The Canadian Arctic Weather Science Project

Introduction to the Iqaluit Site

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ABSTRACT: The goal of the Canadian Arctic Weather Science (CAWS) project is to conduct research into the future operational monitoring and forecasting programs of Environment and Climate Change Canada in the Arctic where increased economic and recreational activities are expected with enhanced transportation and search and rescue requirements. Due to cost, remoteness and vast geographical coverage, the future monitoring concept includes a combination of space-based observations, sparse in situ surface measurements, and advanced reference sites. A prototype reference site has been established at Iqaluit, Nunavut (63°45'N, 68°33'W), that includes a Ka-band radar, water vapor lidars (both in-house and commercial versions), multiple Doppler lidars, ceilometers, radiation flux, and precipitation sensors. The scope of the project includes understanding of the polar processes, evaluating new technologies, validation of satellite products, validation of numerical weather prediction systems, development of warning products, and communication of their risk to a variety of users. This contribution will provide an overview of the CAWS project to show some preliminary results and to encourage collaborations.

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Developmental pressures, combined with social–cultural, technological, and climate–environmental changes are driving and increasing human activity in the Canadian Arctic region. The Northwest Passage is expected to be a prime transportation corridor (Fig. 1) with enhanced ship traffic shifting close to Canadian coasts (Smith and Stephenson 2013). Air traffic statistics showed a substantial increase from nearly 400 transpolar flights in 2000 to 12,759 flights in 2014, with a subsequent annual projected growth of 3.5% (Arctic Council 2017).

Supporting infrastructure for navigation as well as for safety and security and for search and rescue (SAR) operations are yet to be fully defined but will no doubt be required. With increased human activity and changes in weather patterns, the Canadian Arctic (consisting of Nunavut, Northwest Territories, and Yukon Territory), experienced 240.5 ground-based SAR incidents per 100,000 population in 2012, which is about one to two orders of magnitude larger than that in British Columbia and Ontario (Statistics Canada 2020). Weather-related hazards, including blizzards, high winds, and low visibility are the primary contributing factors that affect navigation, safety, and mobility of those requiring emergency response and also those engaged in SAR operations. These hazardous conditions are expected to become more frequent, longer in duration, and less predictable under climate change scenarios (Ford et al. 2013).

The Canadian Arctic is sparsely observed. Recent efforts have been limited-time weather projects or have generally had a climate science focus. Projects include the Beaufort and Arctic Storms Experiment (Asuma et al. 1998), Mackenzie GEWEX (Global Energy and Water Experiment) Study (MAGS 2018), Storm Studies in the Arctic (Hanesiak et al. 2010), Canadian Network for the Detection of Atmospheric Change/Polar Environment Atmospheric Research Laboratory (CANDAC 2018), Atmospheric Radiation Measurement program of the U.S. Department of Energy (ARM 2018), the Indirect and Semi-Direct Aerosol Campaign (McFarquhar et al. 2011), and Canadian Sea Ice and Snow Evolution Network (CANSISE 2019). Results from these projects found that (i) precipitation is very light but ubiquitous (Stewart et al. 1998), (ii) the radiative effects of persistent light precipitation can lead to cold air outbreaks in the midlatitudes (Girard and Blanchet. 2001a,b), and (iii) changes in precipitation are early indicators of climate warming (IPCC 2014).

Environment and Climate Change Canada (ECCC) has begun the process of defining weather monitoring requirements for the Arctic. A network monitoring design consisting of a limited number of surface and radiosonde stations, satellite observations, and reference stations, due to logistics and operating costs, is hypothesized. This project, called Canadian Arctic Weather Science (CAWS), has main priorities consistent with the recommendations of the Fourth Arctic Observing Summit (AOS 2018), namely,

- identify and test future operational monitoring technologies for the Arctic including remote sensing;
- validate weather-related satellite products, in particular, precipitation and wind estimates from the Global Precipitation Mission and Aeolus, respectively;
- understand Arctic weather phenomena and their impact on observation and prediction requirements;
- develop, validate, and verify atmospheric prediction products for high-impact local weather applications;
- co-design communication strategies for predictions and warnings with the indigenous community;
- quantify societal benefits and impacts; and

- collaborate and support other national and international projects such as, the Polar Prediction Project (Jung et al. 2016; YOPP 2019) and the Sustaining Arctic Observing Networks (SAON 2019).

Operationally, fog is frequent, particularly in the summer and fall and is a significant operational hazard for transportation, in particular at sea (with sea ice present), and presents a major concern for navigation and SAR operations. Blizzards can disrupt air traffic for days at a time. Winds can be very strong and affect transportation, sea ice movement, navigation, and hunting and are therefore critical to life among the indigenous people (Gearheard et al. 2010). Winds also affect catchment snow gauge measurements (WMO 2019) and reduce visibility in blizzard situations. Due to the high cost of operations, technologies for replacing radiosondes are also a significant focus of the CAWS project. Solid precipitation measurements of light precipitation in high-wind conditions is also significant challenge. Satellite measurements are able to provide broad coverage of various meteorological parameters with different accuracies and spatial and temporal resolutions compared to ground-based measurements and therefore are part of the overall monitoring network design. Therefore, validation of satellite missions producing precipitation products, temperature, wind and humidity profile products are of prime interest. Missions of interest include current operational geostationary (GOES) and polar (NPOESS, MetOp) satellites and science or preoperational near-polar orbiting satellites such as CloudSat (98° inclination; Stephens et al. 2008, 2018), the Global Precipitation Mission (65° inclination; Hou et al. 2014; Skofronick-Jackson et al. 2017), Aeolus (ESA 2018), and EarthCARE (both with 97° inclinations; Illingworth et al. 2015a).

