High-top clouds play an efficient part in moisture transport to the Antarctic

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Abstract

We verified high-top clouds from satellite imaging that contributed to snow accumulation at Syowa Station, Antarctica, during a blizzard event in 2009. Snow stake data shows that the accumulation recorded in 2009 and 2011 increased during 1993–2012 through the traverse route in East Antarctica. Focusing on 2009 events, the high-top cloud structure in the stitched satellite image was often linked to the atmospheric river (AR) and the values for the high-top cloud area. We found seven new AR events for 2009 with high accumulations and high-top cloud (HTC) areas. After comparing the HTC area to precipitable water and integrated water vapor transport, we determined that the selected cloud images can be used as a parameter for snowfall. This paper introduces a new fusion method for identifying AR using image analysis and in-situ glacial and meteorological data. These HTC clouds are beneficial for predicting the accumulation in the future.

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Key Points:

High-top clouds from satellite imaging analysis contributed to the accumulation of snow at Syowa Station, Antarctica in a blizzard in 2009.

Seven new atmospheric river events were found in 2009 with high accumulations and high-top cloud areas, three events detected by previously.

Compared with precipitable water and integrated water vapor transport, the cloud detected can be a parameter for predicting an accumulation.

Abstract

We verified high-top clouds from satellite imaging that contributed to snow accumulation at Syowa Station, Antarctica, during a blizzard event in 2009. Snow stake data shows that the accumulation recorded in 2009 and 2011 increased during 1993–2012 through the traverse route in East Antarctica. Focusing on 2009 events, the high-top cloud structure in the stitched satellite image was often linked to the atmospheric river (AR) and the values for the high-top cloud area. We found seven new AR events for 2009 with high accumulations and high-top cloud (HTC) areas. After comparing the HTC area to precipitable water and integrated water vapor transport, we determined that the selected cloud images can be used as a parameter for snowfall. This paper introduces a new fusion method for identifying AR using image analysis and in-situ glacial and meteorological data. These HTC clouds are beneficial for predicting the accumulation in the future.

Keywords: surface mass balance, satellite image, image analysis, atmospheric river

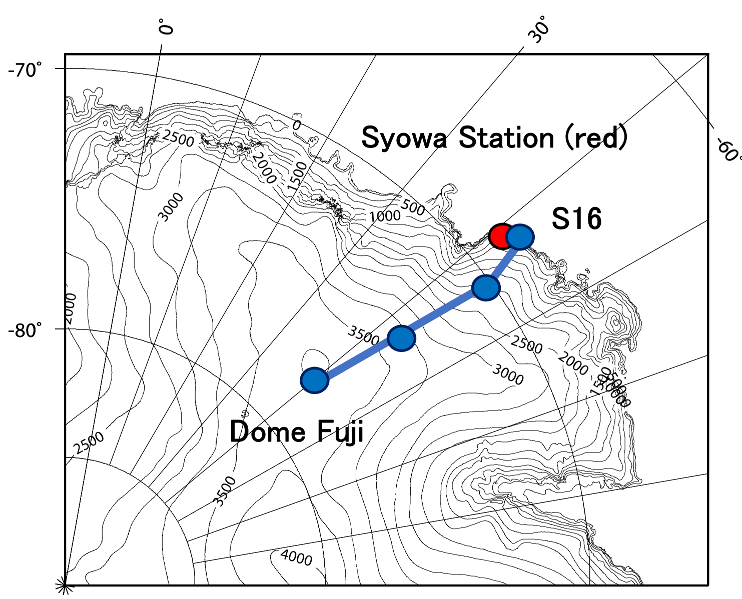
Plain Language Summary

We verified that the high-top cloud from satellite imaging contributed to snow accumulation at Syowa Station, Antarctica, in the blizzard of 2009. From the snow stakes data, the accumulation in 2009 and 2011 increased during 1993–2012 through the traverse route in East Antarctica. Focusing on the events in 2009, the high-top cloud structure in the stitched satellite image often linked the atmospheric river and the values of the high-top cloud area; the heavy snow conditions differed from the light snow conditions. Finally, we found the seven atmospheric river events in 2009 with high accumulations and high-top cloud areas. Precipitable water calculated by radio sonde data indicated the AR clouds had a higher HTC area than non-AR. This result was reflected that the AR is a narrower long moisture band, and the cloud area should expand. We found that the IVT of our AR events exceeded three times of standard deviation of a monthly threshold. The above results indicated that the cloud detected can be a parameter for predicting an accumulation. This method is new for finding moisture transport to the Antarctic.

