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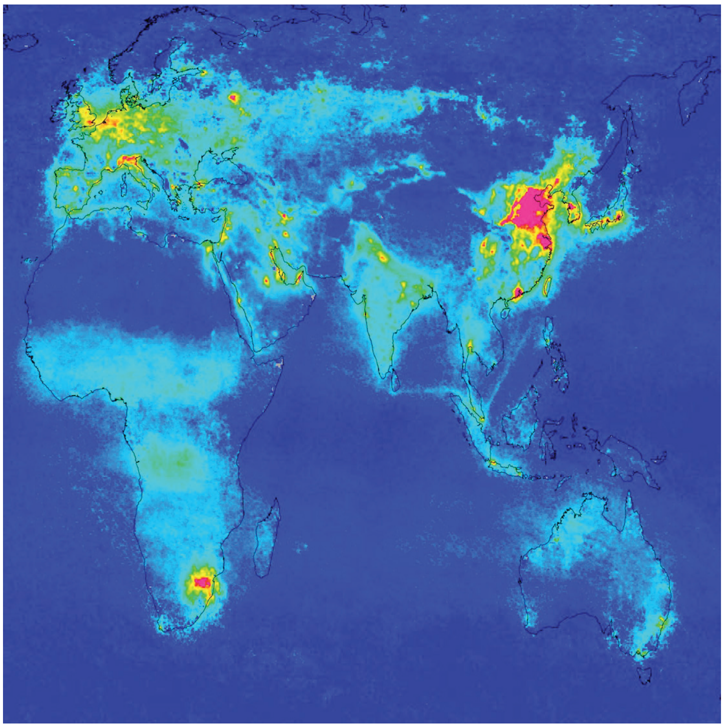
COMPUTING

GPU based interactive 3D visualization of ECMWF ensemble forecasts



NO2 pollution map courtesy of KNM/IASB/ESA

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GPU based interactive 3D visualization of ECMWF ensemble forecasts

Marc Rautenhaus, Christian M. Grams, Andreas Schäfler, Rüdiger Westermann

Nowadays Graphics Processing Units (GPUs) and three-dimensional (3D) visualization are state of the art in the entertainment industry. However, the power that GPUs provide has not been used widely in meteorological data visualization. In the context of weather forecasting during aircraft-based field campaigns, the Technical University of Munich's Chair for Computer Graphics and Visualization is, in collaboration with the DLR (German Aerospace Centre) Institute of Atmospheric Physics, developing a GPU powered 3D weather forecasting tool for ECMWF ensemble forecasts. In our project, we are interested in how we can exploit the computational power of GPUs to create interactive 3D visualizations of ensemble predictions that enable the forecaster to (a) quickly identify atmospheric features of interest to a campaign and (b) assess the features' uncertainty. This includes technical issues as well as the question of how the forecast meteorological fields and the uncertainty information derived from the ensemble can best be presented in three dimensions.

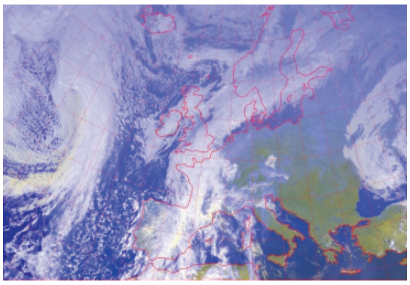
Our research is motivated by forecasting cases from the T-NAWDEX-Falcon field campaign (hereafter TNF, see Box A), which in October 2012 aimed at taking in-situ measurements in warm conveyor belts (WCBs). In this article we describe our visualization approach to predict WCB situations. The weather situation of 19 October 2012 serves as an illustration of the visualization methods and their implementation using the GPU. As it is difficult to convey the full power of interactive 3D visualization in printed, static images, you can find supplementary video content on our project website. Please point your web browser to http://wwwcg.in.tum.de/research/research/projects/met3d.html.

