PICTURE OF THE MONTH

GOES-16 Observations of Blowing Snow in Horizontal Convective Rolls on 24 February 2019

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ABSTRACT

On 24 February 2019, strong winds behind an Arctic cold front led to widespread blowing snow across the northern Great Plains including areas in eastern North/South Dakota and western Minnesota. Impacts of the event ranged from blizzard conditions in northwest Minnesota to sporadic, minor reductions in visibility across the region. This study documents the event using remotely sensed observations from platforms including geostationary and polar-orbiting satellites, an S-band radar, and time-lapse images from a camera located at the University of North Dakota in Grand Forks, North Dakota. Blowing snow is observed as plumes that resemble horizontal convective rolls (HCRs). Variations in near-infrared imagery are documented, and supporting observations suggest this is due to the occurrence or absence of clouds on top of the blowing snow layer. While lack of in situ observations preclude further investigation of physical differences between plumes, the utility of the *Geostationary Operational Environmental Satellite-16 (GOES-16)* satellite to operational forecasters is discussed. Improvements to spatial, radiometric, and temporal resolution courtesy of the Advanced Baseline Imager (ABI) on board *GOES-16* allows for daytime detection of blowing snow events that previously, was only possible with instruments on board polar-orbiting satellites. This has improved Impact-Based Decision Support Services (IDSS) at National Weather Service offices that deal with the hazard of blowing snow.

1. Introduction

Blowing snow is a wintertime hazard in high-latitude regions. Defined as snow that is lofted above the saltation/suspension layer (Mellor 1965) to heights of 2 m or greater, this process is separated from drifting snow (American Meteorological Society 2019). At this level, blowing snow causes a reduction in visibility that leads to dangers with public safety and travel

(Schmidt 1979; Tabler 1979). Whether snow is lofted (and how much the process impacts visibility) depends on a number of factors including condition of the snow-pack, temperature, and wind speed (Li and Pomeroy 1997a,b; Baggaley and Hanesiak 2005).

At the extreme end of impacts, blowing snow can produce blizzard conditions that are frequent over the northern Great Plains (Schwartz and Schmidlin 2002; Coleman and Schwartz 2017). Within this region, the Red River valley of the North stretches along the border of Minnesota and North Dakota and offers the most favorable location for blizzards in the CONUS due to land cover, apparent topographic influence on winds [see Figs. 1 and 2 in Kennedy et al. (2019)], and frequency of snow cover. From 1979 to 2018, the region experienced 2.6 blizzards per year, with 2 years having 10 blizzards in a season (Kennedy et al. 2019). Additional blowing snow events are common but fall

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below blizzard criteria due to the spatial or temporal properties of winds and visibilities.

Approximately 20% of the blizzards in the Red River valley are caused by strong winds behind Arctic cold fronts occurring beneath northwesterly flow aloft (Kennedy et al. 2019). This meteorological pattern leads to the situation where blowing snow is coincident with predominantly clear skies, resulting in events known as ground blizzards (Stewart et al. 1995; Kapela et al. 1995). Forecasting the impacts of these events remains a challenge due to insufficient observations of the snowpack and model biases for boundary layer wind forecasts. The lack of operational blowing snow parameterizations prevents forecasters from directly interpreting short-term guidance from models such as the High-Resolution Rapid Refresh (HRRR; Benjamin et al. 2016). Instead, forecasters at the Grand Forks National Weather Service Forecast Office (NWSFO) use the empirical Canadian Blowing Snow Model (CBSM; Baggaley and Hanesiak 2005) tuned to cases within their County Warning Area (CWA) to determine probabilities of blowing snow and its expected impacts.

While forecasting these events will remain a challenge for the foreseeable future, one positive aspect of ground blizzards is the lack of clouds and precipitation that facilitates analysis of these events with remote sensing data. Within the literature, passive-sensing satellite studies of blowing snow have primarily been confined to Antarctica, with observations being made as early as the 1970s (Godin 1977; Zhdanov 1977). More recently, Scarchilli et al. (2010) used visible imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on board the NASA *Terra* and *Aqua* satellites to document blowing snow plumes (billows) associated with katabatic winds in East Antarctica. These features were tall enough to cast shadows, suggesting plumes heights of at least several hundred meters. This was confirmed by Palm et al. (2011, 2017) who compared daytime near-infrared imagery from MODIS to actively sensed observations of blowing snow over Antarctica. These depths are sufficient for blowing snow plumes to modify outgoing longwave radiation (OLR) as documented by Yang et al. (2014).

