Environnement et Changement climatique Canada
Environment and Climate Change Canada

ANNUAL JOINT WMO TECHNICAL PROGRESS REPORT ON THE GLOBAL DATA PROCESSING AND FORECASTING SYSTEM (GDPFS) AND RESEARCH ACTIVITIES FOR 2017

CANADA

Final version February 7th , 2018

Meteorological Service of Canada,
Science and Technology Branch,
Environment and Climate Change Canada

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1 Generalities

1.1 Highlights for 2017 at the Canadian Meteorological Centre (CMC)

Thursday December 14, 2017 - The High Resolution Deterministic Prediction System (HRDPS) is declared operational at the Canadian Meteorological Centre (CMC)

Effective December 14, 2017, after several years running in experimental mode, the Canadian Meteorological Centre (CMC) of the Meteorological Service of Canada declared operational the High Resolution Deterministic Prediction System (HRDPS v4.4.0).

Wednesday November 1, 2017 - Major Upgrade to Version 6.0.0 of the Global Deterministic Prediction System (GDPS) at the Canadian Meteorological Centre

On Wednesday November 1st 2017, starting with the 1200 UTC run, the Meteorological Service of Canada's Canadian Meteorological Centre (CMC) will upgrade the Global Deterministic Prediction System (GDPS) to version 6.0.0.
The changes included in this upgrade are summarized as follows:

Changes to the forecast model:

- Introduction of two-way coupling with an ice-ocean model. In the GDPS-6.0.0 forecast system, surface conditions evolve through coupling with the forecast component of the Global Ice Ocean Prediction System (GIOPS). click here for GIOPS details.
- GDPS 6.0.0 is using GEM model version 4.8.2 (the main changes are associated with the surface interface, with only minor changes made to model physics and dynamics).
- No modifications were made to the assimilation component nor observations ingested in this upgrade of the GDPS.

Wednesday November 1, 2017 - Upgrade to Version 2.3 of the Global Ice and Ocean Prediction System (GIOPS) at the Canadian Meteorological Centre

On Wednesday November 1st, 2017, the Meteorological Service of Canada's Canadian Meteorological Centre (CMC) will upgrade the Global Ice and Ocean Prediction System (GIOPS) to version 2.3.
The major changes of GIOPS in this upgrade are in the forecast component.

Introduction of two-way coupling between the forecasts of GIOPS and GDPS. This coupling allows two-way interactions between the atmospheric model and the ice-ocean model, such that the evolution of surface marine conditions affects the atmosphere in the GDPS, which in turn affects the GIOPS oceanic forecast fields.

No significant modifications were made to the assimilation component of GIOPS in this upgrade.

The official announcement for the implementation of these changes is included in the GENOT issued for GDPS 6.0.0.

Wednesday November 1, 2017 - The Global Deterministic Wave Prediction System (GDWPS) is declared operational at the Canadian Meteorological Centre (CMC)

Effective November 1, 2017, after over two years running in experimental mode, the Canadian Meteorological Centre (CMC) of the Meteorological Service of Canada declared operational the Global Deterministic Wave Prediction System (GDWPS v1.3.0).

Wednesday November 1, 2017 - The Regional Deterministic Storm-surge Prediction System (RDSPS) is declared operational at the Canadian Meteorological Centre (CMC)

Effective November 1, 2017, after two years running in experimental mode, the Canadian Meteorological Centre (CMC) of the Meteorological Service of Canada declared operational the Regional Deterministic Storm-surge Prediction System (RDSPS v1.3.0).

The RDSPS provides storm-surge forecasts along the Atlantic Coast of Canada. Forecasts are launched twice a day at 00 and 12 UTC and integrated out to 10 days. Forecasts are driven with hourly wind and surface pressure fields provided by the Global Deterministic Prediction System (GDPS). RDSPS products are generated on a 1/30 degree resolution latitude-longitude grid from 42N to 60N and 72W to 44W.

The RDSPS was developed in partnership with Dalhousie University and is based on the Dalcoast5 storm surge model.

Wednesday September 6, 2017 - New High Performance Computing Infrastructure

A major project to migrate to a new supercomputing infrastructure employed by the Meteorological Service of Canada was successfully completed on September 6, 2017. This migration was the result of a joint, sustained effort over several months by experts at the Canadian Meteorological Centre, Science and Technology Directorate, and Shared Services Canada.

Our high-performance computing capacity has now attained the petaflop scale (1015 flops), a level which is comparable to that of the other leading meteorological centres around the world. Over the coming years, this major upgrade will allow further technological transfers from Research and Development into Operations, supporting the continuous improvement of the meteorological and environmental forecast services offered to Canadians and to other federal and provincial government agencies, users, and partners.

1.2 High Performance Computing Infrastructure

The High Performance Computing (HPC) infrastructure in use at the Canadian Centre for Meteorological and Environmental Prediction (CCMEP) underwent a significant upgrade, with operations being transferred over as of September 6th, 2017. Every component of the HPC infrastructure was upgraded as part of a large, complex implementation, including the supercomputers, the pre- and post-processing clusters, the high-performance network interconnect, storage capacity and the data archive system. This milestone is the result of a joint, sustained effort over several years by experts at the Canadian Meteorological Centre, Science and Technology Directorate and Shared Services Canada.

1.2.1 HPC Components

An essential part supporting the 24x7 mission critical operations at CMC, the HPC infrastructure is distributed over two sites, providing a greater degree of redundancy and backup for contingency scenarios. More than just a supercomputer, the HPC infrastructure itself consists of several equally important ancillary components, as detailed below.

1.2.1.1 Supercomputers

The backbone of the HPC infrastructure consists of two Cray XC40 supercomputers, each with 856 compute nodes (30,816 cores) consisting of 2 Intel Broadwell processors and 128 GB RAM. Prior to going operational, the twin supercomputers ranked number 162 and 163 on the top500.org[1] list of the most powerful commercially available supercomputers in the world.

The supercomputers run the Cray Linux Environment, which in this case is a derivative of a SUSE Linux Enterprise Server (SLES) distribution. The job scheduler and resource manager used is PBS Pro linked with Cray ALPS. Each supercomputer has its own scratch file system provided via Lustre on a Sonexion 2000 with approximately 3.6 PB of storage. All user homes are accessed from a high IOPS IBM ESS storage system (see below) via a Cray DVS to General Parallel File System (GPFS) bridge.

1.2.1.2 Pre- and Post-Processing Clusters

The dual pre- and post-processing (PPP) systems, one paired to each supercomputer, are used as interactive and batch platforms. Operational and R&D users can pre-process (e.g. quality control, reformat, prepare) data sets prior to submission to the supercomputer, run small models that would not run efficiently on the supercomputer, and post-process NWP model output data into different products or formats.

Both PPP clusters are Cray CS400 systems, each with 158 compute nodes (6,952 cores), consisting of 2 Intel Broadwell processors and 256 GB RAM connected via an Infiniband fabric. The PPP clusters run on the Linux Operating System, with PBS Pro used as the job scheduler and resource manager. All user home directories are accessed from a high IOPS IBM Elastic Storage Server (ESS) storage system, while the primary storage is provided by an IBM ESS storage system.

1.2.1.3 Primary Storage

Each PPP cluster has access to its own primary storage, provided by an IBM ESS storage system presenting file systems via Spectrum Scale GPFS. These storage systems consist of 24 servers presenting approximately 16 PB.

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[1] The June 2017 edition of the Top 500 list: https://www.top500.org/list/2017/06

1.2.1.4 Home Storage

The home storage used by both the supercomputer and the PPP clusters is a high IOPS IBM ESS storage system presenting file systems via Spectrum Scale GPFS. The single home file system has built in redundancy with GPFS replication and presents approximately 185 TB of storage to all components of the HPC infrastructure.

1.2.1.5 Mass Storage System

Extremely large amounts of data must be retained in long-term storage for backup, legal, verification, and research purposes. The archival needs of the HPC environment are met by dedicated cluster nodes and robotic manipulators accessing tape drives that provide both high data availability and absolute data integrity. The Meteorological Service of Canada has been using a robotized storage/archive facility for Environment and Climate Change Canada since 1994 in order to store and secure critical services and departmental data including:

- Numerical Weather and Environmental Prediction data (essential to improve forecasts);
- Climate change scenarios (including International Panel on Climate Change, IPCC, run results) and the Climate Archive Database; and,
- Computer backups, system logs, and data from routers and firewalls (essential in the investigation of security incidents, performance statistics, etc.).

The current High Performance Near Line Storage (HPNLS) system consists of an IBM High Performance Storage System (HPSS) with two distinct libraries that act as a single system spanning two data halls. Each library houses just over 10,000 IBM 3592 tape cartridges, individually with a capacity of 10 TB, for a total of approximately 100 PB of uncompressed data per library. The HPNLS itself has 2 PB of disk cache to accelerate archival operations.

1.3 Data and Products from GTS in use

1.3.1 Data

The following types of observations are presently used for upper-air data assimilation at the Centre. The numbers indicate the typical amount of data (reports or pixels) received during a 24-hour period in December 2017. When two numbers are presented, the former is for ASCII data while the latter is for BUFR data.

SYNOP/SHIP	96,500/87,500
TEMP	1,325/1,000
PILOT	850/300
DRIFTER/BUOYS	29,000/44,500
AIREP/ADS	23,400
AMV's (including DB)	7,020,000
AMDAR/BUFR	834,000
GB-GPS (E-GVAP)	482,500
GEO radiances (CSR)	4,443,000
AMSU-A (including RARS)	2,959,000
AMSU-B/MHS (including RARS)	24,840,000
ATMS	3,051,000
SSMI/S	5,492,000
AIRS (AQUA)	321,000
CrIS (NPP)	311,500
IASI (Metop-A/B)	647,500
ASCAT (Metop-A/B)	1,908,000
GPS-RO	1,975

1.3.2 Products

- GRIB ECMF
- GRIB KWBC
- GRIB EGRR
- FDCN KWBC
- FDUS KWBC
- U.S. Difax products
- Significant weather forecasts
- Winds/Temperature forecasts for various flight levels

1.4 System run schedule and forecast ranges

Assimilation and final analysis run schedule (all times in UTC)				
Description	**Name**	**Time**	**Cut-off**	**Remarks**
Global assimilation	G2	00, 06, 12, 18	00: T+9:00 12: T+8:15 06,18: T+6:00	Details section 2.1
Global final analysis	G6	00, 06, 12, 18	00: T+8:45 06: T+5:15 12: T+8:00 18: T+5:15	Details section 2.1
Global ensemble assimilation	E2	00, 06, 12, 18	00: T+9:00 06: T+06:10 12: T+8:15 18: T+6:15	Details section 2.2
Global Ice-Ocean assimilation (GIOPS-A)	GD	00	00: T+159:30 (every Tuesday)	Details section 2.8
	GR	00	00:T+4:30 (every Wednesday)	
Global Deterministic Wave Prediction System (pseudo-analysis)	GDWPS-PA	00, 06, 12, 18	00: T+9:50 12: T+9:05 06,18: T+6:50	Details section 2.8
Regional Deterministic Storm-surge Prediction System (pseudo-analysis)	RDSPS-PA	00, 06, 12, 18	00: T+10:05 12: T+9:20 06,18: T+7:05	Details section 2.8
Regional final analysis	R3	00, 06, 12, 18	T+7:00	Details section 2.3
Regional Ice-Ocean assimilation	RIOPS-A	00, 06, 12, 18,	T+3:00	Details section 2.8
Regional Marine Prediction System for the Gulf of St. Lawrence (pseudo-analysis)	RMPS-GSL	00, 06, 12, 18	T+0:35	Details section 2.8
Water-Cycle Prediction System - Great Lakes (pseudo-analysis)	RMPS-GL	00, 12	T+1:45	Details section 2.8
CanSIPS assimilation	M2	00	T+11:00	Details section 2.9
Regional deterministic precipitation analysis	RDPA	00, 06, 12, 18	T+0:55 (prelim) T+6:55 (final)	Details section 2.7

High resolution Regional Deterministic Precipitation Analysis	HRDPA	00, 06, 12, 18	T+0:55 (prelim) T+6:55 (final)	Details section 2.7

Forecast run schedule (all times in UTC)					
Description	**Name**	**Time**	**Cut-off**	**Forecast period**	**Remarks**
Global	G1	00, 12	T+3:00	240 hours	Details section 2.1 All products available by T+5:00.
Regional	R1	00, 12 06, 18	T+2:00	00-48 hours (operational) 48-84 hours (experimental)	Details section 2.3 All products available by T+3:30.
Local high resolution	National North	00, 12 06, 18 00, 06, 12, 18	N/A	48 hours 00, 12: 6 hours 06: 30 hours 18: 18 hours	Details section 2.5 (experimental GEM-LAM 2.5 km)
Global ensemble	E1	00, 12	T+3:00	16 days 32 days on Thursdays at 00 UTC	Details section 2.2
Regional ensemble	ER	00, 12	N/A	72 hours	Details section 2.4
Global Ice-Ocean Forecast	GU/GIOPS	00, 12	T+0:40 (daily)	240 hours	Details section 2.8
Regional Ice-Ocean Forecast	RIOPS	00, 06, 12, 18	N/A	48 hours	Details section 2.8
Air quality	GM	00, 12	N/A	48 hours	Details section 2.6
Global Deterministic Wave Prediction System	GDWPS	00, 12	N/A	120 hours	Details section 2.8
WAM fed by the GDPS	WG	00, 12	N/A	120 hours	Details section 2.8
WAM fed by the	WR	00, 12	N/A	48 hours	Details section 2.8

RDPS		06, 18		54 hours	
Regional Deterministic Storm-surge Prediction System	RDSPS	00, 12	N/A	240 hours	Details section 2.8
Regional Ensemble Storm-surge Prediction System	RESPS	00, 12	N/A	240 hours	Details section 2.8
Monthly	M1	00	T+11:00	One month	Details section 2.9 Produced at the beginning and middle of every month.
Seasonal	MA	00	T+11:00	3-month periods covering 1 year	Details section 2.9 Produced at the beginning of every month.
Nowcast	INCS	Every hour	T+0:15	12 hours	Details section 2.7
autoTAF Automated guidance system	ATAGS	Every hour	T+0:15	48 hours	Details section 2.7
Regional coupled atmosphere-ocean-ice forecast system for the Gulf of St. Lawrence	RDPS-CGSL	00, 06, 12, 18	N/A	48 hours	Details section 2.8
Water-cycle Prediction System	RDPS-CGL	00, 12	T+2:30	84 hours	Details section 2.8

1.5 Annual verification summary

Objective verification of the operational numerical models is carried out continuously at the CMC. CMC participates in a monthly exchange of NWP verification data following WMO/CBS recommendations originally implemented in 1987. Standards for the exchange were originally established in 1998 and were updated in 2011. CMC implemented the new standards this past year. The table below is a summary of the CMC verification scores for 2017, based on the new standards.

Verification summary - 2016
Canadian Meteorological Centre
Global Deterministic Prediction System (25 km, L80)

Verification against analysis

Area	Parameters	T+24h		T+72h		T+120h	
		00UTC	12UTC	00UTC	12UTC	00UTC	12UTC
N. Hemisphere	RMSE (m), GZ, 500 hPa	7.0	7.2	21.5	21.4	45.1	45.2
	RMSVE (m/s), Wind, 250 hPa	3.6	3.6	8.0	7.9	13.3	13.2
Tropics	RMSVE (m/s), Wind, 850 hPa	2.2	2.2	3.6	3.6	4.5	4.4
	RMSVE (m/s), Wind, 250 hPa	3.6	3.6	6.2	6.3	8.1	8.1
S. Hemisphere	RMSE (m), GZ 500 hPa	8.8	8.8	26.8	26.7	54.4	54.6
	RMSVE (m/s), Wind, 250 hPa	3.5	3.5	8.4	8.3	14.1	14.1

Verification against radiosondes

Network	Parameters	T+24h		T+72h		T+120 h	
		00UTC	12UTC	00UTC	12UTC	00UTC	12UTC
N. America	RMSE (m), GZ 500 hPa	9.0	9.3	21.9	22.4	43.6	44.7
	RMSVE (m/s), Wind, 250 hPa	5.8	5.8	9.9	9.9	15.5	15.5
Europe	RMSE (m), GZ 500 hPa	10.9	10.7	24.2	23.6	52.5	52.9
	RMSVE (m/s), Wind, 250 hPa	5.1	4.9	9.6	9.3	15.7	15.6
Asia	RMSE (m), GZ 500 hPa	13.1	12.9	21.4	21.3	38.4	38.5
	RMSVE (m/s), Wind, 250 hPa	5.4	5.5	8.6	8.6	12.5	12.6
Australia - N.Z.	RMSE (m), GZ 500 hPa	8.5	9.9	15.9	19.4	30.3	38.5
	RMSVE (m/s), Wind, 250 hPa	5.0	5.3	8.0	8.3	12.1	12.6
Tropics	RMSVE (m/s), Wind, 850 hPa	4.0	4.0	5.0	4.8	5.7	5.5
	RMSVE (m/s), Wind, 250 hPa	5.2	5.2	7.0	7.1	8.2	8.4
N. Hemisphere	RMSE (m), GZ 500 hPa	12.3	12.3	23.5	23.5	45.9	46.4
	RMSVE (m/s), Wind, 250 hPa	5.2	5.2	8.9	8.9	14.1	14.1
S. Hemisphere	RMSE (m), GZ 500 hPa	10.9	12.7	20.5	23.0	38.5	42.1
	RMSVE (m/s), Wind, 250 hPa	5.4	5.5	8.6	8.8	13.1	13.2

2 Operational Forecasting System

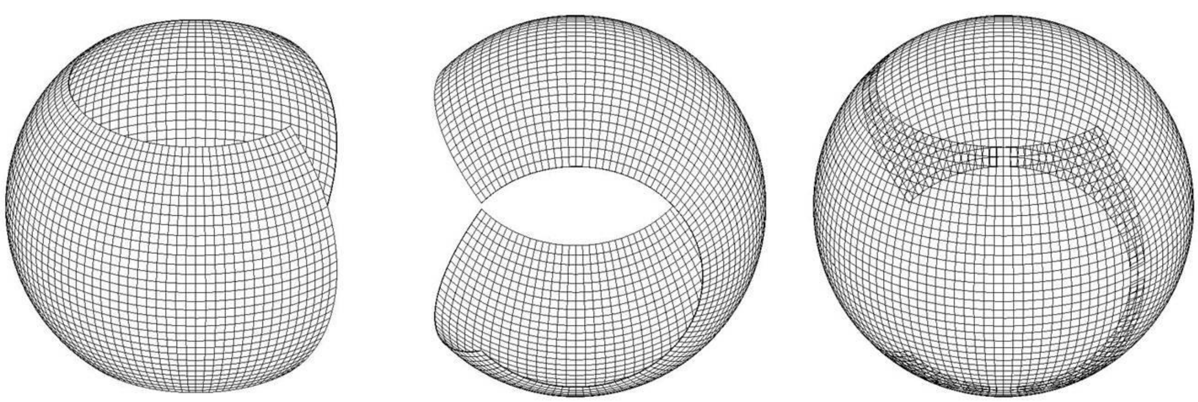
2.1 Global Deterministic Prediction System (GDPS)

2.1.1 Data assimilation and objective analysis

GDPS – Assimilation – Version 5.1.0	
Assimilation approach	Four-dimensional ensemble-variational approach (4DEnVar) system combining variational data assimilation with an Ensemble Kalman Filter, which is used to provide an ensemble of background states to specify the flow-dependent part of the background-error covariances to the 4DEnVar. No outer loop (70 inner-loop iterations), increments computed every hour. Data assimilated at 15 minutes intervals in a 6 h assimilation window. See Buehner et al. (2013a, 2014, 2015).
Variables	T, Ps, U, V and log q (specific humidity)
Domain	Global
Levels	Same 80 staggered hybrid levels as in the forecast model
Analysis increment horizontal grid	0.45° x 0.45° Gaussian grid
Trial fields	9-hour forecast (see section 2.1.2 for details on the model characteristics)
Assimilated radiance data (number of channels)	AMSU-A (11), HS (4) , SSMIS (7), geostationary imagers (1), AIRS (142), IASI (142) New: ATMS (17), CrIS (103). Inter-channel correlation in the radiance observations error matrix (see Desroziers et al.,2005).
Other satellite data	GPS-RO refractivity, AMVs, scatterometer winds, ZTD from GB-GPS over North America and over Europe.
Other data used	TEMP, PILOT, SYNOP/SHIP, BUOY/DRIFTER, ASCAT, aircraft data
Treatment of radiosonde and aircraft data	Radiosonde: use appropriate measured or computed time and horizontal position for each pressure level. Aircraft: static temperature bias correction
Satellite radiance bias correction	Coefficients computed from Obs-minus-Analysis using a separate 3DVar analysis that does not include radiances, based on last 7 days, 4 times per day, except static for AMSU-A channels 13-14 and ATMS channels 14-15.
Background-error covariances	Surface to ~40hPa: Average of NMC method covariances and 4D ensemble covariances from 256 ensemble members (EnKF) every hour over the 6 h assimilation window; Above ~10hPa: Only the 3D NMC method covariances
Treatment of near surface variables	Wind and thermodynamic variables near the surface correctly assigned to 10 m and 1.5 m above the surface
Cut-off time	3 hours for forecast runs. 9 hours for final analyses at 00/12 UTC, and 6 hours at 06/18 UTC.
Frequency	Every 6 hours using data ±3 hours from 00, 06, 12 and 18 UTC.
Processing time	17 min for the analysis as such using 640 cores (not including processing of data, background check, treatment of the EnKF members and so on).

