The Manitoba Agriculture Mesonet

Technical Overview

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ABSTRACT: Established primarily to improve weather monitoring across the agricultural regions of the province, the Manitoba Agriculture Weather Program (MAWP) began officially in 2005 with funding from the provincial government for the establishment of a network of 28 automated weather monitoring stations. The network steadily grew to 46 stations between 2007 and 2014 as a result of partnership with local commodity and research groups. In response to the Manitoba flood of 2011, more stations were installed and the network grew to 108 weather stations in 2019. The stations are solar powered, and scheduled maintenance is conducted at each station twice per year. Weather parameters monitored include air temperature, barometric pressure, precipitation, relative humidity, soil moisture, soil temperature, solar radiation, wind speed, and wind direction using research-grade sensors. The observations are transmitted via cellular telemetry every 15 min in the spring, summer, and fall but hourly in the winter to conserve energy supply due to reduced daylight and below-freezing temperatures. The data can be viewed by the public within 1 min of data collection. The data are used to generate agronomic-related maps such as thermal unit computation of growing degree-days and corn heat units as well as disease risk maps such as *Fusarium* head blight. Beyond agriculture, the data have been used for aviation investigation and for undergraduate course instruction among other applications.

KEYWORDS: Automatic weather stations; Measurements; Agriculture

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Manitoba, the longitudinal center of Canada, is the easternmost of the three Canadian prairie provinces with a population of about 1.28 million people and population density of 2.3 people km⁻² (Statistics Canada 2017). The fertile prairie soil creates thriving agricultural communities in the southern region of the province where most of the agricultural production occurs. This region of the province is referred to as agro-Manitoba and it extends south from the 53rd parallel to the U.S. border (Fig. 1). Agro-Manitoba falls within the humid continental climate (Dfb) of the Köppen climate classification. The annual temperature within the region averaged 2.1°C from 1950 to 2013 with average annual precipitation of 485 mm (McKenney et al. 2011). Snowfall accounts for 20%–25% of the total annual precipitation. Elevation ranges from 200 to 600 m above sea level with medium to light textured soils in the west and heavy clay soils (>60% clay) in the top 1.2 m in the eastern parts of agro-Manitoba. In 2016, Manitoba had 17.6 million acres of total farm area, which

Fig. 1. Location of weather stations in the Manitoba Agriculture Mesonet. The green-shaded area in the inset map represents the agro-Manitoba region, and all 108 stations in this figure were operational as of June 2020.

represented 11.1% of the total farm area in Canada. The average farm size was 1192 acres and cropland accounted for 65.4% of the total farm area in Manitoba with canola (*Brassica napus* L.), spring wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L.) being the top three crops (Manitoba Agriculture 2017). Between 2012 and 2016, the agricultural sector contributed over CAD \$2.2 billion annually to the provincial gross domestic product (Statistics Canada 2019).

Historically, the province of Manitoba has led the advancement of weather monitoring for agriculture in Canada. In the 1880s, then Deputy Minister of Agriculture and Statistics, Acton Burrows, ensured the establishment of about 80 new precipitation gauges in southern Manitoba. The number of stations in the province was significant considering that it represented about one-third of the total 250 precipitation stations that were installed in Canada (Robertson 1998). The rainfall records were important for the decision making of haying and wheat harvest operations. The installation, maintenance, and data processing of meteorological data at the time were mainly coordinated by the Meteorological Service of Canada [MSC; now a division of Environment and Climate Change Canada (ECCC), a department within the Government of Canada].

Weather monitoring has undergone significant changes over the last 50 years in terms of the increase in the variety and accuracy of sensors, temporal frequency of data generated, and improved public access to weather data. These changes have occurred in response to the improvements in computing technologies, data storage, and the increased access to information through the internet. Apart from the regional weather data from a limited number of automated stations operated by MSC, which are mostly located at airports, there was a growing need for local agricultural weather information, especially within the agricultural community, because generic, aviation-focused weather reports did not provide farmers with the area-specific information needed to make farm management decisions. The limited spatial coverage was not sufficient to analyze local extreme events and the impacts to agricultural production in Manitoba. By the mid-1990s, Keystone Vegetable Producers Association (now Keystone Potato Producers Association), the commodity group for potato growers, and the Vegetable Growers Association of Manitoba secured provincial funds to purchase about 20 weather stations for temporary, growing-season weather monitoring. The objective was to set up a weather network as an early detection system for insects and diseases, and to reduce pesticide spraying on a calendar basis. There was great interest by commodity groups, local farm groups and industry to significantly expand the network. Opportunities were identified to support irrigated crop management, livestock expansion, and flood forecasting. In 2000, Manitoba Agriculture, in cooperation with the Carman Community Development Corporation and Adcon Telemetry Inc. established Agrometeorological Centre of Excellence (ACE) as a not-for-profit organization. However, very few farmers were interested in paying for the subscription-based model to keep the program running. This led to ACE closing after a couple of years.

The current vision of the Manitoba Agriculture Weather Program officially began in 2005 with funding through the Agriculture Research Development Initiative to design and deploy an automated surface weather monitoring program that meets or exceeds international standards for meteorological observations. The primary objectives were to ensure Manitoba Agriculture had control of secure, high-quality weather data to fulfill industry requirements; to encourage partnerships with rural communities; and to design value-added agrometeorological tools that provide decision support systems for Manitoba producers. Twenty-eight weather stations were installed using a 3-m tripod, equipped with sensors to record temperature, relative humidity, rainfall, wind, and soil temperature (Fig. 2a). More stations were added and by 2014, the number of stations grew to 46 from the initial 28 stations. All the stations installed from 2010 onward had a 10-m tower. The stations that were initially installed on a 3-m tripod were upgraded to a 10-m tilting-base tower in 2016 (Fig. 2b).

Fig. 2. (a) 3-m tower weather station previously used within the network showing dual tipping-bucket rain gauges. (b) Current weather station with 10-m tower. 109L soil temperature probe installed at 5 cm, ML3 theta probes for soil moisture and temperature are installed at 5-, 20-, 50-, and 100-cm depths.

In 2011, Manitoba experienced significant flooding that cost over CAD \$1.2 billion in flood preparedness, infrastructure repair and disaster payments. Recommendations from the Manitoba 2011 Flood Review Task Force Report (Manitoba Government 2013) led to further expansion to the Manitoba Ag weather network. The report recommended identifying potential spatial gaps and installing meteorological stations to provide real-time weather data, especially precipitation and soil moisture measurements. Between 2015 and 2017, 63 new weather stations were installed to increase the number of stations in the network from 46 to 109 stations. One of the old stations (Letellier) was decommissioned and the total number of weather stations in the network as of June 2020 is 108 (Fig. 1). There is sparse station coverage in the southeast corner of the province, which is mainly forested peatlands. The only weather station in this area is the Sprague Lake station located in an open area, about 500 m from a peat harvesting operation.

