A winter study case, comparing surface and vertical snowfall observations with the operational forecast model MEPS

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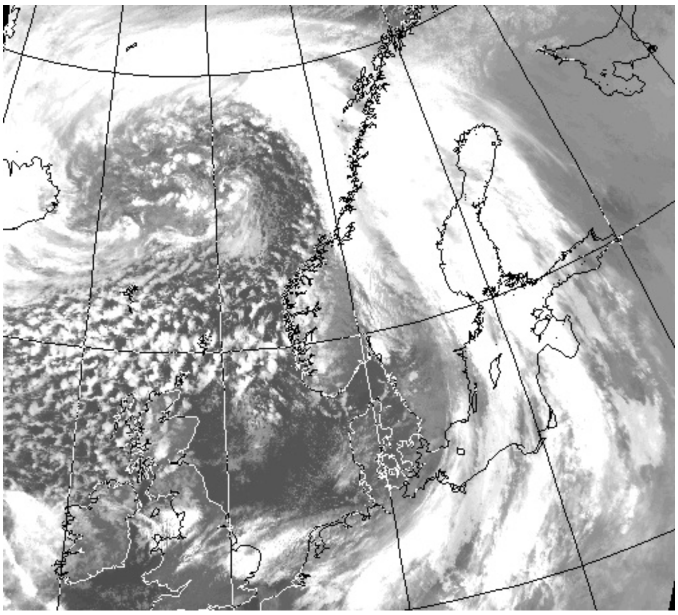

Satellite image of the extreme extratropical cyclone on 24 December 2016 at the coast of Norway. Image obtained from the Dundee Satellite Receiving Station http://www.sat.dundee.ac.uk.

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CHAPTER 4: RESULTS AND DISCUSSION

In this chapter the results of the surface observation, the optimal estimation retrieval and the regional mesoscale forecast model are presented. On the basis of the methodology described in Chapter 2 it should be evaluated if a regional mesoscale forecast model predicts the same synoptic patterns as observed at the measurement site. Also, vertical SWC forecasted by MEPS is being compared with the retrieved vertical SWC at Haukeliseter. Attention should be paid to the fact, that this study study is very unique of its kind. The motivation to compare regional model forecasts with vertical snowfall measurements resulted from a study by Joos and Wernli [2012]. They did sensitivity studies on the microphysical scheme of COSMO (COnsortium for Small-scale MOdelling) and found that the storm development depends on the correct placement of the precipitation inside a modeled storm. Vertical precipitation determines the vertical profile of latent heating, and hence the generation of potential vorticity which in return shows if a storm strengthens or weakens. Correct vertical precipitation observations can then help to correctly model vertical precipitation patterns.

4.1 Sensitivity of the optimal estimation retrieval

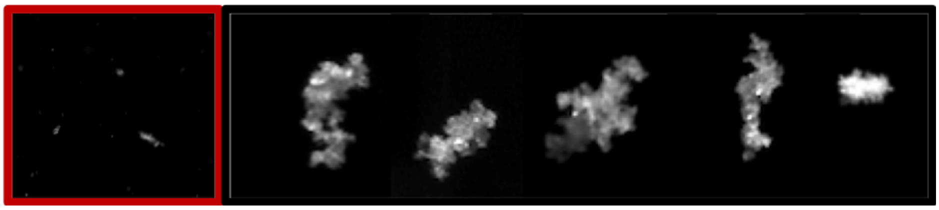


Figure 4.1.1: MASC observations during the Christmas storm 2016. Left (red frame), small ground up blowing snow particles. Five images on the right, rimed particles.

