Annual WWW Technical Progress Report

On the Global Data Processing and Forecasting System 2004

Canada

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1 Summary of highlights

On May 18, 2004 the regional model horizontal resolution was increased from 24 to 15 km. Also, the number of levels went from 28 to 58. At the same time, many physics schemes were improved. This is a significant upgrade with respect to the former model and the new model has shown a clear improvement in its meteorological performance.

On September 21, 2004 new observations were incorporated into the global and regional 3DVar data assimilation systems. IR radiance data from the GOES-E satellite were included, in addition to the GOES-W data which were already assimilated. We also incorporated radiance data from the AMSU-A instrument onboard the NASA AQUA satellite. In addition satellite winds (AMV) in the Polar Regions, obtained from the MODIS instrument onboard the NASA AQUA and TERRA satellites were also incorporated. Finally, data from selected USA wind profilers were included in the systems. There were also changes to the data selection processes (for AMSU-A and AMV) and we applied variational quality control to ATOVS data. A final but important change was the implementation of modifications to the data pre-processing in preparation for the upcoming 4DVar global data assimilation system.

On January 12, 2005 a significant change was made in the analysis cycles for the Ensemble Prediction System (EPS). The ensemble Kalman filter (EnKF) technique was introduced in replacement of the antiquated OI, which was in use since the EPS implementation at the Centre. The technique generates 96 trial fields at each analysis time that are used to adapt the model error statistics. More observations have also been added in the EPS analysis. It is the first time that this technique is used in an operational forecasting system.

Several changes were made in the long-range program in 2004. First, the GEM model replaced the SEF in the multi-model runs. Second, the seasonal forecasts (90-day runs) for season 1 are now issued every month and finally, the monthly forecasts (30-day runs) are now produced using the same method as the seasonal forecasts.

A UMOS temperature guidance was introduced in the global prediction system.

Particulate matter parameters ($PM_{2.5}$ and PM_{10}) and other new additional processes were introduced in the CHRONOS air quality forecast model.

2 Equipment in use at the Centre

Summary of operational computer equipment		
Computer	**Memory (Gbytes)**	**Disk (Gbytes)**
1 IBM P Series 690, 960 cpu	2126	8670 (SAN)
2 SGI ORIGIN 3000, 24 cpu	48	11000
1 SGI ORIGIN 300, 8 cpu	8	4500
1 TANDEM Himalaya, S7400, 2 cpu	1	64
17 node Compaq DL380 Linux cluster, 26 cpu	64	2000 (SAN)
13 Compaq DL580 Linux cluster, various configurations	2-16	
45 Compaq DL380, 2 cpu	90	36000
4 Dell Power-Edge 2850, 2 cpu	4	500

3 Data and products from GTS in use

3.1 Data

The following types of observations are presently used at the Centre. For these types, we use all observations that are available from the GTS, on the global scale. The numbers indicate typical amounts received during a 24-hour period:

- SYNOP/SHIP	46,500
- TEMP (500 hPa GZ)	1,185
- TEMP/PILOT (300 hPa UV)	1,250
- DRIFTER/BUOYS	14,500
- AIREP/ADS	4,000
- SATOB (including BUFR)	775,000
- MCSST (US Navy)	900,000
- SA/METAR	175,500
- AMDAR/ACARS	148,000
- PIREP	900[1]
- PROFILER	1200
- GOES radiances	100,000[2]
- ATOVS (AMSU-A)	1,310,000[3]
- ATOVS (AMSU-B)	8,965,000[3]
- SSM/I	1,000,000[4]

[1] Not assimilated
[2] Locally processed GOES imagery, clear sky radiances
[3] Three NOAA satellites now assimilated, AMSUA on AQUA, obtained by ftp
[4] A third of these are used for ice analyses, obtained by ftp

3.2 Products

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

4 Data input system

Fully automated.

5 Quality control system

Various real-time quality control checks are performed for each observation received from the GTS. In particular:

- all reports are checked for gross errors;
- values for main items, such as height, pressure, temperature, dew-point and wind are checked to be inside physical and climatological limits;
- temperature profile check;
- hydrostatic check;
- horizontal check (spatial consistency with neighbours and first guess fields, now done using variational quality control in addition to background check)

These checks are done at, or after the decoding phase of the bulletins. Canadian observations are put on the GTS before such quality control is performed. However, Canadian observations are subject to quality control at the observing site, before transmission to the national centre.

