Measurements of wind-induced loss of solid precipitation: description of a Norwegian field study

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ABSTRACT

Precipitation measurements have a well-documented and mostly wind-dependent bias which is especially apparent during solid precipitation events. The resulting inaccuracy in precipitation data remains an area of concern in quantifying regional and global climate trends. As a high-latitude country, Norway has many solid precipitation events often accompanied by high wind speeds where the current adjustment functions have only limited validity. The presented study aims at improving the quality of solid precipitation data. In a comprehensive field experiment, precipitation data of standard automatic gauges are compared with data of a reference gauge surrounded by a double fence construction to minimize wind impact. Additional meteorological parameters are measured at the test site, allowing for an in-depth analysis of high-temporal-resolution precipitation data. The goal is to develop new adjustment functions for solid precipitation measurements which account for Norway's typical climate and are suitable for automated measurements. Measurements began in winter 2010/2011 at the alpine test site in southern Norway (chosen after a pre-study in 2009/2010) and will continue for two more winters. In this paper, the test site and its instrumentation are described and preliminary results are presented.

Key words | Double Fence Intercomparison Reference (DFIR), Geonor gauge instrumentation, precipitation measurements, solid precipitation, undercatch, wind-induced error

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INTRODUCTION

It is well known that gauge measurements of precipitation have a systematic undercatch which is mainly dependent upon wind speed (e.g. Sevruk 1989; Groisman & Legates 1994; Peck 1997; Yang *et al.* 1999). The error is substantially higher for snowfall than for rain observations. A large international solid precipitation intercomparison study performed by the World Meteorological Organization (WMO) resulted in a quantification of these errors and a recommended set of empirically derived adjustment formulae for precipitation measurements (Goodison *et al.* 1998). Since the standard gauges in most countries were manual during the intercomparison period, the WMO study was focused on 12-h manual precipitation measurements.

Today, various automated gauges with different wind shield configurations are in widespread use. Rasmussen *et al.* (2012) present an overview of recent field measurements and computer studies investigating the air flow around several gauge and windshield setups.

Most of today's automated gauges provide precipitation data every hour. The adjustment functions from Goodison *et al.* (1998) are not readily applicable to high-frequency measurements. Shorter accumulation periods result in less total precipitation and higher wind averages, both likely to change the adjustment curve. Acknowledging that new adjustment functions need to be determined, Smith & Yang (2010) proposed and assessed a Geonor gauge inside a double fence construction (Geonor-DF) as a new reference for automated measurements. The resulting wind adjustment functions for the Geonor-DF will be used and further tested in this study for determining the reference precipitation.

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Improving the quality of today's and tomorrow's precipitation measurements is necessary to be able to monitor the expected changes in precipitation amount due to climate change with sufficient accuracy. In areas characterized by a large amount of solid precipitation during the winter season (middle and high latitudes), a rise in temperature will be accompanied by a rise of the fraction of annual precipitation falling as rain. As the undercatch error is smaller for rain than for snow, a change only in the precipitation type fraction will cause an ostensible trend in the precipitation amount. Legates (1992) and Førland (1994) suggested this effect. Førland & Hanssen-Bauer (2000) separated the additional virtual precipitation increase from the true precipitation increase and quantified them for data from Spitsbergen. They also estimated that, for future changes, the virtual increase of uncorrected precipitation data would be of the same order of magnitude as the expected real increase in the Norwegian Arctic.

Good-quality precipitation data are also required for hydrological models for catchments with significant winter snow storage. They are typically driven by data from local precipitation gauges and air temperature sensors. A systematic error in solid precipitation measurements during the cold season will propagate through such models and affect the amount of snow stored in the models. This might result in an erroneous prediction of snowmelt spring floods and associated inundation levels in downstream river systems, as well as the production of poor estimates of meltwater inflow into reservoirs used for water supply or hydroelectrical power production. Fassnacht (2004) quantifies the influence of gauge undercatch on the complex relation between the liquid water equivalent of the snowfall (as measured in a precipitation gauge) and the snow water equivalent (the liquid equivalent of the snow present on the ground) and shows its significance compared to other important factors such as sublimation and wind transport.