Fig. 1. Map of major storm tracks (large yellow arrows; ECCC training materials/Ed Hudson, personal communication) are shown overlaid on marine transportation routes (2011–16 from the Environment, Society and Policy Group at the University of Ottawa; www.espg.ca). The location of the Iqaluit CAWS reference site is circled in red. The marine transportation routes for fishing (orange), cargo (black), passenger ships (red), and pleasure boats (green) are shown. The inset shows a shaded 3D representation of the complex topography around Iqaluit (indicated by red–yellow marker). The highest terrain is to the north–northwest at ~550 m.

The CAWS project coincides with a new responsibility for ECCC to provide meteorological services (METAREAs) in the Arctic. Higher-resolution coupled atmosphere–ocean–sea ice models in this region are being developed and require validation and verification. This provides the opportunity to develop products relevant to local weather applications such as terminal operations at airports and products specific to indigenous life the Arctic. These include fog, blizzard warnings, and high-resolution wind nowcasts. Communication of scientific products is a recognized issue to all end users. In particular, risk communication, as well as demonstrating societal impact and benefits, will require engagement of the indigenous community (AOS 2018).

The objective of this contribution is to inform the community about the site, the instruments, and the nature of the data through examples and to provide a base reference for scientific contributions. Examples will highlight the emerging observation requirements, some prediction products, verification/validation methodologies, and the approach for community engagement. This contribution is organized as follows: (i) the CAWS Iqaluit site and instruments are described, (ii) the Pan-Arctic prediction systems and postprocessed forecast products are presented, (iii) examples to illustrate the nature of the weather, (iv) discussion, and (v) a summary.

Iqaluit site and instruments

ECCC has established a meteorological reference site at Iqaluit, Nunavut, which is in the eastern Canadian Arctic (63°45'N, 68°33'W). Figure 1 shows the strategically selected location of Iqaluit, which is

- the primary gateway for air traffic for the eastern Arctic;
- near many current and planned primary transportation corridors for seafaring vessels;
- influenced by a diversity of synoptic storms originating from across the Arctic;
- an operational radiosonde site, with an existing office/data infrastructure and substantial existing field facilities for instrument testing, including a double fence intercomparison reference¹ for solid precipitation with space for additional instruments, enabling research-operations engagement; and
- the capital and largest city in Nunavut with postsecondary schools and is a hub for the indigenous community that enables co-design of weather products and societal impact studies and industrial and scientific resources for logistical support, including SAR. The total population is about 8,000 with more than 80% Inuit ethnicity.

Table 1 shows a basic climatology of the site. Cold temperatures (below –20°C) are very common and while this is a major concern for operating and repairing the instruments (limiting deployment and maintenance to summer months), it is not a significant concern for the indigenous people in their daily lives. Strong wind, however, is important factor for the people (both indigenous and those “from the south”), as it creates blizzard conditions hampering aviation and transport; affects sea travel, particularly by small vessels, and sea ice movement; and, most significantly, affects hunting, which is a critical activity for sustaining the diet of the indigenous people (Gearheard et al. 2010).

Figure 2 provides an overview of the occurrence of hourly weather observations and, in particular, the high occurrence of hazardous blowing snow and fog (red bars) from the start of the project. Figure 3 shows the hours of low-visibility events for 2016–18 during snowfall. Blizzard watches or warnings are issued when 8 consecutive hours of visibility less than 0.5 or 0.25 mi (1 mi ≈ 1.61 km) are expected, respectively. There were 196 days (25%) of near-blizzard (<0.5 mi) and 53 days (6%) of blizzard conditions (<0.25 mi) in the project period, respectively.

¹ A double-fence intercomparison reference (DFIR) is the reference standard for the calibration of solid-precipitation gauges. It consists of a manual catchment gauge with the gauge orifice at 3-m height, surrounded by two fences of 4- and 12-m diameter of 3- and 3.5-m height, respectively, to reduce the wind effect (WMO 2019).