T-NAWDEX-Falcon

A

The T-NAWDEX-Falcon field campaign, jointly organised by DLR and ETH Zurich, took place in October 2012 at DLR's Oberpfaffenhofen base. Several research flights were conducted with the German research aircraft Falcon to take in-situ measurements in warm conveyor belts (WCBs; a WCB is an air stream in an extratropical cyclone that rapidly ascends in the warm sector ahead of the cold front along the sloped isentropes of the midlatitude baroclinic zone). The major forecasting challenge was to predict how favourable the weather situation was for the occurrence of a WCB within aircraft range. *Schäfler et al.* (2014) describe the campaign and the challenges for flight planning in detail.

The visualizations shown in this article consider the T-NAWDEX-Falcon case of 19 October 2012. The figure shows the visible Meteosat image at 12 UTC on 19 October (Meteosat operated by EUMETSAT with image processing by DLR-IPA).



A distinct narrow trough was located to the west of the British Isles. Cold air was advected far south, as can be seen from the convective clouds east of the Iberian Peninsula. The former hurricane 'Rafael', having undergone extratropical transition, can be seen upstream of the trough, south of Iceland. This strong cyclone largely influenced the predictability over Europe and, in particular, the shape and location of the WCB manifest in the cloud band extending from Spain to the British Isles.

AFFILIATIONS
Marc Rautenhaus, Rüdiger Westermann, Computer Graphics and Visualization Group, Technische Universität München, Germany
Christian M. Grams, Institute for Atmospheric and Climate Science, ETH Zürich, Switzerland
Andreas Schäfler, Institut für Physik der Atmosphäre, Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, Germany

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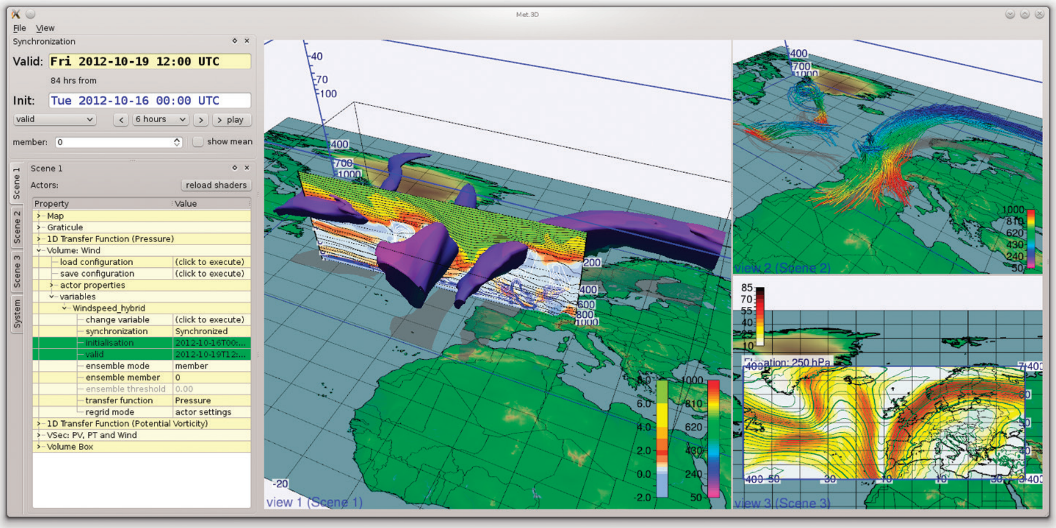

Figure 1 Screenshot of the forecasting tool 'Met.3D' with three views visualizing different variables of the control run of the ensemble forecast started at 00 UTC on 16 October 2012 at 84 hours lead time. View 1 (middle): 40 ms^{-1} isosurface of wind speed together with a vertical cross-section of potential vorticity. View 2 (upper right): Trajectories ascending more than 500 hPa in 48 hours. View 3 (lower right): Horizontal cross-section of geopotential height and wind speed at 250 hPa.

Using GPUs to visualize meteorological data fields

GPUs have become increasingly powerful in recent years. First designed as highly specialized co-processors to speed up graphics operations, they have evolved into massively parallel multi-purpose processors that nowadays can be used for arbitrary computations including numerical simulation (e.g. *Owens et al*., 2008). In our work we use them to execute visualization algorithms, as well as to speed up data processing operations. Current GPUs allow the execution of increasingly complex visualization algorithms at interactive frame rates, that is, a single image can be rendered in a fraction of a second. This enables smooth animations of a scene.