Snowpack stratigraphy modeling can provide the actual avalanche risk of a snowpack and is used for avalanche warning methods. Accurate solid precipitation measurements are indispensable for reliable avalanche warnings (Vikhamar-Schuler *et al.* 2011).

The authors have initiated an extended field experiment (Wolff *et al.* 2010) at Haukeliseter, a mountain plateau in southern Norway. According to the recommendations from Goodison *et al.* (1998) and Smith & Yang (2010), the test site at Haukeliseter is equipped with an automatic precipitation gauge and an Alter wind shield inside a double fence (DF) construction which diminishes the influence of wind on the measurements. The reference precipitation gauge inside the DF is a Geonor T200-BM (1,000 mm, three transducers). The data from the reference will be compared with several precipitation gauges (three of type Geonor in different configurations and one Pluvio2; see Table 1). Numerous additional meteorological parameters will be monitored to support the analysis.

The experiment aims to produce the development of a new set of adjustment functions which are suitable for Norwegian climate and thus improve the data quality of Norwegian precipitation measurements. In addition to providing an improvement in regional climate analysis and models, the higher-quality precipitation data will provide a better database for budget and production calculation of Norway's hydro-electrical power plants.

This paper describes the observation site and its instrumentation. Preliminary results of the analysis of the data from the first winter period (February–April 2011) are discussed and plans for the final analysis after completion of the study (2013) are outlined.

OBSERVATION SITE

The test site at Haukeliseter, shown in Figure 1, is located in a relatively flat area at 990 m altitude close to the European Road E134 in the municipality Telemark (59.81 °N, 7.21 °E); see overview and detail map in Figure 2. Figure 3 shows a schematic overview of the test site and its instrumentation. During winter 2010/2011, three similar precipitation gauges (type Geonor with three transducers and Alter wind shield) were placed along a line 90 degrees to the dominant wind direction with a distance of 15 m between them. To measure true precipitation, the gauge in the middle was surrounded by a DF construction. The specifications of the DF are the same as for the WMO-recommended Double Fence Intercomparison Reference (DFIR) described by Goodison *et al.* (1998). The orifice height of all gauges is 4.5 m above the ground to ensure enough clearing below, even when maximal expected snow depth of 2–3 m is

Table 1 | Description and status of instrumentation at test site

Sensor	Location	Parameter	Status
Geonor T200-BM (1,000 mm, 3 str) Alter wind shield	North sensor	Accum. precipitation	Installed, data since 01/2011
Geonor T200-BM (1,000 mm, 3 str) Alter wind shield	South sensor	Accum. precipitation	Installed, data since 01/2011
Geonor T200-BM (1,000 mm, 3 str) Alter wind shield	Double fence	Accum. precipitation, reference	Installed, data since 01/2011
Pt100	North sensor	Geonor temperature	Installed, data since 02/2011
Pt100	South sensor	Geonor temperature	Installed, data since 02/2011
Pt100	Double fence	Geonor temperature	Installed, data since 02/2011
Pt100	Met. mast	Air temperature	Installed, data since 01/2011
Gill WindObserver extreme	Double fence	Wind inside double fence, orifice height	Installed, data since 02/2011
Young Wind Monitor-SE	North sensor	Wind north sensor, orifice height	Installed, data since 02/2011
Young Wind Monitor-SE	South sensor	Wind south sensor, orifice height	Installed, data since 02/2011
Gill WindObserverII	Met. mast	Wind 10 m height	Installed, data since 02/2011
Vaisala HMP155	Met. mast	Relative humidity	Installed, data since 02/2011
Thies precipitation sensor	Double fence (4 m)	Precipitation yes/no	Installed, data since 03/2011
Thies precipitation sensor	Met. mast (8 m)	Precipitation yes/no	Installed, data since 03/2011
Vaisala PWD21	Met. mast (6m)	Precipitation type, present weather	Installed, data since 03/2011
Thies LPM extended heating	Met. mast (6 m)	Precipitation type, present weather	Installed, data since 05/2011
Ott Parsivel	Met. mast (6 m)	Precipitation type, present weather	Installed, no data
AADI snow depth sensor	North sensor	Snow depth	Installed, data since 11/2011
AADI snow depth sensor	South sensor	Snow depth	Installed, data since 12/2011
Videocamera ACTI CAM-6630	Met. mast	Photo monitoring	Installed, pictures since 02/2011
Geonor T200-BM (1,000 mm, 1 tr) Alter wind shield	Southwest extension	Accum. precipitation	Installed, data since 03/2012
Ott Pluvio 2, Alter wind shield	Northeast extension	Accum. precipitation	Installed, data since 03/2012
Thies 3D Ultrasonic Windsensor	Upstream mast	Horizontal and vertical wind	In progress
5 Thies precipitation sensor	Upstream mast	Precipitation yes/no	Installed, data since 03/2012