Several states in the United States such as Kentucky, Oklahoma, North Dakota, Texas, Kansas, and New York manage similar networks of weather stations (McPherson et al. 2007; Shulski et al. 2018; Mahmood et al. 2019; Patrignani et al. 2020a; Brotzge et al. 2020). These networks are usually referred to as mesonets because they are used to provide weather information over a mesoscale, covering about 30-km radius. The average station spacing at most of these mesonets range from 15 to 100 km and further details about the various mesonets in the United States are reported by Mahmood et al. (2017). Although the data application continues to extend beyond agronomy, Alberta and Manitoba are among the few provinces in Canada with publicly funded mesonets that are primarily dedicated for agriculture. The Alberta mesonet is managed by the Alberta Climate Information Service under Alberta Agriculture and Forestry (<https://agriculture.alberta.ca/acis/>). The Manitoba mesonet is managed by the Manitoba Agriculture Weather Program under the department of Agriculture and Resource Development. Due to the unique requirement for weather information for wildfires, the province also operates a parallel Wildfire Weather Network with monitoring stations situated in forested areas of the province. Both provincial-operated networks collaborate, cross-train, and share data with each other. However, each program maintains their uniqueness due to differences

in location siting criteria, sensor used, and data transmission. The Manitoba Agriculture Mesonet uses cellular connection for data collection, but the Wildfire Weather Network uses the Geostationary Operational Environmental Satellite (GOES) to access data from the stations due to lack of cell signals in the forested areas of the province. This publication provides technical information on the location, sensors, and data applications of the Manitoba Agriculture mesonet.

Site selection

At the inception of the program in 2005, site selection was mostly based on areas with agricultural intensification, diversification, and representativeness of local weather conditions. Local aerodromes were interested in hosting a station to provide real-time data for aviation purposes. About a quarter of the 46 stations installed before 2015 were installed within or close to an aerodrome and the remaining stations were installed at the edge of farmer's fields. For new weather monitoring stations, locations are prioritized based on the agricultural production in the area as well as multipurpose environmental and hydrological need within the largest unmonitored area determined as the location with the greatest distance from existing stations. Patrignani et al. (2020b) provided detailed information on the use of computational geometry to optimize the siting of future monitoring stations. When a generic area is identified (usually a 5 km × 5 km area), regional Manitoba Agriculture staff who are familiar with the area provide assistance with contacting local producers who may be interested in hosting a station within the identified area. The goal of the criteria used for site selection is to meet the Class A guidelines suggested by the World Meteorological Organization (WMO; WMO 2014, annex 1.B). A summary of the specific site selection criteria include the following:

- 15 m × 15 m space required and considered permanent (>10 years). If located in a cropped area, field edges are preferred to allow access with minimal crop disturbance and reduce the likelihood of damage from farm equipment. Must be fenced off or protected from livestock, if applicable.
- Vehicle access at all times.
- The station area must be located at a distance at least 10 times the height of the nearest obstruction (building, shelterbelt, forest, large geological feature, etc.). Example: If a 10-m-high shelterbelt is in the field, the site would have to be at least 100 m away from the shelterbelt (preferably longer to account for future height growth). Hydro lines and poles do not count as an obstruction; however, the station cannot be installed under hydro lines.
- Distance from a municipal road or highway should be >20 m where possible.
- Distance from any water body should be >100 m where possible; site should not be prone to seasonal flooding.
- Average to good cell signal coverage.
- Stations are not situated in major cities such as Winnipeg and Brandon that have ECCC weather stations. Unsuitable locations include areas that may be considered for sale or future development, areas where the weather tower will impede application of fertilizer or pesticides, areas where snow drifting is severe and areas that represent a microclimate within a large region (e.g., a hillside site if the region is not generally hilly).

Prior to station installation, clearance from utility companies is obtained to ensure that there are no buried cables at the selected locations. Metadata collected from each location include geographical coordinates, elevation, and site photographs. The photos are taken from all four major cardinal directions: north, south, east, and west. Undisturbed soil samples were collected six feet from installed soil moisture probes at 0–0.1-, 0.15–0.25-, 0.45–0.55-, and 0.95–1.05-m depths to determine the soil textural classification (Table 1) using the Canadian

Table 1. Mesonet metadata listing geographical coordinates, first year of record, soil texture, dominant land use, and topography.