Although blowing snow plumes across the northern tier of the CONUS have been recognized by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) satellite blog (Bachmeier 1997, 2019), and in forecasting tutorials (UCAR 2004), formal publications documenting these events are sparse. In Kennedy et al. (2019), false-color imagery using the Visible Infrared Imaging Radiometer Suite

(VIIRS) on board the *Suomi National Polar-Orbiting Partnership* (*Suomi NPP*) satellite was shown to demonstrate ground blizzards confined to the Red River valley. A common thread across both informal material, studies in Antarctica (Palm et al. 2011, 2017, 2018b) and Kennedy et al. (2019) is the importance of near-infrared channels (e.g., 1.61 or 2.2 μm) to detect the blowing snow layer.

Blowing snow has also been investigated with active-sensing instruments. Space- and ground-based lidars have been used to determine the frequency and heights of plumes over Antarctica (Mahesh et al. 2003; Palm et al. 2011, 2017; Gossart et al. 2017; Palm et al. 2018a,b). While most plumes have depths around ~ 100 m, they can occasionally reach heights up to ~ 500 m AGL over this continent. Although surface-based signals can occasionally exceed this height, it has been argued that these events are diamond dust (Palm et al. 2017, 2018b). No climatological studies of blowing snow exist in North America (or even the Northern Hemisphere); however, the Wyoming Cloud Radar was used to identify blowing snow in mountainous regions during aircraft campaigns (Geerts et al. 2011; Vali et al. 2012; Geerts et al. 2015).

Given the dearth of literature on blowing snow plumes in northern midlatitude regions of the world, the purpose of this picture of the month is to highlight blowing snow plumes on 24 February 2019 that led to widespread blizzard conditions throughout the Red River valley and surrounding region. Further, this work will demonstrate the utility of the latest generation of geostationary satellites to detect this hazard. Visual images, radar, and satellite data are presented to highlight properties of blowing snow and to briefly discuss how this information is used in real time for short-fuse forecasting. Finally, avenues of future work are discussed as a number of outstanding questions remain for blowing snow.

2. Meteorological environment of 24 February 2019

The occurrence of blowing snow is dependent upon wind speed, air temperature, and condition of the snowpack. While measurable snow was minimal during the 24 February 2019 blowing snow event, 1–4 in. (2.5–10 cm) of snow fell over portions of the northern Red River valley and northwest Minnesota within 48 h leading up to the event. Farther south, higher totals were observed, with maximum snowfall totals reaching ~ 8 in. (20 cm) in southeastern North Dakota. The bulk of this snowfall occurred from 1800 to 1400 UTC 22–23 February 2019 and was not associated with notable surface winds. Between the snowfall and the

FIG. 1. Meteorological fields from the GFS analysis valid at 1800 UTC 24 Feb 2019. (a) 500-hPa geopotential height (black contours), 500-hPa wind magnitude (semitransparent gray contours), and 925-hPa temperature advection (filled contours). (b) Mean sea level pressure (MSLP, black contours) and 6-h MSLP change (filled contours). Yellow boxes denote the *GOES-16* analysis region in Fig. 3.

blowing snow event, surface temperatures ranged from -5° to -20°C , favorable for the lofting of snow crystals when subjected to the appropriate wind shear stress.

Immediately following the initial snow event, a surface low pressure system associated with a deep, upper-level wave developed over the northern panhandles of Oklahoma and Texas by 1200 UTC 23 February 2019 (not shown). This cyclone (and upper-level wave) quickly propagated to the northeast with the center of the surface low passing from Wichita, Kansas, to

Madison, Wisconsin, by 0600 UTC 24 February 2019. Although forcing associated with this system produced significant snowfall across the central Great Plains and into the Midwest, most of this snow fell south of the Red River valley.

