# acp-2021-100 Responses (highlighted with blue) to Referee #1 31 May 2021

Review of manuscript entitled "Observational study for strong downslope wind event under fine weather conditions during ICE-POP 2018" from Tsai et al.

Recommendation: Reconsider after major revisions

#### Summary

The manuscript discusses observations obtained during a downslope wind event in a coastal mountainous setting, the Taebeak Mountain Range in eastern South-Korea, during the winter of 2018. The manuscript aims to explain the acceleration of winds in the lee slopes in a coastal setting, using data obtained in an upstream environment that encompasses a valley that narrows towards the coast. While the data seems quite abundant, and the authors have clearly done an extensive job in figure creation and additional analysis, it is unclear what scientific problem the manuscript aims to discuss. There are also quite a few unclear steps taken in the analysis approach, which need to be addressed. I'm in between major revisions or reject, but want to give the benefit of the doubt at this stage to enable the authors to improve their manuscript substantially. Please refer to the comments below.

We appreciate Referee #1's helpful and constructive comments, which help us to improve the manuscript substantially. We have more emphasized the importance of our study and what scientific problems want to address, the capability of adopted datasets and their specific steps of data processing have been also clarified in our revised manuscript. A set of responses to the reviewer's comments is provided below and specific locations of revised portions were also noted as the number of lines.

#### Major comments:

Data and period selection. Although the authors state that this day was chosen because some parts of the Olympic games were postponed, it would be interesting to know how this relates to climatology of wind events in the area. That would emphasize better the importance of the study. Was this the strongest wind event in the lee slopes at WWG? Or was it just the only event that could be considered as strong? This is a particularly good comment. Except for the Olympic games were postponed, our selected event is one of two extreme wind events in the past decade based on the KMA (Korea Meteorological Administration) observational records. Besides, the persistent strong wind occurred frequently in narrow segment along the valley (i.e., near the DGW site) from the record. The climatological information also manifested the importance of the large-scale weather systems in this extreme wind event. Additionally, snice the dense observational network was built during ICE-POP 2018, this is a good opportunity to investigate this unique event. We have emphasized these in the introduction (Section 1, Lines 139-142) and provided detailed descriptions about the KMA record in last paragraph of Section 3.1 (Lines 352-367).

The study presents a mixture of model simulations and observations, but this is not clear from title, abstract or methodology section, and should be emphasized. More important in this comment is that at times it is unclear whether the authors present observations, simulations or both? In the end, once the WISSDOM is used, this is a mix of observations and numerical output and therefore the study cannot be presented as observations alone. Additionally, not much is discussed regarding the WISSDOM data (how accurate is the approach?), nor the inclusion of the numerical model data into the WISSDOM. Science is about understanding the uncertainties in the data presented, but the authors do not seem to discuss any of it.

Various datasets were acquired in this study including conventional observations [scanning Doppler lidar, automatic weather stations (AWss) and soundings] and reanalysis data (ERA5 and LDAPS). In fact, the forecast outputs of the LDAPS does not adopted in our analysis and it does not to be the constraint in WISSDOM as well. This study is aimed to examine the evolution and mechanisms of an extreme strong wind event associated with a passing LPS (low-pressure system) in Korea with abundant data and reanalysis data. From this statement, the title was modified to "**An analysis of an extreme wind event in a clear air condition associated with a low-pressure system during ICE-POP 2018**" for clarity (Lines 1-2), and we have also emphasized this in abstract (Lines 37-41), introduction (Lines 133-137), and provided more detailed information about the ERA5 and LDAPS datasets in Sections 2.3 (Lines 220-241). Additionally, we explained the role of the LDAPS in WISSDOM in this revision. Its

constraint is used to minimize the squared errors between the horizontal winds of LDPAS and synthesis winds of WISSDOM. Thus, the role of the LDPAS winds in WISSDOM is to improve the accuracy of the retrieved winds (the details have been noted in Lines 288-292). The accuracy of WISSDOM's winds was also discussed by previously studies, the retrieved winds reveal good relations and acceptable

discrepancies (maximum correlation coefficient is 0.86, minimum root mean square deviation is 1.13 m s<sup>-1</sup>) compared with conventional observations (the descriptions have been also added in <u>Lines 293-305</u>).

Some critical explanation of data usage and data treatment is missing. For example, a trend of wind change represented as a percentage per hour is maybe a different way than normal, but just in the sense of diurnal variability it does not make sense. Wind speeds at the surface change over the course of less than 15 hours (the time frame the authors chose for this figure), and so this could also be clearly within the diurnal variability of winds. Is it just a trend based on hourly data? Second, it is unclear what perturbation pressure and temperature represent, as these are not defined. Third, there is a nationwide plot that presents AWS stations, but these are not introduced in the data and methods section. There are some other examples that I leave to the authors to read in minor comments below.

The response to the first comment: to avoid the possible diurnal effects on the wind speed observations, we provided a better analysis to explain the changes of surface wind speed during research period. A sequence of figures (Line 368, Figure 3) shows clear evolution of surface wind speed in northeastern region of Korea and their relations with the moving LPS. The descriptions about these changes have been revised in third paragraph of Section 3.1 (Lines 339-351).

The response to the second comment: since the station pressure and temperature can better represent the of local ambient (follow a Minor comment for "Figure 6" below). Therefore, we use station pressure and temperature for further analysis instead of original one (Lines 450-467, Fig. 6b, and Lines 623-632, Fig. 11b).

The response to the third comment: data processing and the characteristics of these nationwide AWS observations were introduced in Section 2.2 (Lines 174-191). There were 727 regular and additional 32 AWS stations in Korea (mean distance is ~10 km for each station), the AWS observations have to interpolate to the given grids by objective analysis with the influences of radius in 10 km.

- A few statements made in the paper seem incorrect or speculative of nature. Please see comments below.
- The manuscript is quite poorly structured. Section 2 with 2.1 explaining lidar on itself is very dense, while 2.2 is a combination of brief explanation of AWS, sounding, wind profiler and model (!) simulations. Section 3, 4 and 5 basically contain the full results part and could possibly be combined in one section. In the present structure, it is hard to understand what problem the manuscript is trying to address.

Thanks for constructive comments. We have rearranged the structures of this manuscript to clarify the main purposes (i.e., the evolution and mechanisms of strong winds over complex terrain) of this study. Start from Section 2, the detailed introductions of conventional observations (AWS, sounding, wind profiler) and reanalysis datasets (ERA5 and LDAPS) were be separated into two different sections (Section 2.2 and 2.3). In the Section 2.3, the general bases of the LDAPS and ERA5 were clearly addressed, and their spatiotemporal resolution were also noted. The changes of AWS wind speed and their climatologic information have been revised in Section 3.1. In Section 4, we combined the contents from original one (Section 5). The descriptions about evolution of the strong winds in the leeward side of the mountain range, and the LDPAS analysis were switched to Section 4.1. The descriptions about evolution of the strong winds in the upstream of the mountain range were switched to Section 4.2. The explanations for their possible mechanisms were moved to two subsections 4.1.2 and 4.2.2. Finally, the conclusion is in Section 5.

The manuscript is full of grammatical errors, and the phrasing is hard to read. I highlighted only a few, but please let it proofread by an English native speaker, or perhaps pass it through a professional editorial company. While one can clearly not argue on writing style, the text has to be comprehensible, and, unfortunately, in the current state this is not the case.

Thank you for pointing out this problem, we have already checked the grammatical errors carefully. The manuscript has also been edited by professional editorial company.

 There are a handful of studies that use lidar observations to explain downslope windstorm events. Please include these studies. A simple web search would suffice here.

Thank you for this suggestion. We have included four additional studies in the introduction of this manuscript (<u>Lines 120-122</u>). They all utilized lidar observations to document the downslope windstorm.

 A textual note is that the paper is full of abbreviations. Please consider introducing a table that would summarize instrument platforms and locations. This would help the reader greatly to refer back to. The names, instruments, temporal resolution, locations and altitude of adopted stations have been summarized in Table 1 (Line 211). The temporary and permanent observations were also noted in the table.

#### **Minor comments:**

Line 37. Fine weather... What is fine weather? Fair weather? Or just pleasant weather? In the latter, one would not expect much wind... Or is it related to cloudless skies? Please be specific.

We changed these words to "clear air" for clarity based on glossary of AMS (American Meteorological Society). Since there are only strong winds but no precipitation in our selected event, the scanning Doppler lidars and the observations allow us to collect more wind information under clear air condition. All of the words (fine weather) have been replaced by "clear air" throughout the manuscript.

Lines 60-61. It seems very strange to start a paper describing a downslope wind event with a precipitation statement. Suggest to delete this phrase. Removed as suggestion (Line 61).

Line 67. Fine weather... What is this? Reworded to "clear air" throughout the manuscript.

Line 78. "usually occurs at the lee side". By definition, the downslope windstorm occurs at the lee side a mountain range. Please correct. Corrected as suggestion (Line 78).

Line 80-81. "explained by hydraulic jump". Please correct to "accompanied with hydraulic jumps".

Corrected as suggestion (Lines 81-82).

Lines 116-117. "Wider ... conditions." Redundant phrase. Please delete. Removed as suggestion (Line 119).

Line 118. "the best solution". Arbitrary statement. Please change to "one approach to obtain more complete wind data is the use of Doppler wind data". Revised as suggestion (Lines 119-120).

Line 157-169. This is a nice overview that is somehow lacking for any of the other observational platforms.

More complete and detailed introductions for observations, reanalysis datasets and the principle of WISSODM have been improved in following sections (from Section 2.2 to 2.4).

Line 165. "100 km". This is probably not true, please address. The redundant descriptions have been removed for clarity (<u>Lines 166-167</u>).

#### Line 169. "0.04". Why this value?

We have done with many tests from 0.01, 0.02, 0.03  $\sim$  0.1, and this value can appropriately remove most noises and retain sufficient meteorological signals. This explanation has been added in Lines 171-173.

Line 170. LDAPS is derived from model simulations? This needs to be emphasized, as it looks now as if this is an observational dataset.

We have improved the introductions of the LDAPS dataset detailly (as Section 2.3). The forecast outputs of LDAPS dose not used in this study, the capabilities and spatiotemporal resolution were also addressed in this section (from <u>Line 220</u>). Please refer to our responses in second major comment above.

Lines 171-177. Please provide more detail on measurement height and other instrument details. For some reason, these are only provided for the doppler lidar. Were the sounding stations only added for the field experiment time, or are these permanent stations? Was there missing data? Were the soundings always launched at increments of 3 hour? There must have been some discrepancy in release times, but there is no information. It would also be nice to show a table with available observational platforms that accompanies figure 1, for example.

We have provided detailed information about adopting datasets in Sections 2.2 and 2.3 (<u>Line 174 and Line 220</u>), and these information have been summarized in Table 1 (<u>line 211</u>).

Line 177. "are" is "were". Five soundings at one time at all locations? Please let someone proofread.

Revised as suggestion (Line 195), this sentence has been rewritten for clarity (Lines 194-197).

Line 180. What is an "environmental wind"? Please define "very fine-scale".

We want to explain such dense sounding observations, which can represent local horizontal winds in relatively small scale (~15 km). The descriptions and the definition of these two words have been improved in <u>Lines 201-205</u>.

Figure 1. Please include an inset map of South Korea to indicate where this is (figures should be standalone). Presumably the white area in (a) is the ocean? The colormap suggests this is a mountain. It would be good to have a table in addition to this figure to indicate the abbreviations and the platforms used.

The Korea map has been inserted in Figure 1 (<u>Line 212</u>). The color bar in Figure 1 were modified to be corrected one. The names of each station in Figure 1 were also summarized in Table 1.