Table 1. Climate normals for 1981–2010 (ECCC, http://climate.weather.gc.ca/climate_normals/index_e.html#1981, accessed 19 October 2018).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature													
Daily avg (°C)	−26.9	−27.5	−23.2	−14.2	−4.4	3.6	8.2	7.1	2.6	−3.7	−12	−21.3	−9.3
Daily max (°C)	−22.8	−23.3	−18.3	−9.4	−1.2	6.8	12.3	10.5	5.2	−1	−8.3	−17	−5.6
Daily min (°C)	−30.9	−31.7	−28.1	−18.9	−7.6	0.5	4.1	3.6	−0.1	−6.4	−15.8	−25.5	−13.1
Extreme max (°C)	3.9	5.7	4	7.2	13.3	21.7	26.1	25.5	17.2	7.3	5.6	3.4	
Extreme min (°C)	−45	−45.6	−44.7	−34.2	−26.1	−10.2	−2.8	−2.5	−12.8	−27.1	−36.2	−43.4	
Days with minimum temperature													
<−10°C	30.8	27.9	30	24.8	10.3	0	0	0	0	7.1	22	29.3	182.4
<−20°C	28.5	25.9	26.1	15.4	0.38	0	0	0	0	0.59	9.9	23.7	130.6
<−30°C	19.1	17.8	14.8	1.3	0	0	0	0	0	0	0.61	9.3	62.8
Precipitation													
Rainfall (mm)	0	0	0	0.2	3.1	23.8	51.9	68.6	42.2	6.8	0.6	0	197.2
Snowfall (cm)	21.7	21	21.6	31.5	27.6	9.3	0	0.9	13.2	29.4	29.7	23.4	229.3
Precipitation (mm)	19.7	18.7	18.7	27.5	29.2	33	51.9	69.5	55.2	33.3	27.2	19.9	403.7
Avg snow depth (cm)	22	25	26	31	22	3	0	0	0	5	15	19	14
Median snow depth (cm)	21	25	26	30	20	1	0	0	0	5	14	18	13
Snow depth at month–end (cm)	24	28	30	29	12	0	0	0	1	9	20	21	14
Extreme daily snowfall (cm)	30.7	32.2	24.6	21.8	29.5	19.2	3.6	6.2	21.3	20.6	27.9	21.8	
Days with snow depth													
≥1 cm	30.9	28.2	31	30	29.1	10	0	0	2.7	24.6	30	31	247.5
≥20 cm	20.7	20.1	22.8	24.8	15.8	1.1	0	0	0	0.93	5.1	13.3	124.6
Wind													
Speed (km h ^{−1})	15.9	15.3	14.9	16.2	17.1	14.9	12.6	13.5	15.4	17.6	18.6	16.3	15.7
Most frequent direction	NW	NW	NW	NW	NW	SE	SE	SE	SE	NW	NW	NW	NW
Max hourly speed (km h ^{−1})	108	120	129	116	85	72	80	90	97	104	97	111	129
Direction of max hourly speed	E	NE	NW	NW	NW	E	SE	NW	SE	NW	E	NW	NW
Max gust speed (km h ^{−1})	146	114	156	153	103	93	117	109	126	137	126	141	156
Visibility (hours with)													
<1 km	21.6	22.5	19.3	11.5	7.1	3.8	7.9	6.9	7.6	5.5	11.3	13.8	138.7
1–9 km	155	149.8	142.7	111.4	91	40.4	39	47.9	64	91.6	111.1	143.8	1,187.4
>9 km	567.5	504.7	582.1	597.1	645.9	675.8	697.1	689.2	648.5	647	597.6	586.4	7,438.9
Cloud amount (hours with)													
0–2 tenths	282	256.6	280.7	232.9	101.4	114.7	123	88.2	77	97.6	161	253.4	2,068.6
3–7 tenths	144.2	139.6	130.4	113.8	105.2	124.6	182.2	148.9	105	96.8	101.6	140.9	1,533.1
8–10 tenths	317.9	280.8	332.8	373.4	537.4	480.7	438.8	506.9	538	549.6	457.4	349.8	5,163.3

Fig. 2. Distribution of hourly observations of weather for 2016–18. Note the high occurrence of snow, blowing snow, and fog (highlighted in red). The “not available” (NA) category is removed to focus just on the weather types.

Table 2 lists the instruments and observations made at the Iqaluit site. At this stage, with one exception, the instruments were commercial off-the-shelf purchases and not specified to operate in Arctic environments. Figure 4 shows a photo of the site and layout of the instruments. The site is continually evolving, but the first data were collected in the fall of 2015 and collection is ongoing. The extremely limited Internet bandwidth and associated data transfer constraints governed the design of the data collection, processing, and archiving. A limited suite of image products is created on-site and transferred to a web server in the south for access by researchers and forecasters. Raw data are stored on-site and manually retrieved a few times a year during maintenance or repair visits.

ECCC designed, built, and deployed the Canadian Autonomous Arctic Aerosol Lidar (CAAAL) for atmospheric profiling of aerosols and water vapor. It is based on two previous ECCC systems (Strawbridge 2013; Strawbridge et al. 2018) with enhancements to permit operation in the Arctic environment. The lidar system uses a three-wavelength (355, 532, and 1,064 nm)

Fig. 3. Time series of the duration of blizzard conditions at Iqaluit with visibility <0.5 (blue) and <0.25 (red) statute miles (0.8 and 0.4 km, respectively) based on hourly data from 23 Oct 2015 to 2 Apr 2018. The symbols (blue diamonds and red circles) indicate the corresponding average daily wind.

Table 2. Instrument list for Iqaluit site.