Figure 1 | Photograph of the test site on Haukeli (990 m a.s.l.), southern Norway.

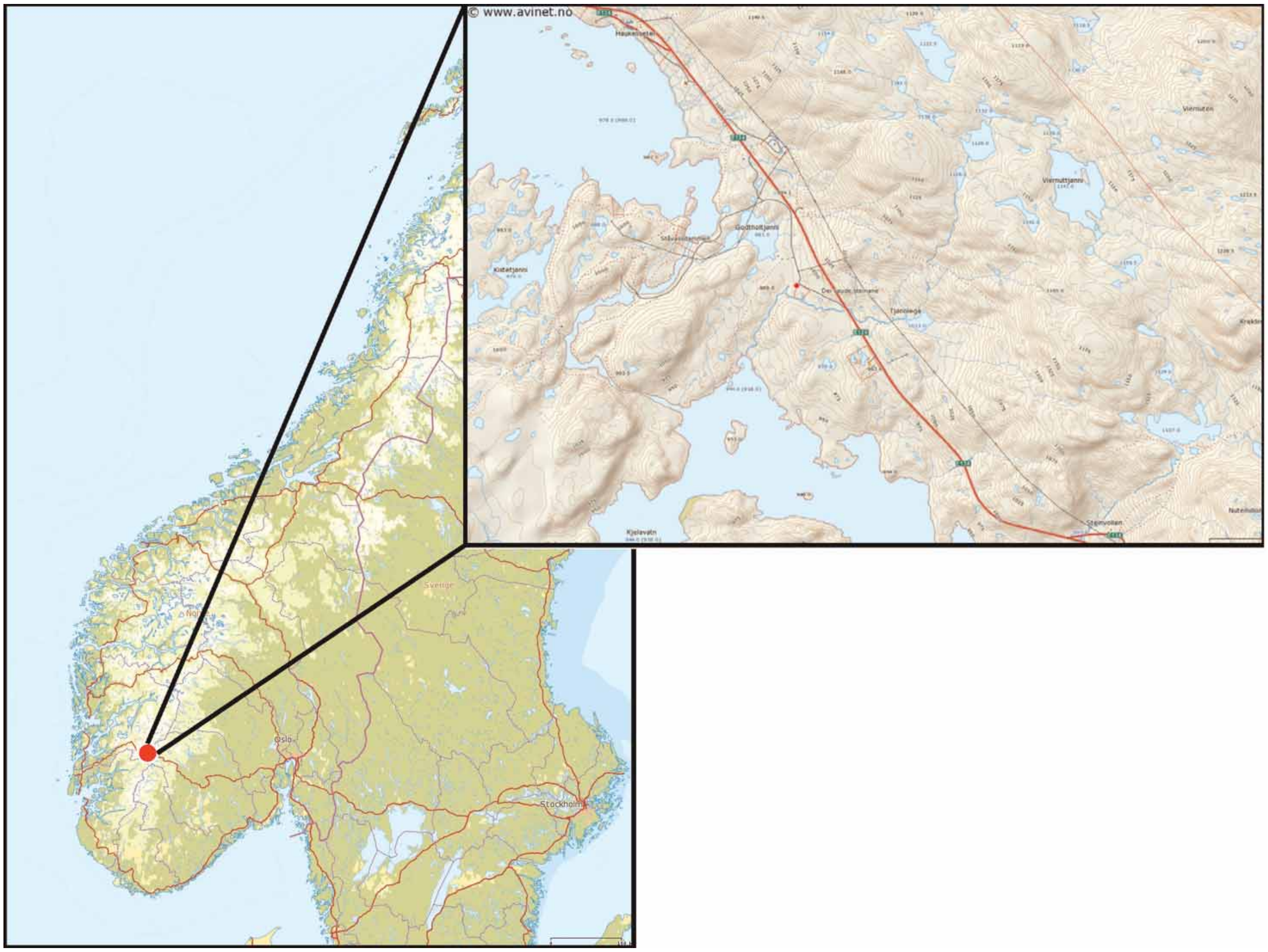

Figure 2 | Localization of the test site, topographic map of Norway and detailed view.

reached. Furthermore, this prevents drifting snow from reaching the orifice.

At each precipitation gauge a wind sensor measures wind speed and direction. A temperature sensor is directly mounted on each of the gauges and measures the temperature of the orifice. The orifice temperature is used for controlling the heating system, which prevents snow blocking the precipitation sensor. At a close-by meteorological mast, additional data are recorded: 10 m wind, 2 m air temperature and humidity.

After the first winter of measurements, new sensors were installed at the test site during summer 2011. Further extensions are planned before winter 2012/2013. Two additional precipitation sensors were installed, extending the line of gauges on both sides. The precipitation gauge furthest to the south was placed a few