By 1800 UTC 24 February 2019, the cyclone and upper-level wave moved into Ontario, Canada (Fig. 1). Behind these features, the Red River valley resided under northwest flow aloft with the jet axis just south of the region (Fig. 1a). Near the surface, cold-air advection

FIG. 2. RAP soundings for Grand Forks, ND (KGFK), valid at (a) 1200 and (b) 1800 UTC 24 Feb 2019.

within the boundary layer and surface pressure rises were noted across the region behind the Arctic cold front (Fig. 1b). Analysis of Rapid Refresh (RAP) soundings from the region suggested cold-air advection depicted in the GFS analysis (most prominent at 925 hPa) may have been weaker than observed, with the temperature profile cooling from the surface to 700 hPa throughout the day (Fig. 2). While truth is unknown due to the lack of upper-air soundings in the Red River valley, favorable comparisons between the RAP and observed soundings at Aberdeen, South Dakota, were found during this time period (not shown).

An area of strong surface winds resulted from an increased pressure gradient as the region found itself

between a southeasterly propagating 1042-mb surface anticyclone over the Canadian High Plains, and the exiting sub-980-mb surface cyclone over Ontario (Fig. 1b). This led to widespread reports of wind gusts >40 kt (21 m s^{-1}) across the Red River valley and surrounding area, well above the threshold needed to cause blowing snow.

3. Regional analysis of blowing snow plumes

a. Background

Space-borne passive detection of blowing snow has proven problematic due to its radiometric properties and limitations of satellite observing strategies and instrumentation. At visible wavelengths, blowing

TABLE 1. Characteristics of the Day Snow-Fog RGB composite imagery. Table adapted from CIRA (2019). Values within parenthesis are used in this study.

Color	Band	Wavelength (μm)	Gamma	Threshold
Red	3	0.86	1.7 (1.9)	0%–100% (0%–80%) albedo
Green	5	1.6		0%–70% (0%–50%) albedo
Blue	7–13	3.9–10.3		0°–30°C (0°–25°C)

snow has a high albedo similar to the snow-covered ground. Although plumes have been readily documented using near-infrared bands, the highest-resolution sensors that provide this information such as MODIS or VIIRS have historically been limited to polar-orbiting satellites. This has precluded their use for short-fuse forecasting due to the limited overpasses associated with these platforms. Ideally, geostationary satellite data should be used, but older generations of Geostationary Operational Environmental Satellites (GOES) featured imagers with lower spatial resolution and a limited number of spectral bands (e.g., the GOES-I series; Menzel and Purdom 1994). Instead, blowing snow detection has been reliant on adequate depth to cast shadows during time periods of larger solar zenith angles (Bachmeier 1997).

The Advanced Baseline Imager (ABI; Schmit et al. 2017, 2018) available on the latest generation of GOES has changed the game for operationally detecting blowing snow plumes. With 16 radiometric bands, improved spatial resolution, and rapid-scan abilities, the ABI is now being used operationally at the Grand Forks NWSFO to detect this hazard. The greatest utility has been multispectral, composite imagery combining information from the near-infrared and longwave infrared channels. Known as the “Day Snow-Fog” product, the 0.86-, 1.6-, 3.9-, and 10.3- μm wavelength bands are used to separate varying land surface cover from liquid and ice phase clouds (Table 1, CIRA 2019). Physically, this combination works due to the varying reflectance of these surfaces and hydrometeors at the near-infrared wavelengths. The first two channels are used, respectively, for the red and green colors of the composite. The blue color of the composite comprises a difference between the 3.9- and 10.3- μm channels. Because the 3.9- μm channel is sensitive to both reflected solar radiation and emitted radiation from the surface, subtraction of the 10.3- μm band results in a proxy for the reflected component during the day. While this composite is handy to identify variability in land cover and cloud phase, the use of near-infrared channels

means that its utility is limited to the daytime when sufficient reflected signal exists.