Box B gives further information on GPUs. For visualizing meteorological forecast data, current models provide sufficient power to enable interactivity for scenes such as the example shown in Figure 1. The images are generated by uploading the forecast data to the graphics card. Spatial interpolation, isosurface extraction, contour line generation and colour mapping is all carried out by the GPU. The user can move around in the scene and change visualization parameters, including the position of cross-sections, isosurface values and colour mappings without having to wait for a new image.

Graphics Processing Units

B

A graphics processing unit (GPU) is a highly parallel processor, with current models possessing up to 1,500 processing cores. Originally designed as special-purpose graphics engines with fixed functionality, GPUs have evolved into fully-programmable processors featuring extremely fast memory. In recent years, the term GPGPU (general-purpose computing on the GPU) has been coined to describe the mapping of arbitrary computations to the GPU.

GPUs are programmed following the single program multiple data (SPMD) paradigm, allowing the processing of many elements (e.g. grid points for fluid simulation or rays casted through a data volume for 3D visualization) in parallel using the same program. This ability to simultaneously use a large number of processing units, paired with the fastmemory interface, leads to very high performance in applications where parallelism is abundant. The very high performance combined with high bandwidth interfaces to the CPU, through which the GPU might even be able to directly access CPU memory in the near future, enables the implementation of streaming methods. Streaming allows the efficient exploitation of the GPU's power to process and visualize datasets too large to fit into its local memory, an approach particularly interesting for ensemble datasets.

For further information on GPUs, we refer the reader to, for example, the survey by *Owens et al.* (2008).

How to visualize the ensemble?

During aircraft based field campaigns, flights often have to be planned several days in advance. Hence, being able to assess the uncertainty of the forecast on whose basis a flight route is designed is very valuable. In contrast to the surface products provided operationally by ECMWF's ensemble forecast (e.g. surface wind gust probabilities), planning of flights with high-flying aircraft focuses on upper-level features, which inherently are of a three-dimensional nature. Hence it seems natural to aid the identification of such features (which can be clouds, the jet stream or, in the case of TNF, warm conveyor belts) in the forecast data with three-dimensional visualization elements. Nevertheless, until now research flight planning at DLR has been based on the 'classic' two-dimensional (2D) plots widely used in meteorology (*Rautenhaus et al*., 2012). We thus considered it essential to provide familiar 2D cross-sections in the new 3D environment, thereby 'building a bridge' from 2D to 3D visualization. By enabling the forecaster to interactively move a cross-section in the scene and to add, for instance, a 3D isosurface, the 3D structure of the forecast atmosphere can be explored very quickly. Figure 2 illustrates the approach with a vertical cross-section of cloud cover (colour) and potential temperature (contour lines) to which trajectories indicating a WCB (see below) are added.

With regard to the ensemble, we are, as a first step, interested in animating the ensemble members and exploring statistical metrics including mean, standard deviation and probabilities derived from the ensemble. Similar to the operational stamp maps showing all the members of an ensemble, animating over the ensemble members helps identify regions of large variation and determine the scenarios indicated by the ensemble forecast. Figure 3 shows a few members of a vertical cross-section of potential vorticity together with a 40 ms^{-1} isosurface of wind speed (indicating the jet stream). The jet stream on the western, upstream side of the trough is influenced by the interaction of hurricane Rafael with the midlatitude flow during its extratropical transition. It is clearly visible that the wind speed isosurface in this region varies much more between the members than on the eastern, downstream side of the trough.

