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Science of Nowcasting Olympic Weather for Vancouver 2010 (SNOW-V10): a World Weather Research Programme Project

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Abstract—A World Weather Research Programme (WWRP) project entitled the Science of Nowcasting Olympic Weather for Vancouver 2010 (SNOW-V10) was developed to be associated with the Vancouver 2010 Olympic and Paralympic Winter Games conducted between 12 February and 21 March 2010. The SNOW-V10 international team augmented the instrumentation associated with the Winter Games and several new numerical weather forecasting and nowcasting models were added. Both the additional observational and model data were available to the forecasters in real time. This was an excellent opportunity to demonstrate existing capability in nowcasting and to develop better techniques for short term (0–6 h) nowcasts of winter weather in complex terrain. Better techniques to forecast visibility, low cloud, wind gusts, precipitation rate and type were evaluated. The weather during the games was exceptionally variable with many periods of low visibility, low ceilings and precipitation in the form of both snow and rain. The data collected should improve our understanding of many physical phenomena such as the diabatic effects due to melting snow, wind flow around and over terrain, diurnal flow reversal in valleys associated with daytime heating, and precipitation reductions and increases due to local terrain. Many studies related to these phenomena are described in the Special Issue on SNOW-V10 for which this paper was written. Numerical weather prediction and nowcast models have been evaluated against the unique observational data set now available. It is anticipated that the data set and the knowledge learned as a result of SNOW-V10 will become a resource for other World Meteorological Organization member states who are interested in improving forecasts of winter weather.

Key words: Nowcast, olympic, snow, mountain, weather, forecast.

1. Introduction

The Vancouver 2010 Olympic and Paralympic Winter Games represented an excellent opportunity for international collaboration towards improving our ability to provide short term weather forecasts or nowcasts of high impact winter weather in complex terrain. The Olympic events were held 12–28 February 2010 with the Paralympics being conducted 12–21 March 2010. The Meteorological Service of Canada of Environment Canada had the mandate and contractual obligation to provide weather support and services for the safety and security of the public and the effective and efficient operation of the games. An overall description of the Canadian activities was described by Joe *et al.*, (2010).

The World Weather Research Programme (WWRP) of the World Meteorological Organization (WMO) previously endorsed international projects associated with the Sydney 2000 (Keenan *et al.*, 2003) and Beijing 2008 (Su *et al.*, 2007) summer Olympic games. WWRP involvement in Vancouver

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2010 was the first collaborative project focused on nowcasts of high impact winter weather. A workshop was held in Whistler, British Columbia, during 26–28 March 2008 and a project was initiated entitled the Science of Nowcasting Olympic Weather for Vancouver 2010 or SNOW-V10. Subsequently, the project was approved by the WWRP steering committee as an official project. This paper provides an overview summary of SNOW-V10, including its objectives, some of the instrumentation installed for the project, the numerical weather prediction (NWP) and nowcast models used during the project, the participants, and examples of data analysis. It sets the scene for more detailed descriptions of SNOW-V10 in this Special Issue of Pure and Applied Geophysics.

There have been several recent projects focused on weather in mountainous regions including the Mesoscale Alpine Experiment (MAP) (Benoit *et al.*, 2002), and its successor, MAP D-phase (Rotach *et al.*, 2009), both conducted in the Alps as well as the Improvement of Microphysical Parameterization through Observational Verification Experiment (IMPROVE) project conducted in the Cascades (Stoelinga *et al.*, 2003). However, SNOW-V10 was uniquely focused on nowcasting winter weather in complex terrain.

The World Weather Research Program generally has two types of projects: Research Development Projects (RDP) and Forecast Demonstration Projects (FDP). The Sydney 2000 and Beijing 2008 summer Olympic projects were mainly FDPs, or demonstrations of existing technology to produce nowcasts of summer high impact weather affecting high profile public events. SNOW-V10 involves research to understand high impact winter weather processes in complex terrain, as well as efforts to produce nowcasts in real time. There are only a few groups around the world doing work on winter weather that have developed prototype nowcast systems. With the notable exception of the Integrated Nowcasting through Comprehensive Analysis (INCA) system validated in the Alps (Haiden *et al.*, 2011), few of these systems have been tested and compared in complex terrain. Because the technology has not matured enough to provide a demonstration of existing techniques in the same manner as was done for Sydney 2000 and Beijing 2008, it was decided to make SNOW-V10 an RDP with FDP components.

2. *Objectives of SNOW-V10*

The main focus of SNOW-V10 is to improve our ability to produce short term forecasts or nowcasts (within 6 h) of high impact winter weather over complex terrain using efforts associated with the Vancouver 2010 Olympic and Paralympic Winter Games. The enhanced observing network developed for the Olympics was augmented by some special research equipment. Similarly, research NWP models developed for this area were evaluated and further developed. The forecasts issued during the Olympics were evaluated for their accuracy in real time, and their usefulness to users. As part of the project, articles have been written (e.g., this Special Issue) and further analysis is ongoing describing the activities and results, and training workshops will be conducted to transfer relevant knowledge to appropriate national meteorological services.

The specific objectives of SNOW-V10 are as follows:

- To improve our understanding and ability to nowcast low cloud and visibility;
- To improve our understanding and ability to nowcast precipitation amount and type;
- To improve nowcasts of wind speed, gusts and direction;
- To develop improved nowcast production systems for winter applications;
- To assess and evaluate value of nowcasts to end users;
- To increase the capacity of WMO member states to provide nowcasts (training component).

Participants were involved from Canada, the United States, Australia, China, Austria, Finland, Germany, and Switzerland. They included scientists and students from government organizations, the private sector, and universities.

3. *Instrumentation and Monitoring*

During the 2010 winter Olympics, there were approximately 56 auto stations, 14 moveable tripod stations, and 22 web camera sites (see Joe *et al.*, 2012). In total, weather observations were received from over 100 sites. The main instrument sites used during the Olympics are listed in Table 1 and some overview maps are shown in Fig. 1. These sites typically had temperature, relative humidity, wind direction and speed, precipitation rate and snow height sensors. Some specialized instrumentation was located as follows:

- Whistler (VVO) scanning C-band Radar located at the junction of the Callaghan Valley Road, and the Whistler-Pemberton and Whistler-Squamish Valleys (see Fig. 1a).
- NOAA/OU X-Band Dual-Polarization Radar (NOX) located at Canada/U.S. Border south of Vancouver as shown in Fig. 1a (see Schuur *et al.*, 2012).
- Vertically pointing X-band Radars were located at TFL, RND and WWA.
- A 915 MHz boundary layer wind profiler located at Squamish Airport (XSK).
- A profiling microwave radiometer located at Timing Flats (TFL).
- A rawinsonde system located at Nesters (VOC).
- Ceilometers located at YVR, WWA, TFL, WSK, WGP and VOG.
- Recording visibility meters located at VOA, VOL, RND, VOT, VOG and YVR.
- Hot Plate Precipitation Sensors located at YVR, VOG, RND, VOA, VOL and TFL.
- Present weather sensors, either the Vaisala FD12P, Parsivel or POSS located at VOA, VOL, WWA, WSK, YVR, TFL/VOT, and RND.
- A 3D anemometer located at the ski jump (VOW).
- Temperature, relative humidity and GPS sensors were installed on the Whistler Village to Roundhouse Gondola, and the Whistler to Blackcomb gondola (see Fig. 1).
- The Roundhouse site, near the helipad, was instrumented with a significant list of equipment. (see Table 2 and Gultepe *et al.*, 2012) as an extension of the Fog Remote Sensing and Modeling Project (FRAM) (Gultepe *et al.*, 2009).
- Special surface sites measuring temperature and humidity were installed by the University of British Columbia up Whistler Mountain (not shown in Table 1).
- Snow density measurements were made at some selected sites, mainly VOA, VOL RND and VOC after significant snowstorms.
- Snow photographs were made continuously at RND as a special project during some intensive periods and then irregularly outside those periods.

4. *Weather Summary During Olympics and Paralympics*

This section gives a very brief summary of weather observed during the Olympics and Paralympics. The games were conducted during an El Niño period which began in mid 2009 and ended in approximately May 2010 (see Mo *et al.*, 2012b). During the January/February/March time frame, the Oceanic Niño Index was +1.5. Typically, an El Niño period would bring warmer and drier conditions to the area. Before the Olympics, because of the warm weather, snow cover at Cypress Mountain disappeared from the lower half of the course. Although there remained some snow over the upper half of the course, it was inadequate to cover the venue. Consequently, heroic efforts were required in the 2 weeks before the games and snow was brought in from elsewhere to prepare for the freestyle events. (see Doyle, 2012). However, there was no lack of snow for the venue locations at Whistler.

Figure 2 shows the temperature, visibility and precipitation time series for Cypress Bowl South (VOG, 903 m) and Whistler Mountain Mid Station (VOL, 1,320 m). The Cypress Bowl South location is at approximately the same height as the finish line of many of the events occurring at Cypress. Whistler Mountain Mid Station is above the finish line of the Alpine events at Timing Flats (805 m) and below the start of the men's downhill near Whistler Mountain High Level (1,640 m) as shown in Fig. 1b. A quick glance at the Fig. 2 shows that at these locations lower visibilities and precipitation occurred regularly. At Cypress during the Olympics (12–28 February) even the night time minimum temperature rarely went below 0 °C which caused significant problems in maintaining the snow cover. Only with a great deal of work transporting snow from other locations were the venue sites kept open (Doyle, 2012). Conditions got colder during the Paralympics (12–21 March) but this location was not used for the Paralympics.

Table 1

A list of the main Olympic measurement sites

Main Olympic measurement sites	Ident	Latitude	Longitude	Elevation (m)
Blackcomb Base Sliding Center Bottom	VON	50.106	−122.942	816.6
Blackcomb Base Sliding Center Top	VOI	50.102	−122.936	937
Blackcomb Mountain Base/Nesters	VOC	50.129	−122.955	651.5
Callaghan Valley	VOD	50.144	−123.109	884
Callaghan Valley Biathlon High Level	VOF	50.142	−123.119	882.7
Callaghan Valley Biathlon	VOY	50.147	−123.116	870
Callaghan Valley Cross Country High Level	VOK	50.143	−123.107	922
Callaghan Valley Low Level	VOV	50.140	−123.117	838
Callaghan Valley Ski Jump Bottom	VOX	50.137	−123.113	860
Callaghan Valley Ski Jump Top	VOW	50.138	−123.110	936
Cypress Bowl Event (Freestyle)	VOZ	49.392	−123.203	969.1
Cypress Bowl Grandstand	VWG	49.396	−123.206	968
Cypress Bowl North/Cypress	VOE	49.402	−123.208	953
Cypress Bowl Snowboard	VWB	49.389	−123.214	1,180.3
Cypress Bowl South	VOG	49.379	−123.194	903
Monitoring Operations Centre	VMO	49.182	−123.078	16
Mount Washington	VOJ	49.747	−125.287	1,473.5
North Cowichan	VOO	48.824	−123.719	60
Pemberton	WGP	50.303	−122.738	204.3
Pemberton Airport (Wind)	WPN	50.301	−122.739	203
Point Atkinson	WSB	49.33	−123.27	35
Port Mellon	VOM	49.51	−123.48	122.6
Powell River	VOP	49.834	−124.500	125
Qualicum	VOQ	49.340	−124.394	65
Sechelt	VOU	49.456	−123.718	86
Squamish Airport 1	WSK	49.783	−123.161	52.1
Squamish Airport 2-Wind Profiler	XSK	49.776	−123.157	52.1
Vancouver Airport	YVR	49.190	−123.192	2
Vancouver Harbour	WHC	49.295	−123.122	2.5
Vancouver Hillcrest	VWC	49.244	−123.106	83.9
West Vancouver	WWA	49.347	−123.193	168
Whistler Peak	PEK	50.059	−122.957	2,165
Whistler Roundhouse	RND	50.067	−122.945	1,856
Whistler Mountain High Level (Wind)	VOH	50.079	−122.951	1,690
Whistler Mountain High Level/Pig Alley	VOA	50.077	−122.948	1,640
Whistler Mountain Low Level/Creekside	VOB	50.088	−122.975	933
Whistler Mountain Mid-Station	VOL	50.085	−122.964	1,320
Whistler Mountain Timing Flats	VOT	50.091	−122.978	804.9
Whistler Timing Flats (SNOW-V10)	TFL	50.092	−122.982	776
NOAA X-Pol Radar	NOX	48.902	−122.773	168
Whistler Radar	VVO	50.0663	−123.110	557

Note there were two sites at Whistler Mountain Timing Flats (VOT and TFL) which were close together. See Joe *et al*. (2012) for a description of the main sites

At Whistler Mid Station, the temperature fluctuated above and below 0 °C which meant the forecasts of precipitation type were a considerable challenge.