Instrument	Manufacturer	Date of deployment	Operation	Measurement(s)	Temporal sampling cycle and resolution
Precipitation imaging package	NASA Wallops	September 2014	380 frame per second grayscale camera with back-lighting	Particle imagery, drop size distribution, precipitation rate and density estimation	1 min; surface observation
Four cameras	Campbell Scientific	September 2015	High-resolution images of the site	Ka-radar, lidar, and sky-view images	5 min; 1080 pixels
Ka-band radar	METEK	September 2015	Scanning pulsed dual-polarization Doppler radar	Line-of-sight wind speed and direction, cloud and fog backscatter, depolarization ratio	10 min; 10-m resolution up to ~25-km range
Ceilometer CL31	Vaisala	September 2015	Pulsed (8 kHz) diode laser lidar	Cloud intensity, cloud octa and height, aerosol profiles, mixing-layer height	5 min; 5-m resolution up to 7.5 km
PWD 52 present weather detector and visibility sensor (x2)	Vaisala	September 2015	Forward-scatter measurement	Visibility, precipitation type	1 min; surface observation only
Doppler lidar	HALO	September 2015	Pulsed (10 kHz) scanning at 1.5 μm (Mie scattering)	Line-of-sight wind speed and direction, aerosol backscatter, depolarization ratio	5 min; 3-m resolution up to ~3-km range
Rosemount icing detector	Rosemount Engineering	September 2015	Magnetostrictive oscillation probe with a sensing cylinder	Detects ice, frost	—
Surface meteorological observations	Miscellaneous	Ongoing	Miscellaneous	Surface temperature (T), relative humidity (RH), pressure, winds, precipitation	1 min; surface observations
Radiosondes	Vaisala	Ongoing	Balloon-launched sonde	Profiles of T , RH, pressure, winds	12 h; ~15 m resolution up to ~30 km
4k Pantilt camera	Axis	October 2016	High-resolution images of the site	Automated pivoting camera provides images in all directions	5 min; 4k
Canadian Autonomous Arctic Aerosol Lidar (CAAAL)	ECCC	October 2016	355-, 532-, and 1,064-nm transmitter and six-channel receiver	Aerosol and water vapor profiles; particle size and shape information	1 min; 3-m resolution up to ~15 km
Doppler lidar: Ridge (T121)	HALO	October 2017	Pulsed (10 kHz) scanning at 1.5 μm (Mie scattering)	Line-of-sight wind speed and direction, aerosol backscatter, depolarization ratio	5 min; 3-m resolution up to ~3-km range
Scintillometer	Scintec	August 2018	Large-aperture optical transmitter/receiver	Turbulence, crosswind, heat flux	5 min; maximum 6-km pathlength
Fog measuring device	Droplet Measurement Technologies	August 2018	Fog sensor	Fog intensity, water vapor at surface	1 min
Far-infrared radiometer	LR Tech.	August 2018	Zenith/nadir-viewing infrared radiometer	Downwelling infrared radiation, cloud microphysics	10 min
Surface radiation fluxes	Campbell Scientific	August 2018	Surface radiation sensors (diffuse and direct)	Shortwave and longwave up, down, and horizontal radiation	1 min
Water vapor lidar	Vaisala	August 2018	Pulsed lidar system	Profiles of aerosols, 24-h water vapor profile	~20 min; 10-m resolution up to ~3 km
Precipitation Occurrence Sensor System (POSS)	ECCC	September 2018	Bistatic X-band Doppler radar	Precipitation type, rate, particle distribution	1 min

Fig. 4. Photo of the CAWS Iqaluit site, looking to the east, with instrument layout. T121 indicates a site located along the ridgeline east of main Iqaluit with a Doppler lidar to detect cross flows across the shallow valley.

diode-pumped, solid-state laser. The lidar produces 11.5°W at 355 nm, enabling water vapor measurements in the dry Arctic climate. The receiving channels measure the elastic backscatter as well as the cross polarization at 355 nm for particle shape, the two nitrogen Raman channels at 387 and 607 nm (for improved aerosol profile products), and the water vapor Raman channel at 407 nm. All raw data are collected at 1-min temporal resolution and with 3.75-m range resolution to a maximum range greater than 30 km with a minimum altitude range of approximately 50–90 m due to lidar overlap considerations. In practice, aerosols were observed to approximately 10-km altitude. Due to weak signals, water vapor retrieval requires additional processing of the data in range and has an effective vertical resolution of 29 m up to 1 km then linearly increases to 1,412 m at 16 km, but it is interpolated back to 3.75-m vertical bin resolution [see Leblanc et al. (2016) for full details]. The CAAAL operates continuously except during precipitation and when aircraft are overhead as detected by a radar.

Prediction and products

Wind and blizzard forecasts (at all scales) are primary weather products for the Nunavut region. In addition, fog is a navigation hazard for both aircraft and sea-faring vessels, particularly in the presence of sea ice and icebergs. ECCC runs several NWP systems for the Arctic region, all based on the Canadian Global Environmental Multiscale (GEM; Côté et al. 1998; Girard et al. 2014). Two deterministic systems have complete coverage of the Arctic: the operational Global Deterministic Prediction System (GDPS), with a 15-km horizontal grid spacing (not discussed here), and the experimental Canadian Arctic Prediction System (CAPS; 48-h forecasts), with a 3-km grid spacing, which is downscaled from the GDPS. Both are coupled to ice–ocean prediction models. The CAPS model is not always available due to its experimental and low-priority status (not discussed here). The Regional (RDPS; 10-km resolution, 84-h forecasts) and High Resolution Deterministic Prediction System (HRDPS; 2.5-km resolution, 48-h forecasts) models are operational local area models also downscaled from the GDPS and used extensively in the CAWS project. Forecasts are produced from operational model runs at 0000 and 1200 UTC.