SN	Station name	Lat (°)	Lon (°)	Elevation (m)	First year of record	Soil textural class ^b (5 cm)	Soil textural class (20 cm)	Soil textural class (50 cm)	Soil textural class (100 cm)	Dominant land use	Topography
1	Alexander	49.8	−100.4	431	2017	Silt loam	Silt loam	Silt loam	Silt loam	Cropland	2%–5%
2	Alonsa	50.7	−99.1	288	2015	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Forage crops	>2%–5%
3	Altona	49.1	−97.5	246	2012	Clay	Silty clay loam	Clay	Loam	Cropland	>0%–0.5%
4	Arborg	50.9	−97.3	230	2006	Silty clay loam	Heavy clay	Silt loam	Heavy clay	Cropland	>0%–0.5%
5	Argue	49.4	−100.3	466	2015	Loam	Sandy loam	Loam	Sandy loam	Cropland	>0%–0.5%
6	Austin	50.0	−98.9	303	2017	Loamy sand	Loamy sand	Loamy sand	Sand	Grassland	>0%–0.5%
7	Bagot	50.0	−98.6	285	2017	Loamy sand	Loamy sand	Sand	Sand	Cropland	>0%–0.5%
8	Baldur	49.4	−99.2	432	2015	Loam	Loam	Sandy loam	Sandy loam	Cropland	>0%–0.5%
9	Beausejour	50.1	−96.4	235	2014	Clay	Clay	Silty clay	heavy clay	Cropland	>0%–0.5%
10	Bede	49.4	−100.9	437	2013	Sand	Loamy sand	Loamy sand	Sand	Forage crops	>0%–0.5%
11	Birch River	52.3	−101.1	306	2017	Sand	Sand	Sand	Sand	Grassland	>0.5%–2%
12	Birtle	50.4	−100.9	542	2006	Clay loam	Clay loam	Clay loam	Loam	Cropland	>2%–5%
13	Boissevain	49.2	−100.1	503	2006	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Forage crops	>0.5%–2%
14	Brunkild	49.6	−97.5	238	2016	Silty clay	Silty clay	Silty clay loam	Silty clay loam	Cropland	>0%–0.5%
15	Carberry	49.9	−99.4	377	2007	Loam	Silty loam	Silty loam	Silty clay	Cropland	>0%–0.5%
16	Carman	49.5	−98.0	271	2006	Clay loam	Sandy clay loam	Sandy loam	Sandy clay loam	Cropland	>0%–0.5%
17	Cartwright	49.1	−99.3	465	2015	Loamy sand	Loamy sand	Loamy sand	Loamy sand	Grassland	>2%–5%
18	Clearwater	49.1	−99.1	457	2015	Sandy loam	Sandy loam	Sandy loam	Loamy sand	Forage crops	>0.5%–2%
19	Dand	49.4	−100.5	472	2017	Silt loam	Loam	Loam	Loam	Cropland	>0%–0.5%
20	Deloraine	49.1	−100.5	514	2010	Sandy loam	Sandy loam	Silt loam	Silty clay loam	Grassland	>0.5%–2%
21	Dominion City	49.2	−97.1	237	2017	Silty clay	Silty clay	Clay	Silty clay loam	Cropland	>0%–0.5%
22	Drifting River	51.4	−100.4	338	2015	Sand	Sand	Sand	Sand	Grassland	>2%–5%
23	Dugald	49.8	−96.8	245	2006	Silty clay loam	Heavy clay	Silty clay loam	Heavy clay	Cropland	>0%–0.5%
24	Eden	50.4	−99.4	384	2017	Sandy loam	Sandy loam	Loamy sand	Sand	Cropland	>0.5%–2%
25	Elie	50.0	−97.7	240	2017	Heavy clay	Heavy clay	Heavy clay	Heavy clay	Cropland	>0%–0.5%
26	Elm Creek	49.7	−98.0	264	2008	Clay	Clay	Heavy clay	Heavy clay	Grassland	>0%–0.5%
27	Elma	49.9	−95.9	284	2016	Loamy sand	Loamy sand	Loamy sand	Sandy loam	Cropland	>0%–0.5%
28	Eriksdale	50.8	−98.1	265	2006	Loam	Loam	Loam	Sandy loam	Grassland	>0%–0.5%
29	Ethelbert	51.6	−100.5	370	2006	Loam	Loam	Loam	Clay loam	Grassland	>0%–0.5%
30	Findlay	49.5	−100.8	434	2015	Sand	Sand	Sand	Sand	Grassland	>0%–0.5%
31	Fisherton	51.2	−97.8	253	2015	Clay	Heavy clay	Heavy clay	Clay	Grassland	>0%–0.5%
32	Fork River	51.5	−100.0	263	2015	Silt loam	Silt loam	Silt	Silt loam	Cropland	>0%–0.5%
33	Forrest	50.1	−99.9	502	2007	Clay loam	Loam	Clay loam	Loam	Cropland	>2%–5%
34	Gardenton	49.1	−96.6	298	2016	Sand	loamy sand	Sand	Sand	Forage crops	>2%–5%
35	Gladstone	50.1	−99.0	279	2006	Loamy sand	Loamy sand	Sand	Sand	Grassland	>0%–0.5%
36	Glenboro	49.5	−99.3	373	2009	Loam	Clay loam	Silt loam	Sandy loam	Cropland	>0%–0.5%
37	Grandview	51.2	−100.7	439	2006	Silty clay loam	Silty clay	Clay	Clay loam	Cropland	>0.5%–2%

Table 1. Continued.

SN	Station name	Lat (°)	Lon (°)	Elevation (m)	First year of record	Soil textural class ^b (5 cm)	Soil textural class (20 cm)	Soil textural class (50 cm)	Soil textural class (100 cm)	Dominant land use	Topography
38	Hamiota	50.2	−100.6	527	2006	Sandy loam	Sandy loam	Sandy loam	Loam	Cropland	>2%–5%
39	Holland	49.6	−99.0	372	2017	Clay loam	Silt loam	Clay	Clay	Grassland	>2%–5%
40	Inglis	50.9	−101.3	572	2016	Loam	Clay loam	Clay loam	Silty clay loam	Cropland	>5%–9%
41	Inwood	50.5	−97.6	266	2015	Loam	Sandy clay loam	Clay	Loam	Forage crops	>0%–0.5%
42	Kane	49.4	−97.7	246	2016	Silty clay	Silty clay	Heavy clay	Clay	Grassland	>0%–0.5%
43	Keld	51.0	−100.2	428	2016	Clay loam	Loam	Clay loam	Clay loam	Cropland	>2%–5%
44	Kenton	50.0	−100.6	474	2017	Clay loam	Silt loam	Clay loam	Loam	Cropland	>0.5%–2%
45	Killarney	49.1	−99.7	511	2006	Loam	Loam	Loam	Loam	Cropland	>0%–0.5%
46	Kola	49.9	−101.4	535	2016	Loam	Loam	Loam	Loam	Cropland	>0%–0.5%
47	Lac du Bonnet	50.3	−96.1	259	2017	Silty clay loam	Heavy clay	Clay	Silty clay loam	Cropland	>0.5%–2%
48	Lake Audy	50.7	−100.3	569	2017	Clay loam	Clay loam	Silt loam	Clay loam	Grassland	>2%–5%
49	Lake Francis	50.4	−97.9	261	2017	Loam	Sandy loam	Sandy loam	Sandy loam	Grassland	>0%–0.5%
50	Lakeland	50.3	−98.6	260	2017	Loam	Silt loam	Silt loam	Loam	Cropland	>0%–0.5%
51	Laurier	50.9	−99.6	303	2017	Sandy loam	Sandy loam	Clay	Silty clay loam	Cropland	>0%–0.5%
52	Manitou	49.2	−98.5	485	2010	Loam	Loam	Clay loam	Loam	Grassland	>5%–9%
53	Marchand	49.4	−96.4	300	2017	Sand	Sand	Sand	Sand	Grassland	>0%–0.5%
54	McAuley	50.2	−101.4	506	2017	Loam	Sandy loam	Silt loam	Loam	Cropland	>2%–5%
55	Menisino	49.1	−96.1	349	2015	Sand	Sand	Sand	Sand	Forage crops	2%–5%
56	Miniota	50.1	−100.9	470	2017	Sandy loam	Sandy loam	Loamy sand	Silt loam	Grassland	2%–5%
57	Minitonas	52.1	−100.9	318	2015	Clay loam	Clay loam	Silty clay loam	Silty clay loam	Cropland	>0.5%–2%
58	Minnedosa	50.3	−99.8	563	2006	Clay loam	Clay loam	Loam	Loam	Grassland	>2%–5%
59	Minto	49.4	−99.9	472	2015	Loam	Loam	Silt loam	Loam	Grassland	>0.5%–2%
60	Moosehorn	51.3	−98.6	253	2006	Clay loam	Clay loam	Loam	Loam	Forage crops	>2%–5%
61	Morris	49.4	−97.3	239	2006	Heavy clay	Silty clay loam	Sandy clay	Heavy clay	Forage crops	0%–0.5%
62	Mountainside	49.1	−100.3	584	2015	Loam	Loam	Sandy loam	Loam	Cropland	>0.5%–2%
63	Narcisse	50.7	−97.5	278	2014	Sandy clay loam	Sandy clay loam	Sand	Sandy loam	Forage crops	0%–0.5%
64	Neepawa	50.2	−99.4	379	2017	Sandy loam	Loam	Loam	Sandy loam	Cropland	>0.5%–2%
65	Newdale	50.3	−100.2	606	2017	Loam	Loam	Sandy loam	Loam	Grassland	>5%–9%
66	Ninette	49.3	−99.7	470	2015	Loam	Loam	Loam	Loam	Cropland	>2%–5%
67	Oakburn	50.6	−100.7	587	2016	Silt loam	Silt loam	Silt loam	Loam	Cropland	>2%–5%
68	Pierson	49.2	−101.2	470	2007	Sand	Sand	Sand	Sand	Grassland	>0.5%–2%
69	Pipe Lake	51.3	−100.7	530	2016	Sand	Sand	Sand	Sand	Grassland	>5%–9%
70	Plumas	50.4	−99.0	273	2017	Loam	Sandy loam	Loam	Sandy loam	Grassland	0%–0.5%
71	Poplarfield	50.9	−97.6	270	2017	Sandy loam	Sandy loam	Sandy loam	Loam	Grassland	0%–0.5%
72	Portage East	50.0	−98.3	257	2008	Silty clay	Silt loam	Silt loam	Silty clay loam	Cropland	0%–0.5%
73	Prawda	49.6	−95.7	306	2017	Clay loam	Silty clay loam	Silty clay	Sandy loam	Grassland	0%–0.5%
74	Reedy Creek	50.9	−98.9	251	2017	Loam	Silty loam	Loam	Loam	Grassland	>2%–5%