The optimal estimation retrieval was applied to the six-day Christmas 2016 storm event. Retrieved estimates of total snowfall accumulation for two different particle models were used to determine which combination produces the best match with snowfall rates observed at Haukeliseter.
The majority of the snow particles looked like the left image in Figure 1.1.1 at Haukeliseter. Once in a great while, the MASC took pictures of more snowflake shaped, rimed aggregates (Figure 1.1.1, five right images). Small ground up blowing snow particles (Figure 1.1.1, red frame), would follow the use of the CloudSat B8pr-30 particle model for the snowfall optimal estimation retrieval. This dry snow particle model was used at Barrow, Alaska [Cooper et al., 2017] and was for their study the best estimated result compared to National Weather Service station. Taking the same approach as Cooper et al. [2017] and the assumption of small particles by the MASC would follow a too high estimates for surface snow accumulation (Figure 1.1.2). The temporal distribution of the snowfall during the event is shown in Figure 1.1.2. The figure presents hourly snowfall accumulations on 22 December 2016 against retrieved values for different particle model assumptions. The CloudSat B8pr-30 particle model did not agree well in magnitude with the double fence hourly observations (blue, dash-dotted line). The optimal estimation retrieval result for surface accumulation is too big, because the amount of mass needs to be high for small particles and much reflectivity would need to be generated.
Since the surface snow accumulation for the most observed particles gives a too high amount, the optimal estimation retrieval is trained for rimed aggregates (Section 2.4.1). These rimed particles were observed once in a while and the structure of the particles varied with wind directions. While small, round aggregates, furthest to the right in Fig-

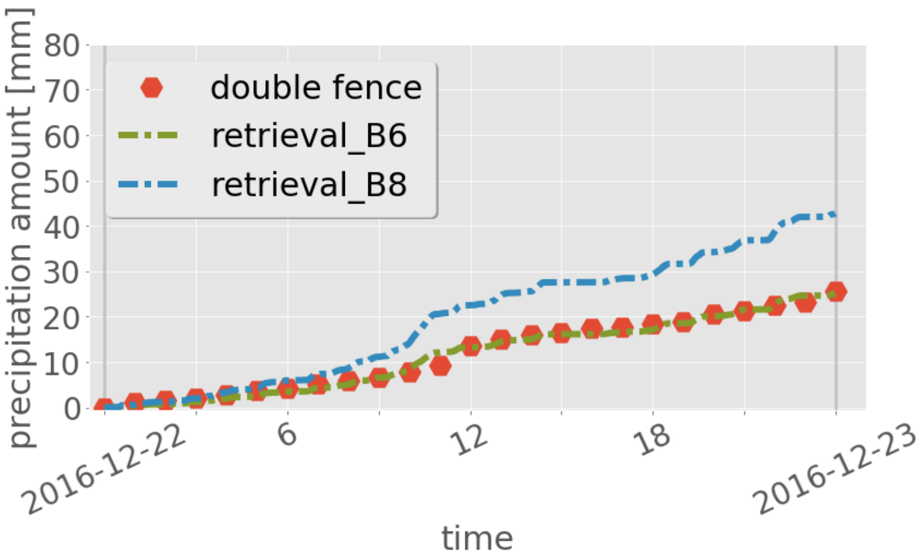


Figure 4.1.2: Hourly double fence snowfall accumulations [mm] plotted against retrieved values for the 22 December 2016 for different retrieval assumptions permutations. Double fence snowfall accumulation, red hexagons, retrieved precipitation amount for the here used study (B6), green, dash-dotted, and for small aggregates (B8), blue dashed.

ure 1.1.1, were more related to west wind, were the other four related to south-east wind.

The best guess were found for the 2D-scattering model for branched 6-arm spatial particles with porosity for reflectivity measurements at 24 GHz (B6, Appendix A.1). This scattering scheme relates to the five crystals to the right in Figure 1.1.1. The percentage difference was small compared to the double fence observations throughout the event (Table 1.2.1) for 12 h and 24 h surface accumulation.
Table 1.1.1 presents the percentage differences for both particle model assumptions, on 22 December 2016. The percentage difference for 12 h surface accumulation indicated an overestimation of 65 % for very small, blowing like particles.
The rimed particle model produced slightly too little snowfall for most of the days throughout the event (Table 1.2.1). Values for 22 December 2016 showed to have the best agreement for 12 h and 24 h (−3.0 % and −2.1 %).
It shows, when very turbulent storms prevail, the approach does not work like for more intense, humid storms, because the particles are too small and the assumption of blowing,

Table 4.1.1: Observations (obs.) and retrieved (ret.) snowfall amounts for 22 December 2016 for different particle model assumptions. B6 indicating the here uses particle model (Appendix A.1) and B8 indicating the retrieved snowfall amounts for small particles.