The information generated by the quality control system inside the objective analysis is fed back into the observations database in order for non real-time monitoring and quality control activities to be performed. This monitoring is done on the global scale. Nationally, we also monitor the bursting altitude of upper-air soundings and results are distributed to data producers on a daily basis and monthly reports are distributed.

Each Canadian synoptic report (manned stations only) is also monitored in real time for completeness and timeliness. Requests to individual stations are made if certain criteria are met. Observing stations send corrections if time permits. These corrections are sent to the GTS for transmission. A monthly summary of errors is produced and distributed to data producers.

6 Monitoring of the observing system

Monitoring the availability of observations on the global scale is an inherent portion of operations at the CMC. Information on the current content of the observational databases is available in real time, by observation types and by geographical areas. A chart showing the geographical distribution of observations, by types, used in the analysis for the numerical models is distributed to forecast centres across the country in real-time. A monthly report describing the availability of upper air observations is produced and distributed to data producers.

The information on the availability and quality of observations available for use in the final global analyses is assembled each month into the "CMC Global Data Monitoring Report". The statistics presented in the reports are prepared in accordance to the WMO/CBS approved procedures. The reports are no longer distributed but, with additional information, are available
in pdf format via a data monitoring web site :
(http://www.cmc.ec.gc.ca/~cmcdev/data_monitoring/).

In 1993, CMC was designated by CBS as the lead centre for the monitoring of the quality of land surface observations in WMO RA-IV (North and Central America). In 1994, the CMC began to fulfil its role and since then has regularly produced its 6-monthly reports entitled "Report on the Quality of Land Surface Observations in Region IV". Two such reports were distributed in 2004. Monitoring results are distributed directly to national focal points for most countries within RA-IV.

7 Forecasting system

7.1 System Run Schedule

CMC model and upper-air objective analysis run schedule		
R1 (00,12)	Regional GEM model run Regional objective analysis Regional forecast model (15 km) All products available by	00 or 12 UTC data Cut-off time T+1:35 To 48 h T+3:00
R1 (06, 18)	Regional early objective analysis	06 or 18 UTC data Cut-off time T+1:20
R2 (00, 12)	Regional assimilation system Start-up of spin-up Regional objective analysis Regional forecast model	00 or 12 UTC data (from global cycle) Cut-off time T+6:00 6-h forecast
R2 (06, 18)	Regional assimilation system Regional objective analysis Regional forecast model	06 or 18 UTC data Cut-off time T+5:30 6-h forecast
R3 (00, 12)	Regional final objective analysis	00 or 12 UTC data Cut-off time T+7:00
RW (06,18) West window	Regional high resolution (HIMAP) 10 km	30-h forecast (initial conditions from the 6-h forecast of R1 (00,12))
RE (06,18) East window	Regional high resolution (HIMAP) 10 km	30-h forecast (initial conditions from the 6-h forecast of R1 (00,12))
G1 (00, 12)	Global GEM model run Global objective analysis Global GEM model forecast (100 km) All products available by	00 or 12 UTC data Cut-off time T+ 3:00 To 120 h 12 UTC To 240 h 00 UTC To 360 h 00 UTC - Saturday only T+5:00
G2 (00, 06, 12, 18)	Global assimilation cycle Global objective analysis Global GEM model forecast	00, 06, 12, 18 UTC data Cut-off time: T+6:00 (06, 18), T+9:00 (00, 12) 6-h forecast
E2, E1 (00, 06, 12,18)	Ensemble prediction system runs (16 member multi-model runs ~150 km resolution))	96 continuous data assimilation cycles based on the Ensemble Kalman Filter technique. 16 representative analyses are chosen to launch 10-day forecasts at 150km resolution issued once a day (00 UTC)
C1 (00)	CHRONOS model for air quality prediction	48-h forecast
M1 (00)	Multi-model global runs (250 km / T20)	To 840 h (monthly forecast) for 6 consecutive days before end and middle of month. To 2400 h (seasonal forecast, every month) issued on the first day of each month.