Lines 192-197. LDAPS is a numerical model. It is misleading to have this included in an observational paper without really emphasizing this. The title of the paper reads "Observational study", besides the model simulations are not mentioned in the abstract. It also remains unclear whether this is based on reanalysis, or whether this is a forecasting tool. This is important, as the results are presented as an observational study, but the model at 1.5 km grid spacing will never represent the terrain in such an accurate manner that one can present these results as observations. How is the data corrected regarding the terrain smoothing in the model?

We have modified the title because the conventional and reanalysis datasets were used in this study (Lines 1-2). We have emphasized what kind of the datasets were adopted in the abstract as well (Line 37-41). The LDAPS reanalysis dataset was assimilated by various platforms with high resolution of wind observations (like lidar, AWS, sounding, wind profiler and satellite). The errors between conventional observations and LDAPS have been minimized conscientiously by the KMA and the quality of wind information is able to resolve small-scale weather phenomena over complex terrain in Korea. The detailed descriptions about the LDAPS dataset have been revised in Section 2.3 (Line 220).

Line 249. "fine weather condition". See above. Reworded to "clear air" throughout the manuscript.

Line 251. This must be plural, please address. Revised as suggestion (Line 307).

Line 258. Stronger than what? This a redundant word and it has been removed (Line 308).

Figure 2. Please modify the caption such that it reflects (a,b,c, etc). The caption of Fig. 2 has been modified (<u>Lines 320-324</u>).

Line 271. "Consequently." Already checked, and it looks a correct use (Line 325)

Line 276. "The other ... from China". Awkward phrasing, please address. The sentence has been rewritten (<u>Lines 330-333</u>)

Line 278. "northerly winds". Is this in figure 2e and 2f? Please make a reference. The reference has been made, and more clear description was also added (<u>Lines 332-333</u>).

Line 280. Not sure why this is important in "fine weather conditions". Was there precipitation elsewhere on the peninsula?

Because lidar is not like radar, it will have severe attenuations when raining or snowing. So, it is a big challenge to collect the good coverage of wind information under clear air condition. Fortunately, many observational platforms were deployed at the time when the extreme strong wind occurred during ICE-POP 2018. We have emphasized this point of view in Lines 335-338.

Lines 282-294. It is arbitrary to use a trend for wind speeds at the surface over the course of only 15 hours, this is clearly within the diurnal variability of winds. How was this calculated? Also, where does this data come from? See also comment on figure 3 below.

Instead of the trends for wind speed, we use consecutive wind speed analysis during research period to explain the relations between wind speed and the LPS. The results shows that the changes of wind speed have clear relations with large-scale weather system and reveals relatively weak relations with diurnal effects. In particularly, the wind speed was increasing when the LPS was passing and was decreasing when the LPS was moving away the Korean peninsula. This new analysis can also be sufficiently presented the uniqueness as the sustained (gusty) strong wind occurred over mountainous area (lee side of the mountain range). The new figure (Figure 3, Lines 368-372) and the detailed descriptions (Lines 339-351) about the changes of wind speed have been revised in Section 3.1.

Line 284. "leaving". Awkward, please rephrase.

This paragraph has been rewritten to clarify the changes of wind speed during research period.

Line 286. "these two stages *are* shown in Fig.". Please use present tense when you refer directly to the figure, and past tense when you describe the event that occurred in the past. There are many grammatical errors like this, please address.

We have checked the grammatical errors and have been corrected throughout manuscript.

Line 290. "described" should be "shown". We have corrected this kind of wrong usages throughout the manuscript.

Line 291-294. "That is, ... 3b)." This is very hard to understand. This paragraph has been rewritten to clarify the changes of wind speed during research period.

Figure 3. It seems like the figure in this data encompasses AWS data for the full country. Correct? This was not introduced in the Data and methods section. How many stations are here? It is impossible to know this since the authors seem to have used some interpolation technique that is also not explained.

Correct, the nationwide AWS data was used. There were 759 AWSs in Korea and their observational parameters were interpolated to given grid based on the objective analysis. We have added detailed descriptions about the characteristic of AWS data (Lines 174-191) and their distributions in Fig. 1 (Line 212).

Line 301. Ambiguous subtitle. Perhaps change to "Upstream environmental conditions?"

Revised as suggestion (Line 373).

Line 306-307. "Three scanning lidars were deployed at ...". Three at each site? I know what the authors want to say, but it should be clear from the sentence directly. This sentence has been rewritten for clarity (Lines 377-379).

Line 307. "Five soundings ... coastal area". Something is missing in this sentence. The missing word has been corrected in this sentence (Line 379).

Line 308. "The sounding ... side (GWW)". This should be in methodology section. This description has been moved to the methodology section (<u>Section 2.2, Lines 197-201</u>)

Line 311. Are BKC and GWW also sounding stations? It is unclear. Yes, they both are sounding stations, we have modified the description for clarity (<u>Line</u> 200). Line 316-317. "Furthermore, ... symbols." Redundant sentence. The redundant sentence has been removed.

Line 320. Please remove "Instead ... site," as it is redundant information. The redundant part has been removed.

Lines 331-332. Awkward phrasing. This sentence has been rewritten for clarity (<u>Lines 397-400</u>).

Figure 4. What is the wind direction in the wind barb plots? Degrees from north, or across the panel? Figure 1a indicates that MOP and JSC are not aligned along this cross section. How is this corrected for? Otherwise, this needs to be acknowledged for somehow: either that data is or is not corrected for the location. Given the WISSDOM dataset doing some interpolation, it seems crucial information at this point of the manuscript. Also, please discard the filled contour for terrain elevation (or make it lighter in color) as it obscures some of the wind barbs at lower elevation.

The wind barb indicates the degree from north, this information has been added in the caption (Lines 404-405). Since the sounding were used here to represent local environmental condition in the scale around 15 km (cf. Lines 204-205). The sounding sites were perpendicularly projected to the cross line (in Fig. 1b) from their original locations, this description has been added in the figure caption as well (Lines 406-407). WISSDOM uses Cartesian coordinate system, thus, the input data have to interpolate to the same coordinate system first, this description has been revised in the introductions of WISSDOM (Section 2.4, Lines 263-265). The filled contour has been removed for clarity (Fig. 4, Line 401).

Line 339. DDG is upstream from the lee slope, but it seems there are more stations even further upstream. Why was this site chosen here?

The DGW is good upstream site than other two sites (MOO and JWC). First, the DGW have no missing data, and it have more tight relations with its downstream site (GWW). These descriptions have been noted in <u>Lines 410-415</u>.

Line 343. Awkard phrasing. It is the air that becomes drier and warmer, not the temperature.

The sentence has been revised (Line 418).

Line 346-347. This is clearly a wrong statement. The authors refer to an elevated

inversion at around 800 hPa in a profile that starts at 900 hPa (Figure 5). Stable boundary layers that develop overnight rarely exceed 300 m agl. Besides, there is clear neutral layer between the surface and the elevated inversion. Thus, this elevated inversion has some other origin, perhaps large-scale subsidence? The authors could address this by simply mentioning that the origin of the elevated inversion at time of writing has not been investigated.

We also agree this point, the large-scale subsident would possibly provide more contributions to the inversion in this event. However, it is not easy to clarify this issue completely from our present analysis and datasets, the numerical study would be good approach. The descriptions about his issue have been improved in manuscript based on the suggestions (Lines 422-426).

Line 348. What is a "good condition" for generating hydraulic jump and downslope windstorm in the lee side? Please be specific.

The "good condition" indicates perpendicularly upstream wind to the mountain range, and upstream inversion. In addition, we modified the word from "good" to "preferred". The specific description about the "preferred condition" has been noted in <u>Lines 426-427</u>.

Line 350. What are environmental winds? Perhaps the authors mean to say "the upstream environment encompassed westerly winds". Yes, we putted "upstream" prior to "environmental winds" (Line 429).

Line 352. "dramatically". Please remove. This word has been removed.

Line 358. Headers should be objective titles such as "Lee slope winds" rather than "stronger winds in the lee slope". Please address also for other subtitles. The subtitles have been revised throughout the manuscript (Line 439, Line 604).

Line 360. Perhaps rephrase to "the prevailing wind direction". Why is this "likely" the wind direction? Wasn't this observed? This sentence has been revised as suggestion (Line 441).

Line 370. Fluctuations of what? This sentence has been improved for clarity (<u>Line 450</u>).

Lines 370, 380. What are perturbation temperature and pressure? We utilized the "station pressure" and "temperature" for further analysis, the descriptions about the station pressure and temperature have been revised in this paragraph (Line 450 and Lines 460-463).

Figure 6. This is quite a nice figure, but perhaps a lower density in the wind barbs (vertically) would make a clearer picture. Perturbation temperature and pressure. What are these perturbations of? A difference from one-day average at a single station? Or a time-difference across a station-average? Why not just present local ambient and dew point temperature evolution?

Thank you for these good suggestions. The figure has been modified (<u>Line 468</u>) and we also use the station pressure and temperature for further analysis.

Line 395. Which two sites?

It should be "two different locations", the description has been revised for clarity (Line 527).

Line 420-421. As the boundary layer height changes over time, this cannot be a fixed value by definition.

In this budget analysis, the mean of boundary layer height was usually used to represent the H. Furthermore, the values of H did not change too much during the research period. Thus, we used these fixed values to represent the boundary layer height here. The description has been modified in Lines 552-555.

Line 433. What is a sub-synoptic scale feature?

It indicates small-scale. The description has been improved for clarity (Lines 567-568).

Line 443. What gusty wind are the authors referring to here?

The gusty wind indicates the wind speed was increased suddenly (like  $\sim$ 3 to 12 m s<sup>-1</sup> in this event) in short period. This description has been also noted in <u>Lines 579-582</u> for clarity.

Line 452-453. Perturbation of what?

We used new analysis to evaluate the contributions of large-scale weather system in the PGF based on suggestions below. This paragraph has been rewritten.

Line 458. Surface or sea-level pressure? This paragraph has been rewritten.

Line 469-470. What would be the rationale between an enhanced PGF and subcloud cooling and/or warming? Wasn't this study performed in fine weather conditions,

meaning there are no clouds involved? Also, just because term B and PGF "trend" overlap, this doesn't necessarily mean that "subcloud warming" is the critical factor explaining the enhance pressure gradient. The "warming" can also come from adiabatic compression as a result of mountain waves involved. In other words, the correlation does not necessarily mean causality here. Is the pressure gradient not just merely a result of the low and high pressure systems going through the area, that with some critical upstream upper-air environment led to some warming down the lee slopes?

We agree this point, and this is particularly an excellent suggestion. Thus, we did new analysis based on this approach. We evaluated the contributions from the large-scale weather system, and the results indicates that relatively lower pressure in the speed-up stage may have produced by adiabatic warming coupled with the LPS. Thus, the large-scale weather system indeed contributed some warming down the lee slope. The detailed descriptions have been revised in last paragraph in Section 4.1.2 (Lines 579-597), and the new figure is shown in Line 599.

Line 504. "Maximum values". What do the authors mean with maximum values? We replaced the words "maximum values" to become "range". The "range" of Froude number ( $F_r = U/NH$ ) was calculated when we assumed represent terrain height (i.e., H in  $F_r$ ) between 1000 and 2000 m MSL (the averaged altitude of the TMR is ~1200 m). This description has been improved for clarity (Lines 505-509).

#### Line 506. What sensitivity test are the authors referring to here?

Except for the different represent terrain height, we also calculated the Froude number with different Brunt-Vaisala frequency (including saturated and dry). After this procedure, the range of Froude number in this event were estimated. This description has been improved for clarity (Lines 505-509).

# Line 506-507. "increasing the topography height between 1000 and 2000 MSL". What does this mean?

Although averaged height of the TMR is ~1200 m, the Fronde number were estimated by adjusting represent height to check its variability in this local area. In addition, it should be 1000 and 2000 "m" MSL, this typo has been corrected (Line 508).

