Progressive Monte-Carlo Rendering of Atmospheric Flow Features Across Scales

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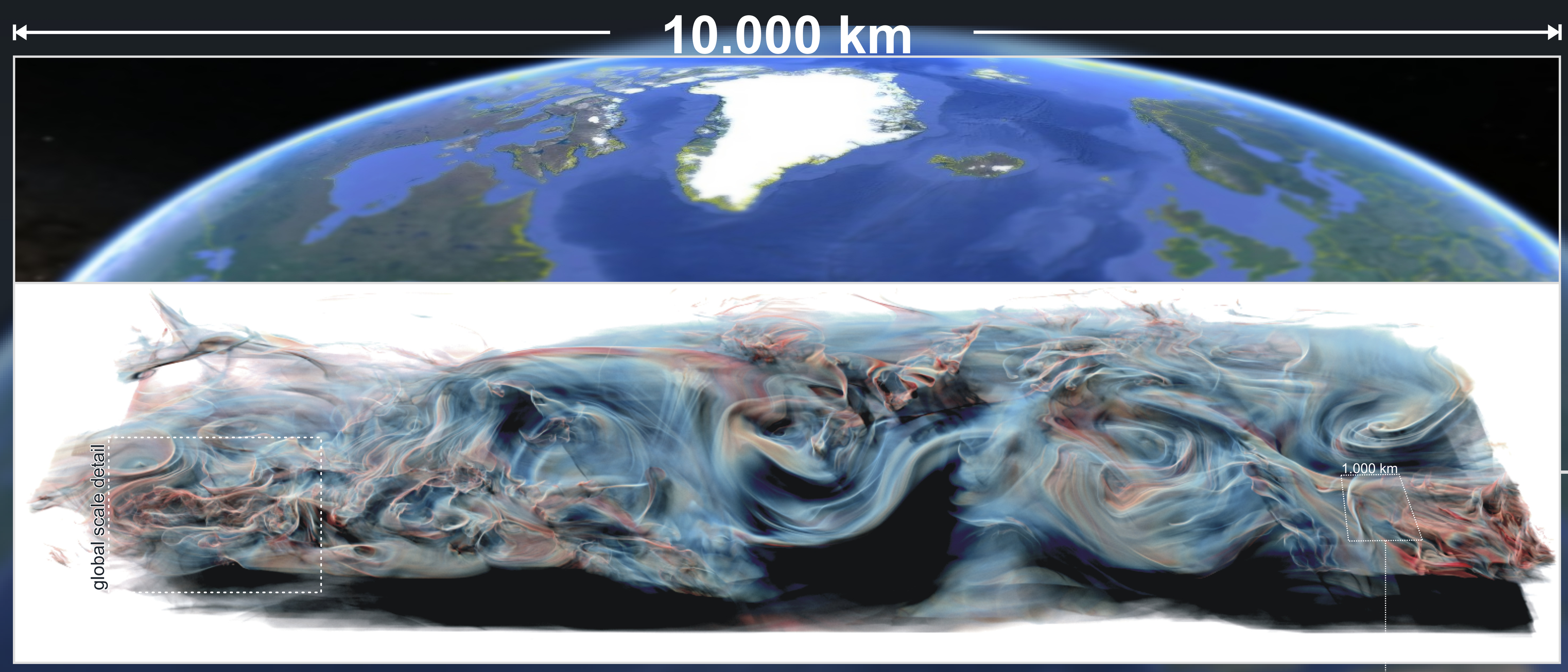
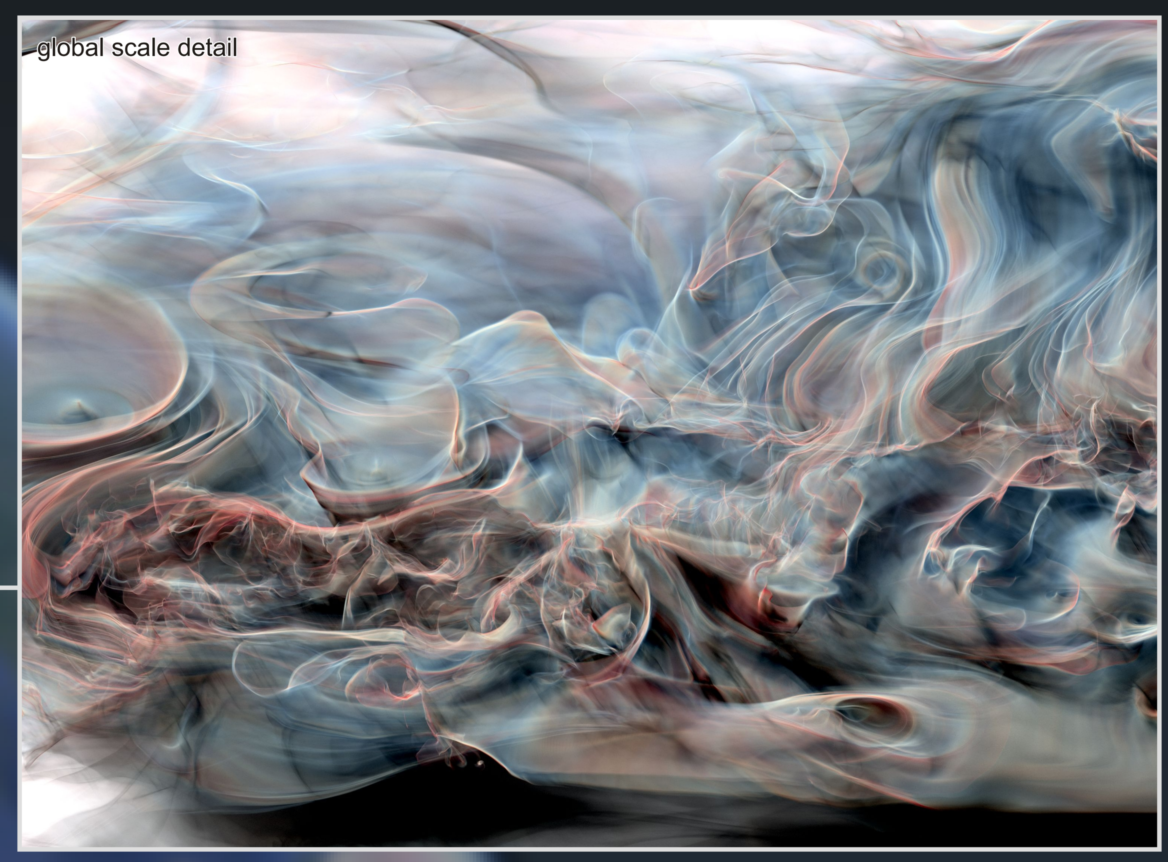
To improve existing weather prediction and reanalysis capabilities, high-resolution and multi-modal climate data becomes increasingly important. High-resolution numerical simulation of atmospheric phenomena provides new means to understand dynamic processes and to visualize structural flow patterns. In the presented figures, we demonstrate an advanced technique to visualize multiple scales of dense flow fields and Lagrangian patterns therein, simulated by state-of-the-art simulation models for each scale. They provide insight into the structural differences and patterns that occur on each scale and highlight the complexity of flow phenomena in our atmosphere. For visualization, we use an unbiased and consistent Monte-Carlo rendering technique [1].