meters offline as a few situations (not shown) suggested a possible shadowing effect of the closest south gauge by the DF. Snow depth sensors were mounted at two locations. The meteorological mast was equipped with two disdrometers and one forward scatter meter. All three instruments are so-called ‘present weather detectors’ as they determine precipitation type and intensity. A camera was installed to monitor sensor status and identify possible problems and error sources as icing or snowcapping. An additional meteorological mast upstream was also equipped with precipitation detectors (yes/no type) at five different heights between 2 and 10 m in order to detect periods of drifting snow. Table 1 gives the status of the instrumentation on site. Two new wind sensors at the site (inside DF and on upstream mast, both at 4.5 m altitude) will also

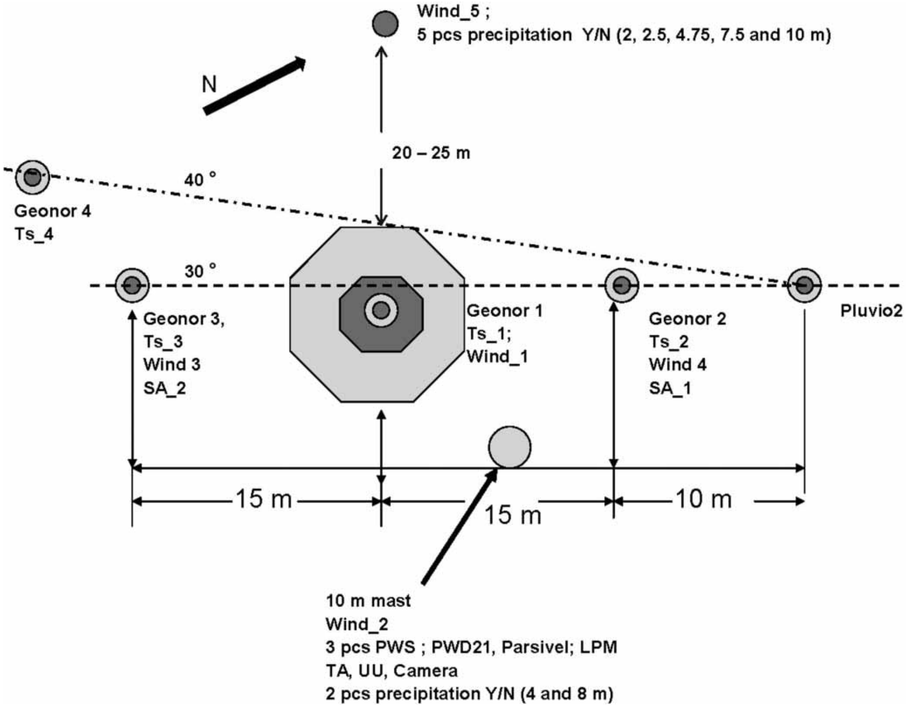

Figure 3 | Schematic illustration of the test site and its instrumentation. The whole test site consists of c. 4,500 m^2 flattened area.