Table 1. Continued.

SN	Station name	Lat (°)	Lon (°)	Elevation (m)	First year of record	Soil textural class ^b (5 cm)	Soil textural class (20 cm)	Soil textural class (50 cm)	Soil textural class (100 cm)	Dominant land use	Topography
75	Reston	49.6	−101.0	481	2013	Loam	Loam	Loam	Sandy loam	Cropland	>2%–5%
76	Rivers	50.1	−100.2	488	2017	Loam	Sandy loam	Sandy loam	Loam	Grassland	>2%–5%
77	Rorketon	51.3	−99.5	260	2016	Silt loam	Clay loam	Sandy loam	Loam	Forage crops	0.1%–<3%
78	Rosa	49.2	−96.8	281	2017	Loamy sand	Loamy sand	Sand	Sandy loam	Grassland	0%–0.5%
79	Russell	50.8	−101.3	554	2006	Loam	Sandy loam	Loam	Sandy loam	Cropland	>5%–9%
80	Ruthenia	50.8	−100.9	591	2016	Silty clay	Silty clay loam	Clay loam	Silt loam	Cropland	>9%–15%
81	San Clara	51.4	−101.4	606	2016	Loam	Loam	Silty clay	Silt loam	Cropland	>5%–9%
82	Selkirk	50.2	−96.8	227	2006	Sandy clay loam	Sandy clay loam	Clay	Heavy clay	Cropland	0%–0.5%
83	Shilo	49.8	−99.7	378	2017	Loamy sand	Sand	Loamy sand	Sand	Grassland	>0.5%–2%
84	Sinclair	49.5	−101.3	496	2017	Loam	Loam	Loam	Sandy loam	Forage crops	>0.5%–2%
85	Snowflake	49.0	−98.7	476	2015	Silt loam	Silt loam	Loam	Silt loam	Grassland	0%–0.5%
86	Somerset	49.4	−98.7	476	2012	Loam	Loam	Loam	Loam	Grassland	5%–9%
87	Souris	49.6	−100.2	449	2006	Loam	Loam	Loam	Loam	Grassland	>2%–5%
88	Sprague Lakea	49.3	−95.4	358	2017					Peatland	
89	St Adolphe	49.7	−97.1	229	2011	Heavy clay	Heavy clay	Heavy clay	Heavy clay	Forage crops	0%–0.5%
90	St Rose	51.1	−99.5	263	2006	Loam	Loam	Sandy loam	Silt loam	Cropland	0%–0.5%
91	St. Claude	49.7	−98.3	305	2017	Loamy sand	Loamy sand	Loamy sand	Sandy loam	Grassland	0%–0.5%
92	St. Lazare	50.4	−101.2	503	2016	Loam	Loam	Loam	Loam	Grassland	>5%–9%
93	St. Pierre	49.4	−97.0	244	2006	Silty clay	Silty clay	Silty clay	Silty clay	Cropland	0%–0.5%
94	Starbuck	49.8	−97.7	236	2006	Heavy clay	Heavy clay	Heavy clay	Heavy clay	Cropland	0%–0.5%
95	Steinbach	49.6	−96.7	258	2006	Clay	Sandy clay	Clay	Silty clay loam	Cultural	0%–0.5%
96	Stonewall	50.1	−97.3	247	2017	Clay	Heavy clay	Loam	Loam	Cropland	0%–0.5%
97	Swan Valley	52.1	−101.5	375	2007	Silt loam	Silt loam	Clay	Clay	Grassland	>0.5%–2%
98	Taylor's Point	50.9	−98.4	250	2015	Clay loam	loam	Clay loam	Sandy loam	Forage crops	>2%–5%
99	Teulon	50.4	−97.2	249	2006	Silt loam	Silt loam	Silt loam	Silt loam	Cropland	0%–0.5%
100	Treherne	49.6	−98.7	371	2006	Sandy loam	Sandy loam	Loam	Loam	Grassland	0%–0.5%
101	Virden	49.9	−100.9	442	2006	Sandy loam	Loamy sand	Sand	Sand	Grassland	>0.5%–2%
102	Vivian	49.9	−96.4	268	2016	Sandy clay loam	Clay	Heavy clay	Sandy loam	Cropland	0%–0.5%
103	Waskada	49.1	−100.9	452	2015	Sandy loam	Loam	Loam	Loam	Grassland	0%–0.5%
104	Wawanesa	49.6	−99.7	374	2010	Sandy loam	Sandy loam	Sandy loam	Silt loam	Cropland	>0.5%–2%
105	Windygates	49.0	−98.4	476	2015	Silty clay loam	Silt loam	Loam	Loam	Grassland	0%–0.5%
106	Winkler	49.1	−97.9	279	2007	Sandy loam	Sandy loam	Sandy loam	Loamy sand	Cropland	0%–0.5%
107	Woodlands	50.2	−97.7	252	2006	Loam	Loam	Loam	Loam	Cropland	0%–0.5%
108	Zhoda	49.3	−96.5	305	2016	Sand	Sand	Sand	Sand	Grassland	0%–0.5%

^a No soil information at the Sprague Lake station, which is a peatland.

