RC1 comment on ‘acp-2021-966' by Volkmar Wirth, 31 Jan 2022

The current paper investigates the occurrence and origin of plumes in the lee of major mountain peaks in the Himalayas. The authors combine satellite imagery from a few episodes with temperature and humidity data at a station close to Mt Everest. They conclude that most of the observed plumes are, indeed, cases of so-called banner clouds, meaning they have been generated by condensation of water vapor in an ascending air stream in the lee of the mountain (rather than just snow being blown off the summit).

The method to analyze the meteorological situation is straightforward: the authors compute the lifting condensation level (LCL) from temperature and moisture data at the observational site, and then check whether the LCL is below or above the summit of the respective mountain. If the LCL is below the summit, they hypothesize that one should expect a banner cloud to occur. Comparing this “expectation” with observations from satellite images indicates good agreement. This then allows the authors to conclude that the plumes observed on the satellite images are, indeed, real banner clouds.

This is the first study of its kind that I am aware of, and I think it is worth a publication in a science journal. My only criticism is that the spatial resolution of the satellite imagery is marginally low for the intended purpose: for me as a reader it required occasionally quite a bit of imagination to see what the authors see. Yet, the movies improve upon this issue, as the non-stationarity of (even a poorly resolved) feature in these movies allows one to more or less clearly identify the presence of a plume.

Below I have two major issues as well as a number of minor issues. My remarks are meant to help to produce a revised version.

Volkmar Wirth

We thank Prof. Wirth for his careful and thorough reading of our manuscript. We respond to his insightful comments in italics:

Major issues:

I think it would be best to be explicit and honest about the low resolution of the satellite imagery. I.e., you best are honest and admit that the resolution is marginal, but (in particular in combination with the animations) just about sufficient to draw the conclusions that you want to draw.

To responds to this issue, the following paragraphs will be inserted between lines 71 and 73:

> *The spatial resolution of the H-8 images is sufficient to resolve the plumes, not as they form, but shortly thereafter. The following is our reasoning. The sub-satellite point is at 0N, 104.7E and the summit of Mount Everest is at 27.99N, 86.93E. At the sub-satellite point, the satellite zenith angle is 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, shown in Figure 2, he estimated to be 15 km in length. Also comparing the plumes in Figure 3 with the map in Figure 1b, it can be seen that the plumes were kilometers in length. So, 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 the both the ‘still’ and ‘animation’ modes. The images could be magnified 300X on the FireFox browser and the site provided animations up to 23-hours. The forming plumes were observed as moving elements against a mostly stationary background. Once they reached a couple of kilometers in length, the lengthening and undulations of the plumes, shown in*

Movie 1, were observed. To permit the reader to observe the formation and development of the plumes, we present animations corresponding to the still images.

In your introduction you state that your results are "conclusive" (as opposed to earlier results); in my view this is somewhat overstated. To be sure, you add some circumstantial evidence, but this is not extremely convincing to me owing to the low resolution of the satellite imagery.

In line 44, "concluded" will be replaced with "reported".

Also, I suggest that you systematically distinguish between the concept of a plume and the concept of a banner cloud. For me, a plume is anything that you see in the lee of a steep and high mountain (including snow blown off the mountain top). By contrast, a banner cloud is a plume that has been generated through condensation of moisture in an upwelling airstream in the immediate lee of the mountain.

As a result of this comment, lines 48 through 52 will be deleted. And, the following paragraph will replace lines 60 through 63.

Schween and colleagues (2007) show still images and animations, all with the same view, from the summit of the Zugspitze in the Bavarian Alps. Because of the best possible spatial and temporal resolution, they were able to show the formation of banner clouds and snow blown off an adjacent peak. Here we use the best possible spatial and temporal resolution images available to us from meteorological satellites to observe the formation of plumes in the lee of the Everest massif. The plumes most likely were banner clouds when our calculations predicted cloud formation through condensation of moisture in the airstream upwelling in the immediate lee of the massif.

Minor issues:

The movies: It would be good if you could provide movie-captions for all the movies.

The movies of the Himawari-8 images (Movies 2, 3 and 4) already are sufficiently captioned with time, date and image band. Significant times in Movie 1 were inserted as captions.

