Mitigating snowdrift at the elevated SANAE IV research station in Antarctica: CFD simulation and field application

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ABSTRACT: The elevated and aerodynamically streamlined South African Antarctic research base SANAE IV, in Queen Maud Land, off the Fimbul ice-shelf in Antarctica, exhibits unique wind driven snow drift formations. The longitudinal snowdrifts that form behind the interconnecting links that join the elevated research buildings are approximately 4 m high, 15 m wide and 60 m long are annually removed during a costly, weeklong operation. The paper shows the results of Computational Fluid Dynamic (CFD) modeling and simulations, developed specifically to study the phenomena and offer insight in the Aeolian processes as well as likely effectiveness of potential remedial measures. The numerical model uses standard multiphase CFD modeling techniques to resolve both the coupled wind and suspended snow velocity and mixture distribution. The snow drift model determines erosion or accumulation rates at the snow surface through simplified mass conservation of suspended and saltating snow at the boundary cells. The CFD simulations performed were able to reproduce the observed drift formations and were subsequently used evaluate the effectiveness of a three mitigation measures. The simulations suggested that a set of strategically placed baffle plates would reduce the drift formations significantly. This mitigation scenario was confirmed through field testing with drifts reduced from 4m deep to 0.5m deep. The paper illustrates that the snowdrift modeling were successful to predict the drifts and help devise a simple but effective snowdrift remediation strategy.

1 INTRODUCTION

South Africa has been involved with science in Antarctica since the summer of 1959/1960 when the first South African Antarctic Expedition (SANAE) took over a Norwegian base on the shelf ice in Dronning Maud land. The new SANAE IV station completed in 1997, is situated on the continent at 71°40’ S, 2°49’ W on a rocky outcrop called Vesleskarvet as shown in Figure 1. The modern SANAE IV station was designed to house a multinational contingent of scientists and support personnel and consists of an elevated structure raised approximately four meters above ground. The outcrop on which it is built is gently sloping upwards from east to west with sharp cliffs surrounding its northern, southern and western edges (Figure 2). The station orientation ensures that it is aligned mostly perpendicular to the prevailing eastern winds and consists of three main buildings, block A, B and C, each approximately 44.0 meters long, 12.0-14.0 meters wide and 7.0 meters high. The main buildings sections are joined by interconnecting links with access stairways, between blocks A and B and between blocks B and C. These links are each approximately 10.0 m long, 8.0 m wide and 4.0 m high and their bottom outside panels are joined flush with the main buildings bottom panels. The whole structure is elevated 4.0 meters above ground on an array of support columns securely anchored onto the rock bed. The location of the structure on the edge of the cliff intends to allow wind driven snow to be channeled at high velocity over and underneath the structure and spill over the western edge of the cliff. However, in the leeward vicinity of the links significant longitudinal snow buildup occurs.

Figure 1: SANAE IV research station

2 SANAE IV SNOWDRIFT SIMULATIONS

The main areas of snow deposition surrounding the SANAE IV station are highlighted in Figure 2. Small windward drifts form along the length of the base (A). These drifts are less than one meter deep. No drifts form anywhere directly underneath the station structure (B) as snow is constantly eroded from the exposed sharp edged rocks by the accelerated wind stream. The most important leeward drifts, studied in this work, are those formed directly behind each of the two links (C). These drifts are approximately 15 m wide, 4 m high and 60 m in length with its highest point 20 m leeward of the link and level with the underside of the main building. From observations during storms it was found that these longitudinal drifts can form over short periods (<48 h) during heavy winds (~20 $m \cdot s^{-1}$) and that their longitudinal axis are aligned with the wind direction during formation, Beyers and Harms (2003a). These drifts are removed annually. Some of the more recent investigations into snow drifts surrounding buildings as well as Antarctic research stations are mentioned below. Kim et al. (1991) and Kwok et al. (1992) carried out wind tunnel experiments to evaluate snow drifting around a model of Syowa station (Japan) as well as elevated single and grouped on-ground and above-ground facilities. Their results indicated that leeward snow accumulation mostly disappeared for a building height to height from ground ratio of larger than 0.5. Their work also presented some notable leeward riming formations. Smedley et al. (1993) investigated the effects of wind deflectors on the snow drift around a workshop at Davis station, Antarctica. Their work indicated that a rounded deflector increased the overall snow drift volume but effectively removed the drift away from the leeward wall. Angular deflectors proved ineffective. Delpech et al. (1998) carried out wind tunnel tests at the CSTB Jules Verne (France) snow wind tunnel to study the possible snow accumulation characteristics surround-