Visibility often went below 100 m at both the Whistler and Cypress sites which caused the Olympic events some problems. Visibility reductions were due to the presence of fog or low cloud and precipitation. Figure 3 shows the cumulative distribution of visibility at Whistler Mountain Timing Flats (VOT), Whistler Mountain Mid Station (VOL), Whistler Mountain High Level (VOA), and Whistler Roundhouse (RND) as measured by a Vaisala FD12P instrument. More frequent lower visibilities were observed at VOL where the persistent mid-mountain cloud, locally known as Harvey's cloud, was reported to exist (Mo *et al*., 2012a). These low visibilities at

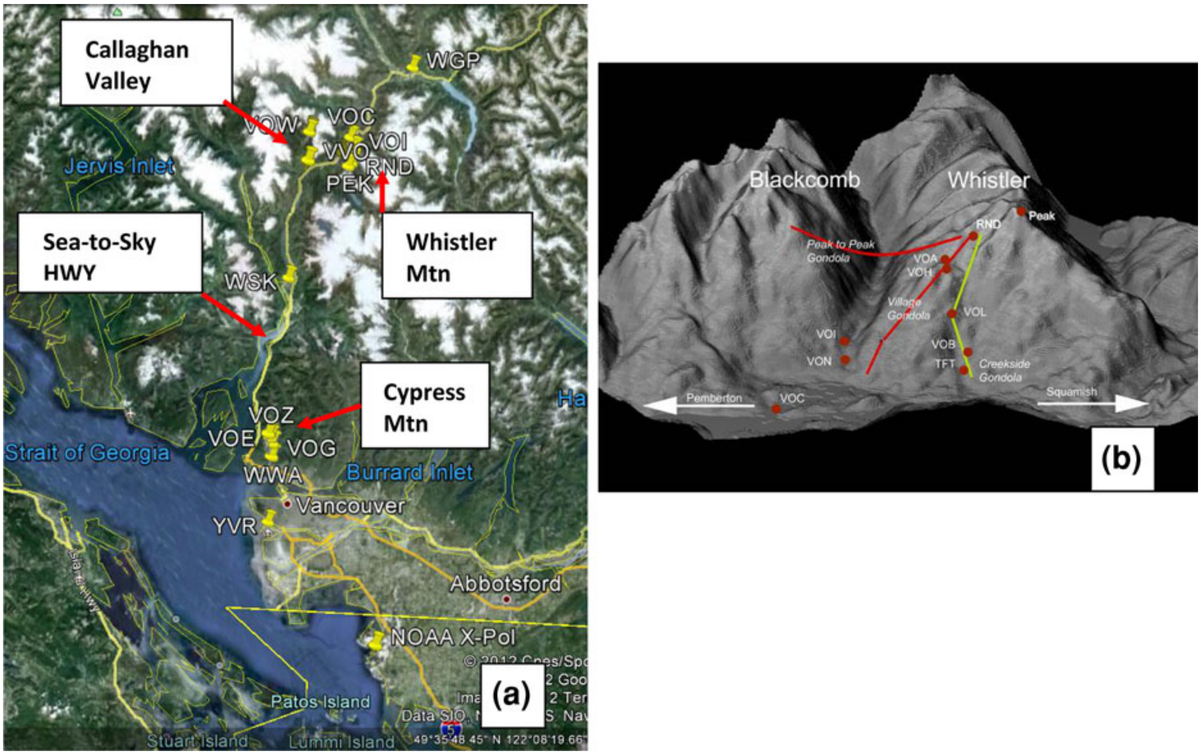


Figure 1
An overview "Google" map (**a**) of the sites for the outdoor venues for the Vancouver 2010 Olympic and Paralympic Winter Games. The straight line distance from Vancouver Airport (YVR) to Roundhouse (RND) on Whistler Mountain is approximately 100 km. The freestyle events were held at Cypress Mountain, the downhill and sliding events were held at Whistler, and the cross country events in Callaghan Valley. Only a few of the sites listed in Table 1 are shown in **a**. The sites in the Whistler area are shown in **b** including the gondola runs where temperature, relative humidity and pressure measurements were made. A persistent cloud known as Harvey's cloud is known to exist near Whistler Mountain Mid Station (VOL) named after Harvey Fellowes who lived there for several years. See Joe *et al*. (2012) for a larger regional map

VOL were generally due to cloud droplets, not falling snow. This conclusion was reached because the probability of seeing low visibilities by the OTT Parsivel probe at VOL, which only sees particles greater than 200 μm, was much lower than that of the FD12P which can see small cloud droplets.

5. NWP Modeling Work

As part of the RDP, the Chinese Meteorological Agency (CMA) (Chen *et al*., 2012), the Central Institute for Meteorology and Geodynamics (ZAMG) of Austria (Haiden *et al*., 2011, 2012), Weather Decision Technologies and NanoWeather of the US (Carpenter *et al*., 2009), as well as Canada, provided modeling products during the project. A summary of all the model products, their resolution, etc., are given in Table 3.

Environment Canada (EC) put considerable effort into producing the best possible NWP models for the Vancouver 2010 Olympic and Paralympic Winter Games. The effort is summarized in Fig. 4 and Mailhot *et al*. (2010, 2012). There was a 15 km regional model (Mailhot *et al*., 2006), run four times per day, a 2.5 km high resolution mesoscale model run twice per day, and specialized high resolution models including a 1 km version of the atmospheric model, as well as an offline land surface system (100 m grid spacing, see Bernier *et al*., 2011, 2012) which is not shown in Fig. 4. Also not included, because it was not related to the nowcasting objectives, was a Canadian regional ensemble forecast run using a 33-km resolution GEM-LAM model

Table 2

List of instruments at the Roundhouse site which were mainly located on three towers

Instrument	Measurement	Characteristics	Location
FMD fog monitor	Droplet/ice spectra	<50 micron	T3
GCIP probe	Droplet/ice spectra	15–960 micron	RND-L
OTT parsivel	Particle spectra	400-max	T1
CAP aerosol	Droplet/aerosol spectra	0.3–10 μm; 8 channels	T1
GEONOR	Precipitation rate/amount	>0.1 mm h^{-1}	T3
YU IPC	Particle spectra	15–500 micron	T2
FD12P vis	Vis/precipitation amount	0.1 mm/h	T3
Sentry Vis	Vis	>10 m	T3
DMIST camera	Vis and images, extinction	For warm fog	RND-R
YES TPS	Precipitation amount	0.25 mm/h	T3
VRG101	Precipitation amount	0.5 mm/h	T3
DSC111	Precipitation amount/friction	Surface phase	T1
DST111	Surface temperature	Surface T/dew point	T1
SR50AT	Snow depth	−45 to 50 °C	T1
Eppley IR/SW	Broadband radiative fluxes	10 %	T2
Campbell RH/*T* (2)	RH and *T*	10 % and ±1 °C	T1 and T2
Young Ultra wind	3D wind and turbulence	4–32 Hz sampling rate	T1
SPN-1	Dir, diff radiation, cloud cover	0.4–2.7 micron	T1
MRR	Rain size spectra, PR, *Z*	For rain/snow	T3
RID (IG)	872E3	Icing amount	T1
Vaisala WXT	*P*, *T*, wind, PR	PR for rain	T1
CRN1	IR and SW BRF	0.2–3 micron	HT1
HSS VPF-730	Visibility/present weather	>0.1 mm/h	T3
LPM 5.4110	Particle spectra	0.1 mm–cm size range, 22 ch	T1
Axis Camera	3D pictures	Zoom/regular	T3
SVI (NCAR)	Snow shape and spectra	>0.5 mm	T2–T3
Snow photography	Particle shape	>100 micron	RND
Young 2D anemometer	2D wind speed		T2

(based on Li *et al.*, 2008). Doyle, (2012) shows that this ensemble system was quite useful for forecasting weather and snow cover conditions prior to the Olympics. Results from these NWP runs were sent to the forecasters in many different products including meteograms showing time series of significant variables over the forecast interval as well as many spatial charts covering areas of interest.

It should also be stressed that the modeling and monitoring efforts were not isolated one from the other. The models had data assimilation schemes that ingested data obtained through the Olympic network, especially auxiliary upper air sondes released from Comox and Nesters.

Higher resolution models were necessary in order to properly resolve phenomena that occur in complex terrain. Figure 5 shows one example using the GEM LAM 1 km model output for 21 February 2010. It shows the surface temperature and wind direction as a function of time of day along the Sea-to-Sky Highway that runs from Vancouver to Whistler (see Fig. 1a). During the day the temperature warmed up due to the influence of the sun. Coinciding with that warming, as the valley slopes became warmer, the flow shifted from drainage towards Vancouver to upslope towards Whistler. Figure 6 verifies this flow reversal using the wind profiler data from Squamish (WSK, see Fig. 1a). This flow reversal was also seen regularly at the ski jump (see Teakles *et al.*, 2012) and occurred quite close to competition time in many cases, making it an event that needed special attention. Such wind flows can only be simulated with a high resolution model since the valley was several kilometers wide in places.

6. Nowcast Systems

Generally speaking, techniques to extrapolate observations have greater skill for forecasting on very short time scales (0–2 h) in comparison to NWP

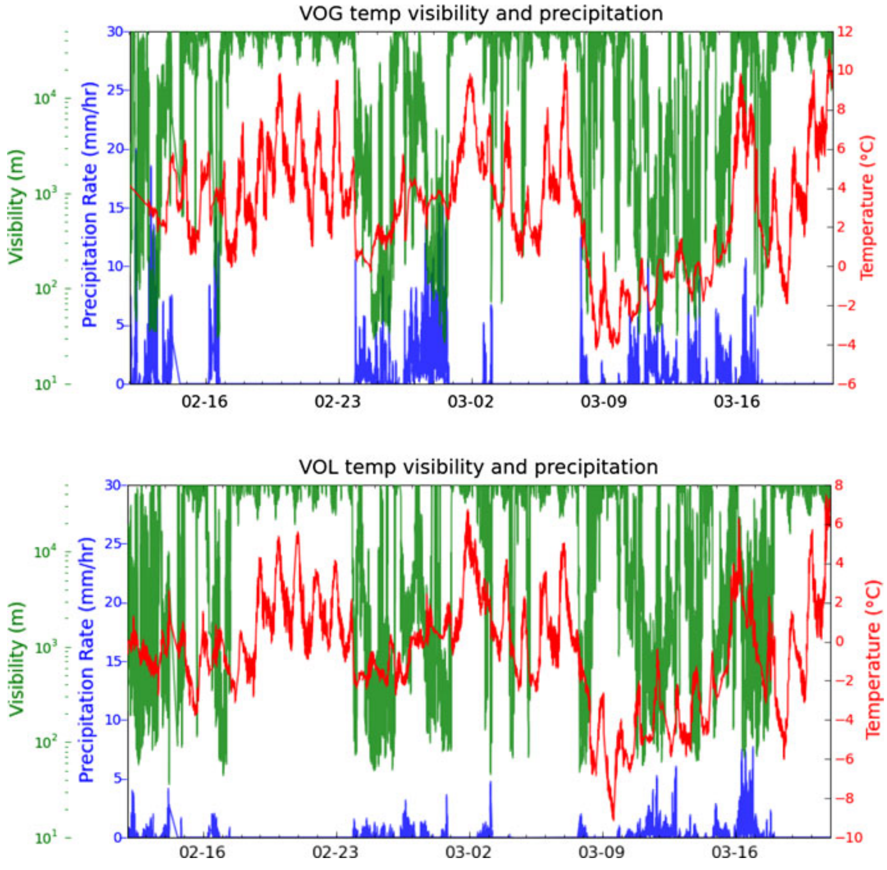


Figure 2

A quick glance summary of the weather conditions at VOG (Cypress Bowl South) and VOL (Whistler Mountain Mid Station) from 12 February to 21 March 2010 covering the time period of the Olympics and Paralympics. For these charts visibility and precipitation were measured using the Vaisala FD12P instrument and were reported at 1 min intervals. For these graphs, visibility is plotted in *green*, temperature in *red*, and precipitation in *blue*

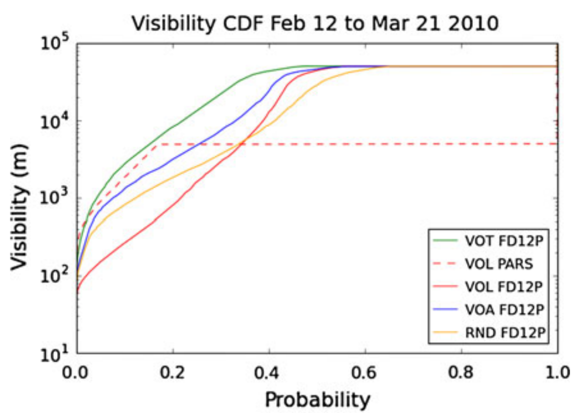


Figure 3

Cumulative probability plot for visibility at VOL, VOA, VOT and RND during the Olympic and Paralympic periods. The OTT Parsivel, plotted for VOL, does not report visibilities greater than 5,000 m

models (see Golding, 1998). Nowcasting systems have been developed that can blend both observations and model predictions into shorter term forecast systems (0–6 h). Short term forecasts of precipitation such as those developed at McGill University (Bellon and Austin, 1978; Turner *et al.*, 2004) which extrapolate radar observations into the future, and those which use a blend of observations and NWP (Bowler *et al.*, 2006) have been utilized. However, these techniques all need further development in order to work effectively in areas with significant radar ground clutter/blockage, as in the case for the mountainous terrain of the SNOW-V10 project.