Line 509-512. It is hard to follow this. The descriptions have been improved for clarity (<u>Lines 509-512</u>) Line 513. "surface velocity". Surface winds perhaps? This word has been corrected (<u>Line 513</u>).

Figure 10. This figure probably provides explanation for the adiabatic compression leading to a warming in the lee slopes. A recommendation is that it would be better to show theta every 2 or even every degree. Figure 10a also raises the question whether rotor behavior was involved or not. By any means, it looks like the development of winds and temperature at GWW could also be influenced by the fact that this location is close to the ocean, which makes the presented analysis a little more tricky. There have been quite a few studies to downslope windstorms in coastal mountainous environments (Corsica, Southern California, Adriatic Sea), maybe have a look at those. The figure has been modified by following suggestion (Line 521). The rotors seem not clear showing when we increased the contours. Additionally, the ocean temperature was not changed too much during the research period when we checked the sea surface temperature of EAR5. Compared to the downslope windstorms in coastal mountainous environments in the other locations (Corsica, Southern California, Adriatic Sea), we may have assumed that the influences from the ocean would be small in our selected event. The descriptions about this statement have been noted in Lines 516-520.

Figure 10. This is clearly numerical simulations, but the title of the paper says "Observational analysis".

This figure was analyzed by using the LDAPS reanalysis dataset, this reanalysis dataset was assimilated with many of high spatiotemporal wind observations. We have addressed this in the introductions of LDAPS and ERA5 datasets (Lines 220-241). Therefore, the title was modified as well.

Line 523. Please change the title of this section to something that is addressed in the section, rather than "stronger winds".

The title of this subsection has been changed as suggestion (Lines 604-605).

Line 526. "westerly". Please change to "westerly winds". This accounts to all occurrences in the manuscript.

These words have been revised throughout the manuscript.

Line 533. "Can sustain". Please change to "sustained". The words have been changed as suggestion (Line 614)

Figure 11. Change figure caption to "Same as Figure 6, but for DGW site". See also

comments on figure 6.

The figure caption has been revised (Line 634, Line 661).

Lines 627-629. This is quite an interesting analysis, but this statement seems off. Regarding the minimum and maximum values at roughly 4.5 and 8.5 km, respectively, one sees a similar increase in wind speed of roughly 40%. 10 vs. 15 m/s and 6.5 vs 4.5 m/s. Why, if the wind direction is the same, would this ratio be different in different wind speed conditions?

This is a valid point. This ratio explained that the westerly winds indeed were accelerated in narrow segment along valley, however, there were different amplifications in the maximum wind speed with different strength of westerly. In this event, the maximum wind speed was amplified significantly (~10 m s<sup>-1</sup> more than averaged) in the narrow segment of valley when the westerly winds were strong. The detailed descriptions have been revised in Lines 695-703.

Figure 14. The y-label says averaged wind speed, but the figure also shows shading. Is that also averaged? Probably it would be better to just change the y-label to wind speed. Does the channel width actually mean valley width? Thank you for pointing out the problem, the figure has been modified (Line 705).

1	An analysis of an extreme wind event in a clear air condition
2	associated with a low-pressure system during ICE-POP 2018
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31	Atmospheric Chemistry and Physics
32	Aunospheric Chemistry und Enysies
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34	31 May 2021

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#### 35 Abstract

36 An extreme wind event under clear air conditions on 13–15 February 2018 during the 2018 37 Winter Olympic and Paralympic games in Pyeongchang, Korea, was examined using various 38 observational datasets and reanalysis data. High spatiotemporal resolution wind information was 39 obtained by Doppler lidars, automatic weather stations (AWSs), a wind profiler, sounding 40 observations, global reanalysis (ERA5) and the local reanalysis datasets from the 3DVAR data 41 assimilation system under the International Collaborative Experiments for Pyeongchang 2018 42 Olympic and Paralympic winter games (ICE-POP 2018). This study aimed to understand the 43 possible generation mechanisms of localized strong winds across a high mountainous area and 44 on the leeward side of mountains associated with the underlying large-scale pattern of a low-45 pressure system (LPS). The evolution of surface winds shows quite different patterns, exhibiting 1) intensification of strong winds in the leeward side and 2) persistent strong winds in upstream 46 47 mountainous areas with the approaching LPS. The two different mechanisms of strong winds were investigated. The surface wind speed was intensified dramatically from  $\sim 3$  to  $\sim 12$  m s<sup>-1</sup> 48 (gusts were stronger than 20 m s<sup>-1</sup> above the ground) at a surface station in the leeward side of 49 50 the mountain range. A budget analysis of the horizontal momentum equation suggested that the 51 pressure gradient force (PGF) contributed from adiabatic warming and the passage of LPS was 52 the main factor in the dramatic acceleration of the surface wind in the downslope, leeward side 53 of the mountains. However, a mountainous station appeared to have persistent strong winds (~10 54 m s<sup>-1</sup>). Detailed analysis of the retrieved 3D winds revealed that the PGF also dominated at the 55 mountainous station, which caused persistent strong winds related to the channeling effect along 56 the narrow segment of the valley in the mountainous area. The observational evidence showed 57 that under the same synoptic condition of a LPS, different mechanisms are important for strong 58 winds in this local areas in determining the strength and persistence of orographic-induced strong 59 winds under clear air conditions.

#### 60 1. Introduction

61 Wind is an important atmospheric phenomenon, and topography can significantly affect the 62 behavior of winds to accelerate/decelerate the wind speed or to change the wind direction 63 (Mitchell, 1956; Brinkmann, 1974; Houze, 2012; Yu and Tsai, 2017; Tsai et al., 2018). Such 64 orographically strong wind and mountain waves can easily induce very large impacts on aviation 65 operations (Clark et al., 2000; Kim and Chun, 2010, 2011; Kim et al., 2019; Park et al., 2016, 66 2019), outdoor sport activities, and forest wildfires in a relatively dry environment under clear 67 air conditions (Smith et al., 2018). Downslope windstorms can produce strong winds on the 68 leeward side and play an essential role in creating and maintaining wildfires near northern 69 California with easterly winds across the Sierra Nevada and southern Cascade Mountains (Mass 70 and Ovens, 2019). Lee et al. (2020) also suggested that downslope windstorms favor wildfires 71 along the northeastern coast of Korea with westerly winds across the Taebeak Mountain Range 72 (TMR). In addition, wind speeds are also usually accelerated locally near narrow valleys or 73 channels between mountains, such as the "gap winds" occurring along the strait of Juan de Fuca 74 in Washington (Reed, 1931; Colle and Mass, 2000), Columbia River Gorge in Oregon (Sharp, 75 2002), and Jangjeon area in South Korea (Lee et al., 2020).

76 The environmental conditions of large-scale weather systems are key factors in determining 77 the locations where strong winds are generated. Downslope windstorms usually occur on the 78 leeward side of a mountain range, and the upstream prevailing wind direction is mostly 79 perpendicular to the orientation of the mountain range. An elevated inversion layer and the height 80 of the mean-state critical level are also important references to evaluate the occurrence of 81 downslope windstorms. The occurrence of downslope windstorms are usually accompanied with 82 hydraulic jumps, partial reflection, and critical-level reflection, according to various numerical 83 and theoretical studies in the past few decades (Long, 1953; Houghton and Kasahara, 1968; 84 Klemp and Lilly, 1975; Smith, 1985; Durran, 1990; Afanasyev and Peltier, 1998; Epifanio and

85 Qian, 2008; Rögnvaldsson et al., 2011; Cao and Fovell, 2016). The combination of hydraulic 86 jumps and wave breaking can also enhance downslope windstorms and increase the wind speed 87 (Shestakova et al., 2018; Tollinger et al., 2019). The pressure gradient force (PGF) is one of the 88 possible factors that accelerates the wind speed near the exit of the gap between the mountains 89 when prevailing winds blow into a narrow valley with appropriate directions (Reed, 1931; 90 Finnigan et al., 1994; Colle and Mass, 2000). Although the characteristics of these two kinds of 91 orographically strong winds (downslope windstorms and gap winds) are fundamentally different, 92 they may occur on adjacent mountains at the same time (Hughes and Hall, 2010; Lee et al., 2020). 93 A few previous numerical studies have provided insightful explanations about the 94 development of the strong winds associated with the downslope windstorms along the 95 northeastern coast of South Korea (on the leeward side of the TMR). Most of the strong 96 downslope wind events were mainly explained by the three mechanisms in this region: hydraulic 97 jump, partial reflection, and critical-level reflection (Lee, 2003; Kim and Cheong, 2006; Jang and 98 Chun, 2008; Lee and In, 2009). Strong winds can occur during any season with the appropriate 99 environmental conditions, such as westerly winds and upstream inversion. Lee et al. (2020) 100 confirmed these conclusions with numerical modeling studies. Furthermore, they also found that 101 the PGF is one of the possible factors to produce the gap wind, and the variability of the PGF is 102 highly related to the local topographic features. However, sufficient observational studies to 103 examine the detailed mechanisms of orographically-induced strong winds and their relations with 104 large-scale weather systems in Korea are still lacking because relatively dense wind observations 105 from ground-based remote sensing techniques cannot be easily collected under clear air 106 conditions.

107 Pyeongchang hosted the Winter Olympic and Paralympic Games in 2018 (most venues were 108 located in coastal and higher elevation areas of the TMR). More detailed weather conditions and 109 accurate prediction for several key parameters, such as precipitation, visibility, wind directions, 110 and wind speed, are important to ensure the safety of all athletes and attendees. The Numerical 111 Modeling Center (NWC) of the Korea Meteorological Administration (KMA) organized an 112 intensive field experiment named the International Collaborative Experiments for Pyeongchang 113 2018 Olympic and Paralympic winter **ICE-POP** 2018 games, 114 (http://155.230.157.230:8080/Icepop\_2018/index.jsp). A very dense observational network was 115 built to provide a high-quality observational dataset at high temporal and spatial resolutions under 116 either precipitation or clear air conditions. Many kinds of instruments were involved in ICE-POP 117 2018, which allows the observationally based investigation of the nature of the strong wind event 118 in the nearby mountainous area.

119 Scanning Doppler lidar can be one approach to obtain more complete wind information in 120 such conditions with even finer resolutions. A few studies have used Doppler lidar to document 121 orographic flow, downslope windstorms and rotors (Neiman et al., 1988; Hill et al., 2010; Mole 122 et al., 2017; Bell et al., 2020). Kühnlein et al. (2013) found that transient internal hydraulic jumps 123 are characterized by turbulence. Menke et al. (2019) identified the recirculation zone over an area 124 with complex terrain using six scanning Doppler lidars. The interactions between the winds and 125 terrain dominantly affected the occurrence of flow recirculation. However, only radial winds 126 were used, resulting in incomplete wind observations that can provide only limited information 127 for realistic airflow structures. Complete 3D wind fields could be retrieved from 4D-Variational 128 Assimilation (4DVAR) using Doppler lidar. The accuracy of wind speed, direction and water 129 vapor flux are improved when assimilating lidar data (Kawabata, 2014). Thus, lidar observations 130 can indeed provide high-quality 3D wind information under clear air conditions.

