Snowfall Measurements in the Amundsen and Bellingshausen Seas, Antarctica

KATHERINE C. LEONARD[1] AND RICHARD I. CULLATHER[1]

ABSTRACT

Unique *in situ* oceanic snowfall measurements in high southern latitudes are presented from two research cruises to the Ross, Amundsen, and Bellingshausen Seas aboard the *R/V Nathaniel B. Palmer* in 2007 (NBP0702 and NBP0709). The number of falling snowflakes passing through the beam of a photoelectric particle counter mounted approximately 30m above sea level was continuously logged during these cruises, and is compared here with model forecast precipitation and with observations of accumulation on the adjacent sea ice. The model precipitation is from daily operational model output of the European Centre for Medium-Range Weather Forecasts (ECMWF). The daily total precipitation measured by the particle counters and calculated for each cruise using two different size distributions is compared with the ECMWF predictions. Synoptic storms led to significant precipitation events during both cruises, and there is good correspondence between the timing of the related maxima in the observed and forecast time series. Overall, the correlations were r=0.19 for NBP0702 and r=0.69 for NBP0709. Calculations of the precipitation mass flux based on the observed snow counts are strongly dependent on the effective size distribution of the precipitating snow, a poorly known variable for this region. The best fit between the precipitation amounts from the ECMWF forecasts and the measured flux of snowflakes was obtained for the February-March cruise NBP0702 in the Ross and Amundsen Seas using an assumed a gamma-distribution of the particle sizes with a mean radius of 25 µm. During the September-October cruise NBP0709 to the Bellingshausen Sea, the ECMWF forecast amounts were better fit by a size distribution with a larger mean radius. An independent measure of changes in snow depth on an adjacent sea ice floe during cruise NBP0709 found approximately one-third as much accumulation on the sea ice as was forecast to precipitate there, suggesting loss by wind transport. The method presented here may prove useful for validation of model forecasts, and information regarding the timing and quantities of freshwater input into the Southern Ocean. The data and methods presented here may be useful in distinguishing among various models' performance in predicting the timing and relative intensity of precipitation in these regions.

Keywords: snowfall; precipitation measurement; Antarctica

INTRODUCTION

Precipitation over the Antarctic continent and Southern Ocean principally falls in the form of snow, with rare rain at some northerly locations over the Antarctic Peninsula and oceans, and pervasive clear-sky precipitation or "diamond dust" at high latitudes over the ice sheet. Falling snow is quickly entrained in and redistributed by the wind, rendering accurate measurement of precipitation extremely challenging. Atmospheric models and remote sensing techniques may be used to explore the seasonal and interannual variability in precipitation (Cullather et al., 1998;

[1] Lamont-Doherty Earth Observatory of Columbia University, 61 Route 9W, Palisades, NY 10964.

Monaghan et al., 2006), but validation remains elusive. Accumulation– the net of precipitation minus wastage terms– is measured on short (daily to monthly) timescales at manned stations (e.g., Gow, 1965) and through snow pits, firn cores, shallow ice-penetrating radar surveys, and other proxy methods on annual and longer timescales (Eisen et al., 2008). These point measurements have been used in various spatial interpolations of accumulation rates over the Antarctic (Vaughan et al., 1999; Arthern et al., 2006; Helsen et al., 2008), which have then been used as validation for precipitation estimates, assuming the wastage terms are small.

Snowfall over the ocean surrounding the Antarctic continent is expected to be higher than over land (Bromwich, 1988; King and Turner, 1997), but is even more difficult to validate. Nevertheless, a quantitative assessment of oceanic snowfall is important for a variety of research equstions, including the attribution of freshening trends in coastal Antarctic waters (e.g., Jacobs et al., 2002) and understanding sea ice morphology and dynamics. The amount of snow on sea ice surfaces in the Antarctic is frequently measured or estimated, but is not necessarily representative of the local precipitation history. The Antarctic Sea Ice Processes and Climate (ASPeCt) volunteer sea ice observation program for Antarctic research vessels has amassed over 20 years of observations of sea ice concentrations and types, and estimates of the depth of snow present on the sea ice at the time of sighting (Worby and Allison, 1999). A recent compilation of these results (Worby et al., 2008) presented average snow depths over different sectors of the Southern Ocean that are often substantially lower than accumulation values on the adjacent land. Among the reasons for this discrepancy is the tendency for research vessels to seek out navigable rather than representative paths through heavy, snow-laden sea ice, the export of snow from the region that it precipitated in by migrating sea ice floes, the formation of "snow ice" when heavy snowfall weighs down an ice floe and allows seawater to flood the snow (Fichefet and Morales Maqueda, 1999), and the inherent storminess of the Southern Ocean, which may cause much of the snow that falls on ice to be blown off into open-water leads or piled up around pressure ridges (Eicken et al., 1994; Massom et al., 2001).