1 Introduction

Recently, variation in the surface mass balance (SMB) has attracted substantial interest because it strongly influences the sea level rise. Based on satellite observations, the loss of SMB around the West Antarctic ice sheet with increasing temperature has been reported for decades (Bromwich et al. 2013; Fernando et al. 2015; Zwally et al., 2015). To capture the correct SMB variation, the processes of accumulation by precipitation, and consumption by runoff, sublimation/evaporation, erosion need to be understood, with further observations being required. The precipitation has an important role on the accumulation because the only phenomena to recharge the icesheet. However, severe environments and snowdrifts make in-situ observation of snowfall events challenging. Given that the snowfall amount provided by several reanalysis datasets and regional climate models show are inconsistent with the observed snowfall event around the Syowa Station (Agosta et al. 2019), it is important to verify that the elements from the reanalysis data are sufficient for interpreting snowfall events. The Japanese Antarctic Research Expedition (JARE) has observed the snow stake data along the traverse route from the Syowa to the Dome Fuji stations from 1992 to the present (Figure 1, data from Motoyama et al., 2008; Motoyama et al., 2015). These data have captured the net interannual accumulation from the coastal to the interior regions around East Antarctica (Figure 1b). Interannual accumulation increased during the late 2000s, especially in the coastal region. The variation of katabatic area accumulation and adding up snow depth at Syowa Station increased around 2009, however, the coastal area accumulation decreased conversely. In 2009, a substantial amount of snowfall was observed in East Antarctica, including at the Princess Elisabeth Station and Syowa Station, and the moisture transport was analyzed (Gorodetskaya et al., 2014). The atmospheric river (AR) in front of a cyclonic disturbance enhanced the poleward moisture flux outside Antarctica and carried substantial snowfall into the region. The blizzard events that occur at the Syowa Station often exhibit similar atmospheric circulation conditions (Sato & Hirasawa, 2007). The interannual variation of SMB focusing on the coastal area shows that the increasing trend of SMB in the late 2000s peaked in 2011 and turned to decrease. Here, we target the events in 2009, the same as in Gorodetsukaya et al. (2014), to verify the water vapor transport by AR at Syowa Station.

(a) The map of East Antarctica and the Japanese Antarctic Research Expedition's traverse.



(b)