b. Satellite and surface analysis of blowing snow

GOES-16 composite imagery from the morning to late afternoon hours (local noon = 1800 UTC) of 24 February 2019 are shown in Fig. 3. Predominant features include blowing snow plumes (tan), cloud cover (purple), surface snow/ice cover (maroon), and vegetated surface (darker purple regions in northern Minnesota). At 1537 UTC (0937 LST), blowing snow is most noticeable in the eastern Red River valley in northeast North Dakota and northwest Minnesota as thin streaks (Fig. 3a). These plumes were coincident with 25–35 kt ($13\text{--}18\text{ m s}^{-1}$) sustained winds and visibilities down to 1/4 mi (400 m) at Thief River Falls, Minnesota (KTVF; Fig. 4). Elsewhere in the region, winds and visibilities reaching blizzard criteria were located in west-central Minnesota at surface sites such as Benson, Minnesota (KBBB). Presence of clouds and the larger solar zenith angle made identifying blowing snow more difficult to discern at times prior to 1537 UTC. Surface observations had reduced visibilities (presumably due to blowing snow) ≤ 1 mi (1.6 km) at KTVF and KBBB as early as 1200 and 1400 UTC, respectively (Fig. 4). The authors’ location also experienced blowing snow at this time (see section 4), but the impacts were less, with visibility reduced to 1–1.5 mi (1.6–2.4 km) from 1500 to 1700 UTC (Fig. 4a).

By 1737 UTC, blowing snow was readily apparent in *GOES-16* imagery across the region (Fig. 3b). Characteristics of these plumes varied by area with the western (eastern) Red River valley having elongated, widely (narrowly) spaced rows of blowing snow resembling horizontal convective rolls (HCRs). In South Dakota, blowing snow was also present, but the structure was more poorly defined. Analysis of higher-resolution VIIRS and MODIS data around this time (not shown) suggested the poor definition in South Dakota was primarily due to *GOES-16* resolution, and the optically thin nature of plumes in this area. This was consistent with visibilities that, while reduced, did not meet blizzard criteria in this state. Overall, the most impressive region of blowing snow (from a visibility standpoint) persisted in northwest Minnesota. The entire region of blowing snow extended at least 300 km, with some individual plumes having lengths that exceeded 100 km. Spacing between the plumes was variable, with some approaching the resolution of *GOES-16* near-infrared bands (2 km).

Starting at 1737 UTC, there was evidence that plumes varied microphysically as appearance in composite imagery ranged from tan to purplish in hues (e.g., eastern

FIG. 3. GOES-16 composite imagery valid at (a) 1537, (b) 1737, (c) 1937, and (d) 2137 UTC 24 Feb 2019. Composites comprise the 0.86-, 1.6-, and 3.9–10.3- μm bands used, respectively, for the red, green, and blue channels. The yellow and red boxes in (b) denote the region of *Sentinel-2* imagery shown in Fig. 6 while the white box represents the area of radar data shown in Fig. 7. Yellow text highlights pertinent surface locations including observations displayed in Fig. 4. The yellow star indicates the location of the UND Department of Atmospheric Sciences Skycam presented in Fig. 8.

FIG. 4. Time series of surface meteorological properties on 24 Feb 2019 including 10-m sustained winds (shaded gray area), 10-m wind gusts (red dots), and visibility (black lines) for (a) KGFK (Grand Forks, ND), (b) KTVF (Thief River Falls, MN), and (c) KBBB (Benson, MN).

North Dakota). This variability was also seen in west-central Minnesota near KBBB. To shed light on these differences, individual channels that construct the composite imagery along with the highest-resolution visible band ($0.64\text{ }\mu\text{m}$, 0.5 km) are presented in Fig. 5. As expected, the full extent of blowing snow is difficult to see in the visible channel (Fig. 5a). Detection is primarily limited to plumes that are tall enough to cast shadows, which subjectively, appear more likely to be associated with the purplish hues seen in Fig. 3b. This analysis is largely identical to inspection of the $0.86\text{-}\mu\text{m}$ channel (Fig. 5b), except some clarity is lost due to the increase of pixel size from 0.5 to 1 km . For this case, blowing snow is most identifiable with the $1.6\text{-}\mu\text{m}$ channel (Fig. 5c). Large differences in reflectivity are seen with the darkest regions coinciding with snow/ice covered ground while clouds are associated with higher albedo. Blowing snow has values of reflectivity between these two extremes although the taller, more isolated plumes appear brighter. These areas are coincident with the brightest regions of the $3.9\text{--}10.3\text{-}\mu\text{m}$ difference band (Fig. 5d). Because this difference channel isolates the $3.9\text{-}\mu\text{m}$ reflectance that is sensitive to cloud phase (water is more reflective than ice) and particle size (smaller crystals are more reflective), the combined analysis of bands 5, 7, and 13 suggest some plumes are topped by clouds (Minnis et al. 1998). Efforts to determine cloud phase with *GOES-16* ABI and MODIS retrievals were inconclusive (not shown). While the higher-resolution MODIS sensor identified the majority of blowing snow plumes as ice phase, pixels of stronger reflectance at 1.6 and

