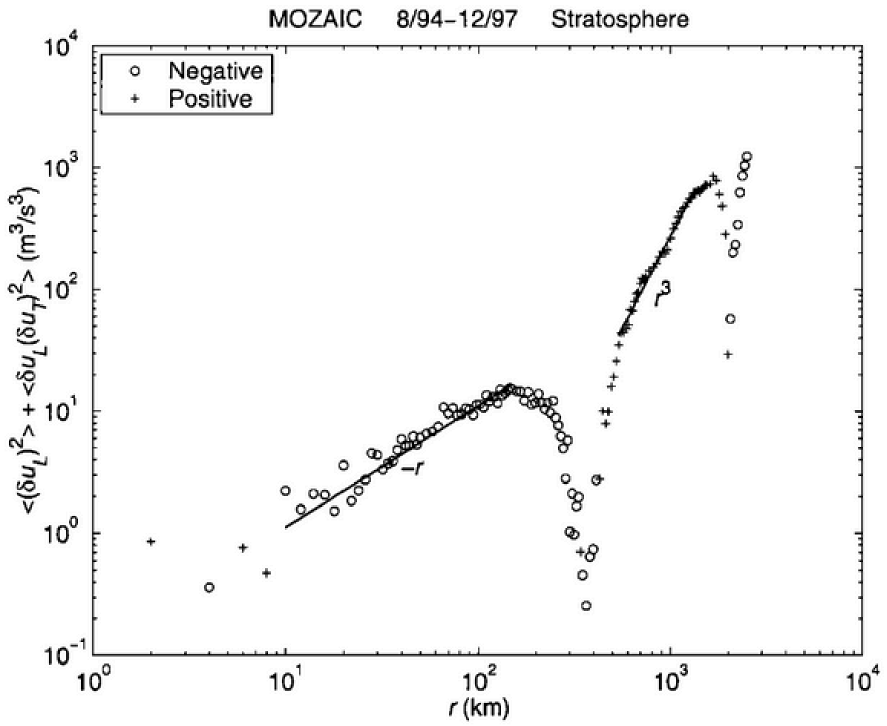
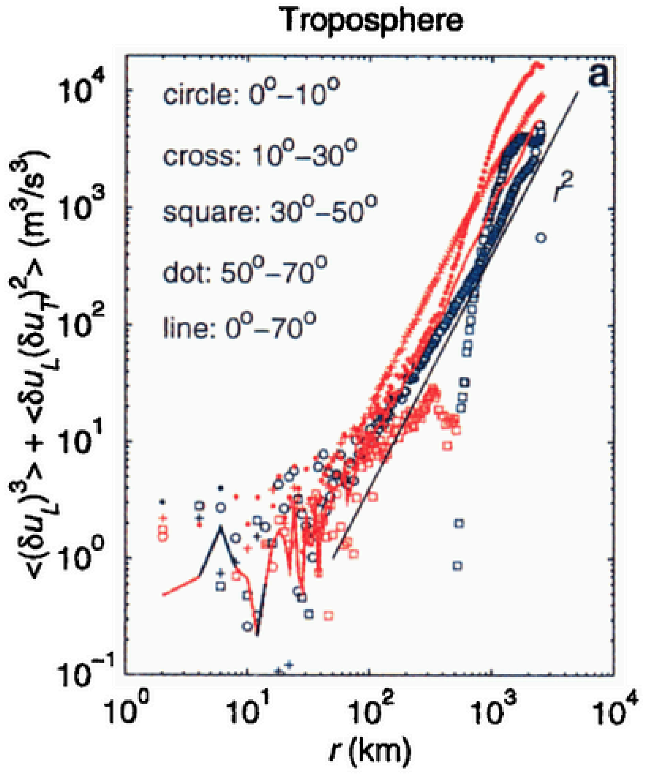
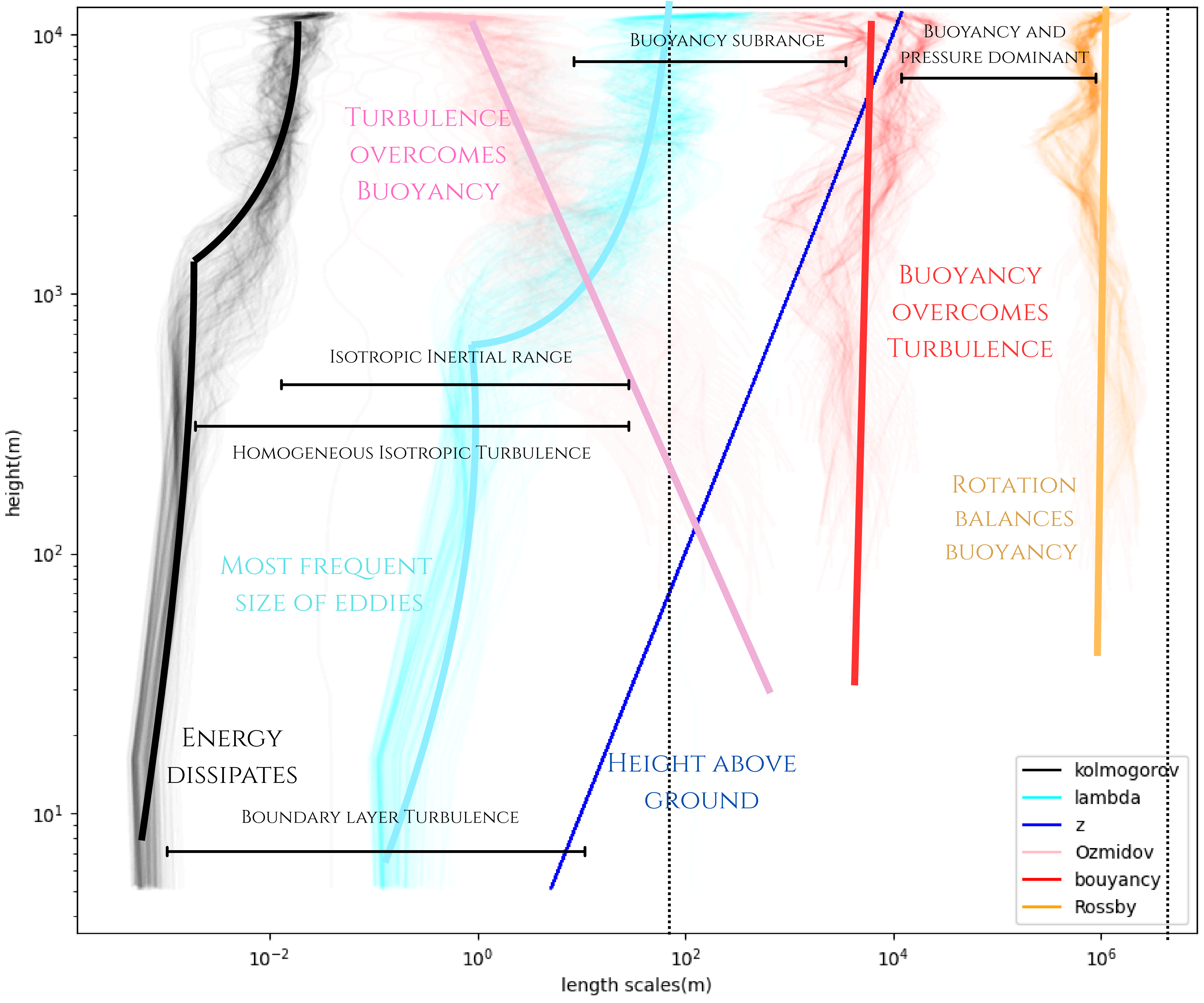


