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Quantitative Precipitation Forecast
Priority Program SPP 1167 of the DFG

Orographic precipitation enhancement over low mountain ranges

Michael Kunz, Stefanie Wassermann

Institut für Meteorologie und Klimaforschung, Universität Karlsruhe / Forschungszentrum Karlsruhe

Overview

The complex interaction between orographically-influenced moist air flow and precipitation enhancement over low mountain ranges is investigated by measurement data and simulations with a diagnostic model. The major goal is to improve substantially the understanding of the underlying processes that determine the efficiency and the spatial distribution of precipitation over mountainous terrain.

Advancing our knowledge of orographic precipitation is a condition "sine qua non" for further improvements of precipitation forecasts for widespread rain from stratiform clouds. In the case of a significant precipitation enhancement over low mountain ranges (see Fig. 1), such systems often result in flooding of medium to large river basins (e.g. Elbe flood 2002).

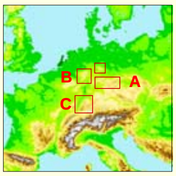

Fig. 1: *Topography of Central Europe with the areas under investigation (A is Thuringian Forest, B are the Rothaar mountains, C is Black Forest).*

Diagnostic precipitation model

The 3D wind field is modeled by using linear theory of stratified hydrostatic flow with uniform incoming wind U and moist Brunt-Väisälä frequency N_m. The basic equations are formulated for an isosteric vertical coordinate (i.e. constant specific volume; Smith 1988).

Condensation rates and vertical mass fluxes of precipitation are calculated from simulated vertical velocities on density surfaces. By integrating the condensation rate dq_s/dt from the lifting condensation level (LCL) to the top of the atmosphere, total rain sums at the ground are obtained (Kunz 2006):

$$R = \int_{t}^{t+\Delta t} \int_{LCL}^{\infty} -\lambda \frac{dq_s}{dt} \rho \, dz dt$$

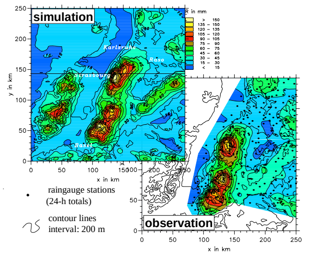

Fig. 2: *Observed and simulated rain sums for Dec 11-13 1997; synoptic precipitation is considered by applying a linear regression $R_{mess} = \delta R_{sim} + R_{syn}$. Horizontal / vertical resolution: 2.5 km / 0.5 km.*

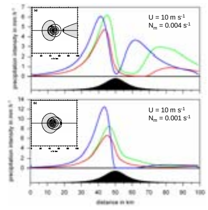

Fig. 3: *Modeled intensities with instantaneous fallout (blue), drifting (green) and drifting + evaporation (blue). N_m is 0.004 s^{-1} (top) and 0.001 s^{-1} (bottom), U = 10 m s^{-1}, H = 1000 m.*

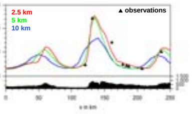

Fig. 4: *Modeled intensities for Dec 11-13 1997 over real terrain (line in Fig. 2a) with different model resolutions.*

Input data are: constant U and N_m, vertical profiles of T, v, and q_s.

Additional parameterizations are incorporated for (see Fig 3):

- precipitation formation time and drifting of clouds,
- fall times of raindrops and ice particles and meanwhile horizontal drifting,
- downslope evaporation in descent regions,
- loss of water related to upstream precipitation for repeated uplift.

Precipitation vs ambient conditions

Modifications of orographic precipitation resulting from realistic changes in ambient conditions were explored by sensitivity studies with the diagnostic model. Upstream of the mountain, R increases considerably with U, H, and T_0 (Fig. 5a). The decrease in R with increasing N_m can be attributed to reduced lifting upstream for a more stable stratification. Downstream of the mountaintop (Fig. 5b), R increases with all variables, despite N_m. R is much higher for lower stability, as is the spillover into the lee. Upward motion in the lee for high stable stratification causes a strong increase in R after the distinct minimum.

However, the sensitivity of orographic precipitation depends on the location relative to the mountaintop (Figs. 5c and d). For U and N_m, the region with the highest sensitivity is found on the lee side of the hill, where mountain-induced gravity waves and hydrometeor drifting exhibit the strongest influence.

These results suggest that horizontal wind governs the amount and distribution of precipitation in close relation with stability as expressed e.g. by the Froude number.

