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The Monitoring Network of the Vancouver 2010 Olympics

PAUL JOE,[1] BILL SCOTT,[1] CHRIS DOYLE,[1] GEORGE ISAAC,[1] ISMAIL GULTEPE,[1] DOUGLAS FORSYTH,[2] STEWART COBER,[1]
EDWIN CAMPOS,[3] IVAN HECKMAN,[1] NORMAN DONALDSON,[1] DAVID HUDAK,[1] ROY RASMUSSEN,[4] PAUL KUCERA,[4]
RON STEWART,[5] JULIE M. THÉRIAULT,[6] TERESA FISICO,[5] KRISTEN L. RASMUSSEN,[8] HANNAH CARMICHAEL,[7]
ALEX LAPLANTE,[7] MONIKA BAILEY,[1] and FAISAL BOUDALA[1]

Abstract—An innovative monitoring network was implemented to support the operational and science programs for the Vancouver 2010 Winter Olympics. It consisted of in situ weather stations on custom-designed platforms. The sensors included an HMP45C for temperature, humidity and pressure, a tipping bucket rain gauge, an acoustic snow depth sensor, a Pluvio 1 precipitation gauge and an anemometer placed at gauge height and at 10 m height. Modifications to commercial automated precipitation gauges were necessary for the heavy snowfall conditions. Advanced or emerging technologies were deployed to support scientific and nowcasting studies into precipitation intensity, typing, visibility and wind. The sensors included an FD12P visibility and precipitation sensor, a precipitation occurrence sensing system (POSS) present weather sensor, a Hotplate precipitation sensor and a Parsivel disdrometer. Data were collected at 1 min sampling intervals. A Doppler weather radar was deployed in a valley location and provided critical detailed low-level data. An X-band dual-polarized radar was deployed by the National Oceanic and Atmospheric Administration to monitor Vancouver and Cypress Mountain. Three remote sensing stations for vertical profiling were established. At the base of Whistler Mountain, a micro-rain radar, a 22-channel radiometer, a ceilometer, a Parsivel and a POSS were installed. At the base of Cypress Mountain, a micro-rain radar, a ceilometer, a low cost rain sensor (LCR by ATTEX) and a POSS were installed. At Squamish, a wind profiler and a POSS were installed. Weather sensors were mounted on the Whistler Village Gondola and on the Peak to Peak gondola. Sites were established along the Whistler Mountain slope and at other key locations. The combination of sites and instruments formed a comprehensive network to provide observations appropriate for nowcasting in winter complex terrain and investigate precipitation, visibility and wind processes. The contribution provides a detailed description of the network, their sensors, the innovations and some examples.

1. Introduction

Environment Canada was responsible for providing weather services support for both the safety and security of the Canadian public and their guests, as well as providing weather services to the Vancouver Olympic Committee for planning and for fair and safe competitions. These requirements posed considerable challenges, as forecasting and nowcasting in winter in the complex terrain in a coastal environment where the Olympic games were conducted had not been done before to the accuracy and precision required (DOYLE *et al.*, 2010; JOE *et al.*, 2010; ISAAC *et al.*, 2012a). Routine public forecasts (12–24 h lead time) had also never been issued nor observations made for the several of the Olympic venues. One venue (Whistler Olympic Park in the Callaghan Valley) was newly developed both for the Olympics and as a permanent legacy recreational facility for the public. Therefore, the public forecast program of Environment Canada needed to be modified, and a specific nowcasting program needed to be developed.

As many of the requirements required research, innovation and development, an internal science program was formulated to support both of these aspects. The goals of the science component included providing enhanced monitoring, enhanced modeling, enhanced nowcast and forecast systems, verification and validation. It also focused on the science and understanding of precipitation intensity, type, visibility and wind.

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[1] Environment Canada, 4905 Dufferin St, Toronto, ON M3H 5T4, Canada. E-mail: paul.joe@ec.gc.ca
[2] National Severe Storms Laboratory, NOAA, Norman, USA.
[3] Argonne National Laboratory, Chicago, USA.
[4] National Center for Atmospheric Research, Boulder, USA.
[5] University of Manitoba, Winnipeg, MB, Canada.
[6] University of Québec à Montréal, Montreal, QC, Canada.
[7] McGill University, Montreal, Canada.
[8] University of Washington, Seattle, Canada.

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In addition, given the short time available and to take advantage of existing expertise, Environment Canada formulated and led an international project to advance and demonstrate the latest advances in science for nowcasting winter weather in complex terrain (Isaac *et al.*, 2012a). This was conducted under the auspices of the World Meteorological Organization's World Weather Research Program's Working Group on Nowcasting Research and formulated as a research development project (RDP).[1] As operational winter complex terrain nowcasting was a novelty, the goal of the RDP was to concentrate on a specific critical aspect of a problem and to focus the attention of international community in order to make scientific progress. The project also had elements of a forecast demonstration project (FDP), with the goal of demonstrating prototypical or operational nowcasting systems. Existing winter nowcasting systems were only developed and prototyped for the aircraft de-icing application at airports (Isaac *et al.*, 2011; Rasmussen *et al.*, 2001). This project was called the Science of Nowcasting for Olympic Weather (SNOW-V10) and is described by Isaac *et al.* (2012a). The objective of SNOW-V10 was to advance the nowcasting of winds, visibility, temperature, precipitation intensity and type out to 6 h with a precision of the order of minutes and hundreds of meters. Therefore, SNOW-V10 was well aligned with the goals of the Environment Canada science goals. Weather services were developed for previous Olympics (Horel *et al.*, 2002; Bianchi *et al.*, 2006; Keenan *et al.*, 2003; May *et al.*, 2003) but did not comprehensively address the scale of the nowcasting requirement or were designed for the summer convective problem. It should be noted that road weather forecasts were the responsibility of the provincial government. Environment Canada was specifically requested (though offered) not to provide snow-surface temperature forecasts as that was a specific project of the secret Own The Podium program funded by Sport Canada and managed by the Canadian Olympic and Paralympic Committees and the Vancouver Olympic Committee (VANOC; Howard and Stull, 2011).

With these high-level requirements to support public forecasts, nowcasting, science and SNOW-V10, a monitoring network was designed and developed by the Regional Weather Centre[2] as well as by the Science Section[3] of Environment Canada. The objective of this contribution is to comprehensively describe and document the observation network used to support the operational forecasting and science components of the Vancouver 2010 (V10) project. Results and examples are described in extended figure captions. The uses of the observational systems are more fully described elsewhere (see references). In this contribution, the challenges, requirements and constraints for the development of the monitoring network will be briefly described (Sect. 2), followed by the network design (Sect. 3), specific instrument innovations (operational innovation are discussed in Sect. 4 and advanced or emerging technologies are discussed in Sect. 5), discussion of the network aspects of the observations tracing the design back to the science requirements is then presented (Sect. 6) and followed by a summary (Sect. 7).

2. *The Challenges*

In this section, climatology of the critical weather elements and a brief overview of the forecast requirements (Doyle, 2010; Mailhot *et al.*, 2010; Isaac *et al.*, 2012a) are described to identify the requirements for the design of the observation network.

2.1. *The Geographic and Climatic Environment*

The Vancouver Olympics and Paralympics were held on the west coast of Canada in a winter coastal complex terrain environment from Feb 14, 2010 to Feb 28, 2010. There was a 2 week break between the

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[1] http://www.wmo.int/pages/prog/arep/wwrp/new/nowcasting_research.html.

[2] Atmospheric Monitoring of the Pacific Weather Centre.

[3] Science Section refers to the Meteorological Research Division (MRD) and the Canadian Meteorological Centre (CMC). The Cloud Physics and Severe Weather Research Section (ARMP) took the lead role, but it included the Récherche Numerique Prediction (RPN) and the Canadian Meteorological Centre Development and Operational groups. ARMP took the primary role for the monitoring for science and nowcasting.

Olympics and Paralympics (Feb 29, 2010 to March 13, 2010). The Paralympics were conducted from March 14, 2010 to March 26, 2010. There were essentially five distinct geographical and weather zones (Fig. 1). These included: (1) urban Vancouver which is essentially at sea level, (2) Cypress Mountain with a base of about 850 m located on the north shore of the lower mainland; (3) Whistler Olympic Park in the newly developed Callaghan Valley; (4) Whistler Mountain (565–1,825 m), and (5) the Sliding Centre at Blackcomb Mountain (~800 to ~950 m). Even though the latter three venues were within ~10 km of the Whistler radar (located at the centre of these venues), the complex terrain and the specific weather requirements of each sport segregated the venues into distinct weather regimes.

Table 1 shows the basic climatology of the venues where there was an extended record of official weather observations. Urban Vancouver is quite a temperate climate with average temperatures of 3–5 °C, during January to March. Snow seldom accumulates in the city. The elevation changes within the urban environment are slight.

The Cypress Mountain venue rises to 1,440 m (Black Mountain peak height) in less than ~6 km from Georgia Strait and less than ~2 km from Howe Sound. Given its southwest facing slope, which is also the direction of the prevailing weather, orographic effects are dominant, and the prevailing freezing level is around the 900 m level, which is essentially the base of the field of play for the V10 events. Vancouver Island is approximately 50 km away, in the south-southwesterly direction, and lee side troughing or subsidence effects can confound the precipitation patterns (Fig. 2). Subtle changes in the precipitation direction can change the location and size of the subsidence.

Whistler Olympic Park was a newly developed venue for the Nordic events.[4] There was very little weather data available from this site prior to the Olympics. Snow surface temperature was a critical element for the cross-country events. For the ski jump, wind and to a lesser extent, visibility, were the critical weather elements. Strong cross-winds were important from an athlete safety perspective but slope (up and down) winds were critical from a competition fairness perspective.

The official weather observations for Whistler area are made on the valley floor (590 m). Whistler Mountain resort collects weather information for their use at the 1,625 m level, and the air quality group of EC conducted a research monitoring site at the peak (2,165 m). It is not uncommon to have strong winds in the high alpine region (>1,800 m), thick fog or low cloud at mid-mountain levels (1,000–1,600 m), snow and rain below that. The high alpine region chairlifts are closed 25 days per year on average (personal communication, Anton Horvath) due to high cross-winds (>25 m/s). While the official snow amount at the valley is about 411 cm per year,[5] the Whistler mountain snow observations made at VOA are about 10 m per year.[6] For the alpine events, precipitation accumulation (for course preparation, work force scheduling and planning) and visibility were the most critical weather elements.

The Sliding Centre was on Blackcomb Mountain (800–950 m). While it is an artificial and managed field of play (refrigerated surface and sun shades), solar radiation and humidity were crucial weather elements to estimate heat and mass transfer from the sliding surface.

In general, the indoor arena events, located in urban Vancouver, were not significantly impacted by the weather. However, humidity did play a role in managing the condition of the ice surface particularly for the curling events.

2.2. *The Forecast and Weather Requirements*

The stated generic high-level requirements for weather information by VANOC are indicated in Table 2. These requirements are basically the same regardless of whether it is winter or summer or complex terrain or flat land, and are used by the Sports Command Centre personnel for strategic decision making. They do not reflect the requirements

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[4] Nordic events refer to those ski events in which the heel is free to lift from the ski. Alpine events refer to ski events in which the heel is always attached to the ski.

[5] http://www.climate.weatheroffice.gc.ca/climate_normals/.

[6] http://www.whistlerblackcomb.com/weather/stats/index.htm.

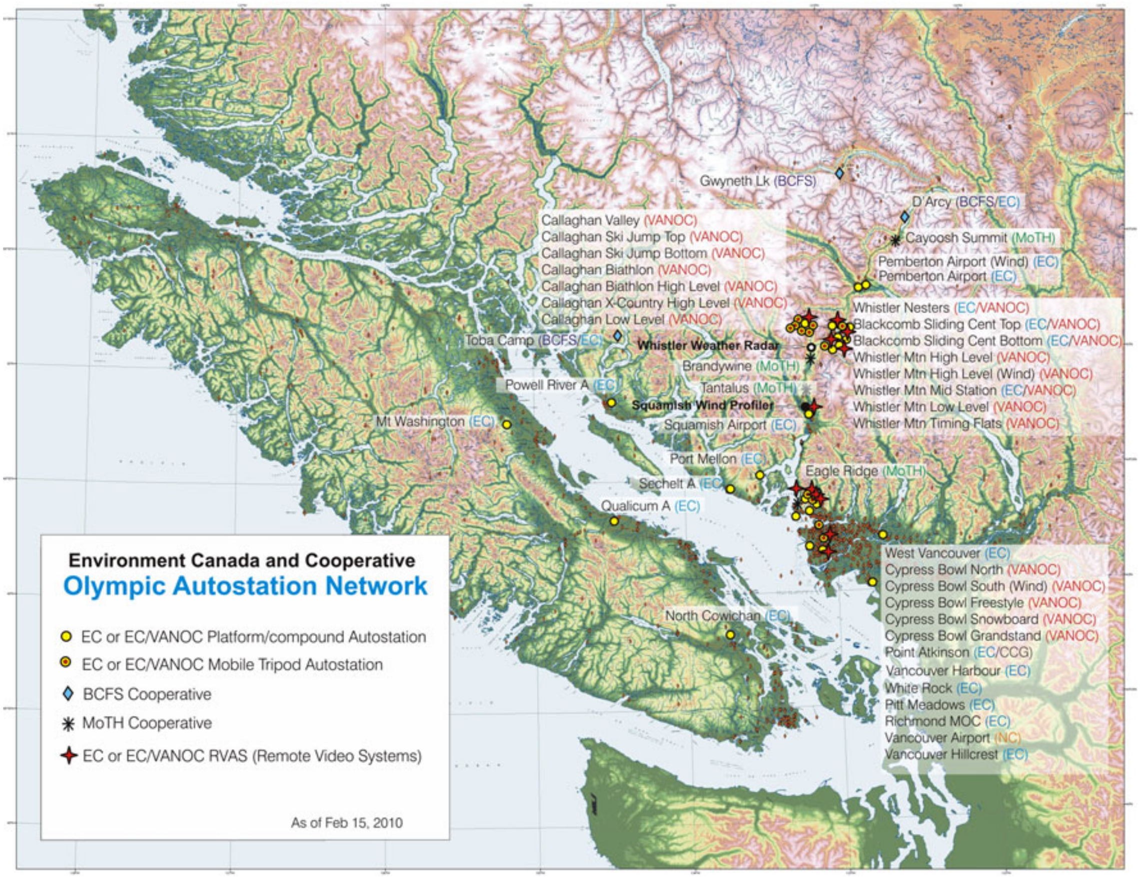

Figure 1
Overview map of the V10 venues. There are five major Olympic venues. The five areas are (a) urban Vancouver, (b) Cypress Mountain Freestyle Venues, (c) Whistler Olympic Park or Callaghan Valley Nordic Venues, (d) Whistler Mountain Alpine Venues and (e) Blackcomb Mountain Sliding Centre. The V10 monitoring stations are also shown

due to the characteristics (temporal and spatial scales) of the local critical weather features or systems (precipitation type, precipitation intensity, visibility or wind) or due to the nature of the sporting events themselves for both a safe and fair competition. For example, the ski jump had a requirement for the prediction of upslope-down slope wind speed variations of less than 1 m/s for a 90 min duration (Teakles *et al.*, 2012) for field of play (about a distance of around 200 m). The alpine races required visibility of about two gates (or turns). For the slalom races, this could be as short at 8–12 m whereas for the downhill race, where there are no gate separation requirements, this could be 200 m. These sports requirements were interpreted, captured, and portrayed as thresholds. This was the first time in which the requirements were presented in such a way (Doyle *et al.*, 2010; Isaac *et al.*, 2012a).