The objective of this study is to use high spatiotemporal resolution datasets to investigate the fine-scale structural evolution of strong winds over the complex terrain in the northeastern part of South Korea (i.e., in the Pyeongchang area) during 13–15 February 2018. Multiple Doppler lidars, automatic weather stations (AWSs), a wind profiler, sounding observations, global reanalysis (ERA5) and the local reanalysis datasets from the 3DVAR data assimilation system (LDAPS: Local Data Assimilation and Prediction System) were adopted to analyze the detailed 137 wind patterns over the TMR and northeastern coastal regions. The 3D winds were also derived 138 through the WInd Synthesis System using DOppler Measurements (WISSDOM, Liou and Chang, 139 2009; Tsai et al., 2018) synthesis. Since only a few extreme wind events were identified here 140 based on the KMA historic record in the past decade (see details in Section 3.1), the impact of 141 large-scale weather systems on triggering strong winds over complex terrain is still unclear, 142 especially under clear air conditions. Therefore, this study is the first observationally based 143 attempt to recognize the mechanisms of the strong winds over the TMR while a low-pressure 144 system (LPS) passes through the northern side of the Korean Peninsula. A unique extreme wind 145 event was selected for further analysis not only because the Olympic games were interrupted due 146 to the strong wind invading the mountainous area and leeward side of the mountain range but 147 also because dense observations are available during ICE-POP 2018. Furthermore, three scanning 148 Doppler lidars were established in this area, which provided more sufficient wind information 149 under clear air conditions.

#### 150 **2. Data and methodology**

#### 151 **2.1 Scanning Doppler lidar**

152 Two different models of scanning Doppler lidars were adopted in this study: (1) "WINDEX-153 2000" produced by the manufacturer Laser Systems and (2) the "Stream Line" produced by the 154 manufacturer HALO Photonics. The scanning Doppler lidar measures the radial Doppler velocity 155 by detecting atmospheric aerosols and dust via a laser (class 1 M) at an exceedingly high spatial 156 resolution. The radial winds were sufficiently observed by an adjustable scanning strategy in three modes: plan position indicator (PPI), range height indicator (RHI), and zenith pointing (ZP). 157 158 Furthermore, these lidar observations were used to construct the complete wind information 159 under clear air conditions via WISSDOM.

160 The WINDEX-2000 lidar operated a full volume scan every ~27 min with seven PPIs 161 (elevation angles of 5°, 7°, 10°, 15°, 30°, 45°, and 80°) and one hemispheric RHI (azimuth angle 162 of 0°, that is, starting from the north). There are 344 gates along a lidar radial direction with 360 163 azimuth angles between 0° and 360°. The gate spacing is 40 m, and the maximum observed radius 164 distance is ~13 km. The Stream Line lidar operated a full volume scan every ~13 min with five 165 PPIs (7°, 15°, 30°, 45°, and 80° before 10:00 UTC on 14 Feb. 2018 and 4°, 8°, 14°, 25°, and 80° 166 after 10:00 UTC) and two hemispheric RHIs (azimuth angles of 51° and 330°). There are 1660 167 gates along the 360 lidar beams with azimuth angles between 0° and 360°.

Quality control (QC) of the radial winds (in PPI and RHI modes) was performed by applying the signal noise ratio (SNR) threshold in advance. To obtain correct and useful measurements, QC is necessary for each lidar observation, where the nonmeteorological echoes are removed when the SNR threshold is smaller than 0.04. This threshold was obtained by a series of tests, and it can appropriately remove most of the noise and retain sufficient meteorological signals at the same time.

#### 174 2.2 Automatic weather stations (AWSs), soundings, and the wind profiler

175 Fig. 1 shows the main study domain (larger box in Fig. 1a), WISSDOM domain (box in Fig. 176 1b) and domain of mountain clusters during ICE-POP 2018. The locations of all AWSs are also marked in Fig. 1a. There were 727 regular operational stations, and the mean distance between 177 178 AWS stations was ~10 km. Two distinct dense areas of the AWS observations were found: one 179 was located near Seoul city (~37.5°N, 126.7°E), and the other was located inside the smaller box 180 over the TMR. This is because additional AWS sites (32 stations) were deployed in the 181 mountainous area during ICE-POP 2018. This dense AWS network (black dots in Fig. 1) is 182 utilized to document the detailed evolution of surface parameters and as one of the constraints in 183 WISSDOM (details are given in the following subsection). The AWSs mainly provide the surface 184 wind speed, wind direction, pressure, and temperature at high temporal resolution (1-min interval). Original AWS observations reveal semirandom distribution and must be interpolated on given grids in a Cartesian coordinate system after applying objective analysis (Cressman, 1959) with a suitable influence of radius (10 km in this study). These gridded AWS data will be of great benefit to WISSDOM and further analysis of wind speed changes in Korea. Note that three AWS stations were selected to represent the fluctuations of pressure, temperature and winds in the mountainous areas (YPO and DGW sites) and the leeward side of the mountain range (GWW site).

192 There is only one regular sounding station (GWW) inside the main study domain operated by 193 the KMA twice a day (00Z and 12Z); such a coarse dataset is quite limited for representing the 194 local changes in environmental conditions near the TMR. Therefore, four additional soundings 195 (DGW, BKC, JSC, MOO) were launched every 3 hours (from 00Z) during the research period (except for the JSC site, see Table 1 for details), and the sounding sites were located inside the 196 197 study domain near the northeastern part of South Korea (black squares in Figs. 1b and 1c). The 198 MOO and JSC sounding stations were located in the southwestern TMR with a gentle slope, and 199 the DGW station was the closest site to most outdoor venues of the Olympic games near the crest 200 of the TMR. The other two sounding stations, BKC and GWW, were located on the northeastern 201 slope of the TMR and in the coastal area, respectively (Fig. 1b). The sounding observations 202 provide detailed horizontal winds, temperature profiles (~1 m vertical resolution), and stability 203 information across the mountainous and coastal areas. Such dense sounding observations are 204 adequate to represent the local environmental conditions on a relatively small scale (~15 km) in 205 the study domain when the LPS passed through.

A wind profiler was deployed at the GWW site to measure the winds in the case of a lack of sounding observations. In addition, the high temporal resolution of wind profiler measurements (10-min interval) could potentially be a reference for the surface and retrieved winds. The names of adopted sites, their equipped instruments and temporal resolutions are summarized in Table. Additionally, intensive observations during ICE-POP 2018 are marked by asterisks.

DGW	Lidar (Stream Line)* Sounding*	13 mins		
	AWS (#100)	3 hours 1 min	37.677°N,128.718°E (mountainous site)	773
MHS	Lidar (WINDEX-2000)*	27 mins	37.665°N,128.699°E (mountainous site)	789
GWW	Wind Profiler Sounding AWS(#104)	10 mins 12 hours 1 min	37.804°N,128.854°E (leeward side)	79
GWU	Lidar (Stream Line)*	13 mins	37.770°N,128.866°E (leeward side)	36
ВКС	Sounding*	3 hours	37.738°N,128.805°E (leeward side slope)	175
JSC	Sounding*	3-6 hours	37.475°N,128.610°E (mountainous site)	424
MOO	Sounding*	3 hours	37.562°N,128.371°E (mountainous site)	532
YPO	AWS(#318)	1 min	37.643°N,128.670°E (mountainous site)	772

Table 1 General information of the observational sites

\*operated only during ICE-POP 2018



125.5E 126E 126.5E 127E 127.5E 128E 128.5E 129E 129.5E 130E



212 128.3E 128.4E 128.5E 128.6E 128.7E 128.8E 128.9E 129.0E 128.65E 128.67E 128.69E 128.71E 128.73E 128.75E 128.77E
213 Figure 1. (a) Observation sites used in this study and the topographic features (color shading) from the digital
214 elevation model (DEM) in Korea; the arrows mark the location of the TMR. (b) The study domain corresponding to
215 the large box in Fig. 1a was chosen in this study. (c) The WISSDOM synthesis domain adopted in this study
216 corresponds to the small box in Fig. 1a. The locations of the scanning Doppler lidar sites are denoted by asterisks.
217 The locations of the sounding sites are denoted by squares. Note that the sounding and lidar observations are both
218 operated at the DGW site and that a wind profiler is located at the GWW site. The locations of the AWS sites and
219 LDAPS grids are denoted by dots and plus symbols, respectively.

### 220 2.3 Reanalysis data: LDAPS and ERA5

Generally, LDAPS is a 3DVAR numerical weather prediction (NWP) product generated by
 the KMA with a spatial resolution of ~1.5 km and temporal resolution of 3 hours with 70 vertical

223 levels. The local reanalysis dataset of LDAPS was used here for further analysis, and the LDAPS 224 forecast outputs were not included in this study. Various observations were assimilated in this 225 reanalysis dataset to be the initial conditions of LDAPS, and those observations included the 226 AWS, sounding, wind profiler, radar, buoy, satellite (polar orbit and geostationary equatorial 227 orbit), and aircraft (research and commercial) data. These observational platforms provided high-228 quality and high spatiotemporal resolution wind observations (especially from the AWSs, radar 229 and satellites) for the LDAPS reanalysis dataset, and the error between observations and this 230 reanalysis dataset was sufficiently minimized after careful corrections from the KMA. Such 231 initial conditions have also significantly improved LDAPS forecasting ability of small-scale 232 weather phenomena over complex terrain in Korea (Kim et al., 2019; Choi et al., 2020; Kim et 233 al., 2020). The wind fields from LDAPS are used as one of the constraints in WISSDOM to minimize the errors of retrieved 3D winds and to compare the discrepancies of winds with 234 previous numerical studies (Section 4.1.1). This dataset is freely available from the KMA website 235 236 (https://data.kma.go.kr).

The ERA5 reanalysis dataset is an atmospheric reanalysis of the global climate and was generated by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 is the fifth generation ECMWF reanalysis with a combination of model and observations. ERA5 provides winds in regular latitude-longitude grid data at  $0.25^{\circ} \times 0.25^{\circ}$  and 37 pressure levels between 1000 and 1 hPa every hour from 1979 to the present (DOI: 10.24381/cds.adbb2d47).

#### 242 2.4 WInd Synthesis System using DOppler Measurements (WISSDOM)

WISSDOM was originally developed by Liou and Chang (2009) and has been applied in the Pyeongchang area (Tsai et al., 2018). This study adopted a newly improved version, which includes more observations as constraints compared with a previous version. In the new version of WISSDOM, the following cost function [eq. (1)] is minimized by using a mathematical variational-based method at the retrieval time:

248 
$$J = \sum_{M=1}^{8} J_M.$$
 (1)

This cost function comprises eight constraints, and the 3D wind fields are obtained by variationally adjusting solutions to simultaneously satisfy those constraints at the same time. The first constraint is the geometric relation between the radial velocity ( $V_r$ ) observations from multiple lidars and Cartesian winds  $V_t = (u_t, v_t, w_t)$ , which are control variables, defined as

253 
$$J_1 = \sum_{t=1}^{2} \sum_{x,y,z} \sum_{i=1}^{N} \alpha_{1,i} \left( T_{1,i,t} \right)^2, \qquad (2a)$$

254 
$$T_{1,i,t} = (V_r)_{i,t} - \frac{(x - P_x^i)}{r_i} u_t - \frac{(y - P_y^i)}{r_i} v_t - \frac{(z - P_z^i)}{r_i} (w_t - W_{T,t}), \text{ and}$$
(2b)

255 
$$r_i = \sqrt{\left(x - P_x^i\right)^2 + \left(y - P_y^i\right)^2 + (z - P_z^i)^2}.$$
 (2c)

256 Any numbers of lidar [subscripts i in eq. (2a)] can be applied to this constraint at two time levels (subscripts t).  $\alpha_1$  in eq. (2a) is the weighting coefficient corresponding to  $J_1$  (which is the 257 same in the following equations for  $J_2 - J_8$ ). The subscripts *i* and *t* in  $(V_r)_{i,t}$  represent the 258 radial velocity observed by the *i*-th lidar,  $(u_t, v_t, w_t)$  indicate the 3D wind at location (x, y, z), 259 260 and the terminal velocity  $(W_{T,t})$  of particles is estimated by radar reflectivity at two time levels.  $(P_x^i, P_y^i, P_z^i)$  are the coordinates of the *i*-th lidar, and the distance between each grid point and 261 262 the *i*-th lidar is denoted by  $r_i$ . Note that  $W_{T,t}$  is zero when there is no radar reflectivity, or the 263 terminal velocity is possibly negligible under clear air conditions. Furthermore, all observational 264 inputs (i.e., lidar radial winds, AWS, sounding and LDAPS horizontal winds) must be bilinearly 265 interpolated to given grids in a Cartesian coordinate system before running WISSDOM.