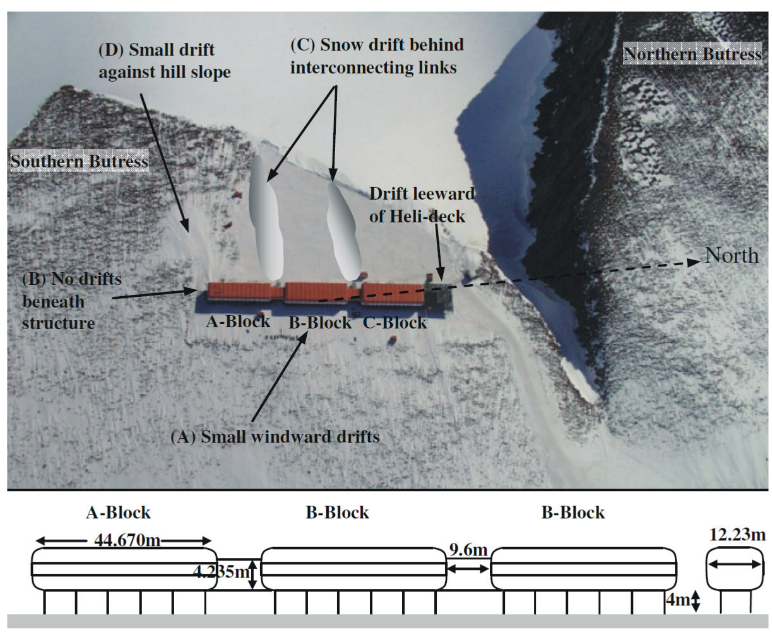


Figure 2. SANAE IV layout on Vesleskarvet, Antarctica showing regions of localised snow drift

ing the new Concordia station in Antarctica. Their work proposed and tested the effects of wind deflection panels to channel the flow between and underneath the station main buildings. The snow drift tests indicate that the deflection panels may be a suitable mechanism to minimise the snow drifts. The aim of this work and the numerical simulations are to understand the important flow mechanisms causing the localised snow drift behind the links (area C in Figure 2), to replicate this drift formation by means of three-dimensional numerical flow simulations and to propose mitigation to minimise the deposition of snow in these areas. Two of the three entrances into the station are positioned on the western side of these interconnecting link structures and accessed via a staircase from the ground. It was observed by the first author that during moderate winds the snow passes relatively undisturbed underneath the structure with small longitudinal drifts forming behind the supporting columns along the length of the base. These finger-like drifts did not continue to develop but were eventually destroyed as wind speeds progressively increased. With stronger wind conditions, a localised drift started to form in the area leeward of the staircase behind both the link structures instead.

The computational fluid dynamic snowdrift modeling methodology used here has previously been described in detail by Beyers et al. (2004a, 2004b, 2004c, 2008). It employs an unsteady RANS simulation with k-ε turbulence model as well as multiphase Euler treatment of the windblown snow transport. The model determines the snow erosion and deposition rates at the terrain surface from particle settling velocity, flow divergence and surface shear stress and dynamically adapts the terrain accordingly. The simulations reported here were performed using the commercial code Flow3D of Flowscience which employs an immersed boundary technique lending itself well to dynamic grid modification, creating and destroying mesh cells representing the solid snow volume to mimic drift development. Inlet velocity profiles employed follows a logarithmic planetary boundary layer profile representing wind flows over smooth open terrain. Turbulence inlet conditions used are as given by Richards and Hoxey (1993). Inlet velocity profile aerodynamic surface roughness (z_0) and shear velocity (u_*) were 0.0005m and 0.35m/s, respectively. The computational domain and mesh used in the simulation is shown in Figure 3. Only

