Project	**664**
Project title	**Dynamik orographischer Wolkenbildung im Hochgebirge**
Project lead	**Prof. Dr. Volkmar Wirth**
Institution	Johannes Gutenberg University, Institute for Atmospheric Physics
Report period	1.1.2014 – 30.9.2015

During the allocation period we continued using DKRZ's resources to carry out various model runs using the EULAG model (Eulerian/semi-Lagrangian fluid solver, see Prusa et al., 2008) . The majority of these runs adressed issues directly connected to the project title, i.e. formation of banner clouds on the leeward side of steep obstacles. As another part of the project we also adopted the EULAG code for studies of urban heat islands and their interaction with topography as well as thermally induced flow transitions in gently sloped mountaineous terrain. Results were published in journals and have been presented at conferences and workshops, see reference list below.

The PhD project on banner clouds, funded by the German Research Foundation (DFG), is still going on and is expected to be finished by mid 2016.

Some important results of this and previous year's work are:

Sensitivity studies on domain size, mountain geometry and inflow conditions: These studies have been continued and extended to cover a broader spectrum of mountain geometries (pyramide shaped peak, ridge, infinite ridge) and aspect ratios (9 scenarios from H/B = 2.8 down to H/B = 0.175). Additionally, the computations for the pyramid shaped mountain have been carried out for varying domain sizes, using doubled extensions in either of the three spatial directions to make sure that the domain size chosen for the reference runs is large enough to obtain results unaffected by boundary conditions.

Significant differences occur between results for the various shapes and aspect ratios of the idealised mountains as well as the chosen inflow profiles. Best conditions for banner cloud formation are thus expected for flow with constant shear around 'steep' mountains with aspect ratios around 1. Broader obstacles, in contrast, inhibit cloud formation.

Dependence of flow separation on mountain shape and flow regime: Within the DFG project, boundary layer separation for flow over a bell-shaped mountain was investigated in quite some detail because of its relevance for banner cloud formation. Following Baines (1995), who introduced a regime diagram for two-dimensional flow, different aspect ratios and thermal stratifications have been evaluated to find analogous regimes for three-dimensional flow.

The flow separation as simulated by EULAG is in good qualitative agreement with Baines' results. Principally, the three-dimensional studies yield a similar behaviour of the flow. Banner cloud formation, however, is simulated only for the three-dimensional flow, which confirms earlier results for pyramid-shaped obstacles.

Evaluation of trajectories: A trajectory module has been incorporated into the EULAG code. It was adopted to study the path of parcels on their way past the mountain before they finally enter the banner cloud zone. It could be manifested that there are essentially two classes of trajectories involved in the formation of banner clouds.

The first class of the air parcels travels right over the mountain near its plane of symmetry, thus reaching the lee vortex after a comparatively short time span. The second class of parcels goes around the lateral edges of the mountain before ending up within the lee vortex too (see Fig. 1). The duration of the transport along this pathway is remarkably longer than in case of the transport over the mountains summit due to the parcels moving upward in a series of cycles through the vortex. In addition the parcels in the second class are slowed down due to surface friction. The division of the trajectory bundle into the two main flow paths occurs on the windward side of the mountain near the flow's stagnation point.

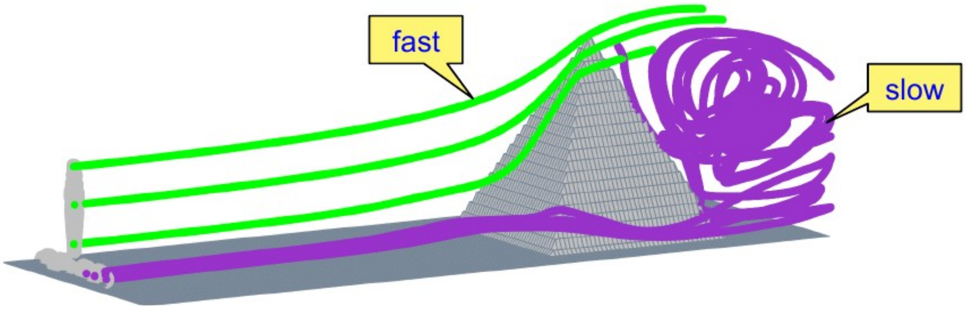

Figure 1: Trajectories of air parcels for flow over and around a pyramid shaped moutain.

Studies of banner clouds at real topographies: EULAG simulations have been carried out for the region around Zugspitze, located on the border between southern Bavaria and Austria. Long term observations at this mountain indicate two favoured wind directions for banner cloud formation, i.e. northerly and, to even greater extent, southeasterly wind.

Model results confirm the higher likelihood of banner cloud formation in case of south-easterly inflow. Plots of the Lagrangian displacement (Figure 2) show the expected distribution with high values of δz especially for southeasterly flow.