7.2 Medium range forecasting systems (3-10 days)

7.2.1 Data assimilation and objective analysis

7.2.1.1 Upper air

Method	Fully three-dimensional multivariate variational analysis of deviations of observations from 6-hour forecast of a 28-level 0.9° uniform resolution GEM. The incremental approach is used for 3DVar. (Gauthier et al., 1997, Gauthier et al., 1999). A digital filter is used to initialize the forecast model.
Variables	T, Ps, U, V and log (specific humidity).
Levels	28 η levels of GEM model.
Domain	Global
Grid	400 x 200. Spectral analyses at T108.
Frequency	Every 6 hours using data ±3 hours from 00 UTC, 06 UTC, 12 UTC and 18 UTC.
Cut-off time	3 hours for forecast runs. 9 hours for final analyses at 00/12 UTC and 6 hours at 06/18 UTC.
Processing time	12 minutes plus 3 minutes for trial field model integration on the IBM.
Data used	GTS data : TEMP, PILOT, SYNOP/SHIP, SATOB, ATOVS level 1b (AMSU-A; AMSU-B), BUOY/DRIFTER, PROFILER, AIREP/AMDAR/ACARS/ADS, and locally processed GOES data.
Bogus	Subjective bogus, as required.

7.2.1.2 Surface

Fields	Analysis Grid(s)	Method	Trial Field	Frequency	Data Source
Surface air temperature	0.9° x 0.9° global	Optimum interpolation	Model forecast of temperature at eta=1.0	6 hours	Land Synops, SAs, Ships, Buoys, Drifters
Surface dew point depresssion	400 x 200 gaussian	Optimum interpolation	Model forecast of dew point depression at eta=1.0	6 hours	Land Synops, Metars, SAS, ships, buoys, drifters
Sea surface temperature anomaly	400 x 200 gaussian	Optimum interpolation	Previous analysis	24 hours	Ships,buoys, drifters, AVHRR satellite data (Brasnett, 1997)
Snow depth	1080 x 540 gaussian	Optimum interpolation	Previous analysis with estimates of snowfall and snowmelt	6 hours	Land Synops, Metars, Sas (Brasnett, 1999)

Ice cover	1080 x 540 gaussian	Data averaging with a return to climatology in areas where data are not available.	24 hours	SSM/I, Ice Centre Data
Deep soil temperature	400 x 200 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

7.2.2 Model

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 A grid in the vertical (Côté, 1997).
Grid	Uniform 400 x 200 latitude-longitude grid of 0.9 degree (~100 km) horizontal resolution.
Levels	28 hybrid levels (0., 0.011, 0.027, 0.051, 0.075, 0.101, 0.127, 0.155, 0.185, 0.219, 0.258, 0.302, 0.351, 0.405, 0.460, 0.516, 0.574, 0.631, 0.688, 0.744, 0.796, 0.842, 0.884, 0.922, 0.955, 0.980, 0.993, 1.000). Hybrid coordinate, η, is defined as $\eta = p - p_T / p_S - p_T$, where p_T is 10 hPa and p_S is the surface pressure.
Time integration	Implicit, semi-Lagrangian (3-D), 2 time-level, 2700 seconds per time step (Côté et al., 1998a; Côté et al., 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.
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 analyses, fixed in time derived from climatology, fixed in time	 Surface temperature and humidity, force-restore method (Deardorff, 1978). Sea surface temperature, snow depth, albedo, deep soil temperature, ice cover. Soil humidity, surface roughness length (except variable over water), soil volume thermal capacity, soil thermal diffusivity.
Horizontal diffusion	Del-6 on momentum variables only, except del-2 applied on momentum variables at the top (last level) of the model.
Vertical diffusion	Fully implicit scheme based on turbulent kinetic energy (Benoît et al., 1989).
Orography	Extracted from USGS, US Navy, NCAR and GLOBE data bases using in house software.
Gravity wave drag	Parameterized (McFarlane, 1987; McFarlane et al., 1987).
Low level blocking	Parameterized (Lott and Miller, 1997; Zadra et al., 2003).
Radiation	Solar and infrared modulated by clouds (Garand, 1983; Garand and Mailhot, 1990).
Surface fluxes	Momentum, heat and moisture based on similarity theory.
Boundary layer fluxes	Based on turbulent kinetic energy (Benoît et al., 1989; Delage, 1988a; Delage, 1988b).
Shallow convection	Turbulent fluxes in partially saturated air (Girard, personal communication).
Stable precipitation	Sundqvist scheme (Sundqvist et al., 1989).
Convective precipitation	Kuo-type scheme (Kuo, 1974).