This problem is particularly severe along the West Antarctic coastline in the Amundsen and Bellingshausen Seas, an area that some researchers suggest is experiencing a warming-induced increase in precipitation (van den Broeke et al., 2006; Massom et al., 2008; Thomas et al. 2008). Observations of snow depths on sea ice or land from this region are sparse and isolated in time. A series of research cruises in the Amundsen and Bellingshausen Seas during the early 1990s found average snow depths of 0.1 to 0.3 meters (Massom et al., 2001), while an early 2007 cruise to the same area found an average of 0.55 m of snow on Amundsen sea ice.

Precipitation at a point can be defined as the mass passing through a measurement area in some time interval. This can be discretized over a particle size distribution with size intervals *i* in a manner similar to that proposed by Hogan (1993):

$$P = \sum_i N_i m_i v_i \tag{1}$$

where P is precipitation as snow-equivalent rate, N is the number of particles within a size class, m is the average mass of a particle in that class, and v is the fall velocity of such a particle.

Point measurements of precipitation are commonly used to verify rain amounts in temperate regions, typically using devices that physically trap the precipitating particles. Such devices are far more effective at capturing rain than snow, which may be transported into and then out of the instrument by even very slight gusts of wind, so gauges for measuring solid precipitation are normally constructed with aerodynamic shielding of some variety (Groisman and Legates, 1994). The under-catch problem is particularly severe for fine snow, limiting the use of such devices in regions with extreme weather conditions or small particle sizes of precipitating snow. In these situations, disdrometers and other electronic devices that measure either the number Nv or mass flux mv of precipitation are often used to record falling precipitation. Disdrometers for recording snowfall are typically optical devices that measure both the size distribution and number frequency of falling snowflakes. In more advanced designs, even the distribution of grain shapes can be documented (e.g. Barthazy et al. 2004). Unfortunately, due to instrument optics, very fine snow in the size ranges reported for Antarctic precipitation is not well resolved by these devices, which are also very sensitive to vibration of their mounting platforms.

Here, ship-based measurements of the frequency of precipitation occurring in the Ross, Amundsen, and Bellingshausen Seas during two research cruises in 2007 are presented in comparison to forecast precipitation from a numerical weather prediction model. The ship-based measurements were acquired using simple optical devices that register the frequency with which snow or ice particles pass through a narrow beam of infrared light.

METHODS / STUDY CONFIGURATION

The presence or absence of falling precipitation was recorded continuously during two research cruises in marginal seas of the Southern Ocean during 2007. As shown in Figure 1, cruise NBP0702 aboard the *R/V Nathaniel B. Palmer* (NBP) began on 3 February 2007 at McMurdo Station, traversed the Ross, Amundsen, and Bellingshausen Seas and concluded in Punta Arenas, Chile on 26 March. It may be seen that for much of the cruise, NBP0702 remained in relatively close proximity to the continent while taking oceanographic station observations in front of ice shelf fronts throughout the Ross and Amundsen Seas. Cruise NBP0709 aboard the same ship began on 1 September and ended on 31 October in Punta Arenas. From 29 September to 23 October, the *Palmer* drifted with and studied processes on and under a large sea ice floe in the Bellingshausen Sea near Peter the First Island (68° 50' S, 90° 35' W), as part of the "Sea Ice Mass Balance in Antarctica" (SIMBA) International Polar Year project.

Figure 2 shows the two different photoelectric sensors used to measure snowfall during these two cruises. The two sensors have many characteristics in common, and were compared in a side-by-side deployment measuring drifting snow on the McMurdo ice shelf in the austral summer of 2006-2007 (manuscript in preparation). The particle counter used during NBP0702 was built at York University (Savelyev et al., 2006) following the design of Brown and Pomeroy (1989). The smallest particle diameter observable using this device is estimated to be between 30 μm (P. Taylor and S. Savelyev, pers. comm., 2006) and 45 μm (Brown and Pomeroy, 1989), but the operational minimum detectable size is dependent on wind speed, grain morphology, and many other constraints, and is likely coarser. During NBP0709, a commercially available photoelectric sensor manufactured by the Wenglor Corporation was used, which has a minimum observable diameter somewhere between 40 (manufacturer-specified) and 100 μm (S. Savelyev, pers. comm.,

