Ground-based remote sensing of snowfall through active and passive sensor synergy

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ABSTRACT

This contribution presents first results of the DFG-funded research project TOSCA – "Towards an Optimal estimation based Snow Characterization Algorithm". A unique combination of in-situ and remote sensing instruments (passive and active) was deployed at an alpine station in the winter season 2008/2009 with the goal to derive the vertical structure of microphysical properties of falling snow. In order to analyze the sensitivities of brightness temperature (TB) and equivalent radar reflectivity (Z_e) to the vertical distribution of snow water content as a function of particle size distribution (PSD) and shape, we simulated the measured data using COSMO-DE model output of snowing cases as input to a radiative transfer model. "Real" measurements from the TOSCA experiment of the winter season are shown and compared with the expected sensitivities from the COSMO-DE simulation study. These analyses will serve as a basis for the future development of an optimal estimation retrieval scheme with goal of improving profiles of snow water content from the synergy of ground-based remote sensing measurements.

1. INTRODUCTION

Although snow is the predominant type of precipitation in sub-polar and polar latitudes, not many reliable remote-sensing methods of determining the vertical distributions of microphysical snowfall parameters (i.e. snow mass density, snow crystal size and type) exist. These parameters - together with temperature, humidity and turbulence - govern processes such as riming and aggregation, which in turn determine the ground-based snowfall rate. However, these parameters are highly variable in space and time and thus their measurement - and subsequent modeling - is a difficult task. The high degree of freedom in the description of snow can only be adressed with a multi sensor approach combining active and passive remote sensing instruments together with in-situ methods.

During TOSCA a large set of ground based instrumentation was deployed at the Environmental Research Station Schneefernerhaus (UFS at 2650m MSL) at the Zugspitze Mountain in Germany in the winter season 2008/2009. The UFS offers a very good infrastructure with laboratories, observation and experimental decks to the national and international scientific community. UFS is situated ideally for snow observation because at the high altitude snow events occur much more frequently than in lower regions and the low water vapor amounts account for clearer scattering signals originating from ice hydrometeors. To determine the vertical distribution of hydrometeors and their Doppler fall velocities a K_a-band cloud radar, a Micro Rain Radar (MRR) and a ceilometer were installed. Two passive microwave radiometers (HATPRO and DPR) - covering together a frequency range from 22 – 150 GHz - were used to determine temperature and humidity profiles as well as Integrated Water Vapor amount (IWV), Liquid Water Path (LWP) and scattering signals from snow. The in-situ observations of several standard meteorological sensors from the German Weather Service and especially a 2D-Video distrometer (2DVD) supplied important information about shape and intensity of snowfall close to the ground. To give an overview of the available measurements Fig. 1 shows some selected variables from a strong snow event in February 2009.

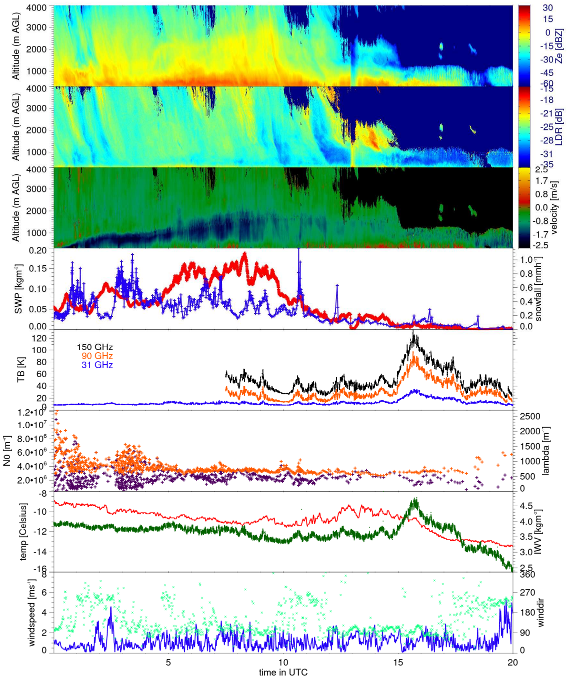

Figure 1. *Selected measurements from a strong snow event on 08. Feb. 2009 (00-20 UTC). From top: Equivalent K_a-band radar reflectivity in dBZ, linear depolarization ratio in dB, doppler velocity in ms^{-1}, radar derived snow water path in kgm^{-2} (red), 2DVD liquid equivalent snowfall rate in mmh^{-1} (blue), brightness temperatures at 150 (black), 90 (orange) and 31 (blue) GHz in K, N0 in m^{-4} (orange) and λ in m^{-1} (violet) for exponential PSD from 2DVD, temperature in ℃ (red) and IWV in kgm^{-2} (green), windspeed in ms^{-1} (blue) and direction in degree (light green).*