New guidance products for warnings are created by postprocessing basic and derived NWP output, such as temperature, wind, and visibility in snow or blowing snow, and include the following:

- (i) The Blizzard Potential (BP) is derived from a set of forecaster expert's rules to identify areas where blizzard conditions could develop over land and ice-covered areas with at least 1 cm of snow on the ground, and it is intended as "heads-up" guidance to alert forecasters a few days in advance to regions where blizzard conditions might occur. The snowpack condition is not considered.
- (ii) A regression analysis of blizzard conditions assumes a "perfect prognosis" forecast of the probability of visibility ≤ 1 km due to blowing snow or to concurrent precipitating snow and blowing snow. It uses nearly 40 years of surface observations of visibility, 10-m wind speed and surface (screen 2 m) temperature (Baggaley and Hanesiak 2005). The number of hours since the last snowfall is included as a proxy for snowpack condition, and there are separate regression equations for six different ranges of elapsed time since the last snowfall of greater than 0.5 cm.
- (iii) The "time-offset model output statistics" (Burrows 1985) prediction uses the Random Forest machine-learning algorithm for classifying events (Breiman 2001) and predicts the likelihood of blizzard conditions. The training dataset were two winters of observations (October–May in 2015/16 and 2016/17) matched with RDPS output (Burrows and Mooney 2018).
- (iv) Similarly, a rules-based model (Burrows and Toth 2011) and a time-offset model output statistics (Burrows 1985) prediction using a Random Forest algorithm (Breiman 2001)

Fig. 5. (top) Reflectivity and (bottom) radial velocity from the scanning Ka-band Doppler polarization radar. (left) PPI at 5° elevation angle and (right) RHI scan along azimuth 135° are shown for a blizzard event at 1420 UTC 20 March 2016. Reflectivities are very low (from -30 to -10 dBZ) indicating ice crystals. Negative (blue/green) radial velocities indicate flow toward the radar and vice versa for positive (red) velocities. The RHI scans are done at constant azimuth angle from horizon to horizon (over the top). The data reveal significant layering of the atmosphere with up to seven wind direction shifts in the lowest layers of the atmosphere in this case (below 5 km AGL).

Fig. 6. (top) Backscatter and (bottom) radial velocity from the scanning Doppler polarization lidar. Low-level 5° elevation angle (left) PPI and (right) RHI displays at 1425 UTC 20 Mar 2016. These data are taken at the same time as Fig. 5. Backscatter is presented on a decibel scale and is mainly from aerosols and small particles, at 1200 UTC with the very bright (yellow) layer indicating water, whereas the Ka-band radar is capable of observing fog and ice crystals.

assesses the likelihood of fog with visibility ≤ 0.5 statute mile (~ 0.8 km) and stratus with ceiling ≤ 500 feet (~ 150 m) using RDPS to predict the environments where dense fog and low stratus cloud ceiling are likely to occur.

Examples

The capabilities the instruments are illustrated with show examples of new observations of the atmosphere. Figure 5 shows reflectivity and radial velocity plan position indicator (PPI) and range–height indicator (RHI) plots from the Ka-band radar showing a multilayer structure at 1420 UTC 20 March 2016 that is best illustrated in the RHI radial velocity plot (bottom right). There was a low pressure center to the southeast, and the synoptic winds over Iqaluit were variable to quite light. The low reflectivities (top) indicate very light precipitation (much less than -5 dBZ) that extend up to 5 km or more in height. The observations may be limited by the sensitivity of the radar, which is approximately -35 dBZ at 5 km and which overlaps with reflectivities associated with clouds. These very light precipitation layers can extend up to 7 km in height and are frequent, occurring about 40% of the time in winter (Mariani et al. 2018). The average hourly surface winds were greater than 5 m s^{-1} (up to 16 m s^{-1}) during blowing snow (from 0000 UTC 19 March to 0500 UTC 20 March 2016) and when radiosondes could not be launched. Figure 6 shows low-level PPI (0.5°) and RHI (135°), of backscatter and radial velocity, from the Doppler lidar for the same time. Note that the lidar backscatter intensity is displayed in decibel units. While the two instruments detect different sizes of hydrometeors (small to larger hydrometeors for the radar) or particles (aerosols to small hydrometeors for the lidar) and have different range and height capabilities, the wind patterns are consistent.

Fig. 7. Time–height display of (left) wind speed and (right) wind direction from the (a) radar, (b) lidar, (c) radiosonde, and (d) HRDPS from 1900 to 2200 UTC Mar 2016. (a) The radar wind is produced by a VAD analysis and (b) the lidar is produced by a DBS analysis at 75° elevation angle. (c) There are missing radiosonde winds due to an inability to launch in windy conditions. (d) The HRDPS plot is produced by using the first 12 h of the forecast. The displays are generated at the resolution (time and height) of the data and use the same color scheme and maximum height for comparison purposes. The plot illustrates the differences in resolution both spatially and temporally. Given the resolution differences, the wind speeds are consistent with each other except for the HRDPS wind directions, which are in disagreement.

