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

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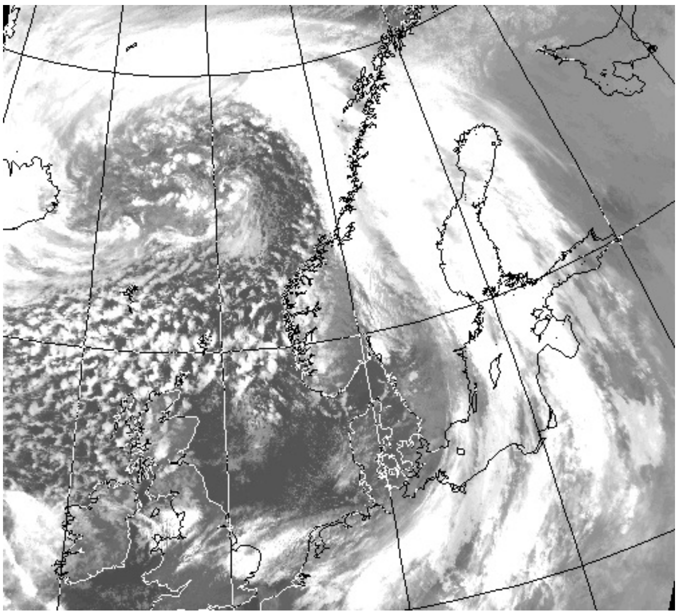

Satellite image of the extreme extratropical cyclone on 24 December 2016 at the coast of Norway. Image obtained from the Dundee Satellite Receiving Station http://www.sat.dundee.ac.uk.

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LIST OF ABBREVIATIONS

ACC	Accretion
AGG	Aggregation
AR	Atmospheric River
AROME	Applications of Research to Operations at Mesoscale
AUT	Autoconversion
BER	Bergeron-Findeisen process
C3VP	Canadian CloudSat-CALIPSO Validation Project
CFR	Contact Freezing of Raindrops
CPR	Cloud Profiling Radar
CV	Coefficient of Variation
CVM	Conversion-melting
DDA	Discrete Dipole Approximation
DEP	Deposition
DRY	Dry processes
DT	Dynamic Tropopause
ECMWF	European Centre for Medium-Range Weather Forecasts

EPS	Ensemble Prediction System
FMI	Finnish Meteorological Institute
HEN	Heterogeneous Nucleation
HON	Homogeneous Nucleation
IVT	Integrated Vapour Transport
LWC	Liquid Water Content
MASC	Multi-Angular Snowfall Camera
MEPS	MetCoOp Ensemble Prediction System
Meso-NH	Mesoscale Non-Hydrostatic model
Met-Norway	Norwegian Meteorological Institute
MetCoOp	Meteorological Co-operation on Operational NWP
MLT	Melting
MRR	Micro Rain Radar
MSLP	Mean Sea Level Pressure
NSF	National Science Foundation
NWP	Numerical Weather Prediction
PIP	Precipitation Imaging Package
PSD	Particle Size distribution
RIM	Riming
SMHI	Swedish Meteorological and Hydrological Institute
SWC	Snow Water Content