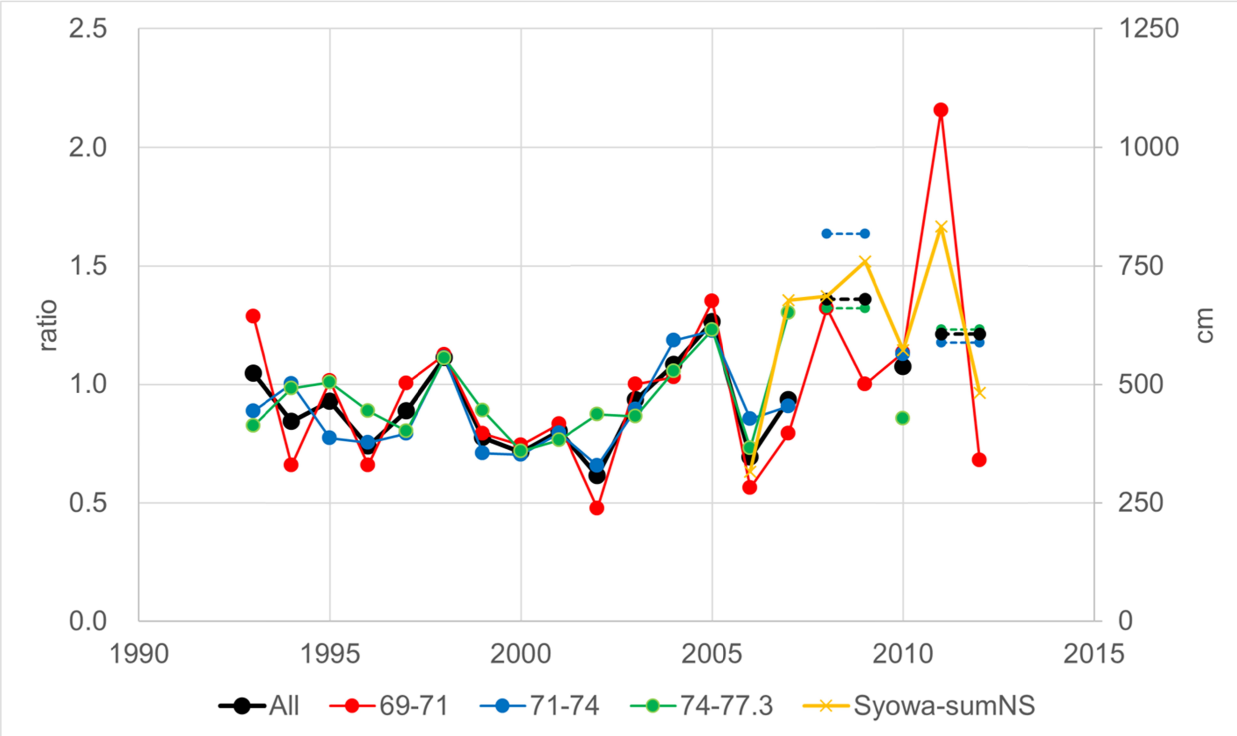


Figure 1. (a) The spatial area averaged annual accumulations from the snow stake data from JARE along the traverse route from Syowa to Dome Fuji stations for 1993 – 2021. (b) The ratio is the value of the snow accumulation rate based on the entire averaged dataset. The area shown includes the coastal (red), katabatic (blue), and interior (green) regions, and the black line is the average for the entire area for 1993 - 2012. The yearly adding up snow depth at Syowa station is shown as yellow. The two years averages connected by dot line.

Wang et al. (2015) compared the SMB from the JARE snow stakes and simulated SMB using regional atmospheric climate model. They divided the SMB components including drift and surface sublimation, wind-driven snow erosion, and deposition and four areas, namely coastal, lower, and upper katabatic, and inland regions and highlighted that in the coastal region, the drift snow sublimation contributed substantially to the net SMB. This means that in examining the snowfall amount in the coastal region, we cannot exclude the effects of wind-driven snow erosion and deposition.

Here, we investigate the relationship between the observed atmospheric elements and cloud patterns from satellite data such as AR to clarify the explanatory variables in estimating the snowfall amount. We have constructed a new convolutional neural network (CNN) architecture to automatically identify the high-height clouds associated with the AR (Suzuki et al., 2021). If the snowfall amount or snow accumulation can be estimated based on the in-situ and satellite observed and reanalysis data, we can estimate the SMB for the entire Antarctic ice sheet under the present climate. This method can play a key role in the adaptation of other meteorological and ice sheet fluid modeling for application in the context of past and future climates.

2 Detection of the high height cloud area

In this study, we used NOAA/AVHRR images (for the infrared band, channel 4) that had been received at Syowa Station. Due to polar orbit satellite observations, the field of vision in the images changed several times each day. Contamination often occurs during blizzard events with heavy storms because their strong winds and snowfall cause electromagnetic interferences from receiving data from the satellites. We stitched several images to analyze the wider cloud structure. The stitching condition is the duration before or after six hours from the observation and using an averaged pixel brightness for overlap area. After the images had been stitched, the HTC area was detected. We made a mask of the land area in the image by using only the over sea or the sea ice area. We then applied image binarization using local thresholding with a pixel brightness of 100 and image erosion three times. After this, we estimated the contour of the HTC using the Chan–Vese segmentation algorithm (Chan & Vese, 1999). In Figure 2, we show an example of the stitched image (upper) and estimated area as HTC, and the red-line enclosure is the HTC area in the image (lower). Gorodetskaya et al. (2014) highlighted that there were deep troughs following cyclonic disturbance and direct moisture transport with polar ward flux were enhanced for the ice sheet (they called them ARs). The area detected in Figure 2 is likely to be in the same condition as AR. The definition of HTC including the top level of storm convection should be over 500 hPa and could potentially reach 300 hPa by chance.

