The Christmas Storm 2016: Comparing Snow Observations and the Operational Forecast Model MEPS

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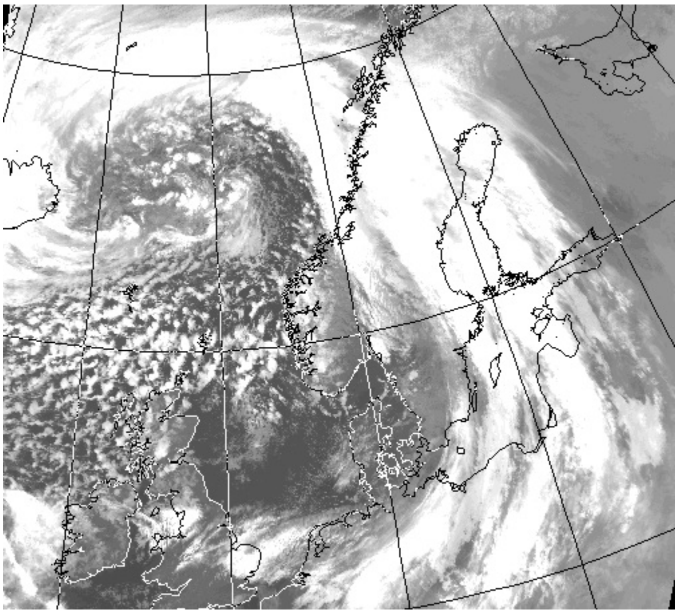

Satellite image of the extreme extratropical cyclone on 24 December 2016 at the coast of Norway. Image obtained from the Dundee Satellite Receiving Station http://www.sat.dundee.ac.uk.

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http://www.duo.uio.no/

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Abstract

Previous studies showed the importance to have information about the vertical distribution of precipitation to simulate precipitation and related cyclone development correctly in mesoscale models. During Christmas 2016, an extreme storm affected the local infrastructure of Eastern, Southern, and Western Norway. In this thesis, the Christmas storm 2016 is investigated for snow observations and the operational forecast model at Haukeliseter (991 m above sea level), Norway. The WMO measurement site Haukeliseter is equipped with a double fence snow gauge to reduce wind affects and increase catch-ratios for frozen precipitation. In winter 2016/2017, three additional instruments were installed for a US National Science Foundation funded field campaign, to estimate snow water content in the column with the help of an optimal estimation retrieval approach. In November 2016 the AROME-MetCoOp ensemble prediction system (MEPS) became operational at the Norwegian Meteorological Institute. The extreme weather event is studied using European Centre for Medium-Range Weather Forecasts weather analysis, precipitation measurements (i.e., double fence gauge), optimal estimation retrieval, and MEPS.

During 21 and 26 December 2016, two cyclones as well as frontal passages affect Norway. Observed frozen and liquid precipitation is associated with the cyclones and the fronts. The meteorological analysis of surface properties from observations and MEPS forecasts agree on the passages of occlusions and warm sector. Wind speeds (mean absolute error $\leq 10\,\mathrm{m\,s^{-1}}$) are predicted too high (mean absolute error ≤ 15 mm) by MEPS during the entire event with westerlies revealing a better agreement with observations than south-easterlies. A sensitivity study of the optimal estimation retrieval shows the advantage of using the Multi-Angular Snowfall Camera to choose the correct particle habit. During the Christmas 2016 storm, the average difference between the double fence gauge observations and the retrieved surface amount for assumed rimed aggregates is less than −5 % for 12 h and 24 h surface snow accumulation. With longer lead time decreases the average difference between double fence gauge observations and forecasted precipitation amount for 12 h and 24 h accumulation (+135 %, +33 %). However, for 24 and 26 December 2016, the surface precipitation amount is predicted too high compared to double fence gauge observations (+60 %). Liquid precipitation was observed at Haukeliseter in the afternoon on 25 December 2016. MEPS initialisations 24 h and 48 h prior successfully simulate the thickness and duration of the liquid layer in the lower most atmosphere, but it predicts less snow water content ($\leq 1.2\,\mathrm{g\,m^{-3}}$) than the profiles of retrieved snow profiles ($\leq 1.5\,\mathrm{g\,m^{-3}}$). Local topography effects by the surrounding mountains lead to continuous snow patterns during weak, south-easterly winds, strong westerlies show high amount of snow water content with a pulsing pattern. Finally, orography impacts on observations and model forecast are discussed.

