https://doi.org/10.5194/acp-2021-966
Preprint. Discussion started: 6 January 2022

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The Mount Everest plume in winter

Edward E. Hindman[1], Scott Lindstrom[2]

[1]Department Earth and Atmospheric Sciences, The City College of New York, New York, 10031, US
[2]Space Sciences and Engineering Center, University of Wisconsin, Madison, Wisconsin, 53706, US

Correspondence to: Edward E. Hindman (ehindman@ccny.cuny.edu)

Abstract. Mt. Everest's summit pyramid is the highest obstacle on earth to the wintertime jet-stream winds. Downwind, in its wake, a visible plume often forms. The meteorology and composition of the plume are unknown. ~~Accordingly, we observed real-time images from a geosynchronous meteorological satellite from November 2020 through March 2021 to identify plumes and collect the corresponding meteorological data.~~ We used the data with a basic meteorological model to show the plumes formed when sufficiently moist air was drawn into the wake. We conclude the plumes were composed initially of either cloud droplets or ice particles depending on the temperature. One plume was observed to glaciate downwind. Thus, Everest plumes may be a source of snowfall formed insitu. The plumes, however, were not composed of resuspended snow.

Commented [e1]: We revised the title following the suggestion by RC2. We inserted: 'The formation and composition of'

Commented [e2]: Responding to a RC2 comment, we replaced the word 'often' with 'can'.

Commented [e3]: We revised this sentence responding RC2's suggestion to develop plume statistics: 'Accordingly, daily, we observed real-time images from a geosynchronous meteorological satellite from 1 Novembe 2020 through 31 March 2021 (151 days) to identify the da plumes formed. The corresponding surface and upper-air meteorological data were collected'.

Commented [e4]: The results of our plume statistics analyses, suggested by RC2, were inserted here before 'w 'The massif was visible on 143 days (95%), plumes forme on 63 days (44%) and lasted an average of 12 hours'.

Commented [e5]: RC2 suggested we estimate the magnitude of plume-produced snow. We inserted the resu here:
'One plume was observed to glaciate downwind. We estimated snowfall from the plumes may be significant'.

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1 Introduction

Mt. Everest's summit is the highest elevation on earth and its summit pyramid (Fig. 1) is the largest obstacle to the upper-air winds. With sufficient flow, a turbulent wake forms downwind of the pyramid and a visible plume can form in the wake (Fig. 2). The meteorology and composition of the plume have been studied, but not been determined conclusively. This study is a first-step to determine its meteorology and composition. We studied the plume in winter as have all previous investigators. The previous studies, to our knowledge, are as follows.

Figure 1. The Mount Everest and Lhotse summit pyramids are identified, respectively, by the black-dashed and black dash-dot lines. The bases of the pyramids are at an elevation of approximately 7900m. The summits are, respectively, 8848m and 8501m in elevation. The map segment is from the November 1988 issue of the National Geographic Magazine.

A January 2004 plume was investigated by Moore (2004) (Fig. 2 - top and middle). He concluded the plume was composed of resuspended snow blown from the peak. He argued that because the atmosphere was too dry the plume could not be a banner cloud (Douglas, 1928), i.e., a collection of cloud droplets. A plume photographed by Venables (1989) looks identical to Moore's plume (Fig. 2 - bottom). Venables, who was on his way to climb Everest's east face (obscured in the image by the plume), referred to the plume as "the usual plume of cloud and snow, blasted off the summit by the prevailing westerlies."

Commented [e6]: At the suggestion of RC2, we inserte 'at 8848 m'.

Commented [e7]: At the suggestion of RC2, we added map of the Everest region to Fig. 1 to help the reader understand the images from the satellite that follow. We a added a stunning and unique image of the Everest summit pyramid to compliment Fig. 1a.

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Figure 2. Top - The Everest plume studied by Moore (2004) imaged from the International Space Station (ISS) on 28 January 2004 at 1001Z (1601LST, Local Solar Time). Middle – The plume 3-minutes later from the ISS, not reported by Moore. Bottom - The Everest plume published in Venables (1989) photographed from the Pang La in Tibet (China) on 6 March 1988 at about 0600Z (1200LST). The major peaks in the images are identified.

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Plumes from the Everest massif were observed in December 1992 by Hindman and Engber (1995), Fig. 3, and captured in a video by Hindman in November 1995 (see *Mt. Everest plume in winter-Videos.zip*). As can be seen in the figure and in the video, the plumes were not present in the morning but appeared in the afternoon. The video illustrates that the plumes formed like clouds and flowed and undulated like clouds. Based on this behaviour plus investigations of the Everest airflow by Hindman and Wick (1990), they concluded these plumes were banner clouds.

Commented [e8]: Because of a suggestion by RC1, 'concluded' was replaced by 'reported'.

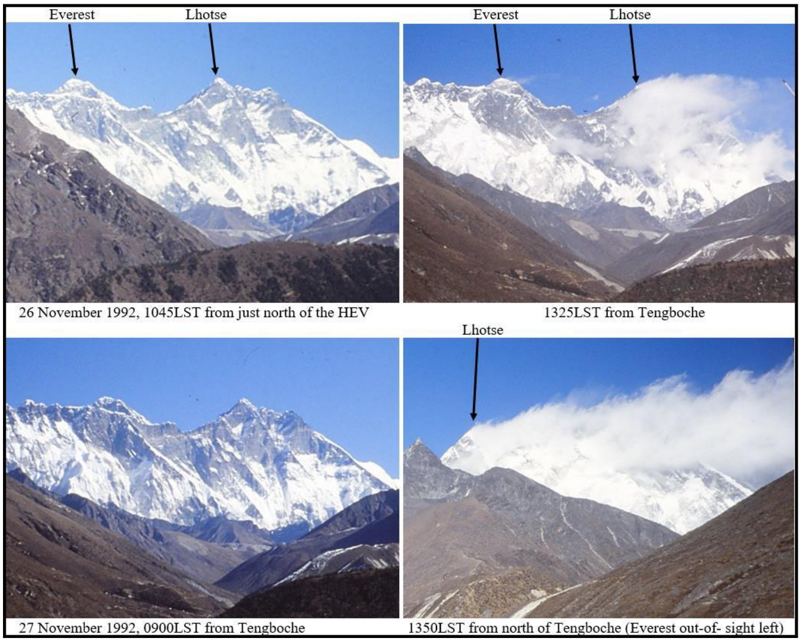

Figure 3. The plumes studied by Hindman and Engber (1995) photographed from Nepal (HEV is the Hotel Everest View located about 20 km south of Everest in Namche Bazar, Nepal; Tengboche is about 10 km south of Everest).

