Response to Referee #1's interactive comment

1. Investigations of snow cornice development is worthwhile since its collapse is strongly related to the snow avalanche release; I cannot agree with you more. In this study, the leading-edge technology including the closed-circuit wind tunnel and the shadow graph imaging technologies. I appreciate very much for the efforts by authors.

Response: We thank the reviewer for a positive view on the importance of the subject covered by our submission.

2. However, that is all. Similar experiments in the wind tunnel were carried out more than 35 years ago by a master student as shown below and much more meaningful outcomes were obtained.

Naitou, A. and Kobayashi, D., Experimental Study on the Generation of a Snow Cornice, Low temperature science. Series A, Physical sciences, 44, 91-101, 1986.

https://eprints.lib.hokudai.ac.jp/dspace/bitstream/2115/18521/1/44_p91-101.pdf

Unfortunately, the text is written in Japanese. However, it cannot be an excuse, since English summary is attached, in which the wind speed of 4 to 8 m/s is suitable for the cornice formation, and the capture coefficient of drifting snow is also referred. Incidentally, I suppose some of the authors can recognize Chinese characters and are understandable what is mentioned in the test as well more or less. Please read through carefully.

Response: We are sorry that we didn't find this thesis before. Many thanks for mentioning this paper, and we have tried our best to translate and strive to understand the content correctly. In the revised manuscript we will highlight the innovations of our work and the progress compared with this paper.

3. Dependencies on not only the air temperature but also crystal shape, which are listed as the future work in the submitted manuscript, have been already studied. Thus, from my point of view, nothing looks new and no findings which deepen our understandings of the snow cornice formation mechanism are introduced in the submitted manuscript.

Response: We disagree that our paper does not present any new insights. No more relevant experimental work has been published except Naitou and Kobayashi's work as the reviewer mentioned. Considering this, we think there are still many open scientific questions on cornice formation. In Naitou and Kobayashi's paper, which has not gone through peer review, potential factors such as wind speed, air temperature, crystal shape, and mass flux have been investigated with respect to the phenomenon of cornice growth. However, the effects are still not fully understood with strong evidence and data from our point of view. In all, for cornice formation research, more detailed physical mechanism explanation and solid scientifical evidence are still lacking to prove the hypothesis.

A detailed comparison of five aspects, in which our work differs from Naitou and Kobayashi is listed below:

1) The mechanism of cornice growth from the micro perspective.

Naitou and Kobayashi believed that the cornice grew because, during the pause of the wind for ten seconds, particles stopped and attached to the cornice tip from the photo captured in the experiment. It is understandable that the intermittent flow facilitates the formation of the cornice.

However, a new mechanism was exposed based on our experimental results, i.e., the cornice formation in a steady and continuous wind condition, as is shown in Figure 3(a) in the manuscript. From this perspective, cornice formation is a result of a dynamic mass balance between deposition and erosion. The particles stop and stick on the cornice because of sudden wind speed decreases near the edge.

2) The suitable wind condition for cornice formation

Both Naitou and Kobayashi's work and our experimental results proposed that snow cornice only grows under a suitable wind speed range. The values are not exactly the same which is caused by the effects of different snow surfaces and environmental conditions. The key point is that, compared with Naitou and Kobayashi's work, we proposed a clearer physical explanation for the suitable wind speed range and a reasonable method to link with field data.

In our study, we did the single variable (wind speed value) controlled experiments in the cold lab. We kept the air temperature as a constant value meanwhile changing the wind speed from 3 m s^{-1} to 6.5 m s^{-1} by the step of 0.5 m s^{-1} continuously. We recorded the whole process of cornice formation using a camera and analyzed the data by an image analysis program automatically. We calculated the cornice growth rates both in length and thickness (while Naitou and Kobayashi only measured the bulk volume growth rate), as well as the erosion rates in length and thickness (after without seeding). Overall, we not only summarized the general rules for cornice growth but also explained the phenomenon that cornices grow at moderate wind speeds from the physical view of the interaction of deposition and erosion. Moreover, Naitou and Kobayashi proposed that the cornices grow only under 4-8 m s^{-1} (for 1m height in the site field and 0.5 m in the wind tunnel), while Vogel (2012) proposed that the cornice can grow when the wind speed is between 12-30 m s^{-1} and scouring can occur when maximum hourly wind speed is as low as 15 m s^{-1}. Hancock (2020) used 5 m s^{-1} as a conservative lower threshold for cornice accretion, which is the threshold wind speed of snow particles entrainment. To figure out the huge gaps among these field observations, we proposed a non-dimensional method to link the gaps between the wind tunnel and the field observations, which could be used as the estimation in field on the threshold wind speed for snow cornice accretion or erosion.