Particle model	12 h accumulation			24 h accumulation		
	Snowfall		Difference	Snowfall		Difference
	obs.	ret.		obs.	ret.	
	[mm]		[%]	[mm]		[%]
B6	13.6	13.2	−3.0	23.1	25.1	−2.1
B8	13.6	22.5	+65.5	23.1	42.7	+66.9

small particles give an overestimation at the ground. It follows from the good agreement between the retrieved surface snowfall amount and the double fence observations with the use of the rimed particle model assumption, that it is important to know what kind of particles are in the storm to get the correct aggregate for the a priori guess in the optimal estimation retrieval. MASC observations would assume to use the CloudSat B8pr-30 particle model, but that would not give the correct answer (Figure 1.1.2 and Table 1.1.1). The use of MRR reflectivity and MASC habit can lead to a closer answer compared to double fence measurements.

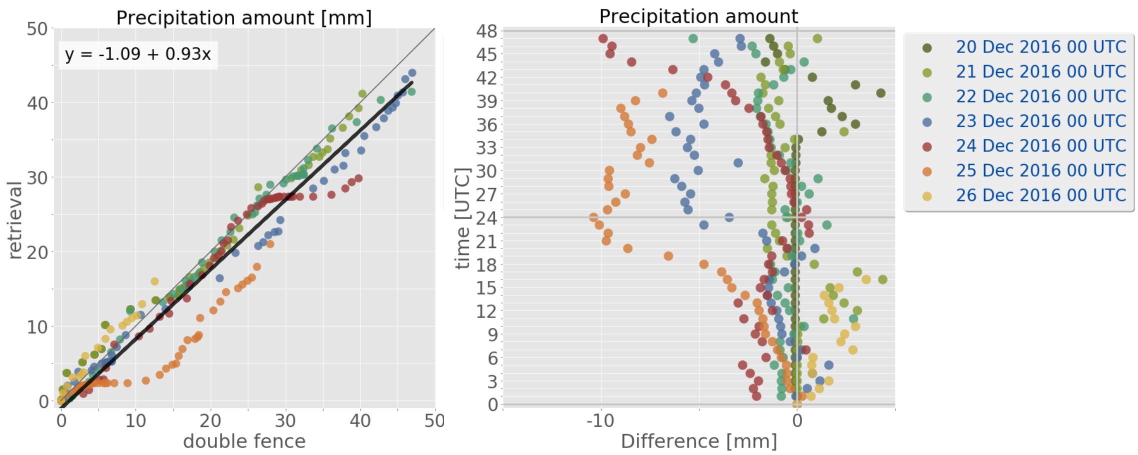
4.2 Comparison of surface observations

To be able to compare the vertical predicted snow water content with the retrieved snow water content a verification of the surface accumulation is made. If the retrieved surface accumulation is confident in comparison to the double fence measurement, then the vertical measurements can be trusted.

The correlation in Figure 1.2.1a demonstrates a good agreement between the 48 h accumulation measured by the double fence and the retrieved surface accumulation. The black line in Figure 1.2.1a presents a linear correlation with a regression coefficient of R = 0.97. In general, the retrieved surface snowfall accumulation is underestimated when compared to the double fence measurements, but not to a large degree.