~~The appearance of resuspended snow and that of banner clouds will help define the composition of the plumes. The appearance, how the phenomena look, has been reported by Schween et. al., (2007). Their time-lapse videos of the Zugspitze peak in the Bavarian alps illustrate that resuspended snow looks~~

Commented [e9]: Because of a comment by RC1, we replaced this paragraph with the following paragraph: 'Movie 1 captures the formation and evolution of the plum The movie began at 0940 LST showing the summits of Everest (poking over the Nuptse ridge) and Lhotse (to the right) were plume free. At about 1050 LST, a plume bega in the wake of Lhotse. Clouds began to form on the valley slopes about 1200 LST. The plume reached full development at about 1400 LST. At that time, the plume began to be intermittently obscured by clouds filling the valley. The movie ends at 1630 LST because the HEV wa enveloped by the clouds that had completely filled the valley'.
Also, we captioned Movie 1 following his suggestion.

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~~different than banner clouds. Their Fig. 10 shows resuspended snow looked fuzzy and white while their Fig. 4 shows banner clouds looked solid and white.~~

Further, numerical simulations by Reinert and Wirth (2009) and Voigt and Wirth (2013) demonstrate banner clouds form in the lee of steep mountain peaks as a result of dynamically-forced lee upslope flow, confirming the flows postulated by Hindman and Wick (1990) that were inspired by Douglas (1928). The simulations show the speed of the lee upslope flow is much smaller than the speed of the wind impacting the peak. Thus, we think the lee upslope flow is too weak to resuspend snow.

~~For this study, we observed daily real-time images from a geosynchronous meteorological satellite to identify when the Everest massif was producing plumes and when it was not. We collected the corresponding meteorological data. To determine the conditions for plume formation, we used the meteorological data with a basic model that approximates the dynamically-forced lee upslope flow.~~

2 Procedures

To our knowledge there is no continuous imaging of the Everest massif from either Nepal or Tibet (China). Additionally, there are no atmospheric soundings launched either. Thus, daily we observed the Everest region during the 2020-21 winter, November through March, using real-time, every ten-minutes images (Band03-visible) from the Himawari-8 Japanese geosynchronous meteorological satellite (GMS, www.data.jma.go.jp/mscweb/data/himawari/sat_img.php?area=ha2). ~~We used archived images to illustrate the plumes studied here. The images and corresponding videos were produced following procedures in the Data Availability section~~.

We collected the atmospheric soundings that corresponded to the GMS images from NOAA (www.ready.noaa.gov/index.php), constant-pressure analyses from the College of DuPage (weather.cod.edu/forecast/) and the surface measurements from the automatic weather station (AWS,

Commented [e10]: RC1 informed us of this important reference that we missed. So, we inserted: 'and Prestel an Wirth (2016)'

Commented [e11]: We revised the paragraph to read: 'Schween and colleagues (2007) show still images and animations, all with the same view, from the summit of th Zugspitze in the Bavarian Alps. Because of the best possi spatial and temporal resolution, they were able to show th formation of banner clouds and snow blown off an adjacen peak.

Here we use the best possible spatial and temporal resolut images available to us from a geostationary meteorologica satellite to observe the formation of plumes in the lee of th Everest massif. When we saw a plume form in the mornin and if our calculations predicted cloud formation through condensation of moisture in the airstream upwelling in the immediate lee of the massif, the plume was likely a banne cloud. The composition of the cloud was inferred from its temperature'.

Commented [e12]: We replaced the sentence with the following:
[Note: Anonymous reviewer (2022) informed us of a live-stream of the massif from the HEV (www.youtube.com/watch?v=RgDjOg4WvGI). The strea was not useful for this study because it began in January 2022)].

Commented [e13]: This statement was removed. The source of the H-8 images is identified in the Data Availability section.

Commented [e14]: This statement was moved to lines and 104 in the revised manuscript.

Commented [e15]: RC1 questioned the spatial resoluti of the H-8 images. So, we inserted the following paragraphs:

The spatial resolution of the H-8 images is sufficient to resolve the plumes, not as they form, but shortly thereafte The following is our reasoning. The sub-satellite point is 0N, 104.7E and the summit of Mount Everest is at 27.99N 86.93E. At the sub-satellite point, the satellite zenith angl 0 degrees (nadir) and the spatial resolution is 0.5 km for images in the visible Band 3 and 2.0 km for images in the infrared Band 13. Careful examination of pixel edges suggests that the 0.5 km and 2 km nadir resolutions are degraded to, respectively, about 1 km and 4 km in the vicinity of Everest. The plume Moore (2004) studied, sho in Figure 2, he estimated to be 15 km in length. Also comparing the plumes in Figure 3 with the map in Figure it can be seen that the plumes were kilometers in length. had the H-8 been in orbit in 1992 and 2004, these plumes would have been observed.

The images from the H-8 website were observed daily in t both the 'still' and 'animation' modes. The images could

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earthpulse-raw.nationalgeographic.org/index.html) at Phortse, Nepal (27.84N, 84.75E). The village of Phortse is about 10 km south of Everest. The AWS is described by Perry, et. al. (2021).

~~We used an atmospheric model to simulate an air parcel ascending the dynamically-forced lee upslope flow in the wake of the Everest summit pyramid. The summit pyramid is illustrated in Fig. 1. It can be seen in the figure that both Everest and its neighbour to the south, Lhotse, present pyramids to the typically west-to-east air flow. Hence, both summit pyramids produce wakes and, as seen in Fig. 2-top, both produced plumes.~~

Commented [e16]: We inserted this paragraph respond to RC1 to describe our atmospheric model:
'It can be seen in Fig. 1a, that both Everest and its neighbo to the south, Lhotse, present significant obstacles to the typically west-to-east air flow. Hence, both peaks produc wakes and, as seen in Fig. 2-top, both produced plumes. Cloud formation was investigated in the dynamically-forc lee upslope flow in these wakes. The lifted-condensation-level (LCL) of the upslope flow was calculated with the following procedure'.