2.1.2 Forecast

GDPS version 5.0.0 – Forecast component	
Model	Global Environmental Multiscale (GEM) model version 4.7.2
Model initialization scheme	4D-IAU (Incremental Analysis Update) applied over 6 hour assimilation window (i.e. *T*-3 h to *T*+3 h). This allows the recycling of a variety of physics variables: Total condensate, Turbulent kinetic energy, Turbulence regime, Mixing length, Friction velocity and PBL height
Formulation	Hydrostatic primitive equations.
Forecast Domain	Global.
Numerical technique	Finite differences: Arakawa C grid in the horizontal and Charney-Phillips grid in the vertical (Girard et al. 2014)).
Grid	•2x 1287x417 Yin-Yang horizontal grid. Horizontal resolution is quasi-uniform and varies from a lower bound value of 17.2km to a maximum of 25 km grid point distance (Kageyama and Sato 2004, Qaddouri and Lee, 2011 and 2015) (*see figure below*)
Vertical Levels	80 staggered hybrid levels (same number of momentum and thermodynamic levels), plus 2 diagnostic levels at 10 and 1.5 meters for near surface winds and temperature/dew point. Model lid at 0.1 hPa. (Girard et al. 2014).
Time integration	Implicit, semi-Lagrangian (3-D), 2 time-level, 720 seconds per time step (Côté et al., 1998a and 1998b). Trapezoid calculation of trajectories, with cubic interpolation.
Independent variables	x, y, ζ and time.
Prognostic variables	Three-dimensional winds, virtual temperature, vertical coordinate displacement, geopotential, specific humidity, pressure, cloud condensate mixing ratio, turbulent kinetic energy (TKE).
Derived variables	MSL pressure, relative humidity, QPF, precipitation rate, omega, cloud amount, boundary layer height and many others.



Yin subgrid (left) Yang subgrid (middle) Yin-Yang grid (right)

Geophysical variables	Surface and deep soil temperature and moisture. Snow depth, snow albedo and snow density: - Derived from analyses at initial time, predictive; Soil variables from ISBA scheme (Noilhan and Planton, 1989; Bélair et al. 2003a and 2003b); Sea ice thickness, sea ice cover and sea surface temperature Obtained from the GIOPS system (described in section 2.8.1) which is run in a 2 way coupling mode with the atmospheric model. The GIOPS systems produces analyses of sea ice cover and sea surface temperature which are provided to the system at initial time while the sea ice thickness is recycled from one run to the next one. Orography, surface roughness length (except over water), subgrid-scale orographic parameters for gravity wave drag and low-level blocking, vegetation characteristics, soil thermal and hydraulic coefficients, glaciers fraction - Derived from a variety of geophysical recent data bases using in house software, fixed in time
Horizontal diffusion **(explicit)**	Del-6 on momentum variables only (4%), except del-2 applied on temperature and momentum variables at the lid (top 6 levels) of the model, with conservation of the dry air mass. The same 6 operator is applied with a 1% coefficient to the diffusion of potential temperature.
Orographic gravity wave drag	Parameterized (McFarlane, 1987; McFarlane et al., 1987).
Non-orographic gravity wave drag	Parameterized (Hines, 1997a,b).
Low level blocking	Parameterized (Lott and Miller, 1997; Zadra et al., 2003) with enhanced drag coefficient (Wells et al., 2008; Vosper et al. 2009).
Radiation	Solar and infrared using a correlated-k distribution (CKD) (Li and Barker, 2005).
Surface scheme	Mosaic approach with 4 types: land, water, sea ice and glacier (Bélair et al., 2003a and 2003b).
Surface roughness length over water	Charnock formulation except Z0T constant in the Tropics.
Turbulent mixing (vertical diffusion).	Based on turbulent kinetic energy (Benoît et al., 1989; Delage, 1988a and 1988b) with mixing length from Bougeault-Lacarrère (1989; see also Bélair et al, 1999) except near the surface and in the upper-troposphere. Includes Richardson number hysteresis (McTaggart-Cowan and Zadra, 2015).
Shallow convection	1) Turbulent fluxes in partially saturated air (Girard, personal communication). 2) Kuo Transient scheme (Bélair et al., 2005).

Grid scale condensation	Sundqvist scheme (Sundqvist et al., 1989; Pudykiewicz et al., 1992. For QPF evaluations see Bélair et al., 2009).
Deep convection	Kain & Fritsch scheme. (Kain and Fritsch, 1990 and 1993).
Frequency and cut-off time	Four 48-h forecasts are produced each day at 00 UTC, 06 UTC, 12 UTC and 18 UTC. They are initiated from GDPS analyses valid 6-hour earlier (with cut-off times of 3:00 hrs at 00 UTC or 12 UTC; and 6:00 hrs at 06 UTC or 18 UTC) to generate the backgrounds for the LAM and the global driver. In each analysis step, the 4DEnVar analysis both for the global driver and the LAM uses a cut-off of 2:00 hours. Data within +/- 3 hours of analysis time are used.
Processing time	11 minutes for the LAM analysis as such using 640 cores (not including processing of data, background check, treatment of the EnKF members and so on).

2.1.3 Statistical techniques and products

Analyses

A series of classic analysis products are available in electronic or chart form (snow depth and snow cover, sea surface temperature, ice coverage, MSLP and fronts, 1000-500 hPa thickness, geopotential height, temperature and winds at different pressure levels).

Forecasts

A series of classic forecast products are available in electronic or chart form (MSLP and 1000-500 hPa thickness, 500 hPa geopotential height and absolute vorticity, cumulative precipitation over given periods and vertical velocity, 700 hPa geopotential height and relative humidity).

A wide range of bulletins containing spot forecasts for many locations are produced. As well, other specialized products such as precipitation type and probability of precipitation forecasts, temperature and temperature anomaly forecasts are produced.

Several calculations using SPOOKI (see following item in this section) are now available until 192 hours at 00 and 12UTC:

- Total Totals , George-K and SWEAT indices.
- Freezing levels, wind chill and instantaneous precipitation types according to the Bourgouin method.

SPOOKI

The system called SPOOKI stands for "*Système de Production Orienté Object contenant une Kyrielle d'Informations*" – Object oriented production system containing a myriad of informations. It is based on a modular approach where each "plug-in" component is specialized, reusable and autonomous. These object-oriented programming characteristics simplify the maintenance of the system.

This system produces summer and winter severe weather calculations as described above.

Perfect Prog

6 h and 12 h probability of precipitation forecasts at the 0.2, 2 and 10 mm thresholds, at all projection times between 0 and 144 hours at 00UTC, and between 0 and 72 hours at 12UTC (Verret, 1987). An error feedback system is applied on the probability of precipitation forecasts to remove the biases (Verret, 1989). Consistency is forced between the 6 h and the 12 h probability of precipitation forecasts using a rule based system which favours forecasts sharpness.

Spot time total cloud opacity at three-hour intervals between 0 and 72 hours (12UTC) or 144 hours (00UTC) projection times (Verret, 1987). An error feedback system is applied on the forecasts to remove the biases and to force the forecasts to show the typical U-shaped frequency distribution like the one observed (Verret, 1989).

Spot time surface temperatures at three-hour intervals between 0 and 72 hours (12UTC) or 144 hours (00UTC) projection times (Brunet, 1987). An anomaly reduction scheme is applied on the forecasts so that they converge toward climatology at the longer forecast hours.

Stratospheric ozone is used to calculate the Canadian UV Index (Burrows et al., 1994).

Model Output Statistics (MOS)

For the global system, the 2-m temperature is post-processed using the UMOS (Wilson and Vallée, 2001 and 2002) package. This is done at three-hour intervals from 0 to 144 hours for the two GDPS runs (00 and 12 UTC). Note that the other weather elements from the global model (winds, probability of precipitation and cloud cover) are statistically post-processed using the Perfect-Prog method.

Before implementing a new version of the numerical model, the statistics are updated using R&D final tests.

Automated computer worded forecasts - SCRIBE

A system, named SCRIBE, is running at all the Regional Weather Centres in Canada to generate a set of automated plain language forecast products from a set of weather element matrices for day 3 to 7 inc. for the public forecast and for day 3 to 5 for the marine forecast (Verret et al., 1993; 1995; 1997). See the following section Weather element matrices. SCRIBE is the main tool for operational public and marine forecast preparation. Operational meteorologists use an interface to add value to the automated forecast as required. Once the meteorologist has reviewed the weather elements, SCRIBE generates the forecast products automatically.

Weather element matrices

An ensemble of weather element matrices including statistical weather element guidance, direct model output parameters and climatological values are prepared at a 3-hour time resolution at 1559 points in Canada and over adjacent waters. The data is valid at the projection times between 0 h and 144 h. Included in the weather element matrices are: climatological maximum / minimum temperatures on a local time window; statistical spot time temperature forecasts; maximum / minimum temperature forecasts calculated from the spot temperatures on a local time window; climatological frequencies of a trace or more of precipitation over 6-h and 12-hour periods; climatological frequencies of 10 mm or more of precipitation over 12-hour periods; statistical spot cloud opacity; statistical forecasts of probability of precipitation over 6-hour and 12-hour periods at the trace and 10 mm thresholds; model precipitation amounts; model cloud ceiling height, Showalter index; vertical motion at 850 hPa; conditional precipitation type; various thicknesses; wind direction and wind speed at the surface; model surface dew-point depression; Canadian UV index; model total clouds; 6-hour and 12-hour diagnostic probability of precipitation; model surface temperature, model temperature and dew-point depression near -level 0.97; sea surface temperature; ice cover; snow depth; wave height forecasts and freezing spray accumulation forecasts. These matrices are disseminated to the Regional Weather Offices where they are used to feed an interactive system for composition of meteorological forecasts called SCRIBE (Verret et al., 1993; 1995 and 1997).

2.2 Global Ensemble Prediction System (GEPS)

2.2.1 Data assimilation and objective analysis

GEPS version 4.2.0 – Assimilation	
Model version	Global Environmental Multiscale (GEM) model version 4.6.3.
Method	Ensemble Kalman Filter is used to do the analyses to initialize the global ensemble forecasts. A trajectory of 3 to 9 hour forecasts with GEM (Houtekamer et al., 2014; Houtekamer et al., 2009) is used as trial fields to assimilate perturbed observations. An ensemble of 256 trial fields is run with different model configurations (see below for more details). The time step of these models is 15 minutes. They are subdivided in 8 sub-sets of 32 members (model configurations). Also, additional perturbations are added with homogenous isotropic model error random fields (Houtekamer et al. 2009). The length of the assimilation window is 6 hours.
Variables	T, Ps, U, V and q (specific humidity).
Levels	74 hybrid levels. Model lid at 1.45 hPa.
Domain	Global
Grid	0.45º uniform resolution (~50 km)
Frequency	Every 6 hours using data ±3 hours from 00, 06 , 12 and 18 UTC.
Cut-off time	• 9 hours for final analyses at 00/12 UTC and 6 hours at 06/18 UTC. • 3 hours for forecast runs twice a day, at 00 and 12 UTC, twenty representative members are chosen among the 256 analyses to initialize the medium-range forecasts. The average of this subset of analyses is constrained to be equal to the 256 member analyses ensemble mean.
Processing time	25-30 minutes analysis (with a maximum of 2304 cores) plus 35-40 minutes for model integration to produce trials (256 x 32 cores) on the IBM P7.
Data used	Radiosonde upper-air, Radiosonde surface, Surface, Aircraft, Satellite wind, oceanic wind Scatterometer, ATOVS level 1b (AMSU-A; AMSU-B/MHS, GLOBAL and RARS), GPS-RO and ATMS

Ensemble perturbations:	
- Observations are perturbed in function of their error statistics - Observational errors for GPS-RO are set to be static and purely depend on the height of the observations). - Homogenous isotropic perturbations are also added at the end of the assimilation process (coefficient of 0.33 for the continuous long cut-off cycle and 0.66 for the short cut-off analyses)	
Perturbations in the trial field model configurations:	
Deep convection	Either the Kain & Fritsch scheme. (Kain and Fritsch, 1990 and 1993) or a Kuo-type scheme (Geleyn, 1985) is used.
Shallow convection	The Girard scheme (named 'conres') that calculates turbulent fluxes in partially saturated air (see in Mailhot et al. 1998) is used by each member. Also, additionally for half of the members the Kuo Transient scheme (named 'ktrans_mg', see Bélair et al., 2005) is used (associated with the Kain&Fritsch convection scheme).
Stable precipitation	Two different formulations (named 'consun' and 'newsund') of the Sundqvist et al., 1989 scheme are used for half of the members respectively (see Pudykiewicz et al., 1992). For QPF evaluations, see Bélair et al. (2009). The 'consun' version is associated with the Kain&Fritsch scheme while the 'newsund' is linked to the deep convection Kuo scheme;
Orographic gravity wave drag	It is parameterized following McFarlane (1987) and McFarlane et al. (1987). 2 different coefficients are used (weak = 4.E-6 or strong = 1.2E-5). The control (member 0) uses 8.E-6.
Turbulent mixing (vertical diffusion).	Turbulent kinetic energy (Benoît et al., 1989; Delage, 1988a and 1988b) with mixing length from either the Bougeault-Lacarrère (1989; see also Bélair et al, 1999) except near the surface and in the upper-troposphere or the Blackadar (1962) formulation are used. All members iInclude Richardson number hysteresis (McTaggart-Cowan and Zadra, 2014) Also, 2 different values for the turbulent vertical diffusion parameter (inverse of the Prandtl number) are used (0.85 or 1.0).
Low level (orographic) blocking	Parameterized (Lott and Miller, 1997; Zadra et al., 2003). 2 different coefficients are used (0.5 or 1.5). The member 0 uses the coefficient 1.0.
Roughness length over ocean	The formulation of Deacu et al. 2012 for the calculation of the roughness length over ocean is now used for half of the members (model key Z0TRDPS300).
Salinity effect on saturation specific humidity	We are now taking into account the effect of ocean salinity on the saturation specific humidity at the ocean surface, which is the boundary condition for the latent heat flux calculation. Again, half the members have this option activated, while it is not the case for the other half.

Diffusion of the potential temperature (theta)	Please note that this is no longer a perturbation because numerical diffusion of the theta fields is applied (since GEPS 4.1.1) for all members (model key Hzd_lnr_theta) with a coefficient of 0.04 and a degree of 6 (del 6). A damping envelop is added to limit the diffusion near the calculation poles (which coincide with the geographical poles) A linear reduction of the diffusion in function of the grid point distance to the pole (more reduction closer to the pole) is used, starting 20 grid points away from the pole

2.2.2 Forecast

GEPS version 4.2.0 – Forecast	
Model version	Global Environmental Multiscale (GEM) model version 4.6.3.
Initialization	Diabatic Digital Filter (Fillion et al. 1995).
Formulation	Hydrostatic primitive equations.
Domain	Global
Numerical technique	Finite differences: Arakawa C grid in the horizontal and Charney-Phillips grid in the vertical.
Grid	800x400 latitude-longitude grid having a uniform 0.45º (~50 km) resolution
Levels	40 hybrid levels. Model lid at 2 hPa.
Processing time	55-60 minutes for a 16-day forecasts (with 21 x 128 cores) on the IBM P7.
Time integration	Implicit, semi-Lagrangian (3-D), 2 time-level, 900 seconds per time step (Côté et al., 1998a and 1998b).
Independent variables	x, y, η and time.
Prognostic variables	E-W and N-S winds, temperature, specific humidity and logarithm of surface pressure, liquid water content, Turbulent kinetic energy (TKE).
Derived variables	MSL pressure, relative humidity, QPF, precipitation rate, omega, cloud amount, boundary layer height and many others.

Geophysical variables:	**Surface and deep soil temperature and moisture; snow depth, snow albedo and snow density**: - Derived from analyses at initial time, predictive; soil variables from ISBA scheme (Noilhan and Planton, 1989; Bélair et al. 2003a and 2003b); **Sea ice thickness**: Derived from climatology at initial time, fixed in time **Sea surface temperature:** Derived from analyses, evolved using persistence of anomaly **Sea ice cover**: derived from analyses, evolved in time linearly in function of sea surface temperature (SST) thresholds **Miscellaneous** (orography, surface roughness length (except over water), subgrid-scale orographic parameters for gravity wave drag and low-level blocking, vegetation characteristics, soil thermal and hydraulic coefficients, glaciers fraction): - Derived from a variety of geophysical recent data bases using in house software, fixed in time
Horizontal diffusion	Del-6 on momentum variables only, except del-2 applied on temperature and momentum variables at the lid (top 4 levels) of the model.
Radiation	Solar and infrared using a correlated-k distribution (CKD) (Li and Barker, 2005).
Surface scheme	Mosaic approach with 4 types: land, water, sea ice and glacier (Bélair et al., 2003a and 2003b).

Ensemble configuration:	
Forecast for 20 members are produced. They differ in their initial conditions; their physics schemes and physics tendencies perturbations and stochastic kinetic energy back-scattering are also applied (with different seeds). For more details see Gagnon et al. (2015).	
Ensemble perturbations (see detailed configuration in the table next page):	
• Each member is initialized with a different set of atmospheric initial conditions coming from the global EnKF (see section 1)	
• Also, the perturbations in the model configurations used to produce the trial fields (see Ensemble perturbations in section 1) are also applied to do the medium-range forecasts. Additionally, the following two schemes are also activated in the forecast model configuration (members 1 to 20 only but not for the control):	
Stochastic perturbations of the physics tendencies	• Stochastic perturbations of the physical tendencies (PTP) and Markov chains with random number between 0.5 and 1.5 with different seeds are used for all members except the member 0 (see description in Charron et al. 2010 and Li et al. 2008). Note: No perturbation is applied in the areas of convective instability (see Gagnon et al. 2013a and Erfani et al. 2013)

Stochastic kinetic energy backscattering	• An implementation of the Shutts (2005) scheme (SKEB) is used with different seeds (see Charron et al. 2010) is used for all members except the member 0.

2.2.3 Reforecast system

A reforecast procedure similar to the one described in Hagedorn (2008) is operational (see Gagnon et al. 2013b and Gagnon et al. 2014b). This procedure consists of doing historical forecasts, extended over the last 20 years in this system version (up from 18), with the same forecast system as the operational one to generate a database that will be used to do post-processing to improve the final forecasts (see Hamill et al. 2008). The initialization of the reforecasts is done using perturbations around the ERA-interim reanalyzes (Dee et al. 2011) atmospheric fields. Random isotropic perturbations (see section 3a of Houtekamer et al. 2009) are added to the reanalysis fields to create 4 different initial conditions for the 4 members that will be run. The 4 members are run instead of 20 to minimize the computing cost. The 4 members are chosen in function of the year to make sure that each of the twenty model configurations is picked as often as the others (ex.: for 1995 we used members 1, 6, 11 and 16; for 1996 members 2, 7, 12 and 17, etc.). Then, every week, 80 historical forecasts of 32 days for the period 1995-2014 are produced by CMC operations.

The surface fields are taken from a 30-year integration of the Surface Prediction System (SPS) forced by the near-surface fields of ERA-interim reanalyzes as well as the 3-hour precipitation amounts. This off-line system includes a land surface scheme, ISBA (Noilhan & Planton, 1989 and Noilhan and Mahfouf, 1996), as well as a sea ice and a glacier schemes. Each of these schemes is used in the GEM model itself. It used to be called GEM-surf (see Carrera et al. 2010). It has been used in several high-resolution surface studies (see Separovic et al. 2014, Bernier and Bélair 2012, Ioannidou et al. 2014).