A number of nowcast systems were run in real time during SNOW-V10, and the emphasis was broadened beyond precipitation nowcasting, which has been the main emphasis of most existing systems, to include significant variables such as precipitation type, visibility, ceiling, wind gusts, etc. The EC Adaptive Blending of Observations and Models (ABOM) (see Bailey *et al.*, 2012) was run using either the EC GEM regional or GEM Olympic 1 km models. This system uses the past observations and model data to predict 6 h into the future for a specific ground site. The Integrated Weighted Model (INTW) system (Huang *et al.*, 2012a, b, c) used the GEM regional, GEM 1 km, and observations to determine a new integrated model prediction into the future. Both ABOM and INTW were developed as part of the Canadian Airport Nowcasting Project (CAN-Now; Isaac *et al.*, 2012) which followed the Airport Vicinity Icing and Snow Advisor (AVISA) Project (Isaac *et al.*, 2006). The NCAR Weather Support to Deicing Decision Making (WSDDM) system (Rasmussen *et al.*, 2001) used the EC radars to produce echo motion vectors and short term precipitation and visibility forecasts. The Austrian Integrated Nowcasting through Comprehensive Analysis (INCA) system combined raingauge and radar data, taking into account intensity-dependant elevation effects (Haiden and Pistotnik, 2009) and the ECMWF model to produce short term forecasts of precipitation (Haiden *et al.*, 2012). The system also provided nowcasts of temperature, humidity, and wind (Haiden *et al.*, 2011) based on surface observations, and blended into the ECMWF forecast. The EC radar point forecast system, based on Bellon and Austin (1986), was also tested during the Paralympics. With the exception of the EC radar point forecast system, all of these techniques are briefly described in Table 3. The EC CAN-Now project also participated through the instrumentation of the Vancouver International Airport site.

7. *Real Time Support to Forecasting Team*

A password protected SNOW-V10 Web site was set up to host real time products produced during the project. This included real time measurements as well as model products. Specialized products using the Olympic Whistler 5 cm scanning radar, the three micro rain radars, the microwave radiometer and the wind profiler were available on the site. In addition, special products from the 3D anemometer used to support activities at the ski jump were also available.

Forecasters were located at each venue and supported by a central office in Vancouver. Since they had little or no experience with many of the new products, a Research Support Desk (RSD) was run at the central Vancouver office. This RSD was staffed by 2–3 scientists who obtained advice from the larger SNOW-V10 Science Team and gave advice to the lead forecaster who then distributed that advice, as and when appropriate, to the venue forecasters. A Science Team briefing was held each morning using WebEx technology to allow participants from across Canada and other countries to participate. The lead forecasters and sometimes the venue forecasters signed into these sessions. Later, a similar WebEx meeting for the forecast team was held which was attended by the RSD. The co-location of the RSD with the Olympic Central Office was quite successful and researchers and operational forecasters learned a great deal from each other. A schematic of how the interactions took place is shown in Fig. 7.

Considerable discussions were held with the Vancouver Organizing Committee for the 2010 Olympics (VANOC) in order to determine the key weather thresholds relevant for each event. These critical and significant decision points, and factors to consider, were used by the forecasters in their interactions with their venue clients who were directing the events. If the critical decision point or threshold was exceeded, the event would be postponed. An example of such thresholds for the downhill and slalom events is shown in Table 4. These thresholds have also been used in the selection of categories for the verification work described later.

Observations at key sites were integrated with model data to produce time series charts of important variables. This data could be viewed in a forecast mode only, showing the past 3 h and the model predictions for the next 6 h, or verification plots of the past 24 h. Many of the EC SNOW-V10 nowcasting products on the Web site were modeled after those used in CAN-Now. Figure 8 shows a sample of a 24 h plot during the time the Snowboard Men's Parallel Giant Slalom was being held on 27 February 2010. It combines the observed visibility and

Table 3

A summary of the NWP Model and nowcasting techniques used during SNOW-V10 which provided input into the forecast tables

Model name	Organization	Country	Spatial resolution	Temporal resolution available	Times of day run (UTC)	Length of forecast (h)	General description
ABOMLAM 1 km	Environment Canada	Canada	1 km	15 min	Every 15 min	Max 6 h	Adaptive Blending of Observations and Models using GEM LAM1k
ABOMREG	Environment Canada	Canada	15 km	15 min	Every 15 min	Max 6 h	Adaptive Blending of Observations and Models using GEM regional
CMA	Chinese Meteorological Administration	China	15 and 3 km	1 h	00 and 12 UTC	48 and 24 h	CMA GRAPES-Meso NWP model
INTW	Environment Canada	Canada	1 and 15 km	15 min	Every 15 min	Max. 6 h	Integrated Weighted Modelusing LAM1k, GEM regional and observations
LAM1k	Environment Canada	Canada	1 km	30 s (model), 15 min (tables)	11 and 20 UTC	19 h	Limited-area version of GEM model
LAM2.5k	Environment Canada	Canada	2.5 km	1 min (Model), 15 min (tables)	06 and 15 UTC	33 h	Limited-area version of GEM model
REG	Environment Canada	Canada	15 km	7.5 min (Model), 15 min (tables)	00, 06, 12, 18 UTC	48 h	Regional version of GEM (global environmental multiscale) model
WDTUSL	Weather Decision Technologies and Nano Weather	USA	Point wise or 100 m grid	–	02, 08, 14, 20 UTC	48 h	Surface layer model nested in NAM. Works particularly well in quiescent conditions
WSDDM	National Center for Atmospheric Research (NCAR)	USA	Radar resolution	10 min (based on radar update)	Every 10 min	2 h	Nowcast based on storm tracking of radar echo using cross correlation and real-time calibration with surface precipitation gauges
INCA	Central Institute for Meteorology and Geodynamics (ZAMG)	Austria	1 km	1 h	Every hour	18 h	Nowcasting system using downscaled ECMWF forecasts as a first guess, applying corrections according to the latest observation
INCARR	Central Institute for Meteorology and Geodynamics (ZAMG)	Austria	1 km	15 min	Every 15 min	18 h	Nowcasting system combining raingauge and radar data taking into account elevation effects, merging into ECMWF forecasts through prescribed weighting

The ABOM, INTW, WSDDM, and INCA are nowcast techniques and provided information at time resolutions <1 h

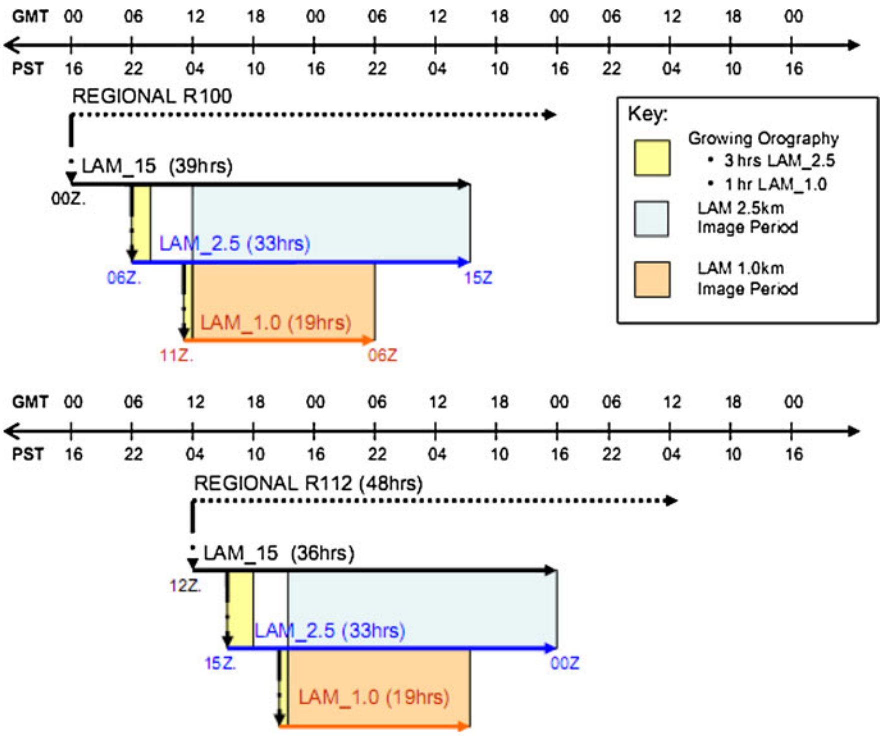


Figure 4
A summary of the Environment Canada numerical weather prediction models for the 2010 Olympics (see Mailhot *et al*., 2012). The upper-air initial conditions were obtained from a three-dimensional variational data assimilation performed with the regional 15-km GEM model (Fillion *et al*. 2010). Although the GEM 15 km system was integrated four times a day at MSC, only two of these runs (at 00:00 and 12:00 UTC) were used to provide initial and lateral boundary conditions for 15-km nested runs, which were used to initialize and drive 2.5-km nested runs, which were then used to initialize and drive further nested runs at 1.0 km

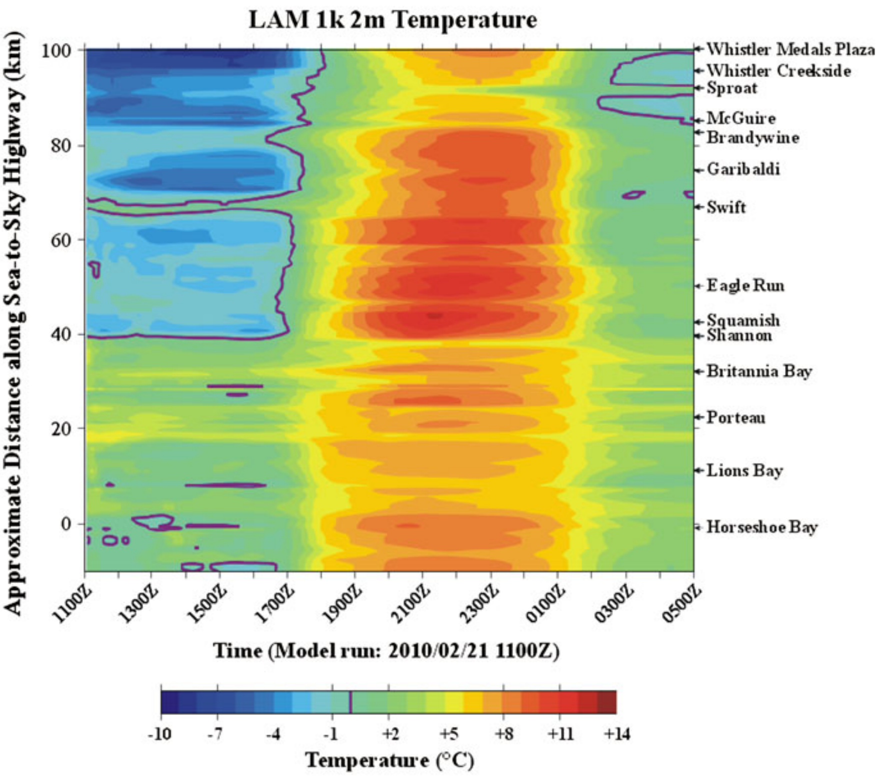
precipitation rates with the Canadian model output onto the same plot.

Figure 9 shows a series of WSDDM composite radar images for 26 February 2010. The flow was generally from the SW over the Olympic Range of Mountains to the south of Vancouver. A hole can be seen in the composites which was due to the shadow effect of the mountains. The hole moved around in time and changed shape probably due to changes in wind direction or other variables. Although this shadow effect is well known, it deserves further study using high resolution models. The precipitation amounts at West Vancouver (WWA) at an elevation of 170 m were often only a fraction of that measured at Cypress Bowl South (VOG) at 900 m or Cypress Bowl North (VOE) at 950 m, even though these sites were only separated by several kilometers. Obviously the presence of the mountains and complex terrain made forecasting precipitation by simple translation of the echoes, as is often done over more even terrain, problematic. That is why techniques which combine observations and NWP information to provide a more realistic prediction of precipitation, like STEPS (Short-Term Ensemble Prediction System; Bowler *et al*., 2006), need to be developed for this area.