The atmospheric soundings, profiles of temperature, dewpoint (moisture) and wind, used with the model were for the location of Phortse. The profiles were displayed using the American Skew-T adiabatic diagram. The profiles were graphically analysed to determine the lifted-condensation-level (LCL): the temperature and dew point values at the 400mb level, the approximate pressure level at the base of the Everest pyramid, were raised, respectively, dry-adiabatically and with moisture constant to the level where saturation was achieved. If the LCL was achieved before reaching the 300 mb level, the approximate pressure level at Everest's summit, a plume was expected to form. If the LCL was not achieved before reaching 300mb, a plume was not expected to form; the unsaturated parcel would be swept downwind by the high-speed summit winds. We checked the LCL values using www.csgnetwork.com/lclcalc.html.

~~The initial composition of a plume was determined from the temperature of the LCL.~~ Baker and Lawson (2006) report the composition of mountain wave clouds, an analogue to Everest plumes. They found the clouds could be ice particles at temperatures colder than about -35C. Thus, if a LCL temperature was warmer than -35C, initially liquid droplets are expected to have formed. Conversely, if a LCL temperature was at or colder than -35C, initially ice crystals are expected to have formed.

Commented [e17]: We replaced the sentence with:
'The composition of a forming plume was inferred from t temperature at the LCL'.

Commented [e18]: Responding to RC2's question abou mixed-phase plume we inserted:
'A mixed-phase plume (coexisting droplets and crystals) i expected near -35 ^{0}C'.

We looked for the following events in the daily satellite images:

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1. A day with no visible plume and no measured snowfall at Phortse either that day or the previous two days. This sequence will illustrate the GMS view of the cloud-free Everest region and the corresponding non-plume atmospheric conditions.
2. A day with a visible plume and no snowfall either that day or the previous two days at Phortse. This sequence will illustrate the atmospheric conditions for plume formation.
3. A day with a visible plume with no snowfall measured at Phortse that day but snowfall measured the previous three days, an event similar to Moore's (2004) study. If the model does not predict a plume, we concluded the plume was composed of resuspended snow. If a plume is predicted, we concluded the plume was a banner cloud.

Lastly, we studied GMS images of the Moore (2004) plume event to determine if the plume behaved similarly as our Event 3.

3 Results

3.1 Event 1

No plumes were observed (Figure 4) and no snowfall was measured at the AWS on 25, 26 and 27 January 2021. Sharp shadows cast by the Cho Oyu and Everest summits can be seen in these afternoon images indicating no plumes present.

The shadows are more easily seen in the animation of the every-ten-minute images for 2021-01-27 from just before sunrise to just after sunset, 0040 to 1150Z (0640 to 1750LST). The animation is in the attached *Mt. Everest plume in winter-Videos.zip*. The Everest massif is in the center of the image. Scrolling across, shadows can be seen moving from the lower right to left while no plumes are streaming from the summits. Further, the animation illustrates the snow-covered, cloud-free east face of Everest illuminated by the rising morning sun.

Commented [e19]: RC2 suggested we develop plume statistics. So, we inserted the following paragraph: 'We recorded the days the Everest massif was observed to produce a plume, the formation time of the plume, the plu duration and how many plume events were predicted by th LCL model. Cases where a plume was observed but not predicted were investigated because they might be plumes resuspended snow.

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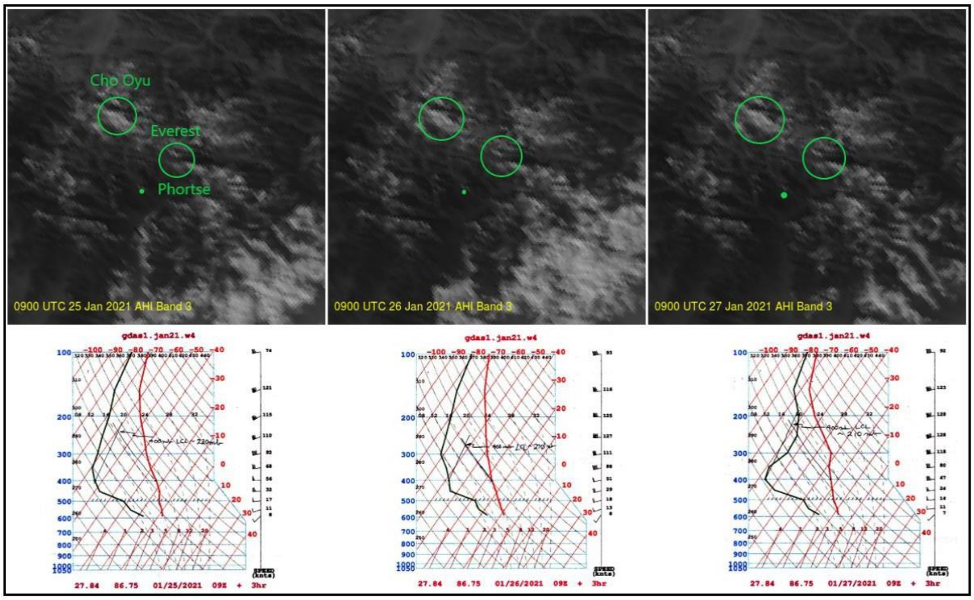

Figure 4: The images and profiles, left-to-right, are for 2021-01-25, -26 and -27 at 15LST (Local Solar Time) or 09Z. The locations of the major peaks are circled. The lifting-condensation-level (LCL) values are determined graphically on the corresponding atmospheric profiles from Phortse and are listed in Table 1. The graphical procedures are described in the text. The approximate pressures at the base and summit of the Everest pyramid, respectively, are approximately 400 and 300mb.

Commented [e20]: We replaced this wording with: ‘(a), (b) and (c)’

We computed the LCL values, as illustrated in Figure 4, on the atmospheric profiles corresponding to the images. The values are given in Table 1. It can be seen the values were all above the level of the Everest summit. The 400mb levels were too dry; the temperature-minus-dew point ($T - T_d$) values were all 21C or larger. This result is consistent with the observation of no plumes.

It can be seen from the profiles and in Table 1, the winds at the summit were from the west at about 100 knots all three days.

Commented [e21]: Following a suggestion by RC1, we added ‘m/s’ to the wind speeds in Table 1 in the revised manuscript.

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Table 1

Air parcels lifted from the 400mb level, approximate pressure at the base of the Everest summit pyramid, to their condensation levels (LCL) using *gdas1* profiles for Phortse, Nepal (27.84N, 84.75E). The approximate pressure at Everest's summit is 300mb. The * signifies the IR images could resolve a plume.