$3.9\text{ }\mu\text{m}$ (the region oriented northwest–southeast of KBBB) were labeled as water. This was not in perfect agreement with the transition seen in composite imagery (Fig. 3). Considering this finding and the lack of in situ observations, the phase of clouds remains unclear.

Fortuitously, the *Sentinel-2* satellite overpassed the region at this time, providing high-resolution ($10\text{--}20\text{ m}$) imagery in the near-infrared, allowing this speculation to be investigated (Fig. 6). Across the subset region, clear differences are seen in near-infrared reflectance with *Sentinel-2* imagery. While blowing snow has increased reflectance over the surface, cumulus clouds are seen as areas of bright reflectivity. In many cases, these clouds are sufficiently optically thick to cast shadows. Comparing the *GOES-16* to *Sentinel-2* imagery, it is obvious that regions with more clouds are associated with the purplish hues in composite imagery opposed to tan, cloud-free scenes associated with blowing snow.

As the afternoon progressed from 1937 to 2137 UTC, the characteristics of blowing snow plumes changed (Figs. 3c,d). Overall, plumes elongated with increased spatial separation between individual bands across Minnesota and North Dakota. Whether plumes were largely blowing snow versus those topped by clouds varied by region with a broad area of cloud topped plumes existing across the border of North Dakota/Minnesota southeastward into west-central Minnesota. The impacts of these changes led to spatial and temporal variability in visibility for many areas. While KBBB and KTVF were within bands throughout the day, sites such as Grand Forks, North Dakota (KGFK), had visibilities that

FIG. 5. *GOES-16* imagery at 1737 UTC 24 Feb 2019 for (a) band 2 ($0.64\mu\text{m}$), (b) band 3 ($0.86\mu\text{m}$), (c) band 5 ($1.6\mu\text{m}$), and (d) the difference between bands 7 and 13 ($3.9\text{--}10.3\mu\text{m}$). Select annotation shown is identical to Fig. 3.

FIG. 6. *Sentinel-2* composite imagery for the 1737 UTC 24 Feb 2019 overpass. The composite comprises the B11 ($1.6\ \mu\text{m}$) and B8 ($0.8\ \mu\text{m}$) bands. B11 was used for the red/green channels, while B8 was used for blue.

oscillated depending on whether it was inside or outside of a blowing snow plume.

4. Photographic and radar analysis of blowing snow plumes near Grand Forks, North Dakota

Although Grand Forks, North Dakota, did not reach blizzard criteria, it did experience several blowing snow plumes. Proximity of the Mayville, North Dakota (KMXV), Weather Surveillance Radar-1988 Doppler (WSR-88D) and time-lapse video from the westward facing University of North Dakota (UND) Department of Atmospheric Sciences Skycam allows for additional analysis of the event. While the discussion focuses on this region, blowing snow plumes were also identified on

other regional WSR-88Ds including KABR (Aberdeen, South Dakota), KFSD (Sioux Falls, South Dakota), KMPX (Minneapolis, MN). KMXV reflectivity imagery coincident with earlier presented *GOES-16* data are shown in Fig. 7 while UND Skycam images during these and several additional times are shown in Fig. 8.