2.3. *Additional Constraints*

Since few observations were historically available, early deployment of monitoring sensors was a priority not only for observing the weather but also to create a data set from which public forecasts could be automatically generated using model output statistics (Landry *et al.*, 2004). Unfortunately, the system could not be adapted in time to meet the forecast requirements (Table 2).

Lack of infrastructure (roads, power, tele-communications) and venue construction limited the locations and constrained the implementation schedule. Also, sites that were established in the early years often needed to be moved in subsequent years. In addition, the final decision on site location was governed by esthetics and visibility to television cameras. The weather sites were considered unsightly. Contractual issues at Cypress Mountain precluded early deployment of instrumentation.

An obvious constraint is the undulating nature of the complex terrain itself. Combined with all the constraints, it was exceedingly difficult to find long fetches of flat terrain. Table 3 provides a qualitative description of sites.

Sustainability was a stated objective of the Olympics. This meant that reduced usage of power, re-use of infrastructure components, return of the sites to pre-Olympic condition were factors in the all aspects of the Olympic project. For example, AC power was not readily available at the cross-country venue for weather instruments.

Table 1

Basic climatology of temperature and precipitation for Vancouver (YVR), Squamish (WSK) and Whistler (VOC) weather stations where a sufficient record length (30 years was available)

	Jan	Feb	Mar
Whistler (VOC)			
Temperature (Celsius)	−3	−0.6	2.3
Rainfall (mm)	68.9	60.3	54
Snowfall (cm)	96.3	66.8	45.5
Precipitation (mm)	157.2	179.5	96.1
Vancouver Airport (YVR)			
Temperature (Celsius)	3.3	4.8	6.6
Rainfall (mm)	139.1	113.8	111.8
Snowfall (cm)	16.6	9.6	2.6
Precipitation (mm)	153.6	123.1	114.3
Squamish (WSK)			
Temperature (Celsius)	0.2	2.3	5.7
Rainfall (mm)	265.7	235.3	188.9
Snowfall (cm)	71.7	47.6	22.5
Precipitation (mm)	337.4	283	211.4

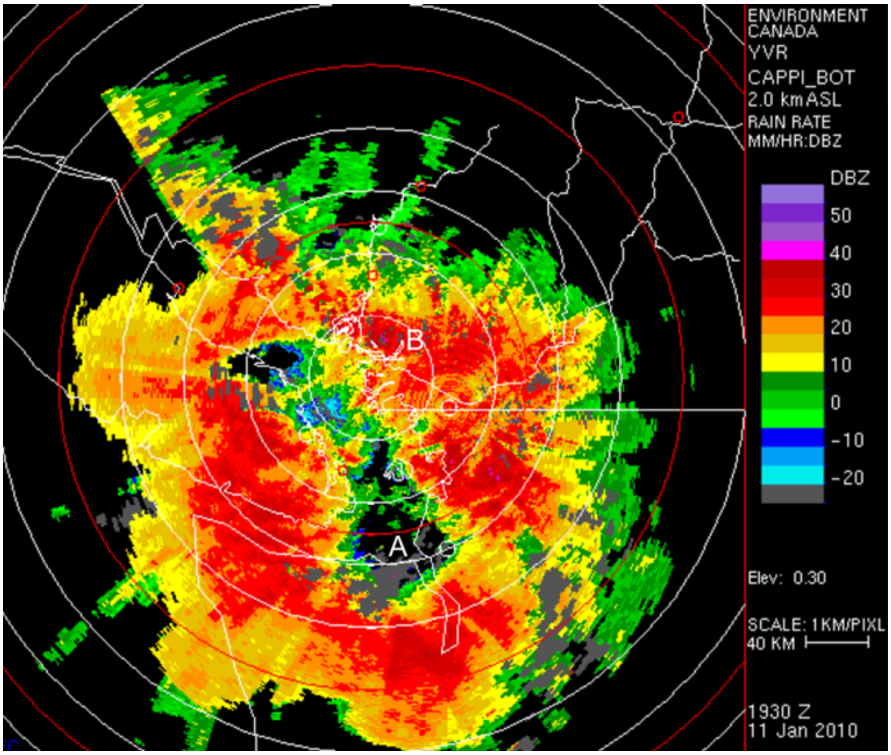

Figure 2
An example of subsidence in the lee of Vancouver Island and the Olympic Mountains in the southwest (USA). The subsidence hole (marked by *A*) evolves and shifts with the prevailing wind direction while, at the same time, orographic enhancement (marked by *B*) of the precipitation occurs at the Cypress Mountain venue

Table 2

High-level VANOC requirements for forecasts and nowcasts

Occurrence	Frequency
2–3 days before	6 hourly, updated twice per day
Day before	3 hourly, updated four time per day
Day of	1 hourly, updated hourly
0–2 h	5 min, update every 15 min

3. *The Observation Network*

The complex terrain imposed a substantial requirement for the measurements. It was clear from previously held alpine events spanning over 30 years that heavy snows and visibility led to the cancellation of several major ski events. The anecdotal stories and experience indicated that the effects were very local. Mo *et al.* (2012) describe a mid-mountain cloud that originates at about the 1,200 m level at the mountain that is confined to about 900–1,500 m that occurs with southerly low-level moisture behind a storm system and is capped by a lee wave over the Khyber Cliff (see Fig. 3). Also, assuming a standard 6 °C per kilometer lapse rate, the near zero temperatures at the official Whistler weather station indicated that identification of the freezing level would be critical for the alpine competitions. Detailed wind information was important at the ski jump venue. Freezing level concerns at the Cypress Mountain aerial venue also required detailed observations.

3.1. *The Observation Network Plan*

Given all of the constraints the observing network was designed and implemented (see Fig. 1). It consisted of modified automatic weather stations and advanced sensors. The in situ automatic weather station network was called the Olympic Autostation Network (OAN). Advanced sensors were needed to support scientific studies of visibility, precipitation and wind nowcasting which still require considerable research. The support was provided by the Science Program of Environment Canada. With the strong linkage to the WWRP project, these sites were colloquially called the SNOW-V10 sites though they are properly called the V10-SCIENCE sites (this terminology will be used in this contribution). They were often co-located with the OAN sites but on a separate platform. The observations from the OAN and V10-SCIENCE measurements were complementary and together form the V10 Observing network.

Webcams operated by NavCanada were also available in addition to several webcam systems associated with the OAN. NavCanada deployed human observers to three locations—Squamish, Whistler and Pemberton—to support enhanced aviation activity during the Olympic year.

Due to the complex terrain, coastal location and lack of infrastructure, there are not many venues upstream of the Olympics venues. There were a few training sites that were located far from the Olympic sites. For example, this included Mt Washington, near the middle east of Vancouver Island, and the Panorama Ski Resort located in the interior mountains on British Columbia. These sites were approximately the same elevation as the Olympic competitions. In the planning stage, remote upstream sites were identified that were only accessible by helicopter but cost and logistic issues eliminated them from consideration. A few existing BC Forest Service remote upstream autostations were upgraded and included into the OAN.

3.2. *Construction and Installation Considerations*

At Whistler Olympic Park (Callaghan Valley), the installation plan had to take into consideration road accessibility, cellular telecommunications, availability of power and the venue construction schedule. A main site was established along the cross-country track (VOD) that relied totally on solar power for sensor, data logger and telecommunication operations (see Fig. 4 for an example of an OAN platform). This lack of AC power also dictated the update rates of the observations that could be transmitted as this affected the power consuming telecommunications devices. While 1 min data were sampled, it could only be transmitted every 15 min. Temporary sensors were established on tripods that were moved as construction proceeded (Fig. 5). It was only in the Olympic year that permission was granted to install a wind sensor near the take-off point of the ski jump.

The optimal location for the weather radar was at the confluence of three valleys. It had to await the

Table 3

Anecdotal descriptions of OAN/V10-SCIENCE sites

	3 Letter Ident	Latitude	Longitude	Elevation	Anecdotal Description
NOAA XPOL	NOX	48.902	−122.773	168.0	Mobile truck. Located at State Park in Blaine Washington with good radar visibility of Cypress Mountain
Roundhouse Helipad	RND	50.067	−122.945	1856	Site of the visibility, fog and low cloud research at the helipad. Site is on a moderate slope and exposed to the wind and blowing snow
Air Quality Research Branch Peak	PEK	50.059	−122.957	2165	Located beside the top of the peak chair. The site is sheltered from the east and locals do not consider the wind to be representative
Whistler Mountain High Level/Pig Alley	VOA	50.077	−122.948	1640	200m below Whistler Mountain Resort site; well sheltered, good for precipitation; poor for wind; main site for precipitation analysis; has V10-Science, OAN and Whistler data; snow density measurements made here; AC power; 1 minute data; about same height as downhill race start; see VOH for campanion ‘10m wind”
Whistler Mountain Low Level/Creekside	VOB	50.088	−122.975	933	Just above Timing Flats, well sheltered; no AC power; so no heating on Pluviso sensor; 1 min data transmitted every 15 min. Full sensor suite
Blackcomb Mountain Base/Nesters	VOC	50.129	−122.955	651.5	Official Whistler Site for weather reports, on the Valley floor; radiosonde release from here; full AC power; snow density measurments made here. Web Cam Snow Verification. Co-located manned 24hr observing
Callaghan Valley	VOD	50.144	−123.109	884	Main site for Whistler Olympic Park, along the cross-country trail; no AC power; no heating; relatively well sheltered and open site
Cypress Bowl North/Cypress	VOE	49.402	−123.208	953	Site is located in the small narrow valley or corridor between Black and Strachan mountains. The Valley connects the Fraser River to Howe Sound and so the wind is channeled. Site is not very representative of the weather at the freestyle venues. North end of Cypress Bowl
Callaghan Valley Biathlon High Level	VOF	50.142	−123.119	882.7	Sheltered Tripod system funded by VANOC to capture temp, humidity, 4m wind and Snow Surface Temp at central elevation of Biathlon track
Cypress Bowl South (Wind)	VOG	49.379	−123.194	903	Located on the opposite side of a gulley separating the freestyle venues and the cross-country trails of Cypress Mountain. It was located at the edge of the parking lot overlooking the road and gulley. It is about the same height as the base of the free style venues. South end of Cypress Bowl
Whistler Mountain High Level (Wind)	VOH	50.079	−122.951	1690	A campanion site to VOA specifically for the measurement of wind. It is well exposed and very near the top of the downhill race course. Also transmitted Snow Surface Temp and air Temp. This wind data is combined with the VOA data for form a single “high level” observation
Blackcomb Base Sliding Center Top	VOI	50.102	−122.936	937	AC powered site located at the parking lot of the Sliding Centre Start building at top of slide. Relatively well sheltered
Mt. Washington	VOJ	49.747	−125.287	1473.5	Provided 15 min data. Site had full suite of sensors including a heated Pluvio and 10m wind. Coastal site at approx elevation of VOA
Callaghan Valley Cross Country High Level	VOK	50.143	−123.107	922	Sheltered Tripod system funded by VANOC to capture temp, humidity, 4m wind and Snow Surface Temp at highest elevation of X-Country track
Whistler Mountain Mid-Station	VOL	50.085	−122.964	1320	Also know as Raven’s nest, the location of the origin of harvey’s cloud. At the top of the Creekside gondola and base of the Big Red chair lifts. Site is located on a knoll that is subject to upslope winds. An important site for visibility measurements

Table 3 *continued*

	3 Letter Ident	Latitude	Longitude	Elevation	Anecdotal Description
Port Mellon	VOM	49.51	−123.48	122.6	Meteorologically upstream coastal MSC site with full suite of sensors but no AC power. 15 min data
Blackcomb Base Sliding Center Bottom	VON	50.106	−122.942	816.6	A small weather sensor was attached to existing scaffolding beside the track for basic meteorological measurements (temp, humid, radiation)
North Cowichan	VOO	48.824	−123.719	60	Meteorologically upstream coastal MSC site with full suite of sensors but no AC power. 15 min data
Powell River	VOP	49.834	−124.500	125	Meteorologically upstream coastal MSC site with full suite of sensors but no AC power. 15 min data
Qualicum	VOQ	49.340	−124.394	65	Meteorologically upstream coastal MSC site with full suite of sensors with AC power. 10m wind had full aviation quality data. 15 min data
Whistler Mountain Timing Flats	VOT	50.091	−122.978	804.9	A critical site for remote sensing. Called TFL in pre-Olympic years and co-hosted V10-Science and OAN sensors. Built on V10-science structure. In the Olympic year, the OAN sensor pluse the FD12P moved uphill to the judges trailers. And the V10-Science remote sensing instruments moved downhill to the the Bell Internet hub building
Sechelt	VOU	49.456	−123.718	86	Meteorologically upstream coastal MSC site with full suite of sensors with AC power. 10m wind had full aviation quality data. 15 min data
Callaghan Valley Low Level	VOV	50.140	−123.117	838	Sheltered Tripod system funded by VANOC to capture temp, humidity, 4m wind and Snow Surface Temp at lowest level of Biathlon
Callaghan Valley Ski Jump Top	VOW	50.138	−123.110	936	An anemometer and temp probe was mounted at the top of the ski jump on the coaches stand. It was relocated to this point (from gound level) at the requirement of VANOC
Callaghan Valley Ski Jump Bottom	VOX	50.137	−123.113	860	A tripod installation located off to the side of the ski jump outrun. It was relocated a few times at the requirement of the sport
Callaghan Valley Biathlon	VOY	50.147	−123.116	870	Sheltered Tripod system funded by VANOC to capture temp, humidity, 4m wind and Snow Surface Temp at top level of Biathlon track
Cypress Bowl Event (Freestyle)	VOZ	49.392	−123.203	969.1	Sheltered Tripod system funded by VANOC to capture temp, humidity, 4m wind at the Freestyle track
Whistler Radar	VVO	50.066	−123.110	557	Located a the junction of the Callaghan Valley Road, the Whister-Permberton and Whistler-Squamish Valleys. Just off the main highway
Cypress Bowl Snowboard	VWB	49.389	−123.214	1180.3	Sheltered Tripod system funded by VANOC to capture temp, humidity, 4m wind at top of Snowboard track
Vancouver Hillcrest	VWC	49.244	−123.106	83.9	Sheltered Tripod system funded by VANOC to capture temp, humidity, 4m wind for Public Wx purposes at Curling Rink
Cypress Bowl Grandstand	VWG	49.396	−123.206	968	Wind sensor mounted at the top of the grandstands on opening day for Public Weather purposes (and for web cams)
Pemberton	WGP	50.303	−122.738	204.3	Located meteorologically downstream of the venues at Pemberton Airport. Full sensor suite, no AC power
Vancouver Harbour	WHC	49.295	−123.122	2.5	15 min data. Tripod system site upgrade to include Pluvio and Snowdepth
Pemberton Airport (Wind)	WPN	50.301	−122.739	203	10m wind (aviation quality) & temp system to supplement WGP (poor wind exposure)
Point Atkinson	WSB	49.33	−123.27	35	Pre-existing coastal site upgraded to include Pluvio and Snow Depth
Squamish Airport 1	WSK	49.783	−123.161	52.1	Wind profiler with RASS was located here. At the end of Howe Sound, just before the road turns inland towards the inland valleys. To the north and north-east are two valleys. Squamish means "big wind". Full suite of sensors including aviation quality 10m wind

Table 3 *continued*

	3 Letter Ident	Latitude	Longitude	Elevation	Anecdotal Description
West Vancouver	WWA	49.347	−123.193	168	Autostation at the base of Cypress Mountain at the exit along the highway. Remote sensing base station for Cypress Mountain. Full suite of sensors at pre-existing site
White Rock	WWK	49.02	−122.767		Pre-existing coastal site upgraded to include Pluvio and Snow Depth. To surround Lower Mainland venue
Mout Sicker Radar	XSI	48.860	−123.756	716	National Radar Program operational radar on Vancouver Island; best view of weather up Howe Sound; Whistler is about 120Km away
Aldergrove Radar	WUJ	49.016	−122.488	93	National Radar Program operational radar ~40 km east of Vancouver; best low level view of Vancouver and Cypress Mountain

construction of a new waste transfer station. The siting requirements and the availability of power and land for the radar dictated the location of the radar tower and the implementation schedule.