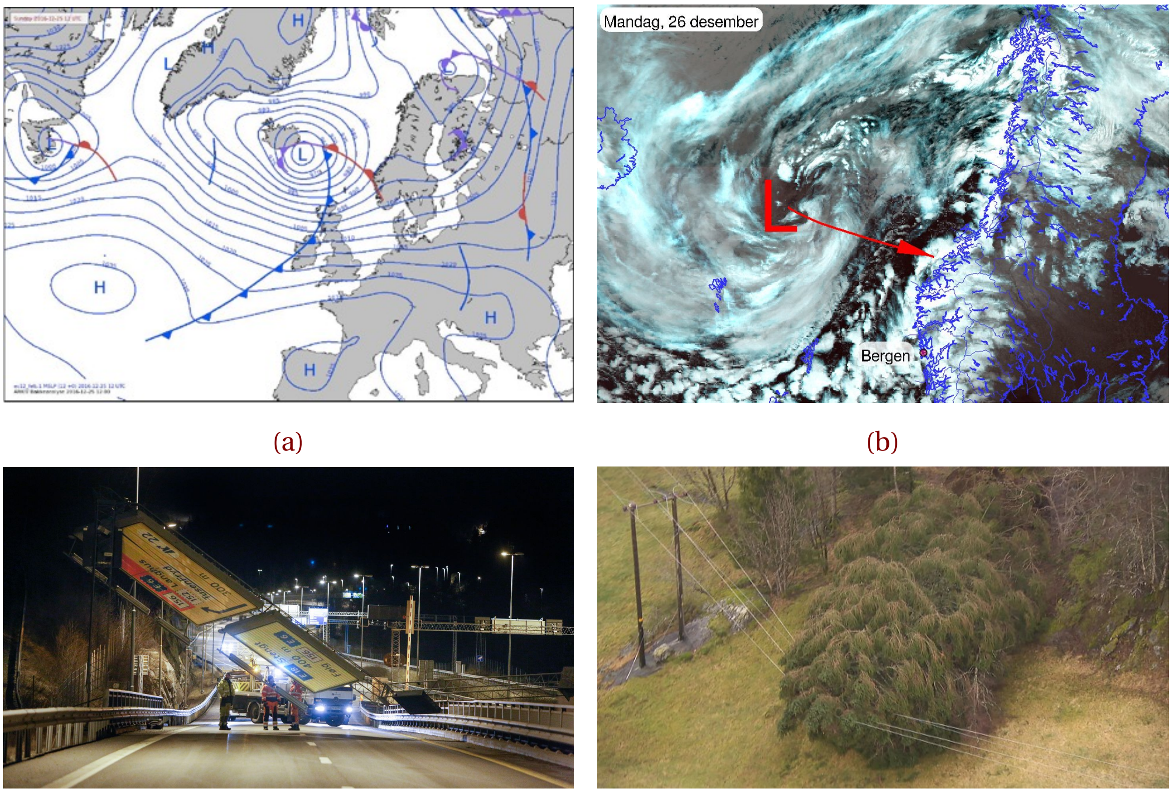
SWP	Snow Water Path
WCB	Warm Conveyor Belt
WET	Wet processes
WMO	World Meteorological Organization

Chapter 1: Introduction

An increased frequency of extreme weather events and heat waves, droughts, heavy rains or extremely high winds is one predicted consequence of global warming [Hansen et al., 2014]. Weather and climate extremes can have serious effects on human society and infrastructure, as well as on ecosystems and wildlife. Severe weather events are mostly in the focus of media reports on the topic of climate warming [Meehl et al., 2000]. Understanding and predicting the impact of extreme weather events is one of the major challenges of current climate research [Field et al., 2014, Stocker et al., 2013].

This work focuses on the extreme event during Christmas 2016, and the snowfall measurements and model forecasts taken at the measurement site Haukeliseter in Southern Norway. The extreme storm was named 'Urd' by the Norwegian Meteorological Institute (Met-Norway), and had a large impact on Norway. Storms of this kind are expected to occur on average every five years. The financial costs associated with 2016 Christmas storm are estimated to about 180 million Norwegian kroner. 'Urd' led to major traffic problems for cars, trains, ferries and air planes. Most mountain crossings were kept closed during Christmas 2016 [Olsen and Granerød, 2017]. A change in temperature and therefore a change of frozen to liquid precipitation followed an increase in avalanche danger. In addition, 40 emergency power stations failed during the extreme event affecting around 70.000 households (Figure 1.0.1). Since people are affected by extreme weather it is important to accurately measure and forecast severe storms. The use of accurate observations will lead to better performing weather forecast models, which rely heavily on observations [Joos and Wernli, 2012].

Since winter 2010, Haukeliseter has been a WMO measuring station with single and double fence precipitation instruments. In the winter of 2016/2017, three additional state of the art radar and snowflake microphysical instruments were deployed, which could be used



(a) (b)

(c) (d)

Figure 1.0.1: Weather situation during the extreme Christmas storm and impact on the infrastructure. In a: Weather situation Sunday 25 December 2016 at 12 UTC from the extreme weather report on Urd [Olsen and Granerød, 2017]. b: Tweet from Meteorologene [2016] on 26 December 2016 at 9:34 am: Here comes #Urd! The low pressure centre will hit Møre og Romsdal, but the strongest wind comes south of Stad. #SørNorge. c and d show the consequences related to the high wind speeds during Christmas 2016. c: This traffic sign, ten meter long and four meter high was blown down during the storm, [Ruud et al., 2016]. d: Trouble maker: The extreme weather during Christmas created problems for the local infrastructure. 80.000 households were without electricity during the storm, [Farestveit, 2016].