7.2.3 Numerical Weather Prediction products

7.2.3.1 Analysis

A series of classic analysis products are available in electronic or chart form (i.e. surface analysis of snow depth and snow cover, sea surface temperature, surface MSLP and fronts, upper-air geopotential, winds and temperature at 1000, 850, 700, 500, 250 hPa, etc.).

7.2.3.2 Forecasts

A series of classic forecast products are available in electronic or chart form (i.e. 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, etc., are produced.

7.2.4 Operational techniques for application of NWP products

Perfect Prog	6- 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 (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-hour and the 12-h probability of precipitation forecasts using a rule based system, which inflates the forecasts. This guidance is also run experimentally out to 240 hours. Spot time total cloud opacity at three-hour intervals between 0 and 144 hour 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). This guidance is also run experimentally out to 240 hours. Spot time surface temperatures at three-hour intervals between 0 and 144 hour projection times (Brunet, 1987). An anomaly reduction scheme is applied on the forecasts so that they converge toward climatology at the longer projection times. This guidance is also run experimentally out to 240 hours. All weather element guidance mentioned above is also produced off each member of the Ensemble Prediction System at all projection times between 0 and 240 hours. Maximum/minimum temperatures forecasts out to day 15 once a week (Brunet and Yacowar, 1982). The predictand is the maximum/minimum temperatures observed over the climatological day (06-06 UTC). Five-, seven- and ten-day temperature anomaly forecasts in three equiprobable categories are generated every day, based on simple linear regression of the temperature anomalies on the thickness anomalies. Fifteen-day temperature anomaly forecasts are generated once a week. (Verret et al., 1998). Stratospheric ozone used to calculate the Canadian UV Index (Burrows et al., 1994).
Model Output Statistics (MOS)	An Updateable MOS system (Wilson and Vallée, 2001 and 2002) has been developed for temperatures. Spot time surface temperatures at three-hour intervals between 0 and 144 hour projection times.
Analog technique	24-h probability of precipitation at the 0.2 mm threshold for the day 3-4-5 ranges (Yacowar, 1975; Soucy 1991). An anomaly reduction scheme is applied on the forecasts. Sky cover forecasts for the daylight part of the day at the day 3-4-5 ranges (Soucy, 1991). Wind forecasts for days 3-4-5 (Yacowar and Soucy, 1990). Day 3-4-5 period based on 00 UTC NWP output and for day 3 based on 12 UTC NWP (Soucy, 1991).
Automated	A system has been developed and installed at all the Regional Weather

computer worded forecasts	Centres in Canada to generate a set of automated plain language forecast products, including public, agricultural, forestry, snow and marine forecasts from a set of weather element matrices for days 1, 2 and 3 (Verret et al., 1993; 1995; 1997). The public forecast type of products can be generated out to day 5. See the following section Weather element matrices. The system, called SCRIBE is in process of being implemented as one of the main tool for public forecast production.
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 approximately 1145 points in Canada and over adjacent waters. The data is valid at the projection times between 0- and 144-hour. 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- and 12-h periods; climatological frequencies of 10 mm or more of precipitation over 12-h periods; statistical spot cloud opacity; statistical forecasts of probability of precipitation over 6- and 12-h periods at the trace and 10 mm thresholds; model precipitation amounts; model cloud height in three categories high, middle and low, Showalter index; vertical motion at 850 hPa; conditional precipitation type; various thicknesses; wind direction and wind speed at surface; model surface dew-point depression; Canadian UV index; model total clouds; 6- and 12-h diagnostic probability of precipitation; model surface temperature, model temperature and dew-point depression near η-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).

7.2.5 Ensemble Prediction System

The 16 member Ensemble Prediction System (EPS) runs once a day up to 10 days (Houtekamer et al., 1996; Pellerin et al., 2003). Since January 12, 2005 the analysis cycles for this system use the ensemble Kalman filter (EnKF) technique. The EnKF uses an ensemble of trial fields to provide four-dimensional flow-dependent statistics of the trial-field error to the assimilation procedure. It approximates the Kalman filter which is the optimal data assimilation method under certain conditions such as linearity of error evolution.

The EnKF technique was developed by the Data Assimilation and Satellite Meteorology Division of the Meteorological Research Branch, in cooperation with the Development Branch of the Canadian Meteorological Center (CMC).