From Naitou and Kobayashi's work, we can not generalize and use the wind at a certain height as an environmental parameter condition to determine the formation of snow cornice because the boundary layer flow state differs in different environments. Even with the simplest logarithmic profile to characterize the airflow near-surface, the differences in roughness lengths can lead to inconsistent conclusions.

Actually, the friction velocity is more closely related to the particle motion near the surface. Moreover, as a combined effect of the snow accumulation and erosion, cornice accretion is also associated with threshold friction velocity. Thus, the non-dimensional wind speed value proposed in our work is more universal.

3) Experimental setup and instruments

In our study, we recorded the whole cornice formation by implementing a state-of-art technology: the shadowgraphy method. We also created a particle-recognition program that could analyze a series of images recorded automatically.

Compared to Naitou and Kobayashi's work, our instrument is more advanced, and the results allow for stronger interpretations. Using this method, we calculated the cornice growth rates in length and thickness, respectively, and found the link between the growth rate and the corresponding erosion/deposition rates.

4) Effect of temperature and crystal shape on the cornice formation

In Naitou and Kobayashi's work, they have shown the particle size distribution in different air temperature conditions using the shape factor method, and concluded that cornice grows under a temperature between 0 and -20 °C, and the new snow in an irregular dendriform shape is more appropriate for the cornice formation than aged round snow.

We also tested the factors of wind speed, air temperature, and crystal shape that influence the cornice formation in the wind tunnel experiment. From the experimental results, we have concluded that the air temperature and snow crystal shape do have influences on the cornice formation process (which are not shown in this manuscript) but not as strong as the wind speed. Thus, we only analyzed the wind effects in the manuscript, and focuses on wind conditions and the internal physical mechanism of cornice formation. In the revised manuscript, we added these sentences: "Except for the suitable wind speed, snow cornice growth also depends on the air temperature and snow crystal shape which has been described by Naitou and Kobayashi (1986). To verify this point, we did the experiments with environmental temperatures of -20 °C, -15 °C, -10 °C, -5 °C, 0 °C, and with snow of different densities and crystal shapes. The results showed that snow cornice can grow under all kinds of air temperatures, and fresh snow is more beneficial than old snow for cornice growth. However, due to the particle collision and fragmentation in the experiment during the experiment, it is difficult to precisely measure the crystal shape of each particle that will stick on the cornice. Thus, we do not in detail investigate crystal shape in this contribution."

5) The collection rate of snow

The collection rate is the ratio of cornice mass increase rate and the drift snow transport rate, which can reveal the efficiency of snow cornice formation with a particular value of mass flux of drift snow. In Naitou and Kobayashi's work, snow particles are collected in the pit below the cornice. The collection rate gets maximum when the Q is between 1-10 g m^{-1} s^{-1}, and its value is no more than 0.1. In our manuscript, the collection rate of cornice decreases with increasing drift rates for higher wind speeds. These two collection rates are actually the same in the method which is to calculate the captured ratio of particles that flow around the cornice. They are different in magnitude values because of different experimental system settings.

However, in our work, we proposed that the collection rate cannot determine the maximum growth rate of snow cornice. Actually, cornice growth is the combined effects of the deposition and erosion processes (shown in Figure 4(a) in the manuscript).

