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The Challenges of Micro-Nowcasting and the Women's Slope Style Event at the PyeongChang 2018 Olympic Winter Games

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Abstract: The Women's Slope Style event of 11–12 February 2018 at the PyeongChang 2018 Olympic Winter Games posed considerable challenges to the competitors and decision-makers, requiring sub-kilometer and sub-minute weather predictions in complex terrain. The gusty wind conditions were unfair and unsafe as the competitors could not achieve sufficient speed to initiate or complete their jumps. The term micro-nowcasting is used here to reflect the extreme high-resolution nature of these science and service requirements. The World Meteorological Organization has conducted several research development and forecast demonstration projects to advance, accelerate and promote the art of nowcasting. Data from compact automatic weather stations, located along the field of play, reported every minute and were post-processed using time series, Hovmöller and wavelet transforms to succinctly present the information. The analyses revealed dominant frequencies of about 20 min, presumed to be associated with vortex shedding from the mountain ridges, but were unable to directly capture the gusts that affected the competitors. The systemic challenges from this and previous projects are reviewed. They include the lack of adequate scientific knowledge of microscale processes, gaps in modeling, the need for post-processing, forecast techniques, managing ever-changing service requirements and highlights the role of observations and the critical role of the forecaster. These challenges also apply to future high-resolution operational weather and warning services.

Keywords: nowcasting; Olympics; ICE–POP; wind gusts; microscale; wavelet transform; Hovmöller; complex terrain; winter

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1. Introduction

The winter Olympic weather service requirements in complex terrain pose scientific and service challenges. They are generally stated as: (i) synoptic (five or more days in advance), (ii) very short term (forty-eight hours) and (iii) hourly nowcasts [1]. They are both for the safety of the spectators (the public) and the safety of and fairness to the competitors. National Meteorological and Hydrological Services (NMHSs) are responsible for public safety and provide synoptic scale weather services in complex terrain. They are often, but not always [2], the provider of choice for venue and sports competition services. Highly tailored nowcast services are required to support the competitions. The requirements can suddenly change, which necessitates the support of an on-site venue forecaster to provide updates and interpretation to the end-users/decision-makers as frequently as every few minutes [3].

Over the past twenty-five years, the Nowcasting and Mesoscale Research (NMR) working group of the World Meteorological Organization's (WMO) World Weather Research Program (WWRP) has organized forecast demonstration (FDP) and research development projects (RDPs) to address and advance these challenges through international collaborations. FDP's have real-time operational, verification and societal impact components, whereas RDPs are designed to focus on a specific scientific topic. Summer projects were focused on convective thunderstorm warnings and precipitation nowcasts. They were conducted in Sydney [4] and Beijing [5]. The winter projects included Vancouver [3], Sochi [6] and PyeongChang [7]. In winter, the weather at a specific venue can vary considerably due to the complex terrain, at spatial scales less than a kilometer, at temporal scales of less than a minute and for specific weather elements (e.g., precipitation, visibility and wind gusts). Borrowing from micro-meteorology, the term micro-nowcasting is used here to reflect the scale of the science and service requirements.

Strong gusty wind events were responsible for the poor performance of the competitors during the Women's Slope Style Event (WSSE, 11–12 February 2018) during the PyeongChang 2018 Olympic Winter Games. It was the most challenging event to forecast and nowcast during the Olympic period. Wind gusts are defined as intense winds of several seconds duration and as intermittencies in turbulent flows. Intermittencies in turbulence remains a scientific challenge [8] and are not captured in the statistical concept of statistical equilibrium (cascading downscaling) turbulence [9,10]. In numerical weather prediction models, sub-grid scale wind fluctuations are parameterized as an eddy dissipation rate and do not capture the gusts or intermittencies.

Winter nowcasting is in its infancy, with a limited number of case studies. Each winter nowcasting project and event has its own specific weather issues. In Vancouver, which first developed a venue nowcasting system, visibility due to fog and clouds [3] and thermal winds during the night–day transition period [11] were the problems. In Sochi, temperatures reached near 20 °C and snow moisture content [6] was the forecast challenge.

The objective of this contribution is to review the challenges of micro-nowcasting. The WSSE event was a defining case that illustrates all the challenges of the forecast system. Experiences from previous projects are also included.

Section 2 provides background information on the International Collaborative Project–PyeongChang Olympic Project (ICE–POP), recent wind-related complex terrain projects and the WSSE event. Section 3 provides an analysis of the 1 min wind data from three meteorological stations located at the WSSE venue to explore what information and clues could be used to develop a forecast technique for wind gusts. Section 4 provides an extended review and discussion of the challenges of micro-nowcasting and Section 5 provides a summary.

2. Background

2.1. The ICE–POP Project

The ICE–POP project was an RDP and an FDP led by the Korean Meteorological Administration (KMA) under the auspices of the WMO. The prime scientific focus of ICE–POP was the RDP which focused on advancing the science and improvement of the parameterization of winter microphysics for high-resolution numerical weather prediction models. As the challenges of nowcasting in complex terrain were recognized by the forecasters after initial trials, the FDP was initiated to leverage the observations, models, products and the international expertise [7,12].

The ICE–POP project study area was in the north-east of South Korea and was approximately 100 km $\times$ 100 km square (Figure 1). The host city was Gangneung, which is located on the coastal plain. To the immediate west of Gangneung are the north–south Taebaek mountains with the ridge line about 15–25 km to the west and parallel to the coast. They are approximately 1100 m in height. To the west of this mountain ridge is a high plain (30–55 km) of 500–600 m altitude surrounded by mountains that rise to about 1200 m.

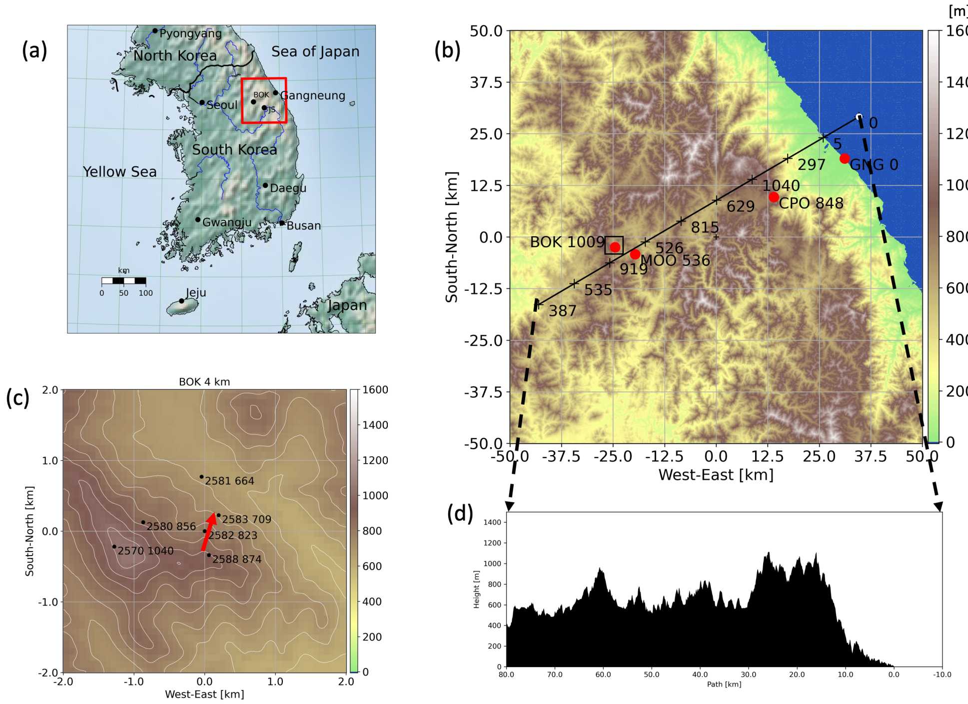

Figure 1. (**a**) The ICE–POP 2018 project area is approximately 100 km × 100 km in the north-east of South Korea. (**b**) The Slope Style venue Bokwang (BOK) is marked by a square in the west of the project area, the upper air station (MOO), the Cloud Physics Observatory (CPO) and Gangneung (GNG) are labeled by altitude. (**c**) The location of the automatic weather stations at BOK are indicated. The Slope Style field of play (BOKSS) is marked by a red arrow. (**d**) The elevation profile based on the line drawn in (**b**) shows the complexity of the terrain with the dominant feature being the coastal mountains that rise sharply from the Sea of Japan.