Figure 6. Plot showing a fit of $-r$ for $10 < r < 150$ km and r^3 for $540 < r < 1400$ km to the sum of the measured stratospheric diagonal third-order functions. Straight lines are fits to $-r$ and r^3 in the respective subranges. Circles and crosses indicate negative and positive values, respectively.



Relevant Length Scales

To aid understanding of what is happening across length scales



Rossby Radius

Formula:

$$L_R = \frac{NH}{2\Omega sin(\psi)}$$

Buoyancy Length Scale (L_b)

Formula:

$$L_b = \frac{2\pi U}{N}$$

Doherty-Ozmidov Length Scale (L_O)

Formula:

$$L_O = \frac{2\pi \epsilon^{1/2}}{N^{3/2}}$$

Taylor microscale (L_λ)

Formula:

$$L_\lambda = \sqrt{\frac{15\nu u'^2}{\epsilon}}$$

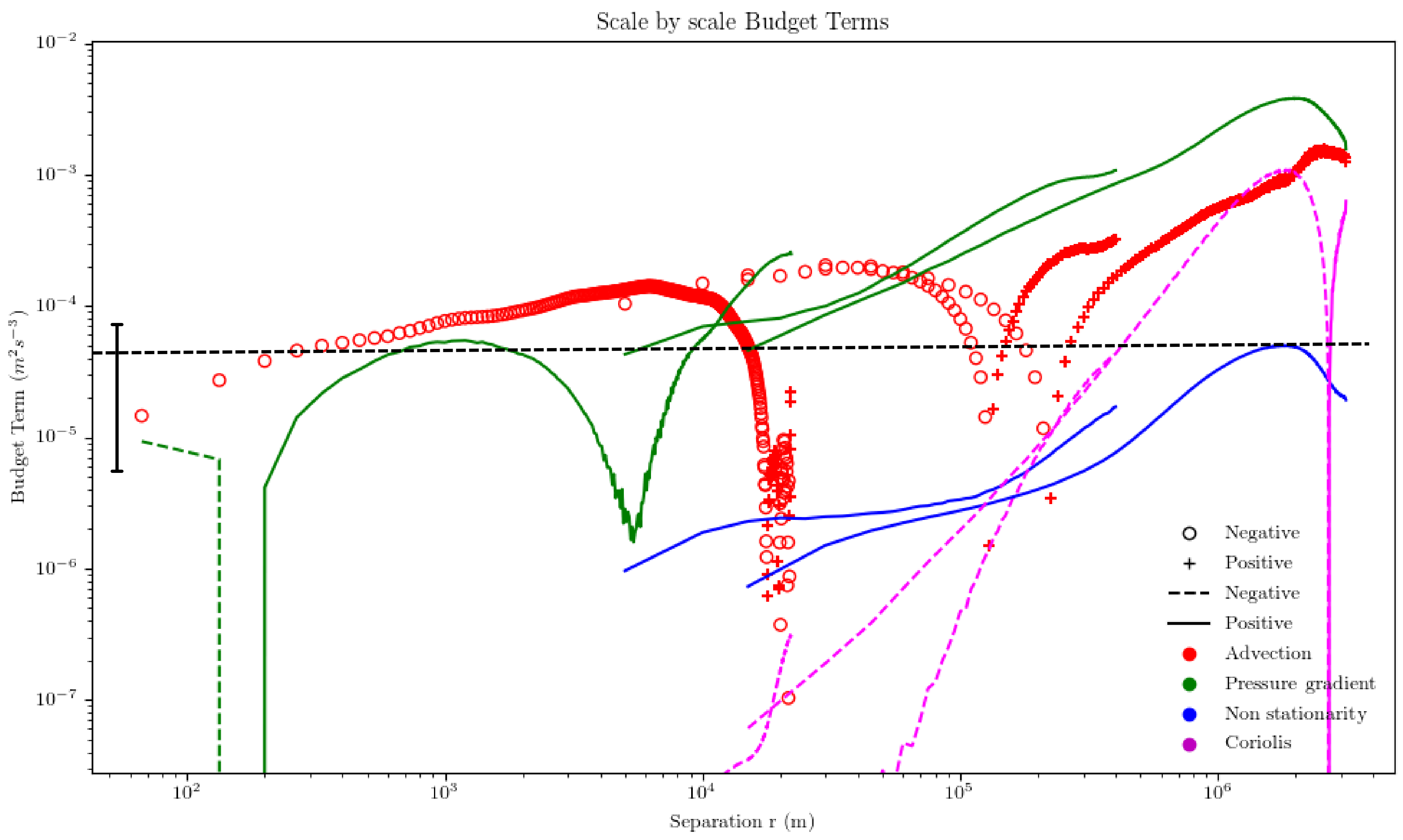
Kolmogorov Length Scale (η)

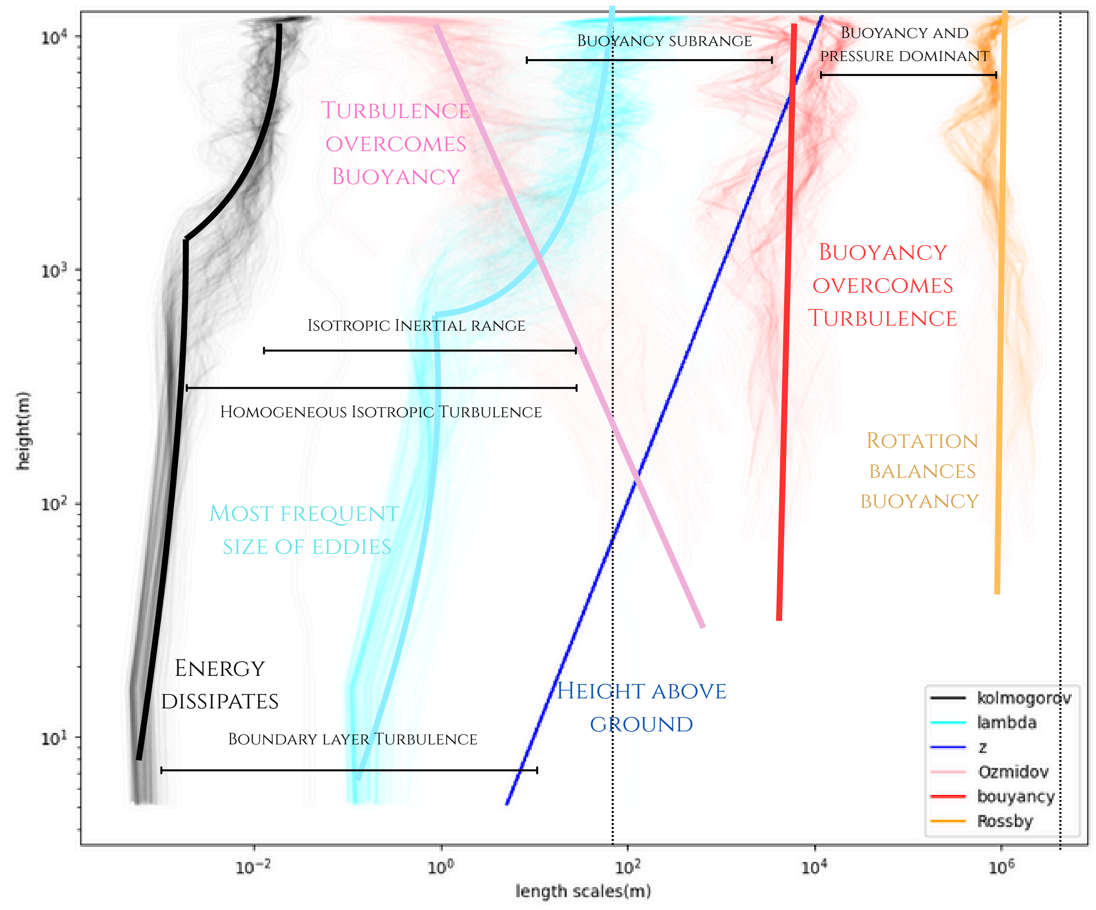
Formula:

$$\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$$

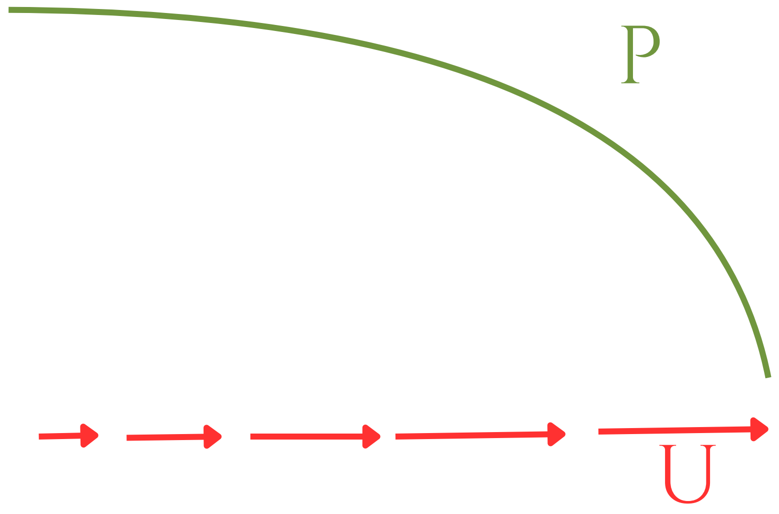
COVARIANCE WITH TERMS IN EVOLUTION EQUATION

How energy travels through length scales





$$\delta(u_j\partial_j u_i).\delta u_i = \delta(-\alpha\partial_i p).\delta u_i - 2\epsilon + \dots$$