The results are representative for one extreme storm during winter, more cases should be investigated in future studies.

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CHAPTER 1: INTRODUCTION

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

This work focuses on the extreme weather event during Christmas 2016, and the snow measurements and ensemble model forecasts taken at the measurement site Haukeliseter (991 m above sea level) in Southern Norway. The Christmas storm 2016, named 'Urd' by the Norwegian Meteorological Institute (Met-Norway), and had a large impact on Eastern, Southern, and Western Norway. The financial costs associated with the Christmas storm 2016 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]. An increase 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].

It has long been known that measuring precipitation, especially in the form of snow, is difficult. Winter precipitation measurement shows biases of more than 100 % between different gauge observation networks and different regions leading to different habit and size of frozen aggregates [Kochendorfer et al., 2017]. An 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. Uncertainties in precipitation measurements under windy conditions can affect water balance calculation and the calibration of remote sensing algorithms [Wolff et al., 2015].

Estimates of snowfall from radar reflectivities are non-unique. This means that a given reflectivity can yield very different estimates of snowfall depending upon the precise microphysical assumptions used in the retrieval scheme. Kulie and Bennartz [2009], for example, used the CloudSat

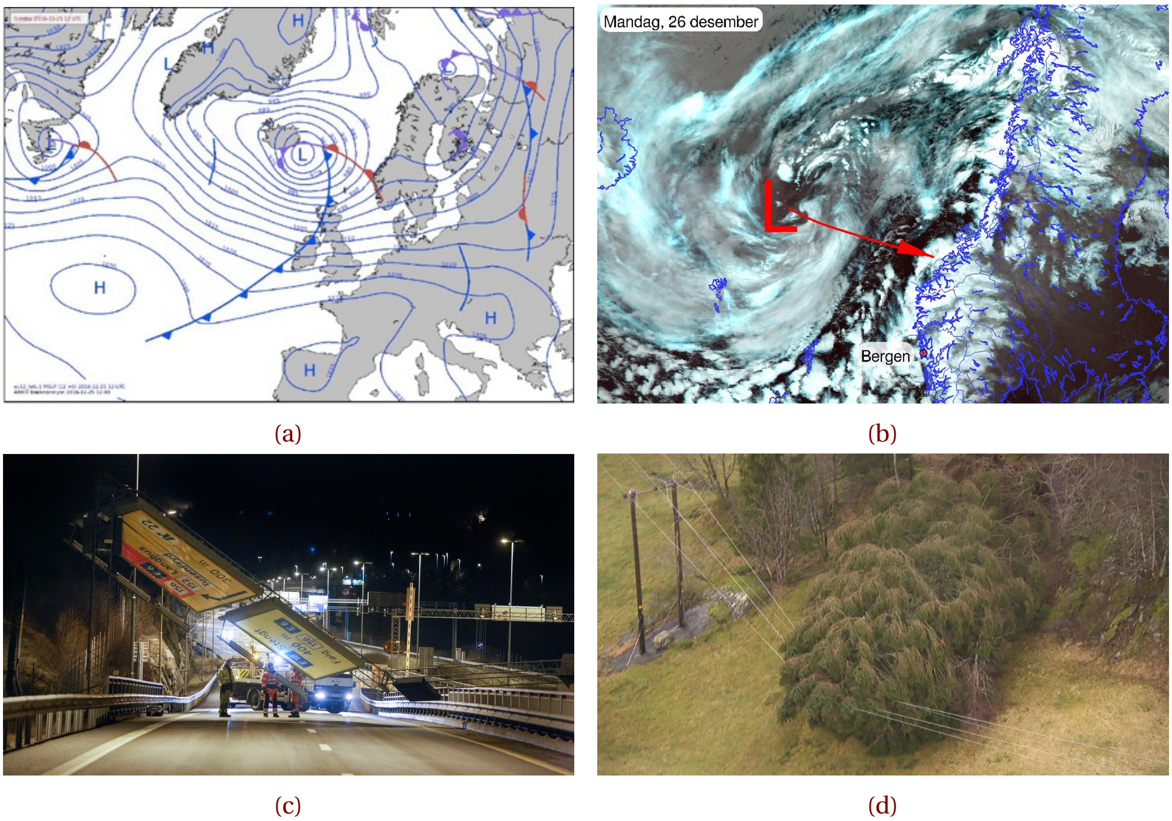

Figure 1.0.1: Weather situation during the extreme Christmas storm and impact on the infrastructure. a: Weather situation Sunday 25 December 2016 at 12 UTC from [Olsen and Granerød, 2017]. b: Tweet from Meteorologene [2016] on 26 December 2016 at 9:34 am c and d Consequences related to the high wind speeds during Christmas 2016 [Farestveit, 2016, Ruud et al., 2016].

Cloud Profiling Radar (CPR) to estimate global snowfall from a year of reflectivity data. They found that snowfall estimates critically depend on assumed snowfall particle size distribution, shape and fall speed. They concluded that the use of traditional Z-S relationships in which snow (S) is derived only from knowledge of radar reflectivity (Z) can lead to large retrieval uncertainties for a given snowstorm. Subsequent studies have tried to incorporate scene dependent microphysical information into the retrieval scheme. Wood [2011] incorporated a particle size distribution-temperature relationship information into the CloudSat operational snowfall retrieval scheme to help reduce retrieval non-uniqueness. In turn, Cooper et al. [2017] used in-situ estimates of snowflake PSD and habit from ground-based instrumentation to explore surface snowfall retrieval performance at Barrow, Alaska. They found reasonable agreement within 20 % of nearby snow gauge measurements. Given limited snowfall observed at Barrow, Alaska, it was difficult to come to any definitive conclusions about retrieval performance.

