ANNUAL JOINT WMO TECHNICAL PROGRESS REPORT ON THE GLOBAL DATA PROCESSING AND FORECASTING SYSTEM (GDPFS) AND RESEARCH ACTIVITIES FOR 2014

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CANADA

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1 Generalities

1.1 Highlights for 2014

- **May 2014 – Addition of IASI observations from METOP-B/1 to the operational data of the GDPS and RDPS**

  Although IASI data from METOP-A/2 will continue to be assimilated into our forecast systems, METOP-B/1 is now the operational METOP satellite of the EUMETSAT agency. The two satellites METOP-A/2 and METOP-B/1 have similar trajectories, but offset by a half-orbit, so the addition of METOP-B/1 IASI data will almost double the number of IASI data assimilated. Furthermore, this new data adds robustness to the data assimilation system in the event of a failure of the IASI instrument on-board either METOP-A/2 or METOP-B/1.

  For details see section 2.1and 2.3.

- **November 2014 – Upgrade of the Global Deterministic Prediction System (GDPS)**

  Summary of the major changes included in this upgrade:

  New 4D-EnVAR assimilation technique replaces 4D-VAR and coupling with the Ensemble Kalman filter (EnKF) to obtain background-error covariances.

  Changes to observations:

  - Improved treatment of radiosonde and aircraft observations
  - Assimilation of ground-based GPS data
  - Improved satellite radiance bias correction procedure
  - Additional AIRS/IASI channels assimilated

  Changes to the forecast model:

  - 4D Incremental Analysis Update (4D-IAU) approach.
  - Recycling of several key prognostic variables

  New sea-ice concentration analysis

  For details see section 2.1.

- **November 2014 – Upgrade of the Global Ensemble Prediction System (GEPS)**

  Changes common to both the assimilation and forecast components

  - Increase in the horizontal resolution (50 km instead of 66 km)
  - Reduction of the model time step from 20 minutes to 15 minutes
  - Addition of 3 physical processes for only half of the members: diffusion on theta fields, salinity effect on the saturation specific humidity over the ocean and change in the calculation of the roughness length over the ocean.
  - New sea-ice concentration analysis
  - Relaxation method used before interpolation of the surface fields

  Changes installed uniquely into the data assimilation component ENKF

  - Coupling with 4D-ENVAR to provide to the GDPS and the RDPS a flow-dependent background error covariance
  - Change to the model top (1.45 hPa instead of 1.78 hPa)
  - Bigger ensemble (256 members instead of 192)

- Changes to observation bias correction and RTTOV operator
- Other minor changes: Cubic interpolation of 3D-VAR perturbations to higher resolution grid, 3D-VAR humidity perturbations are no longer forced to zero between 200 and 100 hPa, and we now use GPS-RO observations above 1000 m (instead of above 4000 m)

Changes installed uniquely into the forecast component

- Modification to the sea-surface temperature evolution method
- Modification to the sea-ice cover such that it evolves as a function of SST thresholds
- The SKEB scheme perturbations are reduced

For details see section 2.2.

- **November 2014 – Upgrade of the Regional Deterministic Prediction System (RDPS)**

  Summary of the major changes included in this upgrade:

  New 4D-EnVAR assimilation technique replaces 4D-VAR and coupling with the Ensemble Kalman Filter (EnKF) to obtain background-error covariances.

  Changes to observations:

  - Improved treatment of radiosonde and aircraft observations
  - Assimilation of ground-based GPS data
  - Improved satellite radiance bias correction procedure
  - Additional AIRS/IASI channels assimilated

  New sea-ice concentration analysis

  For details see section 2.3.

- **November 2014 – Upgrade of the operational Regional Marine Prediction System - Gulf of Saint Lawrence(RMPS-GSL) and the associated Regional Deterministic Prediction System - Coupled in the Gulf of Saint Lawrence (RDPS-CGSL)**

  - The frequency of analysis and forecast runs is increased from one run per day (0000 UTC) to four runs per day : 0000, 0006, 1200 and 1800 UTC
  - The operational ocean model will change from Saucier et al model (MoGSL) to the Nucleus for European Modeling of the Ocean (NEMO) Model

  For details see section 2.7.

- **November 2014 – Upgrade of the Regional Deterministic Precipitation Analsyis (RDPA (CaPA))**

  - This version will assimilate an additional source of important information, the quantitative precipitation estimates (QPE) provided by the Canadian weather radar
  - The number of analysis produced daily is increased from 9 to 10

  For details see section 2.7.

1.2 Equipment in use at the centre

1.2.1 Present

- **Supercomputer platform**

  Two clusters each being an IBM P Series 775, 8192 Power7 cores, 32TB of main memory, 450TB of high-performance GPFS parallel disk capacity. Operating system: AIX 7.

- **Front-end platform**

  Two Linux clusters, each with 80 compute nodes (Dell PowerEdge M610, 8 cores, 48GB of memory). They use about 300 TB of disk space (SATA, SAS, SSD, fast I/O) through Infiniband.

  High performance, networked, parallel file system consisting of 8 IBM System x3650 M2 I/O servers, each with 16 processors and 24 GB of memory, plus 14 IBM 7870 blades each with 2 sockets with 8 cores and 36 GB of memory each held in two HS22 blade centres. There is 2.7 PB worth of SAS and SATA disks attached over FC. The data is shared via GPFS/CNFS.

Summary of equipment in use at the Canadian Meteorological Centre		
Computer	**Memory (GB)**	**Disk Space**
IBM P Series 775, 16384 cores	65536	900 TB
2 Quantum 662 Meta Data Controlers	32	1.4 PB
Dell M610 blade, Intel E5530 @ 2.4 Ghz, 1280 cores	7680	300 TB
8 IBM System x3650 M2 I/O servers, 128 cores + 14 7870 blades 224 cores	696	2.7 PB

- **Mass storage system**

  The Meteorological Service of Canada has been using a robotized storage/archive facility for Environment Canada (operated out of CMC Dorval) since 1994 in order to store and secure critical services and departmental data including: Numerical Weather Prediction data (essential to improve forecasts); Climate change scenarios (including IPCC run results), the Climate Archive Database; computer backups, logs and router and firewall logs/data (essential in the investigation of security incidents, performance statistics, etc).

  The system comprises two Quantum 662 Meta Data Controlers, each with 16 cores, 128 GB of internal memory connected to these via fibre channel is 1.4 PB of high-performance disks. The two tape libraries are Quantum Scalar i6000 with 4000 LTO tape slots and 12 LTO-5 drives each. The hierarchical software manager is StorNext. As of December 31 2013, 16 PB of data was stored (primary copy).

1.2.2 Plans for the future (next year)

- **Computer systems**

  The existing high performance, networked, parallel file system, as described above, will have the 8 older servers replaced by additional IBM blades. An additional 12 PB of disk storage will be provided via a GPFS/CNFS cluster of 28 IBM servers.

- **Mass storage system**

  The mass storage system, as described above, will have each of the two libraries upgraded with dual active robotics, 2200 additional LTO slots, and LTO-6 technology.

1.2.3 Plans for the future (next 4 years)

- Replacement of the Power7 supercomputer in 2015-2016
- A complete overhaul of the archiving system is forecasted for 2015-2016

1.3 Data and Products from GTS in use

1.3.1 Data

The following types of observations are presently used at the Centre. The numbers indicate the typical amount of data (reports or pixels) received during a 24-hour period:

SYNOP/SHIP	62,000
TEMP	1,260
PILOT	830
DRIFTER/BUOYS	41,000
AIREP/ADS	16,000
AMV's (GEO & Polar)	1,951,000
SA/METAR	185,000
AMDAR/ACARS	469,000
PIREP	950[1]
PROFILER	144
GEO radiances	2,824,000[2]
ATOVS (AMSU-A)	2,330,000[3]
ATOVS (AMSU-B/MHS)	18,242,000[3]
SSMI/S	8,160,000[4]
AIRS (AQUA)	320,000
IASI (Metop-1/2)	648,000
ASCAT (Metop-1/2)	1,935,000
GPS-RO	2,150[5]

1.3.2 Products

GRIB ECMF

GRIB KWBC

GRIB EGRR

FDCN KWBC

FDUS KWBC

[1] Not assimilated
[2] Clear sky radiances for 5 GEO satellites
[3] Four NOAA satellites are assimilated, plus AMSU on AQUA, and Metop-2; obtained by ftp
[4] Three DMSP satellites (F16, F17, F18); obtained by ftp
[5] Data from COSMIC, GRACE-A, TERRASAR-X and METOP-1/2 GRAS

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
Regional assimilation	R2	00, 06, 12, 18	00,12: T+3:05 (same as G1) 06,18: T+6:00 (same as G2)	Details section 2.3
Regional final analysis	R3	00, 12	T+7:00	Details section 2.3
Global ensemble assimilation	E2	00, 06, 12, 18	00, T+9:00 12: T+8:15 06,18: T+6:00 (same as G2)	Details section 2.2
CanSIPS assimilation	M2	00	T+9:00	Details section 2.9
Regional deterministic precipitation analysis	RDPA	00, 06, 12, 18	T+50min (final T+6:50)	Details section 2.7

Forecast run schedule **(all times in UTC)**					
Description	**Name**	**Time**	**Cut-off**	**Forecast period**	**Remarks**
Global	G1	00, 12	T+3:05	240 hours at 00 360 hours at 00 on Sundays 144 hours at 12	Details section 2.1 All products available at T+5:00.
Regional	R1	00, 12 06,18	T+2:00	48 hours 54 hours	Details section 2.3 All products available at T+3:30.
Local high resolution	WH EH AH, MH	06, 18 12 06	NA	42 hours 24 hours 24 hours	Details section 3.5 (experimental GEM-LAM 2.5 km) (West window “WH” operational)
Global ensemble	E1	00, 12	T+3:05	16 days 32 days on Thursday at 00	Details section 2.2
Regional ensemble	ER	00, 12	NA	72 hours	Details section 2.4
Air quality	GM	00, 12	NA	48 hours	Details section 2.7

WAM fed by the GDPS	WG	00, 12	NA	120 hours	Details section 2.7
WAM fed by the RDPS	WR	00, 12 06, 18	NA	48 hours 54 hours	Details section 2.7
Monthly	M1	00	T+9:00	One month	Details section 2.8 Produced at the beginning and middle of every month.
Seasonal	MA	00	T+9:00	3 month periods covering 1 year	Details section 2.9 Produced at the beginning of every month.
Nowcast	INCS	Every hours	T+17min	6 hours forecasts	Details section 2.6
Gulf of St-Lawrence	GF	00	NA	48 hours	Details section 2.7

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. The table below is a summary of the CMC verification scores for 2014. The data in the table is based on standards established in 1998. A new set of standards has been adopted and these are being implemented by the participating NWP Centres. CMC expects to adopt the new standards in the near future.