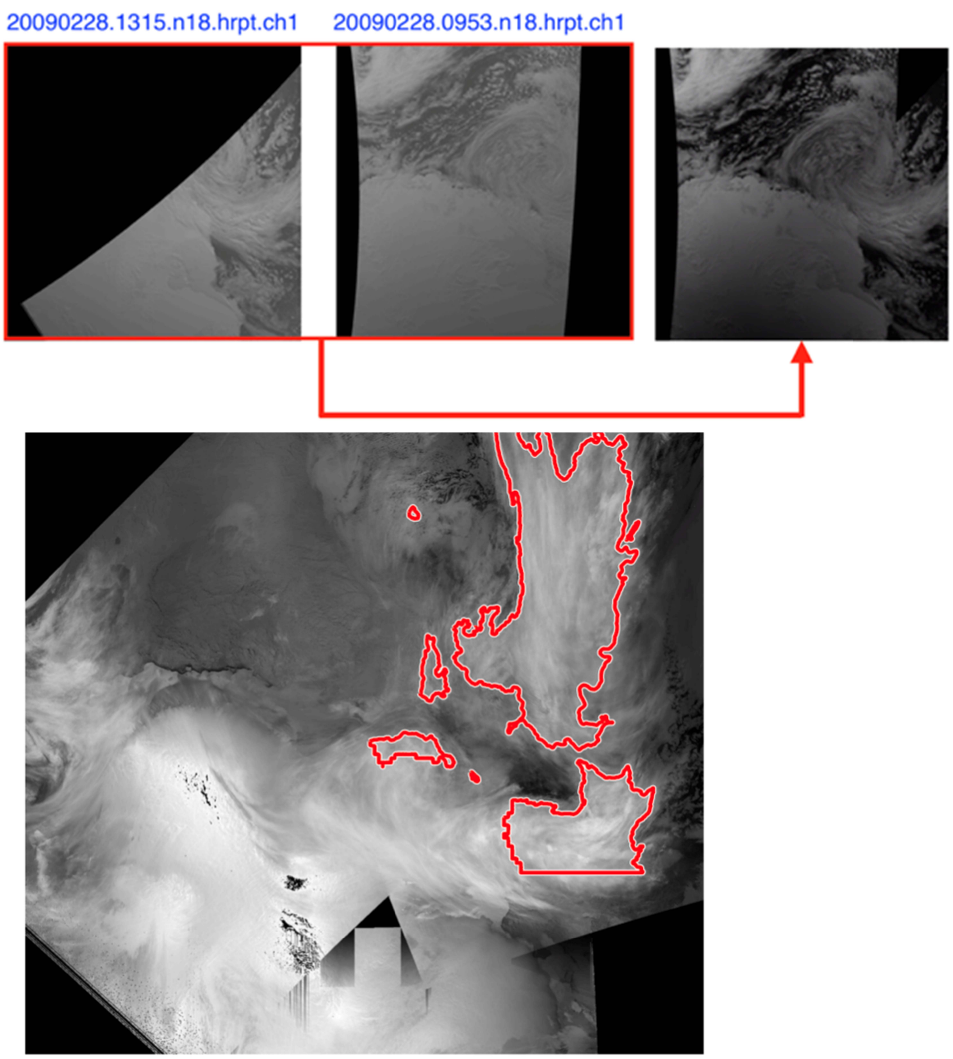


Figure 2. (Upper) The merging process for the satellite images from two pieces. (Lower) Sample merged image and the area surrounded by red lines have high brightness temperatures that we have called HTC.

3 Analysis of Blizzard Events

JARE has operated in-situ meteorological observations over a long time. The surface observations include pressure, temperature, wind speed, wind direction, weather conditions, and the amount of cloud at Syowa Station from February 1957 to the present. Blizzards often occur with severe snowstorms, with approximately 25.1 blizzard events at Syowa per year on average (Sato & Hirasawa, 2007). The in-situ weather conditions were observed as snowfall in all blizzard events for 2009. In this paper, these blizzard events were designated as snowfall events because the blizzard is connected with the heavy storms such as the AR analyzed by Gorodetskaya et al. (2014). We have only focused on the events in 2009 because the accumulation increasing as shown in Figure 1b and the number of blizzards were 28 and more than average, that mean we have large sample size. The criteria have three blizzard grades. Here, we have disregarded the differences between the blizzard grades. However, A-grade blizzards with wind speed over 15 m/s and visibility under 100 m can be treated as severe snowstorms. The structure and the number of clouds with snowfall were analyzed. We compared the heavy snow clouds with light snow clouds based on the snow depth data from Syowa Station. The snow depth was observed using an electronic snow gage and the data were sent by radio. During the blizzard event, the heavy storm made the winds considerably stronger. There was often a lack of snow depth data, especially under storm conditions because of there being weak reception at the station. The one of most simple method to supplement the lack of snow depth data is to employ a time-series analysis. We employed Kalman filtering, is a filtering method based on Bayesian inference using Gaussian probabilities, to predict a time variation of snowfall amount. After filling the gaps in the dataset with predicted values, we compared the pixels within the HTC area for different snow depth conditions.