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]. Information on magnitudes and location of maximum precipitation amount and wind speed is of significant importance when warnings are published by meteorological services for severe weather events and for further use, e.g. the Norwegian Water Resources and Energy Directorate's 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 such as in Norway, and data assimilation of high-resolution data [Sun, 2005]. 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 Meteorological Cooperation on Operational Numerical Weather Prediction (MetCoOp) Ensemble Prediction forecast (MEPS) has been operational at Met-Norway since November 2016. The ensemble prediction system uses the previous deterministic AROME-MetCoOp, a version of the Mèteo-France Applications of Research to Operations at MEsoscale (AROME). In addition to the deterministic forecast, nine perturbed ensemble members are initialised in MEPS.

The Christmas storm in 2016 is an excellent test case for analysing unique available precipitation observations at Haukeliseter, Norway, together with the newly available ensemble system, MEPS. Haukeliseter has been a World Meteorological Organization (WMO) measuring station with single and double fence precipitation instruments since 2010. During winter 2016/17, the Haukeliseter site also housed a Micro Rain Radar (MRR), Multi-Angle Snow Camera [MASC; Garrett et al., 2012], and Precipitation Imaging Package (PIP) as part of US National Science Foundation (NSF) funded field campaign. Such a combination of radar and in-situ microphysical observations provided an ideal mean to estimate vertical precipitation profiles of snowfall rate and snow water content as in Cooper et al. [2017]. Such profiles, in turn, could be used to evaluate the representation of snow water in the weather prediction forecasts for storms such as Urd. Joos and Wernli [2012] stressed the need for improved observational constraints of the vertical profile of precipitation for forecast models. They showed that storm development in a regional forecast model depends upon whether or not the location of the precipitation is correctly simulated. The precise profile of precipitation determines the latent heating profile, which can lead to either potential vorticity generation or destruction.

This thesis is investigating 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 weather systems as well as 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 at Haukeliseter. Observations will help to compare MEPS model forecast to examine the following research questions: Does the regional model cover local affects associated with the topography surrounding the measurement site? How well does the model predict the surface snowfall at the Haukeliseter measurement site during the Christmas storm 2016? Are large scale synoptic weather systems resolved by MEPS? Is there a difference between estimated surface accumulation for different optimal estimation assumptions and locations?