Verification summary - 2014
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	7.3	7.4	21.9	21.8	44.1	43.9
	RMSVE (m/s), Wind, 250 hPa	3.6	3.6	7.9	7.8	12.8	12.8
Tropics	RMSVE (m/s), Wind, 850 hPa	2.4	2.4	3.7	3.6	4.6	4.5
	RMSVE (m/s), Wind, 250 hPa	4.0	4.0	6.5	6.5	8.1	8.1
S. Hemisphere	RMSE (m), GZ 500 hPa	9.5	9.4	27.9	27.6	55.2	55.3
	RMSVE (m/s), Wind, 250 hPa	3.8	3.8	8.5	8.5	14.0	14.0

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	8.8	9.5	21.9	21.6	42.4	42.5
	RMSVE (m/s), Wind, 250 hPa	5.8	5.7	10.0	9.8	15.2	15.0
Europe	RMSE (m), GZ 500 hPa	10.7	10.5	23.2	22.7	45.9	44.3
	RMSVE (m/s), Wind, 250 hPa	5.3	5.0	9.8	9.5	15.6	15.2
Asia	RMSE (m), GZ 500 hPa	12.5	12.4	22.2	21.5	38.6	37.6
	RMSVE (m/s), Wind, 250 hPa	5.7	5.7	9.0	8.9	12.8	12.8
Australia - N.Z.	RMSE (m), GZ 500 hPa	10.0	12.9	17.2	20.7	31.2	37.9
	RMSVE (m/s), Wind, 250 hPa	5.5	5.7	8.5	8.5	12.4	12.3
Tropics	RMSVE (m/s), Wind, 850 hPa	4.0	4.0	4.9	4.7	5.6	5.4
	RMSVE (m/s), Wind, 250 hPa	5.7	5.7	7.4	7.4	8.6	8.8
N. Hemisphere	RMSE (m), GZ 500 hPa	11.9	11.8	23.9	23.3	45.1	44.4
	RMSVE (m/s), Wind, 250 hPa	5.4	5.4	9.3	9.2	14.2	14.1
S. Hemisphere	RMSE (m), GZ 500 hPa	11.5	12.9	21.1	23.4	37.3	42.7
	RMSVE (m/s), Wind, 250 hPa	5.8	5.9	8.9	9.2	13.1	13.4

2 Operational Forecasting System

2.1 Global Deterministic Prediction System (GDPS)

2.1.1 Data assimilation and objective analysis

GDPS – Assimilation – Version 4.0.0	
Assimilation approach	4DEnVar, no outer loop (70 inner-loop iterations), increments computed every hour. Data assimilated at 18 minutes intervals in a 6 hour assimilation window. See Buehner et al. (2013a and 2014).
Variables	T, Ps, U, V and log q (specific humidity)
Domain	Global
Levels	80 hybrid levels of the GEM 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), AMSU-B (4), MHS (4) , SSMIS (7), geostationary imagers (1), AIRS (142), IASI (142)
Other satellite data	GPS-RO refractivity, AMVs, scatterometer winds, ZTD from GB-GPS over North America
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, 2 times per day, except static for AMSU-A channels 13-14
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
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 UTC, 06 UTC, 12 UTC and 18 UTC.
Processing time	17 minutes 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 Model

GDPS – Model – Version 4.0.0	
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.
Domain	Global.
Numerical technique	Finite differences: Arakawa C grid in the horizontal and Charney-Phillips grid in the vertical (Charney and Phillips, 1953)..

Grid	Uniform 1024 x 800 latitude-longitude horizontal grid. Horizontal resolution is 0.35^o in longitude and 0.225^o in latitude, which is equivalent to 25 km resolution at mid latitudes.
Levels	80 hybrid levels. Model lid at 0.1 hPa.
Time integration	Implicit, semi-Lagrangian (3-D), 2 time-level, 720 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: Derived from analyses at initial time, predictive Derived from climatology at initial time, fixed in time Derived from analyses, fixed in time Derived from a variety of geophysical recent data bases using in house software, fixed in time	 Surface and deep soil temperatures, surface and deep soil moisture ISBA scheme (Noilhan and Planton, 1989; Bélair et al. 2003a and 2003b); snow depth, snow albedo, snow density. Sea ice thickness. Sea surface temperature, ice cover. 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.
Horizontal diffusion	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) 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, 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).

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, since September 2013.
  - Freezing levels, wind chill and instantaneous precipitation types according to the Bourgouin method, since April 2014.

- **SPOOKI**

  A new production system has been developed over the past few years to standardise and unify the production of calculations described above. 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.

  A first version of this system has been implemented in 2013 to produce 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 favors 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 days 3 to 7 inc. for the public forecast and for days 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 1426 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

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 of GEM model. Model lid at 1.45 hPa.
Domain	Global
Grid	0.45^{o} uniform resolution (~50 km)
Frequency	Every 6 hours using data ±3 hours from 00 UTC, 06 UTC, 12 UTC 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	30-35 minutes analysis (with a maximum of 2304 cores) plus 50 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) and GPS-RO

Ensemble perturbations:	
Observations are perturbed in function of their error statistics	
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 'newsun') 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 'newsun' 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 Includes 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	Charnock formulation except Z0T constant in the tropics and Deacu et al. (2012) formulation for half of the members (model key Z0TRDPS300).
Diffusion of the potential temperature (theta)	A diffusion is now applied on the theta fields for half of the members (model key Hzd_lnr_theta) with a coefficient of 0.04 and a degree of 6 (del 6).
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 (model key SALTY_QSAT), while it is not the case for the other half.

2.2.2 Forecast

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: Derived from analyses at initial time, predictive Derived from climatology at initial time, fixed in time Derived from analyses, evolved using persistence of anomaly Derived from analyses, evolved in time linearly in function of SST thresholds Derived from a variety of geophysical recent data bases using in house software, fixed in time	 Surface and deep soil temperatures, surface and deep soil moisture ISBA scheme (Noilhan and Planton, 1989; Bélair et al. 2003a and 2003b); snow depth, snow albedo, snow density. Sea ice thickness. Sea surface temperature (SST) Sea ice cover. 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.
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. 2014.
Ensemble perturbations (see detailed configuration in the Table below):	
Each member is initialized with a different atmospheric initial conditions coming from the global EnKF (see section 2.2.1)	
Also, the perturbations in the model configurations used to produce the trial fields (see Ensemble perturbations in section 2.2.1) 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.

Detailed configurations of the GEPS individual members (member 0 is the control):

No.	Deep Convection	Gravity wave drag	Mixing length	Vertical Diffusion	Orographic blocking	Diffusion Theta	Deacu Z0T	Salty QSAT	SKEB	PTP
0	Kain&Fritsch	Standard	Bougeault	1.0	1.0	0.0	Yes	Yes	No	No
1	Kain&Fritsch	Strong	Blackadar	1.0	0.5	0.04	Yes	No	Yes	Yes
2	OldKuo	Strong	Blackadar	1.0	0.5	0.0	No	No	Yes	Yes
3	Kain&Fritsch	Weak	Bougeault	0.85	1.5	0.04	Yes	Yes	Yes	Yes
4	OldKuo	Weak	Bougeault	0.85	1.5	0.0	No	No	Yes	Yes
5	Kain&Fritsch	Weak	Blackadar	1.0	0.5	0.04	No	No	Yes	Yes
6	OldKuo	Weak	Blackadar	1.0	1.5	0.0	Yes	Yes	Yes	Yes
7	Kain&Fritsch	Weak	Bougeault	1.0	0.5	0.04	No	Yes	Yes	Yes
8	OldKuo	Weak	Bougeault	1.0	1.5	0.0	No	Yes	Yes	Yes
9	Kain&Fritsch	Strong	Bougeault	1.0	1.5	0.04	Yes	Yes	Yes	Yes
10	OldKuo	Strong	Bougeault	1.0	1.5	0.04	No	Yes	Yes	Yes
11	Kain&Fritsch	Strong	Bougeault	0.85	1.5	0.04	No	No	Yes	Yes
12	OldKuo	Strong	Bougeault	0.85	0.5	0.0	No	No	Yes	Yes
13	Kain&Fritsch	Weak	Blackadar	0.85	1.5	0.04	Yes	No	Yes	Yes
14	OldKuo	Weak	Blackadar	0.85	0.5	0.0	Yes	Yes	Yes	Yes
15	Kain&Fritsch	Strong	Blackadar	0.85	1.5	0.0	Yes	Yes	Yes	Yes
16	OldKuo	Strong	Blackadar	0.85	1.5	0.04	No	Yes	Yes	Yes
17	Kain&Fritsch	Strong	Blackadar	1.0	0.5	0.0	No	No	Yes	Yes
18	OldKuo	Strong	Blackadar	1.0	1.5	0.0	No	Yes	Yes	Yes
19	Kain&Fritsch	Strong	Bougeault	0.85	0.5	0.04	No	No	Yes	Yes
20	OldKuo	Weak	Bougeault	0.85	1.5	0.04	No	Yes	Yes	Yes

Reforecast system

A reforecast procedure similar to the one described in Hagedorn (2008) is now operational (see Gagnon et al. 2013b). This procedure consist of doing historical forecasts over the last 18 years 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 reanalyses (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, 72 historical forecasts of 32 days for the period 1995-2012 are produced by CMC operations.

The surface fields are now taken from a 30 year integration of the Surface Prediction System (SPS) forced by the near-surface fields of ERA-interim reanalyses 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).

2.2.3 Statistical techniques and products

- **Perfect Prog**

  The weather element guidances for probability of precipitation and spot time total cloud opacity as described in section 2.1.3 are 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://www.weatheroffice.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://www.weatheroffice.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://www.weatheroffice.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)

The RDPS is a forecasting system based on the limited-area (LAM) version of the Global Environmental Multiscale (GEM) model (Côté et al., 1998a and 1998b) with a 10-km grid spacing covering North America. This LAM model is driven by a global GEM driving model at a horizontal resolution of 33-km. This system represents the main NWP guidance for forecasters of the Meteorological Service of Canada for day one and two.

2.3.1 Data assimilation and objective analysis

RDPS – Assimilation – Version 4.0.0	
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 and the global driving model 6-h before the analysis time *T*. Both forecasts from the latter then serves as background for the analysis step at time *T*. In parallel, the same 4DEnVar (no outer loop with 70 inner-loop iterations) procedure is applied to produce both the LAM and the global driver analyses. See Buehner et al. (2013a and 2014). This procedure allows the observations outside the LAM analysis domain to influence the LAM forecasts through the LBCs.
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 of the GEM model
Analysis increment horizontal grid	0.45° x 0.45° Gaussian grid
Trial fields	9-hour forecast 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), AMSU-B (4), MHS (4) , SSMIS (7), geostationary imagers (1), AIRS (142), IASI (142)
Other satellite data	GPS-RO refractivity, AMVs, scatterometer winds, ZTD from GB-GPS over North America
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, 2 times per day, except static for AMSU-A channels 13-14
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
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 Model

RDPS – Models - Version 4.0.0	
Driver model	
The driving model of the RDPS is exactly the same as the GDPS model described in section 2.1 except for the fact that its grid is rotated to be aligned with the LAM model grid and its resolution is 33 km.	
LAMModel	
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 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 as per section 2.1.2 at 33 km resolution. This global model grid is rotated to be aligned with the LAM grid.
Levels	80 hybrid levels. 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:	
Derived from analyses at initial time, predictive	Surface and deep soil temperatures, surface and deep soil moisture ISBA scheme (Noilhan and Planton, 1989; Bélair et al. 2003a and 2003b); snow depth, snow albedo, snow density.
Derived from climatology at initial time, fixed in time	Sea ice thickness.
Derived from analyses, fixed in time	Sea surface temperature, ice cover.
Derived from a variety of geophysical recent data bases using in house software, 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.
Horizontal diffusion	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 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, 2014).

