Table of Contents

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 5: Summary and Outlook

In this thesis, a case study of an extreme event occurring on 21 to 26 December 2016 has been explored for snowfall. The extreme weather event 'Urd' affected large parts of Eastern, Southern, and Western Norway. During this period, the first low-pressure system developed east of Iceland, and the second cyclone evolved in the western Atlantic. Temperature changes related to the cold and warm fronts, and warm sectors followed observation of snow and liquid precipitation at Haukeliseter.
A sensitivity study of retrieved snow accumulation for different a-prior assumptions was carried out. Snowfall comparisons between double fence gauge observations and MEPS forecast of snowfall amount have been investigated at the WMO measurement site Haukeliseter. Meteorological parameters have been evaluated to see if large scale phenomena such as occlusion passages were observed and predicted by MEPS. Furthermore, a vertical comparison between retrieved profiles of snow water content is compared to 48 h forecasts of MEPS. Wind related topographical influence on precipitation and the resolution of MEPS were examined.

Double fence gauge measurements are considered as one of the best surface measurements for snowfall. Since additional instruments such as a MRR, MASC and PIP were installed at Haukeliseter during winter 2016/2017, a state of the art optimal estimation snowfall retrieval allowed to compare surface observations to vertically retrieved snowfall amounts. Assumptions of a particle model for rimed aggregates, climatological particle size distributions and fall speeds followed the best estimate for surface snowfall accumulation compared to the use of the CloudSat PSD estimate at Haukeliseter. The difference between retrieved snowfall amount and double fence was not larger than −5 % for 12 h and 24 h snowfall accumulation. The small difference between observation and estimated snowfall shows that it is important to choose a priori assumptions correctly to achieve reasonable surface estimates precipitation amount at the surface.

AROME-MetCoOp was operational until November 2016 when it got substituted by the ensemble prediction weather forecast model at the Norwegian Meteorological Institute. The change from a deterministic forecast to a ensemble prediction system will help to take into account measurement uncertainties. Since MEPS has just become operational, an unique opportunity is given to do first comparisons between the WMO station Haukeliseter, the additional installed instruments, and the weather forecast model. The closest model grid point to the measurement site Haukeliseter was chosen to answer the research question if MEPS is able to predict large-scale phenomena such as occlusions related to an extreme event. It turns out that the regional forecast model MEPS is capable of predicting changes associated to frontal passages and occlusions. Pressure, temperature, and wind changes associated with passages of fronts were predicted 24 h and 48 h in advance. The correlation between surface observations at the site and the weather forecast model were best for sea level pressure prediction. The mean absolute error for 2 m temperature was never larger than 1 K, but a warm temperature bias occurred on 24 December 2016. Include in results? Or double check During the extreme Christmas storm in 2016, overestimations of wind and precipitation accumulation at the surface by MEPS were seen.

In the meteorological analysis an overestimation of surface precipitation accumulation up to 60 % shows during the intensification of the Christmas 2016 extreme event and hence in detail analysed. The average difference between precipitation amount at the surface decreases with increasing lead time for 21 to 26 December 2016. The 12 h precipitation accumulation had a mean absolute error up to 12 mm which is approximately eight times larger than the Norwegian mean of December 2014.
A comparison of the wind influenced under-catchment by the double fence of 10 % showed a small difference error. The surface accumulation was nevertheless overestimated by more than 40 %. Reasons for the prediction of too much precipitation accumulation at the ground could be initialisation errors as well as the use of one grid point instead of using a variable average of surrounding grid points. The results show that MEPS is not able to predict the precipitation correctly during the Christmas 2016 extreme event.

The vertical snowfall measurements can be trusted after it was shown that the retrieved estimated snowfall at the surface is in good agreement with those observed at the double fence gauge.