ICE–POP had an extensive observation campaign with advanced surface sensors (snow imaging devices, vertical profiling radar–disdrometers, automatic snow gauges with double fence international reference wind shields), upper air observations (radiosondes and dropsondes), multi-wavelength polarization-diversity Doppler research radars, Doppler and water vapor lidars, radiometers, microphysical aircraft and ship borne observations as well as a variety of high-resolution numerical weather prediction models and analysis systems [7]. The RDP focused on deploying instrumentation on the east coast of South Korea and the Taebaek mountains.

The Women's Slope Style Event was located at the Bokwang (BOK) venue at the western edge of the study area. BOK is the site of all the freestyle events and lies along a broad open slope (see Figure 1c) with the highest peak at 1236 m (not marked) just to the northwest of the competition fields of play (600–1100m). Table 1 shows information about the location, altitude and slope information of the weather stations along the WSSE field of play. There was an RDP site located in the BOK valley with a snow gauge and a micro-rain profiling radar but it was not used in this study.

Three events during the Olympic period (9–25 February 2018, with extra days bracketing the opening and closing dates) were selected for this study (Table 2). Event 1 is the primary case study (11–12 February 2018). Limited analyses from two other events are presented for comparison purposes. The second event (Event 2) was a two-day event (15–16 February 2018) with calm wind conditions where diurnal effects were evident. The third event (Event 3, 21–23 February 2018) was a three-day event where the Alpine ski competitions were moved both forward to Wednesday and backward to Friday to avoid the strong winds that were forecasted for the Thursday.

Table 1. The Slope Style Transect at Bokwang (BOKSS). The following information is included: Weather Station Number, Location, Altitude and Transect information. The slope drop is the vertical distance between stations. The slope direction is the horizontal (two-dimensional) direction between the top and bottom stations. The slope inclination is the steepness of the transect.

Station Number	Longitude	Latitude	Altitude (m)	Distance (m)	Slope Drop (m)	Slope Direction (°)	Incline (°)
2588	128.3232113	37.5743463	874				
2582	128.3225450	37.5773941	823	343	51	170	8.4
2583	128.3247780	37.5794284	709	300	114	221	20.8
Summary				581	165	194	15.9

Table 2. List of wind events investigated during Olympic period.

Event	Start Day	End Day	Event	Description
1	11	12	Women's Slope Style	Qualification canceled on 11 February due to strong winds, Finals held on 12 February when winds were even stronger.
2	16	16	Transition	Diurnal event.
3	21	23	Multi-day Wind Event	Strong winds were predicted and events moved to avoid 22 February 2018.
Winter	1 December 2017	31 March 2018	4-month period	For comparison

2.2. Recent Projects

Precipitation patterns in complex terrain have been the subject of recent research studies that examined the relationship between blocked/unblocked flows and the role of microphysics [13–15]. Complex wind flows in valleys, basins, plain–foothill transitions, either side of and in mountain gaps have been studied in several recent major field campaigns with extensive instrumentation, such as networks of meteorological stations, turbulence sensors and Doppler lidars [16–20]. Just prior to the Games, a strong wind event due to gap winds affected the coastal region [21,22]. Teakles et al. [11] describe the impact and forecast issues facing Vancouver 2020 Winter Olympic forecasters at the ski jump, even during seemingly benign sunny days, with early morning drainage flows transitioning to upslope flow due to day-time heating.

2.3. The Women's Slope Style Event

The Women's Slope Style competition consists of a competitor descending about a 20° degree slope on a snowboard, jumping off obstacles and then performing multiple twists, flips, rolls and somersaults while in the air. The obstacles consist of combinations of building-like structures, ramps and rails. At each obstacle, the competitors have multiple options for the jumps that they can select to perform. The competitors are judged and awarded points based on the difficulty, the technical performance and aesthetics of their jumps. The competitor with the most points wins the competition. The competitors has two runs and the run with the highest score determines the winner.

The field of play is about 300–500 m long, with the separation between obstacles approximately 50–60 m apart, with a total of six obstacles. When jumping, the competitors reach heights of ten or more meters above the terrain. After completing a jump, the competitors prepare for the next jump by re-aligning themselves and descending in a such way as to control and optimize their speed for the jump that they plan to perform. The more difficult jumps require faster speeds in order to jump higher and stay in the air longer.

Training and the qualification event for the WSSE, scheduled for Sunday 11 February 2018, were started but then canceled as the winds posed a safety concern for the competitors. Due to the forecasts, the rules of the competition were altered and the qualification component of the competition was canceled and a two-run final was planned for Monday 12 February 2018. The conditions were to be assessed in the late morning (11 AM KST) for an afternoon competition (1 PM). In hindsight, the wind conditions were worse, unfair and unsafe, but nonetheless the decision by the organizers was to conduct the competition.

The gusty or intermittent winds were visually most evident from the blowing snow [23]. The surface snow was lifted in a un-steady, non-uniform chaotic manner several meters into the air and for durations of less than a minute. There were also periods of gusty winds lasting several minutes during which the competition was delayed.

The gust affected competitors in inconsistent ways. Many competitors could not attain sufficient speed to launch off the jumps or land them safely [23]. Some competitors abandoned their attempts as they could not perform even simple jumps, effectively ending their competition. No one was able to complete the two-run finals without falling.

2.4. The Bokwang Observations

Basic meteorological observations were available from compact weather stations (Vaisala WXT520) reporting at a 1 min resolution. The stations were located along the mountain slope and defined the BOK traverse which is approximately aligned with the WSSE field of play (Table 1; see also Figure 1c). Six hourly upper air soundings were launched at the nearby MOO station.

The WXT520 measures wind using the delay in the transit time of ultrasonic signals between three transducers. Signals are sampled at 4Hz and processed to report every minute, as a 10 min running average (WS10), a 1 min average (WS1) and as the maximum in the past minute (WSS). While the trend in some operational NMHSs is toward higher frequency of data reporting, the standard (with specials) is still hourly surface observations. The operational use of 1 min data is still evolving and requires a change to the observation standards. Specifically, the standard defines gust as the maximum wind within the past hour. In this project, the maximum wind reported in the past minute (WSS) is defined as the gust wind. Furthermore, site exposure metadata are needed to assess the impact of the local terrain and obstructions (e.g., groves of trees, buildings, jumps) on the representativeness of the observations [24].

Standard operational weather sites are located on open horizontal flat terrain with a fetch of about 100 m (10:1 ratio to nearest obstacle). Winds are measured at a standard 10 m height using mechanical (cup or propeller) anemometers. The vertical wind is assumed to be zero due to the flat horizontal lower boundary. However, there are no operational standards for weather stations in complex terrain. In this case, the weather sensors were mounted at heights of two to three meters above the surface and along the mountain slope. As snow falls and accumulates, sublimates or melts, the height of the measurement changes throughout the winter. While the weather stations are located on a local horizontal surface along the slope, the vertical wind cannot always be assumed to be zero.

Studies comparing the WXT520 to a reference [25,26] have shown good agreement. However, differences due to sensor response time, signal processing and sensor height are expected. Previous studies have shown that cup anemometers overestimate the wind speed [27,28]. Three-dimensional heated ultrasonic turbulence wind sensors are commercially available but are expensive and were not deployed. This shortfall was also seen in previous FDPs [3,6,29]. Furthermore, one AWS station (station number 2582) was located near groves of trees on the side of the field of play. This may be problematic for use in data assimilation or verification of NWP models. However, they were most valuable to the forecasters and organizers as they represent the conditions experienced by the competitors.

3. Analysis

3.1. Surface Winds

Figure 2 shows the wind traces for W10, WS1 and WSS for Event 1 for the weather station (2582), located at the middle of the BOKSS transect which is at the start of the WSSE field of play. Figure 3 for Event 2 illustrates a low wind case for comparison. The differences within and between W10, W1 and WSS show how they can be used as a visual qualitative measure of turbulence. Events 1 and 3 (Figure 4) show that winds that were strong and turbulent both during the day and night provide a clue of dominating synoptic influences. With Event 2, day–night differences and wind shifts 180° from the west to the east were observed, indicating downslope–upslope wind shifts and suggesting thermal effects.