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.

- **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.

- **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.

- **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, and UMOS guidance is used instead of Perfect Prog. Scribe matrices are produced four times a day (00, 06, 12 and 18 UTC).

Supplementary weather element matrices are also used. The content of these matrices include mean sea level pressure, surface pressure, lifted index, highest freezing level, mean wind direction and speed over the four lowest levels of the driving model, boundary layer height and ventilation coefficients at time of minimum and maximum temperatures, instantaneous and accumulated downward infra-red and visible radiation fluxes, model temperature and dew-point at 925 and 850 hPa, wind speed and direction at 925 and 850 hPa, model boundary layer height. The time resolution of these matrices is 3 hours, with projection times out to 48 hours.

2.4 Regional Ensemble Prediction System (REPS)

On December 2013 the operational REPS version 1.0.0 was changed to REPS version 2.0.1. The system continues to have 20 members that are perturbed and one control member that is not perturbed. The perturbations are from the initial conditions and the lateral boundary conditions as well as the stochastic perturbation of physics tendencies or PTP (Physics Tendency Perturbation) as explained in the following sections.

The main improvements of the REPS 2.0.1 are: a decrease in the horizontal grid spacing (from 33 km to 15 km), an increase in the number of vertical levels (from 28 to 48), the use of a hysteretic effect in the boundary layer scheme, and a new design in the application of the PTP in areas of convectively unstable air masses and topographically enhanced vertical velocities. For more details about the current operational model refer to section 2.4.2.

2.4.1 Data assimilation and objective analysis

The system takes the initial conditions of the global EnKF (as explained in section 2.2.1) prepared for the GEPS (see section 2.2.2). 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 the REPS is at 10 hPa.

2.4.2 Model

REPS – Model – Version 2.0.1	
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), as explained in section 2.2.2.
Levels	48 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: Derived from analyses at initial time, predictive Derived from climatology at initial time, fixed in time Derived from analyses, fixed in time Derived from a variety of geophysical recent data bases using in house software, fixed in time	 Surface and deep soil temperatures, surface and deep soil moisture ISBA scheme (Noilhan and Planton, 1989; Bélair et al. 2003a and 2003b); snow depth, snow albedo, snow density. Sea ice thickness. Sea surface temperature, ice cover. 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.
Horizontal diffusion	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 ZOT 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 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	2.5, 5, 10, 20, 30, 40, 50, 75, 100, 150, 200 mm
Rain accumulation	2.5, 5, 10, 20, 30, 40, 50, 75, 100 mm
Snow water equivalent	2.5, 5, 10, 20, 30, 40, 50, 75, 100 mm
Freezing rain water equivalent	2.5, 5, 10, 20, 30, 40, 50, 75, 100 mm
Ice pellet water equivalent	2.5, 5, 10, 20, 30, 40, 50, 75, 100 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, 25, 30°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)

None.

2.6 Nowcasting

The SCRIBE Weather Forecast Product Expert System is capable of ingesting in real time 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 used to feed short term forecast models. A statistical model called “PubTools” uses the surface observations to forecast the probabilities of occurrences of weather elements. The observed radar reflectivities and lightning strikes are extrapolated in time with a motion vector calculated from observed radar imageries with the McGill Algorithm for Precipitation Lagrangian Extrapolation (MAPLE, Zawadzki and Germann, 2002 and 2004) system.

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.

2.7 Specialized Systems

- **Surface fields assimilation and analysis**

Fields	Analysis Grid(s)	Method	Trial Field	Frequency	Data Source
Surface air temperature	a)1080x540 gaussian b) regional grid	Optimum interpolation	Model forecast of temperature at hybrid=1.0	a) 6 hours b) 24 hours at 18 UTC	Synop, Metar, SA, Ship, Buoy, Drifter, Metar,
Surface dew point depression	a)1080x540 gaussian b) regional grid	Optimum interpolation	Model forecast of dew point depression at hybrid=1.0	a) 6 hours b) 24 hours at 18 UTC	Synop, Metar, SA, Ship, Buoy, Drifter
Sea surface temperature anomaly	a)1080x504 gaussian b)1800x900 gaussian	Optimum interpolation	Previous analysis	24 hours (at 00z)	Ship, Drifter. BuoyBuoy, AVHRR-GHRSST, A/ATSR , A/ATSR (Brasnett, 1997); Plus AAMSR-E for b) (Brasnett, 2008)
Snow depth	a)1080x540 gaussian b)Variable resolution 15 km grid; c)2.5 km grid over British Columbia	Optimum interpolation	Previous analysis with 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
Deep soil temperature	1080x540 gaussian	Derived from climatology and a running mean of the surface air temperature analysis		6 hours	No direct measurements available
Soil moisture	400 x 200 gaussian	Derived from climatology			No measurements available
Albedo	400 x 200 gaussian	Derived from albedo climatology, vegetation type, the snow depth analysis and the ice cover analysis		6 hours	No direct measurements available

- **Regional Deterministic Precipitation Analysis (RDPA)**

  The Regional Deterministic Precipitation Analysis (RDPA) was upgraded in October 2012, following the operational implementation of a 10 km configuration of the Regional Deterministic Prediction System (RDPS). This analysis system provides 6-hourly and 24-hourly estimates of precipitation accumulation on a 10 km grid covering North America in near real-time (a preliminary analysis is available at T+1h, and a final analysis is available at T+7h). Monthly and seasonal anomaly maps are also generated in experimental mode by MSC.

  This version of the RDPA combines a background field obtained from a short-term forecast of the GEM model in its regional configuration (at 10km) with rain gauge data. Observations are obtained by combining the reports from the synoptic observation network with reports from COOP networks (currently only over the US and over the Province of Quebec).

  Objective evaluation of this new version showed that both the categorical bias and the equitable threat score were slightly improved. The most significant improvements in skill were observed for the 24h analysis over the United States during summer. A slight degradation of the precipitation mass is however observed for the 6h-analysis in summer, due to more intense precipitation events being predicted by the 10 km RDPS.

- **Air quality**

  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 and 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). Since October, 2012, the version of GEM-MACH used in the RAQDPS has been upgraded to the GEM 3.3.8 and PHY 5.0.4.2 libraries, and the grid-spacing in the horizontal was reduced from 15 to 10 km. In addition, the number of levels in the upper part of the domain (between 0.1 and 100 hPa) was increased from 12 to 24, bringing the total number of levels from 58 to 80. This latter change was done to increase the numerical stability of the model. The model code was updated in February, 2013 to correct two bugs and 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 3.3.8.2-isba and PHY 5.0.4.4.

The SMOKE emissions processing system is used to produce hourly anthropogenic input emission files on the GEM-MACH 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. Climatological chemical profiles are applied at the lateral boundaries.

Model Output Statistics (MOS)	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.
Automated computer worded forecast: Scribe	The SCRIBE system (see section 4.3.4.1) 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.
Weather element matrices	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.

The operational output from the RAQDPS consists of hourly concentrations of surface tropospheric ozone, $PM_{2.5}$, PM_{10}, 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). Post-processing is performed on this output to provide users with maximum and mean forecasts of ozone, $PM_{2.5}$ and PM_{10} in the boundary layer per 6-hour forecast period. These products are available on the web at:

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

In 2012, the national Air Quality Health Index (AQHI) forecast program was expanded from 63 communities to 74 distributed across Canada. Since then, a few communities have been added and the total number stands at 85 in 2015. This program, which first began as a pilot project in 2007, provides a means to communicate to the public the level of risk associated with exposure to a mixture of O3, PM2.5, and NO2 pollution. Raw 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:

http://www.ec.gc.ca/cas-aqhi/default.asp?lang=En&n=450C1129-1

General information on the AQHI is available at:

http://www.ec.gc.ca/cas-aqhi

Regional Deterministic Air Quality Analysis (RDAQA)

Regional objective analysis for the surface pollutants, ozone and $PM_{2.5}$, 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 and ~700 for PM2.5) 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 NO_2, NO, SO_2, PM_{10} and AQHI. However, the analyses are not used to initialize the air quality forecast model and so the RDAQA is thus off-line.

- **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.

- **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 three Lagrangian stochastic particle models named MLDP0, MLCD, MLDP1, 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 Modeling 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 modeling 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) or Regional Deterministic Prediction System (RDPS) forecasts and analyses, or, in the case of MLCD, also directly from surface observations. Please refer to the above sections 2.1 and 2.3 for more information on these NWP products.

All EER models can be launched easily with a flexible Graphical User Interface (GUI) called SPI. SPI has been under development for many years at CMC and allows duty officers to respond efficiently to requests for modeling support during emergencies.

- **MLDP0 (Modèle Lagrangien de Dispersion de Particules d'ordre 0)**

  MLDP0 is a Lagrangian Particle Dispersion Model described in D'Amours and Malo, 2004, and D'Amours et al. 2010. 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 wind, then 3-D displacements due to unresolved turbulent motions. Dry deposition is modelled using a deposition velocity parameter. Wet deposition will occur when a particle is presumed to be in a cloud. The tracer wet removal rate is proportional to the local cloud fraction.

  The source is controlled through a sophisticated emission scenario module which is a function of the release rate of each radionuclide over time. For volcanic eruptions, a particle size distribution is used to model the gravitational settling effects in the trajectory calculations according to Stokes's law. The total released mass can be estimated from an empirical formula derived by Sparks et al., 1997, which is a function of particle density, plume height and effective emission duration. In MLDP0, 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.

  MLDP0 can be executed in forecast mode up to day 10, using the operational GDPS products, and up to 48 hours using the operational RDPS products. MLDP0 can also be executed in hindcast mode, using the analyzed fields from either the global or regional modelling systems. MLDP0 can be executed in adjoint-backward mode. The model has been used extensively in this configuration as part of the WMO-CTBTO[6] cooperation.

- **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 MLDP0, 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 because the trajectories of the particles are calculated from the velocity increments, while MLDP0 is a zeroth order Lagrangian particle dispersion Model since the trajectories of the parcels are updated from the displacement increments.

  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 (Flesch et al., 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.

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

- **MLDP1 (Modèle Lagrangien de Dispersion de Particules d'ordre 1)**

  A full 3-D first order Lagrangian particle model called MLDP1 has been implemented for short range dispersion problems on horizontal domains of 100-200 km, with a time horizon of about 12 hours. This stochastic dispersion model is well described in Flesch et al. 2004. The fluctuating components of the turbulent wind are obtained by partitioning the TKE that has been calculated by the driving NWP model. MLDP1 is parallelized to run on several nodes on the supercomputer at CMC.

- **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 Runge-Kutta scheme.

  The model estimates the trajectories of the parcels, originating from or arriving at the same geographic location, for different levels in the vertical. 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.

- **Products**

  National mandates

  CMC's Environmental Emergency Response Section 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 Canada (EC). 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 a system to automatically produce simulations, called AutoSim, for long-lasting events such as forest fires, ongoing volcanic eruptions (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 modeling in forward or backward mode for planning, for dose calculations to assess the impact on the population using ARGOS (Accident Reporting and Guidance Operational System) and for source term estimation.