measure the vertical component of the wind (planned to be operational before the winter season 2012/2013).

All data are recorded at a time resolution of 1 min. Data are transmitted hourly via a broadband internet connection from the local storage to a server for further processing. Data are manually checked for quality on a daily basis, and all measured parameters feature stability and high regularity.

PRELIMINARY RESULTS AND DISCUSSION

The homogeneity of the test site was assessed by Wolff *et al.* (2010) during a pre-study in winter 2009/2010 with data from two similar precipitation gauges and additional wind measurements at each sensor. Figure 4(a) graphically compares the recorded precipitation measurements. Only events with more than 0.5 mm accumulation in 12 h were counted. The points are evenly spread around the one-to-one relationship, demonstrating homogeneity. The comparison of the wind measurements from both sensors in Figure 4(b) shows a similar result. Wolff *et al.* (2010) used a set of formulae presented by Goodison *et al.* (1998) to quantify the homogeneity of the site and the results testified a sufficient homogeneity. The new installations which accompanied the extension to a fully equipped test site, however, might have changed the homogeneity of the site. A renewal of the homogeneity analysis, taking the changes at the test site into account, is therefore required. A corresponding analysis of the first winter's data is currently in progress and is meant to continue over the whole course of the study.

Preliminary analysis was carried out for a data period from February to April 2011. Most precipitation was snow in February and March, whereas April precipitation was dominated by rain and mixed precipitation. One hundred and seventy-five events with duration 10 min or more and 21 events with duration 60 min or more were detected during winter 2011. Precipitation event detection, however, could only be based on the 5-min running average accumulation in the gauges, as other support parameters (from precipitation detectors or present weather sensors) were not available during that period. Noise analysis of the precipitation data resulted in a minimal detectable

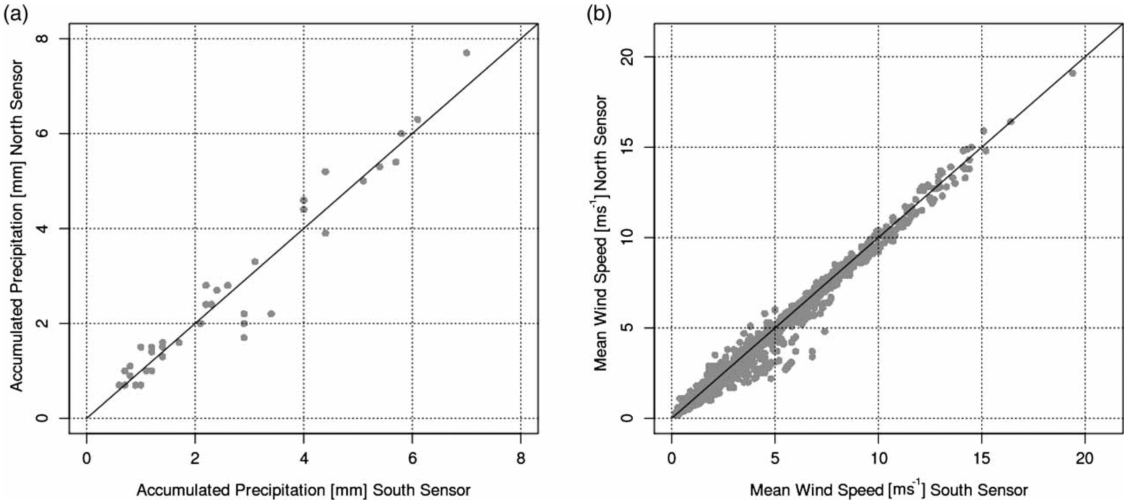

Figure 4 | (a) Comparison of precipitation events (with more than 0.5 mm in 12 h) and (b) wind measurements from north and south sensor at Haukeliseter during the pre-study in winter 2009/2010.

precipitation amount of 0.12 mm and the threshold for a precipitation event was set conservatively to 0.15 mm in 10 min. The duration of a precipitation event was determined by the amount of continuous 10-min periods with growth greater than the threshold.