266 The next constraint is the difference between  $\mathbf{V}_t$  and the background winds  $(\mathbf{V}_{B,t})$  defined 267 in eq. (3)

268 
$$J_2 = \sum_{t=1}^{2} \sum_{x,y,z} \alpha_2 (\mathbf{V}_t - \mathbf{V}_{B,t})^2.$$
(3)

269 The sounding observations are used as the background winds in eq. (3). The constraint of the

anelastic continuity equation is

271 
$$J_3 = \sum_{t=1}^{2} \sum_{x,y,z} \alpha_3 \left[ \frac{\partial(\rho_0 u_t)}{\partial x} + \frac{\partial(\rho_0 v_t)}{\partial y} + \frac{\partial(\rho_0 w_t)}{\partial z} \right]^2, \tag{4}$$

where  $\rho_0$  is the air density. The fourth constraint was deduced from the vertical vorticity equation given by

274 
$$J_4 = \sum_{x,y,z} \alpha_4 \left\{ \frac{\partial \xi}{\partial t} + \left[ \overline{u \frac{\partial \xi}{\partial x} + v \frac{\partial \xi}{\partial y} + w \frac{\partial \xi}{\partial z} + (\xi + f) \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + \left( \frac{\partial w \frac{\partial v}{\partial x} - \frac{\partial w \frac{\partial u}{\partial z}}{\partial y \frac{\partial z}{\partial z}} \right] \right\}^2, \quad (5)$$

where f indicates the Coriolis parameter and the meaning of the overbar in eq. (5) is the temporal average of the two time levels. The constraint of the Laplacian smoothing filter is

277 
$$J_5 = \sum_{t=1}^{2} \sum_{x,y,z} \alpha_5 [\nabla^2 (u_t + v_t + w_t)]^2.$$
(6)

The horizontal winds observed by the soundings, AWSs and LDAPS, can be interpolated to each given grid in the WISSDOM synthesis domain. The sixth constraint is the difference between the  $V_t$  and the sounding observations ( $V_{s,t}$ ), as defined in eq. (7):

281 
$$J_6 = \sum_{t=1}^{2} \sum_{x,y,z} \alpha_6 (V_t - V_{S,t})^2.$$
(7)

The seventh constraint represents the discrepancy between the retrieved winds and AWS ( $V_{A,t}$ ), as expressed in eq. (8):

284 
$$J_7 = \sum_{t=1}^{2} \sum_{x,y,z} \alpha_7 (V_t - V_{A,t})^2.$$
(8)

Finally, the eighth constraint measures the squared errors between the horizontal winds and the LDAPS ( $V_{L,t}$ ), as defined in eq. (9):

287 
$$J_8 = \sum_{t=1}^{2} \sum_{x,y,z} \alpha_8 (V_t - V_{L,t})^2.$$
(9)

288 The main purpose of this constraint is to minimize the squared errors between the horizontal

winds of LDAPS and synthesis winds of WISSDOM, which improves the accuracy of retrieved winds. A relatively weak weighting of the LDAPS reanalysis dataset was applied in the WISSDOM synthesis because more emphasis on the contributions from the other observations is preferred in this study.

293 The original version of WISSDOM is used only in the case of rain or snow with the first five 294 constraints; it has already been comprehensively applied to synthesize high-quality 3D winds in 295 some previous studies. The retrieved 3D winds consistently revealed reasonable patterns 296 compared with conventional observations or observing system simulation experiment (OSSE)-297 type tests (Liou and Chang, 2009; Liou et al., 2012, 2013, 2014, 2016; Lee et al., 2017; Chen, 298 2019). Chen (2019) concluded that the retrieved 3D winds show good relations with observations 299 in several typhoon cases (the mean correlation coefficient was from 0.56 to 0.86, and the root mean square deviation was between 1.13 and 1.74 m s<sup>-1</sup>). The primary advantages and additional 300 301 details of WISSDOM can be found in Tsai et al. (2018). The main improvement of the new 302 version of WISSDOM is that all available wind observations are considered as one of the 303 constraints to minimize the cost function. In addition, this new version extends its applicability 304 by including multiple-lidar observations and thus, realistic wind fields can be retrieved under 305 clear air conditions.

#### **306 3. Overview of the extreme wind event**

#### 307 **3.1 Synoptic conditions**

The hourly ERA5 dataset was used here to document the synoptic conditions. At the beginning of the research period at 12:00 UTC on 13 February 2018, a high-pressure system (HPS) was located in the southernmost Korean Peninsula (as shown in Fig. 2a). Surface southwesterly winds were dominant from the Yellow Sea to the western coast of South Korea associated with the anticyclonic circulation of the HPS. The southwesterly winds were also related to the cyclonic circulation of a LPS centered at 39°N, 117°E near Beijing, China. Compared to the winds over the western coast, relatively weak winds existed over the land and eastern coast of Korea. The westerly wind came from China accompanying warm air in a higher layer (850 hPa, Fig. 2b). This veering wind also indicated that the prevailing southwesterly wind was dominated by warm advection. Thus, a temperature gradient existed between the land and the western and eastern coasts (exceeding an ~4K difference).



Figure 2. (a) Horizontal winds (vectors) and pressure (hPa, color shading) at the surface level, and (b) horizontal winds (vectors) and temperature (K, color shading) at the 850 hPa level obtained from the ERA5 reanalysis dataset at 12:00 UTC on 13 Feb. (c) and (d) Same as (a) and (b) but at 03:00 UTC on 14 Feb. (e) and (f) Same as (a) and (b) but at 00:00 UTC on 15 Feb. 2018. The location of the low pressure system is marked by "L", and the location of the high pressure system is marked by "H".

325 Consequently, the LPS and HPS were both moving eastward. The surface wind became 326 stronger and turned to westerly winds over the Korean Peninsula associated with the confluences 327 between these two systems (Fig. 2c). The horizontal pressure gradient intensified along the 328 northeastern coast of Korea as the LPS moved to the East Sea in Korea. A relatively low 329 temperature was detected over the mountainous area (i.e., near the northeastern coast of South 330 Korea), even when the warm advection was approaching Korea (Fig. 2d). Another HPS was 331 moving out from the northeastern coast of China (~40°N, 120°E) at approximately 00:00 UTC 332 on 15 February 2018 and the environmental winds surrounding Korea switched to relatively weak 333 northwesterly or northeasterly winds over land at the surface (Fig. 2e). Relatively weak pressure 334 gradients and small temperature differences between the western and eastern coasts are shown in 335 Figs. 2e and 2f. Since there was no precipitation along the northeastern coast of South Korea 336 according to the AWS observations during the research period (not shown), the lidar observations 337 certainly had the most complete coverages in the study domain without significant attenuations 338 from precipitation particles in this event.

The evolution of surface wind speed observed from all AWS stations over the Korean 339 340 Peninsula is shown as a sequence of figures in Fig. 3. At the beginning of the research period, the 341 observed wind speeds were weak in most areas of Korea except for an area near the TMR (Figs. 342 3a, 3b, and 3c). The surface wind speed was intensified in most areas of Korea when the LPS was 343 approaching at approximately 03:00 UTC on 14 February 2018 (Figs. 3d, 3e, and 3f) and 344 weakened when the LPS moved away from Korea (Figs. 3g, 3h, and 3i). Two distinct wind speed 345 patterns were clearly identified as sustained strong wind speed existed along the TMR and was 346 even stronger in some local mountainous areas from 12:00 UTC on 13 to 14 February 2018, and the strongest surface winds (exceeding  $\sim 10 \text{ m s}^{-1}$ ) occurred along the northeastern coast of Korea 347 348 during a shorter period (approximately 03:00 to 06:00 UTC on 14 February 2018). Since strong 349 winds occurred during both day and night, the changes in surface winds were mainly affected by 350 the interactions between the movement of synoptic weather systems and complex terrain (cf. Fig.

351 2) and manifested relatively weak relations with diurnal effects in this event.

352 According to the KMA historic record in the past decade during winter seasons (December 353 to March, 2010-2019), the total number of days with daily maximum wind speeds larger than 10 354 m s<sup>-1</sup> is 299 days at DGW and only 19 days at the YPO site. This result indicates that persistent 355 strong winds usually occurred at certain locations over the TMR, such as the DGW site. Although 356 the DGW and YPO sites are both located in mountainous areas with similar elevations and 357 environments (~10 km distance between these two sites), stronger winds are always measured at 358 the DGW site compared to those measured at the YPO site. On the leeward side of the TMR, 359 there were six strong wind events during winter in the past decade based on the KMA AWS measurements (daily maximum wind speed larger than 10 m s<sup>-1</sup>) at the GWW site. Furthermore, 360 361 there were only two extreme wind events (wind gusts over 20 m s<sup>-1</sup>) in the past decade at the 362 same site. In these two extreme wind events, their synoptic conditions were both mainly 363 dominated by LPSs. These historical records imply that the frequency of extreme wind events in 364 this local area is highly related to LPSs. One of these two extreme events was chosen, and this 365 unique extreme wind event allowed us to investigate the mechanisms of persistent strong and 366 gusty winds across the mountainous area and the leeward side of the mountain range associated with the influences of LPS movement. 367



Figure 3. (a) Surface wind speed (m s<sup>-1</sup>, color shading) calculated from all automatic weather station observations
when the low-pressure system passed through the Korean Peninsula at (a) 12:00, (b) 18:00 and (c) 21:00 UTC on 13
Feb. 2018; (d) 00:00, (e) 03:00, (f) 06:00, (g) 12:00 and (h) 18:00 UTC on 14 Feb. 2018; and (i) 00:00 UTC on 15
Feb. 2018.

#### 373 **3.2.** Upstream environmental conditions in the local area near northeastern Korea

Because the evolution of surface wind speed revealed quite different patterns in the mountainous area and on the leeward side of the TMR, two domains were selected in this study, which are shown as boxes in Figs. 1a and Fig. 3. All available observations during the intensive observation period are also marked in Fig. 1b and 1c. One type of scanning Doppler lidar was 378 deployed at DGW and GWU (Stream Line), and the other type was deployed at MHS (WINDEX-379 2000), indicated by asterisks in Fig. 1b. Five sounding stations are aligned from the mountainous 380 area to the coastal area (i.e., perpendicular to the orientation of the TMR). In addition, a wind 381 profiler is located on the leeward side (GWW). The WISSDOM synthesis domain was set over the mountainous area with a horizontal spatial coverage of  $12 \times 12$  km<sup>2</sup>, as shown in Fig. 1c. 382 383 The horizontal and vertical grid sizes were both set to 50 m, and the vertical extent was from 0 384 km to 3 km height mean sea level (MSL). Additional AWS stations were deployed around the 385 venues (black dots in Fig. 1c) during ICE-POP 2018.

386 Fig. 4 shows the variations in the environmental winds observed by the soundings and/or 387 wind profiler along the crossline (black line in Fig. 1b) from the mountainous area to the leeward 388 side of the mountain range. The wind profiler observations are used to provide wind information near the coastal area when the LPS was passing Korea. At the beginning of the research period, 389 390 prevailing westerly winds were dominant at all sounding sites (Fig. 4a). However, stronger winds 391 were measured at heights below ~1.5 km at only the DGW site near the crest of the TMR (~25 m  $s^{-1}$ ), and weaker winds (<15 m  $s^{-1}$ ) were observed in the lower layers at other sites (MOO, BKC, 392 393 and GWW) on both the windward slope and leeward side. The wind direction was still westerly 394 at 03:00 UTC on 14 February 2018 (Fig. 4b). Strong winds were detected at the DGW site and downslope with wind speeds larger than 20 m s<sup>-1</sup> above the BKC and GWW sites. Although the 395 396 wind speed became stronger above 1.5 km MSL over the DGW site, it did not exhibit a significant 397 change near the surface. These results demonstrate that persistent strong winds existed over the 398 mountainous area (i.e., near the DGW site) while the LPS was approaching. The wind became 399 weak over the mountainous area and leeward side of the mountain range when the LPS moved 400 away from the Korean Peninsula (Fig. 4c).