Time–height displays of wind speed and direction from the Ka-band radar, Doppler lidar, radiosonde (high-resolution 2-s data), and the HRDPS model (composite of the first 0–12-h output for each model run that is done every 12 h) are shown in Fig. 7. The displays are created to illustrate the temporal and vertical resolution differences of the data. Note that both the radiosonde and model data extend much higher (35+ km). The Doppler radar and lidar measure only the radial component of the wind. To estimate the true wind, the radial wind measured at different azimuth directions are combined using the velocity–azimuth display (VAD) technique (Browning and Wexlar 1968) or the Doppler beam swinging (DBS) technique. Data at 75° elevation angle from 360° directions are used in the VAD technique and the north

Fig. 8. An example of a probability visibility forecast ≤ 1 km. It is the maximum of (i) the probability of visibility ≤ 1 km in blowing snow or (ii) the probability of visibility ≤ 1 km in concurrent blowing snow and precipitating snow, valid at 1600 UTC 11 Feb 2019 from the operational RDPS. Red circle indicates the location of Iqaluit.

and east directions for the DBS technique. The height of the data increases with range, and hence a profile of the wind can be created with the implicit assumption of uniformity over the scanning region. In addition, there is a limit to the maximum unambiguous velocity and range, but it is not an issue in the examples (for further explanation, see Doviak and Zrnić 2006; Werner 2005; Post et al. 1981; Illingworth et al. 2015b; Pearson et al. 2009). The maximum velocities of the radar and lidar were configured to be 12 and 19 m s^{-1} , respectively. All figures are displayed using a maximum velocity of 24 m s^{-1} , for comparison. Given the resolution differences, the initial impression is that winds are consistent. The exception is that the HRDPS wind directions are in disagreement with the others as was previously noted (Huang et al. 2014a,b).

Figure 8 shows a blizzard forecast example using the regression equations of Baggeley and Hanesiak (2005) generated by the 10-km-resolution RDPS model valid 1600 UTC 11 February 2019. There was a moderate to strong pressure gradient over Davis Strait extending into southern Baffin Island. A high probability of visibility ≤ 1 km in blizzard conditions was predicted for Iqaluit and over Frobisher Bay. Figure 9 shows a forecast product for southern Baffin Island generated by the Random Forest algorithm applied to RDPS model output valid 1700 UTC 11 February 2019, which is close to the valid time of Fig. 8. Strong winds were

Fig. 9. Example of a blizzard forecast valid at 1700 UTC 11 Feb 2019 using the Random Forest algorithm for visibility ≤ 0.25 statute mile in blizzard conditions produced from the RDPS model. Red circle indicates the location of Iqaluit.

predicted by RDPS, with visibility ≤ 0.25 statute mile (~ 0.4 km) in blizzard conditions forecast over Frobisher Bay and along its shore. Iqaluit airport was reporting 0.25 statute mile visibility in blowing snow at the time. However, the winds predicted by the RDPS were not high enough over most of Baffin Island to trigger a high probability of blizzard conditions. The most important predictors in the Random Forest algorithm are the average wind speed from surface to about 400 m and the wind speed at around 35 m. The RDPS model is known to have a bias for low-level wind speeds to be too low, thus there may have been blizzard conditions occurring over the open terrain of Baffin Island that were not predicted by either of the products shown in Figs. 8 and 9. Blizzard conditions caused by blowing snow alone occur in over 65% of blizzard reports from Arctic stations located in mainly open terrain,

and for some stations over 80% of the reports (Burrows and Mooney 2018). The Doppler lidar wind speed measurements from the Iqaluit site will provide high-resolution information on the structure and magnitude of the wind regime during blizzard events. The ceilometer will provide an accurate picture of the depth of the blowing snow layer during blizzard events. By correlating information from these instruments with RDPS, HRDPS, and other model output we hope to improve on the design and quality of predictors for blizzard conditions included in the Random Forest algorithm and to improve on the accuracy of its forecasts. In addition, the data will provide useful information for modeling the Arctic boundary layer.

Figure 10 shows time–height displays of the backscatter, depolarization ratio, and the water vapor mixing ratio from the CAAAL (top to bottom, respectively) for 1200 UTC 1 March to 2400 UTC 4 March 2018. Note the impressive high resolution (temporal and spatial) and vertical extent of the data. Interpretation of the data are indicated with annotations in the figure. CAAAL is able to observe not only aerosols and water vapor but also water and ice clouds, virga (precipitation aloft), and the boundary layer. The fine vertical and horizontal structure as well as the presence and evolution of the water and ice clouds well into the cold season is an example of the challenge for microphysical parameterization schemes in NWP.

Discussion

One of the primary goals of the CAWS project is to explore the development of the operational monitoring network in the Arctic. The prioritized constraints to the deployment of any sustainable operational monitoring network, particularly in the Arctic, are (i) low operating and maintenance costs, (ii) low infrastructure requirements, (iii) low capital costs, and (iv) reliable performance. The hypothesized design of a monitoring network is envisioned to be a combination of satellite-based meteorological observations, sparse in situ surface and radiosonde stations, and strategically located reference stations. The first step in defining the future weather monitoring requirements for the Arctic is to characterize and understand the potentially hazardous weather and their impacts on human activity. Recommendations and evaluation of the individual monitoring technologies must take into account these many factors in a holistic fashion.