Very light precipitation events with significant precipitation over a long period or the typically lighter onset of a precipitation event are consequently not detected. The event identification will be improved for the dataset from winter 2011/2012, including additional parameters such as yes/no sensors, present weather detectors and a camera in order to detect more low-intensity events (especially during cold periods). This work is currently underway. Tests of other time intervals will also be performed.

Total accumulation from February to April 2011 was 336 mm in the Geonor-DF, whereas South and North sensor accumulated only 200 ± 8 mm which is about 40% less than the reference (Figure 5).

Precipitation differences between the Geonor-DF and the mean of the two gauges outside based on 10- and 60-min events are plotted in Figure 6 versus wind speed for different temperature regimes. Air temperature was used as a rough indicator for precipitation type as direct measurements of precipitation type did not exist for the first winter. Results show the relationship between wind speed and precipitation loss. As expected, the undercatch is especially large during low air temperatures when only solid precipitation occurs.

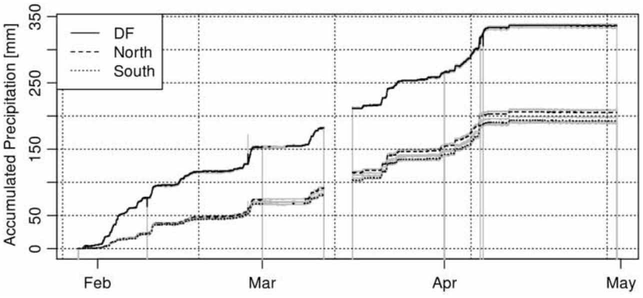

Figure 5 | Total accumulated precipitation of precipitation gauges North (N), South (S) and inside DF for the period February–April 2011.

Initial analysis indicates that the current adjustment formulae as described by Hanssen-Bauer *et al.* (1996) are not applicable to solid precipitation incidents accompanied with high wind speed. Table 2 lists the results for two precipitation events. The Geonor-DF reported around three to five times more accumulated precipitation than the unprotected gauges. The application of the adjustment functions significantly overestimated the reference measurements in both cases.

A more thorough analysis of the limitations of the current adjustment functions and the derivation of a new set will however require a larger dataset than so far available. Events need to be characterized by average and variation of meteorological parameters which might influence the