  International mandates

  Upon receiving a request for a nuclear or radiological support from a World Meteorological Orgnisation (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/m3
  - Total deposition (wet and dry) in Bq/m2 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 modeling 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 modeling 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.

- **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 operationally at the Canadian Meteorological Centre (CMC) since June 9, 2011. 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). This system will be proposed to operations at CMC in 2014.

- **Wave forecasting**

  The regional deterministic wave prediction system (RDWPS) is based on the dynamical wave model WAM (WAve Model - version 4.5.1). 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 UTC, 06 UTC, 12 UTC, and 18 UTC). Four runs are forced by forecast winds from the Regional Deterministic Prediction System. The other two runs are for long-range forecasts (120h) and are based on forecast winds from the Global Deterministic Prediction System. 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.

- **Storm Surge forecasting**

  The Atlantic Storm Prediction Centre (ASPC) located in Halifax produces 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.

2.8 Extended range forecasts (10 days to 30 days)

2.8.1 System

The monthly and seasonal forecast system has been upgraded in December 1st 2011. The current system is based on 10-member ensembles of predictions made with two coupled atmosphere-ocean-land physical climate models (for a total of 20 members), and produces predictions up to a year. For more information about this new system see section 2.9.1. For the monthly predictions, surface air temperature forecasts are issued at the beginning of the months and at mid-months.

The surface air temperature forecasts are made in doing first an average of the daily temperature as predicted by each of the two model ensembles. The climatology of these model ensembles is then subtracted from the mean forecast monthly temperatures to derive their respective forecast anomalies. These anomalies are then normalized and combined using an arithmetic average for a deterministic forecast. The surface air temperature forecast anomalies are the anomalies of the mean daily temperature measured at the Stevenson screen height (2 metres). Finally the anomalies are divided in three categories (above, near and below the normal). Probabilistic and deterministic charts are produced, showing above normal, below normal and near normal temperature categories. The probabilistic forecasts are produced by counting members in each of the three possible forecast categories: below normal, near normal and above normal, and calibrating this probability to take in account what has been observed in the past.

2.8.2 Products

Deterministic forecast of monthly temperature anomaly is available on the Internet:

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

2.9 Long range forecasts (30 days up to 2 years)

2.9.1 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 Products

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

http://weatheroffice.ec.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.

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 and objective analysis

- **Radiances bias correction**

  Modification of the satellite radiance bias correction approach so that a separate 3D-Var analysis that assimilates all observations except for radiances as the reference for bias estimation instead of the background state

- **GPS-RO**

  The assimilation of GPS radio-occultation (GPS-RO) observations from COSMIC (constellation of 6 satellites), the GRAS receiver onboard METOP-A, and GRACE was implemented operationally in 2009. These data are assimilated as refractivity profiles, and have shown significant impact at all levels, in both summer and winter (Aparicio and Deblonde, 2008; Aparicio et al. 2009). GPS-RO data are assimilated as an absolutely calibrated source, i.e. without bias correction. It has been found that this requires a demanding level of accuracy to ensure compatibility with other observations, particularly radiosondes (Aparicio et al, 2009; Aparicio and Laroche, 2011).

  The volume of COSMIC data has slowly but persistently decreased as the constellation ages. Beginning in October 2010, additional GPS-RO data were received, from satellites TERRASAR-X, SAC-C and C/NOFS, which were added to monitoring. TERRASAR-X and SAC-C were found ready for assimilation, and their data were included in the assimilation in Aug 2011. They compensate for the reduction of COSMIC data due to ageing. C/NOFS contains only tropical data and the profiles do not reach the lower troposphere. C/NOFS radio occultation data was otherwise found to be comparable to existing tropical data from other missions. Due to the different distribution, it was decided that further research is required to properly benefit from this source. SAC-C, however, presented problems shortly after being approved for assimilation, and data delivery ceased. COSMIC has improved its performance by data volume over 2012 and 2013, reverting the decline by strongly optimizing the onboard power use, despite ageing of batteries. Decline then continued with ageing, with several COSMIC satellites going offline. Data ceased as well from GRACE-A. To compensate partially, operators switched on two previously offline instruments, on GRACE-B and TANDEM-X. The net result is still a data decline. GRACE-B and TANDEM-X show an adequate statistical behaviour and are considered ready for assimilation. As Oct 2014, acceptance in the operational system is pending formal approval.

  METOP-B, second in the METOP series was launched in 2012. Refractivity data was commissioned after several months. After several weeks of monitoring, the data was found to present certain moderate statistical differences with respect to METOP-A. This was partially expected due to a different (firmware) parameterization of the instrument. It has better performance picking rising occultations early. The statistical differences did not include bias, and only affect the pattern of O-B standard deviation. Since assimilation is performed with dynamically generated a-priori error estimation, this is within the ability of the assimilation system to handle GPS-RO data. Therefore, after monitoring to verify its statistical behaviour, METOP-B refractivity data were added to the assimilation pool.

  The foreseen list of sources will be set to: all available COSMIC, METOP A and B, GRACE A and B, TERRASAR-X, and TANDEM-X.

GPS-RO Source	Received	Approved for assimilation
COSMIC-I	Yes	Yes
METOP-A (aka METOP-2)	Yes	Yes
GRACE-A	No (Oct 2014)	Yes

TERRASAR-X	Yes	Yes
SAC-C	No	Yes
C/NOFS	No	No
TANDEM-X	Yes	No
METOP-B (aka METOP-1)	Yes	Yes
GRACE-B	Yes	No

- **GPS (radio occultation reflections)**

  A project on the analysis of sea surface reflections observed during GPS radio occultation is continuing. The objective is to extract geophysical information relevant to the low troposphere, with potential applications to meteorological data assimilation. An algorithm for the extraction of supplementary information on the refractivity in the lower troposphere was proposed (Boniface et al, 2011), and implemented through an extended bending angle operator. Quantification of the benefit obtained from this information (signals have suffered refraction and reflection), above that obtained from standard processing (signals have only refracted) is underway.

- **Assimilation of radiance data**

  Radiance assimilation was revised in the context of the upcoming EnVar system. Following extensive (2-month) assimilation tests, the number of hyperspectral infrared channels will double with the implementation of EnVar. The number of AIRS channels will increase from 85 to ~140 while that of IASI channels will increase from 62 to ~140 as well. It is also possible to increase the density of AMSU-A data if tests reducing the thinning (currently 150 km for all radiances) are conclusive. The same bias predictors will be used for all radiances. The observation error will be defined by a factor times the std of (O-P). Preliminary tests were made for the assimilation of Cris and ATMS from Suomi satellite. Radiances from IASI from METOP-B are now assimilated (62 channels, same as METOP-A). Research is also conducted to test the impact of considering observation error correlation (temporal and interchannel) in the context of the ensemble system. For the deterministic system, the Desroziers (2001 and 2005) diagnostics were used to define the interchannel correlations for all radiances. The effect was shown to be positive, with implementation planned after that of EnVar (Heilliette et al., 2014). Research has also started aiming at assimilating surface sensitive infrared channels over land. Initial results are encouraging (Dutta et al., 2014). Research on cloudy infrared radiance data will be pursued within EnVar.

- **Observing System Simulation Experiments (OSSE)**

  An OSSE capability was developed at Environment Canada to support future missions. The Nature Run (NR) available from ECMWF for the period 2005-2006 was used as “truth” atmosphere. That original NR (40 km) was interpolated to EC operational 35 km model grid. All data assimilated operationally in 2008-2009 were simulated (date shifted by three years w.r.t. NR). The OSSE was used to support missions such as PREMIER (Rochon et al., 2012) and PCW (Garand et al., 2013, see Section 6 on PCW). EC also contributed to OSSE science via simulation of all-sky infrared radiances (Heilliette et al., 2013). That study also allowed evaluation of the expected level of cloud contamination present in the operational assimilation system, and how it reduces as a function of the peak of the channel response function.

- **Conventional observations**

  Important upgrades to the pre-processing and screening of aircarft reports and radiosonde data have been undertaken. The 4D position of radiosonde balloons, available in BUFR code, is now supported in the data assimilation systems. For all radiosonde bulletins in alphanumeric codes (as for most radiosonde data currently received at CMC), the missing information about the balloon position is now retrieved by using a mean elapsed ascending time profile (Laroche and Sarrazin, 2013). Observations on significant levels are used, but thinned to retain one observation of temperature, wind and humidity per model layer. Aircraft data are also thinned the same way. A temperature bias correction scheme is now part of the data processing for aircraft reports. Observation error statistics for both radiosonde data and aircraft reports have been revised. A verification package (against radiosonde data) that takes into account the balloon drift has been developed. Summer and winter trials with these upgrades have been carried out with the global En-Var system. Verification scores show significant improvements in short-term forecast ranges, particularly in the stratosphere.

- **Microwave and infrared vertical sounders surface channels radiance assimilation**

  New surface emissivity databases are now available with RTTOV-10 in the microwave and infrared domain as well as revised emissivity modeling over ocean for microwave radiances. In the infrared region of the spectrum, the work on the assimilation of surface sensitive channels over land has been initiated with the arrival of a postdoc in May 2013. The selection of channels for CrIS is done, and formats were tested with simulated data. NPOES ATMS (microwave) will also be assimilated operationally. Work on error correlation associated with AMSU data was carried out in the context of ENKF. The resource associated with this work is leaving, but the project will be pursued.

- **Cloudy infrared radiance**

  A methodology to assimilate cloudy infrared radiances was demonstrated in a 1D-var context and is well adapted to hyperspectral sensors such as AIRS and IASI (Heilliette and Garand, 2007). This methodology was implemented in the 4D-var assimilation system, with cloud parameters estimated within the global minimization problem. That work will be pursued in the context of EnVar.

- **Bias correction schemes for radiosonde and aircraft data**

  Recent results from 4DEnVar cycles show that humidity and temperature observations from some radiosonde types are significantly biased. In particular, those from Russia are wet biased by 20 to 30%, which have a non-negligible impact on medium-range forecasts over Canada. In 2007, ECMWF implemented a bias correction scheme for both radiosonde temperature and moisture. The scheme assumes that the nighttime observations from the Vaisala RS92 sondes are unbiased. This approach will be examined and possibly extended to include GPS-RO and GB-GPS data into the scheme.

- **AMV and ADM-Aeolus winds**

  According to the fifth analysis of the NWP SAF AMV monitoring website (Cotton 2012), some known AMV biases have been reduced such as the fast bias in the tropics and the low bias in the extratropics. However, many other sources of errors and biases remain such that improving AMV products is still an active area of research. NWP centers, especially the UK Met Office and ECMWF, have recently made significant progresses for the assimilation of AMVs. In particular, they implemented a new approach to specify the observation errors. In this approach, 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. Given these recent advances, we plan to measure the current impact of AMVs on the GDPS, examine the quality of AMVs over land north of 20N which are currently blacklisted, assess the quality of the new AMV products such as the GEO-LEO AMVs, revise our data selection and thinning, and assess the impact of the new observation error specification proposed by the UK Met Office. ADM-Aeolus will be launched in late 2015 and is designed to be a 3 years mission. It is an operational prototype for a space borne Doppler wind profiler for meteorological applications. The impact of these observations on the GDPS will be assessed and then operationally assimilated if the impact on forecasts is positive.