In summary, compared to Naitou and Kobayashi's work, we obtained the following new results, which deepens the understanding of the snow cornice formation mechanism by quantitative analysis of the macro variables:

1) Offering an explanation why cornices only grow at suitable wind speeds. From the macro view, cornice growth is the dynamic mass balance between deposition and erosion. The wind speed range is limited by the comprehensive effects of drifting snow deposition and erosion on the edge of the ridge.

2) Finding different rates between cornice's horizontal and vertical growth rates in two stages of snow cornice growth.

3) Finding that the collection rate of snow cornice growth decreases with increasing wind speed, and it cannot determine the wind speed value for cornice maximum growth rate.

4) Proposing a comprehensive estimation method of the threshold wind speed value for the cornice accretion to link gaps between the field and wind tunnel experiment, combining the macro variables and the observation data.

4. Further, the discussions, in which authors argue the similarities between the wind tunnel experiments and the observations in the fields, look odd. As is common for the researchers working on blowing/drifting snow, the blowing threshold wind speed in nature is around 5 m/s at 2 to 3 m high (not 11 m/s!), which roughly corresponds to the friction velocity of 0.2 to 0.3 m/s. If you assume, Ut 0.4m=3.2 m/s in the wind tunnel corresponds to Ut2.8m=11m/s in the field, friction velocity and the roughness length will be calculated extremely large (roughly u*=2.4 m/s, z0=0.235m !!; in usual former should be 0.3 to 0.4 m/s and the latter the order of 10-4 m). Thus, discussions below line 175 in this manuscript sound meaningless.

Response: Sorry for the misunderstanding we have caused. Indeed, in order to compare with the field site observation, the wind speeds were normalized using the threshold wind speed of cornice accretion in different cases. Actually, the measurement site of wind velocity is not directly over the ridge. For the field observation, it comes from an automatic weather station - Gruvefjellet meteorological station (464 m a.s.l.), located centrally on the plateau, 300 m from the study site, where the cornice study site is along the edge of the plateau mountain Gruvefjellet [~ 460 m above sea level (a.s.l.)]. For our experiment, the wind velocity is measured by MiniAir which is located at the entrance of S2, with a height of 0.4 m, while the cornice study area is 0.5 m downward, with a height of 0.125 m. From the experiment, we noticed that from the moment the drifting snow started, the cornice grew. Thus, we defined the threshold speed as the wind speed when drifting snow starts, as well as cornice starts to grow.

We used the **nondimensionalization method** to unify the wind speed range between field studies and our laboratory works, using the threshold speed. In our experiments, the cornice accretion starts after the wind speed exceeds the threshold wind speed (3.2 m s^{-1}) with enough snow supply, and no cornice formation when the wind speed is below it (e.g., 3.0 m s^{-1}). In field observation, Vogel et al. (2012) surmised that cornice accretion proceeded during both entire snow seasons (46 h in 2008/2009, 54 h in 2009/2010), when wind speeds averaged 12 m s^{-1}, with a minimum of at least **10 m s^{-1}**, marking the lower limit of the cornice accretion; Eckerstorfer et al. (2012) measured that the initial cornice accretion started along the plateau edge during the first snowfall (10-12, Oct. 2010) with maximum wind speeds of **11 m s^{-1}**, which is lower than the observation result of Vogel et al. (2012). Thus, by analyzing the time series of wind speed data from Gruvefjellet meteo station (http://158.39.149.183/Gruvefjellet/index.html), we can conclude that the corresponding averaged wind speed is about 7.37 ± 0.97 m s^{-1} (and mean friction velocity is about 0.288 m s^{-1} using z_0 = 10^{-4} m) when the maximum wind speed is in the range of 10.5~11.5 m s^{-1}. Considering the harder snow surface in Gruvefjellet (Eckerstorfer et al., 2012), this wind speed value is comparable to the threshold wind speed in previous literature. For the wind in the field is more gusty and turbulent compared to the wind tunnel, the actual threshold wind speed value for cornice growth in the non-dimensional calculation should equal the maximum value of the threshold wind speed measured in the field, according to the study of Li et al. (2020, DOI: 10.1029/2019GL086574). Thus, we chose the maximum wind speed value 11 m s^{-1} as the comparison value with the threshold wind speed in our laboratory experiment where the wind condition is stable and steady. The nondimensional velocity is then defined as: $\tilde{u} = \frac{u_{ref}}{u_{t\_ref}} = \frac{u_*}{u_{*t}}$, in which u_{ref}, u_* are the wind speed at the measurement height and friction velocity, respectively, and u_{t_ref}, u_{*t} are the corresponding threshold wind speed at the measurement height and threshold friction velocity, respectively.