No.	Deep Convection	Gravity wave drag	Mixing length	Vertical Diffusion	Orographic blocking	Deacu Z0T	Salty QSAT	SKEB	PTP
0	Kain&Fritsch	Standard	Bougeault	1.0	1.0	Yes	Yes	No	No
1	Kain&Fritsch	Strong	Blackadar	1.0	0.5	Yes	No	Yes	Yes
2	OldKuo	Strong	Blackadar	1.0	0.5	No	No	Yes	Yes
3	Kain&Fritsch	Weak	Bougeault	0.85	1.5	Yes	Yes	Yes	Yes
4	OldKuo	Weak	Bougeault	0.85	1.5	No	No	Yes	Yes
5	Kain&Fritsch	Weak	Blackadar	1.0	0.5	No	No	Yes	Yes
6	OldKuo	Weak	Blackadar	1.0	1.5	Yes	Yes	Yes	Yes
7	Kain&Fritsch	Weak	Bougeault	1.0	0.5	No	Yes	Yes	Yes
8	OldKuo	Weak	Bougeault	1.0	1.5	No	Yes	Yes	Yes
9	Kain&Fritsch	Strong	Bougeault	1.0	1.5	Yes	Yes	Yes	Yes
10	OldKuo	Strong	Bougeault	1.0	1.5	No	Yes	Yes	Yes
11	Kain&Fritsch	Strong	Bougeault	0.85	1.5	No	No	Yes	Yes
12	OldKuo	Strong	Bougeault	0.85	0.5	No	No	Yes	Yes
13	Kain&Fritsch	Weak	Blackadar	0.85	1.5	Yes	No	Yes	Yes
14	OldKuo	Weak	Blackadar	0.85	0.5	Yes	Yes	Yes	Yes
15	Kain&Fritsch	Strong	Blackadar	0.85	1.5	Yes	Yes	Yes	Yes
16	OldKuo	Strong	Blackadar	0.85	1.5	No	Yes	Yes	Yes
17	Kain&Fritsch	Strong	Blackadar	1.0	0.5	No	No	Yes	Yes
18	OldKuo	Strong	Blackadar	1.0	1.5	No	Yes	Yes	Yes
19	Kain&Fritsch	Strong	Bougeault	0.85	0.5	No	No	Yes	Yes
20	OldKuo	Weak	Bougeault	0.85	1.5	No	Yes	Yes	Yes

2.2.4 Statistical techniques and products

Perfect Prog

The weather element guidance for probability of precipitation and spot time total cloud opacity as described in section 2.1.3 is also produced off each member of the Ensemble Prediction System at all projection times between 0 and 240 hours, along with spot time surface temperatures at three-hour intervals between 0 and 240 hours projection times (Denis and Verret, 2006).

Weather element matrices

The range of the weather element matrices produced using the GDPS data (see section 2.1.3) is extended to 7 days using the results of the GEPS.

Other EPS products

The following EPS products are available on the web as forecast charts at the following address:

http://meteo.gc.ca/ensemble/index_e.html

- 10-day mean temperature anomaly
- Spaghetti plots of the 500 hPa heights
- Calibrated probability of equivalent precipitation for various thresholds
- Accumulated quantity of precipitation
- Sea level pressure centres
- 500-hPa geopotential heights

Also available on the web page is the ensemble spread of the trial fields.

An extreme forecast index (EFI) is computed for max and min temperature, max winds and precipitations amounts. It is made available at the following URL:

http://collaboration.cmc.ec.gc.ca/cmc/cmoi/cmc-prob-products/

The EPS forecast gridded data are available in digital format (GRIB2) from a MSC server. Technical details as well as the terms and conditions of utilization of these data are available at this address:

http://weather.gc.ca/grib/index_e.html

The Canadian ensemble outputs are used in the North American Ensemble System (NAEFS) project, a joint initiative involving the MSC, the United States National Weather Service (NWS) and the National Meteorological Service of Mexico (NMSM). The following products based on the NAEFS joint ensemble forecasts are available on the official MSC web server:

http://weather.gc.ca/ensemble/naefs/index_e.html

- Temperature anomaly for the second week (day 8 to 14 outlooks). This is a common product produced by MSC and the NWS.
- EPSgrams for more than 300 cities in Canada, Mexico and the USA
- Ensemble means and standard deviation charts for various gridded fields
- Charts of probabilities of occurrence of several weather elements

Pressure centres trajectories on the Canadian EPS are computed operationally and maps of these trajectories are made available to forecasters.

2.3 Regional Deterministic Prediction System (RDPS)

2.3.1 Data assimilation and objective analysis

RDPS Version 5.0.0 – Assimilation	
Assimilation approach	This forecasting system adopts an intermittent upper air cycling strategy where the 25-km analysis from the GDPS serves to initialize the LAM 6-h before the analysis time *T*. This LAM forecasts then serve as backgrounds for the analysis step at time *T* using the 4DEnVar procedure used in the GDPS. See Caron et al. (2014, 2015).
Variables	T, Ps, U, V and log q (specific humidity).
Domain	A LAM domain, covering North America and adjacent oceans and global domain for the driver
Levels	80 hybrid levels (staggered)
Analysis increment horizontal grid	0.45° x 0.45° Gaussian grid. This global set of analysis increment valid at the analysis time is then clipped over the LAM domain and added to the 6-h LAM background.
Trial fields	9-hour forecast every 15 minutes for both for the driver and the LAM (see section 2.3.2 for details on the model characteristics)
Assimilated radiance data (number of channels)	AMSU-A (11), MHS (4) , SSMIS (7), geostationary imagers (1), AIRS (142), IASI (142) ATMS (17), CrIS (103); inter-channel error correlation is taken into account for all infrared and microwave satellite data.
Other satellite data	GPS-RO refractivity, AMVs, scatterometer winds, ZTD from GB-GPS over North America and also over Europe (global driver only).
Other data used	TEMP, PILOT, SYNOP/SHIP, BUOY/DRIFTER, ASCAT, aircraft data
Treatment of radiosonde and aircraft data	Radiosonde: use appropriate measured or computed time and horizontal position for each pressure level. Aircraft: static temperature bias correction
Satellite radiance bias correction	Coefficients computed from the GDPS Obs-minus-Analysis using a separate 3DVar analysis that does not include radiances, based on last 7 days, 2 times per day, except static for AMSU-A channels 13-14 and ATMS channels 14-15.
Background-error covariances	Same as GDPS. Surface to ~40hPa: Blend (50/50) of homogenous and isotropic (obtain from the so-called NMC method) global covariances and 4D ensemble covariances derived from 256 ensemble members (EnKF) every hour over the 6 h assimilation window; Above ~10hPa: Gradual transition to 100% homogenous and isotropic global covariances (because the lid of the EnKF, 2 hPa, is lower than the lid of the RDPS, 0.1 hPa)

Frequency and cut-off time	Four 48-h forecasts are produced each day at 00 UTC, 06 UTC, 12 UTC and 18 UTC. They are initiated from GDPS analyses valid 6-hour earlier (with cut-off times of 3:00 hrs at 00 UTC or 12 UTC; and 6:00 hrs at 06 UTC or 18 UTC) to generate the backgrounds for the LAM and the global driver. In each analysis step, the 4DEnVar analysis both for the global driver and the LAM uses a cut-off of 2:00 hours. Data within +/- 3 hours of analysis time are used.
Processing time	11 minutes for the LAM analysis as such using 640 cores (not including processing of data, background check, treatment of the EnKF members and so on).

2.3.2 Forecast

RDPS Version 4.1.0 – Forecast	
Driver model	
The driving model of the RDPS is an exact copy of the GDPS model run (see section 2.1) but it is executed with earlier cut-off time, see section 2.3.1 above.	
LAM Model	
Model	Global Environmental Multiscale (GEM) model version 4.8
Model initialization scheme	Diabatic Digital Filter (Fillion et al., 1995).
Formulation	Hydrostatic primitive equations.
Domain	LAM domain.
Numerical technique	Finite differences: Arakawa C grid in the horizontal and Arakawa A grid in the vertical.
Grid	996X1028 latitude-longitude grid having a uniform 0.09º (~10 km) resolution covering North America and adjacent oceans Note: This LAM is piloted by a Global model at 25 km resolution. This global model grid is rotated to be aligned with the LAM grid.
Levels	80 non-staggered hybrid levels; lowest model level is diagnostic for surface winds, temperature, dew point. Model lid at 0.1 hPa.
Time integration	Implicit, semi-Lagrangian (3-D), 2 time-level, 300 seconds per time step (Côté et al., 1998a and 1998b).
Independent variables	x, y, η and time.
Prognostic variables	E-W and N-S winds, temperature, specific humidity and logarithm of surface pressure, liquid water content, turbulent kinetic energy (TKE).
Derived variables	MSL pressure, relative humidity, QPF, precipitation rate, omega, cloud amount, boundary layer height and many others.

Geophysical variables:	Surface and deep soil temperature and moisture; snow depth, snow albedo and snow density: - Derived from analyses at initial time, predictive; soil variables from ISBA scheme (Noilhan and Planton, 1989; Bélair et al. 2003a and 2003b); Sea ice thickness: - Derived from climatology at initial time, fixed in time Sea ice cover; sea surface temperature: - Derived from analyses, fixed in time. Orography, surface roughness length (except over water), subgrid-scale orographic parameters for gravity wave drag and low-level blocking, vegetation characteristics, soil thermal and hydraulic coefficients, glaciers fraction - Derived from a variety of geophysical recent data bases using in house software, fixed in time
Horizontal diffusion	Del-6 on momentum variables, except del-2 applied on temperature and momentum variables at the lid (top 6 levels) of the model.
Orographic gravity wave drag	Parameterized (McFarlane, 1987; McFarlane et al., 1987).
Non-orographic gravity wave drag	Parameterized (Hines, 1997a,b).
Low level blocking	Parameterized (Lott and Miller, 1997; Zadra et al., 2003).
Radiation	Solar and infrared using a correlated-k distribution (CKD) (Li and Barker, 2005).
Surface scheme	Mosaic approach with 4 types: land, water, sea ice and glacier (Bélair et al., 2003a and 2003b).
Surface roughness length over water	Charnock formulation for momentum. Deacu formulation for Z0T except constant in the tropics.
Boundary-layer turbulent mixing (vertical diffusion) with wet formulation	Based on turbulent kinetic energy (Benoît et al., 1989; Delage, 1988a and 1988b), with statistical representation of subgrid-scale clouds (Mailhot and Bélair, 2002; Bélair et al., 2005). Mixing length from Blackadar. Includes Richardson number hysteresis (McTaggart-Cowan and Zadra, 2015).
Shallow convection	Kuo Transient scheme (Bélair et al., 2005).
Stable precipitation	Sundqvist scheme (Sundqvist et al., 1989; Pudykiewicz et al., 1992).
Deep convection	Kain & Fritsch scheme. (Kain and Fritsch, 1990 and 1993).

2.3.3 Statistical techniques and products

Analyses

A series of upper-air analysis products are available in electronic or chart form (MSLP and fronts, 1000-500 hPa thickness, geopotential height, temperature and winds at different pressure levels).

Forecasts

A wide variety of forecast products are available in electronic or chart form. These include the classic charts such as MSLP and 1000-500 hPa thickness, 500 hPa geopotential height and absolute vorticity, cumulative precipitation and vertical velocity, 700 hPa geopotential height and relative humidity. Series of special charts are produced in the context of the summer or winter severe weather (tropopause, stability indices, wind shear, helicity, wind chill, liquid water content, streamlines, low-level maximum wind, vertical motion, etc.) or in the specific support for aviation forecasting (icing, freezing levels, height of cloud ceiling, momentum flux, vertical shear, tropopause height, high and middle level turbulence, etc.). 18-hour projection time ozone and ultraviolet index charts (two panels) are produced at 00 and 12 UTC. A wide range of bulletins containing spot forecasts are produced for many locations over North America.

Some aviation, summer and winter severe weather charts are produced operationally using parameters calculated by the SPOOKI system (see section 2.1.3). More calculations are planed to be converted to this system in a near future.

SPOOKI

Same as in 2.1.3 except based on the regional model and for lead time within 48 or 54 hours.

Diagnostic techniques on direct model output fields

The calculations for the charts below are in the process of being converted to the SPOOKI post-processing tool (see section 2.1.3).

Aviation Package: Charts of forecast icing (Tremblay et al., 1995), turbulence (Ellrod, 1989), cloud amounts with bases and tops, freezing levels and tropopause heights. The charts are produced at 6-hour intervals out to 24 hours.

Summer Severe Weather Package: Forecast charts of buoyant energy, helicity, convective storm severity index, lifted index, SWEAT index, low level wind shear, precipitable water, low and high level wind maximum, surface temperature and dew points, heights and contours at 250 hPa and tropopause heights. The charts are produced at 6-hour intervals out to 24 hours.

Winter Severe Weather Package: Forecast charts of precipitation type (Bourgouin, 2000), 250 hPa contour heights and vorticity, precipitable water, 6-hour precipitation amounts, wind chill, surface temperature, thickness values and warm or above freezing layers with bases and tops. The charts are produced at 6h intervals out to 24 hours.

Forecast charts of the mean sea level pressure at 21 UTC with the forecast precipitation amounts between 12 and 00 UTC; charts of the streamlines at 21 UTC with the wind mileage (time integration of the wind speed) between 12 and 00 UTC; charts of the forecast minimum and maximum boundary layer height and the ventilation coefficient. These charts are valid for today and tomorrow.

Direct model outputs are used to forecast upper air winds and temperatures for aviation purposes.

Several parameters are interpolated at stations, formatted and transmitted operationally to Regional Offices.

Perfect Prog

Same as in 2.1.3 except based on the regional model and for lead time within 48 or 54 hours.

Model Output Statistics (MOS)

An Updateable MOS system (Wilson and Vallée, 2001 and 2002) is used for the statistical post-processing of the direct regional model outputs. This regional post-processing system currently provides forecasts between 0 and 48-hour projection times at 00 and 12 UTC, and between 0 and 54-hour at 06 and 18 UTC for the following predictands:

- 2-m surface temperatures and dew point temperatures at spot locations at three-hour intervals.
- 10-m surface wind speed and wind direction at spot locations at three-hour intervals.
- 6h and 12h probability of precipitation at spot locations at the 0.2 mm threshold.
- Probability of occurrence of total cloud amount in four categories at three hours intervals.
- Surface winds at maritime locations (mostly buoys) at three-hour intervals. Forecasts are produced for 73 locations including part of Pacific and Atlantic oceans but also for some large Canadian inland water bodies.
- Forecasts are provided for the four RDPS runs (00, 06, 12 and 18 UTC).

Before implementing a new version of the numerical model, the statistics are updated using R&D final tests.

Automated computer worded forecasts - SCRIBE

A system, named SCRIBE, is running at all the Regional Weather Centres in Canada to generate a set of automated plain language forecast products, including public, agricultural, forestry, snow, air quality and marine forecasts from a set of weather element matrices for days 1, 2 and 3. (Verret et al., 1993; 1995; 1997). See the following section Weather element matrices. SCRIBE is the main tool for operational public forecast preparation. Operational meteorologists use an interface to add value to the automated forecast as required. Once the meteorologist has reviewed the weather element, SCRIBE generates the forecast products automatically.

- **Weather element matrices**

Same as section 2.1.3, except the data is valid at projection times between 0 and 48 hours at 00 and 12 UTC, and between 0 and 54 hours at 06 and 18 UTC UMOS guidance is used instead of Perfect Prog, and near-surface dew point depression forecasts are statistical. Scribe matrices are produced four times a day (00, 06, 12 and 18 UTC).

2.4 Regional Ensemble Prediction System (REPS)

2.4.1 Data assimilation and objective analysis

The system takes the initial conditions of the global EnKF prepared for the Global Ensemble Prediction System (GEPS). The lateral boundary conditions for the REPS are provided by the forecast of GEPS at every hour. The REPS is also piloted from the top by the GEPS fields using the piloting method of McTaggart-Cowan et al. (2011). The top of the GEPS driving model is at 2 hPa while that of the REPS is at 10 hPa. The only change to REPS in 2015 is that it is now piloted by the newer GEPS version 4.1.1.

2.4.2 Forecast

REPS version 2.2.0 – Forecast	
Model version	Global Environmental Multiscale (GEM) model version 4.6.1.
Initialization	Diabatic Digital Filter (Fillion et al., 1995).
Formulation	Hydrostatic primitive equations.
Domain	LAM domain.
Numerical technique	Finite differences: Arakawa C grid in the horizontal and Charney-Phillips grid in the vertical.
Grid	600x635 latitude-longitude grid having a uniform 0.1375º (~15 km) resolution covering North America and adjacent oceans Note: This LAM is piloted by a Global Ensemble Prediction System (GEPS)
Levels	48 staggered hybrid levels. Model lid at 10 hPa.
Time integration	Implicit, semi-Lagrangian (3-D), 2 time-level, 450 seconds per time step (Côté et al., 1998a and 1998b).
Independent variables	x, y, η and time.
Prognostic variables	E-W and N-S winds, temperature, specific humidity and logarithm of surface pressure, liquid water content, Turbulent kinetic energy (TKE).
Derived variables	MSL pressure, relative humidity, QPF, precipitation rate, omega, cloud amount, boundary layer height and many others.

Geophysical variables:	Surface and deep soil temperature and moisture. Snow depth, snow albedo and snow density: - Derived from analyses at initial time, predictive; soil variables from ISBA scheme (Noilhan and Planton, 1989; Bélair et al. 2003a and 2003b); Sea ice thickness. - Derived from climatology at initial time, fixed in time Sea ice cover; sea surface temperature: - Derived from analyses, fixed in time. Orography, surface roughness length (except over water), subgrid-scale orographic parameters for gravity wave drag and low-level blocking, vegetation characteristics, soil thermal and hydraulic coefficients, glaciers fraction - Derived from a variety of geophysical recent data bases using in house software, fixed in time
Horizontal diffusion	Explicit, Del-6 on momentum variables only, except del-2 applied on temperature and momentum variables at the lid (top 6 levels) of the model.
Orographic gravity wave drag	Parameterized (McFarlane, 1987; McFarlane et al., 1987).
Non-orographic gravity wave drag	Parameterized (Hines, 1997a,b).
Low level blocking	Parameterized (Lott and Miller, 1997; Zadra et al., 2003).
Radiation	Solar and infrared using a correlated-k distribution (CKD) (Li and Barker, 2005).
Surface scheme	Mosaic approach with 4 types: land, water, sea ice and glacier (Bélair et al., 2003a and 2003b).
Surface roughness length over water	Charnock formulation except Z0T constant in the Tropics.
Turbulent mixing (vertical diffusion).	Based on turbulent kinetic energy (Benoît et al., 1989; Delage, 1988a and 1988b) with mixing length from Bougeault-Lacarrère (1989; see also Bélair et al, 1999) except near the surface and in the upper-troposphere. Includes Richardson number hysteresis (McTaggart-Cowan and Zadra 2014)
Shallow convection	1) Turbulent fluxes in partially saturated air (Girard, personal communication). 2) Kuo Transient scheme (Bélair et al., 2005).
Stable precipitation	Sundqvist scheme (Sundqvist et al., 1989; Pudykiewicz et al., 1992. For QPF evaluations see Bélair et al., 2009).
Deep convection	Kain & Fritsch scheme. (Kain and Fritsch, 1990 and 1993).

Stochastic perturbation	Stochastic perturbations of the physical tendencies and Markov chains with random number between 0.3 and 1.3 described in Charron et al. 2010 and Li et al. 2008. Note: No perturbation is applied in the areas of convective instability and in topographically enhanced vertical velocities of greater than 0.5 m/s.

2.4.3 Statistical techniques and products

The following maps are produced operationally and can be accessed at this URL.

http://collaboration.cmc.ec.gc.ca/cmc/cmoi/cmc-prob-products.reps

Percentile maps: 25%, 50% and 75% on the following variables and intervals:

Variables	Intervals (hours)
Total precipitation amount	12, 24, 48, 72
Rain accumulation	12, 24
Snow water equivalent	12, 24
Freezing rain water equivalent	12, 24
Ice pellet water equivalent	12, 24
Max 10m winds	12
Max 2m temperature	24
Min 2m temperature	24
Max humidex	24
Min windchill	24

Probability maps of exceeding thresholds are produced on the following variables and thresholds:

Variables	Thresholds
Total precipitation amount	0.2, 1, 2.5, 5, 10, 15, 20, 25, 30, 40, 50, 75, 100, 150, 200 mm
Rain accumulation	0.2, 1, 2.5, 5, 10, 15, 20, 25, 30, 40, 50, 75, 100, 150, 200 mm
Snow water equivalent	0.2, 1, 2.5, 5, 10, 15, 20, 25, 30, 40, 50, 75, 100 mm
Freezing rain water equivalent	0.2, 1, 2.5, 5, 10, 15, 20, 25mm
Ice pellet water equivalent	0.2, 1, 2.5, 5, 10, 15, 20, 25 mm
Max winds	20, 30, 40, 50, 65, 75, 90, 100, 118 km/h
Max 2m temperature	-30, -25, -20, -15, -10, -5, 0, 5, 10, 15, 20, 25, 30, 35, 40°C
Min 2m temperature	-40, -35, -30, -25, -20, -15, -10, -5, 0, 5, 10, 15, 20°C
Max humidex	25, 30, 35, 38, 40, 42°C
Min windchill	-50, -45, -40, -35, -30, -25, -20°C

2.5 High Resolution Deterministic Prediction System (HRDPS)

For several years, CMC has been running in an experimental mode a 2.5 km grid spacing configuration of GEM model on a pan-Canadian grid. This model became operational in 2017 with 4 runs per day, each of them producing 48-h forecasts. This model is initialized and driven at its lateral boundaries with the operational RDPS fields, based on a so-called downscaling approach. Land surface initial conditions are provided by CaLDAS (directly on the 2.5-km computation grid).