- **PCW mission**

  CSA is proposing, with EC and DND as main partners, the Polar Communications and Weather mission in 2018 time frame. This mission will provide seamless communications (Ka and X band, possibly UHF) and satellite imagery over the entire region 50-90 N from two satellites in HEO (High Elliptical Orbit) orbits. Phase A was completed in 2012, and provides a comprehensive description of the various components of the mission. Orbit related trade-offs were studied (Trishchenko and Garand, 2011, Trishchenko et al, 2011). Another study evaluated the advantage of the PCW satellite system in comparison to existing constellation of low orbiting satellites (Trishchenko and Garand, 2012). The Science Team is now proposing a 16-h orbit characterized by three apogees, which minimizes radiation hazards substantially in comparison to the 12-h orbit Molniya originally proposed. The main meteorological payload is an advanced 20-channel imager similar to those planned for the next generation of GEO satellites (MTG, GOES-R). Phase-A studies to evaluate other potential payloads (referred to as PHEOS) such as a UV-VIS-NIR imager and a hyperpectral infrared sounder were completed. Research activities at EC focus on demonstrating the technical feasibility and merit of the mission for meteorology. In particular an observing system simulation experiment (OSSE) was developed and allowed evaluating the impact on forecasts of polar winds from PCW. Predictability at day 3 is expected to be improved by 3 hours in the Arctic region and 6 hours in the Antarctic region. That work is soon to be published (Garand et al, 2013). CSA is studying means to realize the mission in Public Private Partnership (PPP). The US military could contribute financially. The target for approval by Treasury Board is 2014 budget.

- **Other research activities and changes**
    - Increased vertical resolution of data from radiosondes and aircraft, combined with the 4D balloon position available from radiosonde reports in BUFR code will be incorporated into the operational analyses
    - An improved bias correction scheme for temperature and humidity observations for radiosondes will be developed.
    - Modification to the assimilation of radiosonde humidity observations
    - Revise assimilation of near-surface observations from land stations, ships and buoys. In particular, near-surface winds over land as well as 3-hourly and hourly observations from SYNOP and METAR will be added to the assimilation systems
    - Revise assimilation of AMV data
    - Assimilation of GB-GPS from the NOAA/ESRL (data over North America) and the E-GVAP (data mainly over Europe)
    - Assimilation of ADM-Aeolus winds in 2016
    - The variational assimilation system will be adapted to the Charney-Phillips vertical staggered coordinate
    - The assimilation of ozone sensitive channels from AIRS and IASI is envisioned, coupled with an ozone analysis replacing climatology
    - Assimilation of CrIS and ATMS radiances from NPP. Implement revision of observation error for all radiances. Revise horizontal thinning of radiance data
    - Include inter-channel error correlations for all radiances
    - Develop assimilation of surface sensitive channels over land from infrared and/or microwave radiances
    - Implementation of the Canadian Land Data Assimilation System (CaLDAS)
    - Data from new satellites will be assimilated: NPP will provide data from CrIS and ATMS. Data from AMSR-2 on GCOM-W will be used (SST, Ice) as work will be initiated to assimilate data from ADM-Aeolus once available
    - Implement additional CSR data for GOES E/W and MTSAT-2 from F17 and F18 additional AIRS and IASI channels, and AVHRR polar winds; modify the bias correction predictors in the infrared as originally planned.

3.1.2 Model

- **Dynamical core**
    - Horizontal grid spacing from 25 to 15 km in 2015-16
    - Number of vertical levels from 80 to 120
    - Lowering of first momentum level from 40 to 10 meters
    - Time stepping schemes will be studied (of the type predictor-corrector)

- Options to use tracer mass fixing or inherently conserving transport schemes
- Icosahedral grid with finite volume
- Use of global Yin-Yang grid
- Semi-Lagrangian scheme calculates upstream point using cubic interpolation and a trapezoidal approach
- Exploring exponential integrators to replace implicit time-stepping

- **Physical parameterizations**
  - Recycling physical parameters in the context of more balanced data assimilation cycles and reduced spin-up time scales after model initialization
  - Planetary boundary layer scheme from turbulent kinetic energy (TKE) to turbulent total energy (TTE)
  - Revision of all parameterized moist processes: deep and shallow convection, condensation, PBL clouds
  - A reformulation of the boundary layer parameterization and its connection with the surface
  - Improved treatment of cloud/radiation feedbacks
  - Research is planned to update the radiative transfer scheme through:
  - The use of global maps of band dependent surface emissivity and albedo
  - Improved parameterization of effective radius for ice crystals
  - Vertically varying trace gases climatology
  - Research to improve the grid-scale precipitation scheme; in particular, plan to develop and test a multi-moment microphysics (prognostic precipitation) scheme suitable for mesoscale configurations (10-30 km horizontal grid spacing)

3.2 Global Ensemble Prediction System (GEPS)

3.2.1 Data assimilation and objective analysis

- **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).**
- Horizontal grid from a 600x300 to a 800x400 and eventually a 1200x600 grid
- The model lid will go from 2 to 0.1 hPa
- The Incremental Analysis Update (IAU) algorithm will be used
- Improved bias correction of observations
- Correlated observation errors will be taken into account
- More satellite observations will be used

3.2.2 Model

- Horizontal grid from a 600x300 to a 800x400 and eventually a 1200x600 grid
- The model lid will go from 2 to 0.1 hPa
- The Incremental Analysis Update (IAU) algorithm will be used
- Land surface fields will come from the CaLDAS system (see section 3.1.1)
- Coupling of atmospheric component with ice-ocean forecasting model
- Coupling of the atmospheric component with a wave prediction system
- Stochastic representation of surface model errors
- Study stochastic convection parameterization
- Additional perturbations will be added near the surface. This may include the use of different fields for different members for variables like sea surface temperature, soil moisture and roughness length.
- To enable the migration of the global EPS to the Yin-Yang horizontal grid, we need to investigate the behavior of the parameterization for Stochastic Kinetic Energy Backscatter in the context of this grid.
- In general, improvements to the deterministic system will be adapted to the GEPS
- Forecast extended to 32 days once a week

3.3 Regional Deterministic Prediction System (RDPS)

3.3.1 Data assimilation and objective analysis

- **Ensemble-Variational (En-Var) data assimilation**

  Research continued in 2014 on the replacement of the limited-area 4D-Var data assimilation algorithm for the limited-area analysis and the associated 3D-Var scheme for the synchronous global driver analysis by the ensemble variational (EnVar) scheme experimented in the GDPS. The Global EnKF ensemble members are used to specify the background-error covariances (same as for the GDPS) in the variational data assimilation system.

  It was shown that a global-based EnVar scheme can provide RDPS forecasts slightly improved compared to actual operational approach, particularly during the first 24-h of the forecasts and in summertime convective regime. Further forecast improvements are also made possible from upgrades in the assimilated observational data

  See also section 3.1.1.

- **Data**

  The GDPS and the RDPS 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 RDPS (see section 3.1.1).

3.3.2 Model

Work will be done to fix the grid-aligned precipitation bands problem.

Research will be performed to improve the physics of the continental GEM model at ~10 km grid spacing, as well as on the tuning of the physics necessary when the resolution of a model is increased.

In the longer term, the resolution of the model will be increased to 2.5 km. Essentially, the model which is currently being run in experimental mode will replace the current model at 10 km. See section 3.5.

3.4 Regional Ensemble Prediction System (REPS)

3.4.1 Data assimilation and objective analysis

We are developing a regional EnKF to initialise the REPS forecast.

3.4.2 Model

- In general, improvements to the global systems (deterministic and ensemble) will be adapted to the REPS
- Horizontal grid spacing at 10 km
- Vertical resolution increase
- Study stochastic deep convection parameterization
- Work on improving spread-skill relationship and dispersion for upper-air fields (too much in summer, too little in winter)
- Stochastic perturbations of surface parameters
- Reformulated boundary layer parameterization
- Coupling with ice-ocean model
- Coupling with CALDAS
- Study multi-model approach with NCEP in the NAEFS-LAM framework

3.5 High Resolution Regional Deterministic Prediction System (HRDPS)

CMC runs in an experimental mode a 2.5 km resolution GEM model on a pan-canadian grid. This model is initialised and piloted using the current RDPS fields. Also, the model is coupled with CALDAS (see section 3.7 for CALDAS documentation).

This model configuration will eventually replace the current RDPS model at 10 km.

3.5.1 Data assimilation and objective analysis

None.

3.5.2 Model

The main avenues of development will be:

- Introduce parameterized convection
- Improve cloud optical properties for reduced biases
- Improve very short-range forecasts for better background fields for data assimilation
- Test P3 microphysical scheme
- Position first momentum level at 5m AGL
- Fix grid-aligned precipitation bands
- Improve model stability over steep terrain
- Reformulated boundary layer parameterization
- Coupling with ice-ocean model

3.6 Nowcasting

- Operational Implementation of INCS version 1.5
- Operational Implementation of the High Resolution Lightning Extrapolation System (HRLES) in support to the 2015 Pan Am games
- Integration of the Regional Ensemble Prediction System (REPS) for the short term probability of precipitation
- Increase the grid resolution used to calculate the motion vectors for the radar and lightning extrapolation
- Improve quality of radar data by using a new radar composite image generation system with statistical dynamic mask, an improved cloud mask and the capacity to distinguish between missing data and zero radar reflectivity
- Improvements on the sampling method used to generate the probability of precipitation from model data (RDPS)
- Improve rules based system for probability of precipitation and lightning
- Update and add more stations in the INCS dictionary
- Integration of a diagnostic cloud fraction product derived from the GOES satellites imagery and the RDPS

3.7 Specialized Systems

- **Surface fields assimilation and analysis**

CalDAS

Development of a first version of the Canadian Land Data Assimilation System (CaLDAS) has been completed. The new system 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) is being examined. This data will be assimilated in conjunction with near-surface air temperature and humidity.

Other changes include the use of a new land surface scheme (Soil, Vegetation, and Snow – SVS scheme). This new land surface scheme will be tested for 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 this new scheme is superior to ISBA, for both NWP and hydrological applications.

In the next few years, research for land data assimilation will focus on finalizing the inclusion of space-based remote sensing data (SMOS, SMAP, AIRS, IASI, MODIS, VIIRS), on downscaling approaches (assimilation directly at the target resolution, or incremental approach for sub-km systems), and the use of more sophisticated land surface models (SVS). An hybrid version of CaLDAS will also be tested, i.e., simple variational combined with an Ensemble Kalman Filter.

For snow, a project has been completed to use space-based high-resolution optical information (e.g., from MODIS) to specify snow fractional coverage and microwave information (e.g., AMSR-E or SSM/I) to retrieve snow water equivalent.

Finally, work is also underway to improve the first guess for the assimilation of leaf area index (LAI). The Canadian Terrestrial and Ecosystem Model (CTEM), predicting the evolution of ecosystems including fluxes of water, energy, carbon, and nitrogen, will be used for the evolution of vegetation. Results from CTEM will be provided to a simple LAI assimilation system developed a few years ago at Environment Canada. Current projects have proceeded to couple CaLDAS with upper-air assimilation systems for global and regional analyses. The impact of CaLDAS land surface analyses (for surface temperatures, soil moisture, and snow) is currently being tested for medium-range NWP systems. It will also soon be done for short-range and longer-range systems.