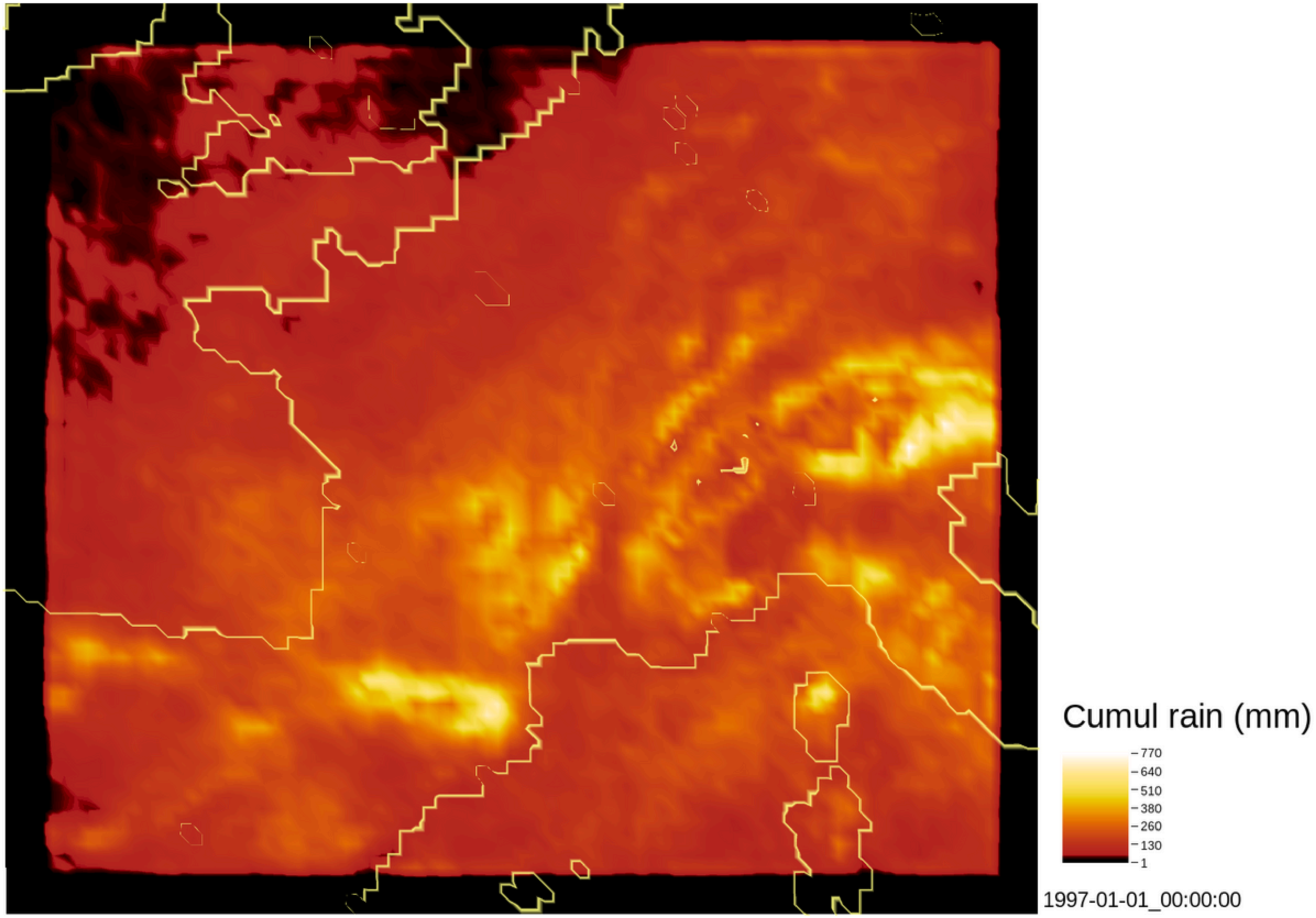
A prsopective picture for the inverse cascade

Simulation for 30 year period

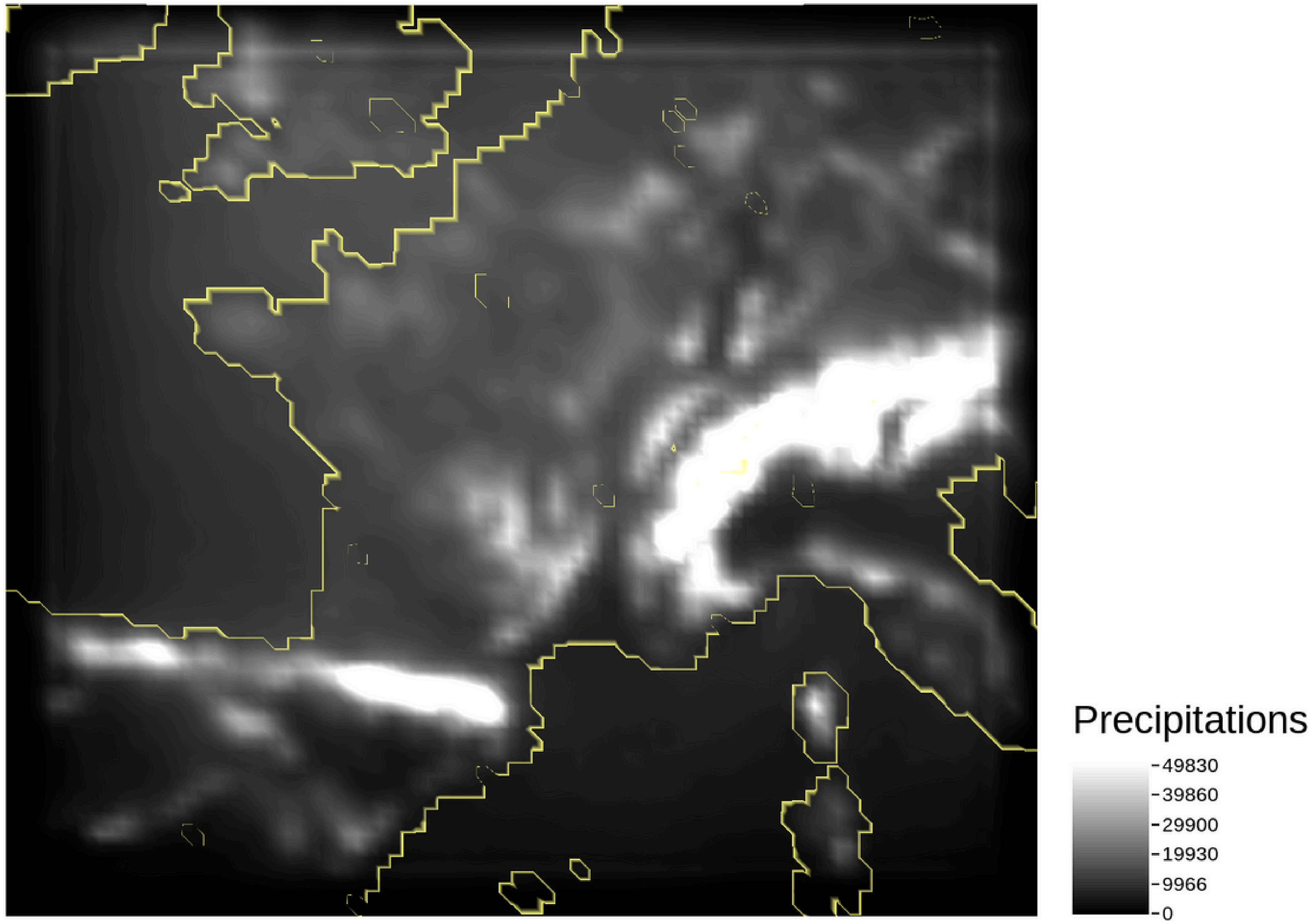
Domain Characteristics:

- 80 x 90 (NSxWE) pixel
- Resolution 20km
- Time step: 45s
- Period: 01/01/1996 - 28/12/2024

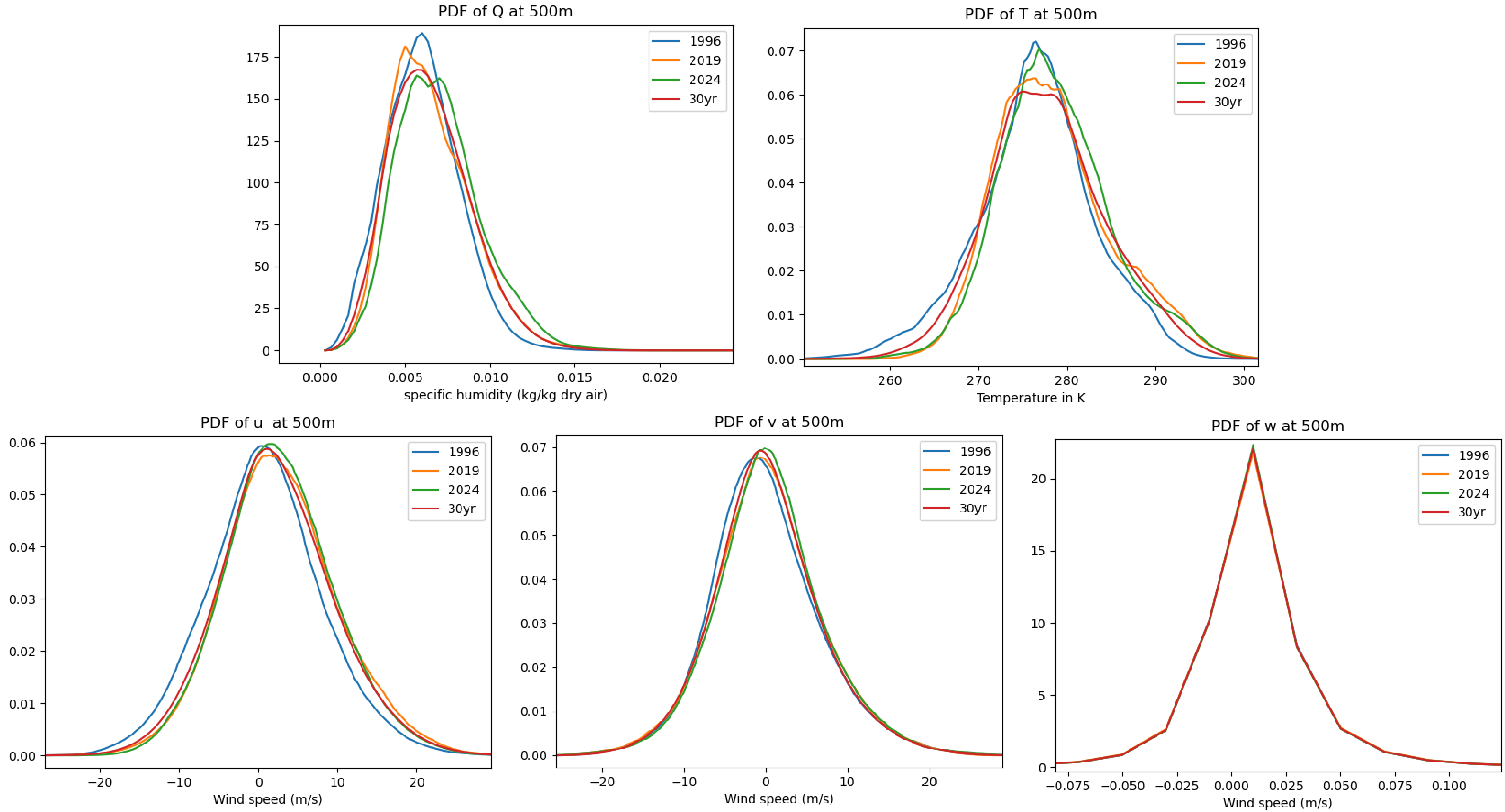
Primary result: Accumulated precipitation