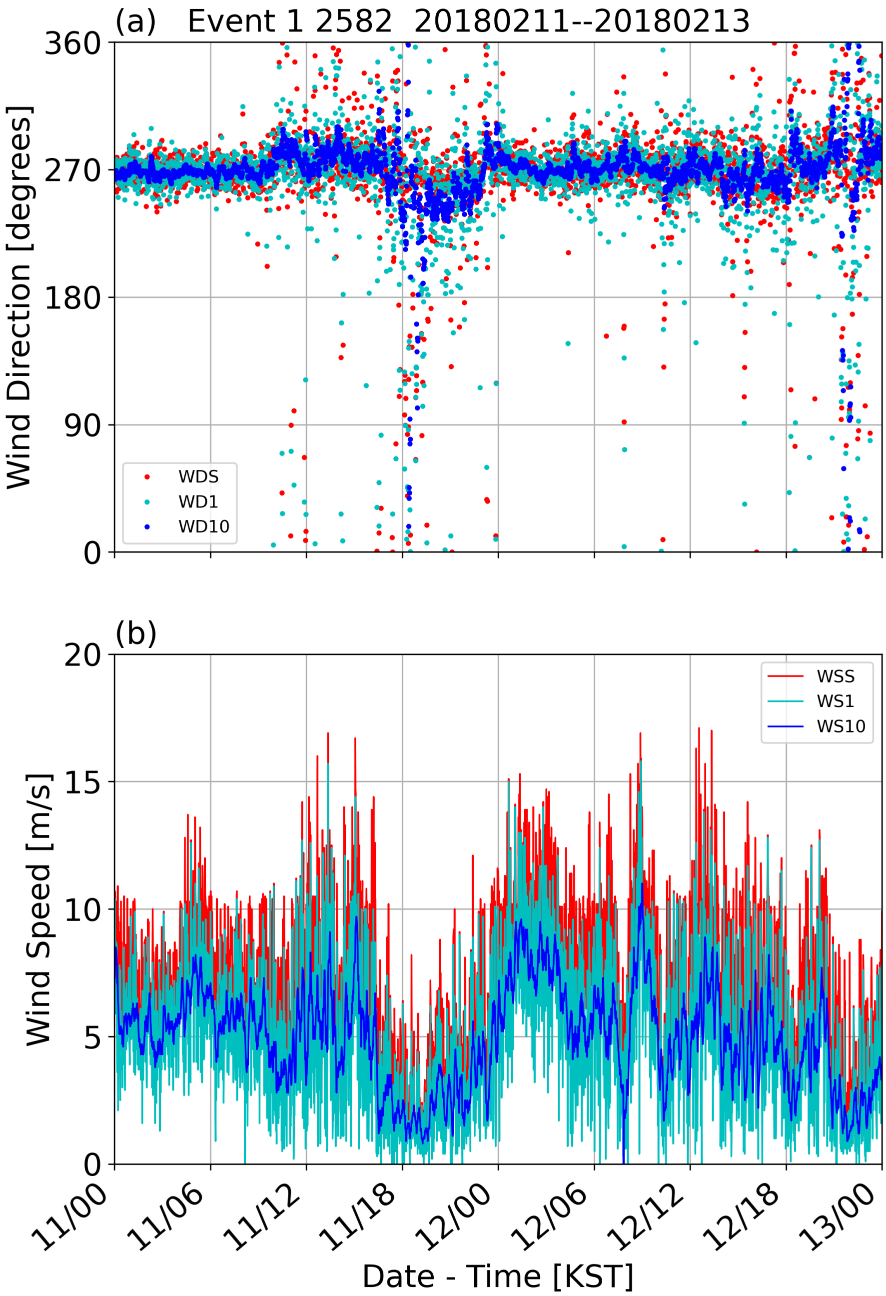

Figure 2. Time series of the wind at the start of the Slope Style field of play (station 2582) for Event 1. Winds were reported every minute consisting of 10 min average (WS10), 1 min average (WS1) and maximum within the latest 1 min (WSS).

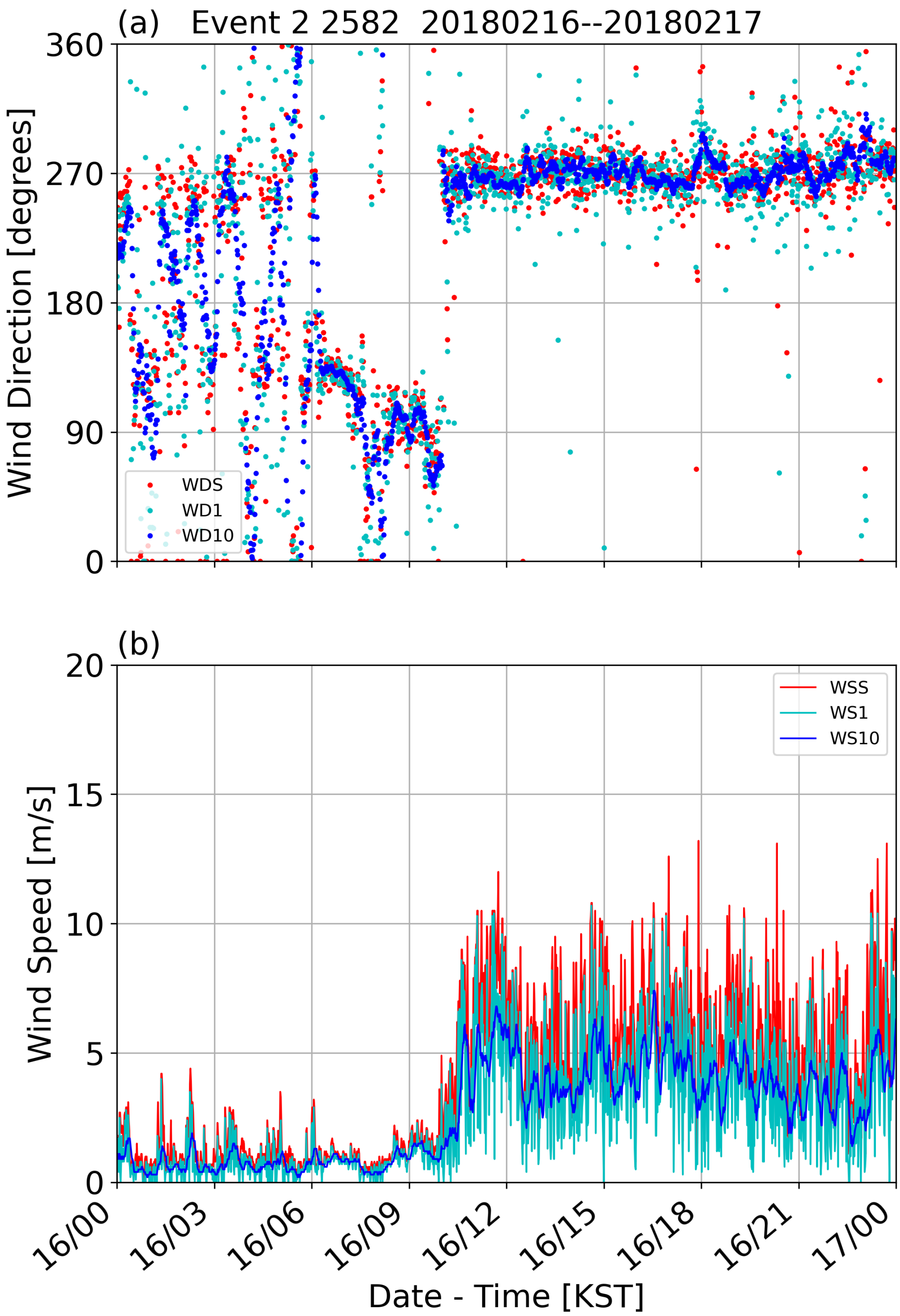

Figure 3. Similar to previous figure except for Event 2. The winds were light during the night (0–10 a.m. Korean Standard Time (KST)) and then became stronger. This is an example of how the three wind types can be qualitatively interpreted as a turbulence sensor.