The method approximates non-local flow integrals to derive the finite-time Lyapunov exponent (FTLE) field, which highlights areas of strong repelling behavior and denotes regions that cannot be crossed by virtual atmospheric tracers. These so-called *material structures* constrain the advection of trace gases (such as CO_2 or SO_2), guide temperature diffusion, and cloud formation. Overall, the Lagrangian perspective provides a novel view into the non-local, long-term dynamics of the atmospheric flow fields at each scale.

[1] T. Günther, A. Kuhn and H. Theisel (2016),
MCFTLE: Monte Carlo Rendering of Finite-Time Lyapunov Exponent Fields
Computer Graphics Forum (CGF), 35:3, 381-390.

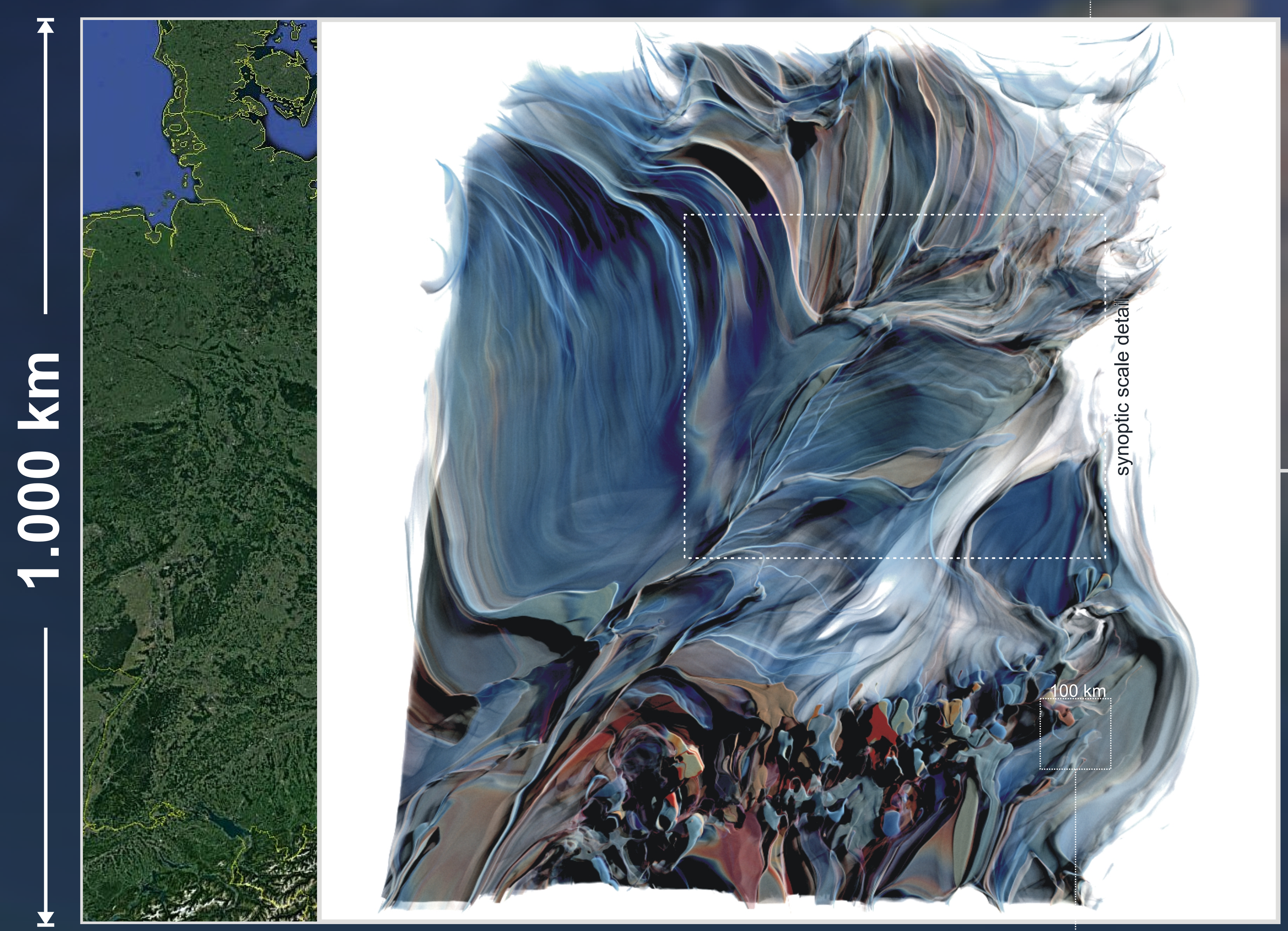


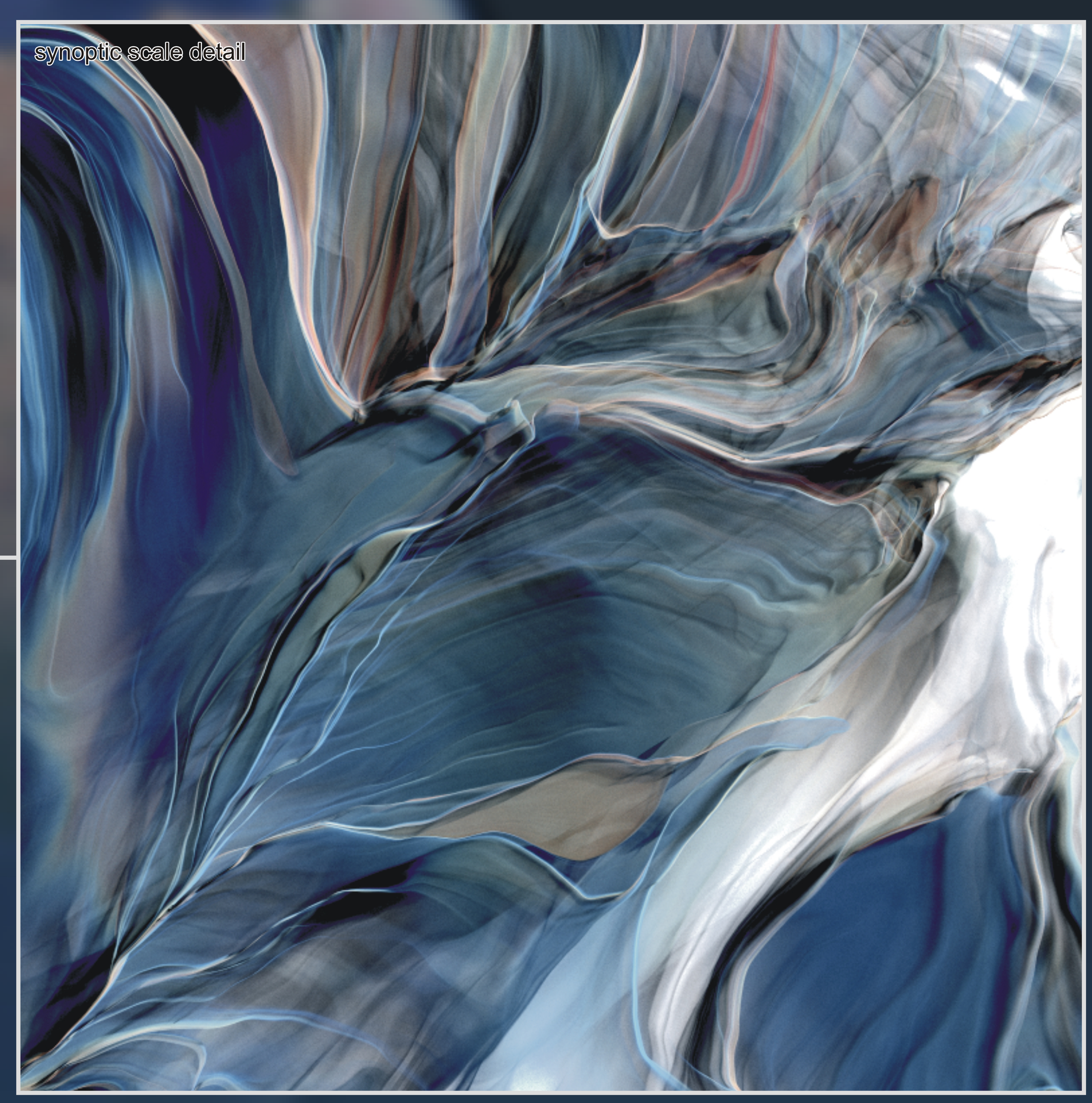


The 10.000 km Scale *(global scale)*

longitudal range:	-120° to 60°,	1200 grid cells
latitudal range:	30° to 90°,	40 grid cells
height:	0 m to 1.1 km,	90 grid cells
time:	April 10, 2010	