^b Soil textural classification is based on the Canadian Soil Textural Classification System and was determined using the pipette method from samples collected 2 m from installed soil moisture probes.

soil textural classification system (Soil Classification Working Group 1998). The standard naming convention for the stations is to name each station after the closest town for easy identification. About 10% of stations have been relocated from their initial installation site either at the request of the host or due to the location being unsuitable for required upgrades such as soil moisture monitoring. New locations are usually within 5 km of the previous site and a suffix “_2” is included with the station name in the database to indicate that the original station has been upgraded and moved.

Station design and sensors

Each station is installed on a 15 m × 15 m open area or fenced if located in a pasture. The area is seeded to grass or native grass is allowed to grow. Figure 2 shows the contrast in ground cover between the station (grass) and adjacent fields (annual cropland). Concrete bases are poured for the all-weather precipitation gauge, main tower, and the tipping-bucket rain gauge to limit wind-induced vibration on the sensors. All three installed bases are checked to ensure that they are level before sensors are mounted. The main structure at the center of the site is a 10-m tower with tilting base for easy access to the wind sensors during maintenance. The tower is supported by three guy wires held by ground anchors. Sensors as well as power and communication peripherals such as datalogger enclosure box, solar panels, and cell antenna are installed on the tower. The stations are powered by a 12-V battery housed in the lower compartment of the enclosure box. The battery must have a minimum of 100 A-hour charged by dual 20-W solar panels with a maximum open circuit voltage of 22 V and current of 1.4 A. The solar panels are installed south-facing at an angle between 47° and 53°. A solar controller is used to regulate the charge from the solar panels to the datalogger.

Air temperature (HMP 155, Vaisala). HMPs are used to monitor both air temperature and relative humidity. HMP-45 and HMP-50 were previously used in the network but discontinued due to product retirement by the manufacturer. Stations currently have one HMP-155 mounted at 2 m above ground level; however, testing with three sensors placed at 0.5, 2, and 3 m started in 2019 at three locations—Minnedosa, Winkler, and Woodlands—to review temperature inversions and provide information on potential spray drift. The HMP-155 combines a platinum resistance thermometer to measure temperature and a capacitive thin film polymer to measure relative humidity. It is housed inside a white thermoplastic, UV-stabilized, 14-plate radiation shield (model 41003P by R. M. Young). Temperature measurement for the sensor ranges from -80° to +60°C and from 0% to 100% for humidity.

The 14-plate radiation shield is designed to maximize airflow; however, similar to what is obtainable at many mesonets that use naturally ventilated radiation shields, the air temperature measurement could be subjected to error under certain environmental conditions. Huwald et al. (2009) found that air temperature error in naturally ventilated radiation shields increases with increasing solar radiation and low wind speed when tested against temperature measurement from sonic anemometers. Mahmood et al. (2017) reported that both maximum and minimum air temperatures were higher for all months when measured with naturally ventilated shields, especially in the late summer months with up to 0.7°C difference in the mean month maximum air temperature. Increased power requirement and the potential deposition of aerosols on the sensors are drawbacks to deploying aspirated radiation shields within the mesonet. The radiation shield used within the mesonet meets the guidelines specified by the WMO (2014).

Precipitation (TB4, Hydrological Services and Pluvio2, OTT HydroMet). Prior to 2011, most stations had Texas Electronics TE525M tipping-bucket rain gauges with 0.1-mm resolution to measure rainfall. Two units were installed at each station for redundancy. These were

gradually replaced between 2010 and 2014. All stations installed after 2014 and old stations that were upgraded have two precipitation gauges: (i) the Pluvio2 weighing gauge, which is an all-weather precipitation gauge, installed on a 1.2-m-high, 12-cm-diameter base of galvanized stainless or heavy gauge aluminum with concrete base and (ii) the TB4 siphoning tipping-bucket rain gauge with 0.2-mm resolution installed 1 m above ground level. The Pluvio2 has a single alter shield around it and is designated as the primary precipitation gauge. It detects precipitation via change in the collecting bucket weight using a high precision stainless steel load cell. The TB4 is not heated and are used as a redundant, secondary precipitation gauge during periods of liquid precipitation, from May to September. Figure 3 shows the one-to-one comparison between the daily total precipitation from the Pluvio2 and TB4 at all the stations for days when either sensor recorded at least 5 mm rain from 1 June to 30 September 2019. The TB4 overestimated precipitation compared to data from the Pluvio2 with a mean bias error of 0.88 mm over the period evaluated. Shedekar et al. (2009) conducted a laboratory calibration of two tipping-bucket rain gauge models and reported slight overestimation at lower intensities ($<25.4 \text{ mm h}^{-1}$) but underestimation at higher intensities ($>50.8 \text{ mm h}^{-1}$). Most of the precipitation received in Manitoba are often at intensities less than 25.4 mm h^{-1} .

Fig. 3. 1:1 comparison of daily precipitation (mm) between the Pluvio2 and TB4 when total daily precipitation exceeded 5 mm across the mesonet from 1 Jun to 30 Sep 2019.

Wind speed and direction (05103-10, R. M. Young). The device has a four-blade propeller whose rotation creates a sine wave with frequency proportional to wind speed. Wind direction is determined by the output of an excitation voltage applied to a 10 K ohm potentiometer (Campbell Scientific, 2015). A few stations had the ORA wind sensor starting from 2016 but most of these have been replaced with the R. M. Young sensor. The sensor, placed on a 10-m tower, is sampled every 5 s for wind speed and direction. These samples are averaged over 15 min, hourly, and daily to obtain the mean scalar wind speed and unit vector wind direction. In line with the manual of surface weather observations, the reported hourly wind speed and direction is the average of 5-s data collected during the 2-min period at the end of an observation (Meteorological Service of Canada 2015). The maximum 5-s wind speed within the hour, wind direction at the maximum speed and the standard deviation of the sampled wind speed are also recorded. The sensor infrequently freezes during freezing rain leading to no change in wind direction and zero wind speed being reported in the raw data collection. The underestimated values are removed from the processed data records during data quality control checks.

Incoming solar radiation (SP-110 or SP-215, Apogee). The sensor outputs an analog voltage, which is directly proportional to the total shortwave radiation incident on a hemispheric planar surface (Apogee Instruments 2020). Due to increased power requirement by heated pyranometers, the two models used in the network do not have integrated heaters. Snow-covered sensors underestimate solar radiation but the duration and extent of snow impact on the performance of the pyranometers within the network is yet to be reviewed. The sensor is installed upward-facing (i.e., zenith) 2.5 m above ground level on a horizontal surface with a cross-arm mount attached to the main tower. About half of the 46 stations installed pre-2015 had pyranometers; however, these were retrofitted in 2016. All 63 new stations built from

2015 had pyranometers installed. Hourly average solar radiation (kW m^{-2}) and hourly total solar radiation flux (MJ m^{-2}) are the two primary data parameters recorded from the pyranometer. Solar radiation data are an important input in calculating reference evapotranspiration (ET_{ref}) at each station. The ET_{ref} is generated hourly using the ASCE standardized reference evapotranspiration equation for a crop with an approximate height of 0.50 m similar to full-cover alfalfa (Allen et al. 2005).