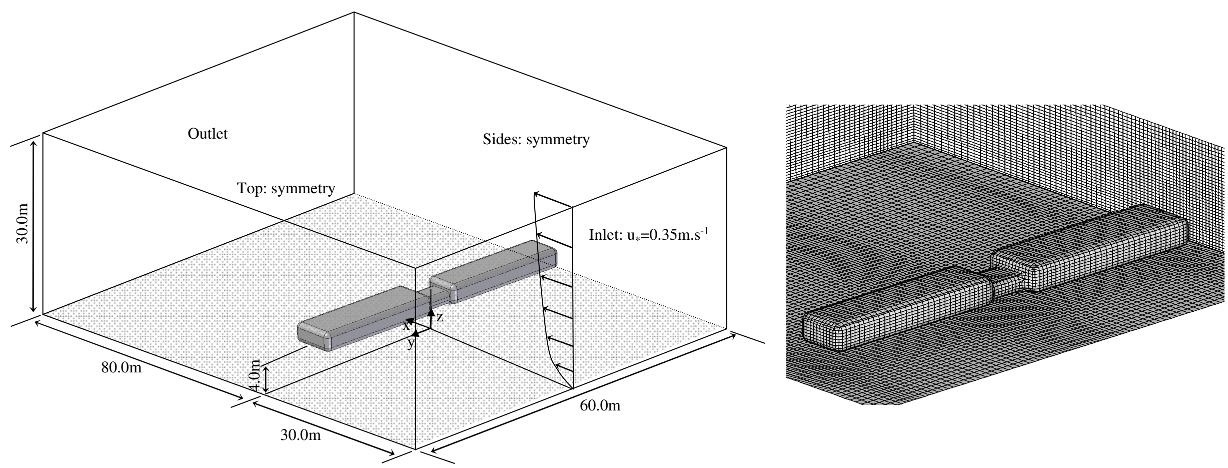


Figure 3. Computational domain and mesh for the three-dimensional flow simulation around SANAE IV.

one of a number of scenarios simulated are reported here. Snow particle diameter and settling velocity were assumed constant at 110 μm and 0.45 m/s, respectively.

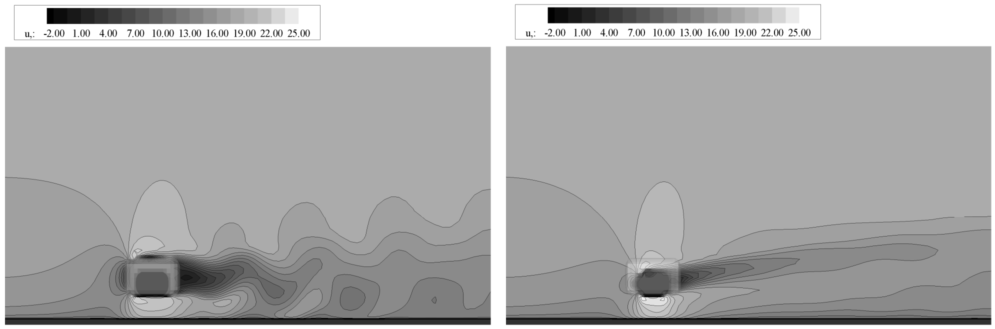


Figure 4. U-velocity contours in section at main building (left) and link (right)

The u-velocity contours in the vertical plane through the main and link sections are shown in Figure 4. This shows the acceleration over and underneath the building structure. For both sections the flow decelerates relatively quickly as it exits underneath the structure. The simulated flow that exits the main buildings exhibits vortex shedding characteristics.

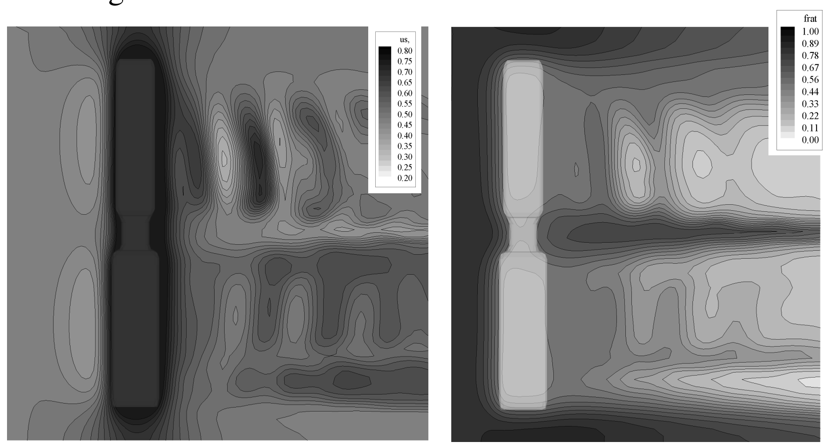


Figure 5: Contours of surface friction velocity (left). Near surface snow concentration (right)