CaLDAS has been recently implemented in the Pan Canadian experimental HRDPS.

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. These new versions of CaLDAS will be more integrated with the deterministic and ensemble assimilation systems.

Sea-ice analysis

A new sea-ice analysis system has been developed, based on the 3D-Var approach to data assimilation. The main system has a domain that includes all ice-covered waters surrounding North America extending up to the North Pole, with a horizontal resolution of ~5 km (Buehner et al. 2013). A persistence forecast from the analysis 6 hours earlier is used as the background state. Retrievals of ice concentration from passive microwave data (SSM/I) and the subjective analyses produced by the Canadian Ice Service that heavily depend on RadarSAT images, are assimilated. This system, which is running in experimental mode at CMC, was recently upgraded by additionally assimilating data from 3 SSM/IS sensors and from the scatterometer instrument ASCAT. A configuration of the system has also been adapted to produce global sea ice analyses for use in the global and regional NWP systems. This global is also currently running in experimental mode is being used in combination with the tests for the next upgrade of all NWP systems.

Research will be conducted to improve the variational data assimilation system for producing analyses of sea ice conditions and for initializing coupled models that include sea ice. The focus of this work is on the use of a sea-ice model to provide the background state within the data assimilation cycle (instead of persistence) and the assimilation of new observation types. The new observation types include AVHRR and VIIRS visible/infra-red data and synthetic aperture radar data from the RadarSat-2 satellite. Observations related to ice thickness (e.g. SMOS) will also be assimilated once a sea ice model is included in the assimilation cycle. Research is also being conducted on approaches to automatically compute the characteristics values (also referred to as “tiepoints”) required by sea-ice retrieval algorithms and simple observation forward operators for assimilating satellite observations.

- **Regional Deterministic Precipitation Analysis (RDPA)**

  The most important input for hydrological prediction and land data assimilation systems is generally precipitation. This led to the development of a Canadian Precipitation Analysis (CaPA).

  Research currently focuses on including other sources of observation in the analysis, including observations of clear sky from GOES imagery, ground radar QPE, and lightning observations. Efforts are also devoted to increasing the number of COOP network stations in the analysis and to correcting bias in solid precipitation measurements.

- **Air quality**

  Regional Air Quality Deterministic Prediction System (RAQDPS)

  The broad direction 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 uses of better initial conditions and, in the case of the limited-area regional configuration, better boundary conditions, are 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 (see Pavlovic et al, (2015) for details). 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 Canada and the Canadian Forest Service. Since 2014, this system, named FireWork, is being run by Environment Canada`s operations in experimental mode and its products are made available to forecasters and external users twice daily. In May 2015, the Regional Deterministic Air Quality Analysis (RDAQA) was connected to the Firework system. RDAQA-FW is now available for two pollutants, PM2.5 and PM10, at surface level. Development of the FireWork prototype will continue and eventually in 2016 a new plume rise-mechanism for wildfire emissions will be tested and probably implemented.

  A GEM4-based version of GEM-MACH, which includes the Charney-Phillips vertical staggered coordinate, has been developed and is being tested and evaluated. Extensive code modifications were made as part of this migration. Further improvements to model process representations, model numerics, and model inputs, including emissions files and meteorological and chemical piloting files, are being implemented in this new model version.

  Short-term avenues of research and development include:

  - Replace meteorological piloting by the RDPS with piloting by the GDPS in order to extend model lead time from 2 days to 3 or more days
  - Introduce a global chemical deterministic prediction system based on the GDPS code for producing ozone analyses and forecasts as well as for improving global UV index forecasts

- In very short term, replace current climatological chemical lateral boundary conditions in RAQDPS with updated seasonal chemical lateral boundary conditions; in the longer term, use a global air quality deterministic prediction system (GAQDPS) to pilot both the RAQDPS meteorological and chemical variables
- 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)
- 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
- Improve some chemistry process representations (e.g., dry deposition, sub-grid-scale tracer transport, size-dependent PM wet removal, two-way feedbacks, J values)
- Improve some model numerics (e.g., mass-conservative advection of tracers; gas-phase and aqueous-phase solvers)
- 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.

Regional Deterministic Air Quality Analysis (RDAQA)

Research and development to improve the existing regional objective analysis system for surface pollutants (e.g., higher resolution, 2.5 km resolution, adaptive bias correction scheme and error statistics) and extend this system to other pollutants (NO_2, NO, SO_2, PM_{10}) continues. Recent experiments, which assessed the impact of assimilating surface ozone analyses on the forecast, show a positive impact of up to 24 hours.

Other avenues of research and development include:

- In the short term, introduce to operations objective analyses of NO_2 and a map of the Air Quality Health Index (AQHI) based on the objective analyses of O_3, NO_2 and $PM_{2.5}$
- Continue with the testing and evaluation of a near-real time, 2.5 km resolution objective analysis of surface pollutants as a demonstration product for the Toronto 2015 Pan Am and ParaPan American Games
- A multi-year objective analysis (non-operational) for ozone (period 2002-2012) and for $PM_{2.5}$ (period 2004-2012) has been produced hourly and is available to the scientific community (Robichaud and Menard, 2014). Application of the multi-year analysis will be used to support epidemiological studies undertaken by Health Canada and some Canadian universities

High-Resolution Air Quality Modeling for the Oil Sands

Ongoing nested GEM-MACH simulations of air pollution at 2.5km resolution for the provinces of Alberta and Saskatchewan have been used to generate maps of acidifying sulphur and nitrogen containing pollutants for an annual simulation. These were compared to maps of critical loads at the same resolution. The critical load of an ecosystem describes its ability to naturally buffer acidifying pollutants, and exceedances of critical loads show regions where deposition is exceeding that capacity, indicating that ecosystem damage may be taking place. The model results, similar to previous EC simulations for the region but now at much higher resolution, suggest that large regions downwind of the oil sands may be in exceedance of critical loads, at 2010 pollutant emission levels. The ongoing run was also used to estimate health risks through the creation of maps of Air Quality Health Index frequency – the latter is a three component human health risk tool developed in partnership with Health Canada and is provided to the Canadian public as part of the operational GEM-MACH forecast. The latter maps were used to show the areas with the largest human health risk impacts of air pollution in the region.

Comparisons with observations taken during the 2013 measurement intensive continued during the year: these have highlighted specific deficiencies in the input emissions and other model processes. The background ammonia concentrations in the observations were much higher than in model simulations, suggesting the presence of a large source of NH_3 in the region that is missing in the inventories, perhaps associated with forest fires and bi-directional fluxes. O_3 predictions over the entire domain are relatively accurate (low biases in O_3), but in the oil sands region O_3 is biased high in the model, indicating missing processes reducing O_3 formation or increasing loss – these are under active investigation. Comparisons between emissions estimates from bottom-up emissions inventories and derived from aircraft-observations. The latter indicate good agreement for some species (e.g. SO_2, when the inventory originates in continuous emissions monitoring), and poor agreement for others (e.g. fugitive dust emissions, where observations indicate emissions 8x higher than inventory levels). The modelling system is also being used to evaluate different methodologies for secondary organic aerosol (SOA) formation and to investigate the potential contribution of semi-volatile compounds towards increasing SOA formation. The model was used to estimate the potential feedbacks between weather and oil-sands generated air pollution: incorporating feedbacks improved model predictions of particulate matter and NO_2 and showed that emissions from the oil sands increased cloud cover downwind.

2015 Pan-American Games High-Resolution Air Quality Modeling

This multi-disciplinary project has field monitoring and meteorological and air quality modelling components. In 2014, version 2 of GEM-MACH was adapted for 2.5km resolution nested simulations for a domain centred over Toronto, along with special forecast products for use during the PanAm and ParaPanAm games. New tools for merging data and observations using objective analysis and other techniques were also developed, in order to improve model predictions of the Air Quality Health Index (AQHI) across the Greater Toronto Area (GTA). This project marks the first use of version 2 of GEM-MACH in a nested high resolution mode, and the first use of data fusion on an experimental operational basis at that resolution. The real-time air quality predictions during the summer of 2015 will be used to direct measurements made by Environment Canada's air quality mobile laboratory (CRUISER). These measurements will focus on characterizing the impact of lake breeze circulation and the urban heat island effect on the dispersion and transformation of air pollution, and will aid in the study of interactions between weather and air quality via aerosol radiative balance and cloud formation feedbacks. Comparisons of current operational air quality forecasts and high-resolution forecasts, evaluated against an expanded network of AQHI measurements during summer 2014 and 2015 over the GTA, will also provide a pilot opportunity to accelerate the rate at which high-resolution air quality forecasting becomes operational for cities across Canada.

Hourly UV index forecasts will also be produced daily as a demonstration product during the Pan-Am Games. This will rely on near-real time forecasts of weather conditions and stratospheric ozone on the GDPS grid and will involve the assimilation of satellite ozone data.

Chemical Data Assimilation

A priority activity over the next several years will be to incorporate the capability for chemical data assimilation into Environment Canada's 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 will focus first on the global analysis solver that will feed analysis increments to either global or regional versions of GEM-MACH. This will take into account features of the global variational chemical data assimilation research system and experience gained from the currently operational regional objective analysis system (RDAQA). The development and the related research will lead to future proposals for 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.

The first phase in the development of the global-regional EnVar assimilation system for chemical data assimilation is the completion, in 2015, of the global configuration in 3D-Var mode (without use of ensembles). This will be followed by completion of the regional configuration in 2016 and, later on, the use of chemical forecast ensembles.

In collaboration with the Belgium Institute for Space Aeronomy, the development a multi-species EnsKF with online error statistics will take place. Currently, Belgium has one of the most advanced stratospheric chemical data assimilation systems. The development of an hybrid assimilation system will be investigated.

The radiative impact of stratospheric ozone on NWP will continue to be investigated.

An investigation on the use of satellite and ground-based observations of aerosol optical depth (AOD) will also be undertaken over the next two 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.