The one and three hourly ensemble means of MEPS displayed the ability to predict more consistent, up-slope storm patterns. For this type of storm the ensemble variability for initialisations 24 h and 48 h prior occurrence was low. MEPS ensemble members prediction were uncertain about the appearance of pulsing patterns related to westerlies. Greater variability between the ensemble members for pulsing storm patterns is probably related to the temporal resolution of MEPS ensemble forecast data and the short appearance of the pulses, of around 30 min.
In general, the estimated snow water content from MRR profiles is greater than the instantaneous average prediction of snowfall. The deterministic and first ensemble member (1 h resolution) predicted high snow water contents on some days during the 2016 Christmas storm.
On 25 December 2016, MASC images could verify the presence of liquid precipitation during the passage of a warm sector at Haukeliseter. MEPS was able to estimate the occurrence of liquid precipitation 24 h and 48 h in advance. Vertical comparison between reflectivity profiles and modelled liquid water content have shown the prediction of liquid precipitation, both in time and layer thickness. This is an important advantage of a regional weather forecast model, as the change from snowfall to liquid precipitation poses a great risk in Norwegian mountains.
Although MEPS has a horizontal resolution of 2.5km, the representation of the mountainous terrain in Norway might still be an issue. MEPS is able to resolve some of the major orographic patterns, such as high mountains to the west and the south-east of Haukeliseter. Westerlies and their associated pulsing precipitation pattern were correct predicted by MEPS. Forecasts for westerlies during 24 and 26 December 2016 showed a good correlation. In contrast, observed south-east winds were often predicted to be south-westerly wind (not along the mountain valley, SE) during 21 and 23 December 2016. Nevertheless is MEPS able to relate southerly winds with up-slope patterns of precipitation.

This study demonstrates the complex interaction of analysing snowfall extreme events with observations and regional model prediction. The here presented results are a first look for only one extreme storm at one station and further studies have to be done.

5.1 Outlook

Only a few studies have addressed similar approaches like the comparison of vertical snowfall prediction to observations, and thus comparison with other work is difficult. Hence, the here presented results motivate to deal more with the subject of vertical snowfall observation and its comparison to regional weather forecast models.
First and foremost it is important to investigate more extreme snowfall events during winter at Haukeliseter. To see if the deviations between surface accumulation and estimated precipitation amount from vertical observations keep as small. Furthermore these results should be compared to different stations in Norway with similar polar tundra climate, to find out if a-priori assumptions can be generalised for the same local climate. More case studies will also help to get a better estimate about the performance of MEPS during extreme winter events. The mean absolute error for 12 h accumulation has shown a great variability, depending on the initialisation time and the intensification of the low-pressure system. This increase in mean absolute error with intensification might be low when compared to other cases.

The previous Chapters have indicated, the regional model MEPS is able to predict larger scale phenomena. This might be related to the outer boundary condition ECMWF or the Christmas 2016 extreme event was more predictable. In general, surface parameters such as wind pressure and temperature were predicted well, only wind speed and precipitation accumulation showed overestimation in MEPS predictions. Wind speed forecasts were higher than observations, this might be related to the representation of the orography in MEPS, or the general overestimation of wind speed already apparent in AROME-MetCoOp. Sensitivity studies for the outer boundary could help to understand how much ECMWF forecast influence the MEPS prediction for local meteorological effects. ECMWF as boundary condition might not have reached its stabilised state when MEPS was initiated during the event, and could also have led to the overestimation of wind speed and surface accumulation. A comparison between ECMWF forecast and MEPS will verify if that might be the case. Re-analysis data can help to show the uncertainty in the initial and boundary conditions. A re-run with analysis data from ECMWF could possibly improve the original forecast. It will be interesting to initiate MEPS with all available observations, to see if this

has an influence on the overestimation of wind and precipitation accumulation.
Another approach could be to perturb the deterministic forecast in other way. Different perturbations might lead to a better correlation between observation and forecast at the ground. Furthermore, the choice of using the closest grid point to Haukeliseter might not have been the best approach. Using four close by grid points instead of only one could help to verify overestimations of MEPS forecasts compared to observations.
Even though MEPS performed well in the vertical by relating the wind to the storm structure correctly, it will be interesting to investigate the here presented results with a higher time resolution to resolve for the short pulses. Since MEPS overestimates the surface accumulation and the ensemble means show to be in general smaller than the estimated snow water content, the afore mentioned solution help to investigate the overestimation of snowfall at the surface and the relationship between the vertical forecast and surface prediction model.
The local affect of pulsing patterns related to westerlies should be examined. To understand if e.g. wave breaking occurs at the mountain to the west, or if it is an effect of local surface fronts.