At the Alpine venue (Creekside of Whistler Mountain), the bottom of the ski run was a critical location for establishing remote sensors. A site was established in the pre-Olympic years, but in the Olympic year major construction to accommodate spectator seating and the installation of infrastructure to support television broadcasting, timing and other race officials and a major internet facility required the station to be relocated from a single station into two stations separated by about 150 m. The remote sensing instruments went downhill and the in situ sensors went uphill.

At Cypress Mountain, access to the field of play was restricted to the Olympic year and so a representative instrument site could not be established beforehand. With the establishment of spectator seating at the ski-cross venue and strong winds that funneled between Strachan and Black mountains, a weather station was requested to be setup at the top of the spectator stands on the opening day of the Olympics.

4. *The OAN Platform and Instruments*

4.1. *The OAN Platform*

Given the constraints already discussed, the complex terrain in situ sites required a small footprint. In addition, considerations also included the strength of construction materials and the fact that snow accumulation over the winter season resulted in changes of the site height above the "ground". Guy wires for stability were not used due to weight bearing stress in icing conditions. Sustainability and telegenic objectives of the Olympics also promoted innovation and color choices (orange for hazard safety). Figure 4 shows the design of the platform with the instruments. A 2 m × 2 m footprint with variable leg length (1, 2 or 3 m floor height) was designed and constructed by the regional MSC Atmospheric Monitoring staff of the Richmond Monitoring Operations Centre. These were deployed when there was reasonable confidence that a site location could remain during and after the venue

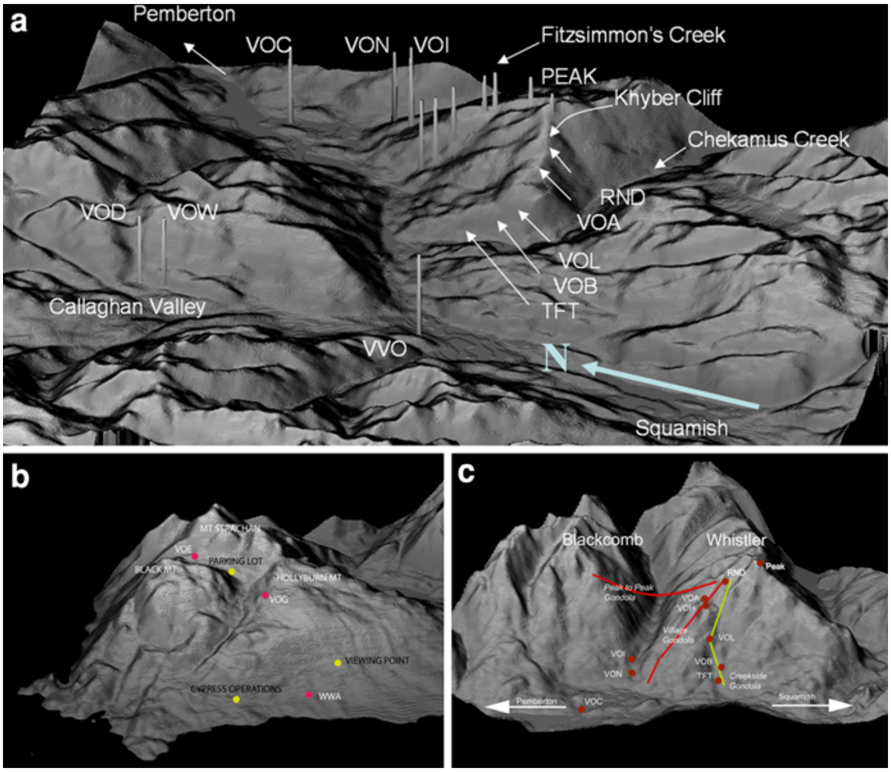

Figure 3
Topographic rendering of the three main Olympic mountain venues. **a** Whistler Olympic Park (plus northeast view of the Whistler to Pemberton valley plus Whistler Mountain), **b** Cypress Mountain and **c** Whistler-Blackcomb Mountain. In **a**, the location of the V10 monitoring stations are indicated by spikes in the imagery. See text for details. *The arrows* indicating the names of the sites are slightly displaced. The Shuttle Radar Topography Mission-3 arcsecond (SRTM03) is the digital elevation model used for visualization

construction. These were also deployed when there were security considerations.

This platform could be used with or without AC power (see solar panel in Fig. 4). At sites that were later converted to AC power, solar panels were left in place as back-up. Data were collated with a Campbell Scientific 23X data logger and then serially transmitted using serial-Ethernet-serial connections using cellular internet technology. The solar panels were designed and selected for local climatological conditions and anticipated power requirements. The power usage of the cellular technology was the limiting factor in the power budget and the system was originally designed for hourly data. Later, minutely data were requested for nowcasting and science applications. At solar powered sites, the minutely data were bundled and transmitted every 15 min. At AC powered sites, the minutely data were transmitted as it was collected.

Figure 5 shows a tripod platform with a solar panel. These were needed for temporary installations of several months or less. Basic measurements of temperature, pressure, humidity and wind were collected. Only hourly data were available from the tripods due to the small solar panels used.

In addition, instruments were set up on existing platforms such as the coach's platform at the take-off point of the ski jump or at the judges building at the bottom of the alpine race course (see Table 3). At the Whistler Mountain High Level site (~1,625 m), the precipitation and the wind measurements used different sites and were combined into a single observation. A well-protected site from wind (VOA) was good for precipitation but had poor exposure for a representative 10 m wind so the site only had a precipitation sensor height wind sensor. An additional nearby exposed site was installed for the purpose of obtaining a 10 m wind (VOH).

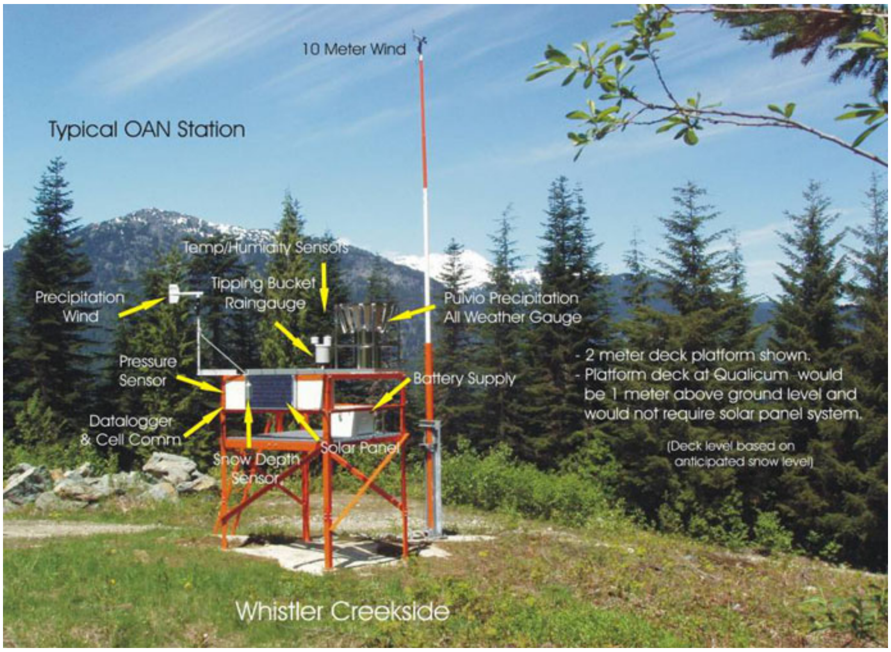

Figure 4
An example of a typical permanent Olympic Autostation Network in situ monitoring platform located along the cross-country track (VOB). This station was totally solar powered due to the lack of AC power. At this station, the 10 m tower for wind measurements was located next to the ground segment but this is not always the case

Figure 6 shows a mosaic of images to illustrate the variety of installation sites. While they are usable and interpretable by human observers, the use of non-standard observations in automated system are more problematic because of the assumptions made in processing the data and also due to the dynamically changing site conditions (height in particular).

4.2. *The OAN In Situ Instruments*

A full suite of MSC nationally approved sensors was deployed on the OAN platform (see Table 4). With the intense snowfalls, a large catchment capacity was needed to reasonably store the catch without undue maintenance. The preferred national standard for automatic solid precipitation measurements was the unheated GEONOR gauge (by GEONOR). The Pluvio 1 was considered as a secondary standard. It was selected for the OAN because it had a catchment capacity of 1,000 mm, compared with the 500 mm water equivalent of the GEONOR. The Pluvio 2, which has an even higher catchment, was not utilized since it was not yet approved as an accepted MSC standard.

Wind shields (factory supplied Tretyakov style) were removed, and custom shroud heating systems were installed at well sheltered venue or alpine sites where wind was not a significant issue and where AC power was available. In the Whistler area, heavy wet snow resulted in a high incidence of capping. Factory supplied heating collars were tested but were unacceptable due to internal ice formation. Wind speed as well as direction at gauge height was measured at all sites for multi-purpose use. In addition to having the speed archived for climatology purposes, it was used by forecasters to assess the localized wind conditions as they would affect the sport. Wind speed corrections described by Goodison *et al.* (1998) were not applied, since that would be more for climatological study purposes (daily corrections) rather than for short interval data outputs (minutely or hourly).

At well-sheltered, low wind speed sites, the prevalent heavy wet snow often accumulated on the shield and resulted in capping and blockage of the orifice. Even when the wind shield was removed, the snow accumulated on the shoulder of the gauge and the heating capability of the factory supplied

Figure 5
An example of a temporary Olympic Autostation Network in situ monitoring platform located at the foot of the ski jump which is still under construction when this station was established. The tripod installation could be easily moved to accommodate the construction schedule. Note that the wind is at a non-standard height (<10 m)

heated collar for the Pluvio 1 was not sufficient to prevent capping. Finally, commercial water pipe heating tape was wrapped around the exterior of the gauge shroud and the heat was controlled by a surface contact thermostat. Heat was applied when the exterior temperature of the aluminum shroud was below 2 °C. Figure 7 shows a mosaic of images showing capping with the various configurations. Since snow capping had proven to occur within an hour of site maintenance, it was of extreme importance to manage this for the urgency of forecast operations during and the lead up to the sporting events even if it resulted in a level of bias or degradation of the climatological data.

4.3. The Weather Radars

4.3.1 Radar Selection

A critical sensor was the Doppler weather radar. Various options were discussed, including bringing in a mobile or portable radar of various wavelengths and capabilities. Considering the length of the deployment and operations (24/7 for several years), expected security issues during Games time, reliability and maintenance requirements, and incorporating the data into Environment Canada data and visualization systems, a radar meeting the national specifications (C Band, Doppler) was selected and constructed by the National Radar Program (NRP) of Environment Canada (LAPCZAK *et al.*, 1999; JOE *et al.*, 2002). Dual-polarization capability was considered to meet the precipitation typing requirements but due to design considerations and scheduling issues, this option was not available.

4.3.2 Site Selection

After considerable discussion, site visits, and analysis, a valley location was selected over a mountaintop location for the radar site. The mountaintop location would provide short-range and high-resolution surveillance and high-resolution nowcasting capability of the local weather primarily above the crest of the mountains (>2,000 m). A site near the helipad on Whistler Mountain, at the 1,650 m ASL level, was extensively explored. Given the geometry of the terrain, even negative elevation angle scanning would not be able to see the low-level valley weather. Also, concerns for public skier safety (it would possibly even require altering ski trails) and esthetics precluded this site. There were no other reasonable mountaintop sites with power and accessibility. The Mount Sicker radar on Vancouver Island could provide an “over the top” or above-mountain–crest view of the weather for nowcasting purposes. The Doppler elevation angles are −0.4°, 0.3°, 0.5° and 3.5° but the data go out only to 113 km. In conventional mode, the three lowest elevation angles are 0.3°, 0.5° and 0.7°. At 145 km, the distance between Mount Sicker radar and Whistler Peak, the 0.7° beam overshoots by only 339 m.

The decision was to locate the radar at a valley site where it could have a good clear view of the venues and major traffic corridors. The site chosen was located at the confluence of three valleys at about 567 m ASL and was chosen with the aid of topographical maps and digital elevation model analysis (Fig. 8). A significant issue was the

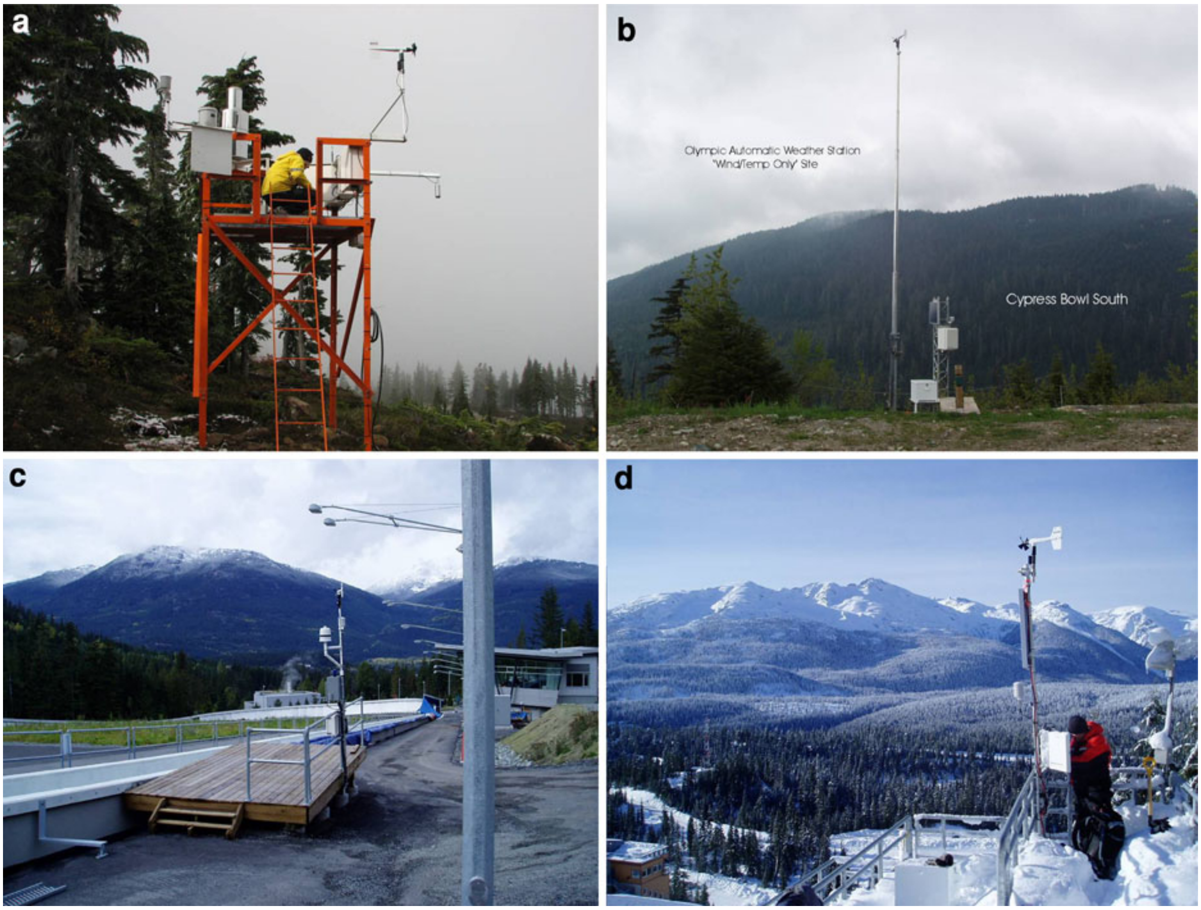

Figure 6
A mosaic of images showing examples of the various configurations of the OAN platform. **a** VOL was on a knoll, downhill is to the *right* and slope winds were a concern. **b** VOG was at the edge and overlooked a significant gully towards the freestyle venues at Cypress Mountain, **c** VON was located on an existing platform near the *bottom* of the Sliding Centre and **d** VOW was located at the Coach's Station at the take-off point of the ski jump

availability of land and power, and so it was tied to the development and completion of a new municipal facility (a waste transfer station). The actual site available was within 2 km of the pre-determined site. To contribute to the sustainability objective, the radar was constructed from spares from the national depot and the tower was previously decommissioned.

