Lake-effect snow at Lake Constance, Austria: Case studies of winter precipitation over complex terrain

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Motivation

Lake Constance is located between Austria, Germany and Switzerland (540 km², 394 m MSL, major axis about 60 km). During the last years, a few heavy, underforecasted precipitation events (e.g., 17 Oct 2009, 29 Nov 2012, 17 Jan 2013, 8 Feb 2013) were noticed at Lake Constance, causing high amounts of accumulated snowfall at the downstream shore of the lake.

The **precipitation** appeared in RADAR imagery as a rather **stationary and banded structure over or in extension of the lake** with a **length of up to 40 km and a width of 5 to 10 km**. Especially the town of Bregenz (BRE) and the mountainious region east of the city (*Bregenzerwald*, see Fig. 1) were affected, while other areas within a few kilometers recieved far less precipitation.

Typically, these events took place **after the passage of a cold front**, resulting in a lower air temperature than the lake surface temperature. Hence, a **lake-effect** is supposed to occur at Lake Constance but at a much smaller scale as it is known at the Great Lakes or the Great Salt Lake in North America.

Research Questions

- What are the *main processes leading to* the formation of *banded precipitation* in the Lake Constance area?
- What is the *impact of the lake* as a source for latent and sensible heat on the formation of precipitation downstream of the lake?
- How does the *surrounding topography* modify the formation of precipitation?

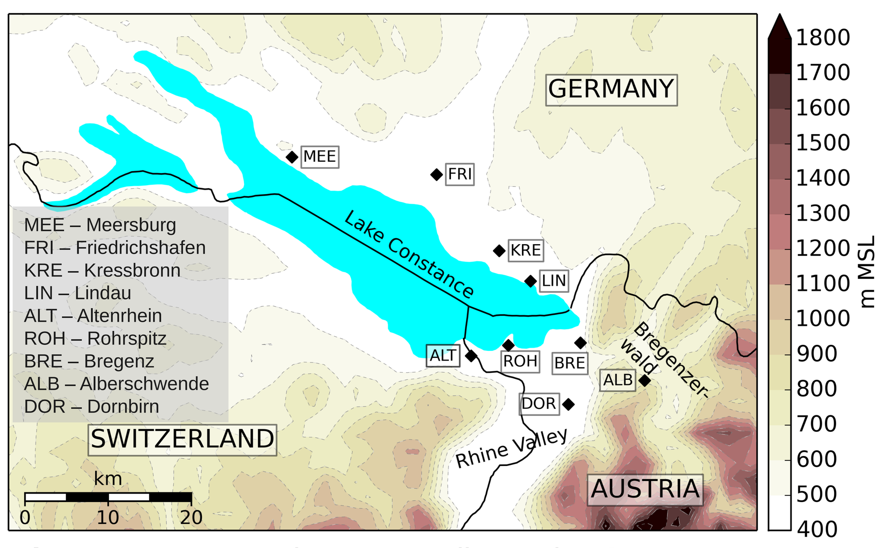

Figure 1: Topography surrounding Lake Constance (contourlines in 100 m interval). Black diamonds denote automatic weather stations.

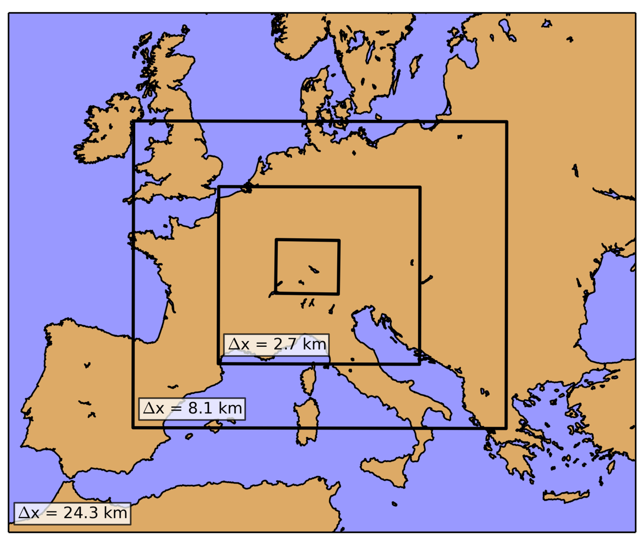

Figure 2: Locations of WRF model domains with horizontal resolution annotated, except for innermost domain (Δx = 0.9 km).