Soil temperature and soil moisture (CS-109L, Campbell Scientific and ML3 Theta Probe, Delta-T Devices). Soil temperature determination has been an integral part of the mesonet since its inception in 2005. A CS-109L sensor from Campbell Scientific is installed 5 cm below grass cover and sampled every 5 s. In an effort to fulfill the recommendations from the 2011 flood task force report (Manitoba Government 2013), the provincial government committed to deploying soil moisture sensors by leveraging the existing monitoring network. The installation of ML3 theta probes for measuring soil moisture and soil temperature started in 2016, which were installed at 5, 20, 50, and 100 cm below the grass surface. This installation duplicates soil temperature monitoring at the 5-cm depth; however, the CS-109L is used as the primary sensor for soil temperature at this depth. The top two layers, 5- and 20-cm depths, were installed in 2016. By June 2020, 105 of the 108 stations in the network had the probes installed at all four depths. During installation, a $1.0 \text{ m} \times 1.0 \text{ m} \times 1.2 \text{ m}$ (length, width, and depth) soil pit is dug. All the four probes are inserted into the soil horizontally at the specified depths at one side of the soil pit. The sensor tines maintain good contact with the soil. The cables are passed through a PVC tube at the opposite end of the pit to limit preferential flow from the cable channel. Soils from each layer are kept separate and back-filled in reverse order after installation. Readings are taken at 15-min intervals; however, only the last reading before the end of the hourly reporting period is included in the hourly data file. The ML3 theta probe was selected for network deployment based on the results of Ojo et al. (2015a). The authors found that although the Stevens hydra probe had the greatest improvement after calibration with root-mean-square error (RMSE) of $0.014 \text{ m}^3 \text{ m}^{-3}$; the theta probe had the best precalibration statistics at $0.025 \text{ m}^3 \text{ m}^{-3}$ RMSE. Sensor calibration of the theta probe did not significantly reduce the error when tested in heavy clay soils with over 70% clay content typically found in the Red River valley region of the province. Errors associated with coarse or medium textured soils are usually lower than that of heavy clay soils (Rowlandson et al. 2013; Ojo et al. 2015b).

Atmospheric pressure (PTB110, Vaisala). The sensor is housed in the enclosure box. The pressure sensor was installed at most of the stations in 2018 and at the end of 2019, only three stations in the mesonet did not have a pressure sensor. The elevation at each location is used to adjust the atmospheric pressure to sea level reference in order to make uniform spatial comparison of pressure level across the network. Table 2 provides a summary of the mesonet observation information.

Data collection and processing

The program running on each station has a 5-s scan rate for all sensors except the ML3 theta probe and the PTB110, which are measured every 15 min. The finest temporal resolution data stored is every 15 min. Hourly and daily aggregate data are also stored. In addition to recording the average of 5-s scans for the hour, the average of 5-s scans over the last minute at the end of an observation period (hour) is reported as the observation for air temperature, humidity, and soil temperature for the hour. The top-of-the-hour values provide current data, which can be different from the hourly average, especially during sunrise or sunset. This is usually important in the fall when farmers plan fall-applied fertilizer on cool but unfrozen soil

Table 2. Observation information.

Measured parameter	Manufacturer	Model	Placement ^a	Sampling period	Record type
Air temperature	Vaisala	HMP-155	2 m AGL	5 s	Avg, max, min
Relative humidity	Vaisala	HMP-155	2 m AGL	5 s	Avg, max, min
Wind speed	R. M. Young	05103-10	10 m AGL	5 s	Avg, max
Wind direction	R. M. Young	05103-10	10 m AGL	5 s	Avg, avg at max
Shortwave solar radiation	Apogee	SP-110/215	2.5 m AGL	5 s	Avg, total
All-weather precipitation	OTT HydroMet	Pluvio2	2 m AGL	5 s	Total
Rainfall	Hydrological Services	TB4	1 m AGL	5 s	Total
Atmospheric pressure	Vaisala	PTB110	1.5 m AGL	15 min	Sample
Soil temperature	Campbell Scientific	109L	5 cm BGL	5 s	Avg, max, min
Soil temperature	Delta-T Devices	ML3 ^b	5, 20, 50, and 100 cm BGL	15 min	Avg, max, min
Soil moisture	Delta-T Devices	ML3 ^b	5, 20, 50, and 100 cm BGL	15 min	Avg, max, min

^a AGL = above ground level; BGL = below ground level.

^b Carman and Carberry do not have the 50- and 100-cm ML3 theta probes installed for soil temperature and moisture. Areas around Sprague Lake in the SE corner are peatlands; no ML3 probes are installed at this station.

to minimize volatilization losses associated with application on warm soil. In addition, daily maximum, minimum, and average soil temperature values are recorded from the 5-s samples.

Data recorded by the sensors are stored on a Campbell Scientific CR1000 datalogger, which is connected to a cellular modem. The network uses three types of modems: Sierra Wireless RV50, Microhard BulletLTena2, and the Red Lion BT-6801/6701. The Red Lion modems are gradually being phased out and replaced with the Microhard modems, which have a low power requirement. Managing the load requirement is important, especially during winter months characterized by limited daylight and extended nights where air temperature frequently drops below -20°C (Fig. 4). The availability of good cellular connection is one of the main challenges that limits stable data collection at some locations. During station installation planning, a map showing the extent of network coverage by the telecommunication service provider and network signal strength greater than -105 dBm are used as criteria to determine installation sites. A directional or omnidirectional antenna is installed with the modem to boost cell signal at each location to at least -95 dBm. Sprague Lake weather station in the southeast corner of the province is the only station that is outside the range of Canadian telecommunication service provider. The station uses a U.S. telecom service provider due to its proximity to the Angle Inlet community in Minnesota.

Scheduled data collection, processing, and public viewing are set up via Campbell Scientific's Loggernet software (version 4.5). Data collection is scheduled every 15 min from 0700 to 1900 LT and hourly overnight from 1 April to 31 October. To conserve the load demand on the reduced battery efficiency due to cold and reduced daylight in the winter months, the modems are turned on hourly for data transmission from 1 November to 31 March of the following year. When battery voltage drops below 12.1 V (which occasionally occurs during the winter months), the stations are programmed to enter a power-save mode. In this mode, data are transmitted only twice every day: 0000 and 1300 LT instead of hourly. The station will remain in

Fig. 4. Precipitation and minimum and maximum air temperature at Lake Audy during winter months.

this mode until the minimum battery voltage is consistently greater than 12.1 V for three consecutive days.

