Abstract

Previous studies showed the importance to have information about the vertical location 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. During 21 and 26 December 2016, the extreme storm was investigated for snowfall at the WMO measurement site Haukeliseter.
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 to estimate snowfall with the help of an optimal estimation retrieval approach. In November 2016 the ensemble prediction system AROME-MetCoOp (MEPS) became operational at the Norwegian Meteorological Institute.
The extreme weather event has been studied using ECMWF weather analysis, double fence gauge measurements, optimal estimation retrieval, and ensemble prediction forecast.
During the 2016 Christmas storm, two cyclones as well as frontal passages affect Norway. Observed frozen and liquid precipitation is associated with the cyclones and the fronts during 21 and 26 December 2016. The meteorological analysis of surface properties from observations and MEPS forecast agree on the passages of occlusions and warm sector. Wind speeds are predicted too high by MEPS during the entire event. Westerlies are better simulated by MEPS 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 size distribution. During the Christmas 2016 storm, the average difference between the double fence gauge observations and the retrieved surface snowfall amount for assumed rimed aggregates is less than $-5\,\%$ for 12 h and 24 h surface accumulation.
During 24 and 26 December 2016, 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 simulate the thickness and duration of the liquid layer in the lower most atmosphere. MEPS predicted less snow water content than the profiles of retrieved snow profiles. Haukeliseter is surrounded by mountains. Local topography effects lead to continuous snow patterns during weak, south-easterly winds. Strong westerlies show high amount of snow water content with a pulsing pattern.
The results are representative for only one extreme storm during winter. More should be investigated to verify the presented results.

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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.
The 2016 Christmas storm was analysed with the help of ECMWF analysis maps at the dynamic tropopause level and at the surface. Meteorological parameters were evaluated to prove if the large-scale phenomena such as occlusion passages and a warm sector were observed and predicted by MEPS. A sensitivity study of retrieved surface snow accumulation for different a-priori assumptions was implemented. Snowfall comparisons between double fence gauge observations and MEPS forecast of precipitation amounts were investigated at the WMO measurement site Haukeliseter. Furthermore, a comparison between retrieved profiles of snow water content and MEPS forecast were carried out. Finally, topographic influence on wind and precipitation next to the impact of horizontal resolution of MEPS were discussed.

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

The ensemble prediction weather forecast system MEPS became operational from November 2016 when it substituted the 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 WMO station Haukeliseter, the additional installed instruments, and the weather forecast model for the Christmas storm. It turned out that 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 extreme storm at Haukeliseter. Transitions of the occlusions and the warm sector were predicted 24 h and 48 h in advance for this particular case study. MEPS simulated too high wind speed (MAE$\leq$10 m s^{-1}) and surface precipitation amount (MAE$\leq$15 mm).

According to public paper the double fence gauge measurement is one of the best surface measurements for snowfall. During winter 2016/2017 additional instruments such as a MRR, MASC and PIP were installed at Haukeliseter. 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 for pristine habits at Haukeliseter. On 22 December 2016, the deviation between CloudSat PSD and double fence gauge was 70 %.

Small differences between observed and estimated snowfall for rimed aggregates (≤ -5 %) shows the importance to choose a priori assumptions correctly to achieve reasonable surface estimates of precipitation amount at the ground.
This followed the use of retrieved estimates of rimed particle models for the continues discussion. 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. On the first three days (21 to 23 December 2016) the average difference was less than +11 % for 12 h and 24 h accumulation. Between 24 and 26 December 2016 an average deviation of +60 % showed. A comparison of 10 % under-catchment of the double fence measurement to the MEPS forecast showed a smaller difference (+40 %) than not taking wind effects into account.

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 timing of liquid precipitation 24 h and 48 h in advance. Comparison between reflectivity profiles and modelled liquid water content showed the accurate simulation of liquid precipitation, in the lower most atmosphere. Both in time and layer thickness.
Less variability was seen for the continues precipitation associated with south-easterlies ($\leq$ 25 %) for initialisations 24 h and 48 h prior. MEPS ensemble members were uncertain about the appearance of snowfall pulsing patterns related to westerlies. The coefficient of variation showed more variability ($\geq$ 50 %) between the ensemble members for the short, pulsed precipitation pattern. Greater variability between the ensemble members for 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 estimated snow water content from MRR profiles is larger than the instantaneous prediction values of MEPS. The deterministic and first ensemble member with 1 h resolution predicted higher snow water content ($\geq 2\,\mathrm{g\,m^{-3}}$) compared to the retrieved values ($\leq 1.5\,\mathrm{g\,m^{-3}}$) during the 2016 Christmas storm.

Although MEPS has a 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, such as high mountains to the west and the south-east of the Haukeliseter station. The one and three hourly ensemble means 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-east winds were often predicted as south-westerly wind (not

along the mountain valley, with south-east direction) on 21 and 23 December 2016. Nevertheless, MEPS is able to relate southerly winds with continous patterns of precipitation.