to estimate the vertical profile of snow water content in the atmosphere. Joos and Wernli [2012] showed on a sensitivity study of the microphysical scheme in a regional model for storm development, whether or not the placement of the precipitation is correct in the simulated storm. Looking at the vertical precipitation, which determines the vertical profile of latent heating, and hence leading to potential vorticity generation or destruction

which then in turn will lead to a storm amplification or decrease, respectively. Vertical pointing radar reflectivities are rare but can be an improvement to understand the microphysical structure in storms. Therefore, radar reflectivities were measured using the 24 GHz Micro Rain Radar (MRR) at Haukeliseter. Snowflake characteristics were estimated using a Multi-Angle Snowflake Camera [MASC; Garrett et al., 2012] and a Precipitation Imaging Package [PIP; Newman et al., 2009]. An optimal-estimation retrieval algorithm was developed that could estimate snowfall rates consistent with each MRR, MASC, and PIP measurement. This method of estimating snowfall is much like the study from Cooper et al. [2017]. The main difference between the studies at Barrow, Alaska and this study is that a 24 GHz MRR is used instead of a 94 GHz Ka-band ARM zenith radar. The double fence measurements will provide a boundary condition to ensure that retrieved surface snowfall accumulations are close to the truth. Such agreement will in turn provide confidence that retrieved snow water contents in the vertical are also valid.
The Meteorological Cooperation on Operational Numerical Weather Prediction (MetCoOp) Ensemble Prediction forecast (MEPS) has been operational at Met-Norway, since 2016. The ensemble prediction system uses the previous deterministic AROME-MetCoOp, a version of the Mèteo-France Applications of Research to Operations at Mesoscale. In addition to the deterministic forecast, nine perturbed ensemble members are initialised in MEPS. The newly developed ensemble prediction systems (EPS) from Met-Norway is used to analyse the extreme winter storm during Christmas 2016. It will be shown in the thesis if the ensemble prediction system is able to forecast the variation of an extreme winter event such as 'Urd' and if the forecast model is able to predict large scale as well as local frozen precipitation. Furthermore, the use of an ensemble prediction system will give the possibility to compare the variation of snowfall precipitation at the surface and in the vertical. Observations will help to compare MEPS model forecast to examine the following research questions: How well will the model predict the surface snowfall at the measurement site? Will large scale phenomena be predicted by MEPS? Does the regional model cover local affects associated with the topography around the site?

The thesis is structured as following: The next section provides the background for the motivation of this thesis. Chapter 2 will give an overview of the measurement site Haukeliseter and its instrumentation, followed by the methodology on the optimal estimation retrieval as well as a description of the regional model MEPS. To compare the forecast system to the observations the data had to be manipultated, this is presented in Section 2.6. The 2016 extreme Christmas event is analysed in Chapter 3. Chapter 4 will show the results and the discussion on large scale effects, surface snowfall accumulation and local wind influence at Haukeliseter. The final chapter summarises the results and findings and suggests future research questions.

1.1 BACKGROUND

It has long been known that measuring precipitation, especially in the form of snow, is difficult. Winter precipitation measurement show biases of more than 100 % between different gauge observation networks and different regions [Kochendorfer et al., 2017]. The local climate changes from station to station leading to different habit and size of frozen aggregates. Measurement uncertainties can be caused by the instrument itself, which varies with wind speed, gauge wind shielding, shape, size, phase, and fall velocity in hydrometeors [Kochendorfer et al., 2017, Wolff et al., 2015]. Uncertainties in precipitation measurements under windy conditions can affect water balance calculation and the calibration of remote sensing algorithms [Wolff et al., 2015].
Precipitation observations are important for hydrological, climate and weather research, as more than one-sixth of the world's population receives water from glaciers and seasonal snow packs [Barnett et al., 2005].
Since winds have an influence on frozen precipitation, a WMO (World Meteorological Organization) precipitation analysis between 1987 and 1993 recommended, that the double-fence inter-comparison reference should be used as a reference for snow measurements [Goodison et al., 1998]. An adjustment for unshielded and single-shielded precipitation gauges followed in 2010. The adjustment transfer function, for single fence gauges, represents a capture efficiency as a function of air temperature and wind speed to delimit the error of measured snowfall [Kochendorfer et al., 2017, Wolff et al., 2015].

The quantitative estimation of snowfall at the global scale from spaceborne measurements has occurred only recently. Initial retrieval approaches were based on passive microwave measurements [Noh et al., 2006, Skofronick-Jackson et al., 2004]. But since these passive measurements can only assess total integrated snow water path for a given column, such efforts were unable to provide much information on the vertical profiles of snow water. The launch of the CloudSat 94 GHz Cloud Profiling Radar (CPR) in 2006, however, provided the first opportunity to examine such vertical structure at a global scale. Several studies, such as Matrosov [2007] and Kulie and Bennartz [2009], have shown that the CPR can be used to estimate snofall rate but that estimated snowfall values depend heavily upon assumed snowflake microphysical properties. So, for a given radar reflectivity, we can get large differences in estimated snow rate depending upon retrieval assumptions such as snowflake habit and particle size distribution (PSD). For the operational CloudSat snowfall retrieval scheme (2C-SNOW-PROFILE), Wood et al. [2015] developed snowflake particle models based upon video snow disdrometer observations from the Canadian CloudSat-CALIPSO Validation Project [C3VP, Hudak et al., 2006]. Scattering properties for these snow particle models were based upon the Discrete Dipole Approximation (DDA) method. It was hoped that the use of realistic snow properties in the retrievals would lead to reasonable estimates of snowfall in the retrieval. In addition, they derived an a priori relationship between particle size distribution parameters and temperature that they could use as an additional constraint for the snowfall scheme. Use of the flexible optimal-estimation retrieval framework allowed a means to develop a best estimate of snow properties that are consistent with both the CPR reflectivities and the a priori constraint.