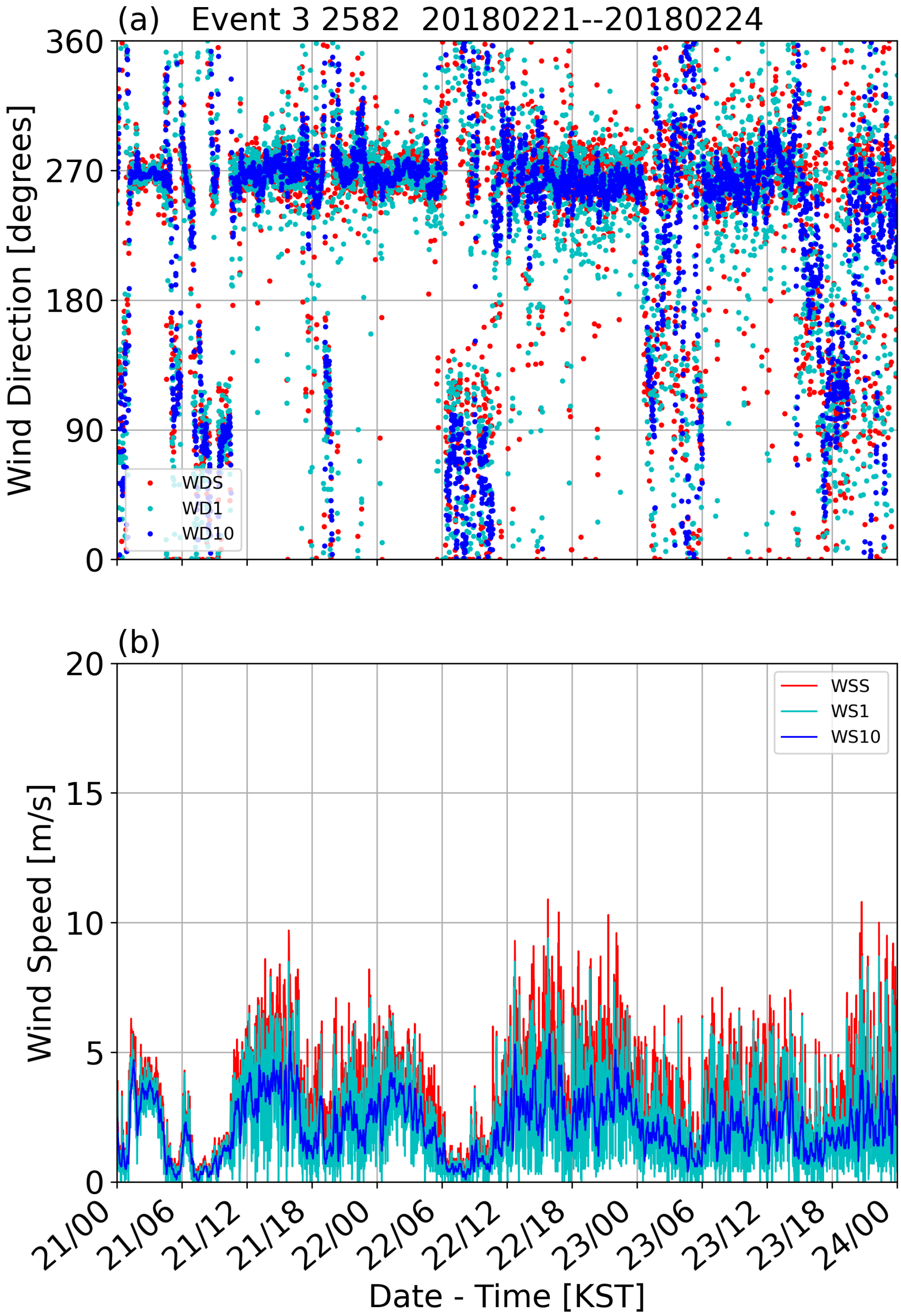

Figure 4. Similar to previous figure for Event 3.

The wind speed distributions for the three events are shown in Figure 5 and are compared to those for the entire winter, the month of February and the Olympic periods. The winds during Event 1 were by far the strongest winds observed. The wind speeds for the two days of Event 2 (green line) show a bi-modal distribution consistent with Figure 3 showing the day–night diurnal differences. Event 3 was forecast to be similar or stronger than Event 1 but this was not the case. The distribution of the winds was also narrower.

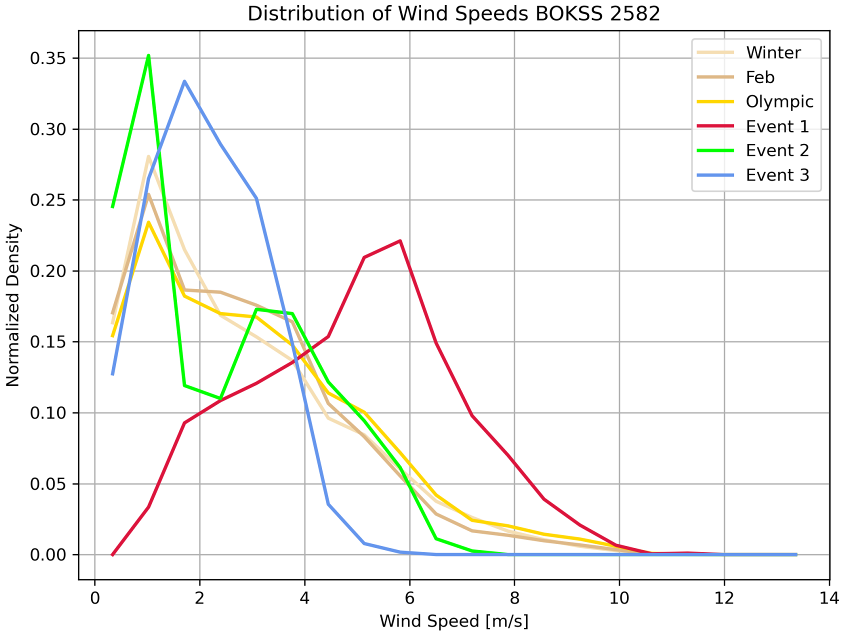

Figure 5. Distribution of wind speeds for the BOKSS mid-station 2582 for all the 3 events, the month of February, the Olympic period and the winter season.

3.2. Upper Air Analysis

Climatologically, there are three persistent synoptic features that affect the project area/Korean Peninsula in winter [30]. The passages of low pressure systems, and in particular warm lows, cause significant snowfalls in the western sides of the Taebaek mountain ridge along the coastal Gangneung area. A Siberian high brings dry cold northerly air. An easterly flow from the Sea of Japan can bring warm moist air to the Gangneung area, leading to intense coastal precipitation.

Figure 6a,b shows wind speed and direction time–height plots from the upper air (radiosonde) soundings from the MOO station located about 20 km south of the BOK venue (Figure 1). During the Olympic period, the dominant flow was a northerly/northwesterly cold strong flow from the Siberian High. In the period between the Olympics and Paralympics, a low-level eastern flow pattern led to significant precipitation.

The 700 mb winds, Reynolds and Froude Number time traces are shown in the lower three panels of Figure 6c–e. The strength of the 700 mb winds greater than 7 m/s has previously been used to distinguish synoptic from local valley flows [31]. Similarly, the Froude number is used to indicate whether the upstream air will pass over [32] or around elevated terrain. The Reynolds number indicates whether flow separation is expected in the lee of the mountains. The Reynolds number (>1) indicates whether the flow separates at the edge of the barrier. It is also used to indicate whether a standing eddy with closed circulation, wake turbulence or vortex shedding occurs in the wake [33].

The 700 mb wind strength is virtually greater than 7 m/s for all times, the Froude number (Figure 6e) is greater than 1 at various times and the Reynolds number (Figure 6d) is greater than 10^5 for almost the entire winter period. These all indicate that synoptic flows are dominant and that the lee side winds at BOK were largely be due to mechanical turbulent processes (vortex shedding or wake turbulence) rather than diurnal influences or plain–slope transitions [11,16–18,31].