The numerical prediction of the vortex shedding causes a fluctuation in the drift formation since the near surface velocity gradients are periodic. Surface friction velocity and near surface snow volume fraction ratio contours are shown in Figure 5. This indicates that the shear field leeward of the main buildings is periodic while leeward of the link it exhibits more steady characteristics. The reason for this could be attributed to swirling flow initiated at the lower trailing edges of the main building at the link joint. The location of a pair of counter-rotating vortices is described in Figure 6 along with a vertical section showing swirling elocity vectors in a plane 17m behind the structure. The snow fraction contours suggests that most of the upstream snow is channeled towards the interconnecting link. This local concentrating effect caused by the trailing vortices assists the downstream localised snow drift development by increasing the available snow.

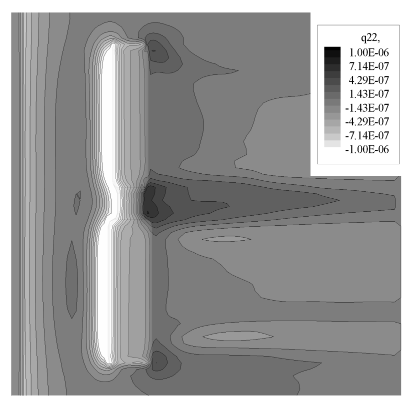


Figure 7. Snow deposition / erosion flux contours

Figure 7 shows the local erosive and deposition snow flux. From these plots it is evident that deposition (positive values) will occur along the windward edge of the SANAE IV structure as well as leeward of the building at the outer edges and behind the link buildings. Strong erosive fluxes (negative values) are predicted underneath the building. Figure 8 show the predicted three-dimensional snow drift compared to the drifts observed at SANAE IV. The predicted leeward drifts behind the main buildings are significantly less than the drifts at the link and leeward of the outer edges of the building. This suggests that the secondary flow present here strongly influences the increased snow drift formation.

The characteristic snow drift behind the link is clearly visible. Based on the simulated results the large drifts at the link areas are believed to be caused by a combination of channeling of upstream snow into the swirling flow region downwind of the link, highly unsteady flow acceleration and deceleration underneath the link, and counter-rotating vortices reducing the shear leeward of the link.

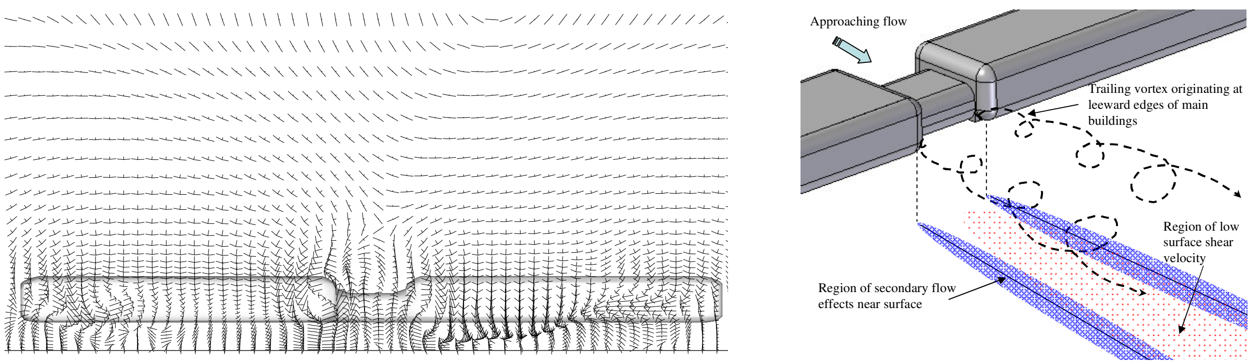


Figure 6: Vector plot in a vertical section 17m behind the structure (left) and diagram (right) of the leeward trailing counter-roating vortices behind the link structure