Further north, there is another model (HRDPS North) at a resolution of 0.0225º (~2.5km), still running in an experimental mode for the Canadian Arctic. This model is also initialized and driven at its lateral boundaries with the operational RDPS fields. However, land surface initial conditions are provided by the RDPS .

2.5.1 Data assimilation

None

2.5.2 Model

HRDPS – Version 4.2.0 – Forecast	
LAM Model	
Model ***New***	Global Environmental Multiscale (GEM) model version 4.8.2
Model initialization scheme	Uses initial surfaces and hydrometeor fields from a 2.5-km data assimilation – HRDPS coupled system. For the North domain, the surface fields are obtained from the RDPS analysis.
Formulation	Non-hydrostatic primitive equations (Girard *et al.* 2014).
Domain	LAM (National and North) domains.
Numerical technique	Finite differences: Arakawa C grid in the horizontal and Arakawa A grid in the vertical.
Grid	2560X1310 latitude-longitude grid having a uniform 0.0225º (~2.5 km) resolution covering Canada, Northern United States and adjacent oceans for the pan-Canadian domain. 1580X880 latitude-longitude grid having a uniform 0.0225º (~2.5 km) resolution covering the Canadian Arctic for the North domain. Note: These LAM is driven by a Regional model at 10 km resolution. The lateral boundary conditions are refreshed every hour.
Levels	62 staggered hybrid levels; 2 diagnostic levels at 10m and 1.5m for near-surface winds and temperature/specific humidity. Model lid at 10 hPa.with nesting over 3 levels;
Time integration	Implicit, semi-Lagrangian (3-D), 2 time-level, 60 seconds per time step
Independent variables	x, y, η and time.
Prognostic variables	E-W and N-S winds, temperature, specific humidity and logarithm of surface pressure, liquid water content, turbulent kinetic energy (TKE), cloud condensate missing ratio..

Derived variables	MSL pressure, relative humidity, QPF, precipitation rate, omega, cloud amount, boundary layer height and many others.
Geophysical variables:	Surface and deep soil temperature and moisture; snow depth, snow albedo and snow density: - Provided by a coupled 2.5-km configuration of the Canadian Land Data Assimilation System (CaLDAS) for the National domain and by the RDPS analysis for the North domain. Sea ice thickness:. - Derived from RDPS analysis. But is provided by Gulf of St. Lawrence(GSL) coupled ocean-atmosphere analysis for GSL region over the National domain. Sea ice cover; sea surface temperature: - Derived from analyses, but are provided by Gulf of St. Lawrence(GSL) coupled ocean-atmosphere analysis for GSL region over the National domain. Orography, surface roughness length (except over water), subgrid-scale orographic parameters for gravity wave drag and low-level blocking, vegetation characteristics, soil thermal and hydraulic coefficients, glaciers fraction - Derived from a variety of geophysical recent data bases using in house software, fixed in time
Horizontal diffusion (explicit)	Del-2 on momentum variables, del-6 on potential temperature
Orographic gravity wave drag	N/A
Non-orographic gravity wave drag	N/A
Low level blocking	N/A
Radiation	Li-Barker correlated k-distribution radiative transfer scheme (called every 15 min)
Surface scheme	Mosaic approach with 4 types: land, water, sea ice and glacier ISBA (Bélair et al., 2003a and 2003b).
Surface roughness length over water	Charnock formulation for momentum. Deacu formulation for Z0T.
Boundary-layer turbulent mixing (vertical diffusion) with wet formulation	Based on turbulent kinetic energy (Benoît et *al*., 1989; Delage, 1988a and 1988b), with statistical representation of subgrid-scale clouds (Mailhot and Bélair, 2002; Bélair et *al*., 2005). Mixing length from Blackadar. Includes Richardson number hysteresis (McTaggart-Cowan and Zadra, 2015).
Shallow convection	Kuo Transient scheme (Bélair et *al.*, 2005).
Stable precipitation	Milbrandt-Yau 2-moment bulk microphysics scheme (Milbrandt, J. A. And M. K. Yau, 2005)
Deep convection	Kain & Fritsch scheme. (Kain and Fritsch, 1990 and 1993).

2.5.3 Statistical techniques and products

The HRDPS post-processing runs after the HRDPS model has executed. The projection times are valid every hour from 0 to 48 hours, starting at 00, 06, 12 and 18 UTC for the pan-Canadian domain. The projection times are valid every hour from 0 to 6 hours, starting at 00 and 12 UTC, from 0 to 30 hours, starting at 06 UTC and from 0 to 18 hours, starting at 18 UTC for the North domain.

The generated products consist of 2D or 3D fields, on the same grid as the main model. Images are also produced. Most, but not all the output fields are generated using the SPOOKI plugins (described in section 2.1.3).

In the severe weather package, convection indices such as the Total-Total , George-K, SWEAT, positive convection energy, SSI, Showalter, lifted, helicity and vertical wind shear are calculated. The windchill, freezing levels, and the Bourgouin precipitation types are output from the winter weather package. The relative humidity is computed in the thermodynamic package. The accumulated amounts of precipitation since the beginning of the integration are also available.

Weather element matrices

Same as section 2.1.3 with the following differences: data is valid hourly from 0 to 48 hours at 00 and 12 UTC and from 0 to 42 hours at 06 and 18 UTC ; there is no statistical forecasts, all forecasts being from direct model output or diagnostic ; and finally there is no wave height or freezing spray forecasts.

2.6 Air quality

2.6.1 Regional Air Quality Deterministic Prediction System (RAQDPS)

Since November 2009, the Regional Air Quality Deterministic Prediction System (RAQDPS) has been based on EC's air quality model, GEM-MACH. GEM-MACH combines the weather forecast model GEM with an in-line chemical transport model. The air quality process representations include gas-phase, aqueous-phase, and heterogeneous chemistry as well as aerosol processes. It uses a 2-bin sectional representation of the PM size distribution, but PM chemical composition is treated in more detail and additional processes affecting PM concentrations have been included (e.g., Anselmo et al., 2010; Moran et al. 2012). In October, 2012, the grid-spacing in the horizontal was 10 km with 80 vertical levels. The model code was updated in February, 2013 to expand the precipitation scavenging module to include wet removal of pollutants by subgrid-scale convection (see Moran et al., 2013 for details). Since, the model has been updated to the most recent libraries, GEM 4.8.3 and PHY 8.0 (as the end of 2016). For a description of the configuration of the weather portion of the model, refer to section 2.3 on RDPS 4.1.0.

Summary RAQDPS versions operated in 2016		
Early 2016	RAQDPS_013	Situation in early 2016 was as of the last update in June 2015, which was an alignment with the GEM library from the v3.3.8.2-isba version
April 7th 2016	RAQDPS_015	Update of the GEM library to version 4.6.2 This includes : • Moving to a new Yin-Yang grid with an horizontal resolution of 10 km. • Switching to 80 new hybrid levels in the vertical dimension. • Update of the chemical boundary conditions obtained from a climatology of the MOZART model • Advection of chemical tracers using a semi-Lagrangian scheme that conserves mass. • . • Vertical diffusion of chemical tracers using the same method as the meteorological variables.
September 7th 2016	RAQDPS_016	Update of the GEM library to version 4.8
October 6th 2016	RAQDPS_017	Update of the GEM library to version 4.8.3

The SMOKE emissions processing system is used to produce hourly anthropogenic input emission files on the RAQDPS rotated latitude-longitude grid. The emissions files account for hour, day, month and primary emissions type (on-road mobile, off-road mobile and area, major and minor point sources, and biogenic). Biogenic emissions are estimated on-line using the BEIS v3.09 algorithms and depend on near-surface temperature, solar radiation, and Julian day (see Moran et al. (2013) for details). The emission inventory for Canada and the USA has been updated in June 2015. The previous RAQDPS emissions data set was based on the 2006 Canadian emissions inventory and a 2012 USA emissions inventory projected from the 2005 version. The new emissions data set is based on the 2010 Canadian national emissions inventory and the 2011 USA national emissions inventory (see Moran et al. (2015) for more details).

The RAQDPS runs twice daily at 00 and 12 UTC to produce 48-hour forecasts. The limited-area domain covers the bulk of North America and adjacent waters and is initialized and piloted at the boundaries by meteorological fields from the RDPS (see section 2.3). Chemical species are initialized using the 12-h forecast of the previous RAQDPS run. Monthly climatological chemical profiles of the MOZART model are applied at the lateral boundaries.

<table>
<tr><th colspan="2">Summary of operational post-processing tools supporting the production of air quality public forecast and warnings</th></tr>
<tr><td>Model Output Statistics (MOS)</td><td>An Updateable MOS system (Wilson and Vallée, 2001 and 2002) is used for the statistical post-processing of the direct air-quality model outputs. This air-quality post-processing system currently provides forecasts at more than 200 observation sites for :
• Ground-level ozone concentrations at hourly intervals between 0 and 48-hour projection times.
• Ground-level particulate matter ($PM_{2.5}$) concentrations at hourly intervals between 0 and 48-hour projection times.
• Ground-level nitrogen dioxide (NO2) concentrations at hourly intervals between 0 and 48-hour projection times.
• Equations are valid for the two daily runs (00, 12 UTC).
Before implementing a new version system, the statistics are updated using R&D final tests.</td></tr>
<tr><td>Automated computer worded forecast: Scribe</td><td>The SCRIBE system (see section 2.3.3) is used to generate a set of automated plain language air quality forecast products for days 1 and 2. See the following section Weather element matrices.</td></tr>
<tr><td>Weather element matrices</td><td>Supplementary weather element matrices have been developed and implemented for concentration of ozone near surface, PM2.5, NO2, as well as PM10, NO and SO2. The time resolution of these matrices is 3 hours, with projection times out to 48 hours. The matrices for the first three (O3, PM2.5 and NO2) are obtained using a statistical interpolation of the increments between model output statistics (MOS) at observation sites and the air quality model predicted concentrations. For the remaining pollutants (PM10, NO and SO2) , the matrices are obtained using the air quality model predicted concentrations.</td></tr>
</table>

The operational output from the RAQDPS consists of hourly concentrations of surface tropospheric ozone, PM2.5, PM10, nitrogen dioxide, nitrogen monoxide, and sulphur dioxide, as well as select meteorological fields. The forecast of PM levels is based on primary PM emissions and the chemical formation of secondary PM (sulphate, nitrate, ammonium and secondary organics).

The Canadian air quality forecast is communicated to the public using the Air Quality Health Index (AQHI). The AQHI communicates to the public the level of risk associated with exposure to a mixture of

O3, PM2.5, and NO2 pollution. Model output from the RAQDPS is corrected with the statistical post-processing package UMOS-AQ and provided to forecasters along with processed pollutant observations to assist in the preparation of AQHI forecasts. AQHI observations and forecasts are available for all 74 active sites across Canada at:

https://meteo.gc.ca/airquality/pages/index_e.html

In addition, post-processing is performed on the raw RAQDPS output to provide specialized users with maximum and mean forecasts of ozone, PM2.5 and PM10 in the boundary layer per 6-hour forecast period. These products are available on the web at:

https://weather.gc.ca/aqfm/index_e.html

2.6.2 Regional Air Quality Deterministic System for forest fire (RAQDPS-FW)

In April 2016, the regional air quality deterministic system for forest fire (RAQDPS-FW or « FireWork ») was implemented operationally. The RAQDPS-FW model is identical to the RAQDPS model except for the inclusion of quasi-real time wildfire emissions. The RAQDPS-FW is run twice a day, at 00 and 12 UTC, to forecast 48 hours of fine particles ($PM_{2.5}$) concentrations. Wildfire emissions are estimated based on the North American fire remote sensing and fuel consumption data provided by the Canadian wildland fire information system (CWFIS) of Natural Resources Canada. Hotspot data are updated twice a day, right before the model is launched.
The RAQDPS-FW is operated from early April to late October.

Summary of the SRPDQA-FW operated in 2016		
April 14th 2016	RAQDPS-FW_015	Update of the GEM library to version 4.6.2
September 7th 2016	RAQDPS-FW_016	Update of the GEM library to version 4.8
October 6th 2016	RAQDPS-FW_017	Update of the GEM library to version 4.8.3

Some products from RAQDPS-FW, including maps and animations of PM2.5 surface concentrations and total columns are made available at:
https://weather.gc.ca/firework/index_e.html

2.6.3 Regional Deterministic Air Quality Analysis (RDAQA)

Regional objective analysis for the surface pollutants, ozone and PM2.5, became operational in February, 2013. The RDAQA has a resolution of 10 km and is issued every hour. It is based on a modified optimal interpolation algorithm and combines, on an hourly basis, chemical trial fields from RAQDPS and surface observations from AirNow US/EPA database (~1250 sites for ozone, ~850 for $PM_{2,5}$, 220 sites for PM_{10}, 350 sites for NO_2, 300 sites for SO_2) and most of the Canadian land-based surface stations including from the CAPMON and NAPS networks (~200 sites). In April 2015, the RDAQA program was extended with NO2, NO, SO2, PM10 and AQHI. However, the analyses are not used to initialize the air quality forecast model and so the RDAQA is thus off-line.

2.6.4 Ozone and UV index forecasting

The Canadian Global model is used to prepare ozone and UV Index forecast at the 18 and 42 hour projection times based on 00 UTC data and at the 30 hour projection time based on 12 UTC data (Burrows et al., 1994). A Perfect Prog statistical method is used for forecasting total ozone, which is then supplemented with an error-feedback procedure. UV Index is calculated from the corrected ozone forecast. Correction factors have been added to take into account the snow albedo, elevation and Brewer angle response.

Charts of the total ozone forecast and of the UV Index forecast are prepared and transmitted to the Regional Offices. Bulletins giving the forecast UV Index at an ensemble of stations across Canada are also generated and made available to the public here:

https://weather.gc.ca/forecast/public_bulletins_e.html?Bulletin=fpcn48.cwao

2.7 Other specialized Systems

2.7.1 Surface fields assimilation and analysis

Fields	Analysis Grid(s)	Method	Trial Field	Frequency	Data Source
Surface air temperature	**Global**: 1080x540 gaussian **Regional**: lat-lon ~10 km	Optimal interpolation	Model forecast of temperature at diagnostic level = 1.5m	**Global**: 6 hours **Regional**: 24 hours (at 18Z)	Synop, Metar, SA, Ship, Buoy, Drifter, Metar
Surface dew point depression	**Global**: 1080x540 gaussian **Regional**: lat-lon ~10 km	Optimal interpolation	Model forecast of dew point depression at diagnostic level =1.5m	**Global**: 6 hours **Regional**: 24 hours (at 18Z)	Synop, Metar, SA, Ship, Buoy, Drifter
Sea surface temperature	**Global**: lat-lon grid (type B) 1801×901 (-> 0,2^o)	Optimal interpolation	Previous analysis	24 hours (at 00Z)	Satellite data (AVHRR from NOAA18, NOAA19, Metop-A, Metop-B), insitu data (ships, drifters, buoys) (Brasnett, 2008)
Snow depth	**Global**: 1080x540 gaussian **Regional**: lat-lon ~10 km	Optimal interpolation	Previous analysis modified from estimates of snowfall and snowmelt	6 hours	Synop, Metar, Sa (Brasnett, 1999)
Ice cover	4000x2000 on a rotated lat-lon grid	3DVAR with a return to climatology over lakes when data not available	Previous analysis	6 hours	SSM/I and SSMI/S data. Retrieval algorithm NASA Team 2 (NT2). Ocean and lakes ice data from the Canadian Ice Centre
Soil temperatures	**Global**: 1249x834 Yin-Yang **Regional**: lat-lon ~10 km	1D Optimal interpolation	Model forecast of soil temperature (ISBA scheme level 1 and 2)	**Global**: 6 hours **Regional**: 24 hours (at 00Z)	Screen-level temperature analysis (used as observations) (Belair, 2003)
Soil water contents	**Global**: 1249x834 Yin-Yang **Regional**: lat-lon ~10 km	1D Optimal interpolation	Model forecast of soil water content (level 1 and 2)	**Global**: 6 hours **Regional**: 24 hours (at 00Z)	Screen-level temperature and relative humidity analysis (used as observations)

2.7.2 Regional Deterministic Precipitation Analysis (RDPA)

Since 2011, ECCC produces a near real-time quantitative precipitation estimates that is required for multiple applications. This product is known as the Regional Deterministic Precipitation Analysis (RDPA) and is generated using the Canadian Precipitation Analysis (CaPA) system. Its domain is almost the same as the RDPS which is all of North-America at a resolution of 10 km. The CaPA system is based on the optimal combination of near real-time precipitation observations from both in situ and radar networks with a first guess provided by the RDPS cumulative precipitation field with lead times of 6 and 12 hours. Two layers of information are generated by the system: a QPE and an estimate of the quality of the product, expressed by a confidence index. Six-hour accumulation analyses valid at 0000, 0600, 1200 and 1800 UTC are generated one hour after the end of the accumulation period and updated six hours later. A separate 24 hour accumulation analysis is also produced and valid at 1200 UTC.

An upgrade of the system was implemented in September 2017 in response to the major High-Performance Computing migration. This new release (version 4.1.0) incorporates only minor technical changes that have practically no impact on the outputs. The small differences observed come mainly from the fact that the trial field provided by the RDPS is slightly different from the previous version.

2.7.3 Nowcasting

The SCRIBE Weather Forecast Product Expert System is ingesting every hour the latest observations and forecast data from nowcasting models to update the SCRIBE weather elements. The Integrated NowCasting System (INCS) has been developed to minimize the necessary manual adjustments done by the forecaster to merge the current weather conditions with the forecast.

The INCS uses surface observations (METAR, SPECI, SYNOP), north American radar composite images and lightning data from the Lightning Detection Network. These observations are also used to feed nowcasting models. A statistical model called PubTools uses the surface observations to forecast the probabilities of occurrences of weather elements.

In addition to the nowcasting models, the regional deterministic prediction system (RDPS) and its post-processing fields and statistical point forecasts (UMOS) are used as a fall back or complementary data set. All these observed and forecast data are processed by a rule based system to determine the best sequence of coherent weather elements representing the current observation and short term tendencies.

The regions associated to stations without cloud cover observation use the maximum value between CF and Total Cloud Coverage (NT) fields, the latter from the RDPS.

The radar composite is created from the observed hourly precipitation amount, using a technique from the RDPA[2]. The satellite diagnostic field cloud fraction (CF) is then used to filter out the radar false echoes.

MAPLE[3] is used to advect the radar composite, the observed lightning strike and the POP field derived from RDPS sampling on the hourly precipitation amount.

INCS suite is launched 10 minutes after the hour.

A component to support the automated production of first guess Terminal Aviation Forecast (TAF) has been added in September 2016. This component, aTAGS[4], run at the end of the INCS suite to produce point forecast for over 200 Canadian airports. The forecast span up to 48 hours and has one hour time resolution. The foundation of aTAGS is a rules based module that merges the different input stream (observations, NWP, climatology, statistics ...) into a coherent standardized forecast data set for aviation. A parallel set of metadata provide a crude confidence index based on the agreement, or not, from the various input.

Post-processing algorithms on NWP has been developed, particularly for ceiling cloud height and surface horizontal visibility. Work is ongoing to improve the performances of the different algorithms.

More details at:
http://collaboration.cmc.ec.gc.ca/cmc/CMOI/product_guide/docs/tech_notes/technote_atags-100_e.pdf

[2] Regional Deterministic Precipitation Analysis
[3] McGill Algorithm for Precipitation Lagrangian Extrapolation, ref.Mcgill University's Research Center on Remote Sensing and Atmospheric Applications
[4] autoTAF Automated Guidance System

2.8 Ocean Prediction Systems

2.8.1 Global Ice Ocean Prediction System (GIOPS)

GIOPS was developed to provide daily ice and ocean global analyses of three dimensional ice-ocean model solutions (temperature, salinity, sea level, currents and ice fields). The system has been designed to meet a variety of needs required from the Canadian marine core service. These include providing initial and marine surface boundary conditions to coupled and forced numerical weather and wave predictions, open boundary conditions to regional ice-ocean systems, as well as providing a basic capacity for marine emergency response (e.g. oil spill). The GIOPS data assimilation code was provided by Mercator Ocean group and it has been running in real-time at CMC since 2011. It was declared fully operational in August 2015. There are some differences compared with Mercator's system, e.g. the ocean model is coupled with a different sea ice model, the atmospheric forcing and the sea surface temperature data are not identical. . The incremental analysis update (IAU) was added to the system in Jun 2016, which reduces the initial shock in the forecast component. GIOPS is limited to an analysis component (GIOPS-A) since the forecast component is part of the coupled GDPS since November 2017.