This scale shows a reanalysis simulation of the Northern hemisphere (data from the European Centre for Medium-Range Weather Forecasts). It shows the atmospheric flow field in a large domain with an 80 km grid resolution. The shown FTLE field is strongly related to the exchange of energy and trace gases, and reveals characteristic flow patterns in the atmosphere. The rendering highlights features above the North American land surface (bottom left, detailed zoom), the North Atlantic Ocean (center) and the European land mass (bottom right corner). Specifically, the spatial turbulent structure of vortices (cyclones) and stream-like features are emphasized.

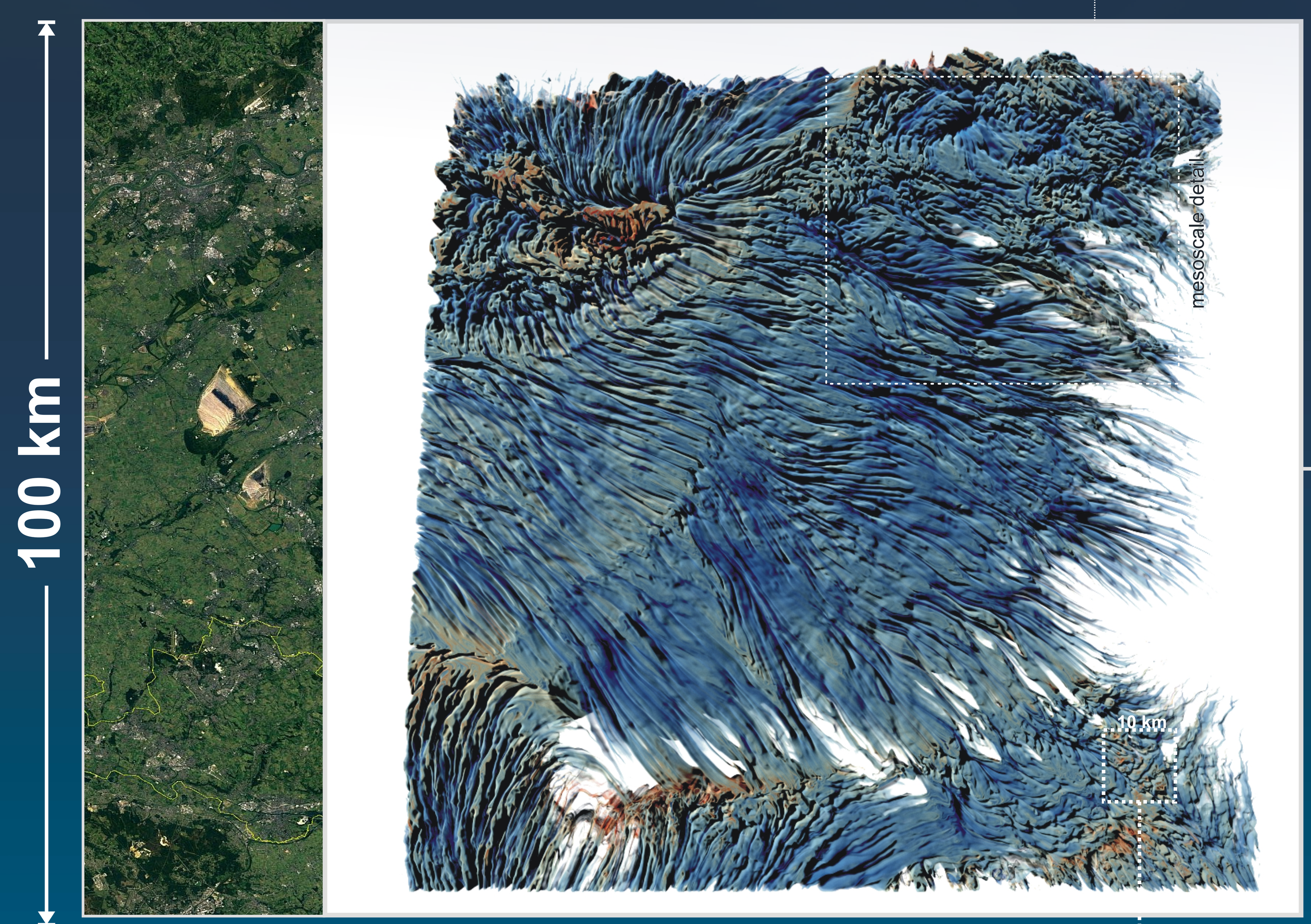


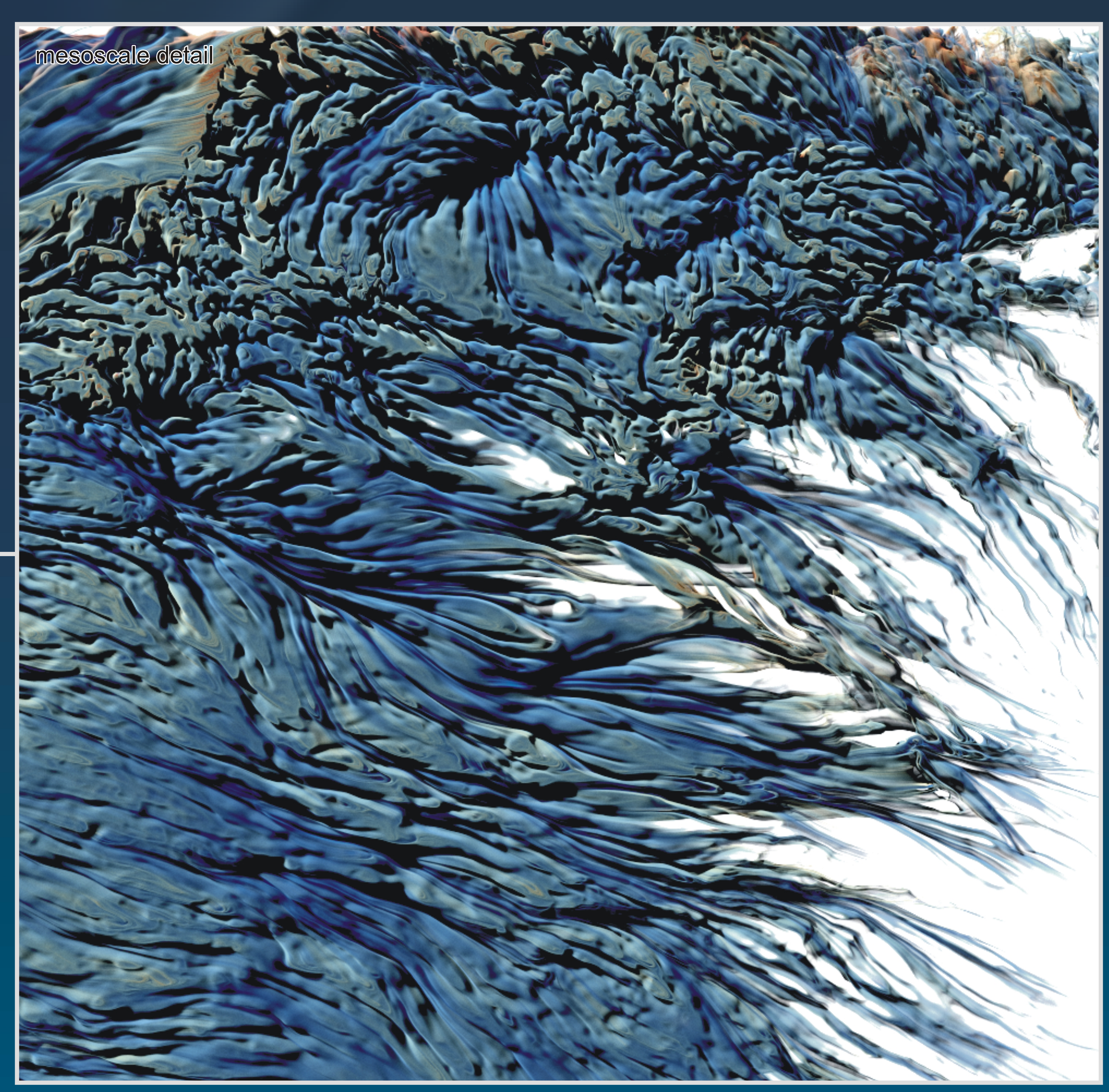


The 1.000 km Scale *(synoptic scale)*

longitudal range:	1° to 20°,	461 grid cells
latitudal range:	44.7° to 56.5°,	421 grid cells
height:	0 km to 14 km,	50 grid cells
time:	April 26, 2013 at 17:00	

The synoptic scale shows COSMO-DE reanalysis simulation over central Europe with a 2.8 km grid resolution. The COSMO-DE model is the current operational weather model of the German Weather Service (DWD). At this scale, the flow field is strongly influenced by global-scale features, the land-sea interaction, and orography. This