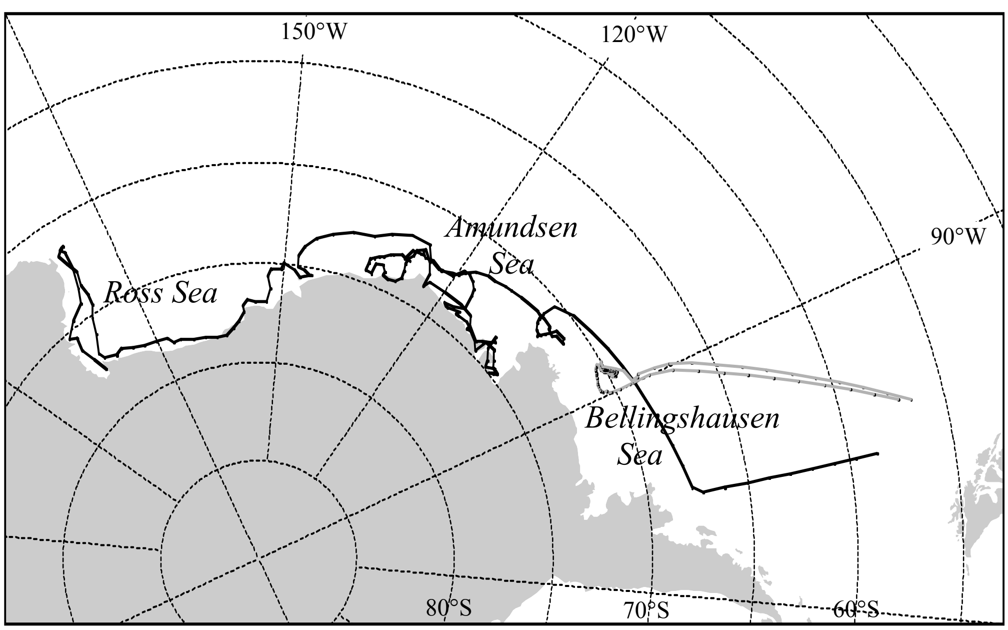

Figure 1. Shiptracks for cruises NBP0702 (black line), and NBP0709 (grey line) near West Antarctica.

Figure 2. (left) *R/V Nathaniel B. Palmer*. The observation tower on which the two particle counters (right) were installed is on the right in this photo, above the bridge. Photographs of the particle counters were taken from the port-side of the observation tower roof facing forward, showing the mounting arm and particle counters pointing towards the bow, in alignment with the ship's long dimension. During cruise NBP0702 the particle counter shown on the upper right was on loan from York University. The counter shown at lower right was manufactured by the Wenglor Corporation, and was used during cruise NBP0709.

2007). Over the course of a month's simultaneous recording on the McMurdo Ice Shelf, the York counter measured at least two times more particles on average than the Wenglor counter did, verifying that the York counter is more sensitive to the more-numerous fine-grained portion of the snow particle size spectrum. This is largely due to the different volumes of air sampled by the two counters. The York counter measures a cylindrical region that is 20 mm long with a 0.15 mm radius. The Wenglor's beam is 30 mm long, with a radius of 0.3 mm. These correspond to volumes of 1.4 mm^3 and 8.5 mm^3 respectively, and the greater observed volume of the Wenglor counter is responsible for its coarser threshold, as is theoretically explained by Brown and Pomeroy (1989).

The instrument positioning and data recording protocol were identical for the two cruises. The counters were mounted approximately 30 m above the water on an arm protruding forward from the top of the lookout tower on the *Palmer* (Figure 2) with the measurement opening upward, positioned horizontally with the beam parallel to the ship's long axis. This location was determined to be the most likely to encounter representative air parcels on the ship, and least likely to experience aerodynamic interference from the ship. The counters both emit near-infrared light from one side of the instrument, and continuously check for the arrival of that light at a detector on the opposite side of the measurement interval. Data was recorded at 10-second intervals, including the total number of flakes passing through the beam during that time, the maximum number detected during one second, the average per second for a consistency check of the total value, and the voltage and temperature of the data logger to monitor system health. The regular meteorology data collection systems onboard the *Palmer* include two anemometers mounted at approximately 35 m above waterline, temperature, relative humidity, and air pressure at roughly 20 m above sea level, and an assortment of radiometers in various locations. These are logged at high frequency, as is the ship's navigational information, and are combined for each cruise in a quality-checked data set of one-minute average values following the Joint Global Ocean Flux Study (JGOFS; Knap et al., 1994) protocol.