Figure 3 shows the HTC area maps for the different snow depth conditions. On the left is the merged image with the maximum snow depth of 23 cm shown as a heavy snowfall event. The HTC area is counted using the pixels. The area with heavy snowfall is 395 154 pixels, and the trained HTC brought rich moisture from the mid-latitude in front of the cyclonic disturbance. The position of the disturbance is quite important, with the synoptic atmospheric circulation pattern having a characteristic pattern in the snowfall at Syowa Station. The main disturbances are west of the station, and moisture transport is enhanced toward the ice sheet. The same situation was identified by Sato and Hirasawa (2007) and Suzuki et al. (2008). However, under light snow conditions, the cloud and disturbance patterns are similar to those of the snowfall. The pixels of the HTC were 85 410, and smaller than those to the left of Figure 3. Using reanalysis meteorological data and analyzing these situations, we were unable to make the characteristic patterns of the elements clear. This method can effectively classify the amount of snowfall and accumulation, which suggests that HTC such as AR substantially influences moisture transport to the Antarctic and snowfall accumulation on the ice sheet.

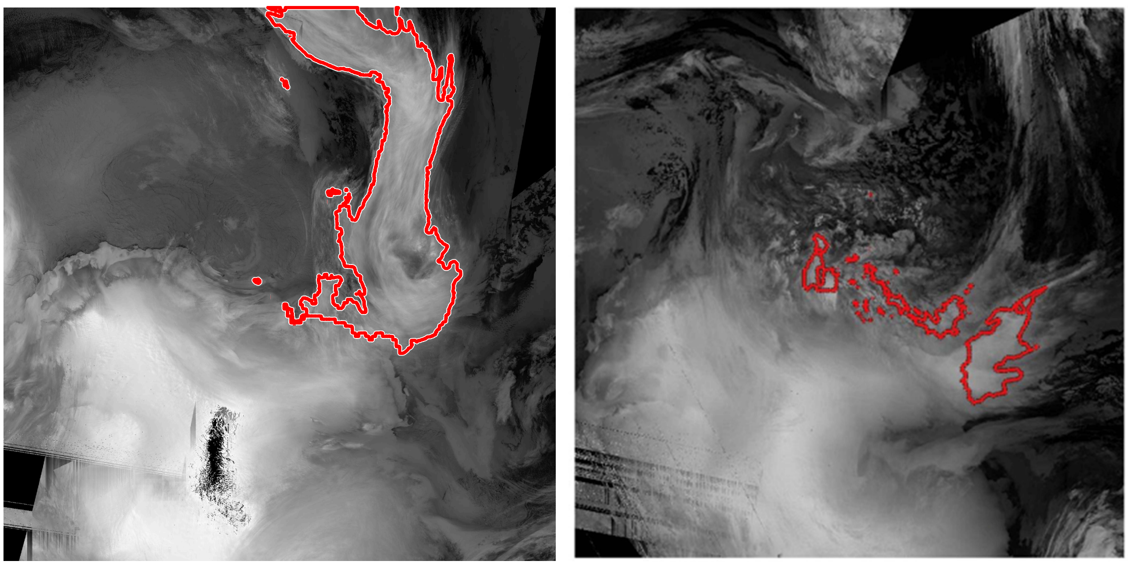


Figure 3. The merged satellite images under heavy (left) and light (right) snow conditions.