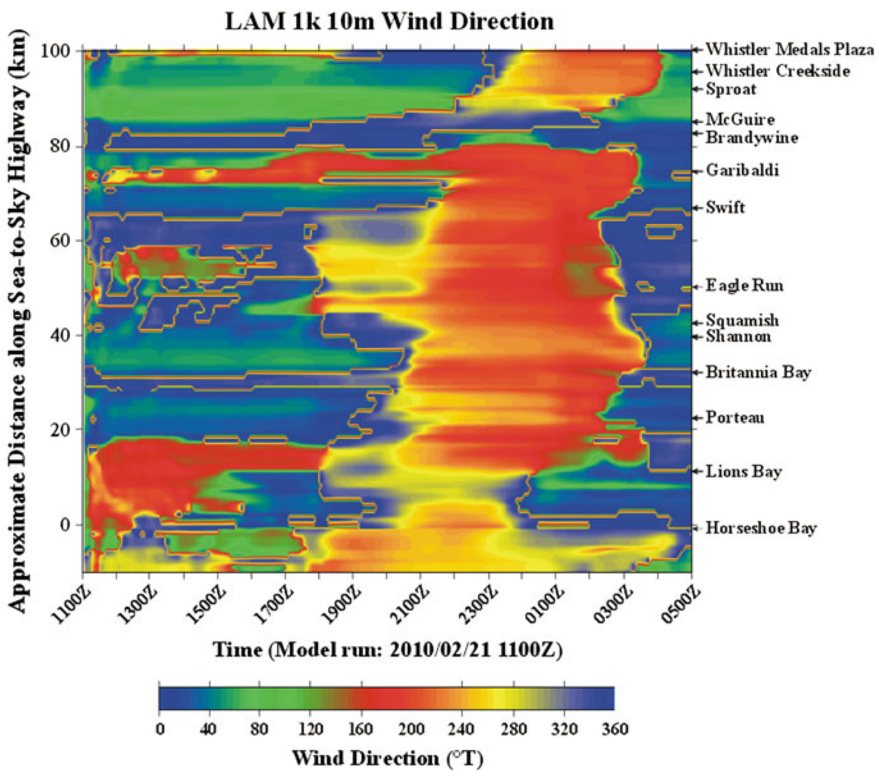
8. *Verification*

It was understood from the beginning that verification metrics for the forecasts would need to be developed as has been done in previous Olympic

Figure 5 ▶
GEM LAM 1 km for points along Sea to Sky highway showing flow reversal with day time heating. The *top panel* shows temperature as a function of time of day and distance along the highway. The *bottom panel* shows wind direction in the same format. Note 23 Z is 15 local time



LAM 1k 2m Temperature
Approximate Distance along Sea-to-Sky Highway (km)
100
80
60
40
20
0
Whistler Medals Plaza
Whistler Creekside
Sproat
McGuire
Brandywine
Garibaldi
Swift
Eagle Run
Squamish
Shannon
Britannia Bay
Porteau
Lions Bay
Horseshoe Bay
1100Z
1300Z
1500Z
1700Z
1900Z
2100Z
2300Z
0100Z
0300Z
0500Z
Time (Model run: 2010/02/21 1100Z)
-10
-7
-4
-1
+2
+5
+8
+11
+14
Temperature (°C)



LAM 1k 10m Wind Direction
Approximate Distance along Sea-to-Sky Highway (km)
100
80
60
40
20
0
Whistler Medals Plaza
Whistler Creekside
Sproat
McGuire
Brandywine
Garibaldi
Swift
Eagle Run
Squamish
Shannon
Britannia Bay
Porteau
Lions Bay
Horseshoe Bay
1100Z
1300Z
1500Z
1700Z
1900Z
2100Z
2300Z
0100Z
0300Z
0500Z
Time (Model run: 2010/02/21 1100Z)
0
40
80
120
160
200
240
280
320
360
Wind Direction (°T)

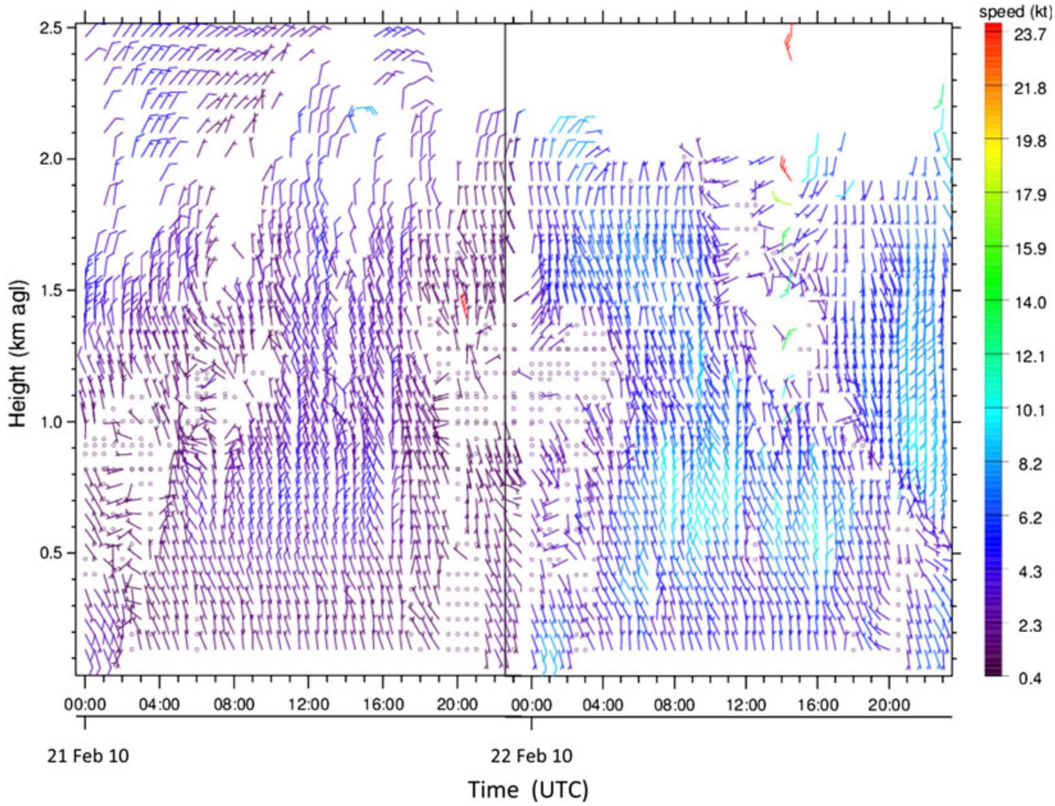


Figure 6
The Squamish (WSK) wind profiler measurements for 00:00 UTC 21 February to 00:00 UTC 23 February showing the flow reversal at that site near 20:00 21 February and ending about 03:00 22 Feburary. Diagrams for 21 and 22 February have been merged together which accounts for the mis-match in the middle. Note also that there were flow reversals the previous afternoon and the following afternoon

WWRP projects (Ebert *et al.*, 2004; Anderson-Berry *et al.*, 2004). Such verifications gives users more confidence in using forecasts, gives developers information on what needs improving, and provide measures of success. The errors associated with the data sets must be assessed and ultimately our ability to nowcast precipitation (e.g., Pierce *et al.*, 2004) and other variables must be determined.

Forecasters at each venue produced a Sport Forecast Table showing forecasts of important variables each hour. These were made available to their clients (for example, the venue managers) who were usually on site. In order to assist the forecaster, it was decided to produce such a Table for many locations shown in Table 1 with a 15 min resolution for the first 2 h and then hourly after that. Examples of such tables are given in Tables 5, 6, 7, and 8 for the LAM 1 km, ABOM, INTW, and INCA nowcast methods, respectively. Because of possible differences between model time steps, etc., it was decided to present the maximum and minimum of variables such as ceiling, and visibility, as well as precipitation rates and accumulations during the intervals shown. This helps to resolve difficulties regarding matching observations with models when meteorological parameters vary rapidly and observations and model sampling frequencies are not the same.

Such tables were also considered important for verification and intercomparison of the various products. So all the forecasts produced for these tables have been verified against observations and compared with the Sport Forecasts for the time period: 5 February to 22 March 2010. For continuous variables, various standard tests have been performed. For non-continuous variables, the Sport Thresholds (e.g., Table 4) were used to design categories for which statistical scores such as the multicategorical Heidke Skill Score (HSS) could be

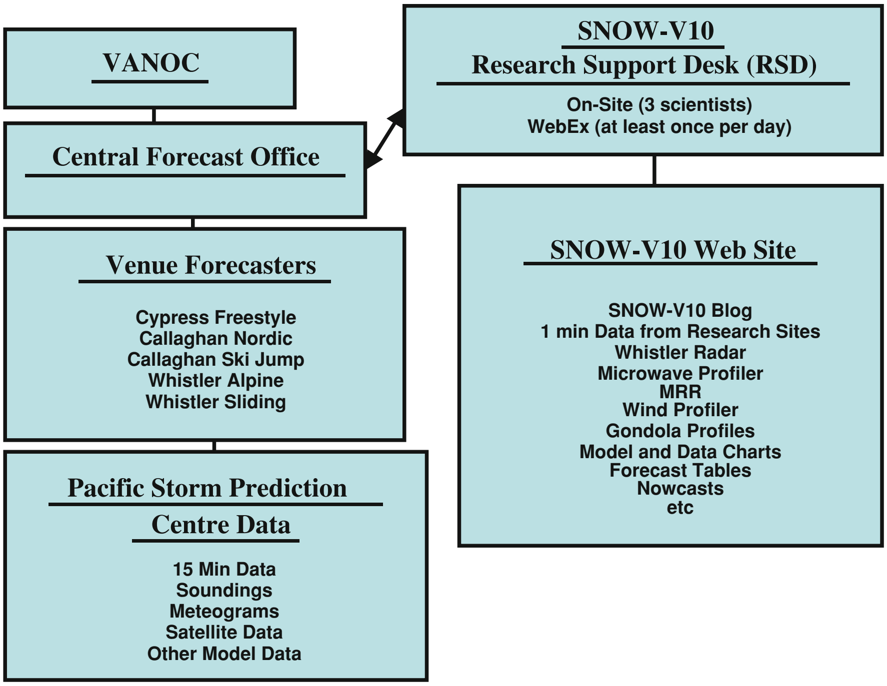


Figure 7
A diagram showing how SNOW-V10 (*right side*) interacted with the operations group (*left side*) who were responsible for delivering the forecasts

Table 4
Thresholds for the downhill and slalom events

Threshold matrix for downhill, slalom and giant slalom (from Chris Doyle)

	New snow (24 h)	Wind	Visibility	Rain
Critical decision point	>30 cm	Constant above 17 m/s or gusts >17 m/s	<200 m on the entire course Lower thresholds for GS…course dependant but ~100 m for GS	15 mm in 6 h or less
Significant decision point	15 and <30 cm, >10 and <30 cm Paralympics	Constant 11 m/s to 17 m/s <	200 m on portions of the course	Mixed precipitation
Factor to consider	>5 cm, >2 cm within 6 h of an event	Gusts above 14 m/s but <17 m/s	>200 but <500 m on whole or part of the course	

calculated (see Table 9). See the WWRP/WGNE Joint Working Group on Forecast Verification Research web pages for the definition of this score (http://www.cawcr.gov.au/projects/verification/verifwebpage.html).

The multi-categorical (M-C) HSS score answers the question 'what was the accuracy of the forecast in predicting the correct category, relative to that of random chance?' with one indicating a perfect score and zero, no skill. Table 10 shows the verification of the Canadian 1 km model using Table 9 and determining the HSS scores for relative humidity (HSS: 0.28), visibility (HSS: 0.1) and precipitation type (HSS: 0.54) for Whistler Mountain Mid Station (VOL) for the Olympic period. The tables show some interesting information. For example, the model tended to under forecast relative humidity as compared to the observations when the observed relative humidity was over 94 %. The model did not forecast low visibilities (between 50 and 200 m) very well, and more frozen precipitation was observed than

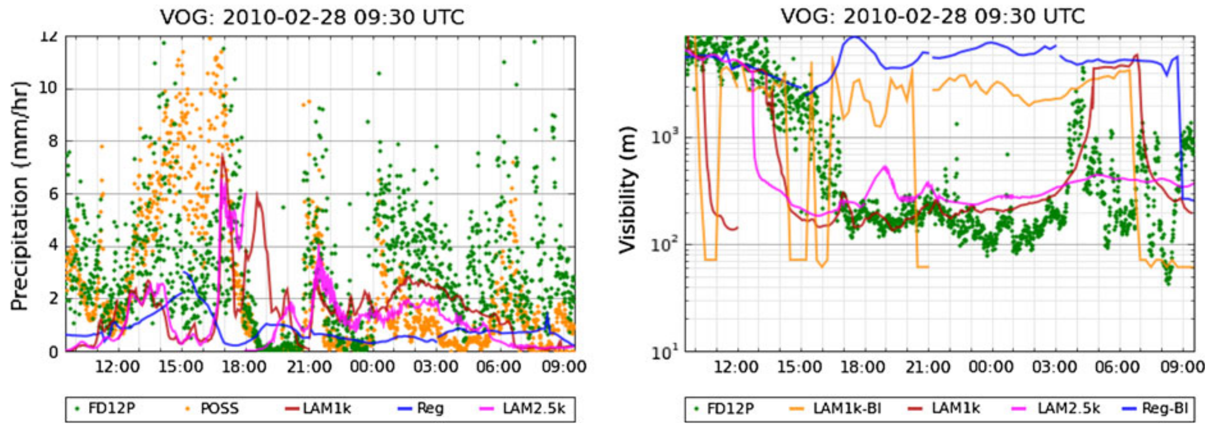


Figure 8

Examples of real time products that were available during SNOW-V10 from Cypress Bowl South (VOG) combining observations and model data. The diagrams show the Canadian model predictions, the most current for that time, plotted along with the observations (*dotted lines*) from various instruments. The *left panel* shows precipitation rate from the models and the Vaisala FD12P, and the POSS. The *right panel* shows the visibility as predicted from the models using two different parameterizations, as well as the observations from the Vaisala FD12P. The Snowboard Men's Parallel Giant Slalom final on 27 February 2010 occurred near the middle of these 24 h plots

forecast by the model. Similar results were found at many of the other SNOW-V10 locations.

Examples of error analyses are shown in Fig. 10 and Table 11. Figure 10 shows the mean absolute error (MAE) for the three Canadian models and the US RUC model for wind gusts at Vancouver Airport. The RUC model is used in the Canadian Airport Nowcasting System (Isaac *et al*., 2012) and has been described by Benjamin et al. (2004, 2006). The higher resolution LAM 2.5 km model clearly has larger MAE values than the coarser resolution GEM REG which is somewhat surprising. However, in general, the higher resolution NWP did have lower MAEs than their lower resolution counterparts (see Mailhot *et al*., 2012; Huang *et al*., 2012a, b; Chen *et al*., 2012). The persistence forecasts, assuming the forecast value remains the same as the start point, beginning at 3, 9 15 and 21 UTC show that persistence is difficult to "beat" for short term forecasts, at least on the average. Table 11 shows that for a 6 h forecast, the INTW nowcast system had the lowest mean absolute errors in relative humidity, even beating persistence for most SNOW-V10 sites.