In Fig. 1 the advantage of multi sensor measurements can be seen. Not going too much into detail, several different cloud properties can be investigated. For example the Doppler velocity from the K_a-band cloud radar shows a region with enhanced fall velocities slightly moving to higher altitudes in time. This may be associated with riming and the presence of supercooled liquid water. The radar SWP (derived from a power law between snowfall rate and Z_e [1]) and snowfall rate from the 2DVD sometimes show similar patterns but with a time lag of approximately 30 minutes indicating strong wind shear effects. Because the TBs at 150, 90 and 31 GHz represent the superposition of signals from liquid water, snow scattering, water vapor and temperature, no direct assumption on hydrometeor contents can be made. But together with radar and 2DVD observations, e.g. the strong TB signal at 16 UTC can be addressed more likely to liquid water than to snow. Under low wind speed conditions ($v<5ms^{-1}$) it is possible to derive PSD from the 2DVD measurements. Here we assume an exponential distribution of the form $N(D) = N_0*\exp(-\lambda D)$ with D the equivolumetric diameter (described in [2]) and N(D) the particle number density in a given particle size range. We calculated N0 and λ for every 1000 particles with the moment method described in [3]. Especially during the stronger snowfall events in the morning hours the two parameters show large scatter which decreases during the day. In general the measured values for N0 and λ are approximately one order lower compared to parameterizations ([3]) which are based on a large dataset of aircraft measurements. Maybe stronger turbulence close to ground (possibly caused by the mountainous orography) has an effect of increasing aggregation and hence larger particles develop with lower values for N0 and λ.

2. SENSITIVITY STUDIES

One of TOSCA's main scientific questions is to investigate the potential of combining multiple active and passive remote sensing instruments. To explore the contribution of passive systems to retrieve snow water path, we performed a sensitivity study of the snow scattering effects on the passive MWR measurements in terms of TB.

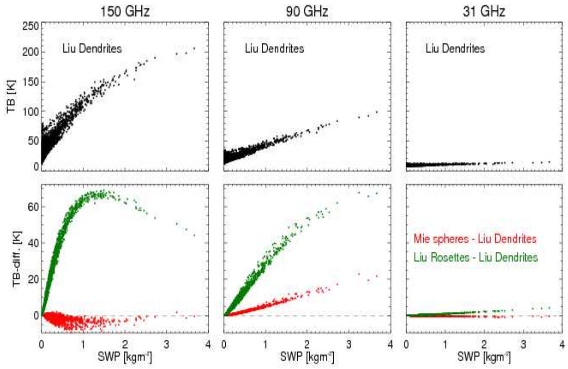

Figure 2.*Simulated TB (K) against snow water path (kgm^{-2}) for 150 (left), 90 (middle) and 31 (right) GHz from 2784 selected snow profiles. The upper line shows the TB for dendrites; the lower line shows TB differences (K) for different snow habits: Mie spheres – dendrites (red) and 6 bullet rosettes – dendrites (green).*

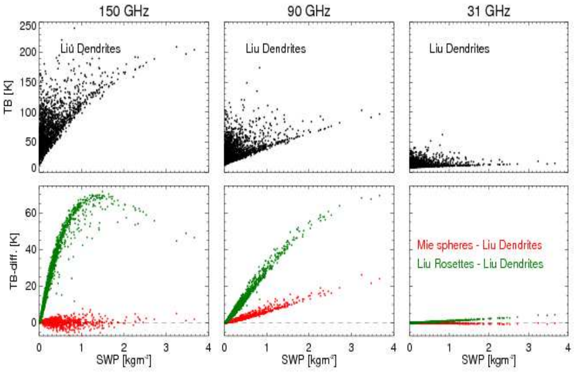

Figure 3. *Same as Fig. 2 but additionally including the whole original mixture of hydrometeors from the COSMO-DE model (graupel, cloud ice and rain).*

For this we selected snow profiles from the COSMO-DE model output from Oct 08 – Mar 09. To solely look at snow we set all other hydrometeors (graupel, rain, cloud ice) to zero. The downwelling TB were then calculated with the RT3 model [4] using the single scattering database for different snow habits from Liu [5].

For the simulation we selected three different snow habits: dendrites, six bullet rosettes and mass equivalent Mie spheres. Figure 2 shows the results for 150, 90 and 31 GHz with increasing sensitivitiy for higher frequencies. At 31 GHz the scattering signals are with a maximum of ~3K only 2K above the instrument noise level and are thus not useful for deriving snow signals. At 90 GHz and 150 GHz the snow signals are much higher with e.g. ~30 K and ~80 K respectively for SWP of 1 kgm^{-2}. The sensitivity to crystal habit also increases with frequency. The TB differences according to different shapes can be of the same order as the scattering signal itself; largest TB differences occur for six bullet rosettes and dendrites.