Global GEM-MACH

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

- Merging of stratospheric (LINOZ) and tropospheric chemistry
- Inclusion of the production of SO2 from dimethyl sulfide (DMS)
- Addition of plume rise algorithms specific to wild fire emissions, along with adapted mechanisms for emission injection.
- Post-processing: Aerosol Optical Depth (AOD) calculations from aerosol mass will be added and compared to observations
- Completion of tests of an improved inorganic heterogeneous chemistry solver
- Parameterizations for lightning NOx generation will be added, with transfer to regional air quality prediction system if successful
- Tests of the generation of initial and boundary conditions for GEM-MACH10 will be carried out and evaluated
- Participation in HTAP model-model and model-observation intercomparison studies
- Piloting of a 7-day AQ forecasting system combining GEM-MACH Global and Regional simulations
- Implementation of heterogeneous chemistry in LINOZ
- Implementation of bromine sources and chemistry in the Arctic
- Implementation of bromine sources and chemistry in global atmosphere
- Implementation of a new module for aerosol physicochemical processes
- Coupling of atmospheric mercury cycling in GEM-MACH with ocean mercury cycling in NEMO

High-Resolution (2.5 km) GEM-MACH

Efforts in the coming years will focus on the following improvements to urban and/or oil sands forecasts with the 2.5 km version of GEM-MACH:

- Continuation of work incorporating on-road mobile emissions for cities based on available results from link-based, traffic flow models
- Improvements to emissions from airports, trains, and food cooking and sources
- Urban gas-phase chemistry based on SAPRC-07 toxics mechanism
- New parameterizations for secondary aerosol formation and polycyclic aromatic hydrocarbons (PAHs)
- Initial comparisons of PanAm air-quality observations to simulations
- Ultra-Fine Particle (UFP) predictions implemented, tested and evaluated

- Nesting down to 500-m (or higher) grid spacing, with studies of urban heat island impact on model results at different resolutions for the PanAm domain.
- Expanding code from a 2-bin particle size representation to a 12-bin particle size representation
- Further simulations employing feedbacks in version 2 of GEM-MACH (see Pan Am and Oil Sands sections) at high resolution
- Further improvements to the algorithms for both direct and indirect effects for feedbacks between air pollution and weather
- Studies of chemical transformations downwind of the oil sands at high resolution
- Addition of mercury to the model for high resolution modelling for the oil sands
- Investigations on the causes of O3 positive biases in model simulations
- Incorporation of aircraft-observation-based emissions into model inventories and evaluation of impacts on model forecasts
- Completion of evaluation of the nested Oil Sands version of the model, and submission of papers on the model results

Feedbacks between Air Quality and Weather

2014 saw the completion of Phase 2 of the Air Quality Model Evaluation International Initiative (AQMEII-2) which investigated the relationships between air quality and weather, with the publication of a special issue of Atmospheric Environment in the summer of 2015 describing the results of the study. Environment Canada led two key papers of the special issue: these papers specifically examined the feedbacks between weather and air pollution by comparing model simulations for GEM-MACH, WRF-CHEM and WRF-CMAQ over North America for 2006 and 2010, and for WRF-CHEM Europe for 2010. The work provides the first quantitative evidence that incorporating air pollution feedbacks into weather forecast models could improve weather forecasts, with improvements in surface temperature and precipitation across different models and domains. The findings also showed that large sources of air pollution, such as large cities and major forest fires, can significantly change weather, decreasing surface temperature and PBL heights, and changing the shortwave radiation budget, with the large forest fires in Russia in 2010 forming a case study. Feedbacks were also shown to be capable of significantly modifying air pollution concentrations and processes, changing the predictions of particulate matter and ozone.

Directions for future research were also identified. While the effects due to feedbacks were statistically significant, differences in the level and direction of model response to feedbacks were seen, and the differences between the results from different models were larger than the differences within a model due to feedbacks, indicating that the details of process implementation are crucial. Short term process studies were recommended to further elucidate these differences between model results. Several papers identified the importance of global air pollution models to provide boundary conditions for regional models. The papers describe directions to improve future forecasts of ozone, particulate matter and their estimation for policy purposes, and well as directions for improving surface temperature, wind speed, boundary layer height, and radiative balance.

The AQMEII-2 work was featured in the WMO sponsored Coupled Chemistry-Meteorology/Climate Modelling meeting in Geneva in February of 2015, and was used to help formulate recommendations for forecasting provided to the WMO by a subgroup of the meeting attendees.

was modified to include aerosol indirect and direct feedbacks. The model was also modified to operate in 12-bin mode (rather than the operational model's 2 bin setup), and other code modifications and improvements were incorporated to allow the model to be able to participate in AQMEII-2 (improved sea-salt flux treatment, additional diagnostics for deposition and emissions, code modifications to allow for hourly changes to forest fire emissions, etc.). Four simulations were carried out for a North American domain at 15km resolution, for the years 2006 and 2010, with and without feedbacks. These simulations along with simulations carried out by other AQMEII-2 collaborators for North American and European domains were used to study the effects of feedbacks on both weather and air pollution forecasts, and are described in two papers currently under review in Atmospheric Environment. The magnitude of the feedback effects were often found to be smaller than the differences between the different models, but the feedbacks were found to have a sufficiently large impact on model forecast predictions to warrant further investigation. Comparisons between feedback and non-feedback models showed that the feedbacks could improve O3 forecasts, as well as improving forecasts of surface temperatures, surface pressures, and rainfall predictions. Particulate matter prediction quality was however degraded with this generation of feedback models – comparisons between the participating models and an in-depth analysis of GEM-MACH's performance suggested that the models are very sensitive to the details of the indirect effect parameterizations, showing that further work is needed in this area.

The feedback work at Environment Canada is being extended to the new version of GEM-MACH, and has been applied in a high resolution nested version for the Canadian Oil Sands (see above).

- **Ozone and UV index 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. This system is being evaluated using various approaches for the computation of UV-index for clear-sky and all-sky conditions. It will serve as a demonstration product during the Toronto 2015 Pan Am and Parapan American Games. Assimilated ozone measurements will consist only of GOME-2 total column data during this exercise. The addition of SBUV/2 partial column data and OMPS partial and total column data will follow after the Games.

  Within the next couple of years, this assimilation system will be proposed for operational implementation. This implementation will take place following the completion of the EnVar-based chemical data assimilation system discussed above,

- **Environmental Emergency Response**

  Minor corrections and improvements were made to the operational atmospheric dispersion models (MLDP0, MLDP1 and MLCD).

  The different models were merged to produce a unified dispersion model called MLDPn

  A more physically-realistic wet and dry scavenging scheme, which takes into account aerosol size distribution and 3-D precipitation rate, was developed by section member Jian Feng (Feng 2007, 2008, 2009). The improved scheme was added to MLDPn as an alternative to the operational parameterization schemes.

  MLDPn will 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 and to automatically switch to an order zero model at some distance from the source. The new model is also able to run in both forward and backward time modes with a restart option, providing more flexibility for complex operational emergencies. Work is also underway to allow MLDPn to ingest hourly analyses, instead of 6-hourly, to run in hindcast mode and to ingest high-resolution fields from GEM-LAM.

  A statistical validation toolkit was developed to confirm that MLDPn can reproduce results obtained from MLDP0 and MLDP1. This new tool will be used to validate MLDPn before it becomes operational in 2015-2016.

  Work is ongoing to develop a transport and dispersion modelling capability to address the problems of dispersion at the urban scale. This objective will be achieved by further developing the Canadian Urban Dispersion Modelling (CUDM) system. In the CUDM system, high-resolution, urbanized meteorological model are used to drive a Computational Fluid Dynamics (CFD) model, called urbanSTREAM, running at the urban scale. In turn, urbanSTREAM provides the high resolution wind and turbulence fields (5-15 m resolution) to drive urbanLS, a Lagrangian Stochastic particle trajectory model.

  This work includes:

- Development of an improved Computational Fluid Dynamics (CFD) urban model, called urbanSTREAM, able to handle all in-flow situations
- Inclusion of topographic capabilities
- Optimization, parallelization and validation of the informatics codes
- Including a transition from urban to non-urban models
- Integration into the operational atmospheric dispersion suite

- **Global Ice Ocean Prediction System (GIOPS)**

  GIOPS was developed to provide daily ice and ocean global analyses and 10 day forecasts 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 system was provided by Mercator Ocean group and it has been running in real-time at CMC since 2011. There are some differences compared with Mercator's system, ex. the ocean model is coupled with a different sea ice model, the atmospheric forcing and the sea surface temperature data are not identical. GIOPS has two components: analysis component (GIOPS-A) and forecast component (GIOPS-F).

  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 initialise the daily 10-day forecast. This system was implemented in experimental mode in september 2013. Implementation of the forecast component (GIOPS-F) in experimental mode is scheduled for 2014.

- **Regional Ice Prediction System (RIPS)**

  RIPS2.0 was installed in July 2013 as an experimental prediction system. The end product of it has been used by the Canadian Ice Service and NOAA in their routine forecasts although it’s experimental status. An update (RIPS2.1), with improved oceanic forcing and initialization, was recently implemented in experimental mode. The operational status is expected to be in effect once the other systems on which it depends are declared operational and once a thorough quantitative and subjective assessment is done. It has two components: RIPS-A and RIPS-F. The former assimilates observational data and produces an analysis of sea ice which is used by the forecast component (RIPS-F) as initial conditions

  RIPS-A runs an analysis cycle independent of the forecast component. At the moment, it uses the previous analysis as background state for the next cycle. It assimilates daily Canadian ice charts, Radarsat image analysis, remote sensing instruments (SSMI, SSMIS, ASCAT). The analysis is done 4 times a day at 00, 06, 12, and 18Z.

  RIPS-F is based in the sea-ice model CICE4.0, with input from RIPS-A, the global and regional NWP products and the Global Ice Ocean Prediction System (GIOPS), yet to be declared operational. RIPS-F provides a 48-hour forecast four times a day.

  RIPS-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). RIPS-F is run on a subset of the same global ORCA tri-polar grid at 1/12th degrees.

- **Regional Ice Ocean Prediction System (RIOPS)**

  Development, validation and implementation of marine forecasts with lead times to 1-3 days based on the EC regional high resolution coupled multi-component modeling and data assimilation system. RIOPS has two components: the analysis component (RIOPS-A) and the forecast component (RIOPS-F), and is based on coupling RIPS-A and RIPS-F to NEMO on the CREG12 grid described under RIPS-A above. The SAM2 ocean assimilation (described under GIOPS above) will be combined with the RIPS-A ice assimilation as described under RIPS-A above except using cycling with CICE for the background state. Experimental implementation of RIOPS is expected in 2015.

- **Regional coupled atmosphere-ocean-ice forecasting**

  An extension of the Gulf of St. Lawrence coupled system over the Great Lakes is also in development. Preliminary results have shown that coupling of the Regional Deterministic Prediction System atmospheric configuration with a 2km ice-ocean configuration leads to improved surface weather forecasts for most areas around the Great Lakes.

  R&D is being performed on several regional coupled atmosphere-ocean-ice systems:

  - A fully-interactive coupled atmosphere-ocean-ice forecasting system for the Gulf of St. Lawrence (GSL) has been implemented in 2011 at CMC. The oceanic component is the ocean-ice model of the GSL at 5-km resolution developed at the Maurice-Lamontagne Institute. Work has been done to replace that component by an adapted NEMO ocean model version. Investigation is also ongoing to better understand the effect of the coupling on the low level atmosphere.
  - A similar system to the previous one is currently in development over the Great-Lakes using a 2km resolution configuration of NEMO. The NEMO ocean model is currently under evaluation and initial development work on a coupled GEM-NEMO configuration for the Great Lakes has begun.
  - 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.

  The research efforts focus on:

  - Development, validation and implementation of marine forecasts with lead times to 1-3 days based on the EC regional high resolution coupled multi-component modeling (atmosphere, land, snow, ice, ocean, wave) and data assimilation system
  - Development and validation of a sea ice analysis system
  - Development and validation of 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)

  The operational implementation of this system is being made in phases beginning with a stand-alone sea ice prediction system. This will be followed by subsequent additions of coupling to an ocean component and full coupling to the atmosphere.

  The initial stand-alone ice prediction system used for the first phase of the METAREAs system is based on the 3DVAR sea ice analysis system combined with the Los Alamos CICE v4.1 multi-category dynamic/thermodynamic sea ice model. CICE also includes a simple mixed-layer ocean model in order to allow growth/melt during the forecast integration. CICE is initialized with the 3DVAR sea ice concentration analyses, CMC sea surface temperature analyses and a climatological ice thickness field. 48hr forecasts on a 5km grid are then produced by forcing the sea ice model with 10 km atmospheric forecasts from Environment Canada’s Regional Deterministic Prediction System and by monthly climatological ocean currents.