It is also interesting to compare how the Sport Forecasts produced by the human forecasters compared with the unadjusted NWP model output, persistence and the INTW nowcast scheme. Figure 11 shows some examples of performance as a function of forecast lead time out to 12 h. This is somewhat unfair for the NWP models because of potential spin up problems but these can easily be filtered out visually, for example, LAM 2.5 km for temperature at VOL and VOT. For the six sites for which sport forecasts could be verified against SNOW-V10 observations, the forecaster had a better mean absolute error than the Canadian NWP models, for 16 of 24 charts for four variables (temperature 6/6, relative humidity 4/6, wind speed 1/6 and wind gust 5/6) for the first few hours. Generally as forecast lead time increased, the differences between the forecaster and NWP model diminished. However, both persistence and the INTW nowcast technique were superior to the NWP models and the forecaster for the first few hours, in all analyzed cases. One might jump to the false conclusion that the human forecaster did not add any value to the forecasts. However, they were certainly necessary at all outdoor sites in order to interact with venue managers/officials. These people relied heavily on their advice and many important decisions were made based on short term and longer term forecasts, as explained and interpreted by the human forecaster.

Figure 12 compares all the NWP models for temperature, relative humidity, wind speed and wind direction for Whistler Mountain Mid Station (VOL)

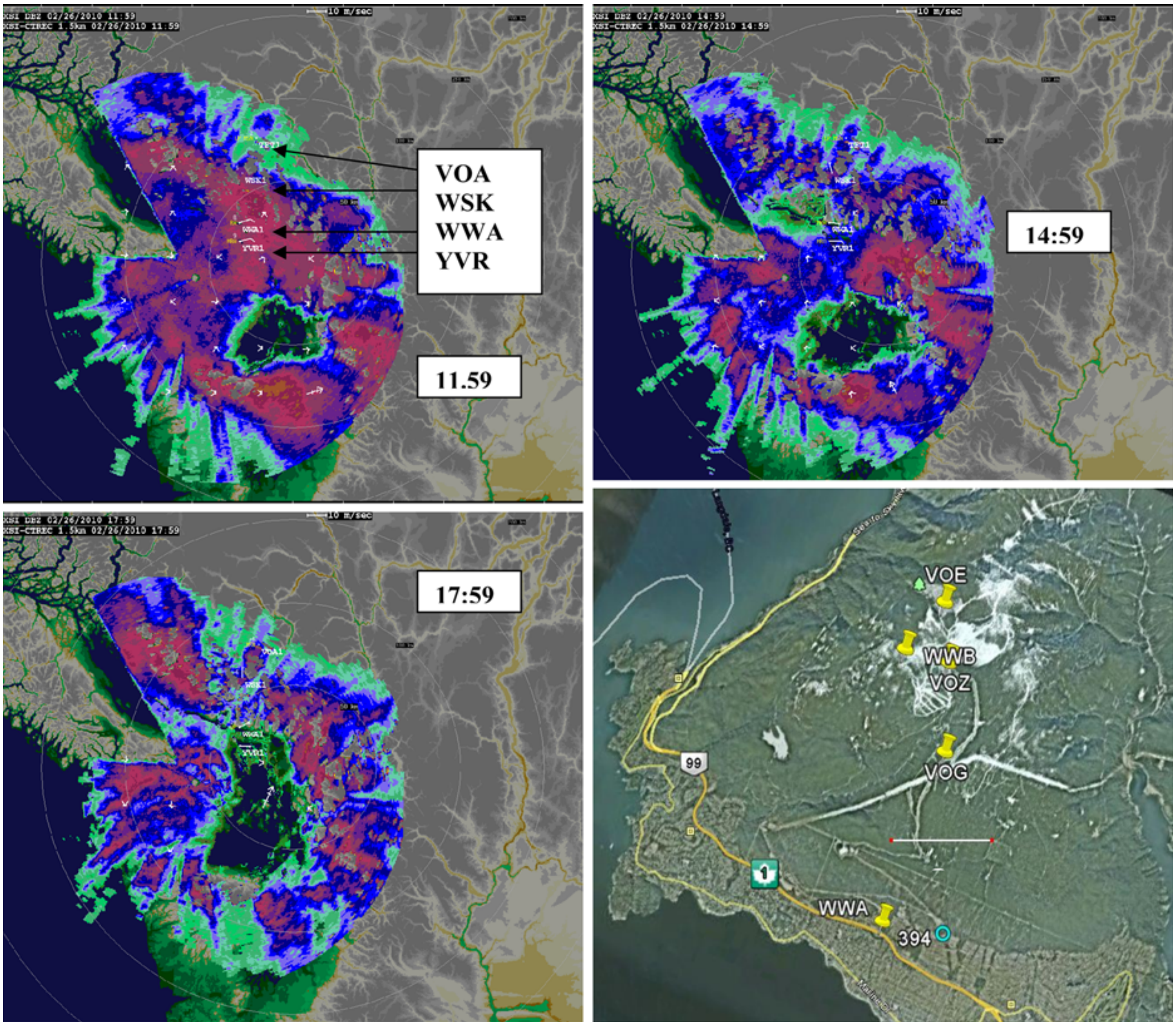


Figure 9
Shows the composite radar image as produced using the WSDDM system using the Canadian C-Band radars. Three different times (11:59, 14:59 and 17:59) are shown for 26 February 2010. The panel on the *lower right* shows a Google map of the area surrounding the Cypress Mountain venue

for the Olympic period. This is only a limited period and stating one model is superior to another is not possible. In addition, model forecast lead times are different as a function of time of day. However, it is obvious that all models have a difficult time predicting relative humidity and wind direction at this site. Mailhot *et al*. (2012) using the larger Olympic data set came to the same general conclusion for the Canadian models. Periods when the observed winds were low (<5 kn) were removed from the wind direction verification analysis. The wind direction errors might be due to representativeness of the observation sites in complex terrain but similar errors were found for Vancouver International Airport where terrain influences would not have been a problem (e.g., Isaac *et al*., 2012).

Although some useful generalizations are possible, the statistical verifications described above were done over a small data set and no significance tests have been applied. It should also be mentioned that forecast accuracy in high impact events (high winds, low visibilities, heavy precipitation, etc.) is most critical and any success criteria for performance must take this fact into consideration.

Table 5

Example of online table showing how users could select for various sites and different models. The models from left to right were the Adaptive Blending of Observations and Models (ABOM) using either the GEM 1 km or GEM REG, the CMA model, the INTW nowcasting technique, the Canadian models (LAM 1 km, LAM 2.5 km and the REG), the WDTUSL model and the two Austrian INCA outputs. The values in the table refer to the LAM 1 km predictions for VOG (Cypress Bowl South site). See also Tables 6, 7 and 8

SNOW-V10 : Science of Nowcasting Winter Weather for Vancouver 2010

ABOMLAM1KM ABOMREG CMA INTW **LAM1K** LAM2.5K REG WDTUSL WSDDM ZAMGINCA ZAMGINCARR

PEK RND VOA VOB VOC VOD VOE **VOG** VOI VOL VON VOT VOW VOX VOZ VWB WGP WSK WWA YVR

LAM1K VOG Forecast download csv model descriptions back to snow-v10 »

run time (UTC)	valid time (UTC)	Clouds	Temp. °C	Dew Pt.	RH (%)	Wind (°/kts)			Visibility (km)			Ceiling (km)			Precip. Type	Frozen/Solid		Rain		Frozen Liquid Equiv.		All Precip. Liquid Equiv.	
						dir	speed	max	inst.	min	max	inst.	min	max		Rate (cm/h)	Accum. (cm)	Rate (mm/h)	Accum. (mm)	Rate (mm/h)	Accum. (mm)	Rate (mm/h)	Accum. (mm)
20Z	2010-02-25 03:15:00	10/10	1.7		99	172	3.1	8.5	Inf	Inf	Inf	Inf	Inf	Inf		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20Z	2010-02-25 03:30:00	10/10	1.7		100	172	3.2	8.7	Inf	Inf	Inf	0.90	0.90	1.28		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20Z	2010-02-25 03:45:00	10/10	1.7		100	179	3.5	11.8	0.27	0.27	Inf	0.02	0.02	0.90		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20Z	2010-02-25 04:00:00	10/10	1.8		100	181	3.7	12.6	0.22	0.21	0.27	0.02	0.02	0.02		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20Z	2010-02-25 04:15:00	10/10	1.8		100	182	4.3	13.8	0.18	0.18	0.22	0.02	0.02	0.02		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20Z	2010-02-25 04:30:00	10/10	1.8		100	180	4.4	14.0	0.14	0.14	0.18	0.02	0.02	0.02	Drizzle	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00
20Z	2010-02-25 04:45:00	10/10	1.9		100	181	4.7	14.6	0.13	0.13	0.14	0.02	0.02	0.02		0.00	0.00	0.04	0.00	0.00	0.00	0.04	0.00
20Z	2010-02-25 05:00:00	10/10	1.9		100	184	5.1	15.8	0.13	0.13	0.13	0.02	0.02	0.02	Rain	0.07	0.00	0.52	0.10	0.24	0.00	0.76	0.10
20Z	2010-02-25 06:00:00	10/10	1.8		100	194	5.6	18.7	0.14	0.13	0.14	0.02	0.02	0.02	Rain	0.30	0.00	1.95	1.00	1.04	0.50	3.00	1.70
20Z	2010-02-25 07:00:00	10/10	1.3		100	211	4.5	18.3	0.13	0.13	0.15	0.02	0.02	0.02	Rain/drizzle & snow	0.86	0.00	1.55	2.40	1.55	2.00	3.13	4.40
20Z	2010-02-25 08:00:00	10/10	1.1		100	213	3.7	10.8	0.14	0.13	0.14	0.02	0.02	0.02	Rain	0.11	0.00	1.71	1.10	0.53	0.70	2.24	1.80
20Z	2010-02-25 09:00:00	10/10	0.9		100	208	2.1	9.9	0.16	0.14	0.16	0.02	0.02	0.02	Rain	0.02	0.00	0.14	0.80	0.04	0.60	0.18	1.50
20Z	2010-02-25 10:00:00	10/10	0.8		100	207	2.1	6.8	0.18	0.16	0.18	0.02	0.02	0.02		0.00	0.00	0.01	0.10	0.00	0.00	0.01	0.10
20Z	2010-02-25 11:00:00	10/10	0.8		100	183	2.0	2.1	0.23	0.18	6.66	0.02	0.02	2.29		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20Z	2010-02-25 12:00:00	10/10	0.9		100	190	3.2	9.2	0.20	0.19	0.23	0.02	0.02	0.02		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20Z	2010-02-25 13:00:00	9/10	1.0		100	170	2.6	9.1	0.16	0.15	0.20	0.02	0.02	0.02	Drizzle	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00
20Z	2010-02-25 14:00:00	10/10	0.9		100	159	3.8	9.3	0.14	0.14	0.17	0.02	0.02	0.02	Drizzle	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00

Table 6

The ABOM nowcast output using the LAM 1 km model for the same time and location as Table 5

SNOW-V10 : Science of Nowcasting Winter Weather for Vancouver 2010

ABOMLAM1KM ABOMREG CMA INTW LAM1K LAM2.5K REG WDTUSL WSDDM ZAMGINCA ZAMGINCARR

PEK RND VOA VOB VOC VOD VOE **VOG** VOI VOL VON VOT VOW VOX VOZ VWB WGP WSK WWA YVR

Adaptive Blending of Observation and Models using GEM LAM1k VOG Forecast download csv model descriptions back to snow-v10 »

run time (UTC)	valid time (UTC)	Clouds	Temp. °C	Dew Pt.	RH (%)	Wind (°/kts)			Visibility (km)			Ceiling (km)			Precip. Type	Frozen/Solid		Rain		Frozen Liquid Equiv.		All Precip. Liquid Equiv.	
						dir	speed	max	inst.	min	max	inst.	min	max		Rate (cm/h)	Accum. (cm)	Rate (mm/h)	Accum. (mm)	Rate (mm/h)	Accum. (mm)	Rate (mm/h)	Accum. (mm)
03:05	2010-02-25 03:15		1.9			122	3.02		0.08			0.03										0.04	
03:05	2010-02-25 03:30		1.9			122	3.02		0.08			0.03										0.04	
03:05	2010-02-25 03:45		1.9			123	3.02		0.07			0.03										0.04	
03:05	2010-02-25 04:00		1.9			123	3.02		0.07			0.03										0.04	
03:05	2010-02-25 04:15		1.9			123	3.02		0.07			0.03										0.04	
03:05	2010-02-25 04:30		1.9			123	3.02		0.06			0.03										0.04	
03:05	2010-02-25 04:45		1.9			125	2.94		0.06			0.03										0.04	
03:05	2010-02-25 05:45		2.0			130	2.93		0.08			0.03										0.04	
03:05	2010-02-25 06:45		2.0			146	4.57		0.08			0.03										0.11	
03:05	2010-02-25 07:45		1.9			174	3.13		0.07			0.03										0.15	
03:05	2010-02-25 08:45		1.9			123	2.47		0.08			0.03										0.18	
03:05	2010-02-25 09:45		1.9			123	2.36		0.07			0.03										0.04	

9. *Summary*

The World Weather Research Project (WWRP) on the Science of Nowcasting Olympic Weather for Vancouver 2010 (SNOW-V10) provided an excellent opportunity to demonstrate existing capability in nowcasting winter weather and to develop better techniques for short term (0–6 h) nowcasts of winter weather in complex terrain. The weather during the games was highly variable with many periods of low visibility, low ceilings and precipitation in the form of both snow and rain. Some preliminary conclusions can be made from the SNOW-V10 experiment.