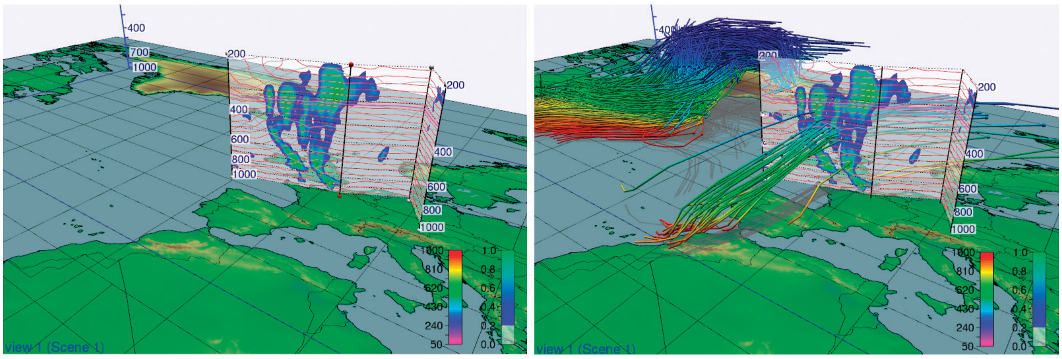

Figure 2 A vertical cross-section of cloud cover along a possible flight route (forecast from 00 UTC on 16 October valid at 12 UTC on 19 October 2012). The waypoints defining the section can be moved by dragging the spherical handles. On the right, 3D trajectory lines are added to the scene to visualize where trajectories and flight route intersect. Trajectory lines are coloured with pressure (hPa) and the vertical section is coloured with cloud cover fraction per grid box (0-1).

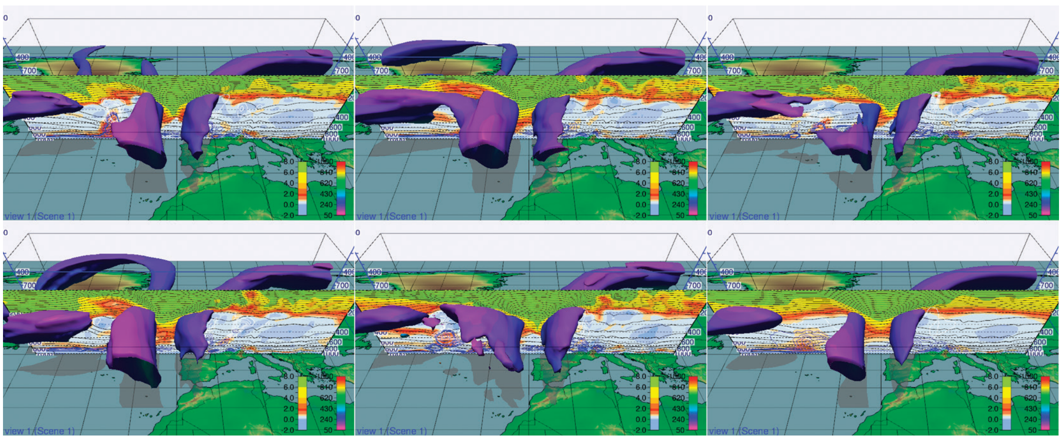

Figure 3 Screenshots from navigating through the ensemble dimension (forecast from 00 UTC on 16 October valid at 12 UTC on 19 October 2012). The vertical cross-section shows potential vorticity in PVU (reddish colours denote the dynamic tropopause at 2 PVU) and the 3D isosurface shows a wind speed of 40 ms^{-1} (colour coded by pressure in hPa). From left to right, top to bottom: Control run, members 8, 16, 31 and 32 and the ensemble mean.

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Probabilities can refer to simple thresholds (e.g. the probability of wind speed exceeding 40 ms^{-1} or the probability of temperature being between 260 K and 270 K), or to features. Figure 4 shows the probability of cloud cover exceeding a grid box fraction of 0.2. Knowledge about clouds along a flight track is important information for many research flights. For TNF, we were particularly interested in the probability of a WCB occurring. To identify WCBs, we followed the approach of *Wernli & Davis* (1997) and computed Lagrangian trajectories for each member of the ensemble with the ETH Zurich LAGRANTO model. Trajectories starting close to the surface and ascending more than 500 hPa in 48 hours were classified as WCB trajectories. By gridding each member's trajectory position at a given time and counting the number of members for which a grid box contains a trajectory, a probability of WCB occurrence can be derived. Figure 5 illustrates the approach. Thresholds for computing probabilities or parameters for feature detection, such as the filter criterion of vertical distance per time to identify WCBs, may not be specifiable in advance. Hence, we provide interactiveness with regard to parameter adjustments in the visualization system. Figure 5 shows an example of adjusting the trajectory filter criterion from 500 hPa to 550 hPa in 48 hours, thereby focussing more strongly on the core region of the WCB where the ascent is strongest.