Operational precipitation forecasts were compared with the shipboard total particle count for each day of the two cruises. Model output of the European Centre for Medium-Range Weather Forecasts (ECMWF; Klinker et al., 2000) has been widely used in polar research and has been demonstrated to correspond well with the timing of precipitation occurrence over Arctic sea ice during the SHEBA experiment (SHEBA: Surface Heat Budget of the Arctic; Beesley et al., 2000). These fields were obtained from the National Center for Atmospheric Research (NCAR) at a horizontal resolution of 1.125° × 1.125° and are an accumulation of the 12 to 36 hour period of the daily forecast that commenced at 12:00UTC on the previous day. Daily total counts of snow particles are compared with the ECMWF precipitation for the grid cell the ship occupied at 12:00UTC during each day of the cruise. In addition to the forecast precipitation, the instantaneous 6-hourly ECMWF analysis of air temperature, pressure, and near-surface winds were compared to the JGOFS meteorological data using the ship location to identify the corresponding gridded values. The instantaneous values correspond well between the ship and the model, supporting the decision to compare ship-based measurements with the ECMWF forecast precipitation.

RESULTS

The continuous record of the number of snowflakes *N* recorded passing through the ship-mounted particle counter beam every ten seconds is presented in Figure 3. Unphysical high counts are rare, occurred only on NBP0702, and are interpreted to be temperature-related instrument errors, possibly due to rime formation on the electronic components.

Figure 4 shows the same data, cleaned of anomalously high counts and re-sampled onto a daily timescale for comparison with the forecast precipitation values. Several discrete storms are obvious in the ECMWF forecast values, and qualitatively appear to be well-represented by peaks in the particle count on those days on the ship.

The measurement program and sensor mounting arrangement were initially designed as a trial study to detect snow blowing off of the Ross and other West Antarctic ice shelves during cruise NBP0702. The ship traversed the front of the Ross Ice Shelf on 8-14 February, frequently

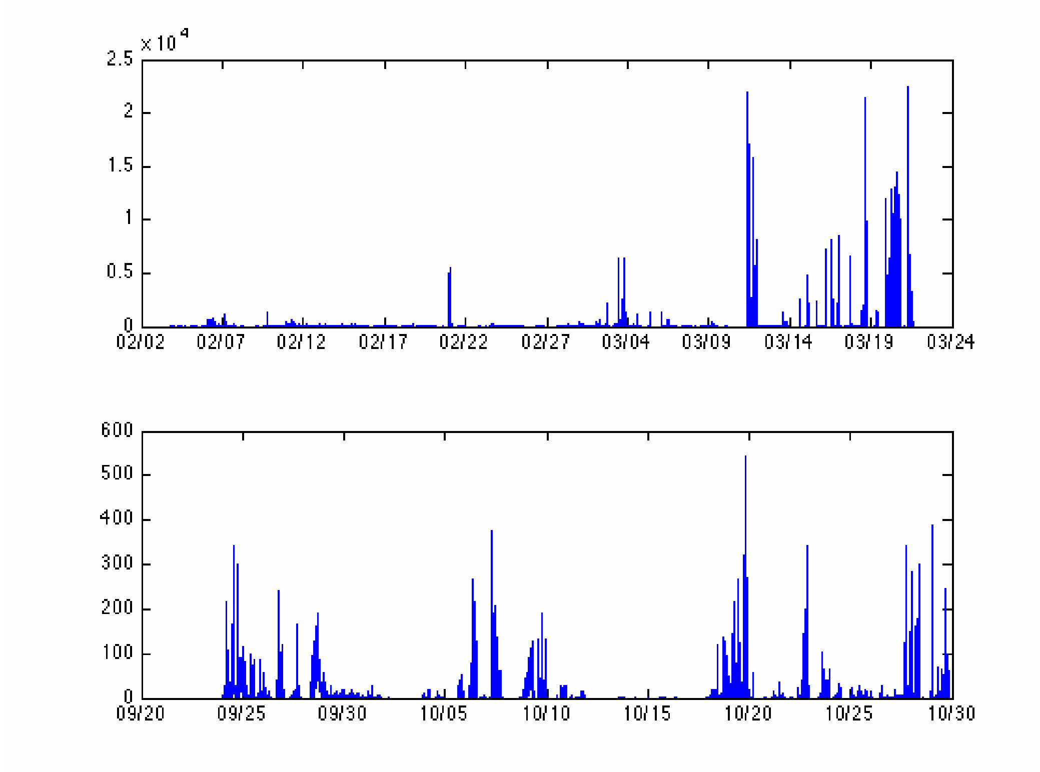

Figure 3. The uncorrected total snow counts per minute during cruises NBP0702 (top) and NBP0709 (bottom). The high counts towards the end of the upper record followed instances of riming of the particle counter, and are interpreted as errors.