It is important to have correct measurements such as the double fence gauge or the MRR-PSD retrieval approach. Correct measurements will help to improve initial conditions for weather forecast models, so that initialisations can start at the true state. Furthermore accurate observations will help to get a greater understanding of vertical snowfall structure. Investigating in more detail microphysical processes within mesoscale storms with vertical measurements of snowfall for extreme events can be a grand improvement for weather and climate prediction.

References

Barnett, T. P., Adam, J. C., and Lettenmaier, D. P. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438(7066):303–309, November 2005. ISSN 1476-4687. doi: 10.1038/nature04141. URL https://www.nature.com/articles/nature04141.

Caniaux, G., Redelsperger, J.-L., and Lafore, J.-P. A Numerical Study of the Stratiform Region of a Fast-Moving Squall Line. Part I: General Description and Water and Heat Budgets. *J. Atmos. Sci.*, 51(14):2046–2074, July 1994. ISSN 0022-4928. doi: 10.1175/1520-0469(1994)051<2046:ANSOTS>2.0.CO;2. URL https://journals.ametsoc.org/doi/abs/10.1175/1520-0469(1994)051%3C2046:ANSOTS%3E2.0.CO;2.

Christensen, M. W., Behrangi, A., L'ecuyer, T. S., Wood, N. B., Lebsock, M. D., and Stephens, G. L. Arctic Observation and Reanalysis Integrated System: A New Data Product for Validation and Climate Study. *Bull. Amer. Meteor. Soc.*, 97(6):907–916, January 2016. ISSN 0003-0007. doi: 10.1175/BAMS-D-14-00273.1. URL https://journals.ametsoc.org/doi/10.1175/BAMS-D-14-00273.1.

Colle, B. A., Garvert, M. F., Wolfe, J. B., Mass, C. F., and Woods, C. P. The 13–14 December 2001 IMPROVE-2 Event. Part III: Simulated Microphysical Budgets and Sensitivity Studies. *J. Atmos. Sci.*, 62(10):3535–3558, October 2005. ISSN 0022-4928. doi: 10.1175/JAS3552.1. URL https://journals.ametsoc.org/doi/abs/10.1175/JAS3552.1.

Cooper, S. J., Wood, N. B., and L'Ecuyer, T. S. A variational technique to estimate snowfall rate from coincident radar, snowflake, and fall-speed observations. *Atmos. Meas. Tech.*, 10(7):2557–2571, July 2017. ISSN 1867-8548. doi: 10.5194/amt-10-2557-2017. URL https://www.atmos-meas-tech.net/10/2557/2017/.

Dahlgren, P. A Comparison Of Two Large Scale Blending Methods. page 16, 2013. URL http://metcoop.org/memo/2013/02-2013-METCOOP-MEMO.PDF.

Dando, P. Introducing the octahedral reduced Gaussian grid, June 2016. URL https://software.ecmwf.int/wiki/display/FCST/Gaussian+grids.

Doviak, R. J. and Zrnic, D. S. *Doppler Radar and Weather Observations*. Courier Corporation, 1993. ISBN 978-0-486-45060-5. Google-Books-ID: ispLkPX9n2UC.

eklima. Norwegian Meteorological Institute, 2016. URL http://sharki.oslo.dnmi.no/portal/page?_pageid=73,39035,73_39049&_dad=portal&_schema=PORTAL.

Farestveit, E. 80.000 mista radioen under ekstremvêret, December 2016. URL https://www.nrk.no/hordaland/80.000-mista-radioen-under-ekstremveret-1.13294980.

Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D., Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y. O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., MacCracken, S., Mastrandrea, P. R., and White, L. L. Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge: Cambridge University Press*, page 34, 2014.

Færaas, A., Rommetveit, A., Duesund, J., and Senel, E. «Urd» har nådd orkan styrke – flytter seg mot Østlandet, December 2016. URL http://www.yr.no/artikkel/_urd_-har-nadd-orkan-styrke-_-flytter-seg-mot-ostlandet-1.13292245.

Garrett, T. J., Fallgatter, C., Shkurko, K., and Howlett, D. Fall speed measurement and high-resolution multi-angle photography of hydrometeors in free fall. *Atmos. Meas. Tech.*, 5(11):2625–2633, November 2012. ISSN 1867-8548. doi: 10.5194/amt-5-2625-2012. URL https://www.atmos-meas-tech.net/5/2625/2012/.

Garvert, M. F., Woods, C. P., Colle, B. A., Mass, C. F., Hobbs, P. V., Stoelinga, M. T., and Wolfe, J. B. The 13–14 December 2001 IMPROVE-2 Event. Part II: Comparisons of MM5 Model Simulations of Clouds and Precipitation with Observations. *J. Atmos.*

Sci., 62(10):3520–3534, October 2005. ISSN 0022-4928. doi: 10.1175/JAS3551.1. URL https://journals.ametsoc.org/doi/10.1175/JAS3551.1.

Geonor Inc. T-200b All Weather Precipitation – Rain Gauge, 2015. URL http://geonor.com/live/products/weather-instruments/t-200b-weather-precipitation-rain-gauge/.

Geonorge. DTM 10 Terrengmodell (UTM33) - Kartverket - Kartkatalogen, May 2018. URL https://kartkatalog.geonorge.no/metadata/uuid/dddbb667-1303-4ac5-8640-7ec04c0e3918.

Goodison, B. E., Louie, P. Y. T., and Yang, D. WMO Solid Precipitation Measurement Intercomparison: Final Report. Instruments and Observing Methods Rep. 67, WMO/TD-No. 872,. *World Meteorological Organization, Geneva, Switzerland*, page 318, 1998.

Gowan, T. M., Steenburgh, W. J., and Schwartz, C. S. Validation of Mountain Precipitation Forecasts from the Convection-Permitting NCAR Ensemble and Operational Forecast Systems over the Western United States. *Wea. Forecasting*, 33(3):739–765, June 2018. ISSN 0882-8156, 1520-0434. doi: 10.1175/WAF-D-17-0144.1. URL http://journals.ametsoc.org/doi/10.1175/WAF-D-17-0144.1.

Hansen, B. B., Isaksen, K., Benestad, R. E., Kohler, J., Pedersen, Ø. Ø., Loe, L. E., Coulson, S. J., Larsen, J. O., and Varpe, Ø. Warmer and wetter winters: characteristics and implications of an extreme weather event in the High Arctic. *Environ. Res. Lett.*, 9 (11):114021, 2014. ISSN 1748-9326. doi: 10.1088/1748-9326/9/11/114021. URL http://stacks.iop.org/1748-9326/9/i=11/a=114021.

Hansen, B. B., Aanes, R., Herfindal, I., Kohler, J., and Sæther, B.-E. Climate, icing, and wild arctic reindeer: past relationships and future prospects. *Ecology*, 92(10):1917–1923, October 2011. ISSN 1939-9170. doi: 10.1890/11-0095.1. URL https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/11-0095.1.

Homleid, M. and Tveter, F. T. Verification of operational weather prediction models september to november 2015. *METInfo Rep*, 16:2016, 2016. URL https://www.met.no/publikasjoner/met-info/met-info-2016/_/attachment/download/b0463915-

cba0-42ac-8539-4233ae2bf01c:3d71565a27f88085373199a33ab8569151c144e9/MET-info-22-2016.pdf.