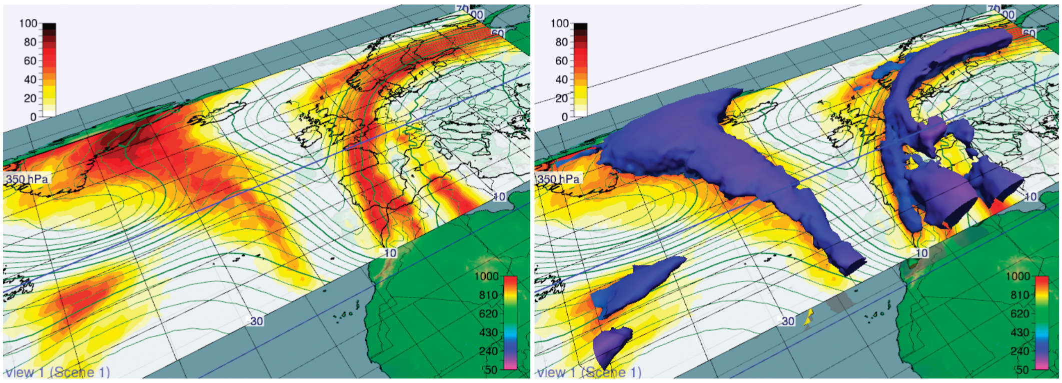

Figure 4 Left: Horizontal section at 350 hPa showing the probability (%) of cloud cover fraction exceeding 0.2. Contour lines show the mean geopotential height field. Right: An isosurface of 50% added to the horizontal section (forecast from 00 UTC on 16 October valid at 12 UTC on19 October 2012).