Raw data are stored as comma-separated values file on a cloud server and are made available to the public as an image display file within a minute after data collection at the top of the hour (www.gov.mb.ca/agriculture/weather/current-ag-weather-conditions.html). The image file generated for each station uses an extension of the Loggernet package called the Real-Time Monitoring and Control (RTMC; version 4.3.3). A note indicating that the data have not gone through quality checks is displayed on every station page. Initial automatic quality control (QC) is conducted using the split program in Loggernet before being displayed on the ArcGIS online platform (Fig. 5). The initial QC involve using a generic threshold rule for each parameter. These rules include air temperature range of -50° to $+50^{\circ}\text{C}$, soil temperatures of -30° to $+30^{\circ}\text{C}$, relative humidity range of 5% to 100%, wind speeds from 0 to 130 km h^{-1} , precipitation ranges of 0 to 100 mm (hourly range) and 0 to 250 mm (daily range), solar radiation range of 0 to 5 MJ h^{-1} , soil moisture from 2% to 65% volumetric water content, and barometric pressure from 950 to 1,050 hPa. Further quality control is done by passing the raw data through a Python program to apply monthly thresholds to air and soil temperature and flag the occurrence of five or more unchanged consecutive values. Exceptions to unchanging consecutive values exist for precipitation, solar radiation data at night, soil temperature and moisture at 50- and 100-cm depths. All raw datasets are maintained to provide an opportunity to review erroneous data. However, values outside the defined range are automatically deleted from the processed database. The upper and lower limits for each threshold are defined from historical weather observations in agro-Manitoba but include a buffer to account for future record-breaking events.

The provincial Hydrometric program and the Ag-weather program are jointly developing a new and more interactive platform, which is expected to be made available to the public by 2021. The functionalities built into the new platform include the ability to view and download

Fig. 5. Current weather conditions updated hourly. Users can click on the tabs to show other weather parameters (www.gov.mb.ca/agriculture/weather/current-weather-viewer.html).

historical data. It uses the Aquarius data management software to collect, organize, analyze, and display time series data. Other organizations that use the Aquarius data management platform include the U.S. Geological Survey and Water Survey of Canada.

Station maintenance and sensor calibration

Two scheduled maintenance visits are conducted annually: one in the spring and the second in the fall. During these planned visits, a maintenance checklist is used to note arrival and departure time. Tasks on the checklist to be performed at the station usually includes Pluvio2 precipitation gauge recharge with oil and antifreeze solution (during fall season maintenance only); visual inspection of the station to ensure that all sensors are leveled and cleaned with wires properly secured in the datalogger and multiplexer terminals; tower bolts, guy wires, and all device mounting brackets are tight and secured; and grass is trimmed for vegetation maintenance. Site hosts at about a quarter of the stations in the network perform vegetation maintenance at their site. Regional provincial staff occasionally assist with grass trimming at weather stations close to their base location. Throughout the year, weather stations are visited for unscheduled maintenance if a sensor stops working or reports erroneous data. An inventory of about 30% spare sensors is maintained except when a sensor is being phased out of use.

Biosecurity protocols are followed during site visit to minimize the spread of soilborne pests such as clubroot, soybean cyst nematode, and verticillium wilt to uninfected fields. These protocols include but are not limited to parking vehicles at the side of municipal roads or in the approach and the field visit done on foot when possible, wearing of plastic disposable booties (worn over existing footwear) or wearing footwear that can be cleaned and disinfected between fields, and thoroughly washing hands and disinfecting every tool used in the field with the disinfectant solution available in every truck. The biosecurity protocols form one part of a comprehensive safety and health program in the Manitoba Agriculture Weather Program.

Sensor calibration is conducted on a 3-yr rotational basis. Each year, one-third of the stations are visited for calibration. A factory-calibrated HMP155 standard is used to check if the HMP device at each location is within an acceptable range of $\pm 0.5^{\circ}\text{C}$ for temperature and $\pm 10\%$ for relative humidity. Three checks are done at least 10 min apart and all three readings should fall within the acceptable range. Sensors that are outside this range are taken back to the workstation for calibration and replaced with new or previously used but calibrated one. Wind direction is verified during scheduled maintenance visits. Every 3 years when a station is visited for calibration, preventative maintenance is done by replacing the wind sensor. The bearings and potentiometers of the removed sensor are checked at the workstation and calibrated. The TB4 rain gauge calibration involves running a measured amount of water through a pipette, which should equate to the theoretical number of tips. Each bucket tips at approximately 5.5–6.0 mL. If either bucket tips outside the expected range, the device is calibrated by increasing or decreasing the screw length on which the bucket sits. The Guided Accuracy Test in the OTT Pluvio2 operating program is used to calibrate the Pluvio2 precipitation weighing gauge. The accuracy test checks if the sensor is within its specified measurement limits by placing a base weight of 2,500 g and a 1,000-g test weight on the scale. The software displays a pass message if the accuracy test is successful or a fail message if not successful. Scales that do not pass the accuracy test are replaced and sent for repairs. In addition to using the clear-sky solar radiation model for assessment (<http://clearskycalculator.com/pyranometer.htm>), basic sensitivity tests are conducted for the pyranometers by covering the sensor to check if the readings drop to near 0 W m^{-2} . The device is replaced every 6 years and the removed sensors are tested side by side with new, calibrated standards to check for drifts. The 109L soil temperature sensor and the ML3 soil moisture and temperature are currently installed as run-to-fail or replaced every 10 years. The ML3 sensors are not calibrated in the laboratory or in situ. They report observations from factory default calibration. The PTB110

barometric pressure sensors are new to the network. Accuracy checks will be performed on the PTB110 barometric pressure sensor during the 3-yr calibration rotation. Five comparative readings between an inspection barometer and the operational pressure sensor will be taken with at least 15 min between readings. The average of the five readings from the operational sensor should be within ± 0.5 hPa of the inspection barometer's average. Operational sensors that fail the test will be replaced and sent for calibration.

The performance of dataloggers, batteries, modems, solar controller, and solar panels are reviewed to check for drifts or reduced performance efficiency. The datalogger lithium battery, which powers both the clock and the static RAM when the main solar power source is disconnected, is monitored annually and replaced when the voltage drops below 2.7 Vdc. The charge cycle of the station batteries are monitored and the power-supply units, which include the battery, solar panels, and solar controllers are replaced if the power supply to the datalogger drops below expected standards such as reduced charge cycle under a clear sunny sky. When a station does not send data at the scheduled interval, the network signal strength in the area is checked to ensure that the issue is not from the telecommunication provider. If the station host or provincial staff in the area confirms good network signal, the data transmission peripherals such as modems, SIM cards, and antennas are tested to determine which unit requires replacement.