Movie 1: it would be good to know how local time evolves as the movie passes by; is it possibly to include a little clock running with the movie accordingly? Or to give at least the time span (beginning and end time) covered by the movie.

It was not possible to insert a 'little clock'. And the movie was captioned following this paragraph that will be inserted between lines 47 and 48:

The video captures the formation and evolution of the plume: The movie began at 0940LST showing the summits of Everest (poking over the Nuptse ridge) and Lhotse (to the right) were plume free. At about 1050LST, a plume began in the wake of Lhotse. Clouds began to form on the valley slopes about 1200LST. The plume reached full development at about 1400LST. At that time, the plume began to be intermittently obscured by clouds filling the valley. The movie ends at 1630LST because the HEV was enveloped by the clouds that had completely filled the valley.

The satellite movies are very coarse resolution. Is there a possibility to post-process them in order to more clearly focus on what you want to show? (Maybe not, indeed, because nothing beats the pattern recognition skills of the human brain.)

In response to this excellent suggestion, we will add the following paragraph between lines 311 and 313 in the 'Data availability' section of our manuscript:

> *Wirth (2022) suggested we attempt to post-process the best-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 resolution band. So, for example on H-8, Band 1 (0.47 micrometers, with 1-km resolution at nadir) or Band 2 (0.51 micrometers, 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.*

Wirth (2022) will be added to the reference list as "doi.org/10.5194/acp-2021-966-RC1".

Table 1: I think it would be better to provide wind speed in m/s rather than knots.

The speeds in m/s will be added to Table 1.

Line 48: Sentence unclear to me.

As a result of this comment, lines 48 through 52 will be deleted. And, the following paragraph will replace lines 60 through 63.

> *Schween and colleagues (2007) show still images and animations, all with the same view, from the summit of the Zugspitze in the Bavarian Alps. Because of the best possible spatial and temporal resolution, they were able to show the formation of banner clouds and snow blown off an adjacent peak. Here we use the best possible spatial and temporal resolution images available to us from meteorological satellites to observe the formation of plumes in the lee of the Everest massif. The plumes most likely were banner clouds when our calculations predicted cloud formation through condensation of moisture in the airstream upwelling in the immediate lee of the massif.*

Line 62: See our paper Prestel and Wirth (2016) where we elucidate the conditions under which one would expect a banner cloud to occur (steep mountain, week stratification).

In line 54, Prestel and Wirth (2016) will be inserted after Voigt and Wirth (2013).

Line 68: what resolution are these satellite images? Is it good enough to well resolve the cloud?

To responds to this issue, the following paragraphs will be inserted between lines 71 and 73:

> *The spatial resolution of the H-8 images is sufficient to resolve the plumes, not as they form, but shortly thereafter. The following is our reasoning. The sub-satellite point is at 0N, 104.7E and the summit of Mount Everest is at 27.99N, 86.93E. At the sub-satellite point, the satellite zenith angle is 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, shown in Figure 2, he estimated to be 15 km in length. Also comparing the plumes in Figure 3 with the map in Figure 1a, it can be seen that the plumes were kilometers in length. So, had the H-8 been in orbit in 1992 and 2004, these plumes would have been observed.*
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> *The images from the H-8 website were observed daily in the both the 'still' and 'animation' modes. The images could be magnified 300X on the FireFox browser and the site provided animations up to 23-hours. The forming plumes were observed as moving elements against a mostly stationary background. Once they reached a couple of kilometers in length, the lengthening and undulations of the*

plumes, shown in Movie 1, were observed. To permit the reader to observe the formation and development of the plumes, we present animations corresponding to the still images.

Line 79: which model? More details!

Our response to this issue will be to replace Lines 79 through 83 with the following:

It can be seen in Fig. 1b, that both Everest and its neighbor to the south, Lhotse, present significant obstacles to the typically west-to-east air flow. Hence, both peaks produce wakes and, as seen in Fig. 2-top, both produced plumes. Cloud formation was investigated in the dynamically-forced lee upslope flow in these wakes. The lifted-condensation-level (LCL) of the upslope flow was calculated with the following procedure.

Line 82: "Hence….": do you want to imply that banner clouds occur only on pyramid-shaped mountains?

Line 82 will be replaced by the previous statement that does not include the words 'summit pyramid'.