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GIOPS-A is based on SAM2 ("Systeme d'assimilation Mercator" version 2, Tranchant et al., 2008; Lellouche et al., 2013). The analysis method relies on a reduced order Kalman filter based on the "Singular Evolutive Extended Kalman filter" formulation (SEEK). SAM2 assimilates observations of sea level anomaly (SLA), sea surface temperature (SST) and in situ temperature and salinity profiles. A delayed-mode analysis is produced every Tuesday valid 6 day prior with a 7-day assimilation window. This analysis is used to initialize a real-time analysis every Wednesday at 00 UTC also using a 7-day window. GIOPS also employs a 1-day real-time cycle for the other days of the week which assimilates only SST observations. These analyses are blended with ice analyses and used to initialize the daily 10-day forecast. This system was implemented in experimental mode in September 2013 and was declared operational in August 2015.

2.8.2 Regional coupled atmosphere-ocean-ice forecasting

A fully-interactive coupled atmosphere-ocean-ice forecasting system for the Gulf of St. Lawrence (GSL) has been running at the Canadian Meteorological Centre (CMC) since June 9, 2011 and with operational status since November 2014. This system includes a daily pseudo-analysis cycle to provide initial conditions for the ice-ocean model (Smith et al. 2012) and daily 48 hr forecasts using a fully coupled atmosphere-ice-ocean model. During 2013, a new version of this system was developed using a different ice-ocean model. The new system uses the NEMO (Nucleus for European Modelling of the Ocean) ocean model together with the Los Alamos CICE (Community ICe codE) sea ice model. In addition, the new system employs a flux-coupling approach as opposed to coupling by variables done in the current system. The updated system uses the same atmospheric and ocean grids as the previous system (with resolutions of 10km and 5km respectively).

2.8.3 Wave forecasting

2.8.3.1 Global Wave Prediction Systems

The Global Deterministic Wave Prediction System (GDWPS), based on the dynamical wave model WaveWatch III® version 5.16, changed from experimental mode to operational status on November, 1st 2017 . The GDWPS domain covers all of the world's oceans at ¼ degree resolution up to 86°N. In addition to the forecast cycle, the system includes a pseudo-analysis cycle. At this time there is no wave data assimilation performed in the pseudo-analysis. The pseudo-analysis is run four times daily for 6 hours centered on 00, 06, 12, and 18 UTC. It is driven with hourly conditions from the G2 late atmospheric forecast analysis. Each new pseudo-analysis is simply a smooth continuation of the previous run. The forecast cycle is run twice a day at 00, and 12 UTC for 240 hours, using the latest available pseudo-analysis as initial conditions. The forecast cycle is forced by forecast winds from the GDPS, and with evolving ice from the Global Ice Ocean Prediction System (GIOPS). The system has a spectral resolution of 36 frequency bin and 36 directional bins. A detailed description of the system can be found in Bernier et al. 2015.

The properties of the various wave predictions systems, operational and experimental, are summarized in the table at the end of section 2.8.

2.8.3.2 Regional Wave Prediction Systems

The regional deterministic wave prediction system (RDWPS) includes systems based on the dynamical wave model WAM (WAve Model - version 4.5.1). The WAM based RDWPS is configured to provide sea-state forecasts over the following domains: Arctic, Eastern Pacific, and North Atlantic Oceans, the Gulf of St. Lawrence, and four Great Lakes (Ontario, Erie, Huron and Superior). Each domain runs up to six times a day at 00, 06, 12, and 18 UTC. Four runs are forced by 48 hour forecast winds from the Regional Deterministic Prediction System (RDPS). The other two runs are for long-range forecasts (120h) and are based on forecast winds from the Global Deterministic Prediction System (GDPS). The resolution over the Arctic and Eastern Pacific Oceans is set to 0.5º. The North Atlantic Ocean is at a resolution of 0.15º and a resolution of 0.05º is used over the Gulf of St. Lawrence and the Great Lakes. The systems have a spectral resolution of 25 frequency bins and 24 directional bins. The Arctic, Pacific and North Atlantic domains are gradually getting phased out starting in November 2017 with the implementation of the GDWPS.

A WaveWatch III based RDWPS was implemented in parallel pass on October 19, 2017, it is configured to provide sea-state forecasts over the five Great Lakes (Ontario, Erie, Huron-Michigan and Superior). Each domain runs four times a day at 00, 06, 12, and 18 UTC for 48 hours and is forced by forecast winds from the High Resolution Deterministic Prediction System (HRDPS). The resolution is 1 km (0.009 x 0.0124 degree). The systems have a spectral resolution of 40 frequency bins and 36 directional bins.

A WaveWatch III based Regional Ensemble Wave Prediction System (REWPS) was implemented in parallel pass on October 19, 2017. It is configured to provide sea-state forecasts over the five Great Lakes. The system has 20 members plus 1 control. The forecast runs twice a day at 00 and 12 UTC for 72 hours and is forced by forecast winds from the Regional Ensemble Prediction System (REPS). The resolution is 2.5 km (0.0225 x 0.0310 degree). The system has a spectral resolution of 40 frequency bins and 36 directional bins.

The properties of the various wave predictions systems, operational and experimental, are summarized in the table..

WAM Based Wave Prediction Systems						
Domain	**Latitude and longitude**	**Grid spacing**	**Forecast range**	**10 m winds**	**Ice**	**Runs per day**
Pacific (long range)	200 °W to 120 °W 25 °N to 60 °N	0.5° x 0.5°	120 h	GDPS 3-hourly	GDPS ice analysis	00, 12Z
Arctic (long range)	165 °W to 45 °W 49 °N to 85 °N	0.4° x 0.8°	120 h	GDPS 3-hourly	GDPS ice analysis	00, 12Z
Arctic (short range)	“	“	48 h	RDPS hourly	RDPS ice analysis	00, 06, 12, 18Z
Atlantic (long range)	82 °W to 15 °W 25 °N to 70 °N	0.5° x 0.5°	120 h	GDPS 3-hourly	GDPS ice analysis	00, 12Z
Atlantic	97.925 °W to 0.25 °E	0.15° x 0.15°	48 h	GDPS	RDPS ice analysis	00, 06,

(short range)	20.075 °N to 70.175 °N			hourly		12, 18Z
Gulf of St. Lawrence (short range)	54.425 °W to 70.925 °W 44.075 °N to 52.025 °N	0.05° x 0.05°	48 h	RDPS hourly	RDPS-CGSL hourly	00, 06, 12, 18Z
L. Superior (long range)	84.043 °W to 92.312 °W 46.318 °N to 48.984 °N	0.05554° x 0.08187°	120 h	GDPS 3-hourly	GDPS ice analysis	00, 12Z
L. Superior (short range)	"	"	48 h	RDPS hourly	RDPS ice analysis	00, 06, 12, 18Z
L. Huron (long range)	79.378 °W to 84.773 °W 42.936 °N to 46.347 °N	0.05502° x 0.07819°	120 h	GDPS 3-hourly	GDPS ice analysis	00, 12Z
L. Huron (short range)	"	"	48 h	RDPS hourly	RDPS ice analysis	00, 06, 12, 18Z
L. Erie (short range)	78.75 °W to 83.6 °W 41.3 °N to 43 °N	0.05° x 0.05°	120 h	GDPS 3-hourly	GDPS ice analysis	00, 12Z
L. Erie (short range)	"	"	48 h	RDPS hourly	RDPS ice analysis	00, 06, 12, 18Z
L. Ontario (long range)	76.074 °W to 79.851 °W 43.164 °N to 44.188 °N	0.05688° x 0.07553°	120 h	GDPS 3-hourly	GDPS ice analysis	00, 12Z
L. Ontario (short range)	"	"	48 h	RDPS hourly	RDPS ice analysis	00, 06, 12, 18Z
WaveWatch III based Wave Prediction Systems						
Domain	**Latitude and longitude**	**Grid spacing**	**Forecast range**	**10 m winds**	**Ice**	**Runs per day**
Global (pseudo-analysis)	0 ° to 360 ° 80 °S to 86 °N	0.25° x 0.25°	6 h	Late GDPS Analysis (G2) hourly	Late GDPS ice analysis (G2)	00, 06, 12, 18Z
Global (forecast)	0 ° to 360 ° 80 °S to 86 °N	0.25° x 0.25°	240 h	GDPS hourly	GIOPS 3-hourly	00, 12Z
L. Superior	92.3116° to 84.1648° W 46.2590° to 49.1120° N	0.009° x 0.0124°	48 h	HRDPS 30-minutes for 24 hours then hourly	HRDPS ice analysis	00, 06, 12, 18Z
L. Huron-Michigan	88.1452° to 79.5024° W 41.4260° to 46.5740° N	"	"	"	"	"
L. Erie	83.6068° to 78.6840° W 41.2190° to 43.1000° N	"	"	"	"	"
L. Ontario	79.9736° to 75.6708° W 43.0640° to 44.4770° N	"	"	"	"	"
Great Lakes ensemble	92.4790° to 75.4600° W 41.0984° to 49.2520° N	0.0225° x 0.0310°	72 h	REPS hourly	REPS ice analysis	00, 12Z

2.8.4 Storm Surge forecasting

The Atlantic Storm Prediction Centre (ASPC) located in Halifax and the Newfoundland and Labrador Weather Office located in Gander produce operational storm surge forecasts over Eastern Canada using Dalcoast1 developed at Dalhousie University specifically for this region (Bobanović 1997). It is run twice daily (00 UTC and 12 UTC). The storm surge model is driven with surface air pressure and winds from the Regional Deterministic Prediction System (RDPS). The Storm Surge forecasting system runs at a resolution of 1/12° and covers the North West Atlantic Ocean, the Gulf of St. Lawrence and the Labrador Shelf.

A long range version of this model, the Regional Deterministic Storm Surge Prediction System (RDSPS) has changed from experimental to operational status on November 1 2017. It uses the Dalocoast5 model and integrates out to 240 hours. The system includes a pseudo-analysis and a forecast cycle. The pseudo-analysis is driven with hourly conditions from the G2 late atmospheric forecast analysis. Each new pseudo-analysis is simply a smooth continuation of the previous run. The pseudo-analysis runs four times daily for 6 hours centered on 00, 06, 12, and 18 UTC. The forecast cycle is run twice a day at 00, and 12 UTC for 240 hours, using the latest available pseudo-analysis as initial conditions. The forecast is driven with surface air pressure and winds from the Global Deterministic Prediction System (GDPS). The system runs over the North West Atlantic Ocean, the Gulf of St. Lawrence and the Labrador Shelf at a resolution of 1/30°.

The Regional Ensemble Storm Surge Prediction System (RESPS) was implemented with experimental status on November 7 2017. The system has 20 members plus 1 control. It uses the Dalocoast5 model and integrates out to 240 hours. This storm surge model is driven with surface air pressure and winds from the Global Ensemble Prediction System (GEPS). It runs twice daily (00 UTC and 12 UTC). The system runs over the North West Atlantic Ocean, the Gulf of St. Lawrence and the Labrador Shelf at a resolution of 1/12°.

A detailed description of the RDSPS and RESPS can be found in Bernier and Thompson 2015.

2.9 Extended and long range forecasts

2.9.1 Extended range (10 days to 30 days)

2.9.1.1 System

Introduced operationally in 2015, this monthly (aka sub-seasonal) forecast system is based on the Global Ensemble Prediction System (GEPS) described in section 2.2 of this document. The forecasts are produced by extending its lead time out to 32 days once a week (see Gagnon et al. 2013, Gagnon et al. 2014a and Lin et al. 2016 submitted). Although it is still a two-tier system, i.e., an uncoupled system with specified SST and sea ice conditions, it likely captures most of the major sources of predictability on the sub-seasonal time scale. To produce anomaly forecasts as well as eventually for the calibration of probability forecasts, a reforecast (hindcast) is run operationally 'on the fly' such that the latest GEPS version is always used. This provides a 20-year (1995-2014) model climatology. More details on the reforecast design and application can be found in section 2.2.3 under **reforecast**.

2.9.1.2 Products

The forecast products are generated by firstly discarding the first 4 days and then averaging over these periods:

- Week-1 (day 5-11)
- Week-2 (day 12-18)
- Week-3 (day 19-25)
- Week-4 (day 26-32)
- Week 1-4 (day 5-32)

The official public monthly (week 1-4) probabilistic forecasts for near surface temperature are posted on the Government of Canada web site for weather information:

http://weather.gc.ca/saisons/image_e.html?img=mfe1t_s

Experimental temperature and precipitation forecasts for the individual weeks are available on this web site

http://collaboration.cmc.ec.gc.ca/cmc/ensemble/monthly/prev_mens_geps.html

2.9.2 Long range (30 days up to 2 years): CanSIPS

2.9.2.1 System

On December 2011, the Canadian Meteorological Centre (CMC) has started using a global coupled seasonal prediction system for forecasting monthly to multi-seasonal climate conditions. This system named CanSIPS for Canadian Seasonal to Interannual Prediction System replaces both the uncoupled (2-tier) prediction system previously used for producing seasonal forecasts with zero and one month lead times and the CCA statistical Prediction system previously used for forecasts of lead times longer than four months. CanSIPS can also skilfully predict the ENSO phenomenon and its influence on the climate up to a year in advance. The development, the implementation and the continual improvement of this multi-seasonal forecast system is the result of a close collaboration between CMC and the Canadian Centre for Climate Modelling and Analysis (CCCma).

CanSIPS is a multi-model ensemble (MME) system based on two climate models developed by CCCma. It is a fully coupled atmosphere-ocean-ice-land prediction system, integrated into the CMC operational prediction suite and relying on the CMC data assimilation infrastructure for the atmospheric, sea surface temperature (SST) and sea ice initial states. The two models used by CanSIPS are:

CanCM3

This model uses the atmospheric model CanAM3 (also known as AGCM3) with horizontal resolution of about 315 km (T63) and 31 vertical levels, together with the ocean model CanOM4 with horizontal resolution of about 100 km and 40 vertical levels and the CLASS land model. Sea ice dynamics and thermodynamics are explicitly modelled.

CanCM4

This model uses the atmospheric model CanAM4 (also known as AGCM4) also with a horizontal resolution of about 315 km (T63) but with 35 vertical levels. The CanOM4 ocean, CLASS land and sea ice components are essentially the same as in CanCM3.

A detailed description of these models is provided in Merryfield et al. (2013a).

CanSIPS has two modes of operation:

Assimilation mode

CanSIPS uses a continuous assimilation cycle for 3D atmospheric temperatures, winds and specific humidities as well as sea surface temperatures and sea ice. The assimilated data comes from the six hour CMC 4D-VAR global atmospheric final analyses and the daily CMC SST and sea-ice analyses. Additionally, just before launching the production of the forecasts, an NCEP 3D ocean analysis is assimilated into the CanSIPS ocean model background state. All the 20 members' initial conditions are independent but statistically equivalent in the sense that their differences are of the same order than the observation uncertainties.

Forecast mode

CanSIPS forecasts are based on a 10-member ensemble of forecasts produced with each of two CCCma climate models for a total ensemble size of 20. Monthly to multi-seasonal forecasts extending to 12 months are issued the first day of each month. Additionally, a one-month and a six-months forecast is issued at mid-month (15th). Deterministic and probabilistic forecasts for surface temperature and precipitation are produced for each category (above/near/below normal) for seasons made of months 1-3, 2-4, 4-6, 7-9, 10-12. The probabilistic forecasts are done by counting members in each of the three possible forecast categories: below normal, near normal and above normal, and adjusting this probability with a calibration method to take in account what has been observed in the past.

CanSIPS climatology is based on a hindcast period covering 1981-2010 and was produced during phase 2 of the Coupled Historical Forecast Project (CHFP2) research effort. The ensemble size (20) is the same for the forecast and the hindcasts.

More technical information on CanSIPS is available in Merryfield et al., 2011.

2.9.2.2 Products

Deterministic and probabilistic products of seasonal forecast are available on the Internet:

http://weather.gc.ca/saisons/index_e.html

Probabilistic products of seasonal forecasts are available with 0, 1, 3, 6 and 9 months lead time. Deterministic products of seasonal forecasts are available with 0 month lead time only. These forecasts are for three months periods and are issued on the first day of each month.

Charts and model output grids for the season 1 are available in real time on Internet at the following site:

http://meteo.gc.ca/grib/grib2_cansips_e.html

The forecast digital data are on a 2.5 degrees grid in GRIB2 format. Monthly means of surface air temperature, precipitation, 500 hPb heights, 850 hPa temperature and mean sea level pressure are available for each of the 20 models runs used to prepare the official forecast. Also, hindcast data as well as their climatological averages are available for each model.

2.10 Environmental Emergency Response (EER)

CMC is able to provide real-time air concentrations and surface deposition estimates of airborne pollutants. These fields are obtained from short-to-long-range atmospheric transport and dispersion models. Operationally, CMC employs two Lagrangian stochastic particle dispersion models named MLDPn and MLCD, as well as a simple Lagrangian particle trajectory model. Applications of these models include the estimation of concentrations of radionuclides and volcanic ash. Based on this operational capability, CMC is designated by the WMO as a Regional Specialized Meteorological Centre (RSMC) with specialization in Atmospheric Transport Modelling Products for Environmental Emergency Response. In addition, CMC is designated by the International Civil Aviation Organization (ICAO) as a Volcanic Ash Advisory Centre (VAAC). There has been an increased application of these operational atmospheric transport modelling tools to the dispersion of chemical and biological agents in support of responses to local environmental emergencies.

The Lagrangian particle dispersion models are "off-line" models. Thus, fields of wind, moisture, temperature and geopotential heights must be provided to them. These are obtained either from the Global Deterministic Prediction System (GDPS), the Regional Deterministic Prediction System (RDPS) or the High-Resolution Deterministic Prediction System (HRDPS) forecasts and analyses.In the case of MLCD, this model can also be driven directly by surface observations. Please refer to previous sections for more information on these NWP products.

All atmospheric transport and dispersion models can be launched easily with a Graphical User Interface (GUI) called SPI. This application is flexible, versatile, robust and powerful and has been designed for operational response. SPI has been under development for many years at CMC and allows modellers to respond efficiently to requests for modelling support during emergencies.

2.10.1 Dispersion model

2.10.1.1 MLDPn (Modèle Lagrangien de Dispersion de Particules d’ordre n)

MLDPn, described in D’Amours et al., 2015, is a Lagrangian Particle Dispersion Model, which combines previous dispersion models MLDP0, MLDP1 and MLGI (D’Amours and Malo, 2004, D’Amours et al., 2010, Flesch et al., 2004). This model is designed for problems associated with events of local, regional, continental and global consequences. In this model, dispersion is estimated by calculating the trajectories of a very large number of air particles (or parcels). The trajectory calculations are done in two parts: 3-D displacements due to the transport by the synoptic component of the mean wind, then 3-D displacements due to unresolved turbulent motions. The scheme of the turbulent diffusion chosen is determined by the spatial and temporal scales of the problem. For events at long-range spatial (distances greater than 200 km) and temporal (time horizon greater than 12 hours) scales, a basic zero order diffusion scheme is used (MLDP0, trajectories of the parcels are updated from the displacement increments). For short-range (local) scale problems, a more advanced first order diffusion scheme is used (MLDP1, trajectories of the particles are calculated from the velocity increments). In the order one scheme, the fluctuating components of the turbulent wind are obtained by partitioning the turbulent kinetic energy calculated and available in the driving NWP models.

Wet deposition in MLDPn is treated with a simple wet scavenging rate scheme and occurs when a particle is in a cloud. The precipitation field is not used directly in MLDPn, but the tracer removal rate is proportional to the local cloud fraction and particle mass. Local cloud fraction is parameterized as a function of relative humidity. Although not used by default, a more realistic physical parameterization can be activated when precipitation rate fields are available. Dry deposition in MLDPn occurs when a particle is subjected to a reflection at the ground surface. It is modelled in terms of a dry deposition velocity and an absorption probability. The deposition rate is calculated by assuming that a particle contributes to the total surface deposition flux in proportion to the tracer material it carries when it is found in a layer adjacent to the ground surface.

The emission source can consider an emission rate that varies in time for each radionuclide or pollutant . For volcanic eruptions, a particle size distribution is used to model the gravitational settling effects in the trajectory calculations according to Stokes's law. This scheme can be activated operationally depending on the case. The released mass can be estimated from empirical formulas derived by Sparks et al., 1997, and Mastin et al., 2009, which is a function of particle density, plume height and effective emission duration. In MLDPn, tracer concentrations at a given time and location are obtained by assuming that particles carry a certain amount of tracer material. The concentrations are then obtained by calculating the average residence time of the particles, during a given time period, within a given sampling volume, and weighting it according to the material amount carried by each particle.

MLDPn can be executed in forecast mode up to day 10, using the operational data from the GDPS, and up to 84 or 48 hours using the data from the RDPS and the HRDPS, respectively. MLDPn can also be executed in hindcast/analysis mode, using the analyzed fields from either the global or regional modelling systems. The model can also be executed in backward (adjoint) mode to go back in time and to reconstruct the source (geographical location of emission, strength, time and duration of emission). The model is been used extensively in this configuration as part of the WMO-CTBTO[5] cooperation. MLDPn is parallelized and runs on several nodes on a supercomputer or workstation, using distributed and shared-memory parallelism standards.