They have also been used to estimate snowfall in remote locations such as the Antarctic and Arctic [Kulie et al., 2016, Palerme et al., 2014], that in turn, have been used to evaluate the representation of snowfall in climate models [Christensen et al., 2016, Palerme et al., 2017]. Similarly, these estimates have been used to assess the performance of ground-based radar schemes such as those based upon the operational weather radar system in Sweden [Norin et al., 2015]. Despite such progress, however, the CloudSat scheme can still lead to uncertainties in the retrievals of up to 140 % to 200 % [Wood, 2011] for individual storms.

Again, these uncertainties arise from the large variance in snowflake microphysical properties as observed in nature. In response, Cooper et al. [2017] explored the use of in-situ, event specific observations of snowflake microphysical properties to improve radar-based retrievals of snowfall. This work was based upon observations from the Ka-band ARM Zenith Radar (KAZR) and Multi-Angle Snow Camera (MASC) deployed at the ARM Climate Facility Site at Barrow in Spring 2014. This ground-based 35 GHz retrieval scheme was modified from the space-borne 94 GHz CloudSat retrieval scheme developed by Wood

[2011]. But instead of using a temperature dependent a priori characterisation of PSD, Cooper et al. introduced the in-situ observations of particle size distribution through the a priori terms of the optimal-estimation framework.
Preliminary analyses suggest good performance for this retrieval scheme at Barrow. Estimates of snowfall from the Cooper et al. [2017] approach differed by 18 % relative to nearby National Weather Service snow gauge measurements for total accumulation over multiple snow events. However, given limited snowfall observed at Barrow during the MASC deployment, it was difficult to come to any definitive conclusions about retrieval performance. The NSF (National Science Foundation) funded field campaign with MRR, MASC, and PIP (Precipitation Imaging Package) deployment at Haukeliseter provides an ideal opportunity to further explore this retrieval approach. This study will continue continue to examine the sensitivity of retrieval surface snowfall rate to assumptions of habit, fall speed, and particle size distribution as in Cooper et al. [2017]. But the work presented here will be different in that we also will examine the vertical profiles of snowfall through the atmospheric column.

With the increasing expansion of computational power, developments of high-resolution numerical weather forecasting models with ≤4 km scales can be able to represent small-scale phenomena, such as convective dynamics [Gowan et al., 2018]. This enhancement provides weather services the ability to improve short-term weather forecasts for convective events, which can seriously impact infrastructure and society [Müller et al., 2017].
Information on magnitudes and location of maximum temperature is of significant importance when warnings are published by meteorologcial services for severe weather events and for further use in downstream impact model, e.g. NVE's (Norwegian Water Resources and Energy Directorate) hydrological model for flooding and avalanche risk.
The ability to use high-resolution models is also followed by various challenges, such as physical parametrisation schemes, accurate representation of topography, and data assimilation of high-resolution data [Sun, 2005].
The weather forecast in Scandinavia covers a wide range of phenomena and includes continental, maritime and polar conditions. Norway has a complicate coastline, gradients in land use, as well as complex topography, which can complicate local weather forecasting of temperature, wind and precipitation [Müller et al., 2017]. Colle et al. [2005], Garvert et al. [2005], Schwartz [2014], for example, have shown, that simulations of orographic

precipitation can be improved in mountainous terrain for horizontal grid spacing below 4 km. Uncertainties on a convective scale can lead to a rapid error growth [Lorenz, 1969], hence high-resolution ensemble prediction makes it possible to estimate the forecast uncertainty by performing several model runs, each with different initial conditions.

The Christmas storm in 2016, might not have led to the same damages as some of the extreme weather events of recent years. As people and infrastructure are affected by extreme weather, it is necessary to further improve the accuracy of snow-ground observations to better verify numerical weather forecasts, hydrological and climate models [Joos and Wernli, 2012]. Changes in snow pack characteristics after extreme rain on snow events can lead to severe avalanches [Stimberis and Rubin, 2011] and to the formation of thick layers of ice in the snow pack or on ground [Hansen et al., 2011, Putkonen and Roe, 2003].

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