To avoid misunderstanding, we revised the description of lines 172 to 178 as:

"Estimates of the threshold wind speeds for cornice accretion (Vogel et al., 2012; Hancock et al., 2020) are compromised by temporal or spatial constraints on data acquisition. Based on this, we made an estimation of the appropriate wind speed using a non-dimensional method to unify the wind speeds in the wind tunnel and fields. The non-dimensional mass concentration of snow particles can be estimated in the following steps:

1) Dimensionless wind speed $\tilde{u}$ can be calculated as the ratio of wind speed at the measured site relative to the threshold wind speed measured at the site when the cornice starts to grow: $\tilde{u} = \frac{U_{0.4}}{U_{0.4t}} = \frac{U_{2.8}}{U_{2.8t}} = \frac{u_*}{u_{*t}}$. Here 0.4 m represents the sensor height in our experiment, 2.8 m represents the weather station wind speed measurement setup height in Gruvefjellet, and * represents the friction velocity over the cornice. In the field observation, Vogel et al. (2012) surmised that cornice accretion proceeded during both entire snow seasons (46 h in 2008/2009, 54 h in 2009/2010), when wind speeds averaged 12 m s^{-1}, with a minimum of at least 10 m s^{-1}, marking the lower limit of the cornice accretion; Eckerstorfer et al. (2012) measured that the initial cornice accretion started along the plateau edge during the first snowfall (10-12, Oct. 2010) with maximum wind speeds of 11 m s^{-1}. Considering more gusty and turbulent winds in the field, the maximum value for threshold wind speed is more comparable to our laboratory data (wind flow is more stable), we chose 11 m s^{-1} as the threshold wind speed in the field. Thus, dimensionless snow transport rate on the flat surface $\tilde{Q} = \frac{gQ}{\rho_a u_{*t}^3}$ can be calculated as a function of the dimensionless wind velocity $\tilde{u}$. Several common formulas of the function are shown in Table 4."

We also added content to discussions:

“Our wind tunnel experiment results can resolve inconsistencies in these observations. From our wind tunnel experiment, we can conclude that the threshold wind speed for cornice accretion is very close to the threshold wind speed for particles entrained from the surface. The inconsistency in the threshold wind speed for cornice accretion is due to the different snow surface conditions. We can conclude from our experiment that: "Drifting snow is necessary for cornice formation. Only when the wind speed is over the threshold wind speed for particle entrainment, there exists an opportunity for particles to impact and stick on the edge surface, where accumulation is the basis for the cornice formation. When the non-dimensional wind speed $\tilde{u}$ is over 2.7, the scouring effect is much stronger than accretion so that no cornice forms, which is consistent with the Eckerstorfer et al. (2012) and Vogel et al. (2012) field observations.”

5. Preferably, missing link between the 4 cm long and 5 mm thick cornice observed in the wind tunnel and the several-meter scale of cornice formed leeside of the mountain ridge should be also referred to answer the motivation in the introduction part.

Response: Thanks a lot for this suggestion. In the field, snow cornices form in snowstorms which can last a few hours and can have multiple growth periods during the snow season, which leads to a much larger scale. The shape and the size of the cornices are indeed an interesting topic, but our experiment here is not mainly focused on it. Due to the limitation of the field of view of the camera, our experiment didn’t last until the final state of the snow cornice growth. In this work, we mainly focused on the laws of growth rates in the initial state and relevant physical explanations. We will make more proper instructions aiming at the research problems and the applicability of the results in the revised manuscript.