Early results from CAWS confirm that very light (less than -10 dBZ) and deep (>5 km in height) precipitation (diamond dust ice crystals) is ubiquitous, and while the contribution to the hydrologic or cryospheric cycle is low, it appears to have significant impact on the radiation budget (Mariani et al. 2018; Stewart et al. 1998; Girard and Blanchet 2001a,b). This is a considerable challenge as solid-precipitation catchment gauges are limited to rates of 0.5 mm h^{-1} (and large particles). Noncatchment technology such as optical or microwave disdrometers, imaging probes, light scattering (scintillation, lidar), or microwave (radar) are needed (WMO 2019) but calibration of such light precipitation measurements, as well as space-based estimates, are outstanding challenges. Radars must be very sensitive (at least -35 dBZ) to detect this light precipitation. Ka band was chosen to take advantage of the short-wavelength effect on sensitivity; however, longer-wavelength radars with higher power may suffice. Further investigations are needed to understand the precipitation characteristics, their climatology, and the impact of the technology choices. The lidars, including the ceilometer, were able to detect light precipitation but to a lesser range. In addition, blowing snow was observed to several hundreds of meters in height by the lidar and radar and may have similar impact on the radiation budget.

Persistent (tens of hours) multiple wind layers, typically more than 5, in the lowest 2–3 km, were detected about 40% of the time in association with light precipitation. Such wind layers have been observed before in midlatitudes in winter in complex terrain (with much less frequency), recently at Barrow (now known as Utqiagvik; ARM 2018) and in the Indirect and Semi-Indirect Aerosol Campaign (McFarquhar et al. 2011). Climate model studies have

Fig. 10. Time–height series of (top) backscatter ratio, (middle) depolarization ratio, and (bottom) water vapor mixing ratio from the CAAAL instrument for 1200 UTC 1 Mar to 2400 UTC 4 Mar 2018. Water clouds generally show up as “off scale” (white) with totally attenuated regions above (black). Black bands on the image represent where no data are available either due to precipitation or during the daytime for the water vapor channel. The ice crystal layers have both a high backscatter ratio and high depolarization ratio whereas the virga, seen below the water clouds, has a high backscatter ratio and lower depolarization ratio.

indicated the importance of the radiative effects of such light precipitation layers and their role in the development of cold-air outbreaks affecting midlatitudes (Hu et al. 2005; Girard and Blanchet 2001a,b). These layers are not well observed in radiosonde data due to the slow response times of the temperature sensor or drift of the radiosonde. Preliminary NWP model evaluation (2016–17) indicated that there was a cold temperature bias and also underforecasting of the surface winds during these events. The thin layers may affect the albedo and therefore the radiation balance of the lower atmosphere, hence turbulent flux and radiation measurements are now included to improve our understanding of the phenomena for weather and climate prediction. Since radar and lidar are complementary due to their very different dependence on particle size, algorithms combining the two datasets can be used to estimate particle size, cloud occurrence, and cloud fraction.

CAAAL observations show the existence of water vapor inversions during the winter months. These inversions are thought to be a function of dominant forcing by the surface during the Arctic winter combined with meridional transport (Devasthale et al. 2011). The extent and frequency of occurrence of these events and their relationship to the height of the mixing layer needs further investigation.

Investigations of water vapor profiling by the CAAAL provides a genuine opportunity to consider the replacement of radiosondes with remote sensing technologies. CAAAL can measure high-resolution vertical profiles of water vapor typically up to 10 km in height due to the dry Arctic environment. With the addition of existing 50- or 400-MHz wind profilers and development of temperature profilers with comparable resolution and coverage, it is conceivable that a continuous automated system can be constructed for clear conditions and at sufficient vertical resolution, though challenges exist (Wulfmeyer et al. 2015). The CAAAL has a 3.75-m raw data resolution capability, though it remains to be determined what resolution is needed for operational forecasting, local applications, and the trade-offs.

The new technologies were commercial off the shelf and were not specified for Arctic environments (particularly temperature). During the study period, the extreme winds were 124 km h^{-1} (October 2018) and the lowest temperatures were -38°C (February 2017). Despite this, the instruments operated normally except for a few computer errors which could be attributed to normal failure modes and power interruptions, which are expected to occur more frequently in more remote Arctic communities.

The site and the CAWS project continue to evolve. New instruments were installed in September 2018. A new differential absorption lidar (Nehrir et al. 2011) has been installed to continuously measure water vapor profiles up to 3 km AGL, and comparisons with radiosonde data, NWP model output, and CAAAL are currently underway. The site was equipped with a Droplet Measurement Technologies fog-measuring device that measures the particle number and size concentrations at high temporal resolution to verify fog forecasts and for process studies. A radiation flux sensor suite, snow depth sensors, soil moisture and temperature probes, and a far-infrared radiometer (Libois et al. 2016) were also installed. This contribution highlights only a few examples of the measurements and capabilities at the Iqaluit site. Radiometry and solid precipitation measurement investigations were not discussed.

The Doppler lidar wind speed measurements from the Iqaluit site will allow verification of the blizzard forecasts for Iqaluit and will provide high-resolution information on the structure and magnitude of the wind regime during blizzard events. In addition, the ceilometer data provide an accurate picture of the depth of the blowing snow layer above ground. By correlating these data with RDPS model output, improvements to the Random Forest algorithm design is expected.

Another exploitation of the measurements is the evaluation of the model microphysical fields produced by the Predicted Particle Properties (P3) bulk microphysics scheme (Morrison and Milbrandt 2015; Milbrandt and Morrison 2016). P3 is a relatively new microphysics scheme

with an emphasis on the smooth (versus categorical) evolution of the physical properties of ice. The scheme has not yet been evaluated in terms of its ability to model microphysical aspects that may be unique to the Arctic (e.g., long-lived mixed-phase clouds; see Fig. 10). Diagnostic or physical validation studies comparing time–height vertical profiles from the radar, lidars, and ceilometer data with relevant P3 variables will be a strong test of the P3 microphysical processes. The polarization data (from the radar and lidar) and the Particle Imaging Package, which produces individual images and distribution of snow particles, will both be particularly useful for P3 phase and crystal habit investigations. Adding snow density measurements (manual) during limited intensive observation campaigns should be considered to validate the ice densification processes in P3.