4 Results and Discussion

Figure 4 shows the time series of the snow depth and the duration of the blizzards, with the red duration being for an A-grade blizzard. The duration is irrelevant to the variation in the snow depth. Under blizzard conditions, in some cases, the snow depth has increased or decreased with no change in the quantities. Given that our final goal is to estimate the surface mass balance of Antarctica, we chose an event with increasing snow depth. The snowfall was confirmed by observation and the snow depth increased. The event was detected as AR based on the conditions with the clouds being over Syowa Station and that the clouds were persistent over a long distance.

It is important to validate the events that were detected using HTC and the snow depth in the context of moisture transport to the Antarctic. The difference between events was initially investigated by calculating the amount of precipitable water from radiosonde data at the time of the observation. In this case, the precipitable precipitation is the integrated value up to the altitude where the temperature does not fall below −40 °C. Figure 5(a) shows a plot of cloud area versus the precipitable water for each blizzard class. The precipitable precipitation is zero because it cannot be calculated due to the missing measurements. The red, green, and blue areas indicate the cloud area for the Grade A, B, and C blizzards, respectively, and all the missing measurements were taken during the Grade A blizzard. Figure 5(b) shows the number of cloud areas for ARs (red) and others (blue), regardless of the grade. The number of cloud areas as a snapshot could potentially be significant.

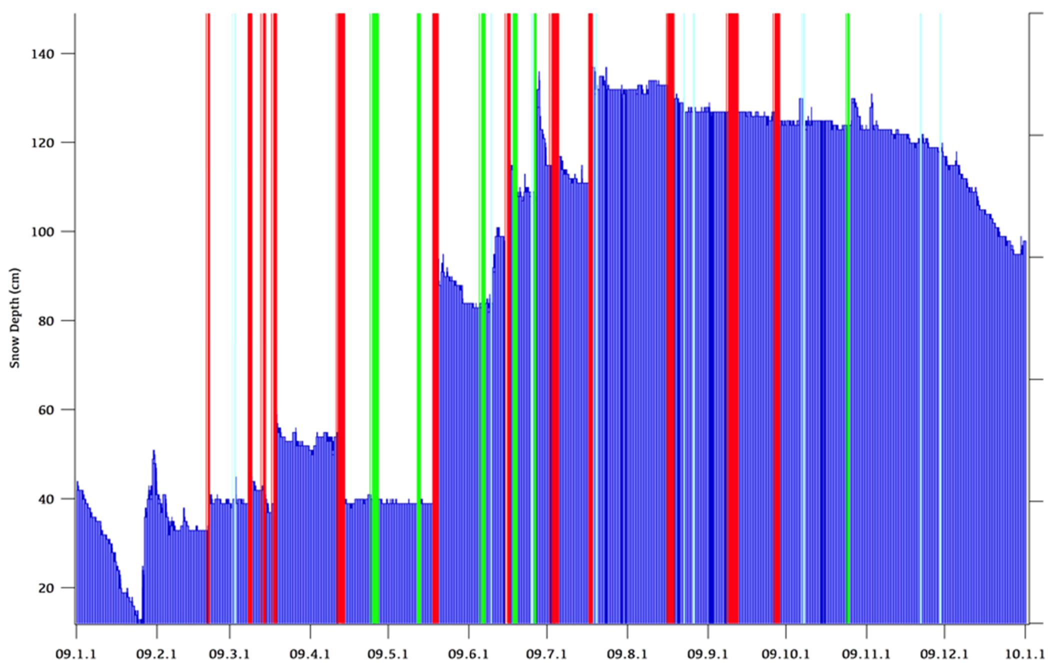


Figure 4. The snow depth at Syowa Station in 2009 (blue) and the strength of the blizzard (Grade A is red, Grade B is green, and pale blue is for Grade C).