Figure 1.2.1b shows the difference between retrieved accumulation and observed accu-

mulation by the double fence. For the time period 20 to 24 December 2016, Figure 1.2.1b indicates an underestimation of retrieved snow accumulation of less than −5 mm for the first 24 h. Snow accumulation calculated on 23 December 2016 at 0 UTC show after 24 h an underestimation by the retrieval of up to −6.5 mm. Larger underestimation after 43 h is related to the observation of liquid precipitation on 25 December 2016 between 12 UTC to 21 UTC for accumulations on 24 December 2016. On 25 December 2016 no fair comparison to the double fence measurement can be performed after 12 UTC because of the neglection of liquid precipitation when temperatures exceed 2 °C.
For a 12 h accumulation follows for the Christmas storm (20 to 26 December 2016) an average error of 85.5 % (Table 1.2.1). For longer, 24 h accumulation decreases the average error to be −4.7 % (excluding values on 25 December 2016 after 12 UTC and on 26 December 2016 after 17 UTC because of attenuation at the MRR). The daily surface snowfall accumulation difference between retrieval and observation in Table 1.2.1 show almost always a well agreement to the boundary condition of the double fence. The only well pronounced mismatch is seen non 21 December 2016, where it measures much more than the double fence gauge (+435.8 %).
Similar to this study, Cooper et al. [2017] used a CloudSat snow particle model, PSD and fall speed from MASC observations for five snow events at Barrow, Alaska. The comparison to the weather station revealed an difference between National Weather Service observations and retrieved accumulations of −18 % for all five snow events.
Table 1.2.1 shows the difference for each individual day and the average difference for six and 4 days, depending on the accumulation of 12 h or 24 h. The choice of the correct PSD model, slope parameters and fall speed in the optimal estimation snowfall retrieval, shows a good agreement with the observations at Haukeliseter for the 2016 Christmas storm in contrast to the 200 % difference when only using the CloudSat snowfall algorithm Section 2.4. It indicates also that the non-uniqueness of snow accumulation is reduced, when using a combination of ground-based observations instead of only Ze-S relationships. During the 2016 Christmas storm the average error for 24 h accumulation is almost similar to the best estimate at Barrow, Alaska. It turns out that there is no relation between high and low precipitation events since the differences vary. Cooper et al. [2017] also showed different combinations of PSD assumptions and snow fall speed. For Barrow, best agreements between observations and retrieved snowfall were found by using the CloudSat particle model, slope parameters and snowfall speeds from the MASC. In the



(a) (b)

Figure 4.2.1: a: Surface precipitation amount comparison between the double fence observations and the retrieved surface accumulation of precipitation for 48 h. In black the linear correlation between the double fence observations and retrieved surface snow. b: Difference between the retrieved and the observed accumulation by the double fence. The colours represent the different starting days at 0 UTC for the 48 h accumulation.

here presented study, the best assumption for surface snowfall accumulation was found by using a particle model for rimed aggregates (Section 2.4 and 1.1) such as in Figure 1.1.1.

On 20 and 21 December 2016, the difference error is large (−97.8 % and 435.8 %, respectively). This is probably related to an observation of precipitation at the double fence, even though no precipitation was observed. The double fence observation might be related to some particles stirred up by wind into the orifice of the gauge. Since no manual observations are done at the Haukeliseter site, is it difficult to say if blowing snow occurred and might introduce additional errors. But from the vertical MRR reflectivity it can be seen, that precipitation was not observed on before 21 December 2016 9 UTC.
Even though it is assumed that the double fence is the absolute correct measurement it still underlies some uncertainties. A better way to asses the accuracy of the retrieved surface snowfall accumulation could be to compare the results to measurements inside a bush gage. A bush gauge is a precipitation gauge surrounded by a large bush to create artificial calm winds to increase the catch ratio of frozen precipitation and is considered as the best available measurement for solid precipitation [Wolff, 2018]. Unfortunately there are only

Table 4.2.1: Comparison of observed (obs.) and retrieved (ret.) snowfall amounts for the Christmas storm 2016. Difference refers to the difference of the retrieved and observed snow accumulation after 12 h and 24 h. The average difference is the value over all six/four days. Excluding values after 12 UTC on 25 December 2016 and after 17 UTC on 26 December 2016.