Observations, 8 Feb 2013

- *Synoptic situation*: postfrontal conditions with Lake Constance region on the rear side of a synoptic-scale trough, influenced by **low-level advection of colder airmasses**
- Lake surface temperature > 2-m air temperature (4 to 8 K difference)
- Snowband visible in RADAR imagery from 0640 to 1200 UTC
- **Highest value of accumulated precipitation at Bregenz: 35.2 mm** between **0640 and 1200 UTC** (see Figs. 3, 4a)
- RADAR-estimated precipitation underestimates maximum value but captures **elongated distribution of precipitation downstream of the lake**
- Wind field characterized by **convergence between northern and southern shore** during the snowband period (grey shading in Fig. 4)
- Other case studies (29 Nov 2012 and 17 Jan 2013) show similar results

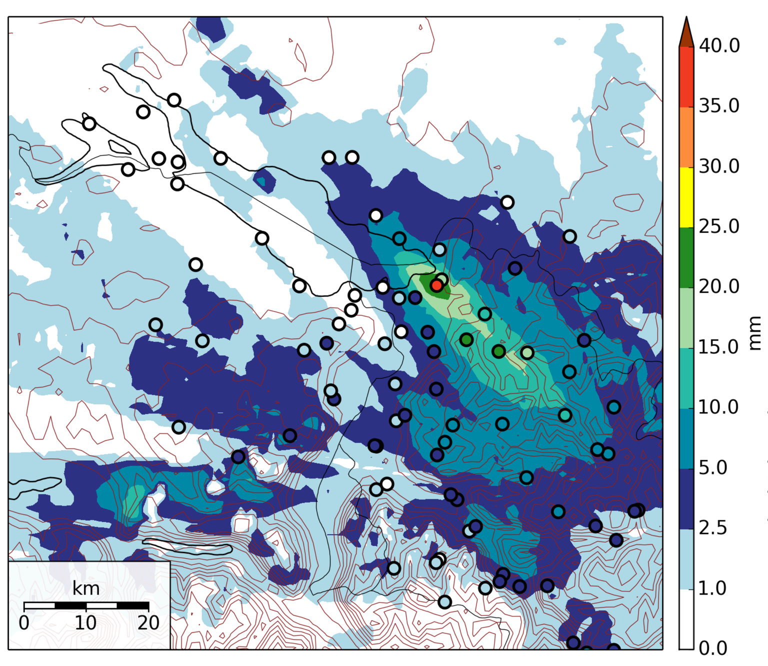

Figure 3: RADAR-estimated accumulated precipitation (mm, shading) and gauge measured accumulated precipitation (dots) from 0640 to 1200 UTC 8 February 2013. Location of RADAR site shown in Fig. 5a