Date	Time (LST)	Time (Z)	T-Td at 400 mb (C)	LCL (mb)	T at LCL (C)	T at 300mb (C)	Plume expected?	Plume observed?	300 mb winds (degrees/knots)
25 Jan 2021	15	09	31	220	-47	-38	No	No	260/92
26 Jan 2021	15	09	33	270	-48	-27	No	No	260/111
27 Jan 2021	15	09	34	210	-50	-32	No	No	260/118
19 Dec 2020	15	09	23	280	-42	-37	No	No	290/103
20 Dec 2020	15	09	21	280	-42	-37	No	No	290/77
21 Dec 2020	15	09	4	380	-27	-38	Yes	Yes	270/81
8 Feb 2021	06	00	20	280	-43	-41	No	No	330/55
8 Feb 2021	09	03	15	290	-40	-39	No	No	330/60
8 Feb 2021	12	06	14	300	-40	-40	Yes	Yes	330/64
8 Feb 2021	15	09	13	310	-39	-40	Yes	Yes	330/70
8 Feb 2021	18	12	11	320	-35	-38	Yes	Yes	330/80
8 Feb 2021	21	15	10	330	-34	-37	Yes	*	320/82
8 Feb 2021	24	18	11	320	-34	-37	Yes	*	320/78
9 Feb 2021	03	21	13	310	-35	-36	Yes	*	330/86
9 Feb 2021	06	24	22	270	-43	-37	No	No	320/80

3.2 Event 2

A plume was observed on 21 December 2020 (Figure 5) but no snowfall was measured at the AWS between the 19th and 21st. Sharp shadows cast by the Cho-Oyu and Everest summits in the 19th and 20th images indicate no plumes present. On the 21st, plumes are streaming from these summits; the ovals in the images are elongated to bracket the plumes. Convective clouds are seen to the south of the peaks.

Commented [e22]: Inserted before 'sharp': 'As observed in Event 1,'

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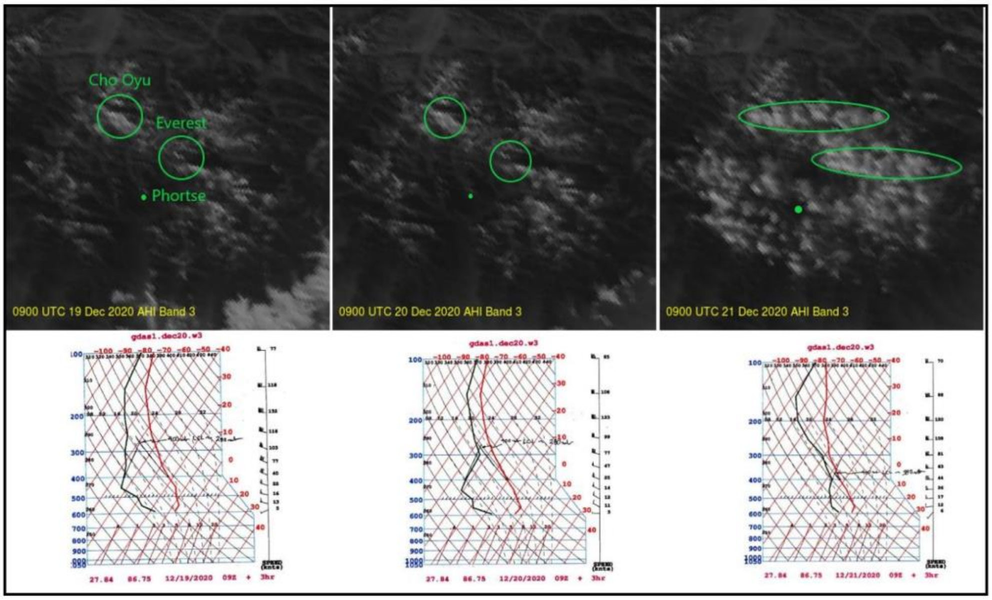

Figure 5. The images and profiles are for 2020-12-19, -20 and -21 at 09Z (15LST, Local Solar Time). The locations of the major peaks are circled. The LCL values are determined graphically on the corresponding atmospheric profiles from Phortse and are listed in Table 1. The graphical procedures are described in the text. The approximate pressures at the base and summit of the Everest pyramid, respectively, are approximately 400 and 300mb.

Commented [e23]: Inserted before 'are': '(a), (b) and (c)'

These features are more easily observed in the animation of the every-ten-minute images for 2020-12-21 from just before sunrise to just after sunset, 0040 to 1150Z (0640 to 1750LST). The animation is in the attached *Mt. Everest plume in winter-Videos.zip*. Scrolling through the animation illustrates the late-morning onset of the plumes and convective clouds.

The LCL values computed on the profiles in Figure 5 are given in Table 1. The values were above the level of the Everest summit the 19th and 20th, consistent with the observation of no plumes. The 400mb levels $T\text{-}T_d$ values were all 22C or larger. The LCL value was below the summit level on the 21st

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consistent with the observed plumes. That 400mb level $T\text{-}T_d$ value was 4C, quite moist. The -27C temperature at the LCL shows the plume was likely a liquid cloud.

It can be seen from the profiles and in Table 1, the winds at the summit were from the west-north-west between 77 and 103 knots for the three days.

3.3 Event 3

A plume was observed on 8 February 2021 and snowfall was measured at the AWS on the 5th and 6th but none on the 7th and 8th (images from the 5th through 7th are not presented in Figure 6 because the region was obscured by clouds from a passing Western Disturbance (Lang and Barros, 2004)). As can be seen in Figure 6, on the 8th shadows from the summits appear in the 0730 and 0900LST images, indicating no plumes. Cho Oyu and Everest are producing plumes in the 1200 and 1500LST images. These plumes along with Makalu's plume are seen as the three bright objects in the 1730LST image. The corresponding 1730LST IR image did not resolve the plumes nor did the overnight IR images. But, the visible image the next morning at 0730LST, looks almost identical to the previous morning's 0730LST image. This is because the skies were clear both mornings. No plumes were observed either morning. Thus, the afternoon plumes on the 8th dissipated overnight.

~~Images from the 5th through 7th are not presented in Figure 6 because the region was obscured by clouds from a passing Western Disturbance (Lang and Barros, 2004).~~

Commented [e24]: Sentence removed because redunda with lines 172 and 173.