Construction of the site and installation of the tower and radar was completed in late Feb of 2009, about 1 year ahead of the Olympics. Given the novelty of the valley radar and the nature of the weather (valley weather can be distinct from the free atmosphere weather); any observations made in the pre-Olympic year were considered invaluable for scientific understanding, data quality, product development, forecast process development and training.

4.3.3 Radar Configuration

While tuning the radar for the ground clutter environment, it was realized that configuring a radar for short-range local weather applications was significantly different from long-range weather surveillance. Primarily, there was much less focus on low-level scanning (where a tenth of a degree change in elevation angle can make a significant difference for long-range surveillance) and so a change in scanning concept was needed. Table 5 describes the scan strategy settings for the Whistler

Table 4

List of OAN sensors

Sensor	Model
Acoustic snow depth sensor	SR50 Sonic Ranger, Campbell-Scientific
Pluvio 1 precipitation gauge	Pluvio 1, OTT, custom heating (alpine sites)
Radiosondes	RS92-SGP, MW31 Digicora sounding system by Vailsala
Temperature, humidity, pressure	YSI 44212EC (primary temp), HMP45AC (humidity and back-up temp) and Setra 270 (pressure)
Tipping bucket raingauge	TB3 and TB4, Texas instruments
Visibility	Model 6200, Belfort (limited deployment)
Web cams	Stardot SC5, Stardot
Wind profiler	915 MHz with RASS, Vaisala
Radiometer	MP3000A, Radiometrics
Snow ruler	Acme
Weather radar	C Band, Doppler, EC
Wind at 10 m	Aerovane. R.M. Young, 05103-10A
Wind at gauge height	Aerovane. R.M. Young, 05103-10A
Snow surface temp	Apogee IRR-P
Radiation	CM-21

radar. Scan strategies for the Mount Sicker and Aldergrove radars are described by Lapczak *et al.* (1999) and Joe and Steve Lapczak(2002). The scan strategy took into consideration: (1) the near-range (<40 km) focus of radar, (2) the transition zone from valley to system weather at the crest of the mountains, (3) the requirement to scan at 13°+ to completely overcome the mountains, (4) the fine scale of the weather in the valley, and (5) the impact of ground clutter. The site had excellent view of the fields of play. In fact, the 6° scan skimmed the surface of Whistler Mountain and the beam was less than 500 m above the in situ weather stations on Whistler Mountain (except for 1 site, VON which was just above 500 m). Note that very few elevation angles at low level were required, since they did not reveal significant differences, and those they did were mostly block. More elevations were placed in the 9°–15° to capture the transition from valley to system weather. Two high-elevation scans (20° and 45°) were collected for VAD analysis. A 60° scan was attempted but caused elevation drive problems.

Very fine range resolution data (125 vs. 500 m or 1 km in the Environment Canada radar network) was used so that ground clutter contamination was not smeared in range. Sixty-four samples (128 samples did not resolve the ground clutter any better) were processed using a spectral domain fixed-width ground

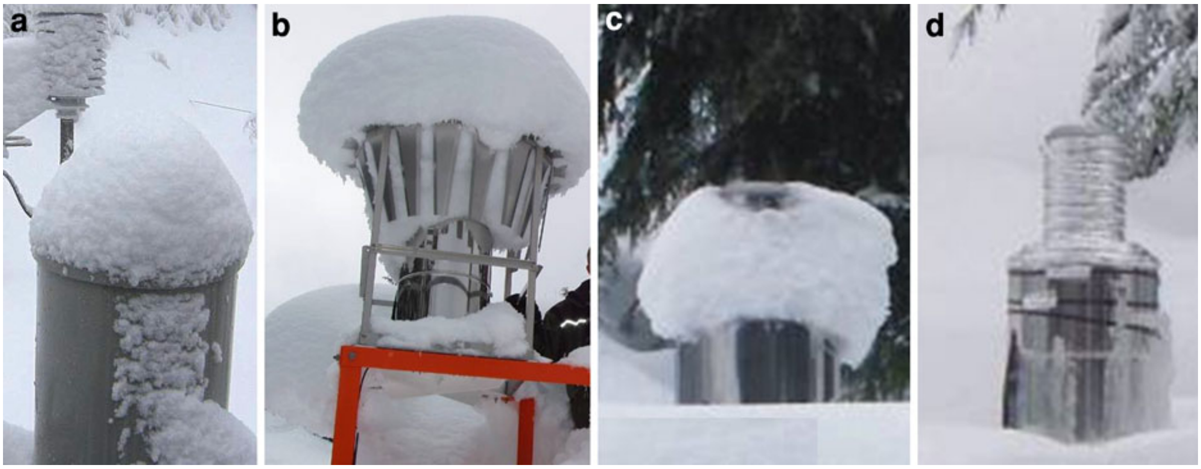

Figure 7

A mosaic of images showing the innovation and evolution of the catchment precipitation gauge used in the OAN. A Pluivo 1 gauge with custom heating was chosen because it had a large reservoir to accommodate the expected heavy snowfalls found in complex terrain. It was also a tested and evaluated sensor by Environment Canada. The Pluvio 2 had not yet been approved. **a** A standard tipping bucket raingauge completely blocks in this environment. Initially, **b** the standard shielding (single Alter shield) with heating was used; **b** then the shielding was removed and the standard heating was insufficient to prevent buildup on the shoulders and **c** finally additional heating (water pipe heating tape) was applied. Configuration (**c**) was used in well sheltered sites (e.g., VOA) but configuration (**a**) was used in windy sites (e.g., VOL) and those without power

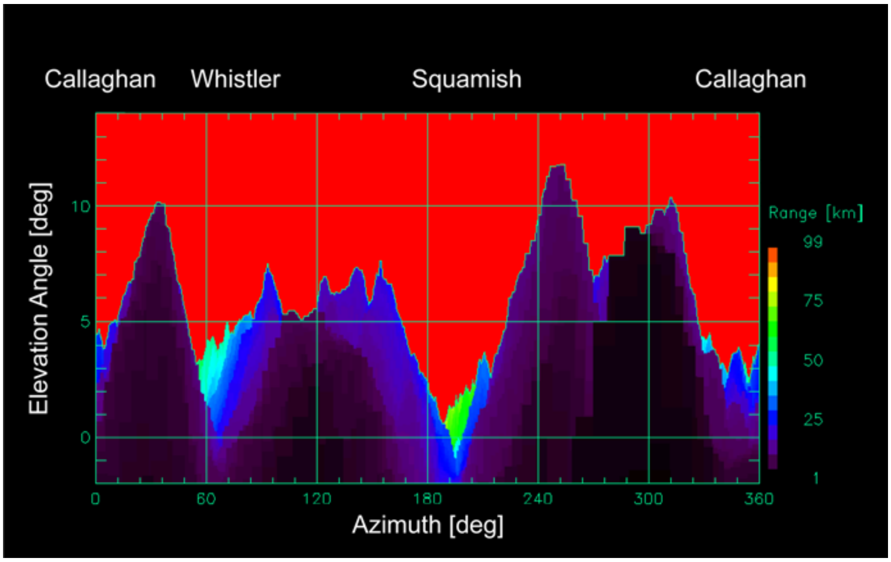

Figure 8
A "range to terrain" diagram. The range to the terrain as a function of radar azimuth and elevation angle is shown in colour shading. The origin of the analysis is the location and height of the radar antenna. The underlying digital elevation model is the SRTM03 data set. This provided an a priori evaluation of the efficacy of various proposed sites. The analysis indicated that a location within 5–10 km along the Squamish to Whistler corridor would meet the venue visibility requirements even though the beams are blocked beyond. For example, in the direction of Whistler Mountain or Callaghan Valley, the beam is blocked at 30–40 km in range but the venues are within 10–15 km (see Table 6). The final site selected was within 2 km of the ideal location

clutter filter (an RVP 7 processor by Vaisala-Sigmet was used). A dual-PRF scheme (on 1° rays, the EC networks collects data at 0.5° rays; 892 and 1,196 Hz were used for the PRF) provided an extended Nyquist of 48 m/s (Joe and May, 2003). Thirteen angles of Doppler data were collected (Table 5).

With the focus on specific sites, RHI scans of reflectivity and Doppler velocity products were collected. These scans were not used in real-time, since the operational radar processing software could not decode and display these scans (Joe *et al.*, 2002). These scans were of very fine resolution (0.1° in elevation) and could used in either post-analysis or processed using non-operational software. However, the operational software could and did generate pseudo RHI (or arbitrary cross-section) products from the volume scan. The pseudo-RHI scans were generated along the azimuth passing over the OAN sites (Table 6). Quick comparison of the real RHI and pseudo-RHI products did not reveal significant differences for operational use, and resources were diverted to other development activities. These kinds of vertical products, particularly the radial velocity RHI, were novel to researchers and forecasters. However, users were already thinking about weather in the vertical and so these products matched their intuition and mindset and were readily adopted with little training. With this success, additional arbitrary cross-sections were generated from the conventional volume scans from the Mount Sicker and Aldergrove radars.

4.4. *Wind Profiler*

A five-beam boundary layer wind profiler (915 MHz by Vaisala) was installed up/downstream (depending of valley flow direction) of Whistler and Cypress Mountains at the Squamish airport. Squamish is located at the end of a fjord (Howe Sound) and at the beginning of the valley towards Whistler. The valley floor rises from sea level to about 560 m at Whistler. It alternatively ran high- (10 km) and low-altitude (3 km) scans. Consensus winds were produced every 15 min. RASS (Radio Acoustic Sounding System) profiles of virtual temperature were done hourly. A range normalized SNR (signal to noise ratio) product using the spectral moments and the vertical beam was produced (Rogers *et al.*, 1993). It helped to identify the bright band and therefore the freezing/melting levels (Fig. 9b,

Table 5

Scan strategy and configuration parameters for the Whistler radar

VVO Radar Specifications	
Power	170 kW
Signal processor	Vaisala-Sigment, RVP7
Transmitter	Magnetron
Antenna controller	RCP02
Beamwidth	1°
Tower height	27 m
Antenna diameter	12 m
Cycle time of scans	10 min
Volume scanning (V10VOL)	Elevation sequence: 45, 20, 17.5, 15, 13, 12, 11, 10, 9, 8, 6, 4, 2
	Rotation rate: 2 rpm
	Pulse width: 0.8 µs
	PRF: 1,192/896 s^{-1}
	Nyquist: 48 m/s
	Azimuth resolution: 1°
	Range resolution: 125 m
	Number of bins: 1008
	Maximum range: 125 km
	Scan time: 7′49″
	Initiation time: 00, 10, 20, 30, 40, 50
RHI scanning (RHIVOL)	Max elevation is 45
	Azimuth sequence:
	0 (VOD)
	73 (TFT)
	78 (VOL)
	94 (Peak)
	187 (WSK)
	Elevation resolution: variable, 0.1° at low elevations
	Maximum elevation angle: 45°
	Scan time: 2′05″

The azimuths of the RHI's were chosen to past over OAN sites (see Table 6)

c). The winds helped provide scientific insights into the battle between the coastal inflows from the Arctic outflow in the valley (see Fig. 9a).

4.5. WebCams

Figure 10 shows the location of high-quality remote video cameras. The networks consisted of Environment Canada and NavCanada cameras. The cameras were updated every 5–15 min and, while they are qualitative in nature, they provide a visual image that is intuitively interpretable by the forecaster. For some measurements, such a visibility, the webcams provided spatial information. For example, Mo *et al.* (2012) demonstrate how the mid-mountain cloud could be identified using the network of webcams. Quantitative information on the occurrence of a mid-mountain cloud can be determined through a manual analysis of the cameras stationed above, in and below the expected location of the cloud. In addition, commercial and other web cam imagery (e.g. Whistler Mountain resort) was also readily available.

4.6. Radiosondes

Special radiosondes were launched every 6 h from Comox and Whistler. At the normal Environment Canada Upper Air Sites of Port Hardy and Kelowna, radiosonde frequency was increased to every 6 h instead of the normal 12 h during the Olympic event period. As well as the mandatory and significant levels, 1 s data from the Whistler sounding was available. This detail was necessary to capture the low-level (<2 km ASL) detail of the atmosphere in the valley.

5. The V10-SCIENCE Instruments

5.1. In Situ Sensors

Advanced in situ sensors (see Table 7) were deployed by the Cloud Physics and Severe Weather Section of Environment Canada to support the scientific and nowcasting objectives of the V10-SCIENCE and SNOW-V10 projects. The scientific objectives of the Environment Canada's science plan are similar to the SNOW-V10, but include basic understanding of precipitation, visibility and wind processes and precipitation intensity and type estimation. The scientific objectives of SNOW-V10 are described by Isaac *et al.* (2012a). Table 8 provides a cross-reference of the sensors deployed at a given site. Traceability to the science objectives of basic understanding of precipitation, visibility and wind processes to the sensors is described below in the discussion. Isaac *et al.* (2012b), Mo *et al.* (2012) provide detailed analyses and examples from these sensors.

Considering the limited deployment time, the instruments were mounted on a platform constructed from commercially available aluminum scaffolding materials that could be erected and de-commissioned quickly. The V10-SCIENCE instruments required AC power to operate and to transmit the data.