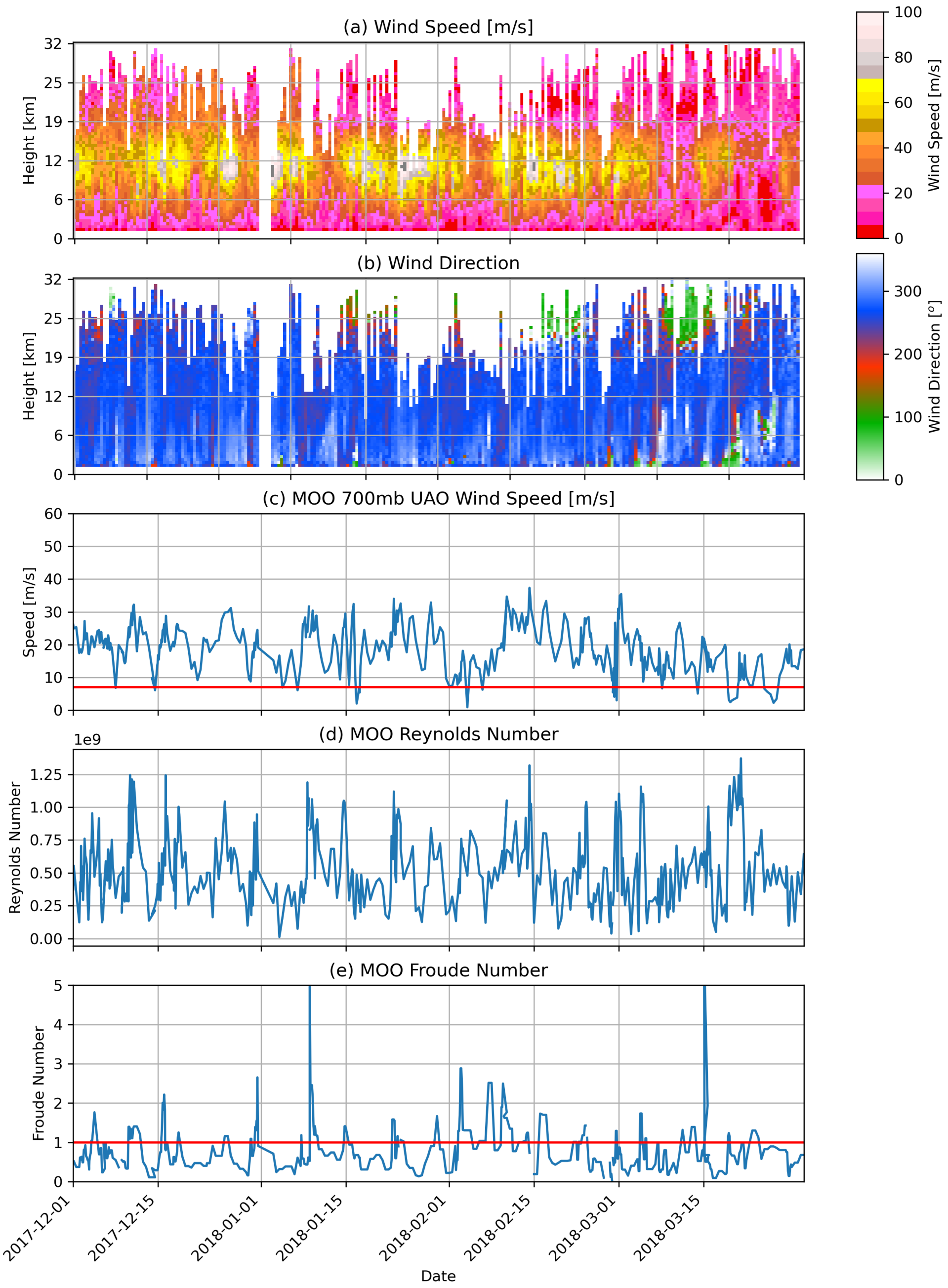

Figure 6. (**a**) Wind speed and (**b**) wind direction from MOO Upper Air Station for the entire winter season (1 December 2017 to 31 March 2018) showing that the predominant winds are northwesterly. The MOO station is located within 20 km of BOK venue and in the lee of the mountains. (**c**) The 700 mb wind speeds, (**d**) the Reynolds number (note the scaling of 10^9 which is indicated in the top-left of the sub-plot and (**e**) the Froude number are estimated from the sounding and indicate that the winds separate over the mountains. The red lines indicate critical thresholds (see text for more details).

3.3. Hovmöller Analysis

Figure 7 shows Hovmöller diagrams of potential temperature (θ) and WS10 wind to investigate the thermodynamic and wind structure of the air along the slope for Events 1 and 2. Potential temperature was computed from temperature, pressure and humidity measured as ten minute running averages and reported every minute. It is a conserved quantity under adiabatic processes. In these Hovmöller diagrams, time runs from top to bottom and altitude decreases from left to right (top station is on the left, bottom station is on the right). The data are linearly interpolated in altitude. An excess of data and the inability to effectively use them in forecast operations, as well as lack of use in data assimilation were some of the arguments against the collecting of 1 min data by operational monitoring managers. However, these Hovmöller diagrams provide an intuitive and scientific presentation for straightforward interpretation by forecasters.

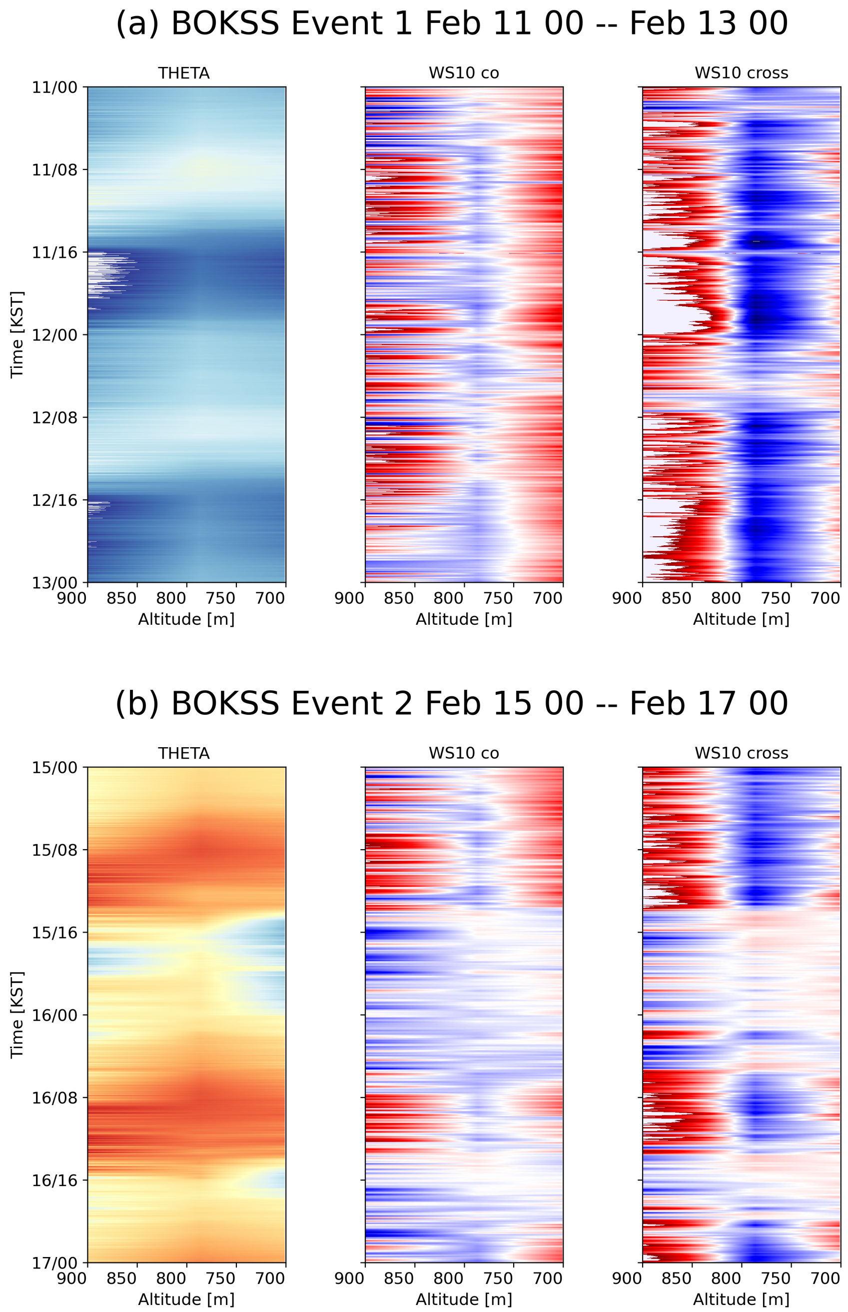

Figure 7. Hovmöller diagrams of potential temperature, collinear and cross-slope 10 min winds for (**a**) Events 1 and (**b**) 2. See next figure for definition of collinear and cross-slope winds. Time runs from top to bottom and altitude is right to left (highest is on the left). The inverted triangles at the top of the plot indicate the location of the stations in altitude. The WSSE started just below the altitude of the middle station.

The slope direction was defined as the average direction from the bottom to the top station (Figures 1c and 8, Table 1). The winds were resolved in the collinear (co) and orthogonal (cross) slope directions (Figure 8). Positive direction is from the bottom to top and from left to right. The terminology of collinear wind is to distinguish it from the along-slope wind which includes the unmeasured vertical wind component. These are presented in Figure 7.