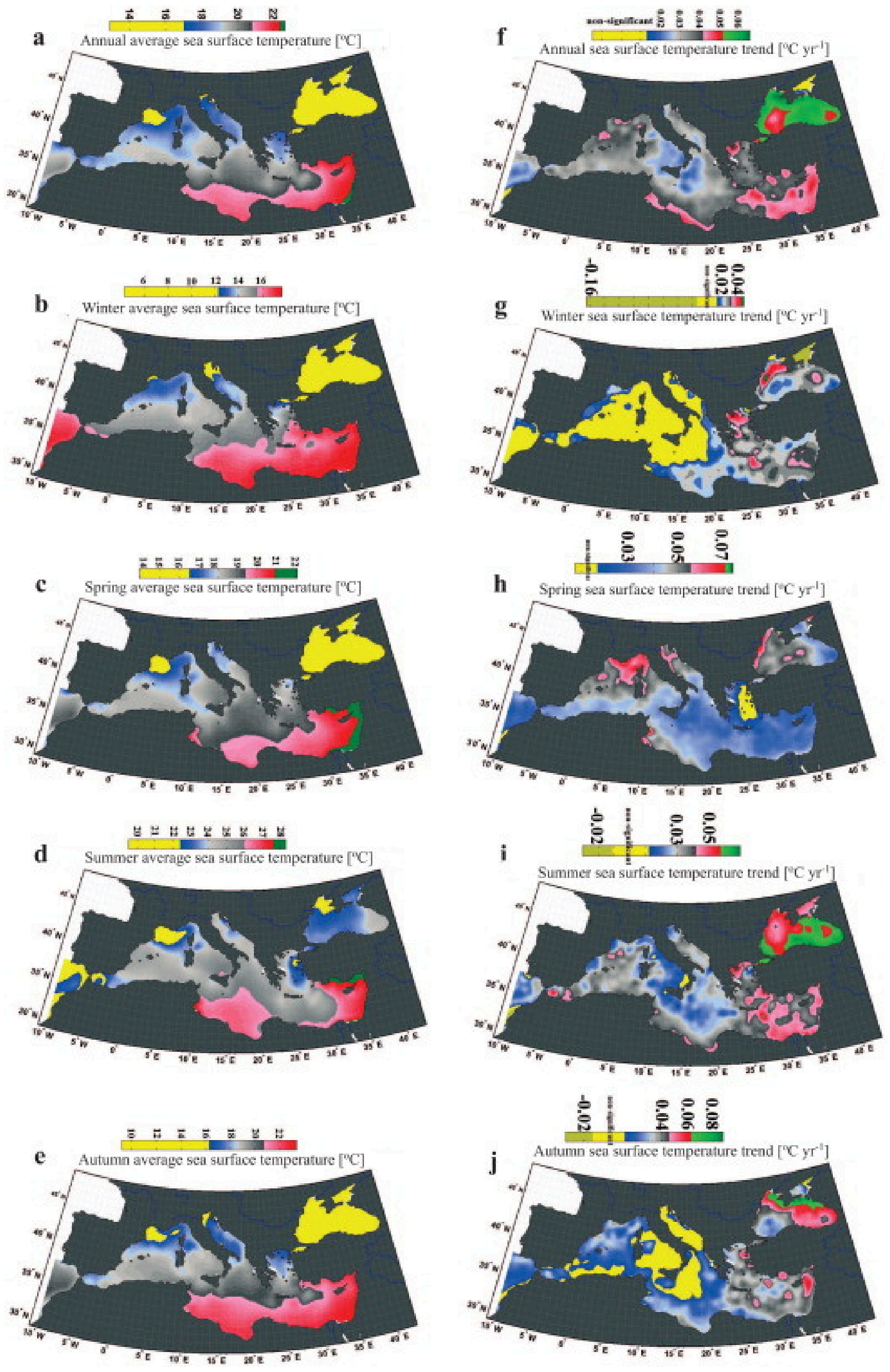
Accumulated rain
on the year 1996
(drought in the north of France)