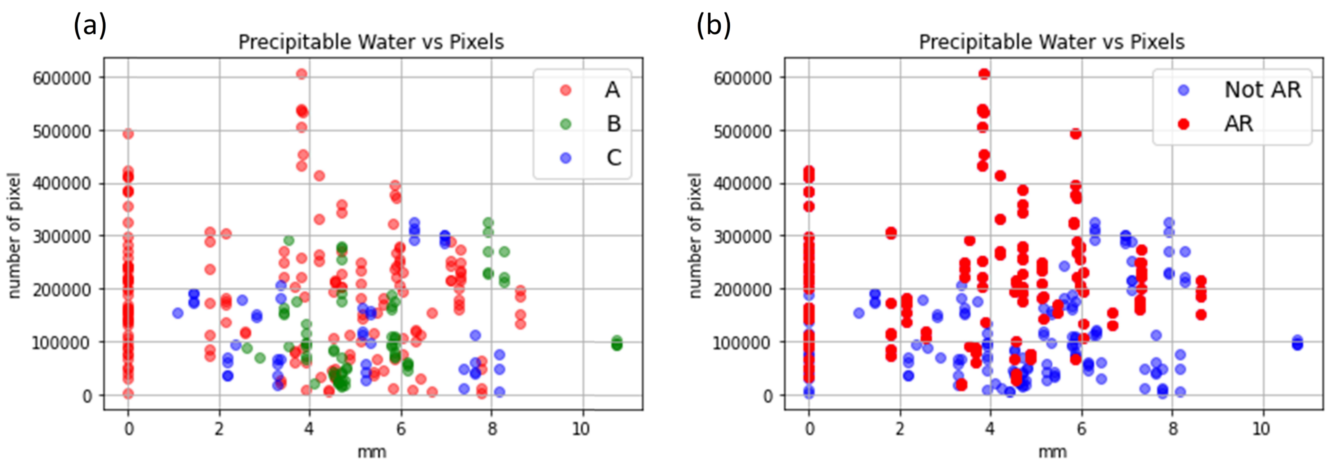


Figure 5. (a) Distribution of precipitable water at Syowa Station and the number of HTC pixels. Color differs from the blizzard grades. When observation data is lacking, the precipitable water equals zero. (b) The precipitable water at Syowa Station and the number of HTC pixels have the same distribution but the colors show whether an AR event has occurred.

Based on the definition of HTC, we identified seven AR events with high accumulations and the HTC area from all the blizzards in 2009 at Syowa Station (Table 1, 10 events). The specific AR events indicated by Gorodetskaya et al. (2014) were also confirmed at Syowa Station (right column of Table 1, three of ten events). The stations are near each other in the Droning Maud Land and the synoptic-scale disturbances often have the same effect on the SMB. In the highest accumulation event, the snowstorm resulted in an accumulation of 43 cm from 18 May to 20 May, and the maximum snow depth in 2009 was 135 cm. During that event, over 30% of the amplitude for the year had accumulated. The mean HTC area for the blizzard was 191 484 pixels and the maxima was 323 297 pixels. Approximately 5 cm of snow depth can be brought by clouds without many HTCs. The correlation is 0.3 between the snow depth and pixels but the possibility of high accumulation can be interpreted.

The next step was calculating the IVT (Mundhenk et al., 2016) using objective meteorological data (ERA5 hourly data on pressure levels from 1959 to present, Hersbach, H. et al., 2018) to detect cloud features as Ars. It is difficult to calculate the specific humidity up to 300 hPa using radiosonde data due to the temperature problem. Therefore, it is necessary to use objective analysis data and to compare the results with those obtained using radiosonde observations. ERA5 is the best reanalysis meteorological data at temperature and accumulation in the Antarctic (Gossart et al. 2019). Here, we used Integrated Water Vapor Transport (IVT, Mundhenk et al. 2016) as the AR threshold. Using ERA5, we obtained the time-series of IVT for each month for Syowa Station in 2009. With a threshold (three times of monthly standard deviation; 3σ as 0.99%) confidential, we could recognize the detected AR events as rare events to find the atmospheric river and the large amount of snowfall. We examined all of AR events shown in Table 1 using IVT. Finally, eight of the 10 events exceeding the monthly threshold (3σ) were found and at least two events were exceeding the monthly threshold (2σ). However, the maximum for IVT at Syowa Station in 2009 was 140.33 kg $m^{-1}s^{-1}$ and did not exceed the anomalous AR threshold (250 kg $m^{-1}s^{-1}$). Because the moisture in the polar region is relatively lower than that in the low and mid latitudes, it is likely that AR does not require a rich water vapor to occur and maintain its structure around the Antarctic. Gorodetsukaya et al. (2014) introduced a new equation for IVT adapted to the polar region, however, we have confidence that HTC with satellite image can take a role to detect the AR and anomalous accumulation event.