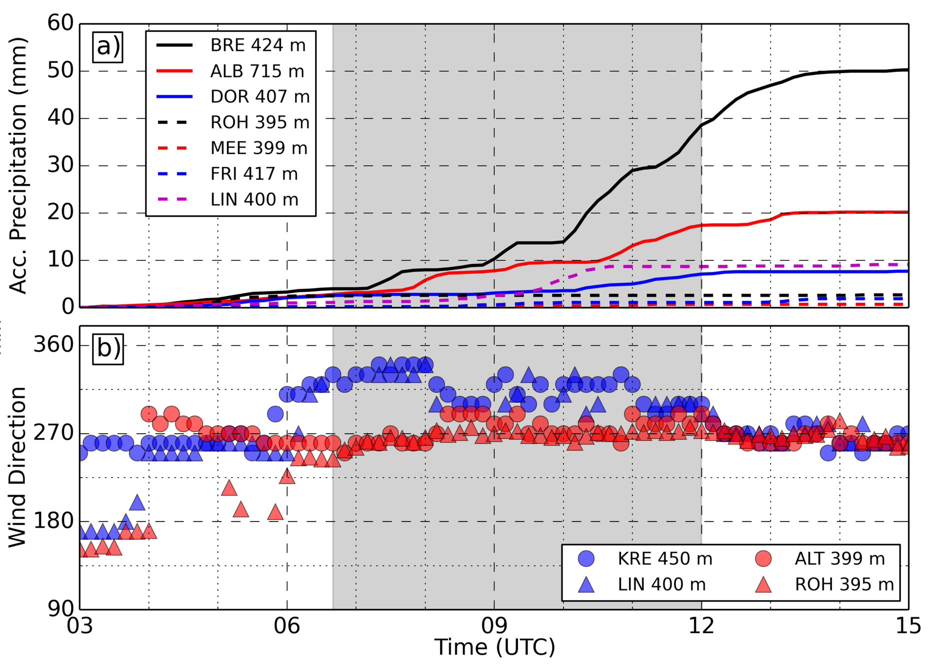

Figure 4: Observations in the Lake Constance region (see locations and abbreviations in Fig. 1) from 0300 to 1500 UTC 8 Feb 2013: (a) Accumulated precipitation in mm and (b) wind direction in degrees. Red (blue) dots in (b) denote stations on the southern (northern) shore. Grey shading denotes period with snowband visible in RADAR data.

Model Setup

- WRF model, version 3.6.1, advanced research core (ARW)
- Four two-way nested domains (see Fig. 2)
- Horizontal resolution of **24.3, 8.1, 2.7 and 0.9 km** with **79 vertical levels**
- Lowest level 26 m AGL, vertical spacing increasing from 60 to 270 m
- Lin microphysic parameterization (single moment, 5 hydrometeor categories)
- **Control run** (*CTL*) **and numerical sensitivity studies**
  - i. Lake Constance removed (*NoLake*)
  - ii. Downstream topography removed (*NoDT*)
  - iii. Lake Constance and downstream topography removed (*NoDT-NoLake*)

Numerical Simulations, 8 Feb 2013

- **Control run**
  - i. *Convergence line* (see Fig. 6a) and *banded precipitation* over and downstream of the lake in comparable intensity to observations. Maximum of accumulated precipitation east of Lake Constance (cf. Figs. 7a and 3)
  - ii. *Good temporal agreement* of banded precipitation (model: 0700 to 1200 UTC ; observations: 0640 to 1200 UTC)
  - iii. *Spatial distribution* of accumulated precipitation *in reasonable agreement* with observations. High amounts of precipitation in the Bregenzerwald not captured by the model (cf. Figs. 7a and 3)

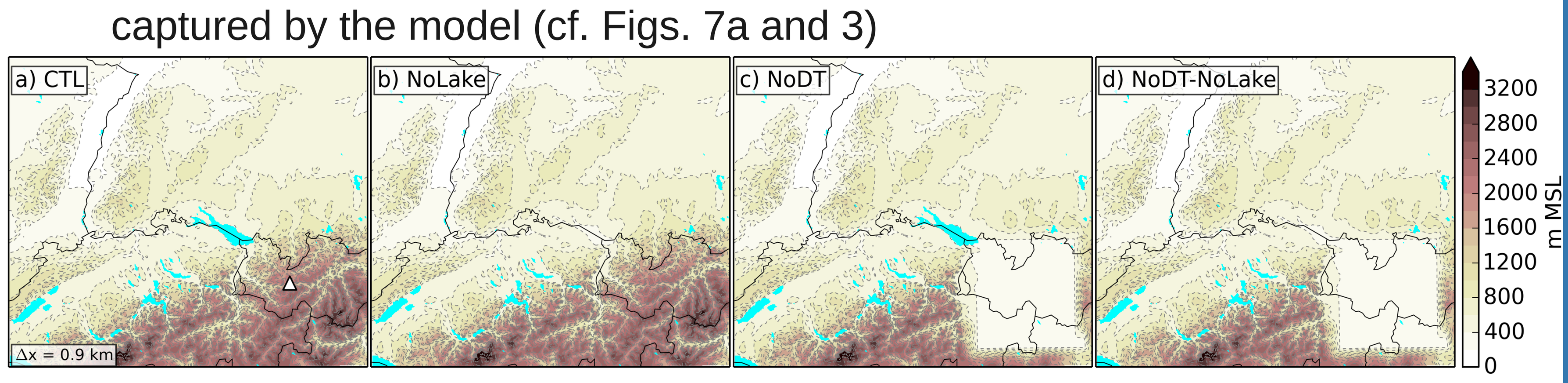

Figure 5: WRF terrain elevation (200 m countour interval) in innermost domain with horizontal grid spacing of 0.9 km for (a) CTL, (b) NoLake, (c) NoDT and (d) NoDT-NoLake. White triangle in (a) shows location of RADAR site.