An animation of the every-ten-minute images for 8 February 2021 from just before sunrise to just after sunset, 0050 to 1210Z (0650 to 1810LST), is in *Mt. Everest plume in winter-Videos.zip*. Slowing the video using the scroll bar, the animation illustrates the development of the plumes in the afternoon and their final illumination at sunset. At sunset, the animation reveals four plumes, one streaming from Cho Oyu's summit, one from Everest's summit, one from the summit of nearby Lhotse and the fourth from Makalu. The animation illustrates the plume from Lhotse was much larger than the plume from Everest;

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similar to the plumes in Figure 2-top (the mosaic image from the ISS, not shown by Moore, shows Cho Oyu was producing a plume, too). Likewise, all four summits were producing plumes in Figure 2-bottom.

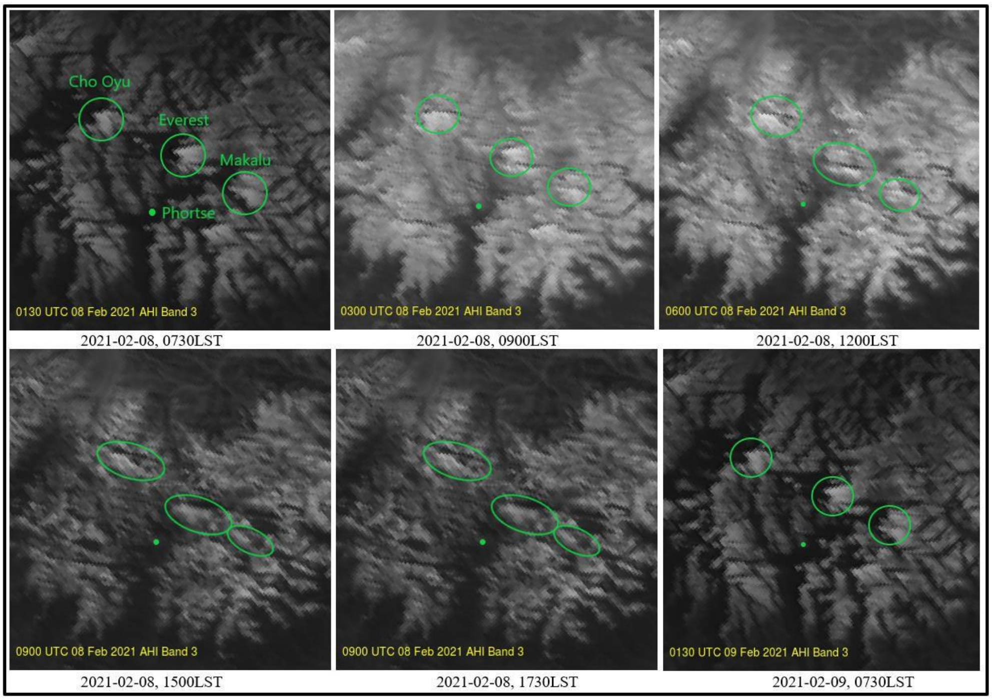

Figure 6. The visible images are for 2021-02-08 and -09 at Local Solar Time (LST). The locations of the major peaks are circled. The corresponding LCL values are in Table 1.

The LCL values, shown in Table 1, were above the level of Everest's summit (~300 mb) at 00 and 03Z (06 and 09LST) consistent with the observation of no plumes. The LCL values were at and below the summit level between 06 and 12Z (12 and 18LST) consistent with the observed plumes. The temperatures at the LCL were colder than -35C showing the plumes likely were ice clouds. The 24Z (06LST the next day) value is above the summit level consistent with the observation of no plumes.

Commented [e25]: Replaced 'are' with '(a), (b), (c), (d and (e) are'

Commented [e26]: Replaced 'and' with 'and (f) is for 2021-02'

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It can be seen from Table 1, the winds at the summit were from the northwest between 55 and 86 knots on the 8th and 9th. ~~The persistent jet-stream during the 8th and 9th is shown in Figure 7 imbedded in the trough of the Western Disturbance east of the Everest region.~~

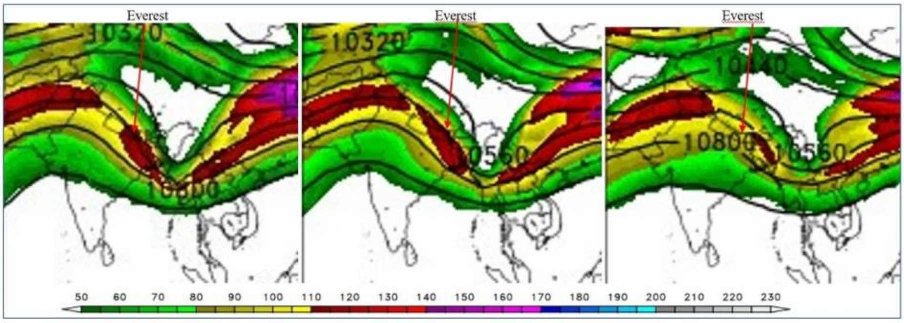

Figure 7. The 00Z Global Forecast System forecast for 8 February 2021 collected from the College of DuPage NEXLAB. Shown are the 250 mb isotachs (knots) and geopotential heights (gpm). Left: 8 February 2021 00Z (06LST), Center: 8 February 2021 12Z (18LST), Right: 9 February 2021 00Z (06LST).

3.4 The Moore plume

Moore (2004) studied the plumes streaming from Everest and Lhotse that were imaged late on the afternoon 28 January 2004 from the International Space Station. To determine if the plumes were present that morning and the next, we analysed all available images from the Geosynchronous Orbiting Environmental Satellite-9 (GOES-9). The satellite imaged the Everest region. The GOES-9 was lent by the USA to Japan after the failed launch of MTSAT-1.

The GOES-9 images are shown in Figure 8. The early-morning image on 28 January 2004 (0725LST) shows the plumes were not present because the sharp shadows of the Everest massif and Makalu. If the plumes had been present, the shadows would have been fuzzy. The cloud-free east face of Everest is visible in the 1013LST image as a bright, white blob. Thereafter, the plumes were not visible until lit by the late afternoon sun (1613 and 1649LST images). This illumination at sunset also occurred in the animation of the 8 February 2021 plumes.