  For a one-year period (2010), daily 48hr 5-km resolution ice forecasts have been validated against Canadian Ice Service (CIS) daily ice charts, sea-ice concentration data derived from RADARSAT measurements and products from the NSIDC Ice Mapping System. Overall, results show a significant improvement of the forecasting skill as compared to persistence of the 3DVAR analysis. This system has been run 4 times/day since August 2012. These forecasts form the basis of a collaborative evaluation between RPN-E Section and CIS operations.

- **Global coupled atmosphere-ocean-ice system**

  Environment Canada (EC), Fisheries and Oceans Canada (DFO), and the Department of National Defence (DND) are preparing an operational global coupled atmosphere-ocean-ice data assimilation and prediction system that can ingest in-situ Argo float data and satellite observations such as sea surface height and temperature.

  In order to initialize coupled atmosphere-ocean-ice forecasts an ocean analysis is required. To this end, the Mercator-Ocean assimilation system has been setup on EC computers. This system has been running in R&D mode since December 2010 producing weekly analyses and 10 day ice-ocean forecasts in real-time using the NEMO modeling system and the Mercator assimilation system. The Mercator data assimilation system is a multi-variate reduced-order extended Kalman filter that assimilates sea level anomaly, sea surface temperature (SST) and in situ temperature and salinity data. Ice fields are initialized using Canadian Meteorological Centre (CMC) daily ice analyses. Research activities have focused on evaluating the SST and sea ice forecasts.

  A 2-way interactive coupling of the GEM and NEMO global models has been completed using a flux-coupling approach exchanging fields via a TCP/IP socket server called GOSSIP. A series of daily 16day forecasts has been produced over the winter 2011 period and is under evaluation.

- **Wave Forecasting**

  Wave modelling research is being conducted primarily under three projects:

  - METAREAS – “Provision of wave forecasts for METAREA XVII/XVIII in support of the Global Maritime Safety and Distress System (GMDSS)”.
  - GRIP – "Retrieval of ice types and floe size distributions over marginal ice zones for improved physical parameterization and development of numerical guidance of waves and ice interactions
  - PanAm Games – A forecast demonstration project for the 2015 Toronto Pan and Parapan American Games.

  The projects’ objectives are:

  - Improvements to the physics of the wave model with the replacement of WAM by WaveWatch3
  - Development and implementation of a Global Deterministic Wave Prediction System for 0-5 day forecasts.
  - 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 being investigated 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.
  - Development and implementation of a Great Lakes Ensemble Wave Prediction System. The combination of 20 members from Canada and 20 members from NCEP into a Great-Lakes super ensemble via NAEFS is under investigation.

  The Global Deterministic Wave Prediction System was developed to run at least twice daily and up to 4 times daily. It is expected to be the first 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 regional grids.

  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 a few months after the global and regional deterministic systems are implemented. Once in operations, EC plans to join NCEP and FNMOC, via NAEFS, into a multi-center wave ensemble of 62 member.

Other wave research currently ongoing include the coupling the wave system with the atmospheric and ice systems.

- **Storm Surge forecasting**

  Storm Surge modelling research is currently conducted to implement nationally an operational Storm Surge model system called the Regional Deterministic Surge Prediction System (RDSPS). The first step will be to implement the 1/30 degree Storm Surge deterministic forecast system based on Dalcoast for the Atlantic coast of Canada along with a 1/12 degree ensemble prediction system. In parallel, a global system, based on NEMO, is being developed.

- **2D Hydrodynamic forecasting system**

  Operational Hydrodynamic Simulation (OPHS) has been successfully transferred to operation as an experimental system in May 2013. The OPHS system produces numerical analyses and simulations of various parameters of interest for the St. Lawrence River and its tributaries. It produces reliable currents and water levels that are used in numerous applications e.g. water quality modelling in emergency responses. It is a brand new system that will be used as a valuable decision-making tool regarding the integrated management of the St-Lawrence. In version 1.0.0 of OPHS, the analyses are produced for the portion of the St. Lawrence between Montréal and Trois-Rivières. These analyses and simulations help us better understand important details of the ecosystem associated with these waterways and can assist those who make use of the St. Lawrence River system. In this version the products that are available include images and ascii datasets. In the future, OPHS will produce an analysis and a forecast of water flow, water temperature, ice movement and other applications. OPHS will also be extended in short term to the entire St. Lawrence River and to other waterways as well.

- **Hydrological and water cycle modeling system**

  A flood event is characterized by an unusual water level occurring on the land surface, generally in proximity of a water body. The FFG-WS only addresses river floods which occur close to a river and which are caused by an excessive amount of runoff upstream. In particular, floods caused by backwater effects, baseflow, ice jams or wind are not considered. The runoff can be a consequence of a combination of intense rainfall and snowmelt effects of soil moisture and water level in the stream prior to the runoff event will be considered. The system will only be applied for now to locations at which water level observations are available in near real-time and for which a valid stage-discharge relationship exists, making it possible to issue flood warnings based on streamflow thresholds instead of water level thresholds. This system relies on inputs provided by current and future operational environmental prediction systems at the Canadian Meteorological Center (CMC), including the High Resolution Deterministic Prediction System (HRDPS), the Canadian Land Data Assimilation System (CaLDAS) and the Canadian Precipitation Analysis (CaPA). It makes use of current observations of precipitation and streamflow, obtained via robust communication mechanisms. A testing and verication procedure will be developed and implemented before the system is proposed for operational implementation at CMC.

  Development of an ensemble hydrological forecasting system is progressing, with efforts being focused in the Great Lakes and St. Lawrence watershed. Both short-term (2-3 days) and long-term (up to one month) forecasting systems are being assessed. It remains difficult to show that higher resolution ensemble forecasts from the Regional Ensemble Prediction System (REPS) provide better forecasts than the Global Ensemble Prediction System (GEPS), partly because the period over which outputs from both the REPS and the GEPS are available is very short. Reforecast experiments, in particular for high impact events, would be required. In all cases, it is expected that statistical post-processing will be required in order to obtain reliable probabilistic forecasts. A Bayesian methodology is currently being tested for updating a climatological prior distribution based on ensemble forecasts of stream flow.

- **Urban modeling**

  Urban areas have a substantial impact on local meteorology and have just been recently 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, additional studies will be performed to further examine the impact of built surfaces on small-scale meteorological events, such as sea/lake breezes, convergence fronts, and the triggering of convective activity. The recently-developed multi-layer version of TEB will be used for these studies, with a possible implementation (in conjunction with the addition of atmospheric levels very close to the soil). 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).

  Research has been done on an “urbanized” version of GEM-LAM at 250-m grid spacing over the Vancouver metropolitan urban area, developed as part of the Urban Meteorology Modeling System. This system is currently being tested over other cities, like Toronto, Canada in preparation for the 2015 Pan American Games and Tokyo, Japan as part of a collaboration with the Japan Meteorological Administration (JMA). It is planned to implement in experimental mode several computational windows covering a few key urban areas of the country (e.g., Toronto, Montreal, Vancouver), shortly after the 2015 Pan American Games which will be used for demonstration.

- **High resolution land surface prediction**

  Forecasts based on the HRDSPS can be improved in three manners: with more realistic atmospheric forcing, more realistic modelling, and more realistic initial conditions. Research and development in the next few years will focus 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 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) or by using an incremental approach (i.e., analysis increments provided at the km-scale).

  The new land surface scheme, SVS, is near completion. This scheme will be thoroughly tested in the next few years for meteorological and hydrological applications. Its development will include the inclusion of a “multi-layer interaction” approach, similar to what has already been coded and tested with TEB. 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.

  A one-dimensional lake model will also be implemented and tested, as part of both modelling and assimilation applications

  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. Adaptation, or downscaling, of atmospheric forcing (precipitation, temperature, humidity, winds) is used to more realistically drive the surface processes. The success of this approach has been demonstrated in mountainous regions (as a prototype was prepared for the 2010 Vancouver Winter Olympic Games). A first implementation of this system at CMC-Operations is expected in the next year.

3.8 Extended range forecasts (10 days to 30 days)

Research will continue to be performed toward a seamless long range forecasting system from day to weeks. In particular, R&D will continue on the sub-seasonal version of the GEPS that will be running experimentally in operation once a week and will cover week 1 to 4.

- **Tropical-extratropical interactions**

  The tropical convective activities associated with the MJO excite Rossby waves that propagate to the extratropical latitudes and influence the Canadian weather. The objective of this study is to identify possible links between extreme weather conditions in Canada and tropical organized convections. For example, heavy precipitation in British Columbia can be related to an intensified low pressure system in the northeast Pacific which can be a result of deepening of the Aleutian low by a tropical forcing associated with the MJO. What is the mechanism and how it is represented in a dynamical model is crucial to improve extended range forecasts of those extreme weather systems.

- **Stratosphere influence**

  Besides the tropics, another important source of skill for extended weather forecasts may come from the stratosphere. An interesting aspect is the downward propagation of the AO (Arctic Oscillation) signal from the stratosphere, which may influence the AO variability and weather conditions on the ground up to two months after. It is planned that an assessment is done for GEM-strato and its impact on weather predictions beyond 10 days. Research on this topic will also continue with CanSIPS.

3.9 Long range forecasts (30 days up to 2 years)

- **Monthly and Seasonal Forecast System**

  Monthly forecast will be based on the extended GEPS (0-32 days) instead of CanSIPS

- **Seasonal to Multi-Seasonal Forecast System**
  - CanSIPS assimilation cycle will ingest the new CMC GDPS ENVar analysis
  - CanSIPS assimilation cycle will use the new CMC sea-ice analysis for nudging
  - CanSIPS assimilation cycle will use a CMC sea-surface temperature analysis modified to be consistent with the new sea-ice analysis for nudging
  - CanSIPS off-line assimilation of global ocean temperatures will use the new CMC GIOPS/SAM2 ocean analysis
  - Methods for land surface data assimilation for CanSIPS, based on CaLDAS land analysis, will be developed
  - Improved methods for initializing sea ice, especially sea ice thickness, will be developed
  - The Canadian Regional Climate Model version 4 (CanRCM4) will be applied to dynamically downscale CanSIPS hindcasts and forecasts in a 25 km resolution North America domain (CORDEX grid). The value added by such downscaling to CanSIPS predictions will be assessed.
  - The number of CanSIPS ensemble members will increase from 20 to 40 (20 for each of the two climate models CanMC3 & CanCM4)
  - CanSIPS will produce forecasts for numerous indices of climate variability
  - CanSIPS will produce forecasts for temperature and precipitation extremes, quantified by calibrated outer quintile probabilities
  - CanSIPS will add new forecast variables including SST, sea ice and snow
  - http://weather.gc.ca/saisons/index_e.html will be significantly upgraded
  - Implementation of a coupled ocean-atmosphere ensemble forecast system for multi-seasonal forecasts based on the GEM-NEMO modeling system. It is planned to add 10 members of this GEM-NEMO configuration to CanSIPS

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