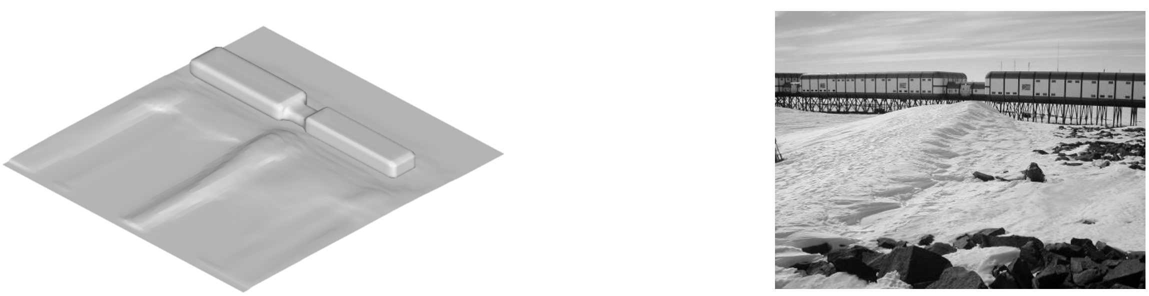


Figure 8: Snow drift development at the end of the simulation (left) with observed drift at SANAE IV.

3 DESIGN MITIGATION SIMULATION

In the following section three design modifications are evaluated to investigate their effect on the minimisation of the snow drifts leeward of the links. Similar computational domain and numerical simulation parameters are employed. Modification 1 includes the addition of a solid baffle plate installed vertically and along the length of the leeward edge of the interconnecting link as shown in Figure 9. This baffle plate should deflect the flow exiting the link to or destroy alter the trailing vortex characteristics. It may furthermore modify the secondary flow structure leeward of the edges of the main building to diminish the effects of the trailing vortex generated by the existing structure. The baffle may be installed onto the leeward supporting columns and just below the bottom panels of the interconnecting link, as indicated in Figure 9. Modifica-

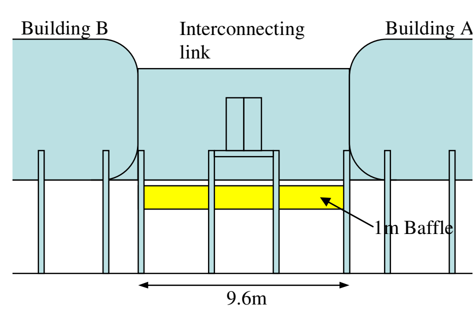
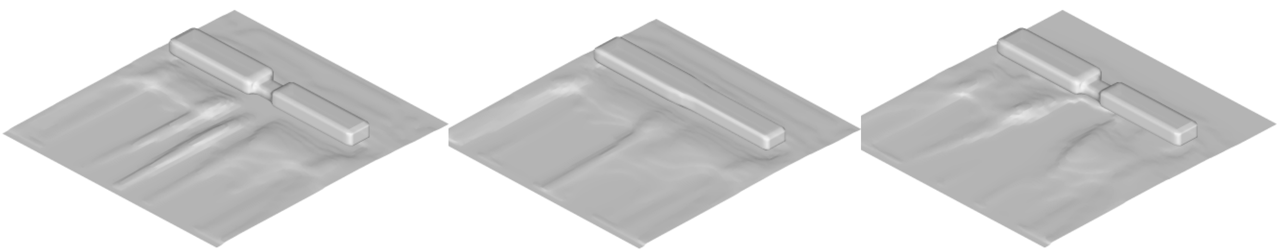


Figure 9. SANAE IV Modification 1

tion 2 evaluates the SANAE IV structure with the link replaced by a continuous structure that joins the two main buildings flush with each other without the abrupt geometry change. The main buildings are not the same width and therefore a slight taper would be necessary. Modification 3 is similar to Modification 1 but the vertical baffle is extended upward along the leeward support pillar to join flush with the interconnecting leeward wall. The numerical simulations were performed to evaluate the influence that the mitigation measures may have on snow drifts leeward of the link buildings at SANAE. These design proposals given here do not include any evaluation of the effects such modifications may have on the structural integrity of the SANAE IV construction. The CFD simulated snow drift development for Modification 1,2, and 3 are shown in Figure 10. Modification 1 and 2 reduced the drift behind the link while Modification 3 removed the drift completely; creating smaller drifts adjacent to the original drift location. Considering the complexity of applying Modification 2 and the improved results shown when modeling Modification 3, it was decided to apply a continuous baffle plate during physical testing at SANAE IV.