**Figure 4.** Horizontal winds observed by sounding and wind profiler along the cross line corresponding to Fig. 1b at (a) 12:00 UTC on 13 Feb., (b) 03:00 UTC on 14 Feb., and (c) 00:00 UTC on 15 Feb. 2018. A full wind barb corresponds to 5 m s<sup>-1</sup>; a half barb corresponds to 2.5 m s<sup>-1</sup>. The tail of wind barbs indicates the wind direction (degrees clockwise from the north). The color indicates the wind speed corresponding to the color bars. The thick black line in the lower portion indicates the averaged topography along the line in Fig. 1b. The sounding sites were perpendicularly projected to the cross line from their original locations and are marked in this figure.

401

408 Detailed environmental conditions upstream of the leeward site in the TMR (i.e., the 409 mountainous area for westerly winds) were investigated by sounding observations at the DGW 410 site (Fig. 5). Note that the DGW sounding site was selected here to explain upstream 411 environmental conditions because the wind observations seem to have relatively weak relations 412 between farther upstream (MOO) and the GWW sounding site. Unlike the DGW site, the MOO 413 site exhibited unchanging wind patterns when the LPS was passing (cf. Figs. 4a and 4c). 414 Additionally, the JSC sounding site lacks wind observations at a critical time step (12:00 UTC 415 on 13 February 2018). An inversion layer existed at a height of approximately 800 hPa mainly 416 due to the warm advection accompanied by the southwesterly winds at 850 hPa ahead of the LPS

417 (Figs. 2a and 2b at 12:00 UTC on 13 Feb. 2018) until it passed through the Korean Peninsula (at 418 03:00 UTC on 14 Feb. 2018). The air temperature increased near the surface and became drier 419 above the inversion layer between the two time steps. The wind direction was westerly at all 420 levels while the LPS passed through. The wind speed became stronger above the inversion layer, 421 but it exhibited no clear changes below ~800 hPa. It is worth mentioning that the inversion layer 422 probably developed due to several factors: (1) large-scale warm advection, (2) a stable boundary 423 layer and (3) large-scale subsidence. However, stable boundary layer is not easily developed at higher levels overnight, and environmental conditions are more like neutral in this event. Thus, 424 425 determining the separate contributions of these three factors will require a modeling study for 426 this event in the future. The sounding observations showed preferred conditions (i.e., upstream 427 wind direction perpendicular to the mountain range, and upstream inversion) conductive to 428 generating hydraulic jumps and downslope windstorms on the leeward side (Lee et al. 2020).

In summary, the upstream environmental winds associated with the LPS were mostly westerly in this event. However, the wind speeds revealed different characteristics across the TMR, as strong winds ( $\sim 10 \text{ m s}^{-1}$ ) persisted near the surface in the mountainous area and the wind speed increased on the leeward side of the mountain range.



Figure 5. Profiles of temperature (solid lines), dew point (dashed lines), and horizontal winds observed by sounding at the DGW site at 12:00 UTC on 13 Feb. (black lines) and 03:00 UTC on 14 Feb. (red lines) 2018. A full wind barb corresponds to 5 m s<sup>-1</sup> and a half barb corresponds to 2.5 m s<sup>-1</sup>. The tail of wind barbs indicates the wind direction (degrees clockwise from the north).

# 438 **4 Results**

433

# 439 **4.1 Leeward downslope winds**

# 440 **4.1.1 A dramatic acceleration of downslope winds**

441 Although the prevailing wind direction was westerly, the wind speed had a dramatic increase

442 on the leeward side of the TMR. The detailed wind speed and surface fluctuations were documented by a lidar quasi-vertical profile (QVP, Ryzhkov et al., 2016) at the GWU site (upper 443 panel) and the AWS observations at the GWW site (lower panel), as shown in Fig. 6. The wind 444 445 speed was relatively weak at approximately 6–9 m s<sup>-1</sup> in the lowest layer at the beginning of the 446 research period. Strong winds were then measured by the lidar OVP reaching  $\sim 36 \text{ m s}^{-1}$  up to 447 ~1.5 km MSL after 00:00 UTC on 14 February 2018 (Fig. 6a). Finally, the wind speed became 448 weak after 09:00 UTC on 14 February. Winds observed from the sounding and wind profiler were 449 consistent with these QVP winds (cf. Fig. 4).

450 Fluctuations in surface observations of wind speed, direction, station pressure and 451 temperature at the GWW site are shown in Fig. 6b. The changes in wind speed were similar to 452 the lowest layer of lidar observations (cf. Fig. 6a). Relatively weak winds were measured at the 453 early stage of the period, and the surface wind speed intensified dramatically, exceeding ~12 m s<sup>-1</sup> between 00:00 and 06:00 UTC on 14 February (named the speed-up stage and highlighted by 454 455 the shaded area in Fig. 6). The surface wind direction also showed similar patterns to the lidar 456 observations, as it had minor changes from more southerly to westerly. Although these two 457 stations were at different locations along the northeastern coast of Korea, they revealed consistent 458 changes in wind fields. The results also implied that the wind fields along the coast and on the 459 leeward side of the TMR have almost the same characteristics, which could be verified by the 460 analysis of the surface wind speed (cf. Fig. 3f). A relatively low temperature was measured within 461 the first 12 hours at the beginning of the period, and the temperature increased after 00:00 UTC 462 on 14 February from ~3°C to 9°C. The fluctuation in station pressure showed an opposite phase 463 with the temperature variations and the magnitude changed from approximately 1008 to 998 hPa. 464 The wind speed increased just after the temperature rose and station pressure dropped. That is, a 465 significant lag between changes in temperature, station pressure and wind speed is evident. Their 466 specific relationships and mechanisms are clarified through a more detailed analysis in next 467 Section.



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**Figure 6.** (a) Time series of quasi-vertical profile (QVP) from lidar observations at the GWU site during 12:00 UTC on 13 Feb. to 12:00 UTC on 14 Feb. 2018. A full wind barb corresponds to 5 m s<sup>-1</sup>; a half barb corresponds to 2.5 m s<sup>-1</sup> and the color indicates the wind speed (m s<sup>-1</sup>) corresponding to the color scale. The tail of wind barbs indicates the wind direction (degrees clockwise from the north). (b) Time series of horizontal winds (wind barbs), wind speed (m s<sup>-1</sup>, black line), station pressure (hPa, P, blue line) and temperature (°C, T, red line) observed from the AWS at the GWW site. The time period with accelerating wind speed is also highlighted by light yellow shading (i.e., speedup stage).

476 To understand more about the discrepancies in downslope windstorm characteristics from 477 previous numerical studies (Lee, 2003; Kim and Cheong, 2006; Jang and Chun, 2008; Lee and 478 In, 2009). Fig. 7 shows the detailed wind fields and the mountain wave feature that were detected 479 in the local reanalysis dataset of LDAPS. Alternating downdrafts and updrafts were present near 480 the crest (near the DGW site) and leeward side of the TMR at 21:00 UTC on 13 February 2018 481 (3 hours prior to the speed-up stage, Fig. 7a). The mountain wave propagated toward the 482 northeastern direction (parallel to the TMR) associated with the interactions between the 483 prevailing west-southwesterly winds and topography (lee wave in Fig. 7a). Stronger downdrafts and updrafts were characterized by positive and negative phases stronger than 3 m s<sup>-1</sup> at the 484 485 DGW, BKC and GWW sites, and the phase lines were parallel to the orientation of the TMR. 486 Subsequently, in the speed-up stage, the mountain wave structure significantly changed at 03:00 487 UTC on 14 February 2018. The wavelength became longer, but the wave was still parallel to the 488 TMR and the northeastern coast (Fig. 7b).



Figure 7. Horizontal distribution of the vertical velocity (m s<sup>-1</sup>, color shading) and horizontal winds (vectors) at 2
km MSL from LDAPS in the domain corresponding to Fig. 1a at (a) 21:00 UTC on 13 Feb. 2018 and (b) 03:00 UTC
on 14 Feb. 2018. The locations of the scanning Doppler lidar and sounding sites are denoted by asterisks and squares,
respectively.

494 The cross section of the potential temperature (thick solid line in Fig. 8) and streamwise 495 velocity (colors in Fig. 8) perpendicular to the orientation of the TMR demonstrated the mountain 496 wave characteristics on the leeward side (between the DGW and GWW sites) at 21:00 UTC on 497 13 February 2018 (Fig. 8a). During this time period, a relatively strong streamwise velocity 498 occurred only near the downslope of the TMR (~128.78°E, ~1 km MSL) and coincided with the 499 stronger downdraft. Weaker streamwise velocity ( $<4 \text{ m s}^{-1}$ ) appeared near the GWW site in the 500 coastal area. However, the potential temperature pattern in the speed-up stage was characterized 501 by a longer wavelength with a higher amplitude of the mountain wave (Fig. 8b), which is 502 consistent with the vertical velocity field (Fig. 7b). A stronger wind exceeding 30 m s<sup>-1</sup> (shaded 503 orange colors in Fig. 8b) stemmed from higher altitudes as the jet stream approached the Korean 504 Peninsula at this time. It was clear that strong upper winds propagated toward the lower layer and 505 intensified the wind speed at 03:00 UTC. The range of Froude number ( $F_r = U/NH$ ) related to 506 the environmental winds (U) at the DGW sounding site was estimated to be approximately 0.55– 507 0.89. These Froude numbers were calculated by using dry and saturated Brunt-Vaisala frequency 508 (N) with different representative terrain heights (H) from 1000 to 2000 m MSL (the average 509 elevation in the TMR is ~1200 m). These upstream environmental conditions and characteristics 510 of winds were similar to those from previous numerical studies on the northeastern coast of 511 Korea, and the stronger streamwise velocity extended from the upper to lower layers (exceeding 512 ~36 m s<sup>-1</sup>) coincident with the downdraft at downslope of the TMR (~128.78°E, ~1 km MSL). Along with this, surface wind was intensified exceeding  $\sim 12$  m s<sup>-1</sup> near the surface at the GWW 513 514 site associated with the downslope wind. Note that the magnitudes of streamwise velocity are 515 consistent with the fluctuations in the surface wind speed observed from the AWS (wind speed 516 in Fig. 6). In this event, the impacts of the ocean on the temperature over the land would be small. 517 The analysis of surface sea temperature (from ERA5) indicates consistent values of 518 approximately 6.85°C offshore of the northeastern coast of Korea during the entire research 519 period (not shown), however, the temperature fluctuates from ~2°C to ~9°C at the GWW site (cf. 520 Fig. 6) associated with the LPS at the same time.



Figure 8. Vertical cross section of the LDAPS potential temperature (K, contours), streamwise velocity (m s<sup>-1</sup>, color
shading), and airflow (vectors) along the black lines in Fig. 7a at (a) 21:00 UTC on 13 Feb. 2018 and (b) 03:00 UTC
on 14 Feb. 2018. The red line in the lower portion indicates the topography along the black line in Fig. 7. Note that
the color bars are different from the Fig. 6.