Commented [e27]: To answer RC1's significance of Fi
7, the following replaces this sentence:
These winds were caused by the jet-stream that moved through the Everest region during the 8th and 9th as show by the sequence of images in Fig. 7. The red sinuous regi defines the jet stream. Additionally, it can be seen in the sequence the trough of the Western Disturbance, in which the jet stream was embedded, was east of the Everest regi and had moved slowly eastward.

Commented [e28]: RC2 suggested we develop plume statistics form our observations. Thus, we insert the following section:

3.4 Plume statistics

Table 2 displays the results from our 151 daily observatio of H-8 imagery and the corresponding 400 mb LCL value calculated from the atmospheric profiles. It can be seen fr the table, Everest was almost always visible (95%), especially

Table 2 inserted

in the morning because the plumes most often formed late in the morning. On almost half of the days Everest was visible (143 days), plumes were observed to form on 63 d (44%). Of these plumes, 59 (94%) were predicted to form and 4 (6%) not predicted. Were the four plumes compose of resuspended snow?

The four plumes were observed on 2020-12-05, 2021-01- and 2021-02-03 and 11. The 400 mb LCL values ranged between 295 to 249 mb, all above the 300 mb level of the Everest summit. The plumes formed between 1200 and 1400 LST and dissipated around 1900 LST. The plumes were not visible at sunrise and visible at sunset. Therefor these plumes were not composed of resuspended snow. Thus, none of the 63 plumes we observed we conclude we composed of resuspended snow. Though, plumes of resuspended snow may have occurred smaller than our detection limit of a couple of kilometers.

Twice-daily images of the Everest summit coincident with portion of our H-8 observations became available from G et al. (2022) while this study was in peer-review. The images were taken from 2020-12-16 through 2021-01-16 (days) at ~10 and ~17 LST. We studied the images to determine the number of days the summit was visible and number of days plumes occurred. The summit was visible on 28 days (88%) while the corresponding H-8 observatio revealed the massif was visible on 32 days (100%). The summit produced 18 morning plumes and 11 afternoon plumes. The corresponding H-8 observations detected 8 o the morning plumes and 4 of the afternoon plumes. This comparison shows a number of Everest plumes did not rea the couple-of-kilometers in length to be detected in the rea time H-8 images.

We observed plumes we suspect were composed primaril

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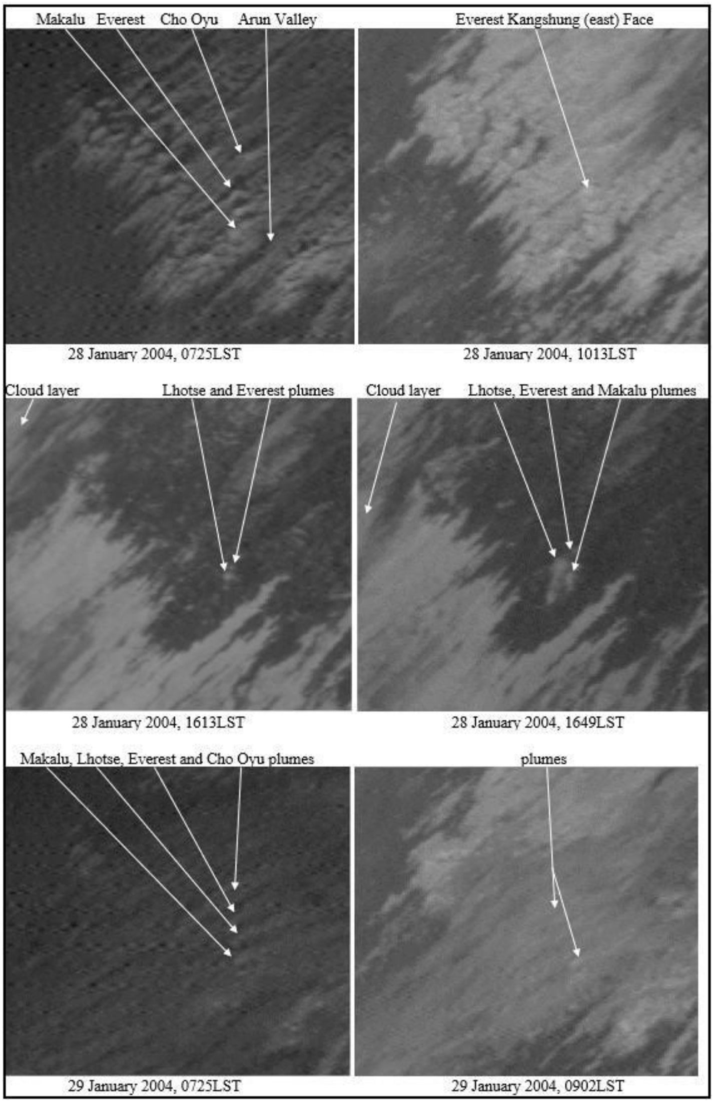

225 Figure 8. GOES-9 0.65 micrometer images of the study region. The major features are labelled.

https://doi.org/10.5194/acp-2021-966
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The GOES images for the afternoon of 28 January 2004 revealed a cloud layer moved toward the Everest region from the west. The layer is visible in the 1613 and 1649LST images. In the 1649LST image, the layer cast a shadow on the lower clouds. Moisture preceding this layer may have formed the afternoon plumes. Based on the GOES images, we conclude the plume Moore studied was not present in the morning and formed in the afternoon.

Overnight, the cloud layer moved into the Everest region because at dawn on 29 January, the plumes produced by the major summits are seen to protrude above the overcast (0725 and 0902LST images).

Commented [e29]: This clarifying sentence was added: 'The protruding plumes are difficult to identify in Fig. 8. we searched the archives for finer spatial-resolution image from polar orbiting satellites'.

Finer detail of these plumes was found in Terra/MODerate resolution Imaging Spectroradiometer (MODIS) image of 0910LST on 29 January 2004 (Figure 9). Unfortunately, the MODIS image on the 28th was not useful because it was on the limb and pixilated, smearing features. This MODIS 0.85 micrometer wavelength image is good for cloud detection (compared to 0.65 micrometers on GOES) because atmospheric scattering is less at 0.86 micrometers and contrasts are better maintained.

Commented [e30]: RC1 questioned the fine spatial resolution claim. So, we inserted the following text: 'The spatial resolution of this MODIS image is 0.38 km p pixel: 3 km between Everest and Lhotse summits and 8 pixels cover that distance.'