Hudak, D., Barker, H., Rodriguez, P., and Donovan, D. The Canadian CloudSat Validation Project. *4th ERAD*, September 2006. URL http://www.crahi.upc.edu/ERAD2006/proceedingsMask/00165.pdf. Barcelona, Spain.

Joos, H. and Wernli, H. Influence of microphysical processes on the potential vorticity development in a warm conveyor belt: a case-study with the limited-area model COSMO. *Q. J. Royal Meteorol. Soc.*, 138(663):407–418, January 2012. ISSN 00359009. doi: 10.1002/qj.934. URL http://doi.wiley.com/10.1002/qj.934.

Kalnay, E. *Atmospheric modeling, data assimilation and predictability*. Cambridge University Press, Cambridge, 2003. ISBN 978-0-521-79179-3.

Kochendorfer, J., Nitu, R., Wolff, M., Mekis, E., Rasmussen, R., Baker, B., Earle, M. E., Reverdin, A., Wong, K., Smith, C. D., Yang, D., Roulet, Y.-A., Buisan, S., Laine, T., Lee, G., Aceituno, J. L. C., Alastrué, J., Isaksen, K., Meyers, T., Brækkan, R., Landolt, S., Jachcik, A., and Poikonen, A. Analysis of single-Alter-shielded and unshielded measurements of mixed and solid precipitation from WMO-SPICE. *Hydrol. Earth Syst. Sci.*, 21(7): 3525–3542, July 2017. ISSN 1607-7938. doi: 10.5194/hess-21-3525-2017. URL https://www.hydrol-earth-syst-sci.net/21/3525/2017/.

Kulie, M. S. and Bennartz, R. Utilizing Spaceborne Radars to Retrieve Dry Snowfall. *J. Appl. Meteor. Climatol.*, 48(12):2564–2580, January 2009. ISSN 1558-8424. doi: 10.1175/2009JAMC2193.1. URL http://journals.ametsoc.org/doi/abs/10.1175/2009JAMC2193.1.

Kulie, M. S., Milani, L., Wood, N. B., Tushaus, S. A., Bennartz, R., and L'Ecuyer, T. S. A Shallow Cumuliform Snowfall Census Using Spaceborne Radar. *J. Hydrometeor.*, 17 (4):1261–1279, February 2016. ISSN 1525-755X. doi: 10.1175/JHM-D-15-0123.1. URL https://journals.ametsoc.org/doi/abs/10.1175/JHM-D-15-0123.1.

Køltzow, M. A. MetCoOp EPS - A convection permitting ensemble prediction system, October 2017.

L'Ecuyer, T. S. AOS 441 - Satellite and Radar Meteorology. January 2017. URL https://lecuyer.aos.wisc.edu/aos441.

Liu G. Deriving snow cloud characteristics from CloudSat observations. *J. Geophys. Res. Atmos.*, 113(D8), September 2008. ISSN 0148-0227. doi: 10.1029/2007JD009766. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007JD009766.

Lorenz, E. N. Atmospheric Predictability as Revealed by Naturally Occurring Analogues. *J. Atmos. Sci.*, 26(4):636–646, July 1969. ISSN 0022-4928. doi: 10.1175/1520-0469(1969)26<636:APARBN>2.0.CO;2. URL https://journals.ametsoc.org/doi/abs/10.1175/1520-0469%281969%2926%3C636%3AAPARBN%3E2.0.CO%3B2.

Markowski, P. and Richardson, Y. *Mesoscale Meteorology in Midlatitudes*. John Wiley & Sons, September 2011. ISBN 978-1-119-96667-8. Google-Books-ID: MDeYosfLLEYC.

Martin, J. E. *Mid-Latitude Atmospheric Dynamics: A First Course*. Wiley, May 2006. ISBN 978-0-470-86466-1.

Matrosov, S. Y. Modeling Backscatter Properties of Snowfall at Millimeter Wavelengths. *J. Atmos. Sci.*, 64(5):1727–1736, May 2007. ISSN 0022-4928. doi: 10.1175/JAS3904.1. URL https://journals.ametsoc.org/doi/abs/10.1175/JAS3904.1.