- Several important physical processes and phenomena were documented during SNOW-V10 including diabatic effects due to melting snow, wind flow around and over terrain, diurnal flow

Table 7

The INTW nowcast output for the same time and location as Table 5

SNOW-V10 : Science of Nowcasting Winter Weather for Vancouver 2010

ABOMLAM1KM ABOMREG CMA INTW LAM1K LAM2.5K REG WDTUSL WSDDM ZAMGINCA ZAMGINCARR

PEK RND VOA VOB VOC VOD VOE VOG VOI VOL VON VOT VOW VOX VOZ VWB WGP WSK WWA YVR

Integrated Weighted Model using LAM1k Regional and Observations VOG Forecast download csv model descriptions back to snow-v10 »

run time (UTC)	valid time (UTC)	Clouds	Temp. °C	Dew Pt.	RH (%)	Wind (°/kts)			Visibility (km)			Ceiling (km)			Precip. Type	Frozen/Solid		Rain		Frozen Liquid Equiv.		All Precip. Liquid Equiv.	
						dir	speed	max	inst.	min	max	inst.	min	max		Rate (cm/h)	Accum. (cm)	Rate (mm/h)	Accum. (mm)	Rate (mm/h)	Accum. (mm)	Rate (mm/h)	Accum. (mm)
03:05	2010-02-25 03:15		1.7			157	4.55	6.82	27.53			1.36										0.02	
03:05	2010-02-25 03:30		1.7			156	4.57	6.76	28.17			1.36										0.02	
03:05	2010-02-25 03:45		1.7			158	4.74	8.3	1.07			1.36										0.02	
03:05	2010-02-25 04:00		1.8			158	4.86	8.67	0.00			1.36										0.03	
03:05	2010-02-25 04:15		1.8			156	5.15	9.29	0.00			1.36										0.08	
03:05	2010-02-25 04:30		1.8			154	5.21	9.45	5.91			1.16										0.15	
03:05	2010-02-25 04:45		1.9			153	5.4	9.82	4.95			1.15										0.24	
03:05	2010-02-25 05:00		1.9			153	5.6	10.5	4.35			0.97										0.57	
03:05	2010-02-25 05:15		1.9			155	5.97	11.47	4.01			0.97										0.58	
03:05	2010-02-25 06:15		1.8			159	6.01	11.82	5.25			0.79										2.48	
03:05	2010-02-25 07:15		1.1			169	4.98	8.26	4.16			0.36										0.77	
03:05	2010-02-25 08:15		1.0			179	4.98	8.69	1.72			0.14										2.47	
03:05	2010-02-25 09:15		0.9			183	4.06	7.29	1.27			0.00										3.20	

Table 8

The INCA nowcast output for the same time and location as in Table 5. The results have been terminated at 15 UTC but the actual output went until 21 UTC

SNOW-V10 : Science of Nowcasting Winter Weather for Vancouver 2010

ABOMLAM1KM ABOMREG CMA INTW LAM1K LAM2.5K REG WDTUSL WSDDM ZAMGINCA ZAMGINCARR

PEK RND VOA VOB VOC VOD VOE VOG VOI VOL VON VOT VOW VOX VOZ VWB WGP WSK WWA YVR

INCA VOG Forecast download csv model descriptions back to snow-v10 »

run time (UTC)	valid time (UTC)	Clouds	Temp. °C	Dew Pt.	RH (%)	Wind (°/kts)			Visibility (km)			Ceiling (km)			Precip. Type	Frozen/Solid		Rain		Frozen Liquid Equiv.		All Precip. Liquid Equiv.	
						dir	speed	max	inst.	min	max	inst.	min	max		Rate (cm/h)	Accum. (cm)	Rate (mm/h)	Accum. (mm)	Rate (mm/h)	Accum. (mm)	Rate (mm/h)	Accum. (mm)
03Z	2010-02-25 03:15														None			0.00	0.00	0.00	0.00	0.00	0.00
03Z	2010-02-25 03:30														None			0.00	0.00	0.00	0.00	0.00	0.00
03Z	2010-02-25 03:45														None			0.00	0.00	0.00	0.00	0.00	0.00
03Z	2010-02-25 04:00														None			0.00	0.00	0.00	0.00	0.00	0.00
03Z	2010-02-25 04:15														None			0.00	0.00	0.00	0.00	0.00	0.00
03Z	2010-02-25 04:30														None			0.00	0.00	0.00	0.00	0.00	0.00
03Z	2010-02-25 04:45														None			0.00	0.00	0.00	0.00	0.00	0.00
03Z	2010-02-25 05:00														None			0.00	0.00	0.00	0.00	0.00	0.00
03Z	2010-02-25 06:00														PPN - slight/moderate			2.60	1.00	0.00	0.00	2.60	1.00
03Z	2010-02-25 07:00														Rain/drizzle & snow mixed - heavy			1.40	2.10	0.00	0.00	1.40	2.10
03Z	2010-02-25 08:00														Rain/drizzle & snow mixed - heavy			0.20	0.30	0.00	0.00	0.20	0.30
03Z	2010-02-25 09:00														Rain/drizzle & snow mixed - heavy			0.30	0.30	0.10	0.00	0.30	0.30
03Z	2010-02-25 10:00														Rain/drizzle & snow mixed - heavy			0.30	0.30	0.10	0.10	0.30	0.30
03Z	2010-02-25 11:00														Rain/drizzle & snow mixed - heavy			0.20	0.30	0.10	0.10	0.30	0.30
03Z	2010-02-25 12:00														Rain/drizzle & snow mixed - heavy			0.20	0.20	0.10	0.10	0.30	0.30
03Z	2010-02-25 13:00														Rain/drizzle & snow mixed - heavy			0.30	0.30	0.20	0.20	0.50	0.50
03Z	2010-02-25 14:00														Rain/drizzle & snow mixed - heavy			0.30	0.30	0.20	0.20	0.50	0.50
03Z	2010-02-25 15:00														Rain/drizzle & snow mixed - heavy			0.30	0.30	0.20	0.20	0.50	0.50

reversal in valleys associated with daytime heating and precipitation reductions and increases due to local terrain influences, etc. Some of these phenomena has been described by MILBRANDT *et al.* (2012), MO *et al.* (2012a), TEAKLES *et al.* (2012), and THÉRIAULT *et al.* (2012a, b).

- Weather changes rapidly in complex terrain and it is necessary to obtain good measurements at time resolutions of 1–15 min. SNOW-V10 attempted to get measurements at 1 min resolution where possible.
- Because of the rapidly changing nature of the weather, weather forecasts also must be given at high time resolution.
- Advances were made in forecasting non-traditional variables such as visibility, cloud base, wind gust, and precipitation type in complex terrain. In addition, the difficulties of verifying non-continuous variables such as visibility and precipitation type were addressed. It should be mentioned that visibility and cloud base are considered non-continuous variables because they can jump to

Table 9

Categories used for SNOW-V10 Verification using the multicategorical Heidke skill score (HSS)

Categories used for SNOW-V1C verification

Variable	Category 1	Category 2	Category 3	Category 4	Category 5	Category 6	Category 7	Category 8	Category 9
Temperature	−25 °C <	$-25 \leq T < -$ 20 °C	$-20 \leq T < -4$ °C	$-4 \leq T < -2$ °C	$-2 \leq T < 0$ °C	$0 \leq T < +2$ °C	$+2 \leq T < +4$ °C	$\geq +4$ °C	
RH (%)	<30	$30 \leq$ RH < 65	$65 \leq$ RH < 90	$90 \leq$ RH < 94	$94 \leq$ RH < 98	≥98			
Winds	<3 m/s	$3 \leq w < 4$ m/s	$4 \leq w < 5$ m/s	$5 \leq w < 7$ m/s	$7 \leq w < 11$ m/s	$11 \leq w < 13$ m/s	$13 \leq w < 15$ m/s	$15 \leq$ w < 17 m/s	≥17 m/s
Wind gust	<3 m/s	$3 \leq w < 4$ m/s	$4 \leq w < 5$ m/s	$5 \leq$ w < 7 m/s	$7 \leq w < 11$ m/s	$11 \leq w < 13$ m/s	$13 \leq w < 15$ m/s	$15 \leq$ w < 17 m/s	≥17 m/s
Wind direction	$d \geq 339$ and $d < 24°$ (N)	$24 \leq d < 69°$ (NE)	$69 \leq d < 114°$ (E)	$114 \leq$ d < 159° (SE)	$159 \leq d < 204°$ (S)	$204 \leq d < 249°$ (SW)	$249 \leq d < 294°$ (W)	$294 \leq$ d < 339° (NW)	
Visibility	$v < 30$ m	$30 \leq v < 50$ m	$50 \leq v < 200$ m	$200 \leq v < 300$ m	$300 \leq v < 500$ m	≥500 m		–	–
Ceiling	$c < 50$ m	$50 \leq c < 120$ m	$120 \leq c < 300$ m	$300 \leq c < 750$ m	$750 \leq c < 3{,}000$ m	$c \geq 3{,}000$ m	–	–	–
Precipitation rate	$r = 0$ mm/h (none)	$0 < r \leq 0.2$ mm/h (trace)	$0.2 < r \leq 2.5$ mm/h (light)	$2.5 < r \geq 7.5$ mm/h (moderate)	$r > 7.5$ mm/h (heavy)	–	–	–	–
Precipitation type	No precipitation	Liquid	Freezing	Frozen	Mixed (*w*/liquid)	Unknown	–	–	–

Table 10

Shows the verification of the Canadian 1 km model at Whistler Mountain Mid Station (VOL) for relative humidity (top), visibility (middle) and precipitation type (bottom). For example, there were 143 observations of relative humidity between 90 to 94% with a forecast of 65 to 90%

Lam l km relative humidity (%) at VOL HSS = 0.275 (Observations in Columns)

Forecasts in Rows	<30	$30 \le x < 65$	$65 \le x < 90$	$90 \le X < 94$	$94 \le x < 98$	>98
<30	3	12	0	0	0	0
$30 \le x < 65$	21	854	227	19	14	5
$65 \le x < 90$	0	525	729	143	253	700
$90 \le x < 94$	0	1	85	53	72	253
$94 \le x < 98$	0	12	51	44	181	525
>98	0	2	23	26	131	514
Total	24	1,406	1,115	285	651	1,979

Lam 1 km minimum visibility (m) at VOL HSS = 0.104 (Observations in Columns)

Forecasts in Rows	<30	$30 \le x < 50$	$50 \le x < 200$	$200 \le x < 300$	$300 \le x < 500$	500
<30	0	0	0	0	0	0
$30 \le x < 50$	0	0	0	0	0	0
$50 \le x < 200$	0	0	52	20	22	43
$200 \le x < 300$	0	0	76	18	19	103
$300 \le x < 500$	0	1	26	15	12	60
>500	0	9	762	236	165	3,743
Total	0	10	916	289	218	3,949

Lam 1 k minimum precipitation type at VOL HSS = 0.539 (Observations in Columns)

Forecasts in Rows	No precip	Liquid	Freezing	Frozen	Mixed	Unknown
No precip	3,054	83	1	428	0	20
Liquid	127	126	3	80	0	3
Freezing	8	0	1	33	0	1
Frozen	244	16	2	963	0	8
Mixed	37	30	3	109	0	2
Unknown	0	0	0	0	0	0
Total	3,470	255	10	1,613	0	34

The verification was done at 15 min intervals for the whole 19 h of each model run between 12 February 2010, 0 UTC and 22 March 2010, 0 UTC

For visibility, the minimum visibility in that 15 min interval was used for the verification

"unlimited" values which are not accurately measured or reported by an observer.

- There are many difficulties in measuring parameters, especially winds, precipitation amount and precipitation type in this environment (see Gultepe *et al.*, 2012). For example, special scanning strategies were necessary for the scanning radar placed at Whistler because of beam blockage. Significant differences were observed with different types of surface precipitation sensors placed at the same location (e.g., Boudala *et al.*, 2012). Measurement of winds in complex terrain is extremely difficult because flat areas with a suitable fetch are not available.
- Some of the nowcast techniques (e.g., INTW, ABOM and INCA) showed skill as shown by Huang *et al.* (2012a, b), Bailey *et al.* (2012) and Haiden *et al.* (2012). However, precipitation nowcasting based on radar echo extrapolation did not work well because of terrain influences (see Fig. 9).