The EnKF of CMC uses two ensembles of 48 members. This configuration is known as a double ensemble Kalman filter (Houtekamer et al., 2005). The EnKF thus uses a total of 96 members. The trial fields are obtained using a configuration of the GEM model with a horizontal resolution of 1.2 degree and with 28 eta levels. The model top is at 10 hPa. These parameters are as in the medium-range forecasting component of the EPS.

In principle, the EnKF can assimilate each observation for which a forward interpolation operator has been made available. The EnKF can thus, at least in principle and after testing, assimilate all data that are currently assimilated in the deterministic variational assimilation system of CMC. With the current system, we do, for instance, directly assimilate the AMSU A and B radiance observations.

With the new EnKF, the 16 initial conditions for the medium-range ensemble forecasts are obtained in the following manner:

i) Once a day, at 00 UTC, sixteen representative members are chosen among the 96 analyses of the EnKF.

ii) The ensemble spread, of the 16-member ensemble of initial conditions, is inflated by a factor 1.5 to arrive at sufficient spread in the medium range.

Two separate models are subsequently used to produce the 10-day forecasts: the SEF model and the GEM model (resolution of 1.2 degree, Cote et al., 1998a and 1998b). Each model uses different configurations of the physical parameterizations.

Ensemble outputs of the following products are available on the web: spaghetti plots of the 500 hPa heights; composite MSLP highs and lows; cumulative precipitation amounts; forecast charts of precipitation amounts probability for various thresholds (http://www.weatheroffice.ec.gc.ca/ensemble/index_e.html).

7.3 Short range forecasting system (0-48 hours)

7.3.1 Data assimilation and objective analysis

7.3.1.1 Upper air

Method	The short-range forecasting system is driven using the analysis produced by the Regional Data Assimilation System (RDAS). This system consists of a 12 hour spin-up period during which 6-hour trial fields are produced by the Regional Global Environmental Multiscale (GEM) model (58 levels). The spin-up is initiated from the 6-hour trial fields of the Global Data Assimilation System. The type of analysis, which is performed three times during the spin-up period, is similar to that of the global analysis (c.f. section 7.2.1). However the computation of innovations for the regional analysis is performed using the high resolution grid of the GEM model. The 3DVar analyses are done in spectral space using the incremental approach. The analysis fields are then supplied to the short-range forecasting model directly on its eta coordinates and variable resolution working grid. (Laroche et al., 1998, Laroche et al., 1999)
Variables	T, Ps, U, V and log (specific humidity).
Levels	28 η levels of GEM global model.
Domain	Global.
Grid	The analysis is done spectrally at T108 using a 400x200 gaussian grid. Results are interpolated on the GEM model's global variable resolution grid: 15 km in the uniform core area with decreasing resolution outside North America.
Frequency and cut-off time	Two 12-hour spin-ups are produced each day (00 UTC to 12 UTC and 12 UTC to 24 UTC). They are initiated from global analyses at 00 UTC or 12 UTC, followed by a regional analysis at 06 UTC or 18 UTC with a cut-off time of 5h30. The final analysis of each spin-up (00 UTC and 12 UTC) has a cut-off of 1h40. Data within +/- 3 hours of analysis time are used.
Processing time	15 minutes for the analysis and 6 minutes for the 6-hour GEM integration on IBM.
Data used	GTS data: TEMP, PILOT, SYNOP/SHIP, SATOB, ATOVS level 1b (AMSU-A), BUOY/DRIFTER, AIREP/AMDAR/ACARS/ADS, PROFILER, and locally derived humidity profiles from GOES (HUMSAT).
Bogus	Subjective bogus, as required.

7.3.1.2 Surface

The medium-range forecasting system for the surface analyses of ice, snow depth and SST are used (see section 7.2.1). The surface temperature and soil moisture are deduced from a sequential assimilation method based on model error feedback to generate analyses of temperatures and moisture in two soil layers (Bouttier et al., 1993). These analyses are produced once a day, with increments added at 00 UTC.