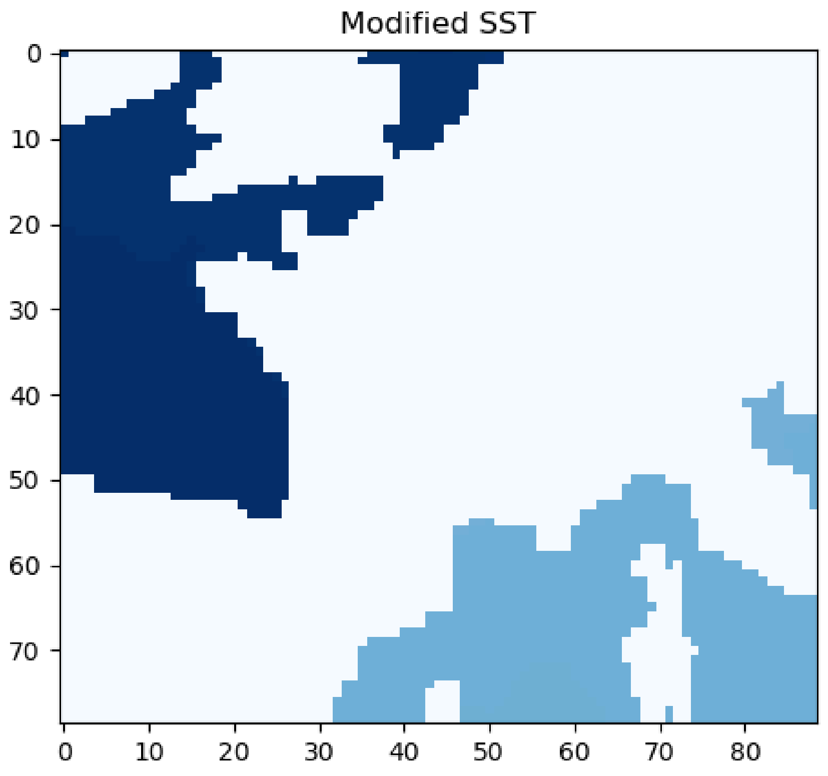
Accumulated rain
on the whole simulation
note: High rain fall on the mountains


PDF of Q at 500m
specific humidity (kg/kg dry air)
PDF of T at 500m
Temperature in K
PDF of u at 500m
Wind speed (m/s)
PDF of v at 500m
Wind speed (m/s)
PDF of w at 500m
Wind speed (m/s)
1996
2019
2024
30yr

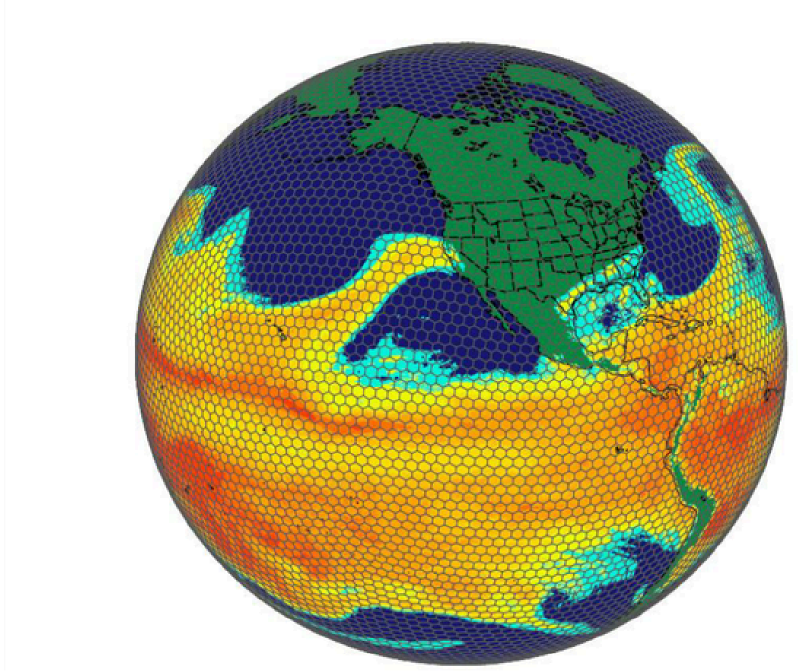
Future work: Modification of the sea surface temperature and Global simulation



Spatial distribution of annual/seasonal SST means and trends over the 1982–2012 period;
Shaltout et al 2014



Modified SST over the mediterranean sea



Global simulation with voronoi grid on MPAS
©Hagos et al, 2015

Thank you

Feel free to contact us for any further inquires:

kazim-hussain-nasir.sayeed@univ-rouen.fr. (Good luck typing that)
clement.blervacq2@univ-rouen.fr