McCumber, M., Tao, W.-K., Simpson, J., Penc, R., and Soong, S.-T. Comparison of Ice-Phase Microphysical Parameterization Schemes Using Numerical Simulations of Tropical Convection. *J. Appl. Meteor.*, 30(7):985–1004, July 1991. ISSN 0894-8763. doi: 10.1175/1520-0450-30.7.985. URL https://journals.ametsoc.org/doi/abs/10.1175/1520-0450-30.7.985.

Meehl, G. A., Karl, T., Easterling, D. R., Changnon, S., Pielke, R., Changnon, D., Evans, J., Groisman, P. Y., Knutson, T. R., Kunkel, K. E., Mearns, L. O., Parmesan, C., Pulwarty, R., Root, T., Sylves, R. T., Whetton, P., and Zwiers, F. An Introduction to Trends in Extreme Weather and Climate Events: Observations, Socioeconomic Impacts, Terrestrial Ecological Impacts, and Model Projections. *Bull. Amer. Meteor. Soc.*, 81(3):413–416, March 2000. ISSN 0003-0007. doi: 10.1175/1520-0477(2000)081<0413:AITTIE>2.3.CO;2. URL https://journals.ametsoc.org/doi/abs/10.1175/1520-0477(2000)081%3C0413:AITTIE%3E2.3.CO;2.

MetCoOp Wiki. Description of MEPS, December 2017. URL https://metcoop.smhi.se/dokuwiki/nwp/metcoop/.

METEK, M. M. G. Micro Rain Radar MRR-2, October 2010. URL http://metek.de/wp-content/uploads/2014/05/Metek-Micro-Rain-Radar-MRR-2-Datasheet.pdf.

Meteo France. The Meso-NH Atmospheric Simulation System: Scientific Documentation, Part III: Physics, January 2009.

Meteorologene. "Her kommer #Urd! Selve Lavtrykksenteret treffer Møre og Romsdal, men den sterkeste vinden kommer sør for Stad. #SørNorge" 26 December 2016, 9:34am, 2016. URL https://twitter.com/Meteorologene.

Müller, M., Homleid, M., Ivarsson, K.-I., Køltzow, M. A. Ø., Lindskog, M., Midtbø, K. H., Andrae, U., Aspelien, T., Berggren, L., Bjørge, D., Dahlgren, P., Kristiansen, J., Randriamampianina, R., Ridal, M., and Vignes, O. AROME-MetCoOp: A Nordic Convective-Scale Operational Weather Prediction Model. *Wea. Forecasting*, 32 (2):609–627, January 2017. ISSN 0882-8156. doi: 10.1175/WAF-D-16-0099.1. URL http://journals.ametsoc.org/doi/abs/10.1175/WAF-D-16-0099.1.

Newman, A. J., Kucera, P. A., and Bliven, L. F. Presenting the Snowflake Video Imager (SVI). *J. Atmos. Oceanic Technol.*, 26(2):167–179, February 2009. ISSN 0739-0572. doi: 10.1175/2008JTECHA1148.1. URL https://journals.ametsoc.org/doi/abs/10.1175/2008JTECHA1148.1.

Noh, Y.-J., Liu, G., Seo, E.-K., Wang, J. R., and Aonashi, K. Development of a snowfall retrieval algorithm at high microwave frequencies. *J. Geophys. Res*, 111(D22), November 2006. ISSN 2156-2202. doi: 10.1029/2005JD006826. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2005JD006826.

Norin, L., Devasthale, A., L'Ecuyer, T. S., Wood, N. B., and Smalley, M. Intercomparison of snowfall estimates derived from the CloudSat Cloud Profiling Radar and the ground-based weather radar network over Sweden. *Atmos. Meas. Tech.*, 8(12): 5009–5021, December 2015. ISSN 1867-8548. doi: 10.5194/amt-8-5009-2015. URL https://www.atmos-meas-tech.net/8/5009/2015/.