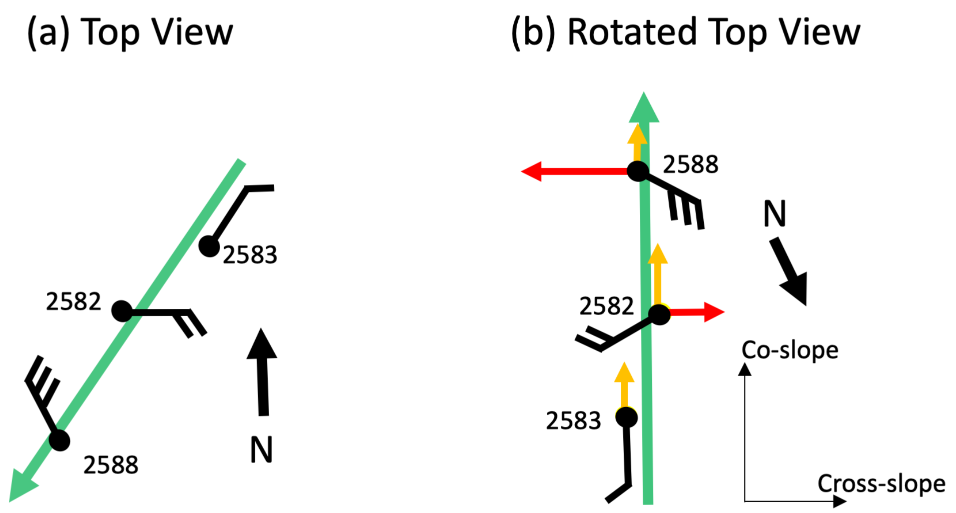

Figure 8. Top view schematic of the collinear (co) and orthogonal (cross) winds. (**a**) The location of the weather stations (black dots) with example wind barbs (black) are shown with north to the top of the page. The average direction of the stations is used to determine the slope direction (green arrow) and (**b**) used to define a rotated coordinate system where the up direction is collinear with the slope and the rightward direction is orthogonal to the slope. The wind components in the collinear and orthogonal directions are indicated as yellow and red arrows, respectively.

Event 1 (Figure 7a) shows uniformity of potential temperature with altitude indicating a well-mixed environment assumed to be due to turbulent processes both day and night, whereas Event 2 (Figure 7b) shows a well-mixed layer in daylight hours (15 February 8–16 KST, marked WM for well-mixed) with a stable stratified environment and an inversion layer at night (16 February 0–8 KST, marked S for stable) indicating diurnal or thermal processes.

In Event 2, the transition from a well-mixed to stable structure in the evening (line marked T-S for transition to stable) occurs more slowly ($\sim$4 h) than the transition from stable to well-mixed structure (line T-WM for transition to well-mixed) in the morning ($\sim$2 h). Fernando et al. [17] showed a micro-frontal structure using lidar data during the transition period. Teakles et al. [11] showed oscillating up–down slope winds with regular periodicities of about 8 to 20 min using 1 s sonic anemometer data during the ski jump event at the Vancouver 2010 Winter Olympic Games.

Event 1 shows that positive co-flows were dominant and reduced the speed of the competitors as they descended the slope, which was consistent with the visual observations. Event 2 shows greater variations in the co and cross-flows. Generally, there are strong positive co-slope flows coinciding with a stable thermal structure. The cross-flows are stronger than the co-flows in this case.

3.4. Wavelet Analysis

A rectified wavelet analysis was performed [34,35] to quantify the intermittency in the wind fluctuations by examining the structure of the power spectrum of the 1 min wind gusts (WSS). Figure 9 shows the wavelet transform for Event 1 for station 2582. The mean was removed from the time series (top sub-plot). There was a consistency throughout this event where there are periodicities observed both in time and in frequency (middle sub-plot). There were broad maxima around 20 min and 250 min. The former were observed both day and night, while the latter appeared in the daytime. For comparison, Figure 10 shows the wavelet transform analysis for Event 2. Weaker spectra observed during the night time were consistent with the Hovmöller analysis. The wavelet analysis with the 10 min average wind (WS10) did not show any structure in the wavelet spectra below periodicities of less than 20 min (not shown).

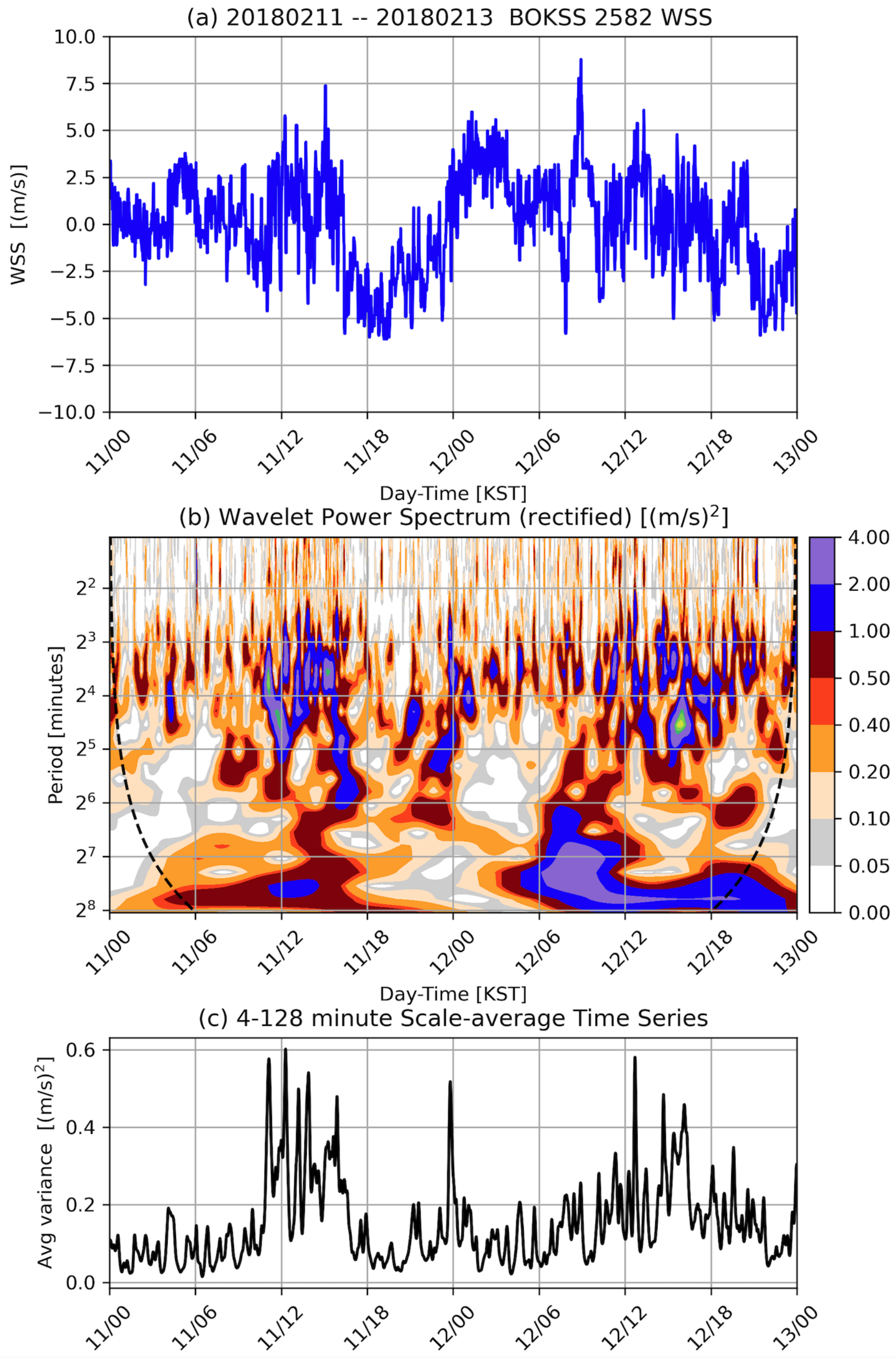

Figure 9. Wavelet transform analysis for station 2582 (mid station) for BOKSS transect for Event 1 for WSS. (**a**) The 1 min gust wind speed time series. (**b**) The rectified wavelet spectrum. The dashed line indicates the 95% confidence level. (**c**) The power time series.