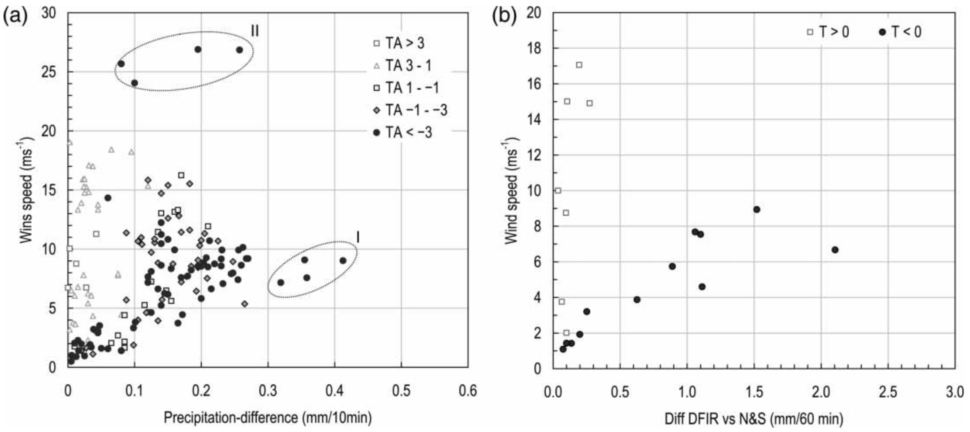

Figure 6 | (a) Precipitation difference in mm per 10 min between Geonor-DF and mean of both standard automatic precipitation gauges outside versus 10 m wind speed for different temperature regimes. Two groups of outliers are encircled: (1) showing events with high precipitation intensity and (2) probable snow drift events. (b) Precipitation difference in mm per 60 min between Geonor-DF and mean of both standard automatic precipitation gauges outside for two temperature regimes: negative temperature (filled circles) and positive temperature (open squares).

Table 2 | Statistics from two incidents with relatively stable wind conditions (direction and speed). Precipitation adjusted according to formulae of Table 6.1 in Hanssen-Bauer *et al*. (1996). Wind speed values in parentheses are minimum and maximum in the period

		Wind speed (m s^{-1})			**Measured precipitation (mm)**			**Adjusted precipitation (mm)**	
Period	**Temp. (°C)**	**DF gauge**	**South gauge**	**North gauge**	**DF gauge**	**South gauge**	**North gauge**	**South gauge**	**North gauge**
30.11.11 04:00–13:00 UTC	−1.8	1.2 (1.0, 1.4)	9.3 (8.0, 12.2)	9.1 (8.0, 11.8)	6.4	2.1	2.0	8.9	8.2
18.01.12 15:00–24:00 UTC	−3.3	1.0 (0.8, 1.4)	11.3 (10.0, 14.8)	11.9 (9.6, 14.6)	6.7	1.2	1.3	7.8	8.4

catch efficiency of the precipitation sensor as wind speed, wind direction, temperature, precipitation type and intensity. Statistical analysis will be resumed in late winter 2011/2012 and continuously updated with the increasing dataset over the project period.

CONCLUSIONS

In cooperation with Statkraft AS and other Norwegian energy companies, the Norwegian Meteorological Institute has commenced an initiative for the improvement of solid precipitation measurements. A pre-study attested the chosen test site in the southern Norwegian mountains sufficient homogeneity.

Instruments for the main period of the study were installed during autumn and winter 2010. The test site has been operational since February 2011, recording 1-min data from two Norwegian standard gauges (Geonor and Alter wind shield) and a reference gauge in a DF construction, as well as from several additional meteorological instruments. The site was extended during the summer seasons of 2011 and 2012. All new instruments are expected to be fully operational during the winter 2012/2013.

As expected, both comparison gauges measure less precipitation than the reference gauge. Both the single-event analyses and the limited statistical examinations based on data from February to April 2011 reveal a significant correlation between the recorded undercatch and the wind speed, as well as the air temperature, reflecting the precipitation type. A complete statistical analysis needs more data than currently available and will be resumed after winter 2011/2012. The extended suite of auxiliary instruments will also give additional valuable information. The precipitation detectors (yes/no type) will improve the event identification. The precipitation type detectors will give a far more accurate precipitation type classification compared to the use of air temperature as indication. The increased number of gauges outside the DF will allow for a more thorough homogeneity analysis and possibly reveal shadowing effects of the construction under certain circumstances (i.e. special wind direction). These findings need to be included in the complete analysis. We expect to gain a solid database over the course of the study (currently prospected over three winter periods in total) for an in-depth analysis and the development of new adjustment functions for solid and mixed precipitation.

The future use of the test site after the completion of this experiment is currently under discussion. As well as the excellent possibility for further precipitation studies, the site has the potential to act as a long-term reference station for true precipitation and may contribute to:

- control and further improvement of the new adjustment functions;
- long-term monitoring of actual precipitation changes in a high-latitude alpine environment; and
- model verification of precipitation amount, precipitation type and wind.

The Norwegian Meteorological Institute is also investigating possibilities of the test site actively participating in the WMO Intercomparison for Solid Precipitation Experiment (WMO-SPICE) proposed by Nitu & Wong (2010). The official start of WMO-SPICE is scheduled for 15 November 2012.

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