is visually apparent when comparing the flow structures over the Alpine region (bottom region) and the Northern coastline (top region). At this day, additional flow separation takes place at the central region over Germany, triggered by a rain front passing from south-west to north east. The detail region shows the coastal region shared by Germany and Poland, highlighting separating flow features in this area.





The 100 km Scale *(mesoscale)*

longitudal range:	0 km to 48 km,	960 grid cells
latitudal range:	0 km to 48 km,	960 grid cells
height:	0 km to 13 km,	144 grid cells

At the mesoscale, a semi-idealized large eddy simulation (LES) is shown for the area around Julich, Germany [2]. It uses boundary forcing from the COSMO-DE model with a spatial resolution of 50 m. Such small-scale, high-resolution models are used to parameterize larger domain simulations. At this scale, turbulence features (such as convective plumes and updraft cells) can be fully resolved and simulated directly. The presented overview shows a convective cell developing at the top-left area, creating a strong, separating updraft with visible intake region around the cell. The detail view highlights the detailed features compared to the synoptic simulations.

[2] Heinze, R., Moseley, C. et al. (2016)
Evaluation of large-eddy simulations forced with mesoscale model output for a multi-week period during a measurement campaign
Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-498

The 10 km Scale

longitudal range:	0 km to 10 km,	384 grid cells
latitudal range:	0 km to 10 km,	384 grid cells
height:	0 km to 3.2 km,	130 grid cells

The smallest scale represents a cloud-topped boundary layer (CTBL) simulation using the UCLA-LES model [3]. The simulation represents a finite-size domain at 25 m spatial resolution under idealized conditions: It uses double-periodic boundary conditions and homogeneous surface forcing, while large-scale information is taken from the COSMO-DE model. Similar to the previous scale, the purpose is to study the detailed cloud dynamics at very high resolutions for sub-scale parametrization of synoptic simulations. Convective flow patterns (e.g. separating plumes visible in the FTLE field) are of central interest since they are tightly coupled with cloud production and flow interaction processes.

[3] Stevens, B., et al. (2005),
Evaluation of Large-Eddy Simulations via Observations of Nocturnal Marine Stratocumulus
Monthly Weather Review (AMS), 133:6, 1443–1462.

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