2.10.1.2 MLCD (Modèle Lagrangien à Courte Distance)

MLCD is a Lagrangian Particle Model described in details in Flesch et al. 2002. It is designed to estimate air concentrations and surface depositions of pollutants at very short ranges (less than ~10 km from the source). As in MLDPn, this 3-D Lagrangian dispersion model calculates the trajectories of a very large number of air particles. MLCD is classified as a first order Lagrangian particle dispersion model as for MLDPn with first order diffusion scheme.

A Langevin stochastic equation is employed, using the turbulent components of the wind associated with the turbulent kinetic energy (TKE). These fluctuating components are generated from a time-dependant "user provided" set of wind observations (velocity and direction) that are passed through a "two-layer" model (Wilson and Flesch , 2004). MLCD can take into account the horizontal diffusion for unresolved scales operating at time scales longer than those associated with the TKE. The removal processes of radioactive decay, wet scavenging and dry deposition can also be simulated by the model. MLCD can be run both forward and backward in time.

2.10.2 Trajectory Model

The trajectory model is a simple tool designed to calculate the trajectory of a few air parcels moving in the 3-D wind field of the atmosphere. The model is described in D'Amours and Pagé, 2001. Only transport by the winds is considered without taking into account any other physical or atmospheric processes. The advection of an air parcel is computed according to a fourth-order Runge-Kutta scheme.

The model estimates the trajectories of the parcels, originating from or arriving at the same geographic location, for different vertical levels. The location and levels are defined by the user. The model can be run to obtain a quick estimate of the expected trajectory of an air parcel, whose point of origin or point of arrival (back trajectory) is specified as the input parameter.

2.10.3 Products

2.10.3.1 National mandates

CMC's Environmental Emergency Response Section (EERS) provides specialized guidance on the dispersion of hazardous materials (chemical, biological) that have been released into the atmosphere. Requests are received through the National Environmental Emergency Centre (NEEC) of Environment

[5] CTBTO stands for Comprehensive Nuclear-Test-Ban Treaty Organization

and Climate Change Canada (ECCC). Products are adapted to each specific situation and may include three dimensional trajectories, air concentrations of pollutants for different layers, wet and dry deposition charts, etc. CMC has developed a system, called AutoSim, to produce simulations automatically for long-lasting events such as forest fires, ongoing volcanic eruptions (e.g. Eyjafjallajökull) or nuclear releases (e.g. Fukushima Daiichi).

In case of releases of radiological materials in the atmosphere, CMC supports the Canadian Federal Nuclear Emergency Plan (FNEP) using atmospheric dispersion modelling for planning, for dose calculations to assess the impact and consequence on the population using the decision support system in case of nuclear accident ARGOS (Accident Reporting and Guidance Operational System) and for source term estimation.

2.10.3.2 International mandates

Upon receiving a request for a nuclear or radiological support from a World Meteorological Organisation (WMO) Member Country Delegated Authority, the Regional Specialized Meteorological Centre (RSMC Montréal, housed at CMC) will provide the following standard set of basic products:

- Three dimensional trajectories starting at 500, 1500 and 3000 m above the ground, with particle locations indicated at synoptic hours
- Time integrated pollutant concentration within the 500 m layer above the ground in Bq/m^3
- Total deposition (wet and dry) in Bq/m^2 from the release time to the end of the third-time period

CMC can also provide charts of air concentration estimates for many levels in the atmosphere as well as total surface deposition estimates at various time intervals.

Backward modelling is provided upon request to support the activities of the Comprehensive Test Ban Treaty Organization, as defined in the WMO Manual on the Global Data-Processing and Forecasting System.

CMC is also designated as the Montréal Volcanic Ash Advisory Centre and provides modelling and guidance for volcanic ash over its area of responsibility in accordance with Annex 3 of the Convention on International Civil Aviation, published by the International Civil Aviation Organisation, for the provision of meteorological services for international air navigation.

3 Planned research activities and changes in the operational DPFS expected in the next few years

3.1 Global Deterministic Prediction System (GDPS)

3.1.1 Data assimilation

- **Radiance assimilation**
  Four hyperspectral IR sensors (AIRS and IASI (Metop 1-2), 142 channels; Cris, 103 channels) are assimilated in operations as well as ATMS MW channels.. Interchannel error correlation is taken into account for all radiances. Using that new configuration, research was carried out on the assimilation of surface sensitive IR channels over land, showing significant impact (Dutta et al., 2016). In order to better coordinate the surface and atmospheric analyses, R&D is now pursued on the assimilation of surface skin temperature in the surface analysis using CALDAS.

  At the time of this writing, only one channel is assimilated for the various geostationary satellites (water vapor channel). Change from MTSAT to HIMAWARI was done. Since the fall of 2016, tests are made to assimilate several channels from geostationary sensors, including adaptation to upcoming GOES-R. A specific goal is to improve the humidity analysis along with a revision of quality control for radiosonde humidity data.

  The impact of horizontal gradients for slant path observations has been tested, and a cost-effective procedure was identified. Higher-peaking temperature channels (AMSU-A and ATMS) were found to be sensitive to these gradients, and the algorithm is found to improve assimilation and forecast performance. The procedure will be clustered with other modifications in an upgrade to operations. Results will be published in early 2017.

  An international comparison on the impact of IASI (Metop 1 and Metop 2) radiance assimilation was organized by Meteo France in 2016. Several NWP centers participated including the Canadian Meteorological Center. We provided assimilation cycle results based on a period of three months using the latest version of our system described in section 1. Results should be published by early 2017.

- **Radiance bias correction**
  The method currently used for estimating the error biases of radiance observations is based on the use of a separate variational analysis in which no satellite radiances are assimilated. This analysis serves as the reference state for estimating the coefficients of the bias model using data over the past 7 days. The procedure was shown to work well (Buehner et al. 2015), but requires numerous additional programs to be executed as part of the operational suite for computing and applying the bias correction, in addition to the separate variational analysis. Mostly to simplify the current procedures, the use of a variational bias correction approach, in which the bias correction coefficients are updated during the main EnVar analysis, is now being investigated and compared with the current approach for possible replacement.

- **AMV and ADM-Aeolus wind**

  Significant progresses for better assimilation of atmospheric motion vectors (AMVs) have been made recently in several NWP centers. In particular, UK Met Office has developed a new algorithm to

specify the observation errors in which the error is split into two components: a static component that represents the tracking error and a flow dependant component that estimates the height assignment error. This algorithm is currently tested into our analysis systems for operationally implementation. Meanwhile, we will test a new algorithm that takes explicitly into account the height assignment error. The results will be compared with those from the UK Met Office algorithm.
Currently, the thinning for the geostationary satellites is made on a lat-lon grid of 1.5 degrees while it is performed on boxes of 180 km for the polar orbiting satellites. We have developed a new way to thin the observations based on data quality and minimal distance and time difference between the data in order to mitigate the detrimental impact of error correlations. This approach does not necessitate a grid to select observations and enables a more flexible way to vary the thinning distance which can depend on, for instance, latitude, region or other criteria that could be used to define optimal thinning distances. Finally, the quality of new AMVs such as from LEO-GEO composite and GOES-16 satellite will be assessed.

Aeolus is scheduled for launch spring 2018. The impact of the retrieved wind profiles from Aeolus will be evaluated as soon as the product is available. We are also involved in a validation campaign of Aeolus products in the Canadian Arctic.

- **Forecast sensitivity to observation**
  A new approach is currently being investigated for computing Forecast Sensitivity Observation Impact (FSOI). The approach combines aspects of existing adjoint-based and ensemble-based FSOI approaches. The new approach is suitable for computing FSOI for an EnVar deterministic analysis. It uses an ensemble of forecasts to propagate the forecast sensitivity from the valid time of the forecast to the valid time of the analysis and an iterative variational approach to obtain the sensitivity with respect to the observations. The approach is being compared with the standard adjoint-based approach in which the propagation from forecast to analysis times is performed using the adjoint of the forecast model. As in other purely ensemble-based approaches to FSOI, the need to use of spatial covariance localization may be a limitation and therefore will be a focus of the research.

- **GPS-RO**
  GPS-RO data are assimilated under conservative procedures. These data provide accurate information on the vertical structure of the atmosphere globally, and are particularly valuable in remote areas, where radiosondes are scarce. The data are very well calibrated (Aparicio, 2016), and control the bias correction of radiance data (Aparicio and Laroche, 2015). Research has been performed towards a reimplementation, using more aggressive observation operators, especially to enhance the benefit of the calibration. Two main lines are identified for transfer: 1) The GPS signals often reflect at the ocean surface, and are also captured. They are normally ignored, but it has been identified that they hold value for assimilation. An observation operator has been developed within a research context, to assimilate bending angles from reflections (Aparicio et al., 2016); 2) While data are well calibrated, linking this calibration to the modelled atmosphere of an NWP requires consideration of horizontal gradients. Thus, the GPS-RO observation operators were adapted to take this effect into consideration. This has been under evaluation in research mode, and will be transferred to operations. It is expected that both reflections and gradients will be treated in operations in the future (~2017).

- **Ground-based GPS**
  Assimilation of zenith total delay (ZTD) from the E-GVAP network of several hundred stations, mostly in Europe, is now included in the analysis. R&D was carried out to evaluate temporal correlations of

GB-GPS errors using the Desroziers diagnostic. It is intended to acquire observations from more GPS sites in Canada. We are exploring the option of processing raw GPS receiver data from North American sites ourselves, since the free distribution of processed ZTD data from the NOAA GPS stopped in fall of 2016.

- **PCW and TICFIRE missions**
  Activities related to PCW (Polar Communications and Weather) are currently on hold due to financial issues. Nevertheless, new options for orbital scenarios were recently published (Trishchenko et al., 2016). If Canada cannot proceed with PCW, another option is to work with ESA who is now investigating a similar mission.
  TICFIRE is a mission aiming at observing the Earth in the far infrared (15-50 micron). The concept will involve a small satellite. A prototype has been developed and tested onboard an aircraft as well as from the ground at Eureka. The project is done in cooperation with U, Quebec in Montreal (UQAM). A fast radiative transfer model was developed which is suitable for both retrievals and data assimilation.

3.1.2 Model

Research activities will focus on simulating an improved water cycle budget, aiming at more realistic energy exchanges between various sub-components. This is expected to increase the general realism of the GEM model through better interactions between the different physical parameterizations.

The model changes expected by 2019 include:

- 84 vertical levels instead of 80, with the first thermodynamic level at 10 m AGL, and the first momentum level at 20 m AGL. The model lid remains at 0.1 hPa. Model resolution monotonically decreases with altitude;
- All physics tendencies will be averaged along semi-Lagrangian trajectories, reducing the precipitation bias;
- Humidity and non-vapour water content will advected conservatively with a mass fixer to reduce precipitation bias;
- The filtering of geophysical fields will be reduced;
- In general, the sensitivity of physical parameterizations to the distribution of vertical levels will be reduced;
- An update the the correlated-k radiation scheme will be implemented, with 3D trace gases;
- Dissipative heating from surface blocking and orographic drag will be introduced to reduce temperature biases;
- Convective momentum transport will be activated in the deep and shallow convection schemes, in addition to several other adjustments;
- The Bechtold shallow convection scheme will replace the current scheme (CLEF);
- Humidity and temperature input for the explicit condensation scheme will be smoothed to reduce precipitation bias;
- The TKE boundary layer scheme will be refactored, including cloud properties, mixing and dissipation lengths, the introduction of dissipative heating;
- In general, the water cycle budget will be greatly improved with better conservation properties, and a reduced precipitation bias.

3.2 Global Ensemble Prediction System (GEPS)

3.2.1 Data assimilation

Data assimilation for the GEPS is performed using an Ensemble Kalman Filter (EnKF). Data assimilation for the GDPS is done using an ensemble-variational procedure that uses background error statistics from the EnKF. The GDPS and the GEPS use more or less the same set of observations. Hence, the research activities and the changes done in the context of the GDPS will also be implemented in the GEPS (see section 3.1.1).

The resolution of the horizontal grid will be increased. The 800x400 global uniform grid will be replaced by a 39 km resolution Yin-Yang grid.

The model lid will go from 2 to 0.1 hPa. The use of the same model lid in the ensemble and deterministic systems will facilitate the use of ensemble statistics in the ensemble-variational global and regional analysis systems.

The Incremental Analysis Update (IAU) algorithm will be used instead of the digital filter finalization procedure.

Currently the EnKF relies on the background check provided by the EnVar for the quality control of observations. A Huber norm procedure will be used for an additional quality control in the EnKF context.

Infrared satellite observations will be used in the EnKF system.

The hybrid gain algorithm will be used to obtain an optimal combination of the EnKF and ensemble-variational analyses.

An ensemble of land surface fields will come from the Canadian Land Data Assimilation System (CaLDAS see section 3.1.1).

The data assimilation cycle will move from a 6h window to a 3h window to better track high-resolution dynamical features and support high-resolution forecasting and/or data assimilation applications.

More satellite and in-situ observations will be used in the EnKF system.

3.2.2 Model

The resolution of the horizontal grid will be increased. The 800x400 global uniform grid will be replaced by a 39 km resolution Yin-Yang grid.

The model lid will go from 2 to 0.1 hPa. The use of the same model lid in the ensemble and deterministic systems will facilitate the use of ensemble statistics in the ensemble-variational global and regional analysis systems.

The Incremental Analysis Update (IAU) algorithm will be used instead of the digital filter finalization procedure.

A 2-way coupling of the GEPS forecast run with the oceanic model NEMO (GIOPS see 2.8.1 and 3.8.1 sections) will be considered as a candidate for implementation either in 2017 or 2018.

3.3 Regional Deterministic Prediction System (RDPS)

3.3.1 Data assimilation

Major changes are planned to the RDPS data assimilation system in the years to come as it will gradually transition towards a rapid cycling system to improve very short-term forecasts by 2020. In 2018, as the model horizontal grid spacing is reduced to 2.5km, the RDPS data assimilation will move from an intermittent cycling strategy to perpetual cycling including the replacement of the digital filter initialization by the IAU approach. In 2019, ensemble-derived background error covariances in the RDPS' 4DEnVar system, currently provided by a global EnKF system, will be provided by a 10-km limited-area ensemble system based on either the EnKF or the VarEnKF approach.

It is also planned to assimilate newer and/or denser observational data in 2018; starting with hourly reporting surface data and by reducing the thinning of satellite radiances as well as by adding the assimilation of skin-surface affected radiances. R&D towards the assimilation of observations from ground-based RADAR is ongoing and their gradual introduction in the RDPS assimilation system should start in 2018 and be completed by 2020.

3.3.2 Model

- The RDPS will be merged with the Regional Ensemble Prediction System (REPS) as its control member (see 3.4.2).
- The horizontal resolution will remain at 10 km, whereas, the domain size will be increased to extend the coverage over the North Atlantic and Caribbean region.
- RDPS will be based on GEM5 and all model-related changes will be aimed at unification of dynamics and physics between different systems (GDPS, RDPS, GEPS and REPS).
- The vertical resolution will be increased by adopting a new set of 84 vertical levels (as in GDPS) with the first momentum (thermodynamic) level at 20 (10) meters AGL.
- A new physics parameterization package will be implemented from the 15-km GDPS with the necessary parameter adjustments for the 10-km resolution.
- The model will use an upgraded version of the geophysics fields based on a sharper filter for resolved-scale topography and an improved calculation of the subgrid-scale topography fields.
- Large QPF bias in the West Coast in winter will be addressed.

3.4 Regional Ensemble Prediction System (REPS)

3.4.1 Data assimilation and objective analysis

In 2018, the 4DEnVar approach used in the RDPS will be introduced in the REPS system to provide a 10-km control analysis. An ensemble of 10-km analysis will be obtained by re-centring the 50-km global EnKF analysis perturbations around the new EnVar-based control analysis.

3.4.2 Model

- RDPS (section 3.3.2) will become the control member of the REPS.
- All members will adopt the configuration identical to that of the control member. Horizontal grid spacing will pass from 15 to 10 km, whereas the vertical resolution will be increased by adopting a new set of 84 RDPS vertical levels with the first momentum (thermodynamic) level at 20 (10) meters AGL. The domain size will be increased to extend the coverage over the North Atlantic and Caribbean region.
- REPS will be based on GEM5, use upgraded geophysics fields and a new physics parameterization package, based on the concept of physics unification.
- Four forecasts will be issued per day (00, 06, 12, 18 UTC) instead of two.
- Forecasts will be available early – at the same time as RDPS (T+3).
- Forecasts will be extended to 84 (120) hours operationally (experimentally).
- Stochastic deep convection and boundary-layer parameterizations will be developed and their impact on the REPS forecasts studied.
- Work on improving spread-skill relationship and dispersion for upper-air fields (too much in summer, too little in winter).
- Coupling with CALDAS will be considered as well as coupling with the ice-ocean model.
- Multi-model approach with NCEP in the NAEFS-LAM framework will be studied.

3.5 High Resolution Deterministic Prediction System (HRDPS)

By 2018,, it is planned that a version of the 2.5-km GEM very similar to the current HRDPS will be implemented at MSC-Operations as the main deterministic guidance for short-range numerical weather prediction, making it in effect the new RDPS system.

A few of the modifications that are expected for the 2.5-km GEM system are listed below.

3.5.1 Data assimilation

The downscaling approach will be replaced by the 4D-EnVar currently run to provide atmospheric initial conditions to the 10-km RDPS; i.e., the atmospheric analysis fields will be directly produced on the 2.5-km grid. It is planned that the RDPS and HRDPS will become a unique system in 2018

In the fall of 2017 it is planned that the HRDPS-2.5 km will become operational, a status change from experimental, and with this upgrade CaLDAS will become operational. Current research and development work with CaLDAS is focused upon (i) the assimilation of more space based remote sensing information, (ii) the coupling of CaLDAS with the newly developed SVS (Soil, Vegetation and Snow) scheme, and (iii) the expansion of CaLDAS to the GDPS domain with more direct coupling with the atmospheric ensemble system GEPS.

The next CaLDAS implementation is planned for the HRDPS in the fall of 2018. In this implementation the goal is to replace ISBA with SVS, include the assimilation of soil moisture brightness temperatures from the SMOS (Soil Moisture Ocean Salinity) / SMAP (Soil Moisture Active Passive) satellites along with skin temperature retrievals from GOES. The coupling of CaLDAS with the upper-air GEPS will begin in early 2018. It is planned that the version of CaLDAS will include SVS, SMOS/SMAP and skin temperature retrievals from polar orbiters, AIRS/CRIS/IASI.

3.5.2 Model

The main avenues of development will be:

- Make some minor adjustments to parameterized convection, related to the trigger function in the Kain-Fritsch scheme.
- Improve very short-range forecasts to produce better background fields for data assimilation by recycling prognostic and semi-prognostic variables from the atmospheric turbulence scheme.
- Implementation of the Predicted Particle Properties (P3; Morrison and Milbrandt, 2015) microphysics scheme.
- Use a new set of vertical levels, with the first momentum / thermodynamic levels at 10 / 5 m AGL.
- Test and implement new land surface schemes, SVS and TEB for natural and urban surfaces.
- Implement a version of CaLDAS, with assimilation of SMAP and SMOS L-band brightness temperatures and analysis increments on the surface stomatal resistance provided by the SVS land surface scheme.
- At a later stage, the HRDPS domain may be extended northward and essentially merged with the new (February 2018) CAPS system over the Arctic region (see section 2.5.2), and eventually coupled with an ocean model (NEMO) and a sea-ice model (CICE).

Improvements to the sub-grid scale physical parameterizations described in sections 3.1.2 and 3.3.2 will be tested in the kilometre-scale model.

3.6 Air quality prediction systems

3.6.1 Regional Air Quality Deterministic Prediction System (RAQDPS)

The broad direction forward for the RAQDPS is to create an operational cascade of air quality forecasts with chemical data assimilation, analogous to the operational weather forecasts, using the same GEM-MACH modeling platform to create global air quality forecasts, which in turn will drive regional and then local/high resolution forecasts.

Another objective is to lengthen the RAQDPS forecasting period. Current operational products only provide forecasters with a 48-hour lead time. The use of better initial conditions and, in the case of the limited-area regional configuration, extended boundary conditions, is considered essential to achieve this goal.

During the 2012 and 2013 fire seasons an experimental set up for ingesting near-real-time wildfire emissions into GEM-MACH based on satellite remote-sensed measurements was tested (Pavlovic et al., 2014). Daily 48-hour forecasts were prepared during the summer and made available for internal evaluation. This prototype system is one of the outcomes of collaboration between Environment and Climate Change Canada and the Canadian Forest Service. During the 2014 and 2015 fire seasons, this system, named FireWork, was run by Environment and Climate Change Canada`s operations in experimental mode and its products were made available to forecasters and external users twice daily (Pavlovic et al., 2016). In May 2015, the Regional Deterministic Air Quality Analysis (RDAQA) was also connected to the FireWork system, and RDAQA-FW produced wildfire-influenced objective analyses for two pollutants, $PM_{2.5}$ and PM_{10}, at the surface level. And most recently, in spring 2016 the FireWork system was upgraded to seasonal (April-October) operational status and will be run each year side by side with the RAQDPS during the fire season (Moran et al., 2016a).