Table 6

Range, elevation angle, optimal scan angle and clearance from VVO radar to OAN/V10-SCIENCE sites

STN_ID	Name	Lat	Lon	Height (ASL)	*R* (km)	Azimuth	Elev angle	Scan angle	Clearance (m)
VOA	High level	50.07704	−122.94625	1,639	11.8	84.1	5.1	6.0	179.7
VOH	High level wind	50.07425	−122.94695	1,643	11.7	85.6	5.2	6.0	168.9
VOL	Mid-station	50.08778	−122.96423	1,320	10.7	77	3.9	6.0	383.8
VOB	Low level	50.08793	−122.97564	933	9.9	75.9	2	4.0	343.8
VOC	Nester's	50.13334	−122.95000	659	13.6	56.8	0.3	2.0	403.3
VOI	Sliding centre top	50.10214	−122.93728	937	13	72	1.5	4.0	553.7
VON	Sliding centre bottom	50.10602	−122.94237	809	12.8	69.7	1	2.0	222.7
AQRB	Peak	50.05917	−122.95808	2,165	10.9	94.1	8.3	9.0	140.6
RND	Roundhouse	50.06708	−122.94697	1,856	11.6	89.5	6.2	8.0	358.4
TFT	Timing flat	50.09122	−122.97984	821	9.7	73.4	1.4	2.0	105.5
VOD	Callaghan valley	50.14433	−123.10927	869	8.7	360	1.9	4.0	322.3
VOW	Ski jump	50.13334	−123.11667	936	7.5	356.4	2.7	4.0	171.9
VOY	Biathlon	50.13722	−123.10584	857	7.9	2.2	2	4.0	280.3
WGP	Pemberton	50.30000	−122.73333	204	37.3	45.8	−0.6	2.0	1,685.5
WSK	Squamish airport	49.78333	−123.16111	52	31.7	186.6	−1	2.0	1,638.7

Optimal scan is the minimum angle in the VVO volume scan that is at least a half a beamwidth above the site. Note the azimuths of the OAN sites (see Table 5)

In general, the data were processed by a data logger on-site, and the serial output stream was transferred via cellular internet technology. Data were transmitted (1) every minute, (2) every 15 min as minute samples, or (3) every 15 min as 15 min samples. The OAN data were recorded on servers located in Vancouver while the V10-SCIENCE data were recorded on servers located in Toronto.

5.2. *Precipitation Intensity and Type Sensors*

The current standard for solid precipitation intensity measurements are manual measurements made every 6, 12 or 24 h (Goodison *et al.*, 1998). However, recent progress in high-resolution observations have been made using non-catchment technologies based on different physical principles, such as microwave backscatter, forward or oblique scattering of visible light, particle counting (disdrometer) or mass/heat transfer (Sheppard and Joe, 2008; Viezee and Evans, 1983; Rasmussen *et al.*, 2011). Many of these instruments (FD12P, POSS, Parsivel, LCR) also report precipitation type (Yuter *et al.*, 2006; Sheppard and Joe, 2000). Given the uncertainty of the operability of the various high-resolution snowfall technologies in heavy wet snowfall conditions, a variety of sensors were deployed to reduce the risks. The VOA site was a well-sheltered site embedded in a grove of trees that could be used as a reference.

5.3. *GOMDAR*

A surface weather sensor was mounted on the top of two gondolas—the Whistler Village (WVG) and the Peak to Peak (P2P) gondola (Figs. 3c, 11). The WVG made a complete return trip about every 40 min (565–1,825 m) depending on the gondola speed (which was reduced in high wind situations) to produce a detailed sounding along the Village side of the Whistler Mountain. These detailed measurements complemented the sparse OAN in situ measurements (Fig. 11). The P2P made essentially a horizontal transect across Fitzsimmon's Creek to measure drainage and other valley effects every 30 min (total return time). Initially, data were reported every minute but preliminary analysis indicated that corrections needed to be made to compensate for instrument lags. Data were sampled every 10 s. They were called GOMDAR systems (Gondola Meteorological Data, Acquisition and Relay). They operated on batteries that had a 2–3 day duration. However, in order to establish a consistent routine, they were pulled off the line and charged every night in a maintenance facility. If the batteries were not charged, they froze and became unusable requiring replacement. The WVG was

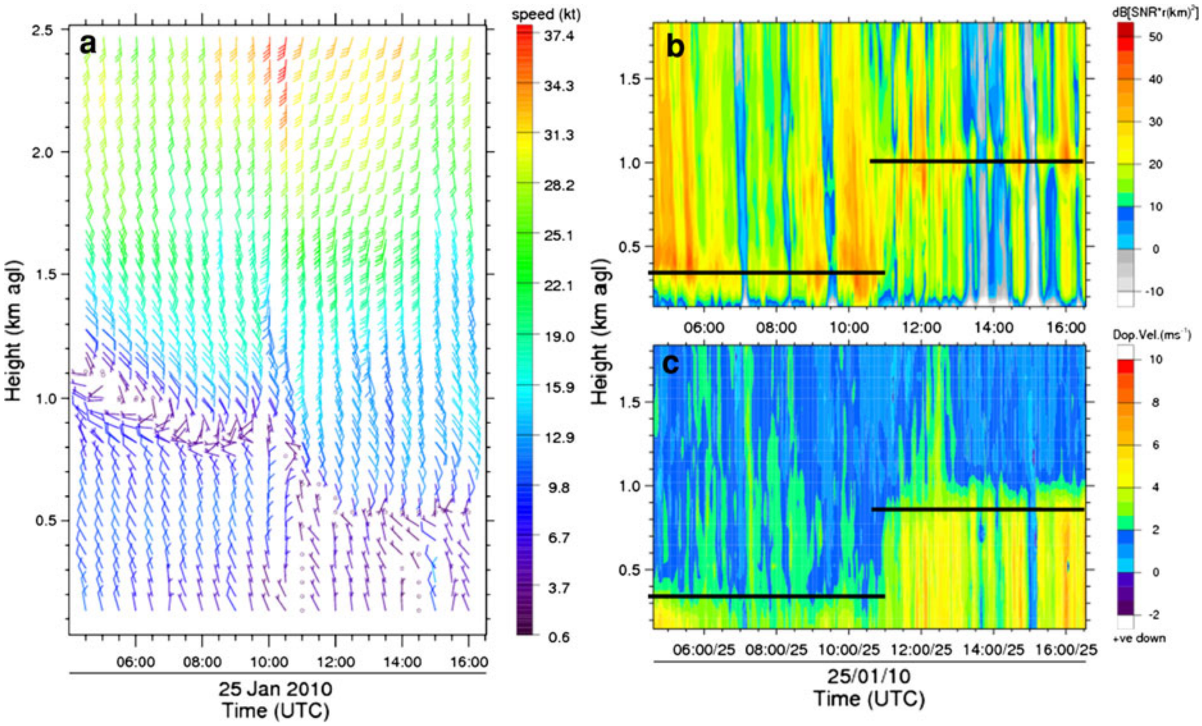

Figure 9
A example of **a** the consensus winds, **b** normalized SNR and **c** vertical velocity time-height display from the wind profiler located at Squamish airport. **a** The winds show the interaction between the inflow (*aloft*) versus the outflow (*below*) which often is linked to the phase transition (rain-snow) of the precipitation. The pattern could be inverted. **b** Range normalized SNR is shown for the vertical beam and can be interpreted as uncalibrated reflectivity. A POSS disdrometer was co-located that could be used to calibrate the power. However, this was not done in real-time but the display is sufficient to identify the freezing level via the bright band. Radio Acoustic Sounding System (not shown) virtual temperatures were retrieved on an hourly basis

mounted on a distinctive gondola and a consistent routine was established with the lift operators which resulted in reliable and robust data. This was not the case with the P2P. The alpine races occurred on Creekside of Whistler Mountain; however, there was no maintenance facility to charge the batteries precluding the installation of a GOMDAR.

5.4. *Visibility, Fog and Low Cloud Research*

At the helipad near the Roundhouse Station on Whistler Mountain, a special site was deployed to specifically study low visibility and fog (Gultepe *et al.*, 2009). While part of the V10-SCIENCE stations, it had over 20+ instruments with redundant measurements of weather variables (Fig. 12). It is described in greater detail in Gultepe *et al.*, (2012). Briefly, it measured with minutely sampling, basic weather elements, radiation, precipitation type and intensity, particle imaging and visibility (see labels in Fig. 12). Two instruments of particular interest were the Snow Video Imager (Newman *et al.*, 2009a) and the Ground Cloud Imaging Probe that imaged the snow particles. Manual snow density measurements and snow microphotography measurements were also made here.

5.5. *Peak Site*

The Air Quality Research Branch of Environment Canada operates a long term monitoring site at the top of Whistler Mountain (2,165 m, Macdonald *et al.*, 2011). Minutely samples of temperature, humidity, wind and pressure were available. The site is just below the highest terrain and east winds observations were compromised. The wind, temperature and precipitation conditions were very harsh. It was difficult to maintain equipment not designed for extensive riming and strong wind conditions.

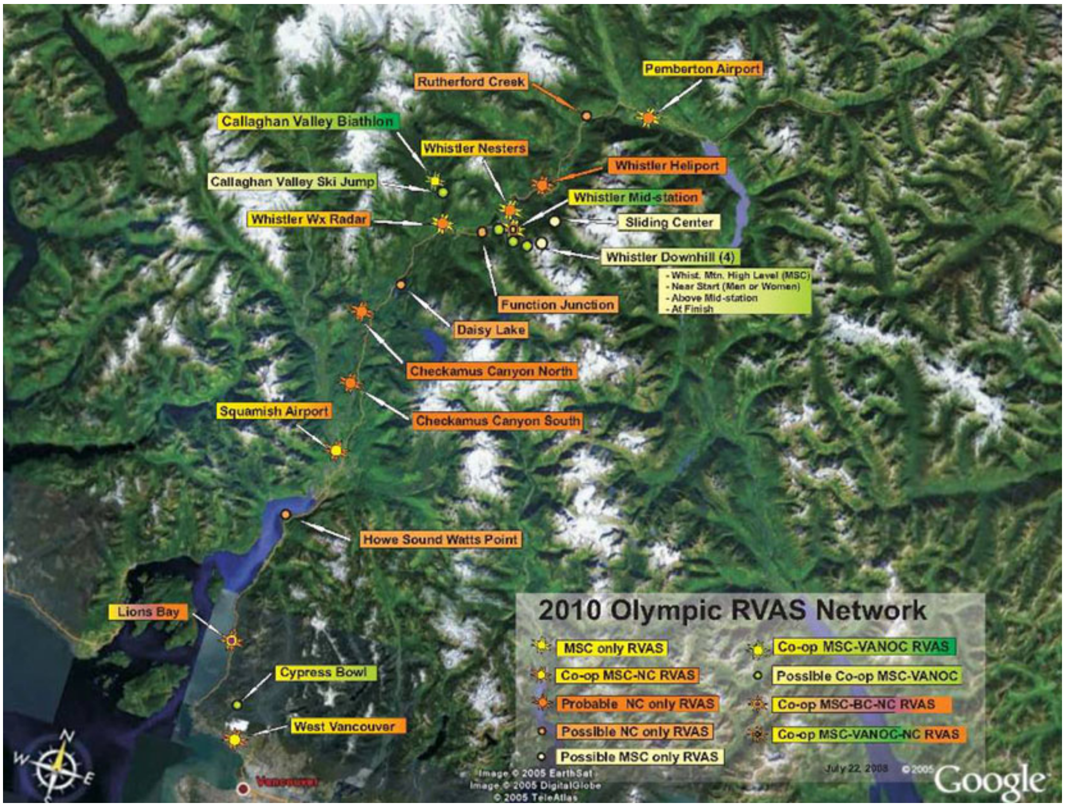

Figure 10

A map showing the location of the webcams (as known as Remote Video Acquisition System). These are the VANOC, Environment Canada and NavCanada sites. There are many other webcams available (e.g., Whistler-Blackcomb resort, Provincial Ministry of Transportation, etc.)

Table 7

List of advanced or V10-SCIENCE sensors

Sensor	Model
Parsivel	OTT
POSS	All weather instruments
Hotplate	Yankee
FD12P	Vaisala
PWD22	Vaisala
3D Wind	WS425 FG, Vaisala
LCR	Kipp and Zonen
MRR	Metek/Atmospheric Technology Services
Ceilometers	CT25K/CL31
Handheld	Kestrel 4500
Snow Photography	Nikon D2000 with macro lens
Snowtubes	Snowmetrics

5.6. *Whistler Mountain*

Whistler-Blackcomb Mountain Resort collects weather observations at the VOA site (1,625 m). In particular, they make twice daily manual snowfall accumulation measurements from a Tretyakov gauge configured with a single Alter shield. The VOA is well sheltered and combined with measurements of wind at gauge height; this provided a known reference for the automated precipitation sensors. This data were made available to Environment Canada for scientific studies.

5.7. *Remote Sensing at Whistler and Cypress Mountains*

Two remote sensing sites were established at the base of Whistler and Cypress Mountains. At the base of Whistler Mountain at the Timing Flats site (TFT), a vertically pointing micro-rain radar (MRR by Metek), a ceilometer (CL31 by Vaisala), a POSS (by AWI) and a Parsivel (by Ott) and a microwave profiling radiometer (MPR model TP3000 by Radiometrics) were installed. The

Table 8

Cross-reference of instruments and sites

Instrument	Whistler Mtn High Level VOA	Whistler Mtn Low Level VOB	Whistler Nesters VOC	Callaghan Valley VOD	Cypress Bowl North VOE	Cypress Bowl South VOG	Whistler High Level (Wind) VOH	Sliding Centre Top VOI	Whistler Mid Station VOL	Sliding Center (low) VON	Timing Flats (OAN) VOT	Timing Flats (V10-Science) TFT	Squamish Airport WSK	West Vancouver WWA	Peak AQRB	Whistler Roundhouse RND*	Ski Jump VOW
YSI/ HMP45C/ PTU300	X	X	X	X	X	X		X	X	X	X		X	X	X	X	
RM Young Wind at Gauge Height	X	X	X	X	X			X	X				X	X			
RM Young Wind at 10 m	X	X	X	X	X	X	X		X		X		X	X			
3D Wind																	X
Tipping bucket	X	X	X	X	X			X	X		X		X	X		X	
Pluvio 1 heated, no shield	X		X		X	X		X	X								
Pluvio 1 unheated with single Tretyakov shield		X		X									X	X			
Acoustic depth sensor	X	X	X	X	X			X	X				X	X		X	
FD12P	X					X			X		X					X	
Belfort									X								
PWD22			X														
Parsivel	X								X			X				X	
Poss	X		X			X			X			X		X		X	
Hot plate	X								X				X	X		X	
Micro-rain radar												X		X		X	
MP3000 radiometer												X					
915 MHz wind profiler													X				
Ceilometer			X									X		X		X	
LCR														X			

* Note that this is only a partial description of the RND site (Gultepe *et al.*, 2012)