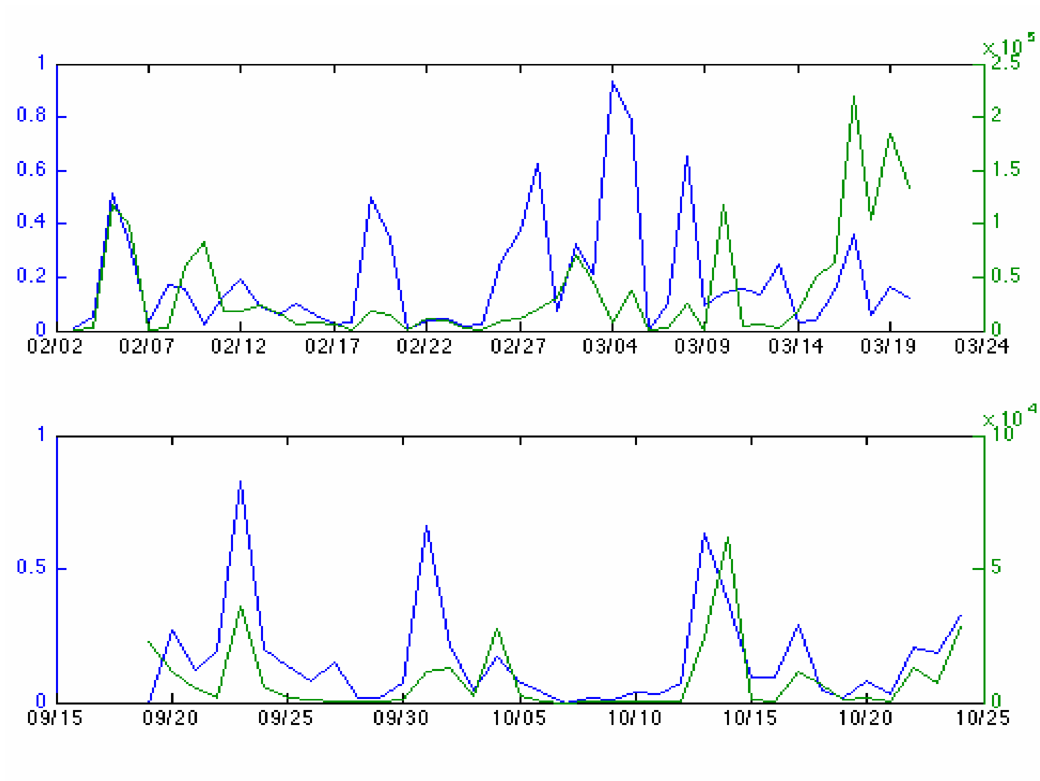

Figure 4. ECMWF operational forecast precipitation (cm water equivalent, in blue) and measured snow counts per day (in green) during cruises NBP0702 (top) and NBP0709 (bottom). The lower panel demonstrates the good correspondence between the forecast and measured synoptic precipitation events while the *Palmer* was drifting with sea ice in the western Bellingshausen Sea.

encountering such north-bound blowing snow, leading to the visually poor correlation between the forecast precipitation and snow counts during that interval. An additional difficulty with the record from the NBP0702 cruise was the ship's rapid progress through the water, as has been observed in most attempts to measure precipitation on ships (Yuter and Parker, 2001). Snow particles travel with the wind, so at wind speeds comparable to or less than the ship's speed, their paths through the air are parallel to the ship's long axis, and do not intersect the particle counter's beam. To a lesser degree this problem also occurs at high wind speeds if the ship's long-axis is directly parallel to the wind direction, but the greater turbulence experienced during high winds in combination with the disruption to the wind-field caused by the ship produces enough irregular particle transport paths that some snow will cross the counter's beam under any high-wind situation. During cruise NBP0709 the ship spent most of its time far from ice shelves drifting slowly with the sea ice, minimizing these problems.