A GEM4-based version of GEM-MACH, which includes mass-conserving tracer advection, an updated gas-phase dry deposition scheme with leaf-area-index scaling as well as several other significant modifications to the treatment of surface fluxes, new chemical lateral boundary conditions, and a new vertical diffusion scheme has been developed and was implemented into operations in spring 2016 (Moran et al., 2016b).

Short-term avenues for further RAQDPS development and improvement include the following:

- Test and evaluate RAQDPS Day 3 forecasts based on extended meteorological piloting with either the extended RDPS or the GDPS
- Test and evaluate a new wildfire emissions estimation module and a new plume rise-mechanism [FireWork].
- Update the emissions files input by the RAQDPS based on the use of newer national emissions inventories and improved ancillary information (e.g., spatial and temporal surrogates and speciation profiles: cf. Moran et al., 2015)
- Test the use of new ozone chemical lateral boundary conditions obtained using a “dynamic” interpolation from a global ozone climatology
- Test the use of chemical lateral boundary conditions for multiple species obtained from a global air quality deterministic prediction system (GAQDPS: see Global GEM-MACH section)
- Test chemical initialization based on new 3-dimensional objective analysis fields (OA version 2)
- Improve meteorological modulation of some emissions sectors such as biogenic emissions and fugitive dust emissions and phenological behaviour of some variables such as leaf area index in dry deposition module

- Improve some chemistry process representations (e.g., dry deposition, J values, sub-grid-scale tracer transport, size-dependent PM wet removal, two-way feedbacks)
- Investigate improvements to representation of wildfire emissions, including the emission factors for different model species and the plume-rise algorithm
- Improve the aerosol optical depth (AOD) representation in the model.

A longer-term goal that is being examined is to assess the feasibility and benefits of an ensemble forecasting approach for regional air quality.

3.6.2 Regional Deterministic Air Quality Analysis (RDAQA)

In 2016, the RDAQA system was extended to include NO_2, NO, SO_2, PM_{10} and Air Quality Health Index (AQHI) analyses. The impact of initializing the air quality forecast model with surface analyses was examined and had a positive impact on the forecast for up to 12-24 hours for the gaseous pollutants, and longer for PM2.5 sulphates and crustal material. There is also research and development to improve the existing regional objective analysis system by using ensemble statistics for error covariances, improving the estimation of parameters using maximum likelihood, harmonizing the assimilation of PM2.5 and PM10, improving the validation strategy by cross-validation. The new system is projected to become operational in 2018.

Other avenues of research and development include:

- Application of the multi-year analysis to support epidemiological studies and collaboration with the Canadian Urban Environment Health Research consortium (CANUE, www.canue.ca) for the distribution of the data.

3.6.3 Chemical Data Assimilation

A priority activity over the recent and the next several years is to incorporate the capability for chemical data assimilation into Environment and Climate Change Canada's (ECCC) integrated global-regional EnVar assimilation system. The global assimilation component shall provide lateral conditions for the regional model as well as prognostic ozone. The development is focusing first on the global analysis solver for stratospheric ozone and on the regional optimum interpolation analysis for air quality purposes. In a later phase, a global tropospheric-stratospheric data assimilation will feed analysis increments to either global or regional versions of GEM-MACH. This takes into account features of the global variational chemical data assimilation research system for ozone and experience gained from the operational regional objective analysis system (RDAQA). The development and related research will lead to future proposals for a global and regional chemical assimilation system. Conditional on having positive impact on forecasts, regional assimilation would become part of the RAQDPS. The assimilation will make use of both surface and satellite observations.

In the short term, the development consists in improving the next version of the objective analysis to generate 3D analyses that will be used to initialize the GEM-MACH model. Preliminary experiments with 6-hour cycling have been conducted that shows impact in reducing the error variance by a factor 2 and significantly decreasing the bias.

With respect to the global configuration, we will incorporate the basic capability for chemical data assimilation without constituent ensembles into ECCC's EnVar assimilation system. The first applications will be assimilations of stratospheric ozone and weather plus ozone with the global system. Additions to follow will include the assimilation of constituent-sensitive channels of brightness temperature measurements and investigating the use of climatological model outputs to provide ensemble information in an hybrid EnVar formulation, initial assimilation experiments for other constituents and extending system element applications to regional assimilation.

In preparation for an implementation of a full EnVar with forecast ensembles, studies in chemical EnKF and harmonization of information content from different chemical constituents have been carried out in collaboration with the Belgium Institute for Space Aeronomy. Computational simplifications to the EnKF have also been explored. The scheme designed for chemical data assimilation is called the Parametrized Kalman filter.

An investigation on the use of satellite and ground-based observations of aerosol optical depth (AOD) will be undertaken over the next few years. This will first consist of a comparison of the GEM-MACH AOD forecasts with observations, followed by developments for assimilation of satellite and ground-based AOD data.

3.6.4 Ozone assimilation and UV index forecasting

The operational implementation of ozone interactive Global Deterministic Prediction System (GDPS) with UV index forecasting capability is expected to take place in the near future. Such implementation necessitates the incorporation of several ozone assimilation modules within the operational Numerical Weather Prediction data assimilation system. Such implementation relies on our capacity to demonstrate that the inclusion of a prognostic and radiatively active ozone constituent in the ECCC GEM NWP model contributes to the improvement of medium range weather forecasting.

Stratospheric ozone assimilation is being conducted in research mode with the current variational global chemical data assimilation system to provide prognostic ozone for use in UV index forecasting. In 2016, the variational assimilation executable of that system was replaced by that of the EnVar, this application without use of forecast ensembles.

A column ozone assimilation study using multiple column ozone satellite instruments and involving bias correction and the re-estimation the ozone observation and background error variances was undertaken and is expected to be completed in about one year. This involves the assimilation of total column ozone data from the GOME2 instruments of the Metop-A and B satellites, OMI on Aura, and OMPS-NM on Suomi-NPP and use of various other sources for validation, including ground-based Brewer and Dobson instruments. Following assimilation studies with SBUV/2 and OMPS-NP partial column profile satellite instrument data and TropOMI are expected to follow.

An approach for the computation of the UV index for clear-sky and all-sky conditions relying on broadband UV irradiances calculated by the weather forecast model is being optimized. It makes use of the above ozone assimilation and forecasting setup to provide the ozone field delivered to the radiative code instead of an ozone climatology. This optimization is expected to be completed in a year. The UV index product derived from this method, if not others as well, is to be evaluated against the current operational product. The new UV index calculation scheme is envisaged to be implemented as part of the global forecasting system in the next few years.

3.6.5 Arctic air quality modelling

A GEM-MACH based capacity for modelling Arctic air quality is in development. The initial enhancement for adapting GEM-MACH for modelling the Canadian Arctic and northern regions included addressing sea ice cover conditions (for dry deposition and sea-salt emission), chemical lateral boundary conditions, and biomass burning emissions. The Arctic version of the GEM-MACH model was used for a model assessment of the impacts of Canadian Arctic marine shipping emissions on air quality and ecosystems in the North. The assessment examined the contributions from Arctic shipping emissions at current and projected future levels to ambient concentrations of criteria pollutants, atmospheric deposition of sulphur and nitrogen, and atmospheric loading and deposition of black carbon. A manuscript has been prepared for publication in a scientific journal (ACP).

GEM-MACH-Arctic was also used to simulate a recent Arctic summertime field campaign conducted under a research network NETCARE project (NETwork on Climate and Aerosols: Addressing Key

Uncertainties in Remote Canadian Environments, http://www.netcare-project.ca). The model results were compared with observational data from both ground-based monitoring and in-situ measurements on-board multiple mobile platforms to: 1) assess model skill in predicting air quality in the Arctic and northern region, and 2) understand sources and processes influencing summertime atmospheric composition in the Canadian Arctic. The model simulations and comparisons with observations were able to demonstrate both the importance of biogenic/oceanic sources under pristine conditions and the major transport routes for anthropogenic and biogenic sources in lower latitudes to impact the Arctic during summer time. Various aspects of this work have been presented at a number of conferences and workshops. Publications are in preparation.

Further model developments include the incorporation of a model representation of atmospheric dimethyl sulphide (DMS), which plays an important role in aerosol formation and growth in the Arctic marine boundary layer during summer time. The addition of DMS in GEM-MACH is also relevant to GEM-MACH global as atmospheric DMS oxidation contributes to a significant fraction of global SO2. Further model investigations on sources contributing to atmospheric ammonia loadings during summer in the Arctic and its role in aerosol formation is also planned, particularly to incorporate new findings on enhanced ammonia emissions from Arctic tundra. With the wealth of new data collected during the recent NETCARE Arctic field campaigns, further model-observation comparisons focusing on size-resolved aerosol number and composition will be pursued to enhance our model capacity for predicting the atmospheric composition in the Arctic.

3.6.6 Global GEM-MACH

Efforts in the coming years will focus on the following improvements to Global GEM-MACH:

- Introduction of an alternative gas phase chemistry mechanism;
- Introduction of prognostic methane;
- Introduction of an alternative biogenic emission module;
- Implementation of bromine sources and chemistry;
- Addition of plume rise algorithms specific to wild fire emissions, along with adapted mechanisms for emission injection at various heights;
- Parameterizations for lightning NOx generation will be added;
- Introduction of deep and shallow convective transport of chemical species;
- Tests of the generation of boundary conditions by global model for limited-area version of GEM-MACH will be carried out and evaluated;
- Post-processing: Aerosol Optical Depth (AOD) calculations from aerosol mass will be added and compared to observations
- Implementation of a new module for aerosol physicochemical processes
- Inclusion of the production of SO2 from dimethyl sulfide (DMS)
- Coupling of atmospheric mercury cycling in GEM-MACH with ocean mercury cycling in NEMO

3.6.7 High-Resolution Air Quality Modeling

3.6.7.1 Canadian Oil Sands Region

High resolution air quality modelling continues at ECCC with experimental forecasts and simulations for the provinces of Alberta and Saskatchewan (with a focus on the oil sands), and for southern Ontario (with a focus on the PanAm/Para-PanAm Games). Both sets of simulations are making use of version 2 of GEM-MACH. Eight papers stemming from the Oil Sands work are in the process of publication. More process related work from these projects is referenced later in this document.

3.6.7.2 Urban Air Quality Modelling

The Pan-American/Para-Pan American Games science showcase results have been summarized in a research article (Joe et al., 2017). The lessons learned from the study were also presented at a special session of the IWAQFR 2017.

The air quality model demonstration has resulted in a model version and high resolution domain that continues to be used for numerous research projects and emission scenario applications. Results are summarized below:

<u>Lake Breezes</u>

Sensitivity simulations were presented to understand the source of the ozone over-prediction over Lake Ontario on light wind, clear sky days. It was deduced that the land to sea breeze in the morning brought ozone precursors from the morning rush hour out over Lake Ontario. The precursors remained in a shallow layer over the lake and were brought back on-shore by the lake breeze in the late morning and afternoon. The combination of sunny skies, light winds and a shallow layer of precursors led to rapid ozone production in the model. More vertical mixing over the urban area in the early morning is one mechanism in the model that would lower the ozone predictions and bring them closer to the observations. The Pan Am Games data base (both observations and model results) have been archived to the Government of Canada Open Data Portal.

http://open.canada.ca/data/en/dataset?q=Pan+Am+Games

<u>Urban Surfaces</u>

An urban surface scheme has been incorporated into GEM-MACH based on the Town Energy Balance (TEB) parameterization. This enables a better simulation of the urban heat island effect and resulting impact on air pollutant circulations. The GEM-MACH-TEB model was run for 1-month in summer and 1-month in winter and results compared to both met and air quality observations. A better forecast for temperature in Toronto was observed when including TEB. Also better scores for primary emitted species (e.g CO and NOx) were observed with TEB because of the enhanced surface mixing. Interestingly, the distribution for Ox (sum of O_3+NO2) showed little change by including TEB suggesting that TEB largely impacts local spatial scales and vertical levels close to the surface. This is still important as humans are exposed near the surface and near VOC and NOx urban sources. This work is being drafted into a manuscript for publication. Research started on improving the anthropogenic heat flux maps for Canadian cities using existing CO and NOx emissions maps and published heat vs pollutant correlations (Lee et al., 2014). Work will continue on these schemes in support of improved air quality forecasting in urban environments.

<u>Carbon Dioxide Modelling</u>

The GEM-MACH urban model was also used to simulate the impact of a new CO_2 emission inventory for the Greater Toronto Area. Wintertime, hourly CO_2 emission maps were developed from the new inventory (termed SOCE) and with existing spatial surrogate fields for different sources (on-road, off-road mobile, residential, industrial). CO_2 was added to GEM-MACH as an emitted and transported species. The model CO_2 output was compared to measurements at 4 surface sites in Southern Ontario (one downtown and one uptown Toronto site, one inland rural and one shoreline rural site). Predictions were better with the developed emissions (SOCE) than the base emissions (FFDAS). The wintertime source apportionment results from GEM-MACH showed that CO_2 at the downtown site was largely impacted by traffic sources during the daytime and residential heat sources at night. This work is summarized in the following manuscript submitted to ACDP:

Near-Roadway Modelling

The GEM-MACH urban model results were compared with observations from a long-path FTIR laser instrument across the busiest highway in Canada (Hwy 401). The model/measurement comparison was performed for different wind directions and wind speeds. As expected, for primary emitted pollutants (NH3, CO and NOx), the model tended to underpredict the observations, as the foot print for the model (2.5km grid spacing) is much larger than the path of the FTIR over the road. However, emission factors calculated from the observations were similar to the emission factors used in the model's mobile emission inventory.

Urban Forest Canopy Modelling:

As part of the Pan Am/Para-Pan Am project, the ECCC forest canopy parameterization (Makar et al, Nature Communications, 2017) was implemented at 2.5km resolution, and coupled to the GEM-MACH feedback parameterization described in the Air Quality Model Evaluation International Initiative, Phase 2 (AQMEII-2). Results of these comparisons were presented at the International Workshop on Air-Quality Forecasting in Toronto, and at the European Geosciences Union Annual meeting in Vienna. The forest canopy environment (shaded and low turbulence) was shown to have a discernible secondary influence on particle radiative transfer and weather patterns in short simulations, though the forest canopy environment had a much more significant impact on model results than the feedbacks alone. This work is intended to further improve air quality forecasting in urban environments and examine feedbacks between air quality and weather.

3.6.8 Process Investigations

Effects of forest canopies on ozone formation

The RAQDPS was reconfigured to include parameterizations and changes to the trunk model code to include the effects of shading (reduction of photolysis rates) and turbulence (modified vertical diffusivity profiles) within forested regions of North America. These modifications had a profound impact on predicted ozone concentrations – essentially reducing the long-standing positive bias of surface ozone in eastern North America to zero. The effects of the forest environment were found to extend throughout much of the lower troposphere (to the 600 mb level and above), with monthly average summer concentrations within the troposphere being reduced by up to 12%, and daily average values within the troposphere being reduced by up to 40%. The results were published in Nature Communications. Further work is planned, with the intention of incorporating this parameterization into the operational forecasts with GEM-MACH.

Secondary Organic Aerosol Formation

ECCC developed a state-of-the-science secondary organic aerosol formation scheme for application over the Oil Sands region (Liggio et al. 2016). This SOA scheme was based on the volatility basis set (VBS) approach. The Lagrangian box model was first constrained to observations and then used to estimate the IVOC emission factors and VBS aging rates. This past year the VBS scheme was added into GEM-MACH and IVOC emissions were processed based on prior-derived box model emission factors. Preliminary GEM-MACH results show a significant increase (up to 10 $\mu g/m^3$) in modelled SOA downwind of the Oil Sands, similar to the increases observed from the aircraft.

Last year, ECCC published a paper on enhanced SOA formation rates from a-pinene oxidation when seed inorganic aerosol is acidic (Han et al., 2016). This past year the enhanced SOA yields were incorporated into GEM-MACH to test the sensitivity of SOA formation in the Oil Sands region. It was found that modelled plumes downwind of coal-burning power plants in Alberta were the most sensitive to this acid-catalyzed mechanism, although model enhancements in SOA were still less than 5% of base model SOA predictions. The acid-catalyzed effect is reduced at higher organic aerosol mass concentrations because the organic phase coats the inorganic phase and prevents the a-pinene products from penetrating into and reacting in the inorganic phase core. This mechanism is clearly seen in the laboratory under controlled conditions, but it is still unclear whether this inorganic core/organic shell particle state really exists in the atmosphere. There was some evidence from the aircraft flights that acidic aerosol in SO_2 plumes were enhancing SOA compared to background air, but more data is needed to confirm this observation.

Transport and Fate of Airborne Toxic Compounds

For the oil sands model development, ECCC continued to develop GEM-MACH capabilities to model toxic compounds by adding isocyanic acid (HCNO). HCNO is a highly toxic species to humans when it is inhaled and passed into the bloodstream. Adverse health effects can be felt when ambient HCNO mixing ratios reach the ppbv level. Rapid formation of HCNO was observed by aircraft sampling downwind of the oil sands. HCNO emissions, transport, chemistry and deposition were added to GEM-MACH to simulate the formation of HCNO downwind of the oil sands. The aircraft observations were used to constrain the secondary production of HCNO. The formation suggested that the heavy-hauler diesel trucks were the dominant source of precursor VOCs, which then react in the atmosphere to form HCNO. The model predicted HCNO mixing ratios in the low ppbv range for populations in the near-range to the emissions (Fort MacKay community, worker camps).

3.6.9 Feedbacks between Air Quality and Weather

The version of GEM-MACH which accounts for feedback between air quality and weather was used in conjunction with the new parameterization for forest canopy shading and turbulence on the PanAm domain (see PanAm description, above). Feedbacks were also examined under a grant and contribution agreement with the University of Quebec at Montreal, with testing and implementation of a new ice nucleation scheme in the feedback version of GEM-MACH to investigate how physical and chemical characteristics of aerosols impact ice nucleation processes and the subsequent impact on cloud microphysics. Work has been focused on analysing the observed ice nuclei (IN) during the Amundsen 2014 campaign (part of the NETCARE field study) to constrain an offline version of the model to develop a parameterization of IN concentration based on the classical nucleation theory. The new parameterization is being implemented in GEM-MACH and being tested in simulations of the NETCARE field campaign.

3.7 Specialized Systems

3.7.1 Surface fields assimilation and analysis

3.7.1.1 SST

A new SST analysis has been implemented in experimental mode. Data from VIIRS (Suomi-NPP) and AMSR2 (GCOM-W2) instruments are assimilated in addition of data used in the operational analysis (4 AVHRR instruments in situ data and ice information). Along with increasing the resolution of the analysis grid at 0.1 deg, additional changes were needed to fully benefit from the improved resolution, as a new background error correlation matrix, addition of ice information from a variational analysis, modifications to capture sudden SST changes due to tropical storms and pre-processing of closely spaced observations. More details about this new product are included in Brasnett and Surcel Colan (2016).

3.7.1.2 CaLDAS

Development of a first version of the Canadian Land Data Assimilation System (CaLDAS) has been completed and implemented in experimental mode in 2014. Compared with the current operational system, CaLDAS assimilates a larger amount of data using an Ensemble Kalman Filter technique. For soil moisture, remote sensing data from ESA's (2008) Soil Moisture and Ocean Salinity (SMOS) mission and from NASA's Soil Moisture Active and Passive (SMAP) continues to be tested. This data will be assimilated in conjunction with near-surface air temperature and humidity, and retrievals of surface temperature from geostationary satellites (GOES, MSG, Himawari) .

Other changes include the use of a new land surface scheme (Soil, Vegetation, and Snow – SVS scheme). This new land surface scheme has been tested for local, regional, and global applications. This scheme is an extension of ISBA currently used at MSC-Operations, and includes a more detailed representation of water and energy budgets (multi-budgets approach), a greater number of soil layers, a more appropriate representation of soil freeze-thaw processes, as well as photosynthesis. Offline tests have shown that SVS is superior to ISBA for both NWP and hydrological applications.

Focus in the next one or two years is to proceed with an operational implementation of CaLDAS for regional and global systems, both deterministic and ensemble. Research and development is currently done to combine satellite information for soil moisture and surface temperatures in the context of more sophisticated land surface modeling. In the long term, an hybrid version of CaLDAS could be developed, with a simple variational approach combined with an Ensemble Kalman Filter.