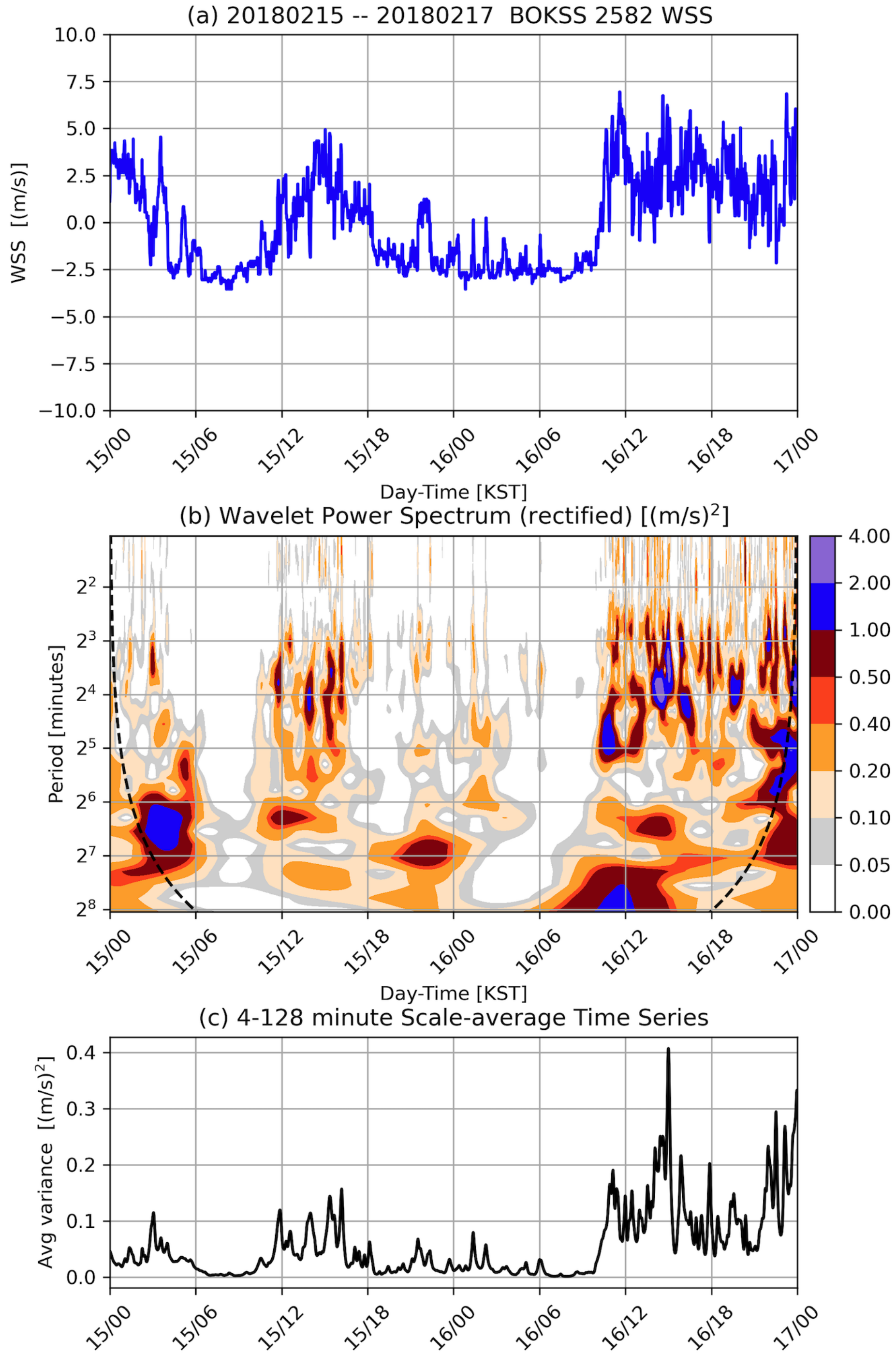

Figure 10. Similar figure to Figure 9 except for Event 2.

Figure 11 provides a summary of the global wavelet spectra for the two events. The location of the local peaks is identified in the figure. In spite of the intensity differences in the two events, there is consistency in the location of peaks in the spectra with a bimodal broad peak around a periodicity or intermittency of 20 min. This is suggestive of vortex shedding rather than Kolmogorov turbulence. Event 1 showed a strong peak at around 240 min (4 h) that is suggestive of diurnal processes.

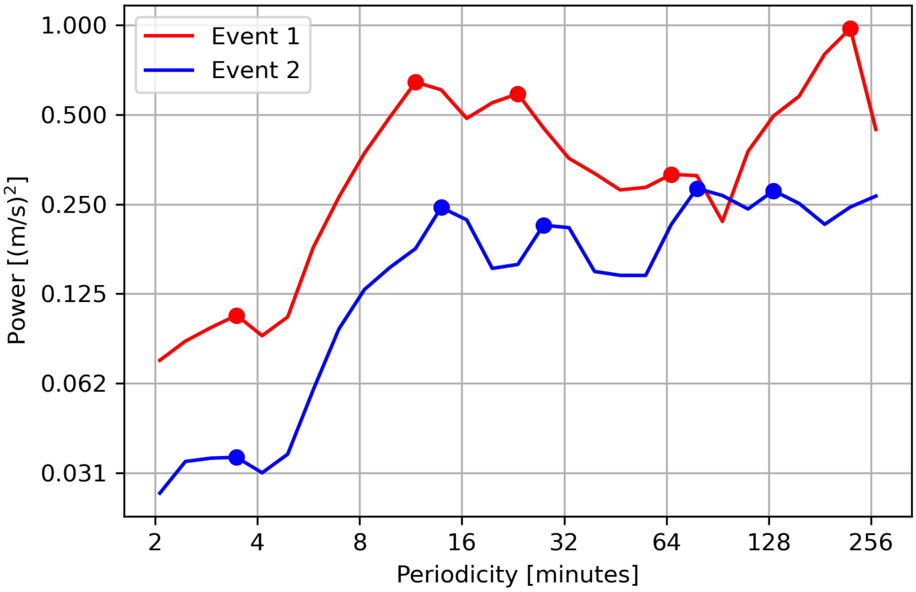

Figure 11. The global wavelet spectra for Events 1 and 2. The dots indicate the location of peaks in the spectrum.

4. Discussion

Golding [36] presents a framework for the *perfect* warning system that includes observations, weather prediction, hazard prediction, impacts prediction, warnings and decision-making. Each component is a discipline unto its own and partnerships were identified as the key factor needed to bridge the gaps. In the WSSE, the responsibility of the latter four disciplines lie with the event judges and Games organizers. They are separate and distinct in a broader disaster risk reduction context. Joe et al. [37] and Heizenreder et al. [38] systematically discussed the observation–weather prediction component and the gaps in the forecast system. This forms the basis to review the issues and the challenges. Experiences from previous projects are also included in this review [1,3,6,25]. Olympic requirements represent the state-of-the-art for nowcasting. There are many parallels applicable to current emergency management operations [25] and to future integrated urban and multi-scale services and applications [39–41].

From an *user requirements* perspective, many of the alpine freestyle competitions are novel and there is little experience in organizing them for the Olympics. These competitions were only included in the Olympics for the second time. They are different from normal competitions which are conducted over a weekend and where the competitions are canceled if weather conditions are not appropriate. During the Olympics, the judges and organizers have considerable discretion to reschedule the event within a two-week window. Therefore, longer forecasts for very specific weather conditions and venues are needed. For example, forecasts for consistent conditions of about 90 min duration were required several days in advance, which is not a normal requirement. The service requirements are not well constrained as the rules of the competition can be changed at the discretion of the organizers. Therefore, the venue forecaster must be flexible, adaptable and have or develop considerable depth of specific knowledge (personal communication, Arnold Ashton).

There is a trend for operational forecast services to issue impact and action messages as part of operational public warning messages [36]. For public warnings, there is a natural bias to be conservative as over-warning leads to mis-trust and over time to in-action. In this situation and in emergency management operations, where there are complex requirements, cascading impacts and considerations by multiple decision-makers, the provision of unadorned and unbiased information for clarity are requisite [39].

In this case, the *end-users* are the competition judges, the event and the Games organizers. The best judges may only be available during the Olympic year and therefore may not have the benefit of shared experiences from pre-Olympic test events conducted in previous years nor with the weather at the venue. The judges and event organizers are generally familiar with the variability of weather in complex terrain and often make their decisions based on this generic knowledge. However, this can pose a barrier for them to learn, to adopt and to trust the new information. Therefore, communication, positive interactions and understanding between the venue forecaster and the end user is vital.

The *forecasters* chosen for the Olympics are generally considered experts [42–44]. However, given the novelty of the services, the uncertain and changing requirements, the lack of familiarity with weather in complex terrain and the event requirements, everyone should initially be considered novices. Unlike normal operations, except in emergency management operations, the venue forecasters are embedded and *interact directly* with the end-user. The frequent interactions, with ever-changing perspectives and requirements provides immediate feedback and opportunities to understand the needs, to develop trust and tailor the services. The adoption and use of new technologies is a diffusive social–behavioral process [45]. The experience has been that not all expert forecasters adopt new technology at the same rate or in the same way [37,42,43]. For example, expert synopticians do not always make expert nowcasters. The challenge is to select venue forecasters, not for their existing knowledge and expertise, but those who can adapt and can work in a rapidly changing environment.