In a broader international context, the CAWS Iqaluit site aims to contribute to the International Arctic Systems for Observing the Atmosphere (IASOA) observatories (Uttal et al. 2016) with new technology measurements to complement traditional observation instruments and enhance monitoring and understanding of Arctic weather. In the context of the WMO Polar Prediction Project (Jung et al. 2016), a better understanding of polar processes (e.g., the delicate balance between cryosphere, radiation, and clouds) is the crucial missing knowledge for advancing environmental predictions (in polar regions and beyond) from short time scales to climate. ECCC is contributing to the Year of Polar Prediction (YOPP) supersite model intercomparison project (YOPPsiteMIP) by providing high-frequency (7.5-min) time series of CAPS model output (7×7 grid points) in correspondence of nine IASOA supersites, the CAWS Iqaluit and Whitehorse (not reported here) sites, and the Russian Ice-Base Cape Baranova (data available on the YOPP data portal at http://thredds.met.no/thredds/catalog/alertness/YOPP_supersite/catalog.html). Several international modeling groups (including the European Centre for Medium-Range Weather Forecasts, Met Norway, United Kingdom's Meteorological Office, and Meteo-France) are also providing high-resolution model output at these sites for process-validation studies. The CAWS Iqaluit and later Whitehorse sites aims to align with the modus operandi of the IASOA observatories (including the creation of the Merged Observatory Data Files), and constitute the ECCC contribution in terms of advanced instrumentation measurements to YOPPsiteMIP.

The communication of risk to the Inuit people is a significant challenge due the cultural and societal differences. Understanding traditional knowledge takes a holistic, experiential, ecological, and environmental systems approach that is fundamentally impacts or adaptation based. Traditional knowledge is based on learning from “elders” and not based on causality or scientific arguments, and co-design to merge the two approaches is a challenge. Understanding of scientific meteorological data does not always correspond to what is learned from experience due to observational errors, interpretation, or representativeness of the observations (Gearheard et al. 2010). For example, the very small scale wind direction (tens to hundreds of meters) can affect how hunting is conducted, and this is not captured by the current models. Products such as the blizzard and low-visibility potential maps may not have meaning and will require mutual capacity building.

Many efforts and community events have been undertaken to bridge not only the research to operations gap but the science-to-society gap. This includes ongoing meetings with government departments (ECCC staff and forecasters, national defense) industry (terminal operations, airlines, pilots), research community (Nunavut Research Institute, universities in the south), and students as well as ongoing government-wide open town halls with the public. To illustrate the challenging path that is being taken to bridge the science to society gap, the CAWS project worked with the local community to co-design a logo to foster engagement with the goal of communicating and integrating the concept of wind from a mutual perspective (Fig. 11). The logo shows a raven, which is related to the origin of life and represents freedom. The circle represents both the sun and the moon (source of light), and the blue color of the

circle represents the sky (M. E. Thomas, Nunavut Research Institute, 2017, personal communication). The raven is an important symbol for the Inuit (Iqaluit) and other First Nations people. The objective is to continue working together with the indigenous community, accessible in Iqaluit, to advance the provision of relevant and reliable weather information for all the Canadian North communities.

The intent of this contribution is to document the capabilities of the CAWS Iqaluit site for collaboration with other Arctic sites and projects (Jung et al. 2016; Uttal et al. 2016; AOS 2018) that address broader scientific issues and larger scales. The Government of Canada has an open data policy and the data will be published on a government portal. Due to the latency in the manual retrieval of the data, quality control, and publication processes, potential collaborators are encouraged to contact CAWS principal investigators directly.

Summary

The Canadian Arctic Weather Science project has established a near-Arctic meteorological reference site at Iqaluit, Nunavut, to explore new monitoring technologies and network design; to develop relevant weather information specific to the Canadian Arctic; to support validation of space-based precipitation and wind observations; to provide data for evaluation, validation, and verification of the Canadian numerical weather forecast models; to better understand the meteorology at high latitudes; and to contribute to other national and international projects.

Preliminary results on meteorological science show observations of unique Arctic meteorological features, particularly in the lowest few kilometers of the atmosphere in a systematic fashion, and have an impact of numerical weather predictions of temperature and perhaps other variables. These results indicate that the observational requirements for the Arctic will differ from other climatic regions of Canada. Limited products were made available, on an experimental basis, to the Edmonton, Alberta, and Winnipeg, Manitoba, weather offices, where the eastern Arctic forecasts are done, and were well received.

The main objective of this contribution is to document the site and its capabilities in order to encourage research and operational collaborations. Future publications on Arctic science, instrument performance, data quality, network design, risk communication, and satellite and NWP validation, particularly in the era of the Year of Polar Prediction, are anticipated.

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Fig. 11. The CAWS logo. This was co-designed with representatives of the Inuit to begin the process of bridging the cultural and knowledge communications gap. See text for an explanation.

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