The thesis is structured as following: Chapter 2 gives an overview of the measurement site Haukeliseter and its instrumentation, followed by the theory and methodology on the optimal estimation retrieval as well as a description of the regional model MEPS. The data calculation for MEPS and the statistical analysis is presented in Section 2.6. Afterwards, the evolution of the 2016 extreme

Christmas storm is investigated, using European Centre for Medium-Range Weather Forecasts (ECMWF) analysis maps. Chapter 4 analyse meteorological parameters at the surface to test if large scale weather systems were predicted at Haukeliseter. Furthermore, the comparison between the double fence gauge measurement and the retrieved snowfall amount at the surface is shown. Followed by an investigation about overestimation of surface precipitation amount by MEPS. Afterwards the retrieved snow water content is compared to MEPS simulations as well as the wind and snowfall related orographic influence is discussed. The final chapter summarises the results and gives an outlook for research.

Chapter 5: Summary and Outlook

The Christmas storm in 2016, an extreme weather event, affected large parts of Eastern, Southern, and Western Norway. In this thesis, a case study of an extreme event occurring on 21 to 26 December 2016 was studied. During winter 2016/2017 additional instruments such as a Micro Rain Radar (MRR), Particle Imaging Package (PIP), and Multi-Angular Snowfall Camera (MASC) were installed at Haukeliseter (991 m above sea level). The modified CloudSat optimal estimation retrieval was applied to estimate surface snow amount. The Meteorological Cooperation on Operational Numerical Weather Prediction (MetCoOp) Ensemble Prediction system (MEPS) became operational from November 2016 when it substituted the Mèteo-France Applications of Research to Operations at MEsoscale (AROME)-MetCoOp system at the Norwegian Meteorological Institute. Since MEPS has just become operational, a unique opportunity is given to do first comparisons between observations at the World Meteorological Organization station Haukeliseter, the additional installed instruments for snow, and the weather forecast model for the Christmas storm. The 2016 Christmas storm was analysed with the help of ECMWF analysis from the surface to the dynamic tropopause level. Meteorological parameters were evaluated to prove if the large-scale phenomena were observed and predicted by MEPS. A sensitivity study of retrieved surface snow accumulation for different a-priori assumptions was implemented. Snow comparisons between double fence gauge observations and MEPS forecast were investigated at the World Meteorological Organization measurement site Haukeliseter. Furthermore, a comparison between retrieved snow profiles of snow water content and MEPS forecast was carried out.

During 21 to 26 December 2016 a low-pressure system developed east of Iceland propagating poleward, followed by a second low-pressure system, which evolved in the western Atlantic, moving eastward. Temperature changes related to a low and high tropopause, occlusions, and warm sector passages led to precipitation changes at Haukeliseter. Within the warm sector passage liquid precipitation was observed at Haukeliseter, followed by a landfall of the Christmas storm 2016 on 26 December 2016 and dissipation afterwards.

The regional forecast model MEPS is capable of predicting sea level pressure, 2 m air temperature, and 10 m wind changes associated to frontal passages and occlusions during the Christmas 2016 storm at Haukeliseter. Transitions of the occlusions and the warm sector were predicted 24 h and 48 h in advance for this particular case. However, MEPS simulated too high wind speed (mean absolute error $\leq 10\,\mathrm{m\,s^{-1}}$) and surface precipitation amount (mean absolute error ≤ 15 mm).

According to literature the double fence gauge instrument is one of the best surface measurements for snow and taken as reference norm for precipitation observations. A state of the art optimal

estimation snowfall retrieval using a-priori guess from MRR, PIP, and MASC, allowed to compare surface observations to vertically retrieved snow amounts.
In the sensitivity study assumptions of a particle model for rimed aggregates ('B6'), climatological particle size distributions (PSD) and fall speeds followed the best estimate for surface snowfall accumulation compared to the use of a less reflective CloudSat aggregate model ('B8') at Haukeliseter. On 22 December 2016, the deviation between retrieval results found using the CloudSat aggregate particle model and double fence gauge measurement was 70 %.

Small differences between observed and estimated snow for rimed aggregates ($\leq -5\,\%$) shows the importance to choose a priori assumptions correctly to achieve reasonable surface estimates of precipitation amount at the ground. The small deviation gives confidence to trust the vertical estimated snow water content.