We extended our simulations from only snow profiles to the original mixtures of hydrometeors of the COSMO-DE model to investigate the influence of other hydrometeors to the total signal (Fig. 3). The scattering due to contributions from the other hydrometeors increases but signal from snow is still significant.

3. FIRST CASE STUDY

To further compare the model sensitivities to real measurements we analyzed a strong snow event on 08 Feb 2009. We ran the model with different combinations of LWP and SWP for a simplified, single-layer cloud. The atmospheric profiles and cloud structure used for the model input are derived mainly from radiosoundings (RS) and cloud radar measurements. The model results for the different LWP-SWP sets are then compared with real passive MWR data (Fig. 4).

We selected the time period from 08-13 UTC because both the 2m temperature and IWV changed only slightly (Fig. 1). As seen before (Fig. 2, 3) the 31 GHz is much more sensible to liquid water than to snow

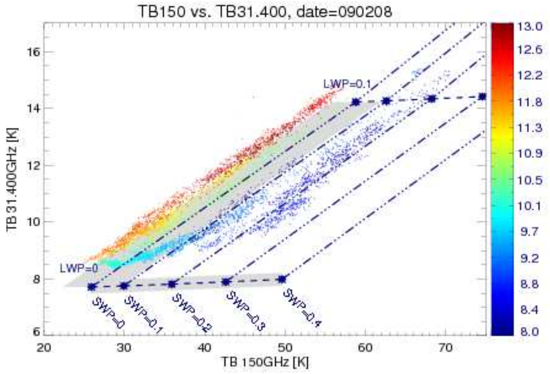

Figure 4. *Measured TB at 31.4 and 150 GHz for the time period 08-13 UTC (color bar) on 08 Feb 2009. The overlaid blue lines show model simulations for different combinations of homogenous distributed LWP and SWP for a 3km thick cloud.The grey shaded areas indicate the maximum possible TB variations due to changes of the humidity or temperature profile (details in the text).*

while at 150 GHz also snow scattering signals can be detected.

Figure 4 shows the measured TB at those two frequencies during the time period 08-13 UTC. At 150 GHz the TB are clearly enhanced (up to 70 K) from 08:00-09:30 UTC while the TB at 31 GHz are changing during the whole time period from 8-15 K.

The overlaid model results are from simulations with different sets of homogenous distributed LWP and SWP (dendritic snow) in a 3 km thick cloud layer close to the ground (similar to the cloud radar observations). For the pressure, temperature and humidity profiles the RS from Munich (~80 km distance) were used. Because the TBs are also sensitive to changes of the temperature and humidity profile, we estimated the maximum possible effect on TB from the three different RS of that day: 4 K for 150 GHz and 0.5 K for 31.4 GHz.

From Fig. 4 we can draw the conclusion (by only regarding the 31 GHz and 150 GHz microwave channels) that significant amount of SWP are above the measurement site between 8:00 and 10:00 UTC. From 10:00 to 11:30 we expect largely liquid water content within the clouds and non-significant SWP amount. Both of these conclusione are supported by the the SWP time series derived from the cloud radar. The offset between model and measurements during the low-SWP times are either caused by erroneous absorption model assumptions or from instrument calibration uncertainties, especially at these low TB. The measurements together with the model results strongly indicate both the presence of super-cooled liquid water (up to 0.1 kgm^{-2}) and snow water paths of up to 0.2-0.3 kgm^{-2} in the cloud. Fig. 4 also shows that these signals can not be explained by temporal variations of temperature or humidity alone.

4. OUTLOOK

First sensitivity studies indicate the potential of passive microwave systems to improve the characterization of snow clouds. The model simulations showed the importance of both, particle shape and PSD for the retrieval of snow. In the future we will analyse the shape and PSD measured by the 2DVD in detail and investigate their dependence on several atmospheric parameters. The modelling and characterization of large snowflakes together with the development of a single scattering database for larger snow particles is a further task of this project. We will also extend our sensitivity studies to other measured parameters and will analyze their information content. The presence of super-cooled liquid water even at very low temperatures and its strong influence on the passive microwave measurements will also be further investigated. The final goal will be the development of an optimal estimation based retrieval scheme where the instruments which contribute the most to the desired variable should be combined.

ACKNOWLEDGMENTS

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NOTE

Access to TOSCA data and a detailed overview of the deployed instrumentation is available through the project homepage: https://gop.meteo.uni-koeln.de/tosca

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