The *forecast system* consists of the monitoring, science, data assimilation, numerical weather prediction models, post-processing, visualization tools, knowledge and forecast techniques [37,38]. Though the Games are awarded six to seven years in advance, time is a severe constraint. It takes considerable time to find resources, built capacity, understand the requirements, and then design and implement the monitoring and forecast systems, develop post-processing corrections and guidance, build trust with the system and form relationships with the end-users. Experience showed that there are changes to the forecast and monitoring systems right up to the time of the Games. With the prestige and importance of a high-profile project, there is great motivation to deliver on time and overcome technology transfer and research to operation barriers [37]. The implementation is often limited in scope but can be leveraged for operational benefits [25].

Numerical weather prediction (NWP) *models* are a primary tool for forecasters. High resolution is needed to resolve weather issues in complex terrain. In terms of representativeness, the models are only able to resolve physical features that are five to eight times the grid size [46]. In addition, the terrain is highly smoothed for numerical stability considerations. In the case of the freestyle events, the horizontal and vertical distances are less than a few hundred meters (Table 1), whereas the current operational models and analysis systems have typical grid sizes of a few kilometers. Hence, NWP models were unable to directly resolve the wind gusts in complex terrain. This results in biases in the model outputs that require observations (real-time or historical), experience and heuristic forecast techniques to overcome.

The meteorological and *scientific* challenges also include mean winds, visibility (humidity) and precipitation intensity and type amongst others [3]. The scale of the scientific challenges are similar to those for urban prediction services (e.g., surface processes, urban canyons, built environment) that require resolving the effects of the urban texture and associated physical processes (e.g., roads, parks, buildings) and canyons [37,39]. Intermittency in turbulent flows is still an outstanding theoretical challenge [8] and the community is turning to experimental studies to understand the downscale cascade mechanism as numerical techniques have limitations [47]. Morrison et al. [48] advocates for a return to laboratory experiments to address fundamental issues of micro-physics. Hence, enhanced observations and data are needed to resolve the science gaps and to have knowledge of the state of the atmosphere for nowcasting [3].

In general, forecasters may not be *knowledgable* about winter weather in complex terrain. Training during winter weather has generally focused on synoptic-scale weather systems. Each RDP or FDP had its own unique challenges. In Vancouver, winds and visibility (humidity) were the significant issues [3]. In Sochi, abnormally warm temperatures was the forecast challenge [6]. At this time, unlike summer convective weather [5], there are insufficient numbers of cases to develop empirical techniques and generalize the results. There are opportunities to learn and gain knowledge about the micro-nowcasting challenges during test events conducted in previous years. However, those events are conducted individually and do not completely simulate the types of decision-making issues encountered with a full two-week Olympic schedule. Furthermore, the events are run during the day and do not include diurnal effects with evening events scheduled during the Olympics. Post-event interviews with forecasters indicated that the training and test experiences were valuable in establishing the mindset. However, usable practical knowledge was acquired *on the job*, and so it is dependent on personal in situ experiences to develop heuristic nowcast techniques (personal communication, Arnold Ashton). Successful nowcasting utilizes local knowledge that can be acquired through interviews with local residents or managers in a *traditional* knowledge approach [49].

In previous projects, 1 min reporting was met with resistance from both the *operational monitoring* and to a lesser extent the forecast community [25,29]. The main arguments were that data volumes would overwhelm communication and storage systems, that forecasters could not use minutely reported data and be overwhelmed by the volume of information and that it was not used in nowcasting systems or for data assimilation. However, experience concluded that:

- There is never enough data or guidance products. Expert forecasters develop the ability to filter out irrelevant information. Current telecommunication speeds and storage systems are more than adequate to handle the data volumes. Computing power is a limitation [37]. A review is needed of the needs/representativeness, standards and metadata for high-resolution data [24,25].
- Post-processing is an important consideration for the effective use of high-resolution data. In the WSSE, the difference and the variability in the wind traces of the three types of wind (WS10, WS1, WSS) provided a qualitative indication of the gusts. The Hovmöller analysis of potential temperature and co- and cross- winds provided a succinct post-processed product for visualizing the data and interpreting physical processes for the forecaster. The wavelet transform analysis was able to provide a quantitative clue about the presence of gusts.
- Intermittencies of about 20 min periodicities were observed and provided the possibility that these post-processed products, and others, may be combined and used to extrapolate to shorter periodicities. There is considerable research to understand the science and physical mechanisms [47].
- Adaptive venue nowcasting systems were successfully demonstrated in the Vancouver RDP that combined observations and trends from models that required 1 min data [3,50].
- Attempts to organize an RDP on high-resolution data assimilation over the past twenty-five years have not been successful. This indicates the lack of maturity, the difficulty in transferring the technology or the inadequacy of the model. For example, if the difference in height of surface meteorological observation and the smoothed topography height in the model are too large, the data are filtered from the assimilation scheme (personal communication, Luc Filion). This would certainly be true in complex terrain. The inadequate or lack of representation of physical processes in the model is another factor [25,39,41].
- Observations lead to science and understanding, better model parameterizations, validation, user-based verification [24] and nowcast technique development. The latter will necessarily be based on advanced data analyses using heuristic, empirical or artificial intelligence techniques, even higher-resolution data (e.g., three-dimensional turbu-

lence sensors), advanced instrumentation such as networks of Doppler lidars [16–18,51], additional cases and interpretation by forecasters for the end-user. The justification for operational networks should not be solely based on its use for data assimilation [24].
- In situ sensors provide information at discrete locations. It is important to have venue forecasters or in situ visual or remote sensing observations (e.g., video cameras, radars or lidars). In hindsight, they provided the only evidence of the impactful nature of the gusts.
- The implementation of new observation technologies and visualization systems are generational and episodic [37,38]. This leads to lags and gaps in the technology transfer process. For example, doppler radar or lidar networks are first demonstrated in research to assess their value; then radial velocity data assimilation research requires at least demonstration networks to be deployed and available. The use of precipitation from radar by research hydrologists require operational networks to be established and high quality quantitative precipitation radar products.

User requirements and expectations are always increasing, and therefore the operational forecast system always lags behind the needs. This results in an *operational community* bias which, when presented with a novel problem, the initial reaction is that work-arounds and creative solutions can be developed [44]. However, as illustrated here, some challenges are beyond this approach, fundamental science research and a research–operations collaboration is needed.

The specificity of the expertise required to address scientific or modeling problems often results in a narrow focus by researchers. A myopic *research bias* develops in which there may be a reluctance to cross research–research and research–operations boundaries. There are few forecast system research programs that holistically address the full gamut of weather service delivery issues.

One of the overarching objectives of the RDPs and FDPs are to bridge the research to operations gaps and to address and focus on a real-life end-to-end weather service problem. They are also an efficient and effective way to conduct research as it brings world-leading experts into a collaborative common weather environment to fairly compare results. First-hand knowledge with the proponents saves considerable time and resources. Experience has shown that lasting relationships develop and promote the building of global scientific communities and future opportunities for mutual benefit.

5. Summary

The Women's Slope Style event was the most difficult event to forecast. The gusty winds made the conditions unfair and unsafe for the competitors. Deficiencies in the forecast system and fluidity in the service requirements illustrated the challenges of micro-nowcasting that apply not only to the Olympics but for future integrated urban and, in general, high-resolution weather prediction services.

At the core of the challenges are the science gaps. In the example presented, turbulence and in particular intermittencies or gusts are acknowledged as unsolved scientific issues. However, this is also true for other physical processes such as microphysics or surface fluxes. However, there are gaps throughout the entire forecast chain, particularly as weather services and numerical modeling advance to finer scales and user expectations continually increase.

In lieu of scientific understanding, observations and forecasters are needed. Empirical relationships and model parameterizations can be developed from well-designed observation campaigns. Increasing the resolution of observations also leads to new science. In some domains, such as turbulence and microphysics, fundamental experimental studies are advocated.

Given the inadequacies of the forecast system, the forecaster performs a critical role in understanding the user requirements and the forecast system to communicate what is known or not known to the decision-makers.

Research development and forecast demonstration projects bring the world's expertise together to collaboratively address the challenges, advance the science and impartially demonstrate the state of the art. They are a critical part of the process to accelerate technology transfer and bridge the gaps.

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