DISCUSSION

Determining the area-averaged water-equivalent mass flux of precipitating snow from a point measurement of number flux is non-trivial, and heavily dependent on knowledge of the particle size distribution and crystal habits of the snow. This problem has been partially-resolved for use of disdrometers in climates with snow diameters greater than 100 µm. Because most physical measurements of the size distributions of snowflakes have been made in temperate climates where snowflakes are relatively large (e.g. data and references contained in Ohtake, 1970, or Pruppacher and Klett, 1997), it is challenging to extrapolate these relationships to other environments. A lack of information on the crystal habits and size distribution of the precipitating snow during the cruises discussed here means that the crystal habit – dependent size to mass relationships of Hogan (1993) may not be confidently applied to the data, although such extrapolations might be appropriate in future studies where these variables are more carefully documented.

Unfortunately rare, *in situ* measurements of falling snow in Antarctica indicate that the mean particle size of precipitation is much smaller than is typically found in more temperate regions or in the Arctic. Walden et al. (2003) report a mean size of 24 µm for precipitating snow at the South Pole, and Lachlan-Cope et al (2001) found similarly fine-grained sizes during snowfall events on the western Antarctic Peninsula. Small particles are both difficult to capture and hard to preserve, thus it is possible that the true geometric mean size of falling snowflakes in Antarctica is smaller still. While snow that has already landed on an ice or snow surface is far simpler to sample and analyze, the size distribution of falling snow is not well represented by the range of sizes of snow found on the ground surface (mean of 100-200 µm across Antarctica; Gay et al., 2001), because small particles rapidly disappear in favor of larger snow particles when the two are in contact (Legagneux et al., 2004).

If a theoretical particle size frequency distribution with a mean radius of 25 µm can be deemed appropriate for snowfall over the ocean in close proximity to Antarctica (perhaps unreasonable, as larger sizes were found on the Ross Ice Shelf by Hogan, pers. comm., 2008), then the counts N measured by the two photoelectric sensors represent 43 percent (York, assuming a minimum observable diameter of 50 µm) and 9 percent (Wenglor, assuming a 100 micron minimum) of the total number of snowflakes that passed through the sampled volumes of air. When the geometric size distribution is re-formulated in terms of particle volume or mass, the median size shifts to a larger value (a radius of 57 µm, in this case), thus both counters employed in this study would detect most of the mass of such a size distribution of snow precipitating through their beams (95 percent and 62 percent, respectively).

Many factors besides the poorly-constrained particle size distribution of snow could lead to under-counting of precipitation using photoelectric devices such as these. The difficulties arising from adverse relative wind direction due to ship motion have already been mentioned. In cases where ship speed is insignificant relative to wind speed and the angle of the wind is neither parallel nor perpendicular to the instrument's beam, some particles will pass through the beam, but undercounting will occur relative to the number that might have been counted had the wind blown the particles directly through the beam. Riming of the detector in heavy fog conditions during NBP0702 led to an absence of precipitation measurements during observed snowfalls on at least two occasions. Turbulence due to the ship's superstructure and air-flow patterns around the superstructure could prevent snowflakes from passing through a particle counter. Spatial and temporal variability in the number of flakes passing through the beam of the particle counter are an additional complication, since snowfall is not a uniform process, and is additionally complicated by gusty winds.

Given these uncertainties, an estimate is made of the mass transport P based on the number flux Nv of snowflakes passing through the known cross-sectional area of the detector's field of view. Using a particle size probability distribution that is discretized for diameters greater than the photoelectric sensor's lower size threshold yields a set of size-distributed bins of observed snow. The average mass of a particle within the size distribution is assumed to be represented as a sphere with a fixed density. Substituting these assumptions into equation (1) gives the precipiation rate as follows (Rogers and Yau, 1989):

$$P = \sum_i \frac{N_i \left(\frac{4}{3}\pi r_i^3\right)\left(\frac{\rho_{snow}}{\rho_{water}}\right)}{\left(\frac{\pi}{4}\delta + r_i\right) L} \qquad (2)$$

where P is the water-equivalent (w.eq.) precipitation rate, r_i is the average radius for bin *i,* δ and L are the fixed diameter and length of the particle counter's beam, and ρ_{snow} is estimated here as 450 kg m^{-3}. The undetected (fine) fraction of the size distribution is then added as a percentage of the calculated mass flux.