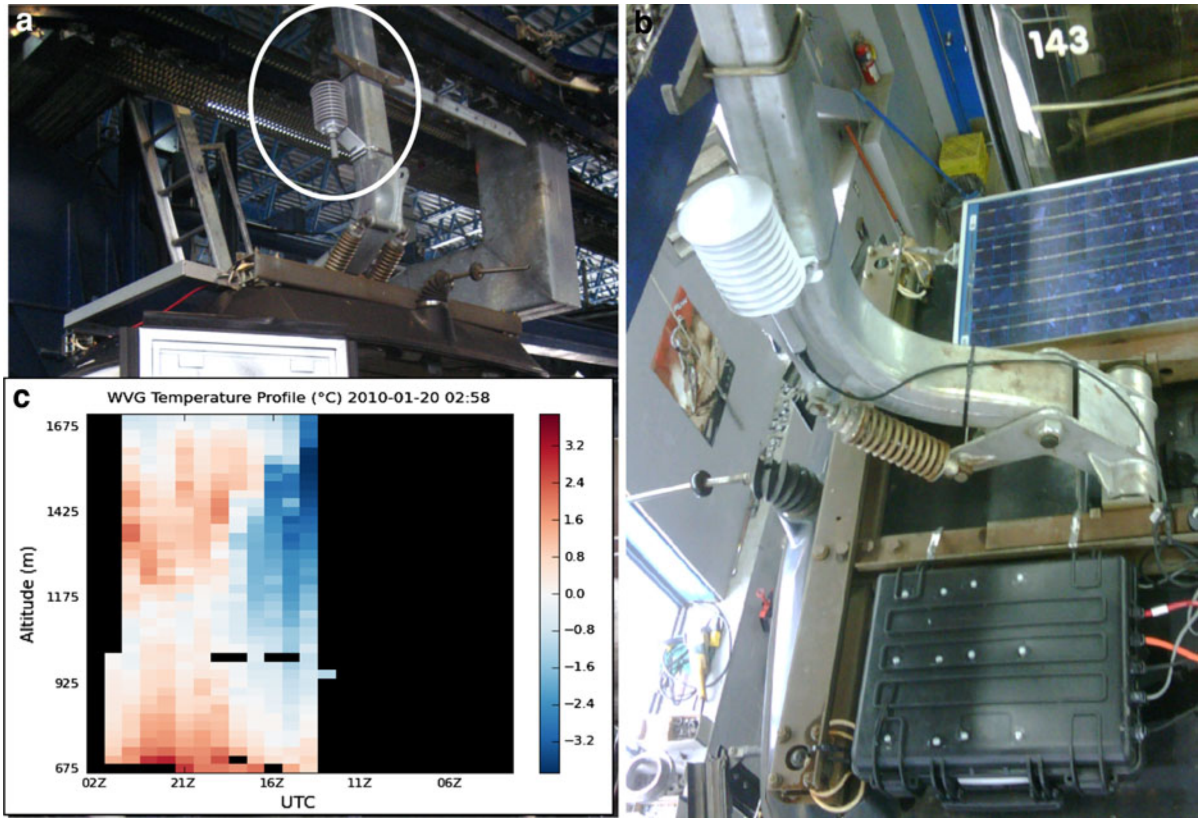

Figure 11

An photo of the GOMDAR sensor mounted on top of a Gondola and an example of the detailed sounding showing a inversion at the 1,100 m level that complemented the in situ OAN sensors. The Whistler Village Gondola (WVG) provided 10 s data to provide a detail sounding every 20 min from 560 to 1,865 m. The Peak to Peak (P2P provide a transect across Fitzsimmon’s creek every 15 min (not shown)

former three instruments were also installed at West Vancouver Autostation, at the base of Cypress Mountain. The MRR radars, the Whistler and NRP radars and vertical network of disdrometers (POSS and Parsivel) formed the core sensors for precipitation science research (JOE *et al.*, 2010; GULTEPE *et al.*, 2012). Ceilometers (CT25K) were located at WSK (Squamish), VOC (Whistler) and WGP (Pemberton).

A unique aspect of the data products from the MRR was the presentation of velocity-height diagram of Doppler spectral power. This is not a usual sort of forecaster user product, but with the vertical nature of the weather and the need to accurately identify and nowcast the freezing level, the dramatic shift in fall velocities from snow (less than ~2 m/s) to rain (greater than ~2 m/s) was intuitive for interpretation (Fig. 13).

The standard retrieval algorithm for the MPR was a neural network that required statistical training with radiosondes and accurate calibration of the instrument using liquid-nitrogen–cooled sources. Quillayute radiosonde data were initially used, and later Prince George data were employed, since they provided better comparisons with the Whistler soundings made in 2009 (personal communication, Ware and Campos). There were insufficient soundings from Whistler to perform the neural network training. CIMINI *et al.* (2011) developed a new retrieval 1D-VAR technique using LAPS analysis (ALBERS *et al.*, 1996) to improve the retrieval accuracy. Adapting it to the Olympic data sets was not possible due to resource and schedule constraints. In precipitation conditions, the top of the MPR radome became obstructed with rain or snow. An off-zenith (15°) scan was employed to effectively avoid the blockage (personal communication, Campos).

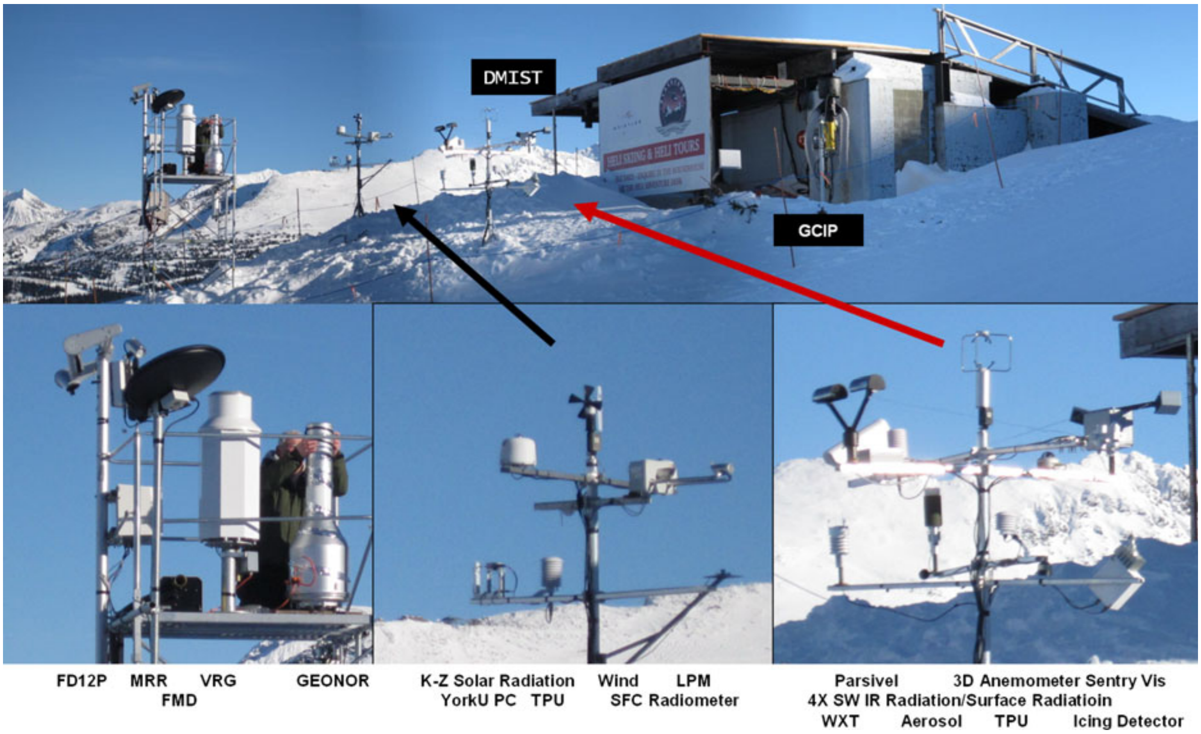

Figure 12
A photo of the instruments used for measuring visibility, precipitation, radiation, wind and other meteorological parameters during the SNOW-V10 project at the RND site located at the helipad (1,865 m AGL) near the Roundhouse gondola terminus. The measurements at this site were made in harsh winter weather conditions (see Gultepe *et al.*, 2012)

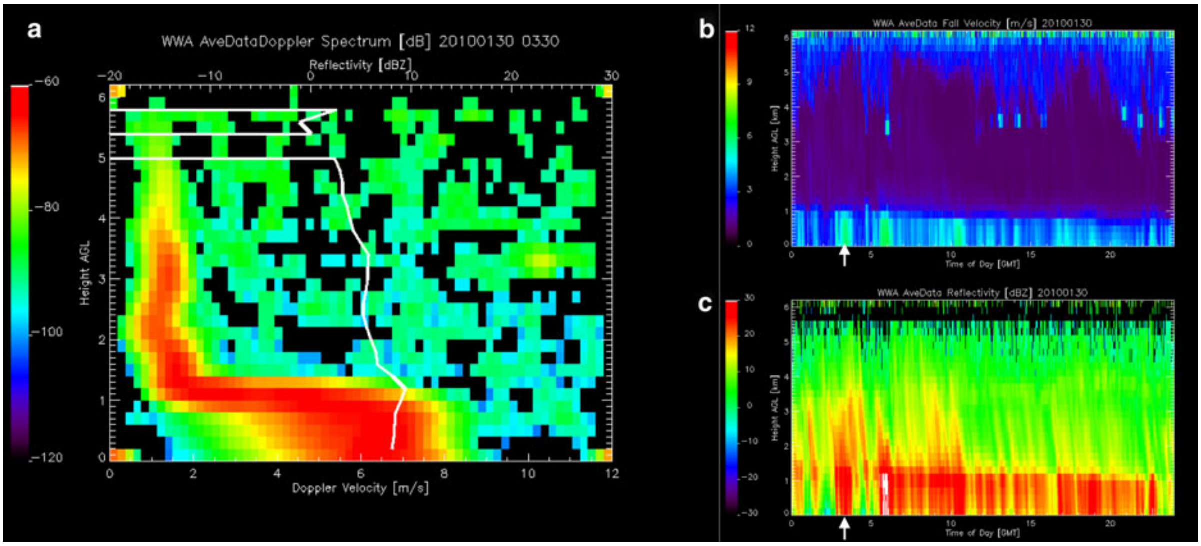

Figure 13
An example of **a** an innovative Doppler velocity-height diagram of the Doppler spectrum for 0330UTC. Figures **b** and **c** show the daily time-height diagram of reflectivity and vertical radial velocity, respectively. In **a**, the shift in particle fall velocity provided the forecaster with an indication of the melting level which was a critical high-impact weather element to monitor

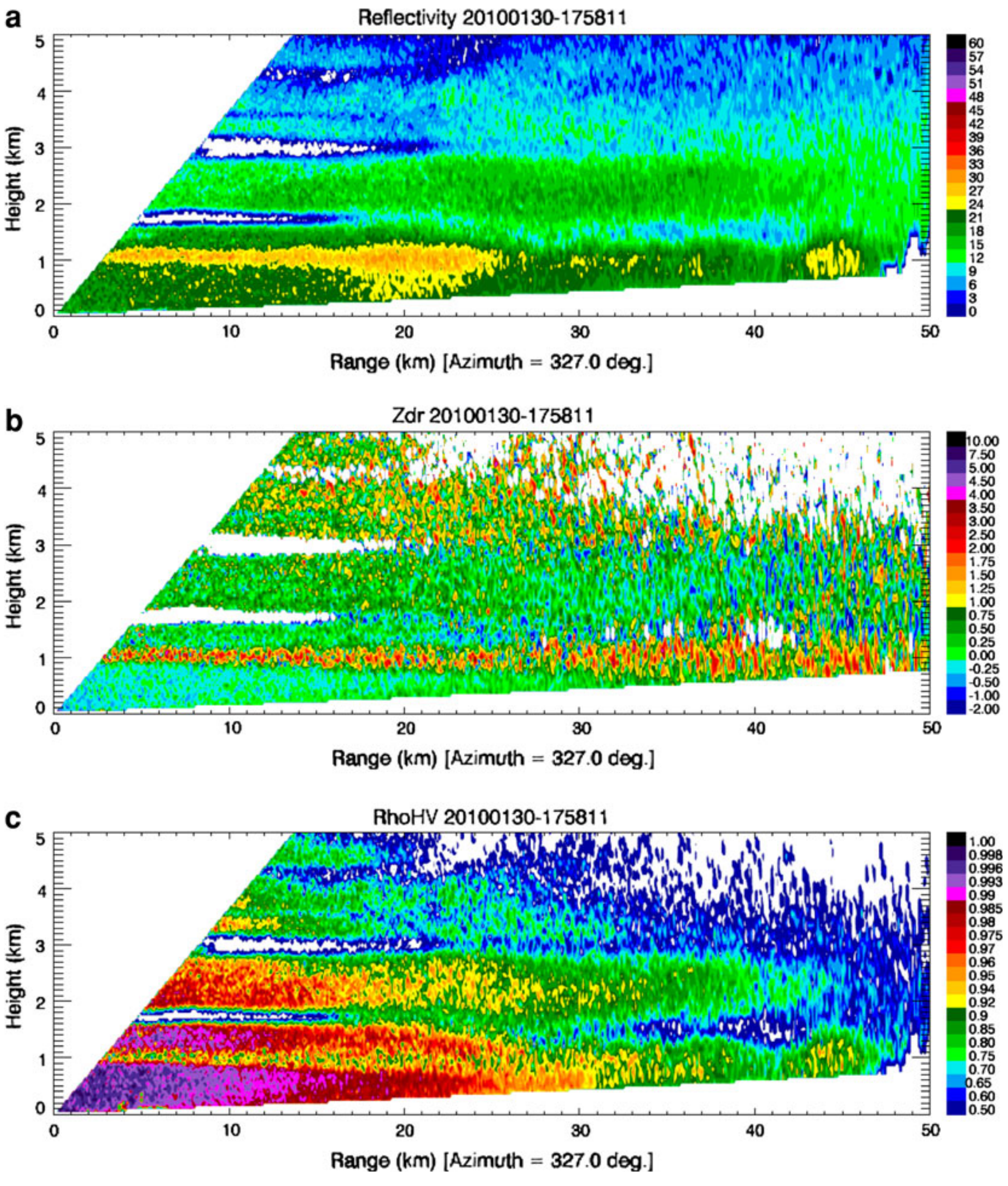

Figure 14

An example of the dual-polarization data from the NOAA X-POL radar. This shows the **a** reflectivity (Z), **b** differential reflectivity (ZDR) and **c** correlation (ρhv) This example illustrates very nicely a common observation of layering made in winter complex terrain. In **a**, the bright band can be observed in reflectivity but also Zdr and in ρhv at the 1 km level. Layering can also be observed above. There are definitive layers of no radar signal indicating absence of scatters/precipitation (see also Fig. 17). Note that due to narrowness and the layering and beam smoothing, the precipitation-free layers are not evident at longer ranges (>15 km). This provided enhanced low-level coverage over Vancouver, better understanding of the precipitation processes, and capability to monitor the rain–snow boundaries at Cypress Mountain

5.8. The NO-XP Radar

The National Oceanic and Atmospheric Administration's (NOAA) National Severe Storms Laboratory (NSSL) deployed a new X-band Doppler dual-polarization radar (NO-XP). The radar was located at Birch Bay State Park, WA, USA and had an excellent view of Vancouver and Cypress Mountain. This provided additional low-level coverage in the Vancouver area, and the dual-polarization capability provided the potential for rain-snow boundary detection capability, a critical nowcast variable. Figure 14 shows an example of the dual-polarization data from the radar. It is described in greater detail in Schurr *et al.* (2012).