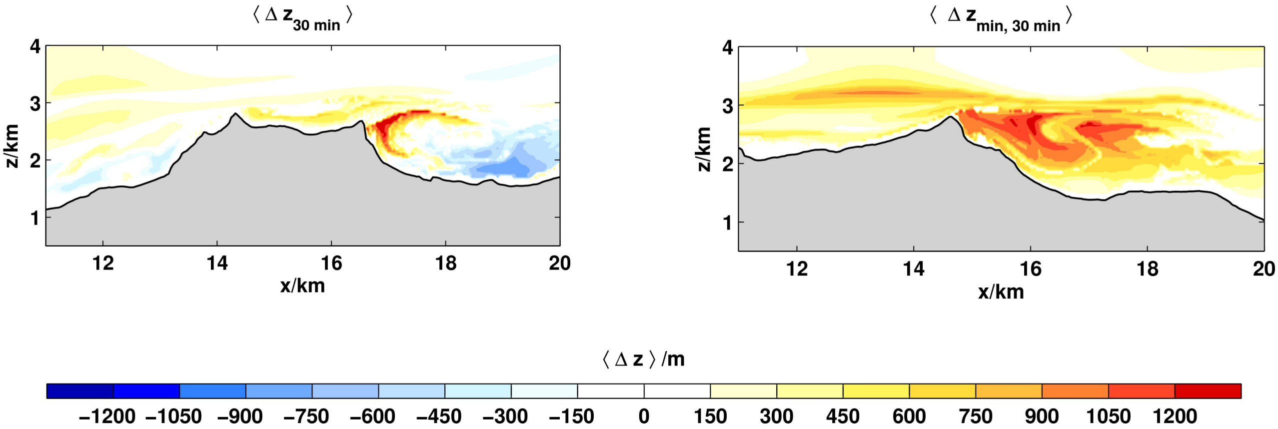

Figure 2: Lagrangian displacement δz for flow over the Zugspitze mountain, northerly (left) and southeasterly (right) inflow.

Thermally induced microscale boundary layer circulations in complex terrain: In Brötz et al. (2014) we investigated the micrometeorological observation that coherent updrafts/downdrafts occur in quiet predictable locations in complex terrain while such preferred locations do not exist in non-complex (i. e. flat and homogenous) terrain. Those investigations were made with numerical simulations using EULAG in large eddy simulation (LES) mode running on blizzard. Based on an ensemble of LES simulations we were able to calculate statistics that led to spatial probability density distributions of coherent updraft/downdraft or unstable intermediate areas.

Air pollution transport in urban valleys: By a series of EULAG simulations for an idealised valley it was shown that different mechanisms of air pollution transport may arise in urban valleys as a result of the interplay between the temperature inversion, the slope winds, and the urban heat island.

Three types of air pollution transport mechanisms were identified from the model results, their persistence could cause severe air pollution episodes in urban valleys.

Journal publications

Broetz, B., R. Eigenmann, A. Doernbrack, T. Foken, and V. Wirth 2014. Early-morning flow transition in a valley in low-mountain terrain under clear-sky conditions. *Boundary Layer Meteorology,* **152,** 45--63, DOI 10.1007/s10546-014-9921-7.

Prestel, I. und V. Wirth, 2015: What flow regime is conducive to banner cloud formation? *Submitted to J. Atmos. Sci.*

Rendon, A. M., V. Wirth, J. F. Salazar, and C. A. Palacio, 2015: Temperatur inversion breakup with impacts on air quality in urban valleys influenced by tropographic shading influence by topographic shading. *J. Appl. Meteor. Climatol.*, in print.

Schappert, S. und V. Wirth, 2015: Origin and Flow History of Air Parcels in Orographic Banner Clouds. *J. Atmos. Sci.*, **72**, 3389–3403.

Presentations and conference contributions

Rendón, A. M., V. Wirth, J. F. Salazar, C. A. Palacio, B. Brötz, 2014: Mechanisms of air pollution transport in urban valleys as a result of the interplay between the temperature inversion and the urban heat island effect . AGU Fall Meeting, San Francisco, December 2014 .

Eichhorn, J., I. Prestel, V. Wirth , 2014: Sensitivity of Banner Cloud Occurence to Mountain Geometry , EULAG workshop Oct 20-24 2014 , Mainz.

Prestel, I. and V. Wirth, 2015: Dynamics of Banner Clouds - Idealized and realistic Simulations. Doktorandenseminar Oktober 2015, Mainz.

Wirth, V., 2015: Dynamik orographischer Bannerwolken. Vortrag beim Zweigverein Frankfurt der Deutschen Meteorologischen Gesellschaft.

Wirth, V., 2015: Dynamics of orographic banner clouds: observations and numerical simulations. Vortrag im Seminar am Institut fuer Meteorologie und Geophysik Innsbruck.

Wirth, V., 2015: Origin and History of Air Parcels in Orographic Banner Clouds. Vortrag auf der 26. IUGG General Assembly in Prag.

Wirth, V., 2015: Origin and Flow History of Air Parcels in Orographic Banner Clouds. Vortrag auf der 33. International Conference on Alpine Meteorology.

Thesis work

During the report period one MSc and on BSc thesis were finished within the framework of the project:

Schappert, S., 2014: Ursprung und Strömungsverlauf von Luftpaketen aus orographischen Bannerwolken beim Überströmen eines idealisierten Berges. MSc Thesis, Institute for Atmospheric Physics, University of Mainz, Mainz, Germany.

Martin, A. (2014), Auftreten von Bannerwolken an asymmetrischer idealisierter Orographie. BSc thesis, Institute for Atmospheric Physics, University of Mainz, Mainz, Germany.

References

Baines, P. G. (1995), Topographic Effects in Stratified Flows. Cambridge University Press, 482 pp.

Prusa, J. M., P. K. Smolarkiewicz, and A. A. Wyszogrodzki (2008), Eulag, A Computational Model For Multiscale Flows, Computers & Fluids, 37 (9), 1193-1207, doi: {10.1016/J.Compfluid.2007.12.001}.

Schween, J. H., J. Kuettner, D. Reinert, J. Reuder, and V. Wirth (2007), Definition Of Banner Clouds Based On Time Lapse Movies, Atmospheric Chemistry And Physics, 7 (8), 2047-2055.