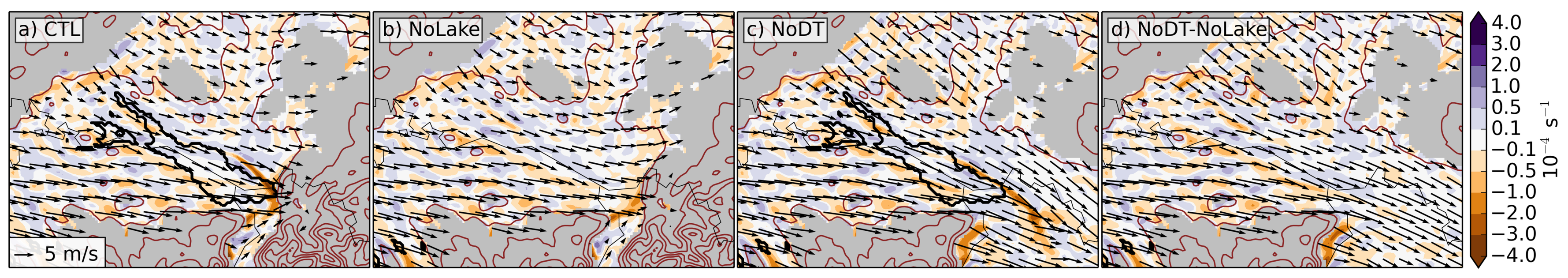

Figure 6: WRF terrain elevation (200 m contour interval) and wind at 700 m MSL (app. 300 m above lake surface) as vectors (scale in a) for (a) CTL, (b) NoLake, (c) NoDT and (d) NoDT-NoLake at 0900 UTC 8 Feb 2013. Divergence of vector field in 10^{-4} s^{-1} (color contours). Grey shading denote where model field intersects with topography.

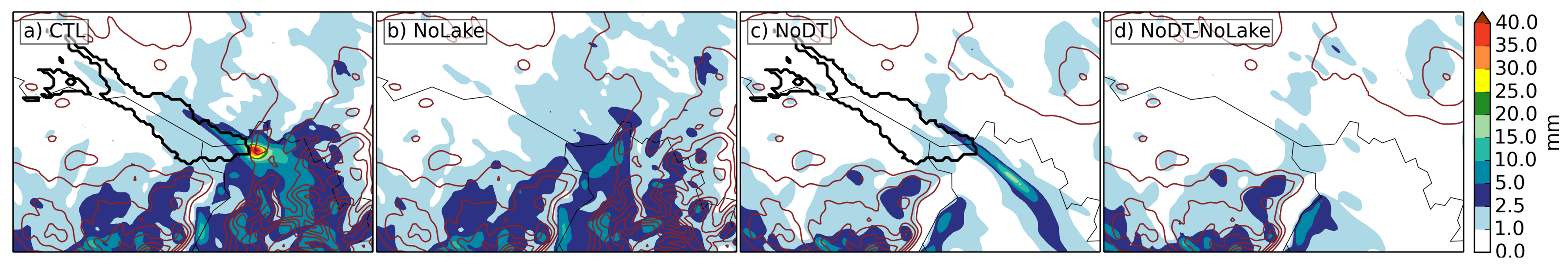

Figure 7: WRF accumulated precipitation (color shading) between 0700 and 1200 UTC 8 Feb 2013 and terrain elevation (200 m contour interval) for (a) CTL, (b) NoLake, (c) NoDT and (d) NoDT-NoLake.