Line 96: What do you mean by "initial composition" here? (It becomes clear somewhat later….).

Our response to this issue will be to replace Line 96 with the following:

The composition of a forming plume was inferred from the temperature at the LCL.

Can you exclude the possibility that these clouds are mixed-phase clouds?

Our response to this insightful statement will be to insert the following paragraph after line 100:

A mixed-phase plume (coexisting droplets and crystals) could not be determined because, at present, the observer must be immersed in the plume. When Everest experiences a westerly wind, climbers of the SE Ridge, the East Face (Kangshung Face) and the NE ridge could make the observation because the wake forms between these ridges and covers the Kangshung Face (Figure 1b). During his climb of the Kangshung Face, Venables (1989) recorded numerous meteorological observations. But, he did not report being immersed in a fog and seeing scintillations from forming, pristine ice crystals.

Fig. 4: Make the Tephigrams larger, they are important!

Here is revised Fig. 4:

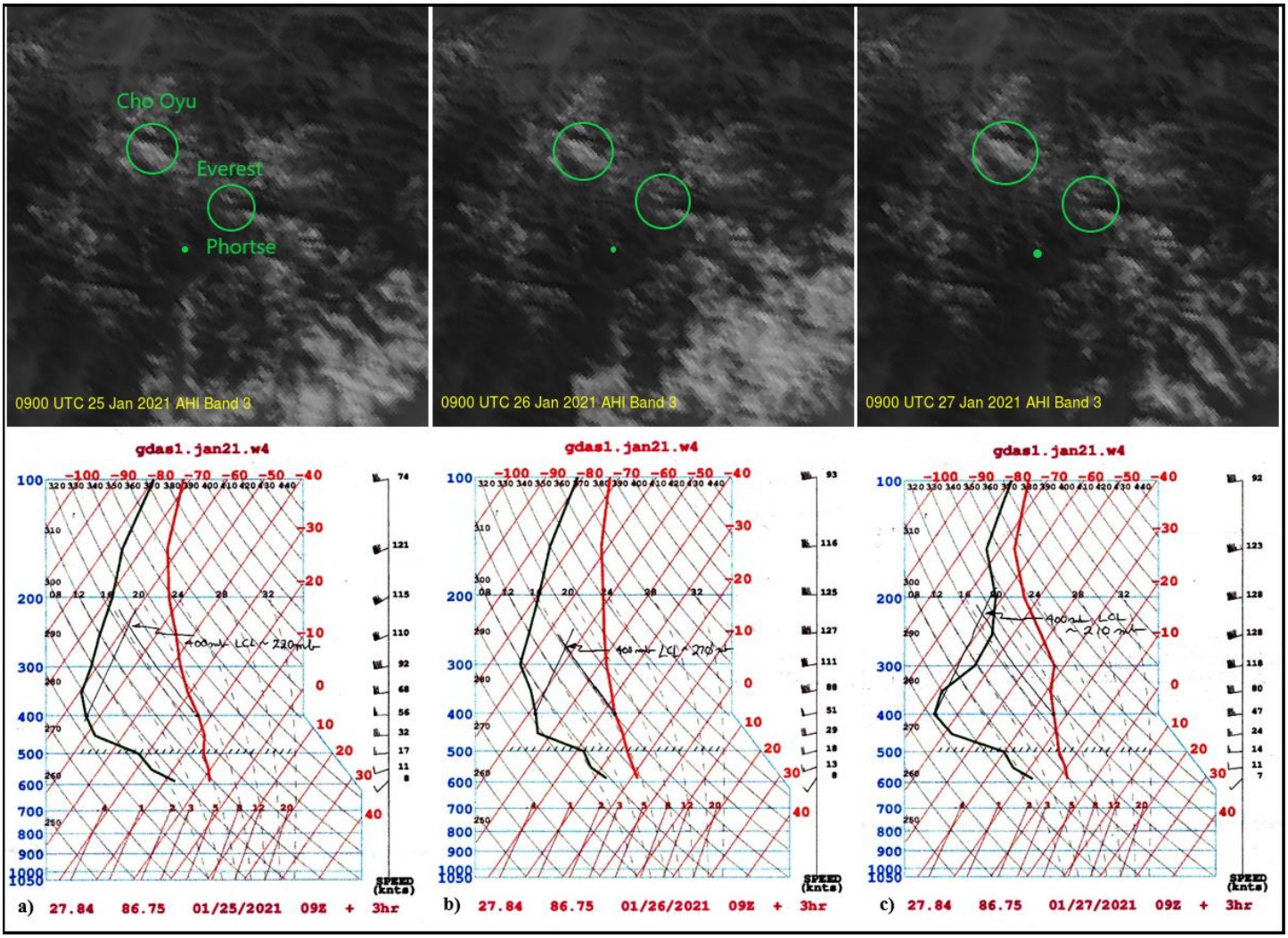

Figure 4: The images and profiles, a) to c), are for 2021-01-25, -26 and -27 at 15LST (Local Solar Time) or 09Z. The locations of the major peaks are circled. The lifting-condensation-level (LCL) values are determined graphically on the corresponding atmospheric profiles from Phortse and are listed in 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.

Fig. 6: There seems to be a problem/mismatch between the yellow caption inside the image and the added caption below the image in the bottom row left and middle column.

Here is the corrected Figure 6:

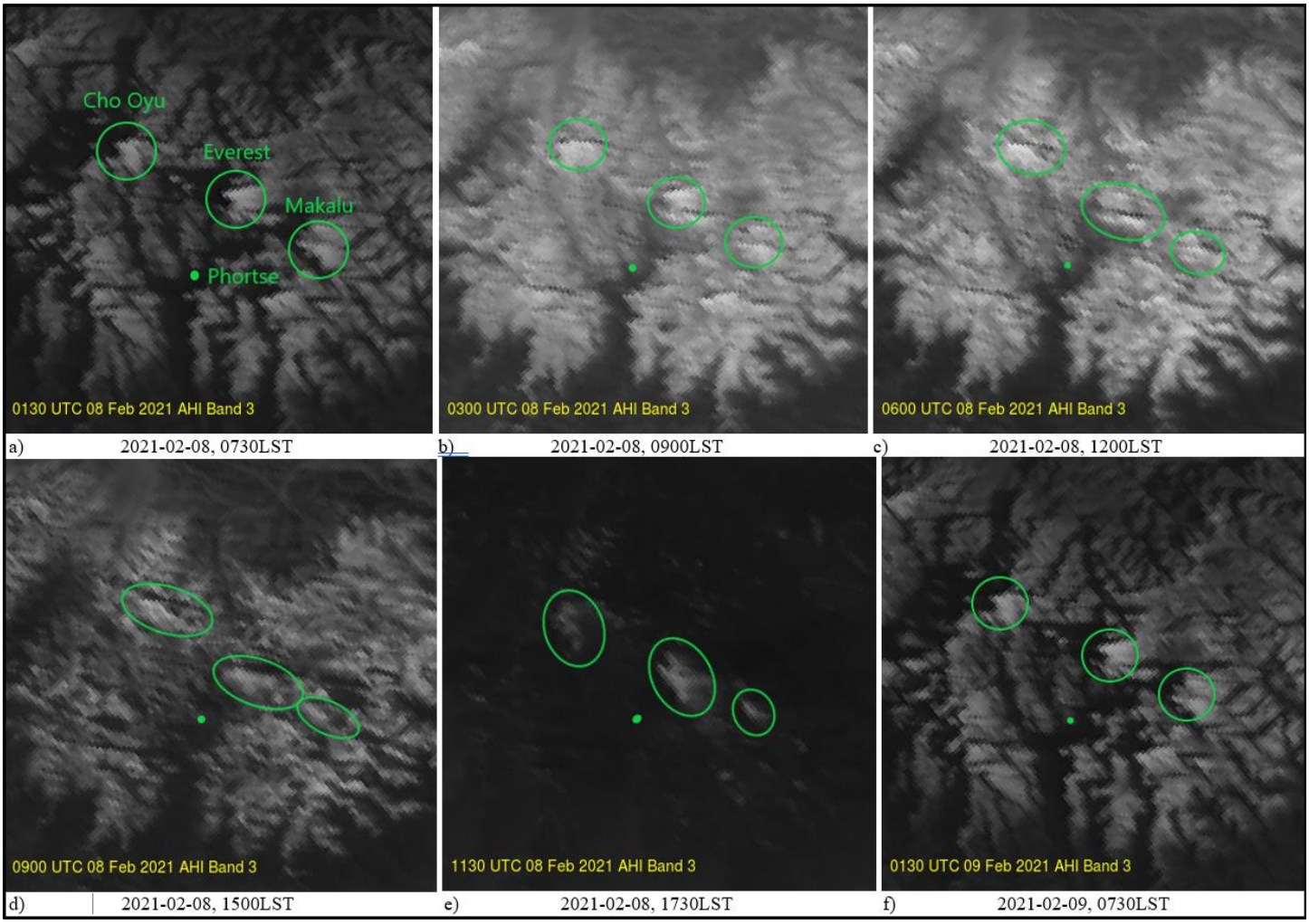

Figure 6. The visible images a) through f) are for 2021-02-08 and -09 at Local Solar Time (LST). The locations of the major peaks are circled. The corresponding LCL values are in Table 1.

Line 146 ff: I found it hard to verify the description/interpretation that you provide in the text when viewing the images.

The following words will be inserted in line 147 to make the sentence read:

As observed in Event 1, sharp shadows cast…….,

Line 164: 4C? Do you mean 4 degrees Celsius?

Yes

Line 182/183: Haven't you said something very similar a few lines earlier?

Woops! Lines 182 and 183 will be deleted.

Line 204: What do you mean if you mention a “Jet stream…. embedded in a trough….”?

The importance of Figure 7 will be clarified by modifying the sentence in lines 204 and 205 to read:

> *The jet-stream moved through the Everest region during the 8th and 9th as shown by the sequence of images in Figure 7. The red sinuous region 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 region and had moved slowly eastward.*

Figure 7: What do you want to clarify by showing this sequence of maps? Is the evolution important? Could you show just one panel as representative for the entire episode?

The evolution is important as described above in your Line 204 question.

Figure 9: Apparently, upward is not northward in these satellite images. Please notify the reader in the figure caption accordingly.

The following will be inserted in the caption:

> *The north-south direction is vertical, north points toward the top of the image and south toward the bottom.*

Also, it would be nice if you could somehow indicate the northward direction on these satellite images.

To resolve this issue, the following sentence will be added to the ending of line 71:

All of the H-8 images presented here are oriented such that the vertical points toward true north as seen in Fig. 1a.

Line 228: Am I supposed to see that shadow in the satellite image?

Yes. The shadow is labeled in revised Figure 8:

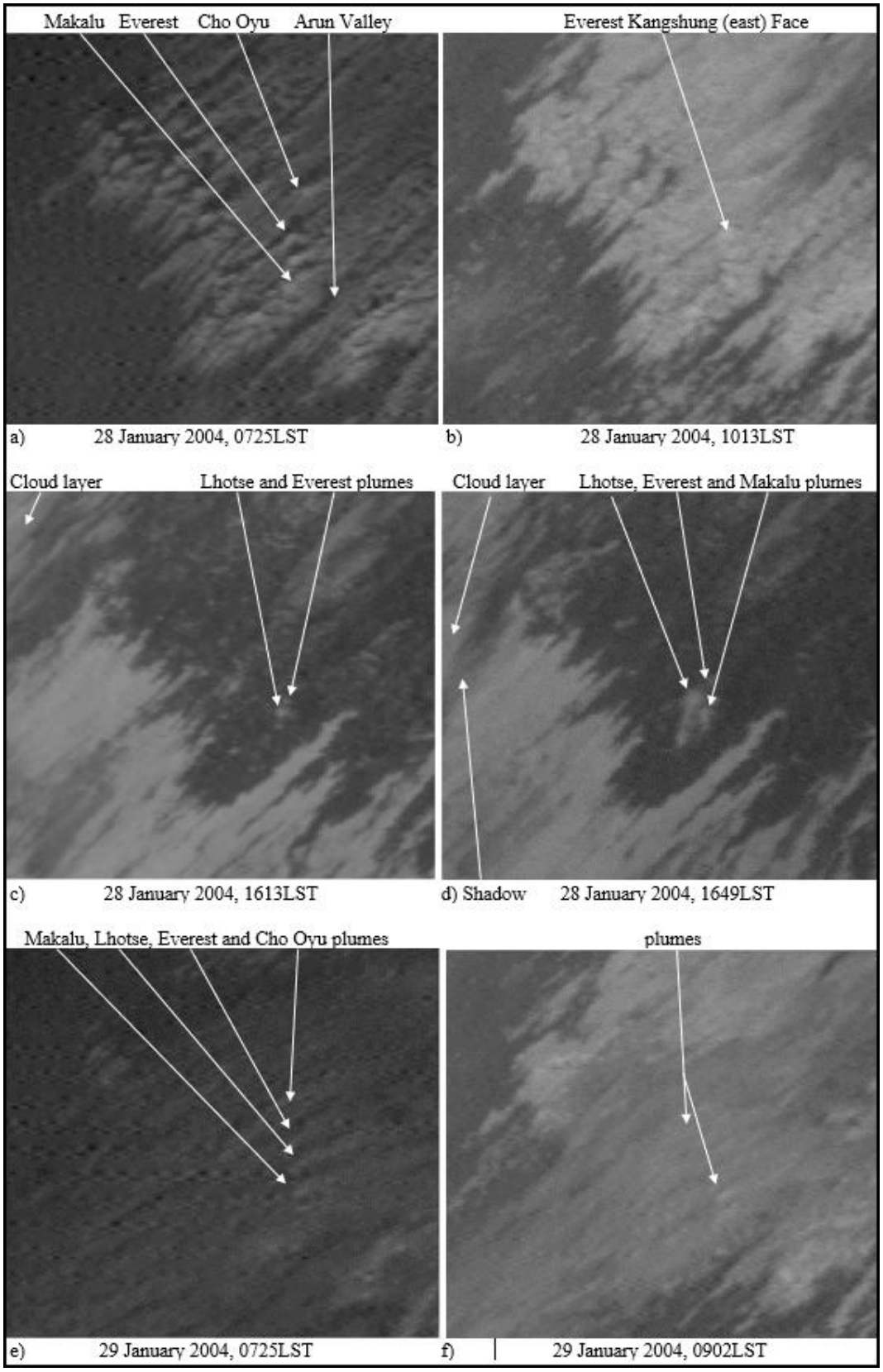

Figure 8. GOES-9 0.65 micrometer images a) through f) for local solar time (LST) on 28 and 28 January 2004. The major features are labelled.

Line 232/233: For me this is hard to see on the satellite image.

The following sentence will be added to the end of line 233:

> *The protruding plumes are difficult to identify in Figure 8. So, we searched the archives for finer spatial-resolution images from polar orbiting satellites.*

Line 244: The difference between sharp and fuzzy is hard for me to see on the satellite image.

The following sentence will be inserted after the sentence ending in 'suggesting glaciation':

> *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 much larger ice crystals are less reflective and appear dimmer and grayer.*

Line 259: here you could specifically point to their Fig. 5b, which explicitly shows the diurnal cycle at Mt Zugspitze.

In line 259, 'Wirth, et. al. (2012)' will be expanded to read 'Wirth, et. al. (2012, Fig. 5b)'.

Line 290: "…. Presented evidence…", well, rather weak evidence, essentially based on the interpretation of a very low-resolution satellite image.

The statement 'very low-resolution' is not correct. Therefore, the following sentence will be inserted following the word '(Figure9)' in line 236:

> *The spatial resolution of this MODIS image is 0.38 km per pixel (3 km between Everest and Lhotse summits / 8 pixels); images from the MODIS give the finest spatial-resolution at our disposal.*

Line 295: "… expect the plumes to form …." not clear whether I understand the logic behind this argument.

Accordingly, the last two sentences in the final paragraph of the paper will be rewritten as follows:

> *If the summit is continuously viewed from the surface with a multi-wavelength imager and, simultaneously, upwind atmospheric profiles of temperature, moisture and winds are measured, the best possible data will be obtained. Analyses of these data are expected to improve our study of the plumes produced by the Mount Everest massif.*

References:

Prestel, I., and V. Wirth, 2016: What flow conditions are conducive to banner cloud formation? J. Atmos. Sci., 73, 2385–2402.

This reference will be added to the list.