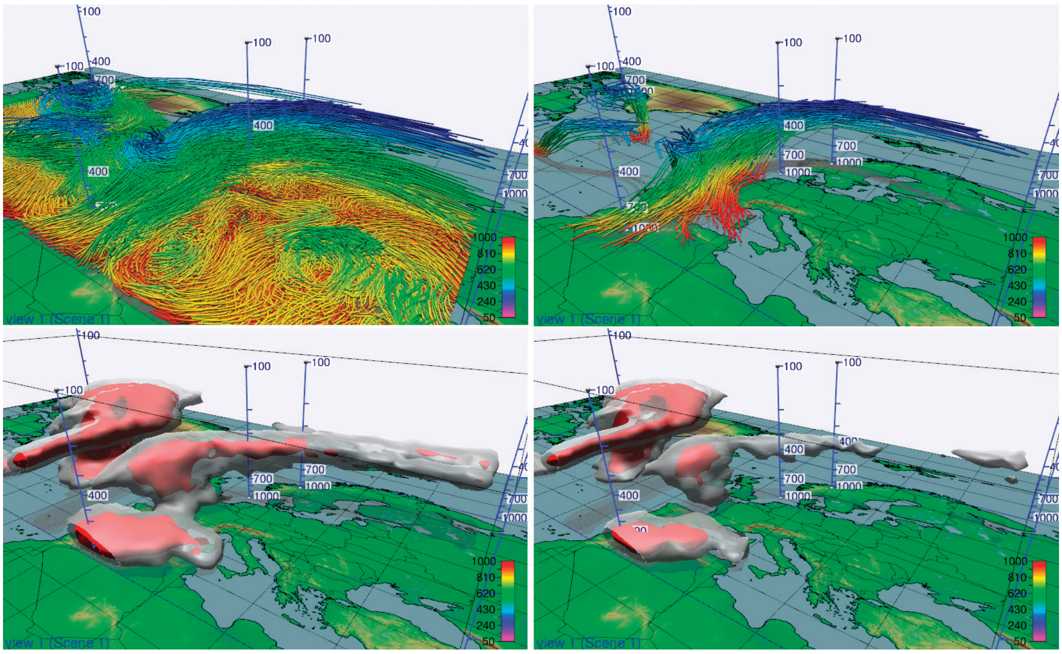

Figure 5 Probability of warm conveyor belt occurrence p(WCB) computed from trajectories. Top row: Single member of 48-hour trajectories started near the surface (left) and filtered according to an ascent of 500 hPa in 48 hours (right). Bottom: Volume rendering of p(WCB) with two different probability surfaces, derived from gridded trajectories ascending 500 hPa in 48 hours (left) and 550 hPa in 48 hours (right).

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Met.3D – a 3D forecasting tool

We have integrated the visualization methods into a software tool that is intended to be used for forecasting during future field campaigns. Figure 1 shows a screenshot of the current version of the tool, which we have called 'Met.3D'. The software provides multiple views that can display the same or different datasets from arbitrary viewpoints in 3D space. A number of global parameters concerning time and ensemble dimensions and camera position can be synchronized and hence be changed simultaneously for all views. As common in meteorology, the logarithm of pressure serves as the vertical coordinate.

To achieve the best possible vertical accuracy in the visualizations and trajectory computations, we use ensemble forecast data on the original hybrid sigma-pressure model levels. Although these datasets are not operationally archived in the ECMWF Meteorological Archive and Retrieval System (MARS), the last three forecast runs are available and can be retrieved during field campaigns. For our project, we have recorded multiple ensemble forecasts for the TNF period. As we are typically not interested in the entire global forecast but only in a limited domain, we use the data on the regular horizontal grid that is output by the MARS system.

To enable smooth animation over time and ensemble dimensions, Met.3D uses caching and pre-fetching techniques to avoid time-consuming disk reads when the user changes time or ensemble settings. Depending on the resolution of the dataset to be visualized, the system hence requires multiple GB of system and video memory. However, for a dataset covering the domain shown in Figure 1 with a horizontal resolution of one degree, Met.3D can already be used on a standard Laptop equipped with 4 GB of system memory and 1 GB of video memory.

Ongoing developments

Our current focus is to continue research on how to best visualize the uncertainty information derived from the ensemble. Uncertainty visualization is an active field of research in the visualization community, and meteorological data visualization may greatly benefit from it. Relevant recent research includes work on the positional uncertainty of isosurfaces (*Pfaffelmoser et al*., 2011), uncertain particle trajectories (*Bürger et al*., 2012) and using non-parametric probabilistic models to compute feature probabilities (*Pöthkow & Hege*, 2013). We are, for example, pursuing further experiments to visualize probabilities of atmospheric features such as fronts and jet streams.

Furthermore, spatial perception is an important issue with 3D visualization. In particular, in meteorology it often is essential to know the exact location of a feature. In Met.3D, we currently use shadows (all figures) and user-placed poles (Figure 5) to aid the perception of the spatial location of a feature. Nevertheless, we are continuing to investigate the issue to further improve spatial perception. The same applies to detailed labelling of the elements shown in an image. Real-time label placement in three dimensions is a difficult problem, though labels can greatly improve the quantitative information conveyed by an image.

When using model data on hybrid sigma-pressure levels, every ensemble member is defined on a different model grid (the surface pressure field defining the elevation of the individual grid points varies with the ensemble). Hence, computing ensemble statistics on a grid-point basis strictly speaking requires a regridding of the members to a common grid. However, the difference in the produced images often is small. We will soon publish a discussion on the impact of regridding on the visualization of derived statistical quantities.

Beside the usage of Met.3D for planning research flights, the software's modular architecture allows the straightforward integration of new visualization methods. Hence, the system also serves as an infrastructure for atmospheric visualization research, enabling the development and evaluation of methods for visualizing ensemble simulation data. It is thus usable for applications other than flight planning. In this context, we are considering the release of Met.3D as open source software in 2014. If you are interested in collaboration, or if you are encountering any unsolved issues with regard to uncertainty visualization in your work, please do not hesitate to contact us.

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Further reading

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