Table 1. The AR events were detected using the proposed method from the blizzard at Syowa Station in 2009. “N” means the serial number for the blizzard events.

	AR event identified by our methodology			AR event identified by our methodology as same as analyzed by Gorodetsukaya et al. (2014)	
n	start time	end time	n	start time	end time
4	2009/3/13 21:50	2009/3/14 18:15	9	2009/5/18 3:50	2009/5/20 3:05
16	2009/7/2 21:50	2009/7/5 12:20	12	2009/6/15 19:30	2009/6/16 21:50
18	2009/7/17 3:10	2009/7/18 10:10	17	2009/7/5 13:20	2009/7/7 17:40
20	2009/8/16 12:50	2009/8/18 21:28			
23	2009/9/8 19:00	2009/9/12 12:50			
24	2009/9/26 17:10	2009/9/28 14:55			
26	2009/10/24 15:40	2009/10/25 5:50			

For undertaking research on past climates, many ice cores obtained from Antarctica were analyzed and they predicted the past atmospheric circulation and moisture transport to the ice sheet (Buizert et al., 2018). Determining the origin of the moisture transport is critical to understand the variation in deuterium-excess records as the surface temperature. The distribution of the modeled moisture sources for the Dome Fuji ice core is similar to the AR in this study around Syowa Station and the ocean area close to Syowa. This AR condition can also bring moisture to the interior region which can accumulate. In the backward trajectory analysis using reanalysis meteorological data, we found many tracks such as AR that directly impacted the station. This means that moisture transport from the mid-latitude is enhanced and moves poleward as the AR occurs during the development of cyclonic disturbances, and the snowfall accumulated directly on the ice sheet. The amount of snowfall cannot currently be simulated. We have confirmed that HTC contributes to the accumulation or decrease of snow on the ice sheet. In the further work, the SMB can be solved as stochastic model with HTC and snow depth, and some meteorological parameters. Our final goal is a coupling between CNN to find AR and stochastic model to predict accumulation for whole Antarctica.

5 Conclusion

Using satellite images, we verified that AR events associated the HTC contributed to the accumulation at Syowa Station, Antarctica in the blizzards for 2009. The detected HTC structure in the stitched satellite image with imaging analysis method often linked the AR and the values of the HTC area, and in the heavy snow conditions, they were different from the light snow conditions. We found the new seven AR events in 2009 with high accumulations and the HTC area at Syowa Station as well as three same events of Gorodetsukaya et al. (2014) with IVT method. As in other stations in the Droning Maud Land, high accumulate events were confirmed in May at Syowa Station. The snowstorm with the HTC area can affect the high accumulation of more than 10 cm of snow depth. Precipitable water calculated by radio sonde data indicated the AR clouds had a higher HTC area than non-AR. This result was reflected that the AR is a narrower long moisture band, and the cloud area should expand. We found that the IVT of our AR events exceeded three times of standard deviation of a monthly threshold. Detected ARs with high HTC area were satisfied as anomalous accumulation events. However, in the polar region, the IVT for AR should be treated as the different measure from low - mid latitudes. This is a new fusion method for finding moisture transport to the Antarctic using image analyzing method and in-situ glacial and meteorological data and can be a prototype for adapting machine leaning and stochastic method.

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Open Research

The NOAA/AVHRR infrared channel brightness temperature data are available, https://www.avl.class.noaa.gov/saa/products/search?datatype_family=AVHRR. The provided data are HRPT type, so we introduce a site where you can see quick-look images. The National Polar Research Institute archives the converted images in this repository, https://scidbase.nipr.ac.jp/modules/metadata/index.php?content_id=121; doi acquisition is in progress. Snow depth data along the JARE traverse route are shown in Motoyama et al. (2015), https://doi.org/10.15094/00010905. Hourly snow depth data at Syowa Station are available from the Japan Meteorological Agency, https://www.data.jma.go.jp/gmd/risk/obsdl/index.php (only Japanese). Three-hourly present weather and three-hourly cloud amount at Syowa Station are available from the Japan Meteorological Agency, https://www.data.jma.go.jp/antarctic/datareport/index-e.html. ERA5 hourly data on pressure levels from 1959 to present (Hersbach, H. et al. 2018) was downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store, https://doi.org/10.24381/cds.bd0915c6.

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