Over time the experimental data set gathered during SNOW-V10 will help improve techniques related to nowcasting during the winter season, and it will become a resource for other interested WMO member states. A WMO endorsed project entitled the Forecast and Research Olympic Sochi Testbed

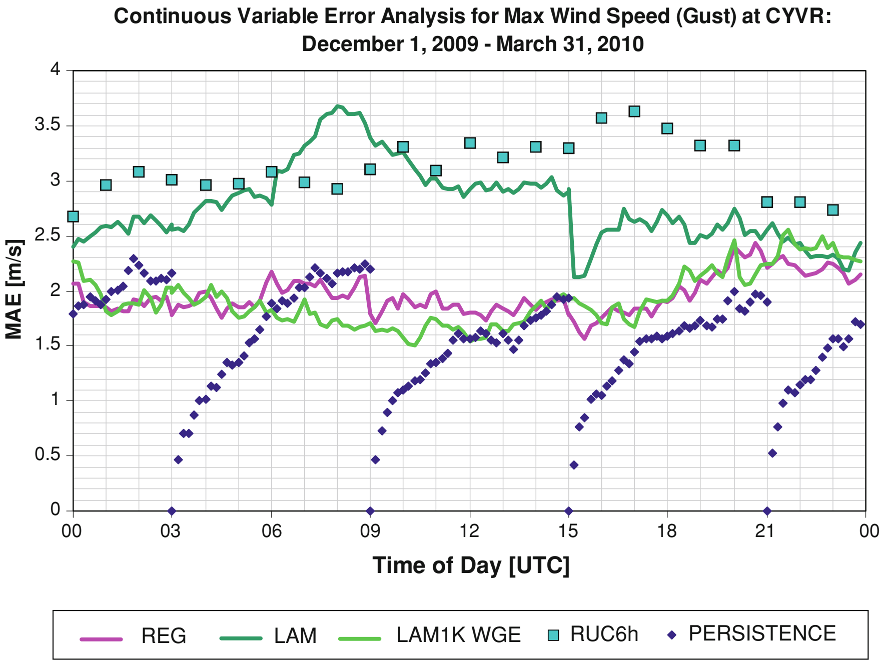


Figure 10
The mean absolute error of wind gust for Vancouver Airport for 1 December 2009 to 31 March 2010 for the GEM REG, GEM LAM 2.5 km, GEM LAM 1 km, and US RUC model versus persistence

Table 11

A comparison of the mean absolute error (MAE) averaged over the first 6 h forecast for relative humidity (%) for the GEM LAM 1 km, GEM LAM 2.5 km and GEM REG models, the INTW nowcast technique using these three models, and the persistence error (PERS) at the indicated site

MAE in relative humidity (%)						
Site	Altitude (m)	LAM 1 K	LAM 2.5 K	REG	INTW	PERS
Vancouver (YVR)	2	6.9	8.1	8.5	5.2	6.4
West Vancouver (WWA)	168	10.1	11.6	10.9	7	7.5
Cypress Bowl North (VOE)	953	6.7	7.6	9.1	4.7	5.5
Squamish Airport (WSK)	52.1	11.8	13.1	10.2	6.2	8
Pemberton Airport (WGP)	204.3	15.9	16.7	10.8	6.8	9.1
Callaghan (VOX)	860	12.3	10.4	9.1	6.7	7.8
Callaghan Ski Jump Top (VOW)	936	9.8	9.6	12.5	5.7	5.9
Callaghan Valley (VOD)	884	12.9	10.4	8.9	7.1	8.6
Blackcomb Mountain/Nesters (VOC)	651.5	10.4	8.3	7.8	5.8	8.2
Whistler Mountain Timing Flats (VOT)	804.9	9.3	8.2	10.3	5.8	7.9
Whistler Creek side (VOB)	933	8.6	8.7	12.2	5.2	5.9
Blackcomb Sliding Centre (VOI)	937	8.9	8.2	11.1	5.4	7.4
Whistler Mountain Mid Level (VOL)	1,320	9.1	8.6	15	5.4	4.7
Whistler Mountain High Level (VOA)	1,640	7.7	8.8	10.5	5.6	6.8

The period 5 February to 21 March 2010 was chosen for this comparison (see Huang *et al.*, 2012b)

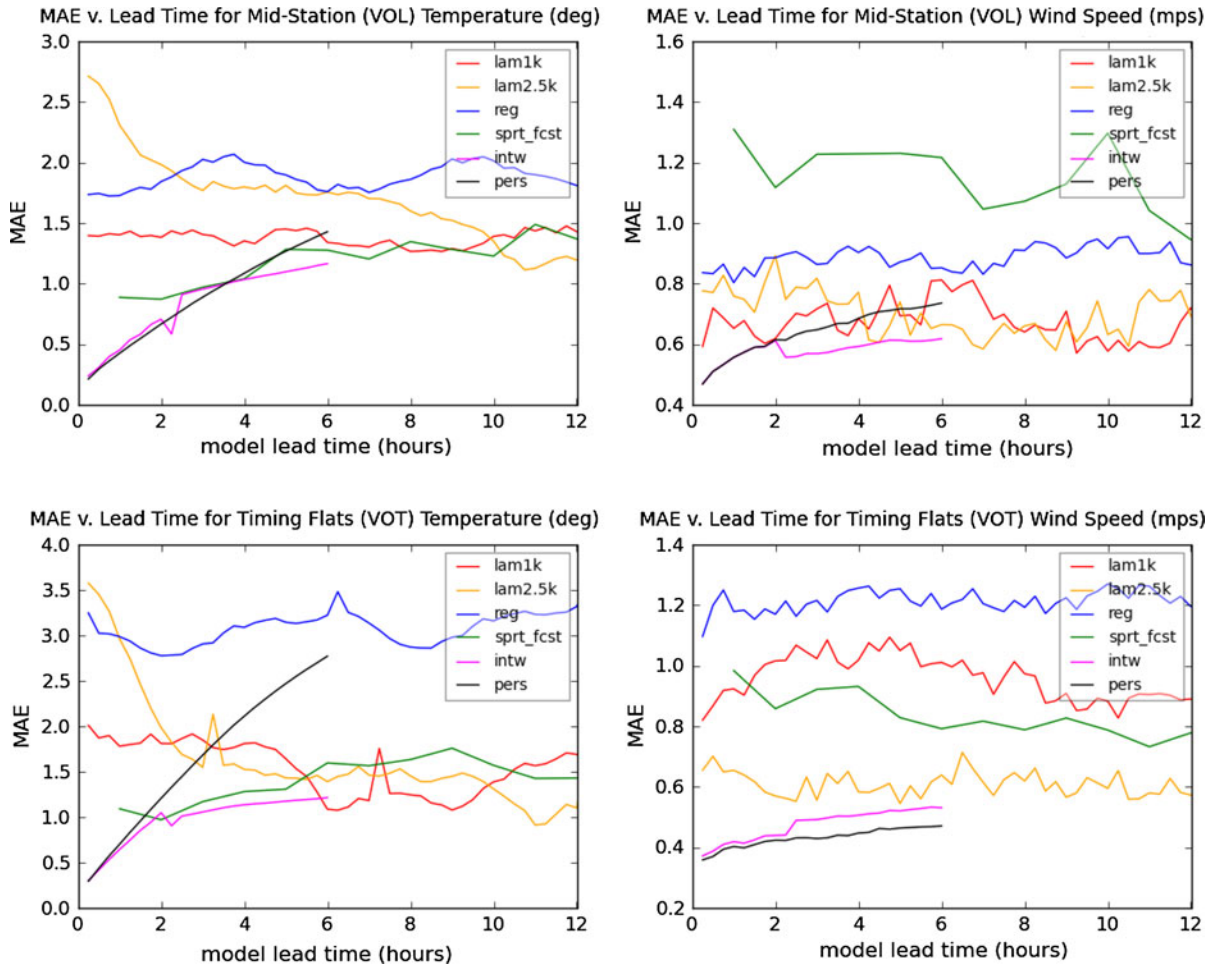


Figure 11

Shows the errors in temperature and wind speed for Whistler Mountain Mid Station (VOL) and Timing Flats (VOT) as a function of forecast lead time out to 12 h for the three Canadian NWP models, the SPORT forecasts, INTW, and persistence. This analysis was done for the Olympic Period

(FROST-2014) is now under active planning for the Sochi Olympic Winter Games in 2014 Kiktev *et al*., (2012). Many SNOW-V10 participants are actively involved in that project.

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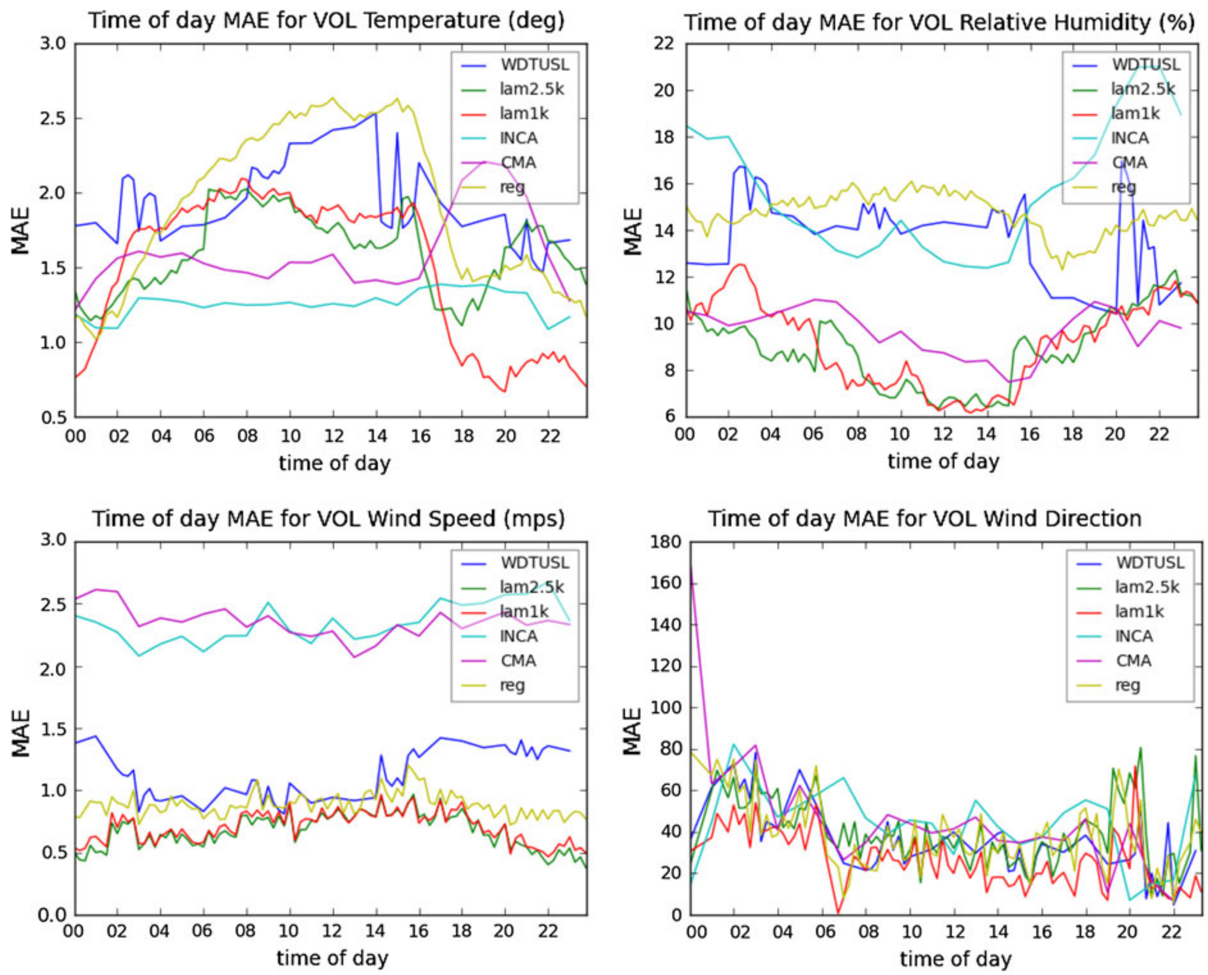

Figure 12
A comparison of the Canadian (REG, 2.5 and 1 km), WDT, CMA and INCA models as a function of time of day (UTC) for temperature, relative humidity, wind speed and direction for Whistler Mountain Mid Station (VOL) for the Olympic period. All forecasts for each model for that time of day were included. Direct comparisons between models is difficult because model forecast lead times are not necessarily the same for each time of day

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References

Anderson-Berry, L., Keenan, T., Bally, J. Pielke, R., Jr., Leigh, R., and King, D. (2004), *The societal, social and economic impacts of the World Weather Research Programme Sydney 2000 forecast demonstration project (WWRP S2000 FDP)*. Weather and Forecasting, *19*, 168–178.

Bailey, ME., Isaac, GA., Gultepe, I., Heckman, I., and Reid, J. (2012), *Adaptive blending of model and observations for automated short range forecasting: Examples from the Vancouver 2010 Olympic and Paralympic Winter Games*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0553-x.

Benjamin SG, Devenyi D, Smirnova T, Weygandt S, Brown JM, Peckham S, Brundage K, Smith TL, Grell G, Schlatter T (2006), From the 13-km RUC to the rapid refresh. *12th Conference on aviation, range, and aerospace meteorology (ARAM), Atlanta*. CD-ROM 9.1. American Meteorological Society: Boston, MA.

Benjamin SG, Devenyi D, Weygandt SS, Brundage KJ, Brown JM, Grell GA, Kim D, Schwartz BE, Smirnova TG, Smith TL, Manikin GS (2004), *An hourly assimilation/forecast cycle: the RUC*. Mon. Weather. Rev., *132*: 495–518.

Bellon, A., and Austin, GL. (1978), *The evaluation of two years of real-time operation of a short-term precipitation forecasting procedure (SHARP)*. J. Appl. Meteor., *17*, 1778–1787.

BELLON A., AUSTIN G.L. (1986), *The accuracy of short-term radar rainfall forecasts*. J. of Hydrology, *70*: 35–49.