6. Discussion

Current operational standards (including network design) are designed for synoptic scale forecasting (e.g., hourly data) and do not take into consideration the short temporal scales of nowcasting requirements (minutely). This affects the response time and sensitivity requirements for the measurements. The current synoptic network also does not take into consideration the large gradients in the various weather parameters dictated by complex terrain (WMO 2010, 2011). As precipitation is the highest societal–economic impact variable, nowcasting has focused on the high spatial and temporal resolution capability weather radar as the prime observation tool. Other weather variables such as visibility, wind and precipitation type have received much less attention. Hence, significant efforts using innovative and emerging technologies were needed to even begin to attempt to meet the requirements of winter complex terrain nowcasting. In many cases, standards or references are not available for measurements for the scales under consideration. For example, the classic rain gauge radar pointarea comparison suffers from a lack of an appropriate comparison methodology (Villarini *et al.*, 2010). Sheppard and Joe (2000) describe how a comparison algorithm using automated measurements could be formulated to mimic the rules governing a human report of precipitation type.

Many of the advanced instruments used a combination of the sensors or parameters to report multiple measurements. For example, the FD12P uses forward scattering to determine the occurrence and infer the intensity of precipitation. The POSS derives accurate rain rate via a drop size distribution retrieved from the Doppler spectrum, but derives snowfall rate via an empirical power-snowfall rate relationship. Once precipitation rate is determined, some systems (FD12P, Parsivel) report visibility.

Table 8 summarizes the list of instruments and their location that were deployed in the OAN and V10-SCIENCE sites. The design of the monitoring can be appreciated by a traceability analysis with the science objectives and the measurements. Most of the focus of the science was on the weather at Whistler Mountain because of the accessibility of the sites and the cooperation of Whistler-Blackcomb Mountain resort. Weather had a significant impact at Cypress Mountain, but access to sites was limited to the Olympic year. In this section, we provide examples of the integrated view of the observations to illustrate the holistic utility of the network design.

6.1. The Solid Precipitation Intensity and Type Network

6.1.1 In Situ

It was anticipated that the snow would vary considerably with altitude, and therefore location, along the mountain slope. In the Whistler and Winter Park (official name of the Callaghan Valley venue) venues, the Whistler radar and the vertically pointing MRR at TFT provided the remote-sensing capability for precipitation. Catchment gauges and the advanced precipitations sensors (POSS, Hot Plate, FD12P, Parsivel and RND instruments) formed the suite of in situ instruments installed along the slope of Whistler mountain (VOC, TFT, VOB, VOL, VOA, RND) Post-event snow density measurements were made at VOA and VOC. For limited-observations periods, snow microphotography was conducted at the RND site (Thériault *et al.* 2012a, b). There was a single catchment precipitation gauge at Winter Park. For precipitation, a catchment gauge, the MRR, POSS and LCR sensors were installed at the base of Cypress Mountain at the West Vancouver Autostation (WWA) site, and a POSS was installed at VOG (at the 800 m ASL level). A catchment gauge was installed at VOE but it was located in a non-representative site between Strachan and Black Mountains. A POSS was deployed at the Squamish site that can be used to calibrate the wind profiler for precipitation retrievals.

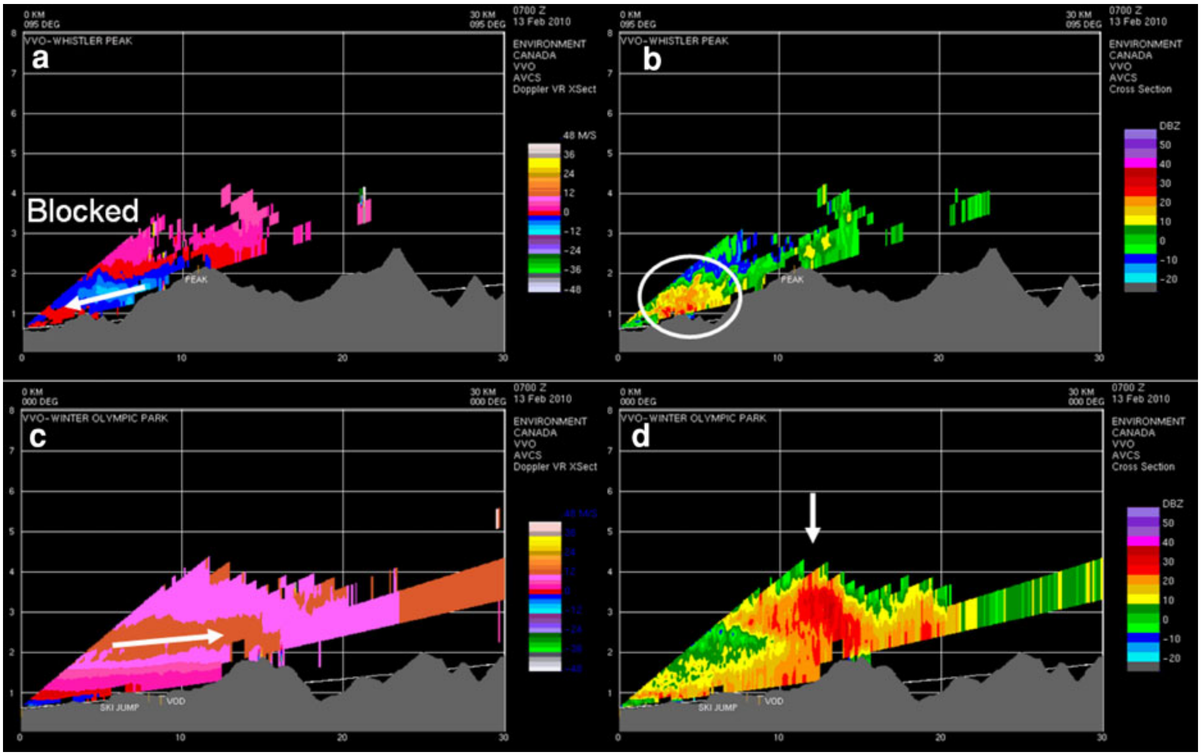

Figure 15

Reflectivity and radial velocity pseudo-RHI's showing the relationship between blocked (there is a layer where the flow towards the radar) and unblocked flow (all the velocities are away from the radar) and the precipitation patterns. In the former case, the precipitation falls along the slope of the mountain, and in the latter case the precipitation is on the mountain crest

6.1.2 *Whistler Radar and Doppler RHI's*

The decision for the valley radar site (Whistler Radar or VVO) was a very good choice, as it had a good view of the various venues. Figure 15 shows several RHI images that illustrate several of the key characteristics of the weather related to the formation of the precipitation on the slope or at the crest of the mountain that could be interpreted using the results of MEDINA *et al.* (2005) and ROTUNNO and HOUZE (2007). They described the dependence of the flow field and the precipitation patterns on the Froude number. With relatively strong radial velocities away from the radar (higher Froude number) and towards and over the mountain, the most intense precipitation was located on the crest. With lower speed flows (lower Froude number) or the presence of radial velocities towards the radar, the flow was blocked, resulting in precipitation along the slope of the mountain. THÉRIAULT *et al.* (2012a, b) discuss possible diabatic origins and Mo *et al.* (2012) discuss dynamic origins of the flow.

6.2. *Vertical Profiles of Reflectivity*

Virga is a prevalent feature of winter weather. Figure 16a shows a probability distribution function (PDF) of the reflectivity's from the 20° elevation scan for a particular moment as a function of reflectivity and height. It shows several breaks in the precipitation and indicates that, in the vertical, there are several fine scale layers of growth and decay of the precipitation. Figure 16b shows an analysis of hourly profiles for Dec 2009 to March 2010. The profiles are classified into five categories. The results show that virga occurs 30 % of the time.

6.2.1 *Micro-Rain Radar*

A novel display for forecasters was the Doppler power spectrum as a function of height and Doppler velocity, as shown in Fig. 13. The solid line shows the "raw" power (uncorrected for attenuation). Fall velocities of snow particles are generally less than

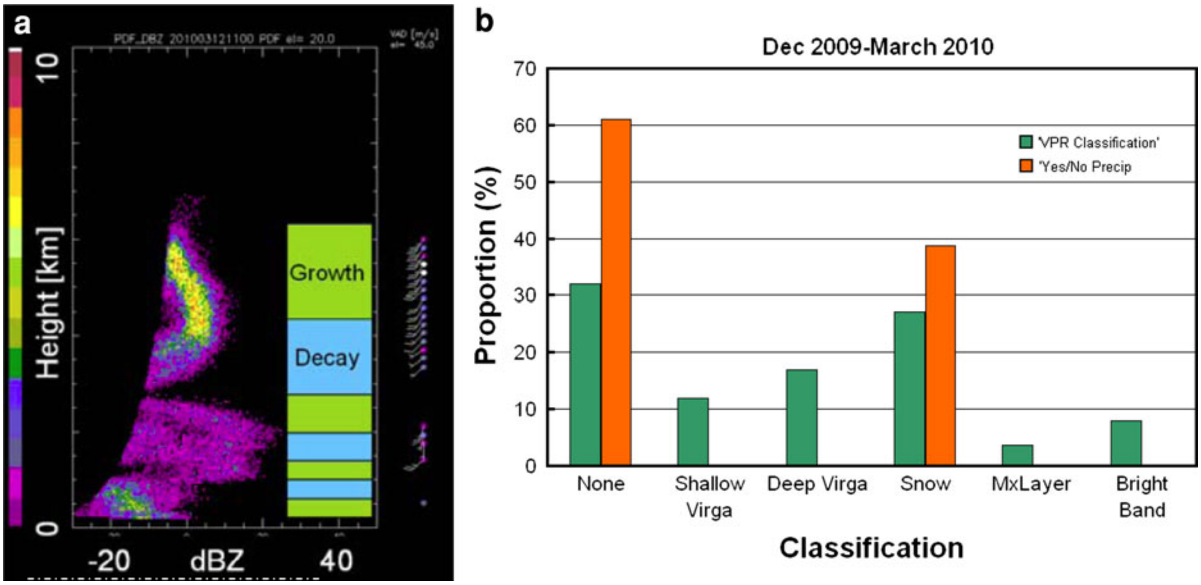

Figure 16

a Probability distribution of the reflectivities from the 20° elevation scan as a function of reflectivity and height. The data is representative of the area within a 20 km radius around the radar. On the *right* of the figure is an interpretation of the profile in terms of growth and decay of the precipitation. This documents the layering of atmosphere that was commonly observed. **b** An analysis of hourly profiles showed that virga occurred about 30 % of the time. The distinction between deep and shallow virga is whether the *top* of the profile was above or below 3 km (arbitrary) in an attempt to separate out virga due to synoptic versus local precipitation systems. Bright band refers to rain situations and multi-layer (labelled as mx layer) indicates layered situations (virga aloft) but precipitation reached the ground

2–3 m/s, whereas fall velocities of rain drops are generally higher than 3 m/s, though there is a strong dependence on particle size when they are small (see Rogers and Yau, 1996). The figure shows that Doppler velocities are generally around 2 m/s aloft (3–6 km AGL) but are around 4–6 m/s below. This is consistent with snow melting into rain. From this, the forecasters were able to monitor the height of the freezing/melting level without a temperature sounding. Note that at K band (24 GHz), the bright band commonly observed at lower frequencies is not as evident. It is beyond the scope of this contribution but in situ particle sizing instruments along the slope of Whistler Mountain (POSS, Parsivel and others) could be related to the Doppler spectra from the MRR (see Yuter *et al.* (2006), Rogers *et al.*, 1993 and Tokay *et al.*, 2009, for discussion).

Figure 9b shows a normalized SNR plot from the vertical beam of the wind profiler at Squamish. The full potential of the precipitation analysis using the POSS for calibration is yet to be realized.

6.2.2 *Photography*

Special snow microphotography was conducted in the pre-Olympic and inter-Games period. Snow particles were collected on velvet and were photographed (Thériault *et al.* 2012a, b). Gultepe described imagery made with imaging probes called the Ground Cloud Imaging Probe (GCIP) and the Snow Video Imager (SVI, Newman *et al.*, 2009a, b).

6.2.3 *Snow Density*

Acoustic sensors were deployed to measure snow depth height. Theoretically, when combined with precipitation intensity, the snow density of freshly fallen snow could be computed. Given the uncertainty in both measurements, the errors are significant. Independent manual snow density measurements were made to validate the assumptions of the retrievals. Snow density measurements were made using a calibrated "snow tube" by Snowmetrics. Snow boards were located at different sites and

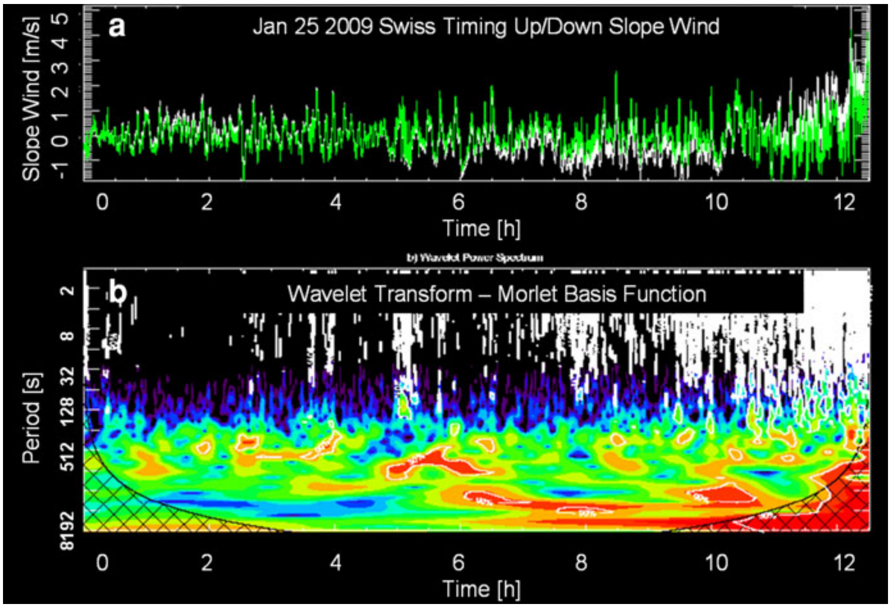

Figure 17

Example of the time series and wavelet analysis of the upslope–downslope wind component measure from one of the Swiss Timing sensors located along the outrun of the ski jump. The wavelet analysis shows the strength of the wind fluctuations at ∼512 s or ∼8.5 min time scale between 5 and 6 PST. The two traces in **a** are a quality check on the wavelet transform. The *green line* is a wavelet reconstruction of the original data. The hatched areas in **b** are areas where edge effects are significant. White contours indicate significant power above noise

altitudes at the VOA, VOL, RND, VOB and VOC stations. These were manual measurements that require about 5 cm of accumulated snow before a reliable observation could be made. The procedure was to make these measurements after an event, regardless of accumulation amount, and so they were representative of the storm total snowfall density.

6.3. *The Visibility Network*

Current operational standards for visibility are manual measurements. There is a procedure for human observers to report prevailing visibility where several directions are surveyed before an estimate is provided (Viezee and Evans, 1983). As lowering cloud can impact the visibility, a visibility network was created using ceilometers, in situ sensors and web cams.

At Whistler Mountain, automated measurements using the FD12P (VOT, VOL, VOA and RND) and a Belfort Visibility sensor (VOL) were deployed at several sites along the slope of Whistler Mountain. This was combined with cloud base reports by a network of ceilometers (TFT, VOC, WSK and WGP). Note that WWA also had a ceilometer.