For 5000 counted snow particles, and a particle size distribution weighted around a median snow radius of 25 µm, the mass flux in water equivalent is calculated as 0.028 mm m^{-2} with the Wenglor counter and 0.023 mm m^{-2} with the York particle counter. Using a more typical size distribution for fine snow according to the literature (Pruppacher and Klett, 1997), with a median radius of 150 µm, equation (2) produces 2.7 mm m^{-2} w.eq. with the Wenglor and 5.8 mm m^{-2} with the York counter. On days when counts of around 5000 snowflakes were recorded, the ECMWF forecast precipitation was on the order of 1.5-3 mm w.eq. during NBP0709 (Wenglor counter) and 0.2-2.5 mm during NBP0702 (York counter). The precipitation amount was calculated for each of the daily snow counts using these two particle size distributions. During cruise NBP0702 the total snowfall calculated based on measurements with the York particle counter was 5.3 cm w.eq. using a size distribution with a median of 25 µm, or 127.5 cm w.eq. using a size distribution about 150 µm. During cruise NBP0709 the comparable numbers based on measurements with the Wenglor counter are 0.5cm (for a distribution about 25 µm) or 15.4 cm. The ECMWF forecast totals are 5.8 cm for NBP0709 and 8.97 cm for NBP0702.

The forecast precipitation and measured daily snow counts shown in Figure 4 are in reasonably close agreement, given the many uncertainties in the snow count measurements, and in the

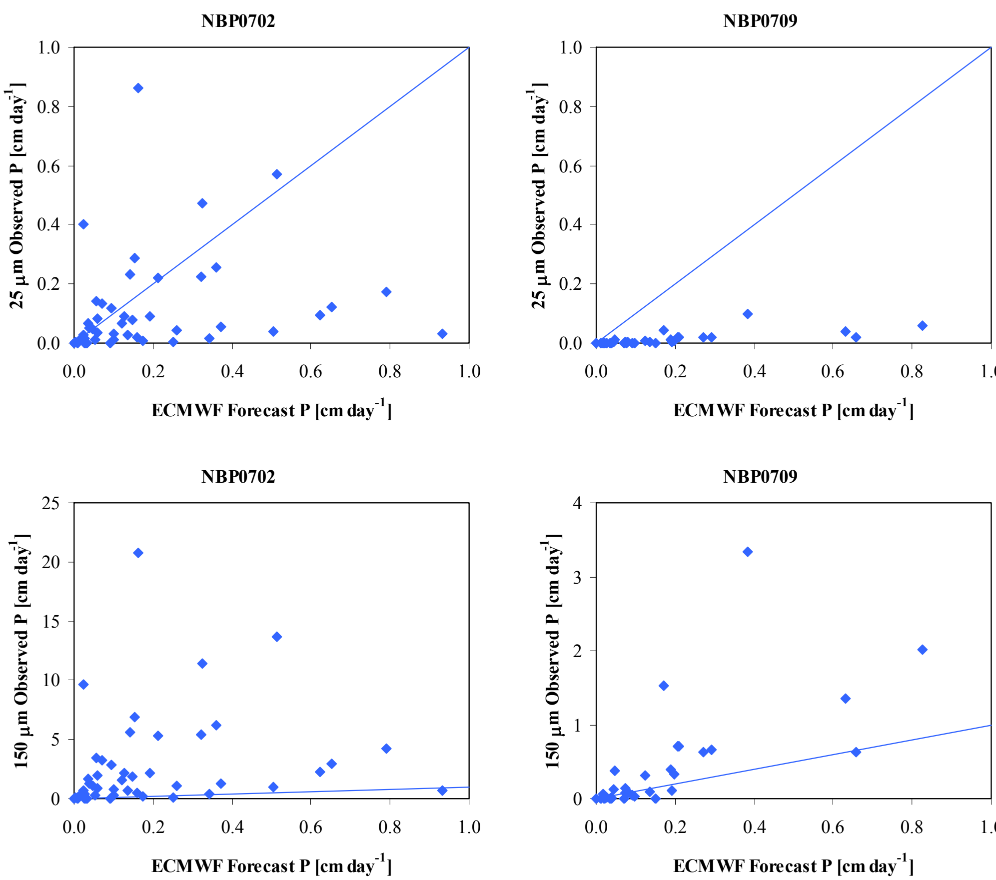

Figure 5. Comparison of forecast and calculated precipitation amounts. ECMWF forecast precipitation is shown in cm w.eq. on the x axes, calculated daily precipitation amounts in cm w.eq. on the y axes. NBP0702 is shown in the left two panels, NBP0709 on the right. Y-axis precipitation amounts were calculated from measured N based on particle size distributions centered around 25 µm (top two panels) and 150 µm (bottom). The solid line included for reference in each plot shows an idealized 1:1 relationship between forecast and calculated precipitation amounts.