Data application

Weather is one of the primary factors affecting agricultural investments. Access to important weather information is critical to farming operations. The Manitoba Agriculture mesonet provides information used for growing-season precipitation and the computation of crop-specific thermal units; assessment of frost severity, duration, and spatial extent; and crop disease risk and forecasting. Some applications of the mesonet data includes the following:

- (i) Thermal unit computation for growing degree-day (GDD) and corn heat unit (CHU) are important for determining crop phenology and developmental stages. These values are computed and mapped using Eqs. (1) and (2):

$$\text{GDD} = \left(\frac{T_{\max} - T_{\min}}{2} \right) - T_{\text{base}}, \quad (1)$$

$$\text{CHU} = \frac{1.8 (T_{\min} - 4.4) + 3.33(T_{\max} - 10) - 0.084(T_{\max} - 10)^2}{2}, \quad (2)$$

where $T_{\max}$ and $T_{\min}$ are the daily maximum and minimum air temperatures, T_{base} is the base temperature. The base temperature used for the mapped GDD thermal computation is 5°C (McMaster and Smika 1988), and no daily accumulation is computed when $T_{\text{mean}} < T_{\text{base}}$. CHU accumulation uses 4.4° and 10°C as the base temperature for daily minimum and maximum air temperatures, respectively (Major et al. 1978). In addition to creating spatial maps of the thermal units, growing-season accumulation of the thermal units are compared to historical averages for each location to compute the percent of normal accumulation (Fig. 6a).

- (ii) Crop disease risk models: The mesonet provides data required to run the *Fusarium* head blight risk model (De Wolf et al. 2003) across agro-Manitoba. An increase in the severity of *Fusarium* (*Fusarium graminearum*) damaged kernels (FDK) of Canadian Wheat Red Spring (CWRS) from 0.5% to 2.2% can have minimal impact on yield quantity with less than 0.2 bu per acre yield loss. However, the economic impact is significant with a projected revenue loss of about CAD \$89.19 per acre (Government of Alberta 2018). Figure 6b shows a sample of the daily map produced during the wheat flowering period

Fig. 6. Maps published by the Manitoba Agriculture Weather Program showing (a) growing-season accumulated corn heat units compared to a 30-yr climate normal, (b) risk of *Fusarium* head blight using De Wolf et al. (2003) model, (c) areas of high cumulative precipitation over a 3-day period, and (d) growing-season accumulated precipitation compared to a 30-yr climate normal.

from early June to late July and it shows areas of low to high risk based on antecedent weather conditions over the previous 7 days. Potato late blight risk determination is another crop disease risk that the mesonet supports. The model uses 15-min air temperature and relative humidity data to determine the disease severity value (Stevenson 1993). The use of the mesonet data for modeling other crop diseases such as white mold in beans and creation of decision support tools to assist producers with agronomic planning, timing of field operations, and irrigation management are being considered.

- (iii) Severe weather events: In addition to the crop disease risk maps, crop insurance providers use the information on severe wind or precipitation for adjustment logistics after storms. Crop adjusters visit areas where severe weather events occurred to assess and determine the severity of the damage. They use seasonal precipitation data to validate the annual cause of loss experienced in different regions within agro-Manitoba (Figs. 6c,d). The provincial crop report issued every week during the growing season provides regional information from seeding, through crop development, to harvesting. Among other information sources, the regional staff that compile the report depend on local weather information from the mesonet to provide accurate information on the state of crop development in their area (Manitoba Agriculture and Resource Development 2020).
- (iv) Hydrologic forecast: One of the major reasons for the post-2014 expansion of the Manitoba mesonet was the need for accurate, timely hydrologic forecasts and to provide information for the public and all levels of government by integrating weather data with other required information. Data from the mesonet have provided critical information on soil moisture status at freeze-up in the fall. This information, combined with increased density of real-time winter precipitation measurement and frost depth data, provides the Hydrologic Forecast Centre with critical information and input data for modeling flood, especially spring flood (<https://gov.mb.ca/mit/floodinfo/>). Manitoba is prone to seasonal flood every spring from snowmelt. The mesonet data assist with timely decisions for deploying resources where they are required.
- (v) Prediction of surface temperature boundary: Gheysari et al. (2021) used artificial neural network to train data from the mesonet to predict soil temperature from air temperature and solar radiation. Their results, used in part for analyzing mitigation capacity of geothermal heat pump systems, showed that the use of average daily air temperature from the previous 14 days had the lowest root-mean-square error when compared to varying degrees of air temperature latency and daily average solar radiation.
- (vi) Remote sensing validation campaign: The network provided weather information during the Soil Moisture Active and Passive Validation Experiment in 2016 (SMAPVEX16), which was conducted around Carman, Manitoba. The SMAPVEX16 field campaign was designed to provide extensive data to support the postlaunch calibration and validation of the SMAP satellite for global soil moisture monitoring. The Carman and Elm Creek station datasets were included in the SMAPVEX16 Manitoba Meteorological Data (McNairn et al. 2018) available through the U.S. National Snow and Ice Data Center (https://nsidc.org/data/SV16M_MET/versions/1).
- (vii) Analysis of evapotranspiration models: The study by Ndulue and Ranjan (2021) used the mesonet data to compare the performance of FAO-Penman–Monteith reference evapotranspiration ($FAO-PM ET_o$) with limited dataset to 14 empirical ET_o models. The newly developed empirical coefficients from their results can be used to compute ET_o values for periods that do not have the full dataset required to run the FAO-PM ET_o equation.
- (viii) SOIL 3060—Introduction to agrometeorology class: Professors at the University of Manitoba have used data from the mesonet to create term projects for a third-year

undergraduate course. During the 2019 and 2020 fall semesters, each student that registered for the course was assigned data from a weather station close to their home town (when possible) to analyze changes in soil moisture availability and evaluate the ability of the soil to meet crop water demand (B. Amiro and P. Bullock 2020, personal communication).

In addition to the specific applications that were highlighted, data generated from the network have been used by local radio stations and regional newspaper media to report local weather observations in their communities. It was also used to investigate a plane crash near Brunkild, Manitoba, in 2017.

Conclusions

The Manitoba Agriculture mesonet is one of the few province-led weather monitoring networks in Canada. Most of the 108 weather stations in the network are located at the edge of cropped fields in rural areas at about 1 per 30-km spatial coverage. Thirteen additional stations were approved to fill identified gaps with the installations scheduled to start in 2020 but delayed due to COVID-19. Before introducing new devices to the network or when program updates are required, the sensors/programs are tested at the mesonet workstation located at the Bruce D. Campbell Discovery Centre at Glenlea, Manitoba. Data applications are primarily rooted in agriculture-related interests but continue to extend beyond the initial intended agronomic focus when the program officially started in 2005. Improvement in data accessibility and further development of products that utilize weather data are the immediate next steps the Manitoba mesonet are positioned to achieve as it continues to support teaching, extension, and research activities in Manitoba.

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