#### 526 4.1.2 Possible mechanisms of a dramatic acceleration

The winds could usually be accelerated by the PGF between the two different locations, as 527 528 the stronger wind usually occurred at the site where lower pressure was located. Therefore, the 529 DGW site was selected as the upstream location from the GWW site, and the differences in their 530 surface temperatures and sea level pressures were analyzed. A relatively warm environment was 531 present om the leeward side of the TMR, and the temperature difference between the DGW and 532 GWW sites suddenly increased from ~7°C at the beginning of the research period to ~8.5°C after 533 00:00 UTC on 14 February (Fig. 9a). The expected temperature difference between the two sites is approximately 6.9°C (adiabatic cooling rate for 0.7 km height difference) when adiabatic 534 heating is assumed. The sea level pressure also decreased from ~-1 hPa to -4 hPa when the 535 536 temperature increased. The observed wind speed at the GWW site showed no obvious changes 537 in the beginning. However, the wind speed significantly increased just ~1 hour after the sea level 538 pressure decreased and the temperature increased. This result revealed that the changes in wind 539 speed are possibly related to the fluctuations in temperature and pressure. To clarify the effect of 540 the pressure gradient on the wind speed at the DGW site, the local accelerations between the two 541 sites could be approximated based on the horizontal momentum equation expressed as

542 
$$\frac{\partial u}{\partial t} = -\frac{u}{\partial x}\frac{\partial u}{\partial x} - \frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{fv}{D} + \frac{C_d W_s u}{H_E}.$$
 (10)

In equation (10), Term A is the change in the u component with time and also corresponds to the wind accelerations along the west-east direction, and Term B is the advective acceleration amount relative to the distance (x) between these two selected sites. Only the u component was considered in this study since the v and w components could be neglected because the environmental winds were mostly composed of westerlies (Yu et al., 2020). The PGF was indicated by Term C, where  $\rho$  is the air density and P is the sea level pressure. Coriolis acceleration and friction were indicated by Term D and Term E, respectively, where  $C_d$ ,  $W_s$ , and *H* in Term E are the drag coefficient, wind speed and boundary layer height, respectively. The value of the drag coefficient would most likely be a unitless constant based on Stull (1988) and was set as  $\sim 3.9 \times 10^{-3}$  in this study. The representative height of *H* used in this study was 150 m (MSL) according to the mean boundary layer height from GWW, and a height of 1500 m (MSL) was observed from the DGW sounding observations during 12:00 UTC on 13 and 00:00 UTC on 15 February 2018 (not shown).

556 Basically, the wind accelerations (i.e., Term A) that are derived from equation (10) by adding 557 terms from B to E are in good agreement with the fluctuations in wind speed at the GWW site 558 (Fig. 9b). A relatively weak wind speed occurred in the beginning and coincided with negative 559 and weak accelerations. Consequently, the wind speed rapidly increased at the GWW site in the 560 speed-up stage (i.e., shaded area in Fig. 9) associated with the increased and positive accelerations 561 (i.e., Term A). Furthermore, the contributions of Terms B-E to Term A could also be evaluated 562 individually by calculating each term. The PGF (Term C) dominated the changes in Term A with 563 almost the same magnitudes during the entire research period as shown in Fig. 9c. In the 564 beginning, advective acceleration (Term B) could provide slight positive contribution to Term A, 565 while the PGF term was negative. However, both Term B and friction (Term E) gave negative 566 feedback to Term A in the speed-up stage. Coriolis acceleration (Term D) always exhibited an 567 almost zero acceleration to Term A in such small-scale wind patterns (~10 km distances between these two sites and time periods of a few hours). The results suggested that the PGF would be the 568 569 main factor dominating the changes in wind speed at the GWW site on the leeward side of the 570 TMR.



**Figure 9.** (a) Time series of wind speed (m s<sup>-1</sup>, black line) observed from the AWS at the GWW site and the differences in sea level pressure (hPa, blue line) and temperature (°C, red line) between the GWW and DGW sites from 12:00 UTC on 13 Feb. to 12:00 UTC on 14 Feb. 2018. (b) Time series of the u component acceleration ( $10^{-3}$ m s<sup>-2</sup>, Term A, black dashed line) estimated from the horizontal momentum equation [eq. (10)] between the GWW and DGW sites. (c) Time series of the u component acceleration (Term A, black dashed line), advective acceleration (Term B, red line), PGF (Term C, blue line), Coriolis acceleration (Term D, gray line), and friction (Term E, green line). The time period with accelerating wind speed is also highlighted by light yellow shading (i.e., speed-up stage).

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579 Since the gusty wind (the wind speed suddenly increased from  $\sim 3$  to 12 m s<sup>-1</sup> at the GWW 580 site, cf. Fig. 9a) was mainly explained by the PGF and this result was also consistent with the 581 fluctuations in the sea level pressure from the AWS observations at the GWW site (cf. Fig. 6b), 582 the observed station pressure at the GWW dropped deeply during the speed-up stage. To understand the possible causes of the relatively low pressure occurring on the leeward side of theTMR, more detailed analysis is needed.

585 To evaluate the contributions of pressure and temperature from large-scale weather systems, 586 average values of sea level pressure and potential temperature were calculated from selected 24 587 AWSs (Fig. 1b) to represent the contributions of the passing LPS. The elevations of the selected 588 AWSs must be higher than the GWW site to avoid the effects of adiabatic warming along the 589 northeastern coast. The time series of average sea level pressure and average potential 590 temperature are shown in Fig. 10 with the speed-up stage indicated by shading. In the speed-up 591 stage, the average sea level pressure decreased ~3 hPa (from ~1015 hPa to 1012 hPa), and the 592 average potential temperature increased ~3K (from ~279.5K to 282.5K) (Fig. 10). This variation 593 (contributions from large-scale weather systems, i.e., from the LPS) is similar to sea level 594 pressure (~-3 hPa: from approximately -1 hPa to -4 hPa in Fig. 9a) and temperature (~2.5°C: 595 from approximately 6 °C to 8.5 °C) difference between the DGW and GWW site. Therefore, the 596 coupled effect of adiabatic warming and the passing LPS is probably the main factor that induced 597 the extreme winds on the leeward side of the TMR.



599



**Figure 10.** Time series of average sea level pressure (SP, blue line, unit: hPa) and average potential temperature ( $\theta$ , red line, unit: K) over the 24 AWS stations. from 12:00 UTC on 13 Feb. to 12:00 UTC on 14 Feb. 2018. The time period with accelerating wind speed is also highlighted by light yellow shading (i.e., speed-up stage).

#### 604 **4.2 The winds in mountainous areas**

#### 605 **4.2.1 Persistent strong winds in mountainous areas**

The combination of the LPS and HPS provided a large-scale environmental wind favorable 606 for westerly winds over the mountainous area. According to the DGW QVP from observations 607 (Fig. 11a), the wind speed ranged from  $\sim 12$  to 36 m s<sup>-1</sup> at the low-level layers ( $\sim 900$  to 1800 m 608 MSL) during 12:00 UTC on 13 February to 12:00 UTC on 14 February 2018. After this time 609 610 period, the wind decayed so quickly that it became nearly calm associated with the approaching HPS (Fig. 2e). The surface wind fluctuated in the range of 7 m s<sup>-1</sup> to 12 m s<sup>-1</sup> with a periodicity 611 612 of 6 hours at the DGW site, similar to the pattern in the lidar QVP (Fig. 11b). These characteristics 613 were quite different from the AWS and lidar observations on the leeward side of the mountains 614 (for example, the GWW site). Unlike the coastal site, the strong wind was sustained for a day in 615 the mountainous area. In particular, there were persistent westerly winds at all altitudes over the 616 mountainous area, and the winds were enhanced, especially in some local areas (i.e., the DGW 617 site). However, the wind direction was quite variable from southerly to westerly on the leeward 618 side of the TMR (GWU or GWW site). Significant strong winds were measured at the DGW site 619 above 1000 m MSL on 13 February (Fig. 11), and the wind was weak at the GWU site (Fig. 6). 620 Although the wind strengthened at the GWU and GWW sites at ~02:00 UTC on 14 February, the 621 low-level or surface winds became slightly weaker at the DGW site. This pattern is consistent 622 with the wind fields from the sounding observations at the DGW site (Figs. 4a and 4b).

The AWS observations at the DGW site demonstrated sustained strong westerlies (~10 m s<sup>-1</sup>) with periodic fluctuations from 12:00 UTC on 13 February to 12:00 UTC on 14 February 2018 (Fig. 11b). Although the wind speed fluctuated periodically, no periodicity was shown in the station pressure or temperature. Instead, the station pressure monotonically dropped from ~925 hPa at 12:00 UTC on 13 February to ~920 hPa at 05:00 UTC on 14 February and then increased back to ~925 hPa at 12:00 UTC on 14 February 2018. The temperature showed a nearly opposite trend to that of the station pressure. The temperature was nearly steady until 22:00 UTC and then
increased from approximately -4 to 3°C at 07:00 UTC on 14 February 2018. Although the
movement of the LPS affected the changes in the station pressure and temperature at the DGW
site, the changes in the wind speed had no clear relation with the station pressure or temperature.



**Figure 11.** Same as Figure 6, but for DGW site.

#### 635 4.2.2 Possible mechanisms of persistent strong winds

636 To document the possible mechanisms of sustained strong winds occurring at the DGW site 637 over the mountainous area, differences in temperature and pressure were analyzed in detail. A 638 western surface station (YPO site in Fig. 1b) was selected to calculate the temperature and 639 pressure differences with the DGW site. Fig. 12a reveals that the fluctuations in pressure 640 differences (blue line in Fig. 12a) had an almost negative relation (opposite phase) with the 641 fluctuations in wind speed (black line in Fig. 12a) at the DGW site. Furthermore, the wind speed 642 gently decreased with periodicity (wavelength of approximately 6 hours). This result provided a 643 clue that the pressure gradient likely dominated the wind speed in this local area. Compared to 644 the leeward side of the mountains at the GWW site (Fig. 9), negative values of the temperature 645 differences (minimum of -1.3°C) were calculated in the mountainous area and even became 646 smaller (-0.5°C) after 12:00 UTC on 14 February. Thus, the differences in pressure seemed to 647 affect the wind speed patterns, and the fluctuations in wind speed were less related to the 648 differences in temperature between these two sites. The periodic characteristics of the surface wind may have been linked to nonlinear dynamics, such as gap flow and gravity wave 649 650 mechanisms (Shun et al., 2003).

651 The acceleration of wind speed at the DGW site can also be estimated by equation (10). Most 652 of the estimated Term A and wind speed were also in a good agreement except for a short time 653 period (Fig. 12b). Basically, the wind speed increased (decreased) when the estimated 654 acceleration (i.e., Term A) was positive (negative). To understand the main contributor that 655 dominates such strong local winds in this area, a detailed budget analysis of the momentum 656 equation was performed (Fig. 12c). The PGF (Term C) was the most important factor for the 657 estimated acceleration, which means that the PGF could possibly determine the changes in the 658 wind speed at the DGW site. The advective acceleration was relatively small. The Coriolis force 659 and friction had no clear impacts on the acceleration (Term A).



660 661

Figure 12. Same as Fig. 9, but for the DGW and YPO sites, and the y-axis indicates the wind speed at DGW site.

The above results show that the PGF is the main factor accelerating wind speed, but 662 663 temperature is not a critical factor changing the PGF over the mountainous area. To determine 664 the possible factors that contribute to the PGF, a more detailed analysis of horizontal winds was 665 performed with WISSDOM synthesis. Fig. 13 demonstrates the fine-scale wind fields at 800 m 666 MSL (near the surface in the studied domain). At this height, a unique topographic feature was 667 explored, as it occurred over a relatively wide (narrow) area on the western (eastern) side along 668 the valley. This channel-like feature is marked by the area between two thin dashed lines in Fig. 669 13 for emphasis. Four periods (00:00 UTC on 13 February, 00:00 UTC on 14 February, 12:00

670	UTC on 14 February, and 00:00 UTC on 15 February 2018) were selected to investigate the
671	changes in wind patterns in this channel along the valley. The prevailing wind was westerly with
672	a slight deflection near the center of the domain and the eastern side of the valley, while the LPS
673	approached Korea (Figs 13a, 13b, and 13c). Nevertheless, a relatively weak wind (~6 m s <sup><math>-1</math></sup> )
674	always existed in the center of the domain near the MHS lidar site (wide segment of the valley)
675	and a stronger wind (14 m s <sup>-1</sup> ) was observed near the DGW site (narrow segment of the valley).
676	The wind speed decreased and nearly became calm after the LPS moved away from Korea (Fig.
677	13d).