The average difference between observations and forecasted precipitation amount at the surface decreased with increasing lead time (12 h: +135 %, 24 h: +33 %) for 21 to 26 December 2016. The results revealed, the average difference for 12 h and 24 h accumulation was less than +11 % (21 to 23 December 2016) and +60 % (24 to 26 December 2016).
Taking the 10 % negative bias of the double fence measurements due to wind effects into account, reduces the forecasted surface snow error to +40 %.

On 25 December 2016, MASC images allowed to verify the presence of liquid precipitation during the passage of a warm sector at Haukeliseter. MEPS was able to simulate the timing of liquid precipitation 24 h and 48 h in advance. Comparison between MRR reflectivity profiles and modelled liquid water content showed the accurate simulation of liquid precipitation, both in time and thickness layer, in the lower most atmosphere.
Less variability ($\leq 25\,\%$) of snow water content between the ensemble members was seen for the continues precipitation associated with south-easterlies for initialisations 24 h and 48 h prior. MEPS ensemble members were certain about the appearance of pulsing snowfall patterns related to westerlies, but not the timing. The coefficient of variation showed more variability ($\geq 50\,\%$) between the ensemble members for the short, pulsed than for continuous precipitation pattern. The larger variability of the ensemble members for the pulsing storm patterns is likely related to the temporal resolution of MEPS ensemble forecast data and the short appearance of the pulses of around 30 min.
The hourly averaged estimated snow water content from MRR profiles is larger ($\leq 1.5\,\mathrm{g\,m^{-3}}$) than the ensemble mean of instantaneous MEPS forecasts ($\leq 1.2\,\mathrm{g\,m^{-3}}$). But, the deterministic and first ensemble member with 1 h resolution predicted higher snow water content ($\geq 2.0\,\mathrm{g\,m^{-3}}$) compared to the retrieved values ($\leq 1.5\,\mathrm{g\,m^{-3}}$) during the 2016 Christmas storm, showing the importance of high temporal resolution.

Although MEPS has a high horizontal resolution of 2.5 km, the representation of the topography in Norway might still be an issue. MEPS resolves some of the major orographic patterns at the Haukeliseter station, such as high mountains to the west and the south-east. The one and three hourly ensemble mean forecast of snow water content displayed the ability to predict more continuous, up-slope snow storm patterns related to occlusion passages as well as pulsing precipitation

associated to strong westerlies.
Forecasts of westerlies during 24 and 26 December 2016 showed a good correlation with observations. In contrast, observed south-easterly winds were predicted as south-westerly wind on 21 and 23 December 2016. Finally, topographic influence on wind and precipitation next to the impact of horizontal resolution of MEPS were discussed.

The here presented results are a first case study for one winter storm at a Norwegian station in the mountainous. Further studies have to be investigated.

5.1 OUTLOOK

Only a few studies have addressed similar approaches like this study here by comparing snow observations with weather forecast model.

First and foremost, it is important to investigate more extreme storm events during winter at Haukeliseter, whether deviations between observed and retrieved surface accumulation from vertical observations keep as small. Furthermore, these results should be compared to different stations in Norway with similar polar tundra climate, to investigate if the a-priori assumptions can be generalised for as similar local climate.

It is important to have correct measurements such as the double fence gauge or the MRR-PSD retrieval approaches. The double fence gauge observations should be investigated further to understand the wind related under-catchment of surface precipitation amount. Correct measurements will help to improve initial conditions for weather forecast models. Furthermore, accurate observations will help to get a greater understanding of the vertical snow structure.

Even though MEPS performed well in the vertical by relating the wind to the storm structure correctly, it will be interesting to investigate the presented results with a higher time resolution to resolve for the short pulses. The afore mentioned solution helps to investigate the simulation of high snow amount at the surface and the relationship between the vertical forecast and surface prediction model.

Sensitivity studies for the outer boundary could help to understand the influence of European Centre for Medium-Range Weather Forecasts (ECMWF) forecast on the MEPS predictions for local meteorological effects. This means e.g. initiating MEPS with and without all available observations for the outer boundary and MEPS domain. An initialisation with all available observations inside ECMWF will help to see an influence on the wind and precipitation predictions in MEPS.

More case studies will also help to get a better estimate about the performance of MEPS for snow prediction for storm events during winter. The mean absolute error for the 12 h accumulation of precipitation revealed large variability depending on the initialisation time of MEPS and the intensification of the cyclone.

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

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