The MODIS image reveals the overcast shown in the GOES images and distinct plumes in the wakes of the major peaks. The Everest plume casts a shadow on the lower cloud layer indicating it rises above that layer. The shadow indicates the plume has a sharp edge, the edge of a liquid cloud. A short distance downwind, the plume merges with the plume from Lhotse and becomes fuzzy, suggesting glaciation. The fuzzy plume traveled across the Arun Valley. It is possible crystals fell as snow that may have reached the surface.

Commented [e31]: Responding to a comment by RC2: The regions of the plumes containing primarily cloud droplets are the most reflective hence the brightest, the whitest. The region of the plume containing primarily mu larger ice crystals are less reflective and appear dimmer ar grayer.

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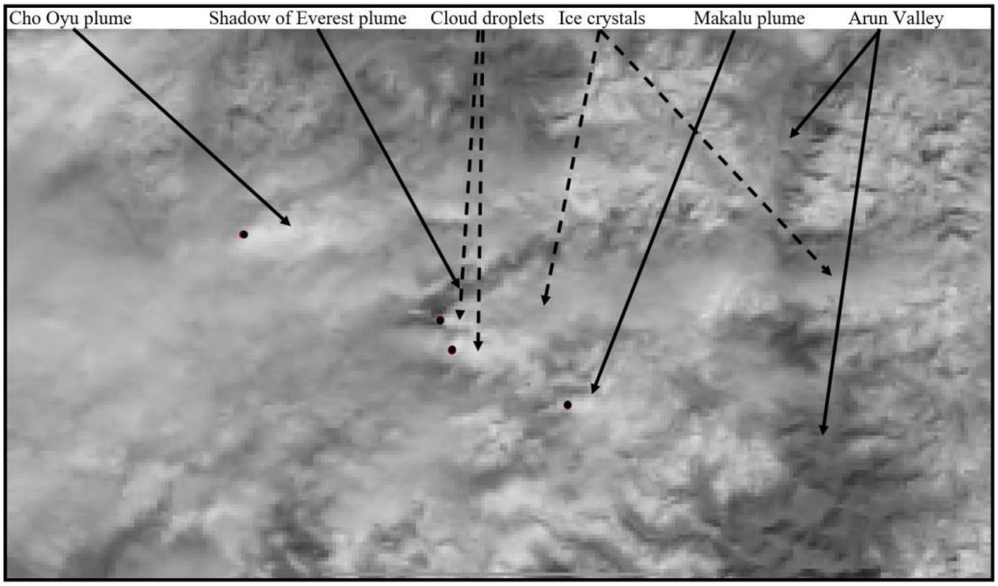

Figure 9. Terra/MODIS 0.85 micrometer image of the study region on 29 January 2004 at 0910 LST. The main features are labelled. The dots are the locations of the summits.

Commented [e32]: To help the reader orient this image the following sentence was added: 'Figure 1c is a map of the region displayed in this image.'

4 Discussion

4.1 Meteorology

~~The plumes we observed (Figures 5 and 6) and analysed the corresponding meteorological data (Table 1) show moisture condensed in the Everest and Lhotse wakes forming the plumes. The plumes appeared only in the afternoons. In the mornings~~, moisture likely was transported vertically in convection (Hindman and Upadhyay, 2002) and entrained by the wakes producing the afternoon plumes. Some of the moisture could have come from sublimation of snow. Stigter, et al. (2018) measured cumulative sublimation and evaporation from a glacier in the Nepalese Himalayas to be 21% of the total annual snowfall. Finally, the morning moisture transport and afternoon appearance of the plumes are consistent with the findings of Wirth, et al. (2012) for banner clouds produced by Mount Zugspitze.

Commented [e33]: Replaced text with the following: 'The plume observations and the corresponding meteorological analyses are summarized in Tables 1 and 2 The LCL values show plumes were observed when the 40 mb LCL was below the 300 mb level of the summit of Everest. This result shows that moisture condensed in the dynamically-forced rising air in the Everest wake to produ the plumes.'

Commented [e34]: Replaced with: '2012, Fig. 5b'

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All the plumes we present were absent in the mornings and visible in the afternoons (Figures 3, 5 and 6). The plumes with corresponding meteorology (Figures 5, and 6) occurred with summit wind speeds 50 knots or greater and 400 mb $T\text{-}T_d$ values of 14C or less. If the $T\text{-}T_d$ values were larger than 14C, no plumes were observed.

The plume Moore (2004) investigated was not observed in the morning (Figure 8). Had it been a plume of resuspended snow, as he concluded, the plume would have been visible in the morning because the wind speeds were between 85 and 120 knots all day (from the REANALYSIS archive at NOAA). On the next day, the plume was observed in a MODIS image to glaciate downwind (Figure 9). The plume may have produced snow.

4.2 Composition

The initial composition of the plumes was deduced from the temperature of the LCL. The initial composition of the 21 December 2020 plumes (Figure 5) was expected to be cloud droplets because the cloud formed at a temperature warmer than -35C. The plumes of 8 February 2021 (Figure 6) likely began as ice clouds because the clouds formed at a temperature colder than -35C. The Everest plume imaged in Fig. 9 appears initially liquid that glaciated downwind. This change in composition is supported by the measurements by Baker and Lawson (2006) that revealed cloud droplets that formed initially could nucleate to form ice/snow crystals further downwind (their Figure 6).

The plumes we observed, plus Moore's, could not have been composed of resuspended snow because they were not present in the mornings. The wind speeds were always high throughout the day. Thus, if they were composed of resuspended snow, they also would have appeared in the mornings.

Commented [e35]: RC2 suggested we estimate the snowfall from a plume. Therefore, we insert the following section:

4.3 Estimate of snowfall from the observed plumes

Assume a saturated parcel of air ascends moist adiabatical from the elevation of the South Col of Everest (~7900 m, ~400 mb) to the summit (~8900 m, 300 mb). The parcel i initially -33 0C (the average plume temperature, Table 2) and cools to -40 0C at the summit. The initial parcel saturated mixing ratio is 0.59 g/kg and the final is 0.39 g/k for an average of 0,49 g/kg. Employing the precipitable water calculator at http://www.shodor.org/os411/courses/_master/tools/calcu ors/precipwater/, ~1 mm of water is expected to precipitat from the parcel.