The worst conditions for KGFK occurred from 1500 to 1700 UTC as evidenced by visibilities down to 1 mi (1.6 km) at approximately 1530 UTC (Fig. 4a). At 1537 UTC, blowing snow northeast of KMXV was associated with a broad area of meteorological backscatter (correlation coefficient >0.95 , not shown) with equivalent radar reflectivity (Z_e) ranging from -10 to $10\ \text{dBZ}$ (Fig. 7a). Although signal was not present over the UND Skycam (presumably due to beam height and plume characteristics), blowing snow is viewed as a hazy white sky, with some reduction in visibility at the surface (Fig. 8a). By 1737 UTC, this layer moved away from Grand Forks, North Dakota, and visibility increased at both KGFK and the UND Skycam (Fig. 8b). Consistent with *GOES-16* satellite imagery (Fig. 3b), plumes were associated with linear features of Z_e that decreased in intensity from southwest to northeast (note that the signal just southwest of KMXV is clutter). At this location, bands were oriented within ten degrees of the boundary layer mean wind vector seen with both the radar (not shown) and the RAP soundings (Fig. 2). Relating this data to the presence of cloud as detected by *GOES-16*, signal southwest (northeast) of KMXV was associated with blowing snow (blowing snow+cloud). This analysis is supported by UND Skycam imagery depicting blowing snow near the horizon, but rows of thin clouds closer to the camera.

As time progressed into the afternoon, radar analyzed blowing snow plumes varied with respect to intensity, spacing, width, and length (Figs. 7c,d). Plumes were more equally spaced earlier in the day, separated by an average distance of 6–7 km near KMXV at 1737 UTC. Assuming standard refraction, detectable signal of plumes reached 0.7 to 0.9 km AGL, consistent with the 1800 UTC RAP sounding for KGFK (Fig. 2b). Estimated plume heights should be viewed as a conservative estimate because there are clear limitations of detecting these features with an S-band WSR-88D radar. Values yield HCR aspect ratios of 6.7–10, which is on the high side of land-based rolls (Atkinson and Zhang 1996; Young et al. 2002). One possible explanation for this result is the existence of additional HCRs that fell below the sensitivity of the WSR-88D. In other regions (e.g., KTVF), aspect ratios were likely smaller due to the reduced distance between rolls.

Of particular note is the blowing snow plume located just west of KGFK and observed by the UND Skycam

FIG. 7. Base tilt (0.5°) equivalent reflectivity factor from the KMXV—Mayville, ND, WSR-88D radar for (a) 1537, (b) 1736, (c) 1934, and (d) 2139 UTC 24 Feb 2019. The location of the UND Department of Atmospheric Sciences Skycam is denoted by the black star and label.

from 1937 to 2137 UTC. From a *GOES-16* perspective, this feature was identified as a cloud topped plume due to the purplish hue in composite imagery (Figs. 3c,d). On radar, this plume had Z_e up to 10–15 dBZ, and widths from 3 to 9 km as it slowly progressed eastward toward Grand Forks, North Dakota (Figs. 7c,d). The plume was observed by the UND Skycam as a white band on the horizon topped by cloud (Figs. 8c,d). Time-lapse footage of the plume documented roll-like features within the clouds consistent with the nature of HCRs (see the online supplemental

material). At times, this footage also suggested some of the clouds may have also been producing snow, leading to a blurred distinction between falling and blowing snow.

By 2200 UTC, the plume impacted KGFK, and visibility was reduced to 2–2.5 mi (3.2–4 km) for approximately 1 h. The plume passed over the Skycam approximately 15 min later (Figs. 8e,f). While detectable signal was not seen on KMXV due to either the beam height or intensity of the plume, the presence of the blowing snow layer was supported by optical phenomena

FIG. 8. Image captures from the UND Department of Atmospheric Sciences Skycam taken at (a) 1537, (b) 1737, (c) 1937, (d) 2137, (e) 2217, and (f) 2312 UTC 24 Feb 2019.

on the UND Skycam and informal surface observations by the lead author. Initially, weak parhelia (sundogs) were observed with a 22° halo. The latter feature is supportive of a random orientation of ice crystals that would be expected with blowing snow. As the plume progressed across the camera, the intensity of the optical phenomena increased. At its peak, the aforementioned features were accompanied by a parhelic circle (Fig. 8f). Shortly thereafter, the plume passed and the blowing snow event of 24 February 2019 was officially over for Grand Forks, North Dakota.