Modification 1 **Modification 2** **Modification 3**

Figure 10: Three-dimensional snow drift predictions for three mitigation concepts

4 FIELD MITIGATION

During the 2007/2008 annual Antarctic summer takeover, an intensive annual maintenance, research and year staff exchange period, consideration was given on site with regard to a baffle mitigation design for the link between the A and B blocks keeping the BC link unaltered as a control case. A modular, clamp-on design was proposed, such that the baffle entailed three horizontal segments, each approximately 500 mm in height, which would allow some experimentation with regard to the affect on snow accumulation of this parameter. The baffle design was manufactured and installed at SANAE IV during the 2008/2009 field season (Figure 11).

Figure 11: Test wind baffle installation at interconnecting link (Photo: Stander)

All three authors visited the base at several points in time, most recently Stander during the 2009/2010 take over period. Observations below are augmented by comments from other researchers and maintenance staff, who visited the base throughout its existence. After the first over-wintering period of the new base (1997), when the drifts behind the links were first observed, is was suspected that the access staircases leading to the entrances in the links were the predominant reason for their formation. Therefore one of the staircases was removed for the duration of an entire year, to see whether this was this case. No mitigating effect was, however, observed during this entire period (Bezuidenhout, 2008). This serves as a further confirmation of the numerical results reported here. With regard to the effectiveness of suppressing snow accumulation with the baffle mitigation installed, SANAE IV base staff reported early in 2009 (Browne 2009) that the baffle was found to be "very effective". Due to the near symmetry of the base buildings, without baffle plate installation on the BC link, a direct comparison of drift reduction was possible. A reduction of snow buildup from approximately ~3m to ~0.5m deep (post snow storm conditions) is reported as a result of the baffle plate installation (Browne, 2009) at link AB, which serves as an excellent confirmation of the numerical analysis. The photographs shown in Figure 12, taken at the same time after a storm event during March 2009, demonstrate this result. Furthermore Stander, during his recent visit, was able to observe some minor preferential snow built-up in the space adjacent to the downwind areas of the links as predicted by the 3D modeling (Figure 12, Modification 3). As was suggested by Beyers (2004a) and subsequently confirmed by a minor study , Basson (2009), one effect of the baffle installation is an increased pressure differential across the BC link outer entrance door. Base staff reported minor damage done to the door during a 70 knots wind event early 2009 (Browne, 2009). Anecdotal evidence from base staff suggests that the baffle adds noticeably to the vibration and noise loading of the occupied space during storm periods.

Figure 12: (Top) Negligible snow deposition behind AB link (in line with stair case) with baffles. (Bottom) Extensive snow deposition behind BC link (in line with stair case) without baffles.(Photo: Keith Browne)

5 CONCLUSION AND FUTURE WORK

The field work results provide a qualitative verification that the modeling approach shown by here and in Beyers (2004a, 2004b, 2004c, 2008) correctly captures the snow transport and deposition phenomena as observed at SANAE IV. This approach allowed the numerical evaluation of low cost remedial measures, which were predicted to be effective in significantly reducing downwind drift formation. The result of the 12 month trial installation of test baffles confirms this. While some secondary effects as a result of increased pressure loading (suction) of the entrance doors and perceived increased wind noise under storm conditions were reported, these are not considered significant impairments of the remedial measures implemented and will be investigated in future work related to fluid-structure interaction, particular vortex shedding induced vibration and noise effects in the base structure and habitable spaces. Good preparatory progress with regard to computational fluid dynamics (use of OpenFOAM) and finite element method studies and consulting processes for broad band satellite communication based real-time vibration and strain monitoring of the base structure has already been made (Joubert 2010, Basson 2009, Gärtner 2009). At the time of writing, due to a review of the SANAP and National Research Foundation (NRF) Antarctic activities, no registered SANAP/NRF research project relating to the baffle installation is in place and, as a result, the installed test baffle set reported here paper was dismantled early 2010.

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