Assume the parcel ascends in the turbulent wake the 1000 from the South Col to the summit at 0.1 m/s, the ascent ta 10^4 s. So, every 10^4 seconds 1 mm of liquid precipitates from the parcel. The average duration of the observed plumes was 12 hours (Table 2) or 4.32 x 10^4 seconds. Th amount of precipitation from the average plume was 1 mm/10^4 s x 4.32 x 10^4 s or about 4 mm.

Sixty-three (63) Everest plumes occurred during our four-month observation period (Table 2). So, 63 plumes x 4 mm/plume equals about 252 mm (~25 cm) of liquid-equivalent may have precipitated. The amount of liquid-equivalent precipitation measured at Phortse during our observation period was 284.5 mm (~28 cm). Thus, Evere plumes may be a significant source of precipitation.

The plume-generated snowfall is expected to be a maximu in the immediate lee of the Everest massif and diminish downwind as drier air is entrained. The always-white Kangshung face of Everest (Fig. 1b) may be evidence of plume-generated snowfall, although, much of this snow probably may be captured from snow-filled clouds flowin around the summit pyramid. This capture is similar to sno collecting on the tailgate of a truck speeding through a sno storm.

5 Conclusions

We studied the formation and composition of two wintertime plumes produced by the Mt. Everest massif. We found the massif produced the plumes when the air entrained into its wake was sufficiently moist, 400 mb temperature-minus-dew point values 14C or smaller. The plumes studied occurred with summit

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winds 50 knots or greater. We concluded one plume initially was composed of cloud droplets, not resuspended snow and the other was initially composed of ice particles. We present evidence that one plume glaciated downwind. Hence, Everest plumes may be a source of snowfall formed insitu.

~~The animations of the GMS images we created, although pixilated, reveal the diurnal nature of the plumes. The animations are a new tool for observing the Everest region. But, if the summit is continuously imaged from the surface and, simultaneously, the atmospheric profiles measured, we expect the plumes to form at lower wind speeds and larger moisture contents. The plumes we studied formed at large wind speeds and small moisture contents.~~

~~The plume studied by Moore (2004) we show was a banner cloud, not a plume of resuspended snow. Our study provides a framework and direction to Moore's concluding statement: "It is hoped that this initial analysis will provide the motivation for the further study of this interesting phenomenon."~~

Data availability

Still images in Figs. 4, 5, 6 and 8 were created using Geo2Grid software (cimss.ssec.wisc.edu/csppgeo/geo2grid_v1.0.0.html) and Himawari Standard Data (HSD) files from Himawari-8 available at the UW-Madison SSEC Data Center (courtesy of JMA, the Japan Meteorological Agency).

Animations were created from the still imagery using ImageMagick. Tutorials on how to use Geo2Grid are available at this CIMSS Satellite Blog link: cimss.ssec.wisc.edu/satellite-blog/?s=geo2grid. The videos, themselves, are in the accompanying archive *Mt. Everest plume in winter-Videos.zip*.

Data for the MODIS imagery were downloaded from the NASA LAADS (Level-1 and Atmosphere Archive and Distribution System) DAAC (Distributed Active Archive Center) archive and processed into imagery using Polar2Grid software available at www.ssec.wisc.edu/software/polar2grid/. A tutorial on how to access and display archived MODIS data is at cimss.ssec.wisc.edu/satellite-blog/archives/36727.

Commented [e36]: Here we summarize our plume statistics.by inserting the following paragraph: 'The Everest massif was visible on 143 of the 151 observation days (95%), especially in the morning becaus the plumes most often formed later in the morning. On th days the massif was visible, plumes were observed to forn on 63 days (44%). The plumes lasted an average of 12 hours. Of these plumes, 59 (94%) were predicted to form and 4 (6%) were not predicted. These four plumes were n composed of resuspended snow because they were not visible at sunrise. Though, plumes of resuspended snow m have occurred smaller than our detection limit of a couple kilometers.'

Commented [e37]: Insert the following paragraph: 'Our analysis of the Grey et. al. (2022) images of the Ever summit from the surface showed a number of Everest plu did not reach the couple of kilometers in length to be detected in the real-time H-8 images. Thus, our plume-occurrence values should be considered a lower-limit.'

Commented [e38]: The paragraph was replaced by the following sentence: 'The plume studied by Moore (2004) we show was a bann cloud, not a plume of resuspended snow.'

Commented [e39]: Inserted the origin of Movie 5: 'Movie 5 was constructed from *.GIF images downloaded real-time from the Himaware-8 website (www.data.jma.go.jp/mscweb/data/himawari/sat_img.php ea=ha2). Images were downloaded every 30 minutes. Th images were animated and labelled using EzGIF.com.'

Commented [e40]: Inserted the following paragraph: 'Wirth (2022) suggested we attempt to post-process the be resolution H-8 visible imagery to improve the movie resolution. In general, the sharpening techniques we are aware of (in SatPy for example) require a higher resolutio band. So, for example on H-8, Band 1 (0.47 micrometers, with 1-km resolution at nadir) or Band 2 (0.51 micromete also 1-km resolution) can be sharpened with information from Band 3 (0.64 micrometer, with 0.5-km resolution at nadir). So, there is no practical method to improve the spatial resolution in Band 3.'

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Author contributions

Edward Hindman initiated the study and provided the meteorological interpretations. Scott Lindstrom produced the satellite images, the animations and sensor interpretations.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

EH's participation was self-funded. SL was partially supported by the Cooperative Agreement between NOAA and the University of Wisconsin-Madison Cooperative Institute for Meteorological Satellite Studies (CIMSS).

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Commented [e41]: Inserted
'Conrad, A., et. al., The call of Everest. National Geograp
Society, 303 pp. ISBN 978-1-4262-1016-7, 2013.'

Commented [e42]: Inserted:
'Grey, L., Johnson, A. V., Matthews, T., Perry, L. B., Elmore, A. C., Khadka, A., Shrestha, D., Tuladhar, S., Baidya, S. K., Aryal, D., and Gajurel, A. P.: Mount Everes
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Commented [e43]: Inserted 'Prestel and Wirth (2016)' reference.
'Prestel, I., and V. Wirth, 2016: What flow conditions are conducive to banner cloud formation? J. Atmos. Sci., 73, 2385–2402.'

Commented [e44]: Wirth (2022) will be added to the reference list as "Wirth, V., reviewer comment. doi.org/10.5194/acp-2021-966-RC1".