5. Discussion

a. Operational impacts of GOES-16

The blowing snow event of 24 February 2019 was one of eight blizzards observed within the Grand

Forks NWSFO CWA during the 2018–19 winter. With *GOES-16* fully operational, these events provided an excellent opportunity to understand the platform's role within the forecast environment. From this perspective, the added spectral bands within the near-infrared, rapid scan strategies, and relatively high spatial resolution offered by the ABI made detection and monitoring of blowing snow easier, supplementing limited radar observations and automated/human surface reports of visibility. At the Grand Forks NWSFO, forecasters used *GOES-16* imagery to refine wintertime products (e.g., confine blizzard warnings to a spatially smaller and more representative area). The utility of imagery has also led to *GOES-16* mesoscale sector requests for some events, which has highlighted the sometimes rapid temporal evolution of the process. Overall, these activities have led to

better situational awareness of blowing snow extent that has improved Impact-Based Decision Support Services (IDSS) when used in tandem with other observations. Of particular note has been the recent development of snowplow cameras that allow for real-time monitoring of visibility in often rural areas to validate areas of blowing snow identified by *GOES-16*.

Despite the benefits that have already been realized by the *GOES-16* platform, best-practices are still poorly understood, and known limitations exist. For now, the “Day Snow-Fog” composite has seen the most usage with some modifications (e.g., gamma and clip settings) made on the fly to account for the time of day. It is unknown whether a better combination of channels exist, or how this composite can be tuned (preferably automatically) for varying solar zenith angles. It is also unclear how near-infrared reflectance is related to surface visibility, and this begs the question of whether a retrieval for blowing snow particle size or surface visibility is possible. To this end, the use of *GOES-16* Level-2 products such as particle size and cloud phase has not been thoroughly explored, and efforts to use the latter product were inconclusive in determining cloud phase of cloud-topped plumes. At a minimum, this case study demonstrates there will be limitations due to optically thick clouds that top some of the plumes. More broadly, cloud cover (at any height) can interfere with the detection of blowing snow, and this means the greatest utility of *GOES-16* is for ground blizzards under predominantly clear skies versus blizzards forced by patterns such as Colorado lows and Alberta clippers (Kennedy et al. 2019). Finally, the current identification of blowing snow is dependent on near-infrared reflectance, preventing the detection of the process during nighttime hours.

b. Other outstanding questions and future work

Arguably, this case study has provided more questions than answers regarding blowing snow. The plumes in this case appear as HCRs, but the spacing, intensity, and microphysical structure vary spatially and temporally. While there is a breadth of literature pertaining to boundary layer rolls (see Etling and Brown 1993 for a review), to the authors’ knowledge, no studies have addressed rolls that contain blowing snow. The closest study that resembles this work is a previous picture of the month by Schultz et al. (2004) who characterized snowbands associated with HCRs in a cold-air outbreak across the southeastern United States. The concern of drawing conclusions from prior work include the conditions of the surface (snow cover) and the thermodynamic cooling process of sublimation associated with blowing snow (Pomeroy et al. 1997; Taylor 1998).

Modeling efforts by Yang and Yau (2011) have demonstrated this latter process can be significant enough to impact the dynamical evolution of synoptic-scale systems. More recently, dropsonde observations from Antarctica have provided evidence that sublimational cooling may be offset by turbulent mixing (Palm et al. 2018a). Overall, the boundary layer structure and how it is modified by blowing snow is poorly understood, and more work is needed.

Modeling blowing snow is another critical issue that warrants effort. At the present time, this process is not included in operational NOAA models, and this forces operational forecasters to use empirical models such as the CBSM. Parameterizations of blowing snow exist, and have been developed from surface observations at high-latitude locations such as Canada and Antarctica (Déry and Yau 2001; Gallée et al. 2001; Yang and Yau 2008). A major limitation of these efforts has been the lack of spatial and vertical validation of blowing snow properties. Such comparisons are necessary to properly understand blowing snow fluxes and the associated sublimation rates, as well as radiative (scattering and absorption) properties of the layer. This case study demonstrates *GOES-16* observations may provide a way to quickly evaluate the spatial extent of simulated blowing snow. What remains to be seen is how to assess and improve the vertical and microphysical representation of blowing snow. While more work is needed with *GOES-16* derived products, future efforts should include field work that combines data from remote sensing platforms with in situ observations and modeling activities. Instrumentation advancements such as unmanned aircraft or balloon-borne hydrometeor imagers are needed before this goal can be fully realized.

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