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Interactive Comment

Interactive comment on "Comparing model and measured ice crystal concentrations in orographic clouds during the INUPIAQ campaign" *by* R. J. Farrington et al.

Anonymous Referee #2

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This paper presents a numerical investigation on the reasons for high ice number concentration observed in orographic clouds at Jungfraujoch in Switzerland. Several processes are considered. The first ones are purely atmospheric processes while the last one involves a particle flux of surface hoar emitted from the surface. As a scientist studying mass and energy exchanges between the snowpack and the atmosphere in complex terrain (including blowing snow), I have read this paper with a great interest.

Through the paper, the authors follow a clear step-by-step investigation based on several WRF numerical simulations. My main questions concern the reliability of a surface hoar flux emitted from the surface and the potential influence of blowing snow. These

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Interactive Discussion

Discussion Paper

questions need to be clarified prior to publication in ACP. They are listed below (General comments) followed by more specific and technical comments.

General comments

1) In their paper, the authors follow the assumptions of Lloyd et al (2015) and test if a flux of ice crystals emitted from the surface can explain the high ice number concentration observed at Jungfraujoch. Their results show that emitting such flux increases modelled ice number concentration and allow getting simulated number concentration closer to observed values. The source of this surface ice crystal flux is surface hoar crystals present at the snow surface.

The authors mention the conditions required for surface hoar formation in the text (P 25665 l. 15-25) but they do not really check if these conditions are present in the simulations. Before assuming that a flux of surface hoar crystals can be emitted from the surface, I highly recommend them to show that realistic conditions required for surface hoar formation are present around Jungfraujoch in the simulation. Surface hoar forms at the snow surface due to deposition of water vapour from the air onto the snow surface (Colbeck, 1988, Stoessel et al. 2010). Therefore, during growth conditions a water vapour flux toward the snow surface is required. This is for example the case when humid air is present above a snow surface on clear winter night when radiative cooling lowers the surface temperature of the snow (Stoessel et al. 2010). Horton et al (2014) showed that factors affecting surface hoar growth and shrinkage were captured by modelling the latent heat flux. The authors could study the latent heat flux between the snow surface and the atmosphere in the WRF control simulation and provide an estimation of the occurrence of favourable conditions for surface hoar formation during the study period. How does the occurrence of favourable conditions compare with the conditions used by the authors for emitting the particle flux (air temperature is below 0°C and supersaturated with respect to ice; P 25666 l25 to P 25667 l 2)? The conditions they use may generate the emission of ice crystals towards the atmosphere even when conditions are not favourable for the presence of surface hoar at the snow

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surface. In the current version of the paper, it is hard to believe that the assumption of a flux of surface hoar is realistic.

The authors use an adapted version of the aerosol flux from frost flowers (Xu et al. 2013). The authors should keep in mind that the fact that frost flowers can served as a source of aerosols is not widely accepted. In laboratory experiments, Roscoe et al. (2010) showed that no aerosol could be observed from frost flowers, despite winds in gusts up to 12 m/s. They concluded that frost flowers are unlikely to be the major direct source of sea salt aerosol. This limitation should be mentioned in the paper. Note that this point does not concern surface hoar at the snow surface and the fact that surface crystals can be removed from the snow surface by wind.

The flux in Eq. 5 depends only on wind speed and gives a positive flux even if the wind speed is equal to zero. This formulation is not realistic for the emission of any crystals from the snow surface (blowing snow or surface hoar). As mention by the authors (P 25666 l. 13-15), surface hoar is removed from the snow surface when wind blows the crystals in the atmosphere. The physical processes involved are similar to the ones observed when snow at the top of the snowpack is transported by the wind with a transport in saltation and turbulent suspension (e. g. Pomeroy and Gray, 1995). Therefore, similar to the initiation of snow transport by the wind (Schmidt, 1980; Guoymarc'h and Mérindol, 1998; Clifton et al, 2006), a threshold wind speed is required for the transport of surface hoar by the wind. The authors should at least introduce a threshold wind speed in their adaptation of the aerosol flux from Xu et al (2013). For example, a value of 4 m s^{-1} at 5 m above the ground typical for fresh fallen snow could be used. The authors should also better justify (P 25666 l 15-20) why they use a formulation different from the typical formulations used to represent the emission of blowing snow particles in the atmosphere (Gallée et al, 2001; Lehning et al, 2008; Vionnet et al. 2014).

Two additional comments regarding the formulation of the surface crystal flux are:

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- in Equation (5), at which height above the ground is considered the horizontal wind speed? Is it the same value as in Xu et al (2013)? It should be at least mentioned in the paper and if the values are different the authors should discussed the impact.

- the authors assume a size of 10 μm for emitted surface hoar crystal. This value is small for ice crystal emitted from the surface and will have a large impact on the sedimentation of the particles. During blowing snow events, the diameter of blown snow particles ranges typically between 40 and 200 μm in the first meter above the snowpack and follows a two-parameter gamma distribution (Nishimura et al, 2005, Gordon et al 2009, Naaim Bouvet et al, 2010). The authors should discuss this assumption and the expected impact on the number of ice crystals in the atmosphere.

2) Based on the analysis of Lloyd et al (2015) the authors consider that blowing snow cannot explain the ice number concentration at Jungfraujoch and that a second source of ice crystals from the surface must be considered. This is based on the lack of a relationship between the number of ice particles and the wind speed found by Lloyd et al (2015) in the observations at Jungfraujoch. It would be very interesting if the authors could carry out a similar study using the simulated values. How does simulated ice number concentration in simulations Surf-6 and Surf-3 compare with simulated wind speed? As done by Lloyd et al (2015), the authors could pick up events identified as blowing snow event and non blowing snow event.

Specific comments

1) P 25654 l. 27 P 25655 l. 3: a map of the simulation domain showing the topography would help the reader to better figure out how looks the topography in the region. On this map, the authors could also mention the location of the Jungfraujoch station and the 3 other AWS stations used for model validation.

2) P 25656 l 24: the model validation is based on a comparison between simulations and observations at four stations (including Jungfraujoch). The validation is purely based on a visual comparison between observed and simulated time series over the

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period of interest. The authors should include a more quantitative evaluation and compute error statistics such as Bias and Root Mean Square Error for each meteorological variable, and each station. They could use a table to summarize the results.

3) P25657 l 18-21: at which level is taken the simulated ice number concentration: at first atmospheric level or at the real altitude of Jungfraujoch?

4) In Section 4, the authors compare observed ice number concentrations with modelled values from different simulations. Time series are shown on Fig. 5, 7, 10 and 11. Based on a visual comparison, the authors discuss if a given process can explain the high ice number concentration observed in orographic clouds at Jungfraujoch. It would be interesting for the reader to have complementary figures showing for example scatter plots of observed and simulated ice concentrations.

Technical comments

Text

P 25656: l. 19-23: The description of the stations used for model validation should be part of the Methodology section.

P 25656: l. 20-21: please mention at which height above the ground are measured wind, air temperature and humidity.

P 25666: l. 23: mention the units of Φ.

Figures

Fig. 12 and 13: add the prevailing wind direction on the maps or in the caption.

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