For terrestrial snow, two important modifications to the current approach will be developed and tested in the next few years. In the short term, high-resolution optical information (e.g., from MODIS and VIIRS) will be used to specify snow fractional coverage in CaLDAS following a rules-based technique. Second, more sophisticated modelling is being put in place, including multi-layer snow modelling (part of SVS) and microwave radiative transfer modelling with DMRT-ML (Dense Media Radiative Transfer on Multi-Layers), in order to better assimilate microwave information from AMSR-E or similar sensors in CaLDAS.

Two different CaLDAS suites are expected to be implemented in the next few years, one for the North American region (at 2.5-km grid spacing) providing initial conditions to the HRDPS, RDPS, and REPS, and a global one (at 10-km grid spacing) for the GDPS and GEPS systems.

3.7.2 Precipitation analysis

3.7.2.1 Regional Deterministic Precipitation Analysis (RDPA)

The RDPA has reached maturity. It will eventually be included into an analysis system combining a high resolution deterministic precipitation analysis (see HRDPA 3.7.2.3) and a Regional Ensemble Precipitation Analysis (REPA). The analogous of current RDPA analysis product will then become the control member of the regional ensemble. In 2018, the plans are to update the RDPA for including more observations from provincial networks, and for maintaining the compatibility of the RDPA with the changing regional model which provides the precipitation background field.

3.7.2.2 Regional Ensemble Precipitation Analysis (REPA)

The Regional Deterministic Precipitation Analysis (RDPA, see previous section) is generated by an optimal interpolation system called CaPA (Canadian Precipitation Analysis). CaPA provides an important input to the Canadian Land Data Assimilation System (CaLDAS), namely a stochastic ensemble of precipitation analyses: observations are perturbed proportionally to their measurement and representativeness errors, and the background field is also randomly perturbed (in location and intensity) proportionally to its standard error. However, the version of CaPA used by CaLDAS is old and needs to be upgraded, in particular to take advantage of radar data assimilation, operational in the RDPA configuration of CaPA since November 2014. Work is ongoing to upgrade the version of CaPA used is CaLDAS so that it is as close as possible to the RDPA version. Furthermore, instead of making stochastic perturbations to the background field, this new system will instead use background fields from the Regional Ensemble Prediction System (REPS), and hence will be known as the REPA configuration of CaPA (Regional Ensemble Precipitation Analysis).

3.7.2.3 High-Resolution Deterministic Precipitation Analysis (HRDPA)

The HRDPA is a precipitation analysis product currently in development that is very similar to the RDPA. The main difference is that the background of the RDPA is the RDPS NWP system, whereas the HRDPA uses the HRDPS NWP system for the background. For this reason, the HRDPA produces an analysis on a 2.5-km grid, whereas the RDPA has a 10-km resolution. Both products share the same temporal resolution of 6-h. The HRDPA also produces watershed mean precipitation for all of ECCC operated hydrometric stations. This product will be used for improved planning of the measures campaign aiming at the construction or updates of level-flow empirical relationships.

The HRDPA should become fully operational in the beginning of 2018. Challenges for the HRDPA include the sampling frequency of radars, which create a “stroboscope” effect because rain cells can move more than one grid cell between two radar scans. For this reason, radar data is smoothed at a resolution of 5-km. Despite this, the radar data that is assimilated by the HRDPA still is at higher effective resolution than the model background, since the HRDPS precipitation fields are much smoother than the nominal 2.5-km resolution.

Improvements to the HRDPA are planed for the second half of 2018, allowing more observations from provincial and cooperative networks to be assimilated.

3.8 Ocean and coupled modelling

3.8.1 Global Ice Ocean Prediction System (GIOPS)

Development plans for GIOPS includes upgrading the assimilation system to include bias correction of subsurface temperature and salinity fields, real-time background error covariance updates, and improved ice-ocean coupling. In the context of an extension of GIOPS to produce coupled ensemble forecasts, an "multi-analysis" framework is being developed for SAM2. A project is also underway to produce weakly-coupled daily analyses for the GDPS-GIOPS coupled forecast system.

3.8.2 Regional Ice Ocean Prediction System (RIOPS)

RIOPS runs since June 26 2016 as an experimental prediction system. It replaces the ice-only prediction system (RIPS). The end product of it has been used by the Canadian Ice Service and NOAA in their routine forecasts despite its experimental status. It has three components: RIOPS-A, RIOPS-PA and RIOPS-F. The first assimilates observational data and produces an analysis of sea ice which is used by the ocean-analysis and forecast components (RIOPS-PA, RIOPS-F) as initial conditions. The second, RIOPS-PA, produces an ocean analysis by running over the last 24h a spectrally nudged ice-ocean simulation to constrain the large scales of the ocean component toward the Global Ice Ocean Prediction System (GIOPS) analyses. A version of SAM2 on the RIOPS domain with an extension to cover the north-east Pacific Ocean is under development. The last, RIOPS-F is the 48h forecast component.

The RIOPS-A ice analysis uses the previous analysis as background state for the next cycle. It assimilates daily and weekly regional Canadian ice charts, Radarsat image analysis, remote sensing instruments (ARMS2, SSMI, SSMIS, ASCAT). The analysis is done 4 times a day at 00, 06, 12, and 18Z.

RIOPS-PA is based on the ice-ocean model NEMO3.1-CICE4.0, with input from RIOPS-A, the global and regional NWP products and GIOPS analysis.

RIOPS-F is based on the same ice-ocean model and provides a 48-hour forecast four times a day with input from RIOPS-A, RIOPS-PA, the global and regional NWP products and persistent open boundary conditions coming the GIOPS analysis.

RIOPS-A is run at a horizontal resolution of 0.045 degrees (or approximately 5 km) with the final product available on a global ORCA tri-polar grid at 1/12th degree nominal resolution (approximately 5km over the Arctic with double the resolution on the Canadian side). RIOPS-PA and RIOPS-F are run on a subset of the same global ORCA tri-polar grid at 1/12th degrees.

Development and validation are on-going on automated techniques for near-real-time utilization of various satellite data types to improve surface wind estimation, extract sea ice features and detect and estimate the presence of ice hazards (icebergs, ice islands).

3.8.3 Regional coupled atmosphere-ocean-ice forecasting

The original coupled atmospheric-ocean-ice system at CMC is the Gulf of St. Lawrence system based on GEM, NEMO and CICE models. R&D is being performed on several regional coupled atmosphere-ocean-ice systems with the goal of improving marine and weather forecasts and with lead times of 1-3 days:

- A similar system to the previous one is currently in development over the Great-Lakes using a 2km resolution configuration of NEMO-CICE. Preliminary results have shown that coupling of the RDPS atmospheric configuration leads to improved surface weather forecasts for most areas around the Great Lakes.
- Development and validation of an integrated marine Arctic prediction system. The objective is to allow the expansion of the end-to-end analysis and forecasting system (with a few days lead time) for production of marine information products beyond the Canadian Arctic into the international waters of METNAV Areas XVII and XVIII.

Development is also on-going to include other modelling components (land, snow, wave) and associated data assimilation.

3.8.4 Global coupled atmosphere-ocean-ice system

Results have shown that coupling of the GDPS atmospheric configuration to GIOPS-F leads in significant improvement of weather forecasts in hurricane seasons (cold wake effect) but also in shoulder seasons where the ocean model provides a negative feedback to the natural tendency of the atmospheric model to over-intensify storms. The coupled GDPS system was implemented experimentally at CMC in July 2016 and will be made fully operational in 2017.

3.8.5 Wave Forecasting

Wave modelling research is being conducted primarily on the following topics:

- Upgrades to the physics of the wave model with the replacement of long standing systems
- Development and implementation of a Global Ensemble Wave Prediction System for 0-10 day probabilistic forecasts. The integration of Canada's 20 members in a North American Ensemble is continuing under NAEFS. NOAA and the US NAVY currently each contribute 20 members to the super ensemble (Alves et al. 2013).
- Investigation of impacts of coupling with other systems such as the atmospheric, and ice models on wave forecast skills and other component forecast skills.

The Global Deterministic Wave Prediction System will become operational in 2017. Itis the first Canadian wave forecast system in operations based on WAVEWATCHIII® (WW3). The global system was designed to provide adequate boundary conditions for the future replacement of the coastal regional grids. Regional system replacement has begun with the replacement of the Great Lakes system by a combination of both deterministic and ensemble prediction systems that cover all 5 lakes. Other regions will follow in the coming year.

A Global Ensemble Wave Prediction System, based on WW3, is also under development. The system consists of one control and 20 perturbed members. The forecasts are produced twice daily with 10 day lead time. The wave ensemble is expected to be transferred to operations in 2018. Once in operations, EC plans to join NCEP and FNMOC, via NAEFS, into a multi-center wave ensemble of 62 members.

3.8.6 Storm Surge forecasting

Storm Surge modelling research was conducted and led to the operational implementation of a Storm Surge model system called the Regional Deterministic Surge Prediction System (RDSPS). This 1/30 degree model for the Atlantic Coast of Canada is based on the Dalcoast model. A corresponding 1/12 degree ensemble prediction system was developed and recently installed in operations. In parallel, a global system, based on NEMO, is being developed.

3.8.7 2D hydrodynamic forecasting system

Since May 2013, the operational hydrodynamic system SHOP (Simulation Hydrodynamique OPérationnelle) produces two-dimensional (2D) numerical analyses and nowcast simulations of various physical parameters for the St. Lawrence River and its tributaries, representing the current hydrological conditions. In SHOP experimental version 1.0.0, the analyses are performed over a reach of the St. Lawrence River extending from Montréal to Trois-Rivières. The numerical model H2D2 is used to solve the stationary 2D Saint-Venant equations on a triangular finite-element mesh, and incorporates information on local friction caused by substrate and aquatic vegetation. SHOP uses flow and water level averaged observations for a 24-hour period between 18 UTC the day prior to the analysis and 18 UTC on the day the analysis is produced.

Planned development of this system includes an extension upstream to cover the Montreal archipelago, Lake Des-Deux-Montagnes and Lake Saint-Louis, as well as downstream to include the St. Lawrence fluvial estuary down to Île-aux-Coudres. A non-stationary version of H2D2 has been developed for this purpose. Work is ongoing to implement this hydrodynamic forecast system in experimental mode, using 1) winds from the HRDPS forecast system, 2) streamflow at the tributaries and upstream boundaries from the WATROUTE 1-km routing model, and 3) tidal predictions at the downstream boundary from the ONE-D operational model (SPINE). A preliminary version of the experimental system is currently being tested. It runs four times a day (at 00, 06, 12 and 18 UTC) and produces a deterministic 48-h forecast of water levels and velocities.

The same type of system will be deployed elsewhere in Canada, possibly starting with Lake Champlain/Richelieu River, and the connecting channels between Lake Huron and Lake Erie (including Lake St. Clair).

3.8.8 Hydrological and water cycle modeling system

ECCC has deployed in June 2016 an experimental water cycle prediction system for the Great Lakes and St. Lawrence River watershed. This unique system includes a limited-area configuration of GEM running at 10-km over the watershed (forced at its boundaries by GEM RDPS), two-way coupled to the ice and ocean model NEMO-CICE running at 2-km resolution over the Great Lakes. Furthermore, river flow for all tributaries to the Great Lakes and St.Lawrence River is computed by routing the surface runoff predicted by GEM using the WATROUTE routing model on a 1-km grid. Over the Great Lakes region, the streamflow at the mouth of each river is provided to NEMO as a boundary condition, thereby creating a fully coupled system.

The analysis system is run twice per day (at 00 and 12 UTC), and assimilates streamflow observations and ice cover data using a simple nudging technique. The forecast system is also run twice per day and produces a deterministic 84-h forecast of meteorological variables, land-surface variables, streamflow and lake variables, such as surface current, lake levels and ice cover.

This system has been shown to accurately forecast all of these variables out to 84-h, but for water management purposes, there is a clear need to provide weekly, monthly and eventually seasonal forecasts. Thus, we expect to run the same system in ensemble mode in the future.

The same type of system will be deployed elsewhere in Canada, perhaps starting only with streamflow routing using WATROUTE, as two-way coupling of the atmosphere and lake systems is not as critical everywhere in the country.

3.8.9 Urban modeling

Urban areas have a substantial impact on local meteorology and have recently been included in atmospheric models. In GEM, the positive role of the Town Energy Balance (TEB) scheme has been well established for several meteorological situations, as documented by several publications. In the next few years, ongoing studies regarding the role and impact of built surfaces on small-scale meteorological events, such as sea/lake breezes, convergence fronts, and the triggering of convective activity will be continued. The recently-developed multi-layer version of TEB will be reinstated and evaluated for these cases, with a possible implementation (in conjunction with the addition of atmospheric levels very close to the soil) in upcoming versions of RDPS (2.5-km grid spacing) and HRDPS (250-m grid spacing). Future development of TEB will include improvement of its representation of vegetation (in canyons) and its modularization (i.e., one scheme for the roads, another for the buildings, all connected through the shell provided by the multi-layer TEB).

Current research and development with urban-GEM is now mostly based on the analysis of cases from the Pan American Games in Toronto (2015). As part of this project, comfort indices such as the Universal Thermal Climate Index (UTCI) and the Wet Bulb Globe Temperature (WBGT) have been coded in TEB and evaluated against the Pan Am 2015 dataset.

An important objective at ECCC is to implement urban-GEM, with 250-m grid spacing and with TEB, in an experimental mode over the 3 largest urban centers of the country, i.e., Toronto, Vancouver, and Montreal. This will be in fact considered as the next generation of HRDPS, the experimental counterpart to the operational short-range prediction system, RDPS. In preparation for that, urban-GEM 250-m will be tested over several cities, in Canada and abroad. Simulations over Tokyo were already shown to successfully represent the impact of the urban environment on the intensity of precipitation. Other cases, as part of WMO's Aviation RDP (AvRDP) are expected to be used for the evaluation and calibration of urban-GEM.

3.8.10 High resolution land surface prediction (HRDSPS)

Several new models and approaches are currently being examined to better predict surface or near-surface conditions over land. An external land surface modelling system has been developed and is now integrated at grid sizes much smaller than that of the atmospheric models. This increased resolution allows better exploitation of geophysical information on orography, land use / land cover, and water fractional coverage. Downscaling of atmospheric forcing (precipitation, temperature, humidity, winds) is used to more realistically drive the surface processes. Because of its relatively low computational cost, HRDSPS is able to produce realistic surface simulations at fairly high resolution (e.g., with grid spacing of 100-200 m) and over fairly large regions. As presented in several articles produced at ECCC, this downscaling technique has been shown to be particularly effective in mountainous and urban areas (Vancouver, Rocky Mountains, Montreal, Oklahoma City). It also provides more realistic land surface conditions, mainly related to soil wetness, to hydrological forecasting systems integrated at ECCC.

Forecasts based on the HRDSPS can be improved in three manners: with more realistic atmospheric forcing, more realistic surface modelling, and more realistic surface initial conditions. Current research and development is focusing on all three aspects. More realistic forcing will be provided by using km-scale versions of GEM, with possible improvements to the downscaling approach (for precipitation for instances). More realistic modelling will be obtained with the use of the new SVS scheme (in replacement of the current ISBA), and an improved version of TEB. The possibility of a more intimate coupling between the surface system and the atmospheric model will also be investigated, as well as two-way coupling. Finally, better initial conditions for land surface variables could be obtained by running CaLDAS directly at the sub-km resolution (probably too costly), by using an incremental approach (i.e., analysis increments provided at the km-scale), or by nudging subkm-scale trial fields from HRDSPS with 2.5-km CaLDAS analyses.

As part of the new SVS land surface scheme, a "multi-layer interaction" approach, similar to what has already been coded and tested with TEB will be evaluated. Emphasis will be on detailing the complex interactions between the surface canopy and the atmospheric surface layer, in a one-way and two-way mode. Furthermore, a one-dimensional lake model will also be implemented and tested, as part of both modelling and assimilation applications.

A first implementation of the HRDSPS at MSC-Operations is expected in the next one or two years.

3.9 Extended and long range forecasts

3.9.1 Long range (30 days up to 2 years)

The Global Environmental Multiscale (GEM) - Nucleus for European Modelling of the Ocean (NEMO) global coupled model has been developed for seasonal predictions. The atmospheric component, GEM, has a horizontal resolution of 1.4 x 1.4 and 80 vertical levels, while the ocean component, NEMO, has 1 degree resolution and 50 levels. The forecast is initialized at the beginning of each month and runs for 12 months with 10 ensemble members. A hindcast of 30 years from 1981 to 2010 has been produced, which is used to calibrate the real-time forecast and for verification purpose. This new model will be part of the operational Canadian Seasonal and Interannual Prediction System (CanSIPS).

Seasonal forecasts of new variables

Several new variables will start to be produced operationally, including snow water equivalent, surface solar radiation, cloud fraction, and near-surface specific humidity. These variables, together with near-surface temperature, precipitation and sea surface temperature, will be communicated through new interactive maps for Canada and the globe that provide all three tercile categorical probabilities together with skill information at user specified locations.

Improved sea ice initialisation

Improved initializations for sea ice concentration and sea ice thickness are being developed for the current operational seasonal prediction models CanCM3 and CanCM4. These changes are leading to major improvements in sea ice prediction skill in selective hindcast experiments, and will be demonstrated through contributions to the 2017 Sea Ice Outlook of the Sea Ice Prediction Network. Operational implementation will be considered following completion of a full set of hindcasts.

3.10 Environmental Emergency Response

The statistical validation toolkit TheJudge was improved in 2016 and was used to validate the numerical implementation of the new operational dispersion model MLDPn by comparing MLDPn results with those from previous model MLDP1. An extensive dataset of cases was used, which has permitted to identify and fix some bugs.

MLDPn also include a new capability called 'mixed mode' allowing the model to start as a first order Lagrangian particle dispersion model close to the source (MLDP1 mode) and to automatically switch to an order zero model at some distance from the source (MLDP0 mode). The MLDP1 mode has been implemented and validated with TheJudge toolkit. Nevertheless, the implementation of some schemes must be investigated further in order to better understand how they work.

CMC is participating occasionally in model intercomparison and verification studies using air concentration and ground deposition measurements. Such studies allow to validate dispersion models as well as identify and correct problems within the models. In 2016, CMC participated, in close collaboration with other meteorological organisations in the world, in an intercomparison and verification study of long-range transport modelling of xenon. This study allowed to correct a minor problem within the model associated with the emission source term.

Improvements were also made to the meteorological input of atmospheric dispersion models, such as atmospheric stability parameters. Work is underway to generate improved meteorological fields specially tuned for atmospheric dispersion modelling applications.

Moreover, work is ongoing to develop absolute concentrations products based on realistic emission scenarios of accidental atmospheric releases of burning oil, petroleum products and typical hazardous chemicals involved in industrial processes. The final products, instead of being expressed in atmospheric dilution factors, will be presented in term of Protective Action Criterias (PAC), which will significantly improve risk evaluation for on-site responders. EERS has established a collaboration with toxicology experts at Health Canada to derive new toxicological thresholds for some pollutants. The development of these new thresholds will eventually be incorporated into CMC's modelling suite when Health Canada finishes development.

Regarding dispersion at the urban scale, work is ongoing to add an operational transport and dispersion modelling capability. This objective will be achieved by further developing the Canadian Urban Dispersion Modelling (CUDM) system. In the CUDM system, wind observations or wind numerical forecasts provide inflow boundary conditions for a Computational Fluid Dynamics (CFD) model, called urbanSTREAM, running at the urban scale. In turn, urbanSTREAM provides the high resolution wind and turbulence fields (1-10 m resolution) to drive urbanLS, a Lagrangian Stochastic particle trajectory model. This work includes:

- Implementation of an improved Computational Fluid Dynamics (CFD) urban model, called urbanSTREAM, able to handle all inflow situations;
- Activation of topographic capabilities;
- Optimization, parallelization and validation of the informatics codes;
- Investigating the transition from urban to non-urban models;
- Integration into the operational atmospheric dispersion suite (anticipated in 2017).

Following the development of aquatic and coupled atmosphere-ocean modelling at MSC and ST (GIOPS, RIOPS, etc.), a new field is emerging: aquatic dispersion modelling. Applications are numerous, such as search and rescue drift calculations, contaminant drift, biological productivity (larval drift), ballast water, etc.

A new tool dedicated to the modelling of oil spills will be developed in the coming years. Oil spills are frequent and can adversely affect large populations. This new integrated system, called COSMoS (Canadian Oil Spill Modelling Suite), will include:

- Transport : spreading and advection;
- Transformation: evaporation, emulsion formation, dispersion in water column, beaching, chemical composition, density, viscosity and composition.
- physicochemical properties: density, viscosity and composition.

The transport module will be based on MLDPn core, originally designed for the atmosphere, adapted to aquatic applications. Combining MLDPn with fate & behaviour modelling of oil in aquatic and coastal environments, high-quality forecast of marine and atmospheric environmental data; and a 24/7 emergency response capability with access to high-performance computing facilities will allow COSMoS to become a leading oil spill modelling suite. A prototype is scheduled for 2017 and is expected to become operational in 2018.

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