BENOIT, R., SCHÄR, C., BINDER, P., CHAMBERLAND, S., DAVIES, HC., DESGAGNE, M., GIRARD, C., KEIL, C., KOUWEN, N., LÜTHI, D., MARIC, D., MÜLLER, E., PELLERIN, P., SCHMIDLI, J., SCHUBIGER, F., SCHWIERZ, C., SPRENGER, M., WALSER, A., WILLEMSE, S., YU, W., and ZALA, E. (2002), *The real-time ultrafinescale forecast support during the special observing period of the MAP*. Bulletin of the American Meteorological Society, *83*, 85–109.

BERNIER, N.B., BÉLAIR, S., BILODEAU, B., and TONG, L. (2011), *Near-surface and land surface forecast system of the Vancouver 2010 Winter Olympic and Paralympic games*. J. Hydromet., *12*, 508–530.

BERNIER, N.B., BÉLAIR, S., BILODEAU, B., and TONG, L. (2012), *Assimilation and high resolution forecasts of surface and near surface conditions for the 2010 Vancouver Winter Olympic and Paralympic games*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0542-0.

BOUDALA, F.S., ISAAC, G.A., RASMUSSEN, R., COBER, S.G., and SCOTT, B. (2012), *Comparisons of snowfall measurements in complex terrain made during the 2010 winter Olympics in Vancouver*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0610-5.

BOWLER, N., PIERCE, C.E., and SEED, A.W. (2006), *STEPS: a probabilistic precipitation forecasting scheme which merges an extrapolation nowcast with downscaled NWP*. Q. J. R. Meteorol. Soc. (2006), *132*, 2127–2155.

CARPENTER, R., SHAW, B., SPENCER, P., DUFRAN, Z., and HAUGLAND, M. (2009), Advanced NWP for short-term wind power and precipitation forecasting. Extended abstracts, WMO symposium on nowcasting, Whistler, BC, Canada.

CHEN, C., WANG, D., LIU, Y., ZHANG, Z., FENG, T., DU, J., WANG, J., ISAAC, G.A., MAILHOT, J., MILBRANDT, J.A., MCTAGGART-COWAN, R. (2012), *Comparison of high- and low-resolution regional models' performances over complex terrain during the 2010 Vancouver Winter Olympic and Paralympic Games*. Pure and Applied Geophysics.

DOYLE, C., (2012), *The impact of weather forecasts of various lead-times on snowmaking decisions made for the 2010 Vancouver Olympic Winter Games*. Pure and Applied Geophysics. doi: 10.1007/s00024-012-0609-y.

EBERT, E.E., WILSON, L.J., BROWN, B.G., BROOKS, H.E., BALLY, J., and JAENEKE, M. (2004), *Verification of nowcasts from the WWRP Sydney 2000 forecast demonstration project*. Wea. Forecasting, *19*, 73–96.

FILLION, L., TANGUAY, M., LAPALME, E., DENIS, B., DESGAGNE, M., LEE, V., EK, N., LIU, Z., LAJOIE, M., CARON, J.-F., PAGÉ, C., (2010), *The Canadian regional data assimilation and forecasting system*. Wea. Forecast, *25*, 1645–1669.

GOLDING, B.W. (1998), *Nimrod: a system for generating automated very short range forecasts*. Meteorol. Appl., *5*, 1–16.

GULTEPE, I., PEARSON, G., MILBRANDT, J.A., HANSEN. B., PLATNICK, S., TAYLOR, P., GORDON, M., OAKLEY, J.P., and COBER, S.G (2009), *The fog remote sensing and modeling field project*. AMS Bulletin. *90*, 341–359.

GULTEPE, I., ISAAC, G.A., JOE, P., KUCERA, P., THERIAULT, J., and FISICO, T. (2012), *Roundhouse (RND) Mountain top research site: measurements and uncertainties for alpine weather conditions*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0582-5.

HAIDEN, T., PISTOTNIK, G. (2009), *Intensity-dependent parameterization of elevation effects in precipitation analysis*. Adv. Geosci., *20*, 33–38.

HAIDEN, T., KANN, A., WITTMANN, C., PISTOTNIK, G., BICA, B., GRUBER, C. (2011), *The Integrated Nowcasting through Comprehensive Analysis (INCA) system and its validation over the Eastern Alpine region*. Wea. Forecasting, *26*, 166–183.

HAIDEN, T., KANN, A., and PISTOTNIK, G. (2012), *Nowcasting with INCA during SNOW-V10*. Pure and Applied Geophysics. doi: 10.1007/s00024-012-0547-8.

HUANG, L.X., ISAAC, G.A., and SHENG, G. (2012a), *Integrating NWP forecasts and observation data to improve nowcasting accuracy*. Wea. Forecasting, *27*, 938–953. doi:http://dx.doi.org/10.1175/WAF-D-11-00125.1.

HUANG, L.X., ISAAC, G.A., and SHENG, G. (2012b), *A new integrated weighted model in SNOW-V10: Verification of continuous variables*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0548-7.

HUANG, L.X., ISAAC, G.A., and SHENG, G. (2012c), *A new integrated weighted model in SNOW-V10: Verification of categorical variables*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0549-6.

ISAAC, G.A., BAILEY, M., COBER, S.G., DONALDSON, N. DRIEDGER, N., GLAZER, A., GULTEPE, I., HUDAK, D., KOROLEV, A., REID, J., RODRIGUEZ, P., STRAPP, J.W., and FABRY, F. (2006), Airport vicinity icing and snow advisor. *AIAA 44th aerospace sci meeting and exhibit*, Reno Nevada, 9–12 Jan 2006, AIAA-2006-1219.

ISAAC, G.A., BAILEY, M., BOUDALA, F.S., COBER, S.G., CRAWFORD, R.W., DONALDSON, N., GULTEPE, I., HANSEN, B., HECKMAN, I., HUANG, L.X., LING, A., MAILHOT, J., MILBRANDT, J.A., REID, J., and FOURNIER, M. (2012), *The Canadian airport nowcasting system (CAN-Now)*. In press, Meteorological Applications. doi: 10.1002/met.1342.

JOE, P., DOYLE, C., WALLACE, A., COBER, S.G., SCOTT, B., ISAAC, G.A., SMITH, T., MAILHOT, J., SNYDER, B., BELAIR, S., JANSEN, Q., and DENIS, B. (2010), *Weather services, science advances, and the Vancouver 2010 Olympic and Paralympic winter games*. Bulletin American Meteorological Society, *91*, 31–36.

JOE, P., SCOTT, B., DOYLE, C., ISAAC, G.A., GULTEPE, I., FORSYTH, D., COBER, S.G., CAMPOS, E., HECKMAN, I., DONALDSON, N., HUDAK, D., RASMUSSEN, R., STEWART R.E., THÉRIAULT, J.M., CARMICHAEL, H., BAILEY, M., and BOUDALA, F.S. (2012), *The monitoring network of the Vancouver 2010 Olympics*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0588-z.

KEENAN, T., JOE, P., WILSON, J., COLLIER, C., GOLDING, B., BURGESS, D., MAY, P., PIERCE, C., BALLY, J., CROOK, A., SEED, A., SILLS, D., BERRY, L., POTTS, R., BELL, I., FOX, N., EBERT, E., EILTS, M., O'LOUGHLIN, K., WEBB, R., CARBONE, R., BROWNING, K., ROBERTS, R., and MUELLER, C. (2003), *The Sydney 2000 world weather research programme forecast demonstration project: overview and current status*. Bulletin American Meteorological Society, *84*, 1041–1054.

KIKTEV D., and Co authors, (2012), *Development of weather forecasting systems for winter Olympic Games "Sochi-2014", in preparation*. Russian Meteorology and Hydrology.

LI, X., CHARRON, M., SPACEK, L., and CANDILLE, G. (2008), *A regional ensemble prediction system based on the moist targeted singular vectors and stochastic parameter perturbations*. Mon. Wea. Rev., *136*, 443–462.

MAILHOT, J., BÉLAIR, S., LEFAIVRE, L., BILODEAU, B., DESGAGNÉ, M., GIRARD, C., GLAZER, A., LEDUC, A.-M., MÉTHOT, A., PATOINE, A., PLANTE, A., RAHILL, A., ROBINSON, T., TALBOT, D., TREMBLAY, A., VAILLANCOURT, P., ZADRA1, A., and QADDOURI, A. (2006), *The*

15-km version of the Canadian regional forecast system. Atmos-Ocean, *44*, 133–149.

Mailhot, J., Bélair, S., Charron, M., Doyle, C., Joe, P., Abrahamowicz, M., Bernier, N.B., Denis, B., Erfani, A., Frenette, R., Giguère, A., Isaac, G.A., McLennan, N., McTaggart-Cowan, R., Milbrandt, J., and Tong, L. (2010), *Environment Canada's experimental numerical weather prediction systems for the Vancouver 2010 Winter Olympic and Paralympic games*. Bulletin American Meteorological Society, *91*, 1073–1085.

Mailhot, J., Milbrandt, J.A., Giguère, A., McTaggart-Cown, R., Erfani, A., Denis,B., Glazer, A., and Vallée, M. (2012), *An experimental high-resolution forecast system during the Vancouver 2010 Winter Olympic and Paralympic Games*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0520-6.

Milbrandt, J.A., Theriault, J., and Mo, R. (2012), *Modeling the phase transition associated with melting snow in a 1D kinematic framework: sensitivity to the microphysics*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0552-y.

Mo, R., Joe, P., Isaac, G.A., Gultepe, I., Rasmussen, R., Milbrandt, J., McTaggart-Cowan, R., Mailhot, J., Brugman, M., Smith, T., and Scott, B. (2012a), *Mid-mountain clouds at Whistler during the Vancouver 2010 Winter Olympics and Paralympics*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0540-2.

Mo, R., Joe P.I., Doyle, C., and Whitfield, P.H. (2012b), *Verification of an ENSO-based long-range prediction of anomalous weather conditions during the Vancouver 2010 Olympics and Paralympics*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0523-3.

Pierce, C.E., Ebert, E., Seed, A.W., Sleigh, M., Collier, C.G., Fox, N.I., Donaldson, N., Wilson, J.W.W., Roberts, R., and Mueller, C.K. (2004), *The nowcasting of precipitation during Sydney 2000: an appraisal of the QPF algorithms*. Weather and Forecasting, *19*, 7–21.

Rasmussen, R., Dixon, M., Hage, F., Cole, J., Wade, C., Tuttle, J., McGettigan, S., Carty, T., Stevenson, L., Fellner, W., Knight, S., Karplus, E., and Rehak, N. (2001), *Weather support to deicing decision making (WSDDM): a winter weather nowcasting system*. Bull. Amer. Meteriol. Soc., *82*, 579–595.

Rotach, M.W., Ambrosetti, P., Appenzeller, C., Arpagaus, M., Fontannaz, L., Fundel, F., Germann, U., Hering, A., Liniger, M.A., Stoll, M., Walser, A., Ament, F., Bauer, H.-S., Behrendt, A., Wulfmeyer, V., Bouttier, F., Seity, Y., Buzzi, A., Davolio, S., Corazza, M., Denhard, M., Dorninger, M., Gorgas, T., Frick, J., Hegg, C., Zappa, M., Keil, C., Volkert, H., Marsigli, C., Montaini, A., McTaggart-Cowan, R., Mylne, K., Ranzi, R., Richard, E., Rossa, A., Santos-Muñoz, D., Schär, C., Staudinger, M., Wang, Y., Werhahn, J. (2009), *MAP D-PHASE: real-time demonstration of weather forecast quality in the alpine region*. Bulletin American Meteorological Society, *90*, 1321–1336.

Schuur, T. J., Ryzhkov, A.V., Forsyth, D.E., Zhang, P., Reeves, H.D. (2012), *Cloud observations with NSSL's X-band polarimetric radar during the SNOW-V10 campaign*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0569-2.

Stoelinga, M.T., Hobbs, P.V., Mass, C.F., Locatelli, J.D., Colle, B.A., Houze R.A., Jr., Rangno, A.L., Bond, N.A., Smull, B.F., Rasmussen, R.M., Thompson, G., and Colman, B.R. (2003), *Improvement of microphysical parameterization through observational Verification Experiment*. Bull. Amer. Meteriol. Soc., *84*, 1807–1826.

Su, D., Wang, J., Wang, Y., and Liang, F. (2007), A brief introduction of B08FDP for Beijing 2008 Olympics. In: 33rd conference on radar meteorology, 6–10 Aug 2007, Caines, Australia, paper 5.2 extended abstract.

Teakles, A., Mo, R., Joe, P.I., Dierking, C.F., Emond, C., and McLennan, N. (2012), *Realizing user-relevant conceptual model for the ski jump venue of the Vancouver 2010 Winter Olympics*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0544-y.

Thériault, J.M., Rasmussen, R., Smith, T., Mo, R., Milbrandt, J.A., Brugman, M.M., Joe, P., Isaac, G., Mailhot, J., and Denis, B. (2012a), *A case study of processes impacting precipitation phase and intensity during the Vancouver 2010 Winter Olympics*. Wea. Forecasting. doi:10.1175/WAF-D-11-00114.1, in press.

Thériault, J.M., Rasmussen, K.L., Fisico, T., Stewart, R.E., Joe, P., Gultepe, I., Clément M., Isaac, G.A. (2012b), *Weather observations along Whistler Mountain in five storms*. Pure and Applied Geophysics. doi:10.1007/s00024-012-0590-5.

Turner, B.J., Zawadzki, I., and Germann, U. (2004), *Predictability of precipitation from continental radar images. Part III: operational nowcasting implementation (MAPLE)*. J. Appl. Meteriol., *43*, 231–248.

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