Webcam images were made and archived every 10 min to provide a qualitative information source to interpret the data from and to interpolate between the in situ weather sites. See Mo *et al.* (2012) for an example of the quantitative analysis of a webcam network. Visibility was one of the critical weather elements and also discussed extensively by Isaac *et al.* (2012b).

6.4. *The Wind Network*

The Doppler radar, the wind profiler, the in situ sensors formed the main measurement suite for wind studies. See Fig. 15 for an example using the Doppler radar. Mo *et al.* (2012) show how the high-resolution (1 and 2.5 km) models combined with the Doppler radial winds provided considerable guidance and insight into the wind flow but also mid-mountain cloud formation. In situ wind was measured using standard anemometers and recorded at 1 min sampling interval. A significant issue was the definition of wind gusts. The definition for synoptic data (hourly data) is the peak wind in the last hour (ref: CIMO guide, chapter 5). For minutely data, a

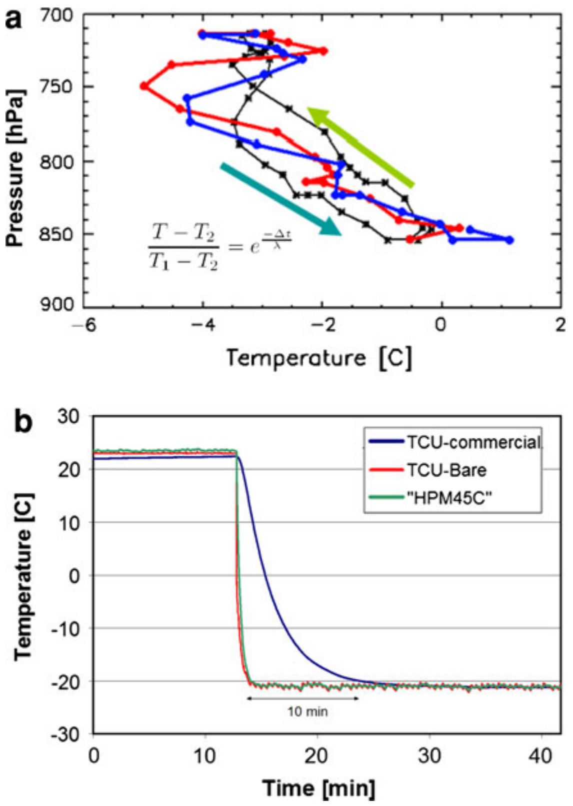

Figure 18

a Temperature response of three different sensors (1 s data) showing the very slow response of a standard operational sensors (HMP45C by Vaisala) compared to a commercial thermocouple and copper-constantan twisted wires. The sensors were cooled in a cold chamber to −20 °C from a room temperature of 20 °C. Both the HPM45C and commercial thermocouple were installed on the GOMDAR due to operational robustness considerations. **b** While the temperature differences in the measurements are less than 1 °C in this example, the location of the inversion is misplaced upwards on the ascent and downwards on the descent legs

similar definition was used. However, it was not clear how to compare the measured gust measurements from the 1 min data (or other time sampling) to the model gusts due to temporal and spatial differences.

In addition, the 1 s data from Swiss Timing provided considerable insight into sub-grid scale turbulence or small-scale wind flows at the ski jump. Wind sensors were located at three locations along the outrun of the jump. They were only available during Olympic events and 'test' events in the previous years. The data were provided to Environment Canada to aid with scientific studies and was not normally available. Figure 17 shows an example of the slope-wise component of the wind. A wavelet analysis using a Morlet wavelet shows the temporal variation of the frequency content (Torrence and Compo, 1998). In this example, a high-frequency component can be identified in the 13–14 UTC (marked as 5–6 PST). This component was created in the transition from drainage down slope flow to an upslope flow due to solar heating (Teakles *et al.*, 2012).

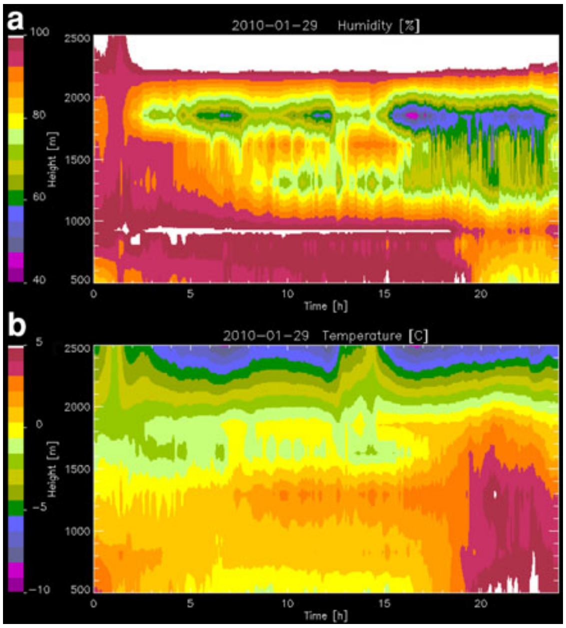

Figure 19

A time–height diagram of **a** humidity and **b** temperature from the in situ OAN sensors located along the slope of Whistler Mountain. Similar to Figs. 13 and 16, this shows the layering of the atmosphere in this environment. This was a common observations. Note that in **a**, a low moisture layer is observed at the 1,900 m level but is sandwiched between two moist layers at 900 m and above 2,100 m

Note that 3D 8 Hz anemometer measurements were made at RND and at VOW (coach's station at the take-off point of the ski jump).

6.5. *Temperature and Humidity Network*

The basic weather elements of temperature, humidity and pressure were made at the in situ sites and by the radiosondes. While the scientific objectives did not focus on temperature and humidity, these measurements are fundamental to many of the studies. Figure 19 shows a temperature and humidity

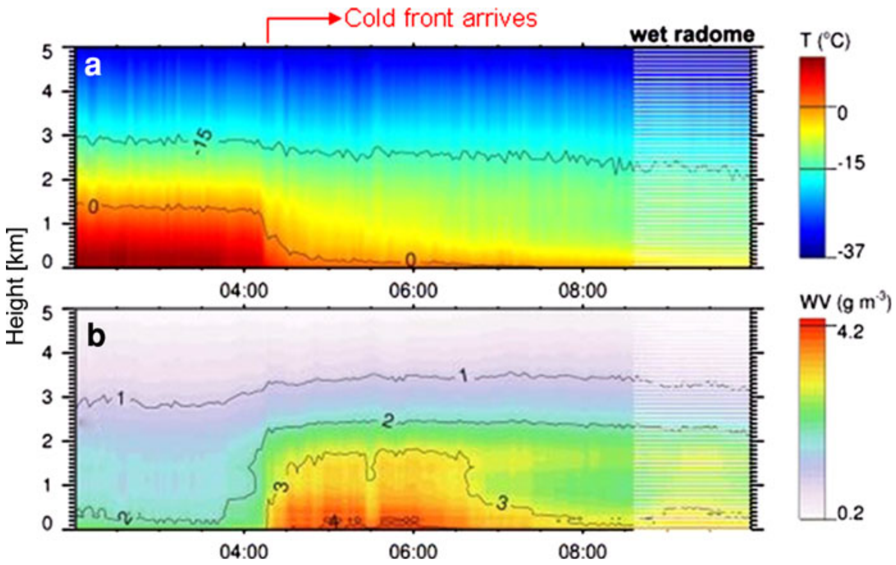

Figure 20
An example of the microwave profiling radiometer showing the arrival of a cold front with the temperature decrease and increase in water vapour. Note that at end of the time sequence precipitation was on the radome but a 15° off-zenith pointing angle was used to void the blockage and attenuation problem

time–height diagram created from the sensors along the slope of Whistler Mountain. The example presented shows the ubiquitous atmospheric layering (see also Figs. 11, 13, 14, 15, 16 and 18). In addition, the GOMDAR provided additional detail to the OAN in situ sites along Whistler Mountain and the RASS at Squamish provided virtual temperature profiles. The microwave profiling radar provided temperature, humidity and integrated liquid water retrievals.

Even for temperature, nowcasting requirements can not be met by current operational sensors. Figure 18a shows the step response of a standard temperature sensor (Vaisala HMP45C) plus that of two thermocouples (a twisted pair and a commercial version). The time to reach 90 % of the temperature difference was estimated to be about 8 min for the HMP45C and about 60 s for the thermocouples. The impact of the slow response is shown in the companion figure showing the measured and retrieved temperature (assuming a lagged response) for the temperature sensor positioned on the Gondola (GOMDAR). A temperature inversion was located at approximately the 760 hPa level. The location of the inversion is displaced upwards on the ascent and downwards on the descent in the measured data, but is much closer in height in the retrieved results (Fig. 18b). Some of this difference is due to the temporal change in height of the inversion (not shown). The humidity sensor also suffers from a lagged response as it is often saturated when the surface sensors do not indicate this. Straka *et al.* (1996) also noted this effect. Mo *et al.* (2012) shows additional example of the use of the temperature and humidity network at Whistler Mountain for the diagnosis of a mid-mountain cloud.

The radiometers located at the bottom of Whistler Mountain also contributed to the temperature and humidity network. Figure 20 shows a dramatic example of a cold frontal passage where the temperature drops dramatically (Fig. 20a) and where the moisture increases a low level after its passage (Fig. 20b).

7. *Summary*

The observation and monitoring network that support the Vancouver 2010 Winter Olympics and Paralympics was comprehensively described. The weather element observation requirements included precipitation intensity and type, temperature, wind speed, wind direction, wind gust and visibility. To understand the processes and to validate the innovations in the numerical weather prediction models (microphysical and precipitation parameterizations), additional ancillary measurements were needed and included snow particle type, snow depth and amount, snowfall density, snow microphotography, particle size distributions and radiation. Snowfall intensity and type were measured by a variety of highly modified traditional technologies (specially heated catchment gauge) and emerging technologies that exploit heat and mass transfer, scattering, particle and aerosol extinction and backscatter properties of the precipitation particles. Radiosonde and remote sensing systems providing a vertical profiling capability using vertically pointing radars, scanning Doppler and dual-polarization radars, wind profilers and radiometers.

Scale analysis of the weather in complex terrain indicates a temporal length scale of about 60–90 min. The spatial scale of the weather is highly influenced by both the horizontal and vertical scales of the topography. This is of the order of kilometers. Hence, high spatial resolution networks of observation were needed. For pragmatic reasons, they were limited and highly localized. Given the high temporal changes in the weather, high-resolution temporal measurements of the order of a minute were also required. Webcams were extensively used and provided visual confirmation and qualitative interpolation of the observations. Even with six sites at the Alpine venue, it was not sufficient to capture the fine vertical structure of the weather, and webcams provided an important visual but qualitative spatial interpolator of the in situ visibility measurements. This also lead to the development and installation of a weather sensor on the gondola (GOMDAR).

A limiting factor to the deployment of the observation systems and networks was the evolving infrastructure. For example, new sites and roads were created in the Callaghan Valley and the bottom of the Alpine events and were not finished and accessible until the Olympic year. In the latter case, spectator stands, tarmac roads, and shelters for telecommunications were installed just before the Olympics and restored to the original condition afterwards. Limited space in complex terrain and rising snow levels also required innovations in locating the instruments on elevated steel platforms instead of at ground level.

An overarching goal was to create a legacy data set that could support operations but also science. While considerable progress was made and novel products were created for the V10 games, there is still considerable analysis to be done to fully exploit the data set, and so this contribution is necessarily incomplete. The reader is directed to the other contributions in the SNOW-V10 special volume. The nowcast and spatial requirements in complex terrain are much higher than that in summer and for flat terrain. The high spatial resolution requirement was related to the strong gradients in temperature, wind and humidity with altitude which translates into horizontal gradients. A key observation was the identification of the freezing level which determined the critical boundary between rain and snow. The observation requirements continued to evolve throughout the project as end-users came to trust the data and it interpretation for end-user decision making. For example, the installation of spectator stands at the Cypress Mountain venue was completed just before start of the Olympic games. Strong winds were experienced at the top of the stands. A sensor was deployed on opening day to monitor high wind conditions for spectator safety purposes.

All of the outdoor venues had different weather challenges. At the ski jump, the main forecast issue was wind and turbulence. On windy days, the nowcast challenge was on the strength of the cross and slope winds. On sunny calm days, the transition from nighttime drainage flows to upslope thermally forced flows took about 2 h and was quasi-organized with fluctuations on a 7.5 min cycle. The nowcast challenge was the prediction of quiescent periods (90 min) of calm winds (variance of less than 1 m/s). At the alpine events, the main issue was precipitation and visibility. Mo *et al.* (2012) showed a mid-mountain cloud has a very limited spatial extent. This cloud and other low-visibility events resulted in significant schedule changes and delays. This even resulted in the inversion of the race schedule during the paralympics (speed races were run last instead of first). At the freestyle venue, visibility and precipitation type were the main problems. It was right at the coast and was considerably warmer than the Alpine and Nordic venues. So, the instrumentation suite and design was tailored to each venue.

There significant gaps in the instrumentation. Precipitation intensity, amount and type are foremost. Operating catchment snow gauges in this environment required specialized heating of the reservoir. This gap is exacerbated by the requirement for high temporal resolutions. Use of emerging technology, such as hotplates, optical scattering, microwave scatter (radar) is still considered unproven. Snow on the ground is subject to a wind drift and snow ablation processes. Snowfall density require manual measurements and are limited in resolution (at least 5 cm of snow must be accumulated). Particle size distributions are derived from one (Parsivel) or two-dimensional views (Ground Cloud Imaging Probe or Snow Video Image) or from snow microphotography. The highly irregular particles shapes defy simple analysis. Current operational visibility measurements are manually made and are reported from prevailing visibilities in various horizontal directions while emerging technology sample a small volume. This contribution showed that temperature measurements suffer from slow response of the sensor. GULTEPE *et al.* (2012) showed that at around freezing, there were significant discrepancies in temperature, humidity and precipitation amounts. Doppler radar showed complex flows and multiple layering of the atmosphere. The normal reporting of significant and mandatory levels of the radiosonde data, combined with sensor lags, was not sufficient to identify these layers. With decreasing temporal resolution of the data (from hourly to minutely), even the definition and measurement of wind gust was challenge.

Given the weather and the complex terrain, the siting requirements are very high. Vertical and spatial resolution of data of the order of 10s or 100s of meters is highly desirable, and this requires a combination of remote and in situ sensing to satisfy. With telegenic constraints, ever an ever-changing infrastructure environment and user requirements, it is very difficult to locate sensors sufficiently early in optimal locations relative to the venues.

The success of the monitoring network is also dependent on the products, their visualization, their quality, their interpretation and their use. Some unique or innovative products were presented here. For example, a Doppler velocity–height display of power spectrum from the micro-rain radar was popular amongst SNOW-V10 participants and some forecasters, since it clearly showed the transition from snow to rain. Meteogram type displays were required to visualize the high temporal measurements from a single site. The innovation in the products described more fully in other papers and beyond the scope of this paper.

The legacy of the observation network will be better understanding of the weather and their processes. The data is needed to validate the forecast and nowcast systems and this will ultimately lead to operational improvements. The forecasts and nowcasts for winter Olympics may be very specialized and push the envelope of currently available weather services. However, this contribution provides a glimpse into observation and monitoring requirements to support the envisioned services that could be provided by National or commercial weather services of the future.

Acknowledgments

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