Norwegian Meteorological Institute. MET Norway Thredds Service, 2016. URL http://thredds.met.no/thredds/catalog/meps25epsarchive/catalog.html.

Olsen, A.-M. and Granerød, M. Ekstremværrapport. Hendelse: Urd 26. desember met. info. no. 18/2017 ISSN X METEOROLOGI Bergen, - PDF, September 2017. URL http://docplayer.me/48734203-Ekstremvaerrapport-hendelse-urd-26-desember-met-info-no-18-2017-issn-x-meteorologi-bergen.html.

Palerme, C., Kay, J. E., Genthon, C., L'Ecuyer, T., Wood, N. B., and Claud, C. How much snow falls on the Antarctic ice sheet? *The Cryosphere*, 8(4):1577–1587, August 2014. ISSN 1994-0424. doi: 10.5194/tc-8-1577-2014. URL https://www.the-cryosphere.net/8/1577/2014/.

Palerme, C., Genthon, C., Claud, C., Kay, J. E., Wood, N. B., and L'Ecuyer, T. Evaluation of current and projected Antarctic precipitation in CMIP5 models. *Clim. Dyn.*, 48(1-2): 225–239, January 2017. ISSN 0930-7575, 1432-0894. doi: 10.1007/s00382-016-3071-1. URL https://link.springer.com/article/10.1007/s00382-016-3071-1.

Pedersen, K. and Rommetveit, A. Hva er et «ekstremvær»?, November 2013. URL http://www.yr.no/artikkel/hva-er-et-_ekstremvaer__-1.7890946.

Peel, M. C., Finlayson, B. L., and Mcmahon, T. A. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences Discussions*, 4(2):439–473, March 2007. URL https://hal.archives-ouvertes.fr/hal-00298818.

Pinty, J.-P. and Jabouille, P. A mixed-phased cloud parameterization for use in a mesoscale non-hydrostatic model: Simulations of a squall line and of orographic precipitation. pages 217–220. Amer. Meteor. Soc., 1998.

Putkonen, J. and Roe, G. Rain-on-snow events impact soil temperatures and affect ungulate survival: RAIN-ON-SNOW EVENTS IMPACT SOIL TEMPERATURES. *Geophysical Research Letters*, 30(4), February 2003. ISSN 00948276. doi: 10.1029/2002GL016326. URL http://doi.wiley.com/10.1029/2002GL016326.

Rinehart, R. E. *Radar for Meteorologists: Or You, Too, Can be a Radar Meteorologist.* Rinehart Publications, 2010. ISBN 978-0-9658002-3-5. Google-Books-ID: VqatcQAACAAJ.

Rutz, J. J., Steenburgh, W. J., and Ralph, F. M. Climatological Characteristics of Atmospheric Rivers and Their Inland Penetration over the Western United States. *Mon. Wea. Rev.*, 142(2):905–921, January 2014. ISSN 0027-0644. doi: 10.1175/MWR-D-13-00168.1. URL http://journals.ametsoc.org/doi/abs/10.1175/MWR-D-13-00168.1.

Ruud, S., Carr Ekroll, H., Bakke Foss, A., Torgersen, H. O., and Annar Holm, P. To tonn tungt skilt blåste ned da ekstremværet traff Oslo og Østlandet i natt, December 2016. URL https://www.aftenposten.no/article/ap-2z6wy.html.

Schirle, C. Characterization of snowfall at high latitudes using an optimal estimation-based retrieval algorithm. Private Communication, 2018.

Schwartz, C. S. Reproducing the September 2013 Record-Breaking Rainfall over the Colorado Front Range with High-Resolution WRF Forecasts. *Wea. Forecasting*, 29(2): 393–402, January 2014. ISSN 0882-8156. doi: 10.1175/WAF-D-13-00136.1. URL https://journals.ametsoc.org/doi/abs/10.1175/WAF-D-13-00136.1.