ECMWF forecast precipitation amounts. Significance cannot be obtained from the relatively small number of days of data from either cruise. Nevertheless, the correlation is particularly good for the NBP0709 cruise (r=0.68), which experienced three distinct synoptic storms. As shown in Figure 5, the calculated mass flux is strongly dependent on the choice of particle size distribution. The daily measured precipitation during cruise NBP0702 calculated using a particle size distribution with a geometric mean radius of 25 μm is shown in the upper left panel of that figure. As predicted by the likely under-counting discussed above, most daily values (y-axis) are lower than the forecast precipitation for the same day (x-axis), with some exceptions during times when the *Palmer* was adjacent to ice shelves. Calculating the precipitation flux for cruise NBP0702 with a particle size distribution about 150 μm leads to values that are unphysically larger than the forecast precipitation. This suggests that the particle size distribution about 25 μm was appropriate for the snowfall experienced during late summer in the near-coastal Ross and Amundsen Seas.

Precipitation recorded during cruise NBP0709 does not appear to be well represented by the 25 μm size distribution that provided good agreement with forecasts during cruise NBP0702 (figure 5, upper right panel). This is reasonable, as NBP0709 took place at lower latitudes, farther from the Antarctic coastline, in the Bellingshausen Sea. Calculations based on a size distribution with a mean of 150 μm (suggested by the literature) appear to slightly over-represent precipitation relative to the ECMWF forecasts, suggesting that although precipitation in the Bellingshausen during late winter 2007 may have been coarser grained than that at higher latitudes, it is still not as large as more commonly observed and studied temperate snow.

An independent measurement of the snow accumulation on the sea ice between 2-22 October 2007 comes from two ice mass-balance buoys (IMB: Richter-Menge et al., 2006) that were sited on level ice surfaces roughly 1 and 2 km from the ship. The net snow accumulation calculated from sonic depth gauge measurements on the two IMBs while the ship was drifting with the ice floe was approximately 1 ± 0.5 cm w.eq. once densification of the snow with time is accounted for. The ECMWF forecast data from the same interval shows 3cm w.eq. falling on that sea ice floe. This suggests that snow accumulation on sea ice surfaces in this area may under-represent precipitation by a significant amount. Measurements of drifting and blowing snow at multiple locations on the sea ice floe during the SIMBA drift experiment demonstrate that these were common processes, observed whenever precipitation occurred, and frequently when snow was not recorded to be actively falling past the ship's ice tower. Dery and Tremblay (2004) model that between 60-100 percent of snow that is blown across leads in Arctic sea ice is lost into the ocean. While much of the snow that was entrained by the wind during the SIMBA experiment appeared to be trapped by sea ice topography such as pressure ridges before it could be lost into the water, we propose that this process could easily account for the discrepancy between forecast precipitation amounts and observed accumulation.

CONCLUSIONS

This study appears to be the first successful attempt to measure snowfall at sea in Antarctica. Precipitation was recorded on 81 of 82 days that the sensors were operating during the two research cruises. While the Antarctic coast is expected to receive more moisture than the interior of the continent, prior studies have typically assumed that most precipitation is associated with synoptic events. The ship-based records presented here suggest that synoptic storms are responsible for more intense precipitation than is observed at other times, but precipitation is not exclusively due to such discrete events.

The correlation between the timing of precipitation occurrence and ECMWF forecasts of precipitation noted for the SHEBA drift experiment in the Arctic also appears true for the regions discussed here in the Antarctic. Determining the success of the model in forecast precipitation amounts is considerably more challenging, due to the many uncertainties in calculating a mass flux of snowfall from a point measurement of number of snowflakes, and the difficulties inherent in using accumulated snow as a validation of precipitation amount. While the precipitation measurements presented here cannot be claimed to accurately represent the mass flux of freshwater into West Antarctic seas via precipitation, further effort and refinement of these methods may eventually help constrain the contribution of precipitation. These records are already useful in selecting among various model data sets of precipitation for the regions discussed here.

In future, more than one sensor should be employed in such studies to quantify and account for discrepancies in data collection due to ship motion through the water. In future deployments on the same ship, one counter should be mounted as described in this study for continuity of data collection, with a second mounted nearby with the beam perpendicular to the ship's long axis. This will allow the influence on particle counts of the ship's orientation and motion relative to the wind field to be better constrained. Another topic needing additional research is to more accurately determine the particle size distribution of precipitating snow. While use of a disdrometer that could measure particle size distributions of snow is indicated, such instruments are sensitive to vibration, a usual condition on a ship under way. Conventional methods of collecting and determining the size distribution of falling snow should be employed on a regular basis during any future studies of precipitation at sea in Antarctica.

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