This study demonstrates how difficult it is to merge different observations to verify a regional model during an extreme event. 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 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 presented results motivate to deal more with the subject of vertical snowfall observations and its comparison to regional weather forecast models.

First and foremost, it is important to investigate more extreme snowfall events during winter at Haukeliseter, whether 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 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 for snowfall prediction for extreme 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

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, so initialisations can start at a more 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 snow for extreme events can be a grand improvement for weather and climate prediction.

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

References

Azad, R. and Sorteberg, A. Extreme daily precipitation in coastal western Norway and the link to atmospheric rivers. *Journal of Geophysical Research: Atmospheres*, 122(4):2080–2095, January 2017. ISSN 2169-8996. doi: 10.1002/2016JD025615. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016JD025615.

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.

Buizza, R., Hollingsworth, A., Lalaurette, F., and Ghelli, A. Probabilistic Predictions of Precipitation Using the ECMWF Ensemble Prediction System. *Wea. Forecasting*, 14(2):168–189, April 1999. ISSN 0882-8156. doi: 10.1175/1520-0434(1999)014<0168:PPOPUT>2.0.CO;2. URL https://journals.ametsoc.org/doi/full/10.1175/1520-0434%281999%29014%3C0168%3APPOPUT%3E2.0.CO%3B2.

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.

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.

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.

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.

Foote, G. B. and Du Toit, P. S. Terminal Velocity of Raindrops Aloft. *J. Appl. Meteor.*, 8(2):249–253, April 1969. ISSN 0021-8952. doi: 10.1175/1520-0450(1969)008<0249:TVORA>2.0.CO;2. URL https://journals.ametsoc.org/doi/10.1175/1520-0450%281969%29008%3C0249%3ATVORA%3E2.0.CO%3B2.

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/.

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.

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.

Hurrell, J. W. Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. *Science*, 269(5224):676–679, August 1995. ISSN 0036-8075, 1095-9203. doi: 10.1126/science.269.5224.676. URL http://science.sciencemag.org/content/269/5224/676.

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.

Kartverket. Norgeskart, November 2018. URL http://www.norgeskart.no/?_ga=2.7509489.291164698.1524482471-1352211079.1517515119#!?project=seeiendom&layers=1002,1015&zoom=4&lat=7197864.00&lon=396722.00.

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/.

Køltzow, M. A. Ø. Spin-up time of MEPS. Private Communication, 2018.

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.

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.

Moore, R. Large-scale dynamics inducing atmospheric rivers and extreme precipitation over norway. unpublished.

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.

Nielsen-Gammon, J. W. A Visualization of the Global Dynamic Tropopause. *Bull.*

Amer. Meteor. Soc., 82(6):1151–1168, June 2001. ISSN 0003-0007. doi: 10.1175/1520-0477(2001)082<1151:AVOTGD>2.3.CO;2. URL https://journals.ametsoc.org/doi/abs/10.1175/1520-0477(2001)082%3C1151:AVOTGD%3E2.3.CO;2.

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.

Petroliagis, T., Buizza, R., Lanzinger, A., and Palmer, T. N. Potential use of the ECMWF Ensemble Prediction System in cases of extreme weather events. *Meteorological Applications*, 4(1):69–84, March 1997. ISSN 1469-8080, 1350-4827. URL https://www.cambridge.org/core/journals/meteorological-applications/article/potential-use-of-the-ecmwf-ensemble-prediction-system-in-cases-of-extreme-weather-events/C63050704CB35CD43BC4E5998A390DDC.

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.

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.

Shi, W., L'Heureux, M., and Halpert, M. Climate Diagnostics Bulletin - December 2016, Near Real-Time Ocean/Atmosphere: Monitoring, Assessments, and Prediction. Technical report, Climate Prediction Center, 2016. URL http://origin.cpc.ncep.noaa.gov/products/CDB/CDB_Archive_pdf/PDF/CDB.dec2016_color.pdf.

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.

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.

Uvo, C. B. Analysis and regionalization of northern European winter precipitation based on its relationship with the North Atlantic oscillation. *International Journal of Climatology*, 23(10):1185–1194, July 2003. ISSN 1097-0088. doi: 10.1002/joc.930. URL https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.930.

Warner, T. T., Peterson, R. A., and Treadon, R. E. A Tutorial on Lateral Boundary Conditions as a Basic and Potentially Serious Limitation to Regional Numerical Weather Prediction. *Bull. Amer. Meteor. Soc.*, 78(11):2599–2618, November 1997. ISSN 0003-0007. doi: 10.1175/1520-0477(1997)078<2599:ATOLBC>2.0.CO;2. URL https://journals.ametsoc.org/doi/abs/10.1175/1520-0477(1997)078%3C2599:ATOLBC%3E2.0.CO%3B2.

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.

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.