Skofronick-Jackson, G. M., Kim, M.-J., Weinman, J. A., and Chang, D.-E. A physical model to determine snowfall over land by microwave radiometry. *IEEE Geosci. Remote Sens. Lett.*, 42(5):1047–1058, May 2004. ISSN 0196-2892. doi: 10.1109/TGRS.2004.825585.

Stephens, G. L. *Remote Sensing of the Lower Atmosphere: An Introduction*. Oxford University Press, 1994. ISBN 978-0-19-508188-6. Google-Books-ID: 2FcRAQAAIAAJ.

Stimberis, J. and Rubin, C. M. Glide avalanche response to an extreme rain-on-snow event, Snoqualmie Pass, Washington, USA. *Journal of Glaciology*, 57(203): 468–474, 2011. ISSN 0022-1430, 1727-5652. doi: 10.3189/002214311796905686. URL https://www.cambridge.org/core/journals/journal-of-glaciology/article/glide-avalanche-response-to-an-extreme-rainonsnow-event-snoqualmie-pass-washington-usa/2B6E48BD92F0700B7BEA02EF156E203F.

Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M. M. B., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge: Cambridge University Press*, page 14, 2013.

Sun, J. Convective-scale assimilation of radar data: progress and challenges. *Quarterly Journal of the Royal Meteorological Society*, 131(613):3439–3463, 2005. ISSN 1477-870X. doi: 10.1256/qj.05.149. URL https://rmets.onlinelibrary.wiley.com/doi/abs/10.1256/qj.05.149.

Wolff, M. A. WMO Solid Precipitation Intercomparison Experiment (WMO-SPICE), Ch. 4.2.4 Precipitation measurements in areas with high winds and/or complex terrain. unpublished, 2018.

Wolff, M. A., Brækkan, R., Isaksen, K., and Ruud, E. A new testsite for wind correction of precipitation measurements at a mountain plateau in southern Norway. In *Proceedings of WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation (TECO–2010). Instruments and Observing Methods Report*, 2010.

Wolff, M. A., Isaksen, K., Brækkan, R., Alfnes, E., Petersen-Øverleir, A., and Ruud, E. Measurements of wind-induced loss of solid precipitation: description of a Norwegian field study. *Hydrol. Res.*, 44(1):35–43, February 2013. ISSN 0029-1277, 2224-7955. doi: 10.2166/nh.2012.166. URL http://hr.iwaponline.com/content/44/1/35.

Wolff, M. A., Isaksen, K., Petersen-Øverleir, A., Ødemark, K., Reitan, T., and Brækkan, R. Derivation of a new continuous adjustment function for correcting wind-induced loss of solid precipitation: results of a Norwegian field study. *Hydrol. Earth Syst. Sci.*, 19 (2):951–967, February 2015. ISSN 1607-7938. doi: 10.5194/hess-19-951-2015. URL https://www.hydrol-earth-syst-sci.net/19/951/2015/.

Wood, N. B. *Estimation of snow microphysical properties with application to millimeter-wavelength radar retrievals for snowfall rate.* Ph.D., Colorado State University, 2011. URL https://dspace.library.colostate.edu/bitstream/handle/10217/48170/Wood_colostate_0053A_10476.pdf?sequence=1&isAllowed=y.

Wood, N. B., L'Ecuyer, T. S., Vane, D. G., Stephens, G. L., and Partain, P. Level 2c snow profile process description and interface control document. Technical Report, 2013. URL http://www.cloudsat.cira.colostate.edu/sites/default/files/products/files/2C-SNOW-PROFILE_PDICD.P_R04.20130210.pdf.

Wood, N. B., L'Ecuyer, T. S., Heymsfield, A. J., and Stephens, G. L. Microphysical Constraints on Millimeter-Wavelength Scattering Properties of Snow Particles. *J. Appl. Meteor. Climatol.*, 54(4):909–931, January 2015. ISSN 1558-8424. doi: 10.1175/JAMC-D-14-0137.1. URL http://journals.ametsoc.org/doi/10.1175/JAMC-D-14-0137.1.