- Cross section along German coast shows **potential unstable stratification** ($d\theta_e/dz < 0$ and $N_m^2 < 0$; Fig. 8a) and **conditional unstable stratification over the lake** ($d\theta_{es}/dz < 0$, not shown)
- Convergence induced low-level vertical displacement triggers **convection over the lake**
- Formation of hydrometeors and precipitation over the lake and the mountains downstream of the lake (see Fig. 8a)

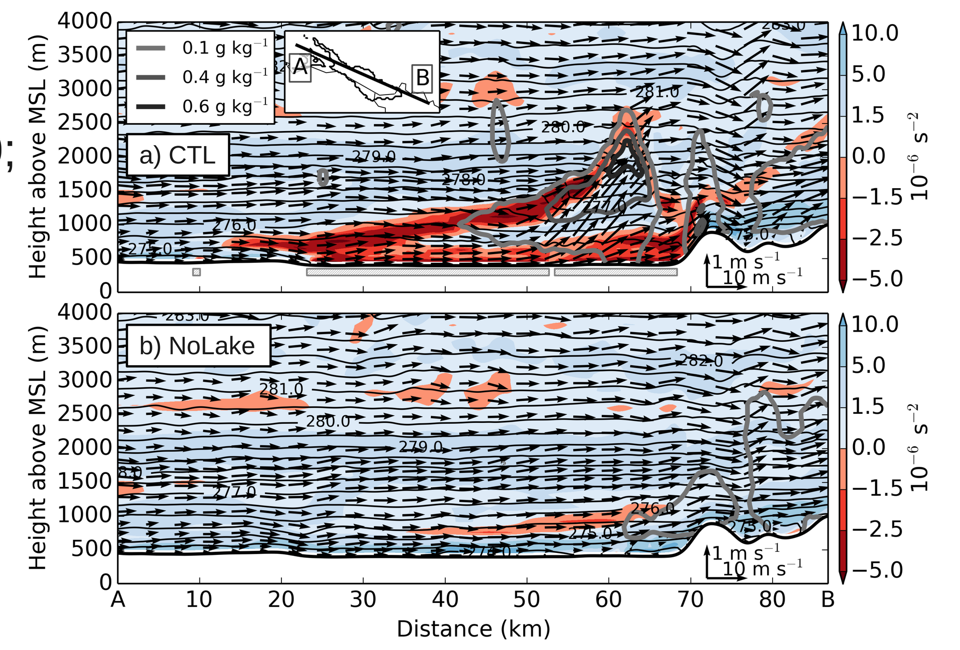

Figure 8: Cross section along northern coast (location in a) for (a) CTL and (b) NoLake at 0700 UTC. N_m^2 in 10^{-6} s^{-2} (shaded), potential temperature (black contour lines with 0.5 K interval) and hydrometeor mixing ratio in grey according to legend. Hatched rectangle denotes cross section intersecting with water body.

- **NoLake:**
  - i. *Unstable stratification over the lake disappears, no convection initiated (see Fig. 8b)*
  - ii. *Stable orographic precipitation* on windward side of first orographic feature downstream of the lake; weaker intensity than in CTL (cf. Figs. 8a and b)
- **NoDT:**
  - i. Snowband colocated with convergence line
  - ii. Weaker intensity and lower amounts of accumulated precipitation than in CTL (see Figs. 6c, 7c)
  - iii. Potential unstable stratification present over the lake (not shown)
- **NoDT-NoLake**: *snowband dissappears* (see Fig. 7d)
- Simulations *with (without) lake show (no) convergence line* (see Fig. 6a-d) and *(no) banded precipitation* (see Fig. 7a-d)
- Low-level air at the southern shore expercience flow deflection to westerly directions by complex topography south of the lake (see Fig. 6a-d), while overlying air show northwesterly wind directions

Conclusions

- *Potential and conditional unstable stratified layer* over the lake caused by latent and sensible heat fluxes from the lake
- *Flow deflection of low-level air* on southern coast cause *convergence*, induces vertical lifting and *initiates shallow convection*
- Convection causes lateral inflow and reinforces convergence line
- *Orographic effects* downstream of the lake include:
  - i. Trigger mechanism for convection of potential and conditional unstable stratified layer due to forced ascent
  - ii. Amplification of precipitation by forced ascent
- Orographic precipitation is amplified by the presence of the lake (stable or convective orographic precipitation)

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