Day in 2016	12 h **accumulation**				24 h **accumulation**			
	Snowfall		**Difference**	**Average difference**	**Snowfall**		**Difference**	**Average difference**
	obs.	**ret.**			**obs.**	**ret.**		
	[mm]		[%]	[%]	[mm]		[%]	[%]
20 Dec	0.1	0.0	−97.8		0.1	0.0	−97.8	
21 Dec	0.7	3.8	+435.8		17.1	16.6	−2.7	
22 Dec	13.6	13.2	−3.0		25.6	25.1	−2.1	−4.7
23 Dec	6.3	5.2	−16.8	+85.5	23.3	19.8	−14.9	
24 Dec	14.7	13.4	−8.6		24.8	25.0	+0.8	
25 Dec	4.3	–	–		+15.4	–	–	
26 Dec	8.8	10.6	+20.1		25.1	–	–	

two bush gauges in the world, and because of local limitations a double fence construction is developed as reference for the Solid Precipitation Measurement intercomparison study during 1986 to 1993 [Goodison et al., 1998]. Comparisons between bush gauge and double fence precipitation measurements have shown, that for wind speeds up to 9 m s^{-1} outside the fence, the double fence will measure up to 10 % less precipitation. While wind speeds outside the double fence might reach 20 m s^{-1} show measurements inside a decrease to 5 m s^{-1}. Wolff [2018] believes the underestimation of the double fence will not be more than 20 % during frozen precipitation events with high wind speeds.

The low average difference value for 24 h accumulation, in Table 1.2.1 during the Christmas 2016 event (−4.7 %) follows a much lower average difference between retrieved and observed surface accumulation than at Barrow (36 %) and therefore a very good agreement between observed and retrieved snow accumulation during 21 to 24 December 2016. In **??**, the vertical SWC will be compared to the forecasted MEPS values for the 2016 Christmas storm. Despite the condition that the double fence measurement is influenced by wind will the small average difference for 21 to 24 December 2016 give confidence in the retrieved profiles of snow water content when comparing to the forecast, but it should be kept in mind that retrieved snow accumulation is underestimated and therefore may the vertical SWC be too low.

4.3 Observation and predictions of large scale weather phenomena at the surface

One of the main factors, that made the Christmas 2016 storm so interesting is the fact, that fronts passed over Norway during the six-day period. One aim of this work is to determine if large scale features were observed at the measurement site during the extreme event.
A comparison between the surface observations at Haukeliseter and the ECMWF analysis of the dynamic tropopause and geopotential thickness maps show that frontal passages occurred on three days during the Christmas storm (Section 3.6). A typical cyclone has a prevailing warm front and a faster moving cold front. As the storm gets more intense and the cold front rotates around the low-pressure centre and catches the warm front the cyclone will begin to occlude. Changes in pressures, temperature, wind direction and wind speed can occur. In some cases, an intensification of the precipitation can be observed as well. Figure 1.3.1 shows the different parameters forecasts initialised at 0 UTC for 21, 25, and 26 December 2016, as well as the observations at the Haukeliseter measurement site in dash-red. Typical pressure decreases and increases, as well as temperature increases, and wind changes are present on 23 and 26 December 2016, since these changes show in the surface observations in Figure 1.3.1, it is assumed that frontal boundaries passed. The 25 December 2016 shows only an increase of temperature leading to the assumption of a warm air passage in Figure 1.3.1d.
As described in Section 3.6 shows the ECMWF dynamic tropopause analysis map (Figure 3.6.3a) more ridging and therefore warmer air over Southern Norway on 23 December 2016. The low-pressure system approaches in the course of the day south-east of Iceland and hence stronger west to south west wind are associated with the cyclone (Figure 3.6.3c). The MEPS forecast, initialised on 23 December 2016 at 0 UTC in Figure 1.3.1a follows the observations and shows the decrease in pressure after 12 UTC due to the passage of the occluded front with a constant pressure after the transition. Since warmer air is more advected to the north and the DT in Figure 3.6.3a shows a warm low-pressure