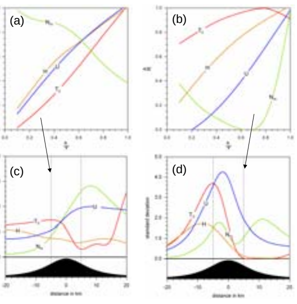

Fig. 5: *Sensitivity of orographic precipitation to changes in ambient conditions at a location 5 km (a) upstream and (b) downstream of the mountaintop. Both are scaled with their maximum value. (c) Variation coefficient and (d) standard deviation of rain intensity.*

Data analysis

Over several low mountain ranges in Germany (Fig. 1) the best relation to orographic precipitation is given for the product of moist Froude number and moisture transport, $Fr_m \cdot U \cdot r_s$ (Fig. 6, Steller 2005). It is obvious that precipitation intensity relies strongly on the continuous replacement of humidity after condensation. The connection with the Froude number can be explained by 3D low-level flow going directly over ($Fr >> 1$) or partial around ($Fr > 1$) an obstacle. As Fr increases, orographically induced vertical velocity and, as confirmed by the findings, precipitation intensity increases as well.

The closer relation of ΔR to $Fr_m \cdot U \cdot r_s$ than to Fr_m means that ΔR, scaled by $U \cdot r_s$, obviously shows a clearer dependence on Fr_m than ΔR itself. Since ΔR can be considered as the total mass of water removed from the atmosphere, and $U \cdot r_s$ is proportional to the water vapour mass passing the region within the same period, $\Delta R / (U \cdot rs)$ turns out essentially as a **non-dimensional quantity** of the orographic precipitation efficiency.

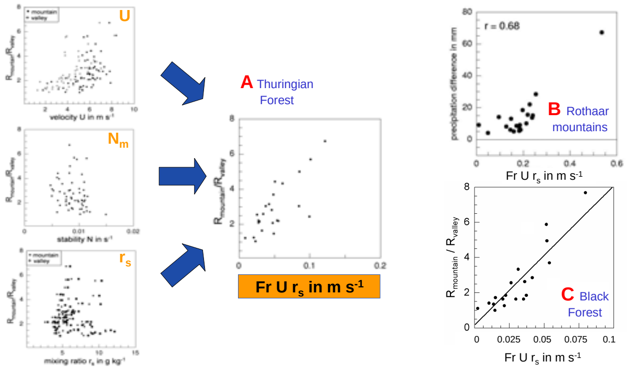

Fig. 6: *Orographic precipitation enhancement between two neighbouring stations against different ambient conditions (left; only for Thuringian Forest) and flow parameter (right, for different mountains), derived from SYNOP station data from German weather service (DWD). Each point indicates a 24 hours mean.*

Precipitation sensitivities

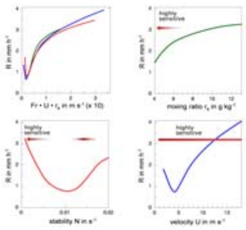

Fig. 7: *Sensitivity of orographic precipitation at the location of Neuhaus (Thuringian Forest) to changes of ambient conditions.*

Simulation results for the Thuringian Forest (station Neuhaus) with the diagnostic model show the significant increase of R with U and r_s (Fig. 7), as already obvious in the idealized cases.

The results for the combined parameter $Fr_m \cdot U \cdot r_s$ bear strong resemblance regardless which of the three parameter, U, N, or r_s was varied. This is a necessary condition for an appropriate parameter to explain the orographic precipitation enhancement and confirms the empirical findings above.

Conclusions and Outlook

As shown by means of data analyses and model simulations, the enhancement of precipitation over low mountain ranges is strongly controlled by flow effects on a local scale. The strongest enhancement is found for situations with high moisture transport in addition to high Froude number, where the flow tends to pass directly the mountains.

Regarding the improvement of operational precipitation forecasts, several open questions arise that will be examined further on (see Poster of Wassermann et al.) in the priority program "Quantitative precipitation Forecast" of the DFG:

- Are the findings of the relationship between orographic precipitation and the parameter $Fr_m \cdot U \cdot r_s$ universal for all regions?
- How does the horizontal length-scale of a mountain determine flow characteristics and thus the precipitation enhancement?
- How do diabatic phase transformations change the static stability and, thus, flow characteristics? What variability causes this on orographic precipitation?
- Are the flow conditions and resulting effects represented correctly in Local Model (LM/LMK of DWD) simulations?

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contact: michael.kunz@imk.uka.de