679

**Figure 13.** Horizontal distribution of the wind speed (m s<sup>-1</sup>, color shading) at 800 m (MSL) retrieved in the WISSDOM domain at (a) 00:00 UTC on 13 Feb., (b), 00:00 UTC on 14 Feb., (c) 12:00 UTC on 14 Feb., and (d) 00:00 UTC on 15 Feb. 2018. The black dashed lines mark the area of the channel to calculate the average wind speed and channel width as shown in Fig. 14. The rectangular box indicates the average area in the vertical cross sections along the valley (A-A'). Topographic features are indicated by the gray shading and contours. Locations of the scanning Doppler lidar sites are denoted by asterisks.

The relations between the topography, average wind speed (thick colored lines in Fig. 14) and channel width (thick black line in Fig. 14) along the valley at 800 m MSL were calculated in two time periods when the LPS was approaching (before 12:00 UTC on 14 February 2018) and leaving (after 12:00 UTC on 14 February 2018). The channel width was approximately 2 km at x = 0 km to 3 km (western side) and became wider (~5.5 km) at x = 3 km to 6.5 km. The channel width then decreased significantly to nearly 0 km at x = 6.5 km to 9.5 km.

692 When the LPS was approaching (average wind speed in red line and range of minimum and 693 maximum wind speed in shading in Fig. 14), the average wind speed increased from  $\sim 10$  m s<sup>-1</sup> to ~14 m s<sup>-1</sup>, which was coincident with the change in channel width from ~5.5 km to 0 km along 694 the valley. When the LPS was leaving (blue line and shading), the average wind speed increased 695 from ~5 m s<sup>-1</sup> to ~ 7 m s<sup>-1</sup> in the narrow segment. There was a similar increase in wind speed of 696 697  $\sim$ 40% in these two stages, and this result also reflected that the wind was indeed accelerated by 698 the channeling effect in this local area. However, the maximum wind speed was larger than 24 m s<sup>-1</sup> near the narrowest segment of the valley when the LPS was approaching and was only 12 m 699  $s^{-1}$  when the LPS was leaving. The maximum wind speed was amplified significantly (~10 m s<sup>-1</sup> 700 701 more than average) in the narrow segment along the valley when the westerly winds were stronger. In contrast, the wind speed was amplified by only 6 m s<sup>-1</sup> when prevailing winds became 702 703 weaker. This analysis reveals that the channeling effect may play an important role in dominating 704 the spatial distribution of wind speed with the valley.



Figure 14. Average wind speed and its range along the valley corresponding to the area indicated by the dashed lines in Fig. 13 at two times: 12:00 UTC on 13 Feb. to 12:00 UTC on 14 Feb. (red line and shading) and 12:00 UTC on 14 Feb. to 00:00 UTC on 15 Feb. (blue line and shading) 2018. The red and blue shading show the maximum and minimum values along the valley for the two times. The average channel width along the valley is plotted by a thick black line.

705

711 Fig. 15 shows the mean vertical structures of wind speed, airflow, and topographic features 712 from each cross section along the boxes in Fig. 13. The boxes were set on our main focus area 713 from wider to narrower segments along the valley and parallel to the environmental wind 714 direction (westerly). These analyses allow us to investigate detailed airflow features from near 715 the surface to higher altitudes and their interactions with topography. The four time periods were 716 12:00 UTC on 13 February 2018, 00:00 UTC and 12:00 UTC on 14 February, and 00:00 UTC 717 on 15 February 2018. The mean vertical structures in the first three periods (when the LPS was 718 approaching) revealed similar characteristics: uniform and stronger westerly winds (larger than ~18 m s<sup>-1</sup>) in the layers above 1 km MSL. In contrast, the airflow had more significant variability 719

in the layers near the surface. In the layers below 1 km MSL, the westerly winds were lifted upslope and became downdrafts behind the mountain crests. In the three time periods, the wind speed was quite weak near the MHS site and was strong near the DGW site, which are coincident with the relatively wide and narrow segments in the valley, respectively. In particular, the high wind speed area was only between x = ~6.5 km and 9.5 km (i.e., the narrowest segment of the valley). The winds became more uniform and weaker in the upper layers and near the surface when the LPS moved away from Korea at 00:00 UTC on 15 February 2018 (Fig. 15d).



Figure 15. Average vertical cross section of the WISSDOM-derived wind speed (m s<sup>-1</sup>, color shading) and wind vectors (combined cross barrier flow and threefold vertical velocity) at four time periods (a) 12:00 UTC on 13 Feb. 2018, (b) 00:00 UTC on 14 Feb. 2018, (c) 12:00 UTC on 14 Feb. 2018, and (d) 00:00 UTC on 15 Feb. 2018. The area of the cross section is shown by the black box in Fig. 13. The black line in the lower portion indicates the topography along the box.

Because the winds manifested clear variations only near the surface layers, the mean vertical structures of wind speed and directions could be further averaged below 1 km MSL. Fig. 16 shows the continuous time series of the averaged wind field during the entire period with the 737 same x axis as that in Fig. 15. The results demonstrate that the winds near the surface layers were accelerated in the narrow segment between x = -6.5 km and 9.5 km for sufficiently strong 738 739 westerly winds (before 00:00 UTC on 14 February). This characteristic is similar to the gap wind 740 or channeling effect from previous simulation and observational studies (Overland and Walter, 741 1981; Neiman et al., 2006; Heinemann, 2018). Consequently, a relatively weak channeling effect 742 induced weaker winds in the narrow segment of the valley during 00:00-15:00 UTC on 14 743 February 2018 because the environmental winds became weaker. Finally, the channeling effect 744 no longer exited when the environmental winds became calm after 15:00 UTC. The wind might 745 accelerate when it blows from wider to narrower segments of the valley due to the PGF, as 746 indicated by Bernoulli's Law, i.e., the pressure decreases when the flow speed increases and vice 747 versa. Observational analysis reveals a relatively low pressure in the narrow segment of the 748 valley, and thus, the PGF would locally dominate the airflow acceleration over the mountainous 749 area.



Figure 16. Temporal variation in the average wind speed (m s<sup>-1</sup>, color shading) and the horizontal winds (wind barbs)
from WISSDOM derived in the valley from 00:00 UTC on 13 Feb. to 00:00 UTC on 15 Feb. 2018. The low-level
winds (below 1 km MSL) within the black boxes in Fig. 15 were averaged in a direction normal to the orientation of
the boxes. The black line in the lower portion indicates the average topography along the boxes.

#### 755 **5. Conclusion**

This study uses Doppler lidar, wind profiler, sounding, surface observation, global 756 757 reanalysis (ERA5) and local reanalysis (LDAPS) datasets to examine an extreme wind event 758 during ICE-POP 2018. Detailed characteristics of wind fields and possible mechanisms during 759 the passage of a low-pressure system (LPS) over the northern part of the Korean Peninsula on 760 13-15 February 2018 were explored. Although the wind speed in South Korea generally 761 increased when the LPS was approaching, the winds comprised more significant gusty winds 762 along the downslope and on the leeward side of the Taebeak Mountain Range (TMR). In contrast, the wind speed was persistently strong in several local areas over the TMR. Conspicuous 763 764 gradients in wind speed patterns existed only between the mountainous areas and the leeward 765 side of the mountain range. Moreover, the wind speed decreased synchronously after the LPS 766 moved away from Korea.

767 From the sounding observations, low-level environmental winds revealed high variability 768 from the mountainous area to the leeward side of the mountains. The wind direction was mostly westerly associated with the LPS, and the wind speed was persistently strong (~10 m s<sup>-1</sup>) at the 769 770 DGW site (i.e., mountainous area) during the research period. However, the wind speed on the 771 leeward side (GWW) clearly changed from relatively weak to stronger. The winds then become 772 nearly calm both in the mountainous area and on the leeward side of the mountain range after the 773 LPS moved away from the Korean Peninsula. In addition, upstream inversion layers (at the ~850 774 hPa level) were also detected by sounding observations at the DGW site, while strong winds 775 occurred on the leeward side of the mountains.

On the leeward side of the mountains, the surface wind speed dramatically increased (from  $\sim 3 \text{ to } 12 \text{ m s}^{-1}$ ) at the GWW site during the research period. The surface temperature increased and station pressure decreased, and the fluctuations in temperature and pressure showed a significant time lag with wind speed changes. In addition, the strong winds were well depicted

along the downslope and the leeward side of the TMR from the LDAPS reanalysis data. This result is similar to those from previous numerical studies in Korea, and the development of strong downslope winds is related to mountain waves and hydraulic jumps. In the mountainous area, persistent strong surface winds were observed at the DGW site when the LPS was approaching. The surface wind has no clear relationship with the station pressure or temperature during the research period.

786 The sea level pressure and temperature differences between the mountainous station at the 787 DGW site and the leeward station at the GWW site demonstrate that the wind speed suddenly 788 increased with increasing temperature (from ~6°C to 8.5°C) and decreasing sea level pressure 789 (from ~-1 hPa to -4 hPa) in the speed-up stage. The estimated wind accelerations [Term A in eq. 790 (10)] are in good agreement with the observed wind speed, which are mainly contributed by the 791 PGF [Term C in eq. (10)]. In the speed-up stage, the average sea level pressure and potential 792 temperature in the AWS observations show fluctuations of approximately -3 hPa and +3K when 793 the LPS passed over. The differences in the sea level pressure (~-3 hPa) and temperature (~2.5°C) 794 between the DGW and GWW sites were almost equal to the contributions from large-scale 795 weather systems. The results indicate that adiabatic warming coupled with the LPS plays an 796 important role in reducing the surface pressure and those winds are accelerated by the PGF on 797 the leeward side of the TMR.

798 The sea level pressure differences between the YPO and DGW stations show almost 799 negative relations with the fluctuations in surface wind speed. In contrast, the temperature 800 differences are small (between -0.5°C and 1.2°C) with no clear relations with the fluctuations in 801 surface wind at the DGW site. Although the temperature has no clear relation with the strong 802 wind, estimated wind accelerations [Term A in eq. (10)] are in good agreement with the observed 803 surface wind speeds. This means that the PGF is still the main contributor to the wind acceleration 804 at the DGW site. The 3D winds derived from WISSDOM synthesis also reveal that the wind 805 speed at the DGW site (narrow segment in the valley) was always stronger than that at the YPO

site (wider segment in the valley). In addition, the channeling effect was amplified to effectively accelerate the winds at the DGW site when the westerly winds were stronger due to the approaching LPS. Thus, the channeling effect is a possible mechanism dominating the wind acceleration in the mountainous area.

810 In this study, observationally based evidence shows that different mechanisms are important 811 for determining the strength and persistence of orographically strong winds in the same 812 underlying LPS under clear air conditions. In the future, high-resolution numerical modeling 813 analysis will be performed for all strong wind events during ICE-POP 2018 because detailed 814 thermodynamic information is desired to provide more complete descriptions about the distribution of potential temperature across the mountainous area. The kinematic and 815 816 thermodynamic information from the simulations will be important indicators to further 817 investigate the existence of mountain waves, including hydraulic jumps, wave breaking, and 818 partial reflection for the generation of the downslope windstorms. More cases will be included to 819 provide comprehensive explanations of the strong downslope wind in the northeastern 820 mountainous part of South Korea. More importantly, we aim to extend our understanding of the 821 variability in winds around terrain on a very fine-scale even in different seasons.

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837

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