7.3.2 Model

Initialization	Diabatic digital Filter (Fillion et al., 1995).
Formulation	Hydrostatic primitive equations.
Domain	Global.
Numerical technique	Finite differences: variable resolution Arakawa C grid in the horizontal and Arakawa A grid in the vertical (Côté 1997).
Grid	575 x 641 variable resolution on latitude-longitude grid having a uniform .1375 degree (~15 km) window covering North America and adjacent oceans.
Levels	58 hybrid levels: 0.0000, 0.0102, 0.0233, 0.0374, 0.0508, 0.0625, 0.0720, 0.0795, 0.0852, 0.0897, 0.0941, 0.0990, 0.1044, 0.1104, 0.1172, 0.1248, 0.1334, 0.1431, 0.1541, 0.1667, 0.1812, 0.1976, 0.2149, 0.2331, 0.2522, 0.2721, 0.2928, 0.3144, 0.3369, 0.3602, 0.3843, 0.4091, 0.4348, 0.4612, 0.4883, 0.5161, 0.5446, 0.5737, 0.6034, 0.6337, 0.6646, 0.6959, 0.7272, 0.7567, 0.7845, 0.8104, 0.8346, 0.8571, 0.8780, 0.8973, 0.9151, 0.9316, 0.9467, 0.9606, 0.9733, 0.9850, 0.9950, 1.0000. The hybrid coordinate, η, is defined as η=p-p_T/p_S-p_T, where p_T is 10 hPa and p_S is the surface pressure
Time integration	Implicit, semi-Lagrangian (3-D), 2 time-level, 450 second per time step (Côté et al., 1998*a*; Côté et al., 1998*b*).
Independent variables	x, y, η and time.
Prognostic variables	East-west and north-south winds, temperature, specific humidity and logarithm of surface pressure, cloudwater 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, predictive derived from analyses, fixed in time derived from climatology, fixed in time	 Surface and deep soil temperatures, surface and deep soil humidity ISBA scheme (Noilhan and Planton 1989); snow depth, snow albedo Sea ice thickness Sea surface temperature, ice cover Surface roughness length (except variable over water); soil volume thermal capacity; soil thermal diffusivity.
Horizontal diffusion	Del-6 on momentum variables only, except for top sponge layer (del-2 applied on momentum variables at the 4 uppermost levels of the model).
Vertical diffusion	Fully implicit scheme based on turbulent kinetic energy (Benoît et al., 1989).
Orography	Extracted from USGS, US Navy, NCAR and GLOBE data bases using in house software.
Gravity wave drag	Parameterized (McFarlane, 1987; McFarlane et al., 1987).
Low level blocking	Parameterized (Lott and Miller, 1997; Zadra et al., 2003).
Radiation	Solar and infrared modulated by clouds (Garand, 1983; Garand and Mailhot, 1990; Yu et al., 1996).
Surface scheme	Mosaic approach with 4 types: land, water, sea ice and glacier (Bélair et al., 2003a and Bélair et al., 2003b).
Boundary-layer turbulence	Based on turbulent kinetic energy (Benoît et al., 1989; Delage, 1988*a*; Delage, 1988*b*), with statistical representation of subgrid-scale clouds (Mailhot and Bélair, 2002, Bélair et al., 2005)
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; Kain and Fritsch, 1993)

7.3.3 Numerical Weather Prediction products

7.3.3.1 Analysis

A series of standard analysis products are available in electronic or chart form (i.e. surface analysis of snow cover and snow depth, sea surface temperature, surface MSLP and fronts, upper-air geopotential, winds and temperature at 1000, 850, 700, 500, 250 hPa, etc.).

7.3.3.2 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 level, height of cloud ceiling, momentum flux, turbulence, etc.). A wide range of bulletins containing spot forecasts are produced for many locations over North America.

7.3.4 Operational techniques for application of NWP products

Perfect Prog	6- and 12-h probability of precipitation forecasts at the 0.2, 2 and 10 mm thresholds, at all projection times between 0 and 48 hours for a 264 Canadian station set (Verret, 1987). Consistency is forced between the 6-hour and the 12-hour probability of precipitation forecasts using a rule based system, with emphasis on inflation of the forecasts. Spot time total cloud opacity at three-hour intervals between 0 and 48 hour projection times (Verret, 1987). Consistency between the cloud and the probability of precipitation forecasts is forced using a rule based system. Emphasis is put on inflating the cloud forecasts so that they show a frequency distribution similar to that observed (Verret, 1988). Spot time surface temperatures at three-hour intervals between 0 and 48 hour projection times (Brunet, 1987). Maximum/minimum temperature forecasts for day 1 and day 2 (Brunet and Yacowar, 1982). The predictand is the maximum/minimum temperatures observed over the climatological day (06-06 UTC). Surface wind forecasts at 6-h intervals out to 48 hours. The forecasts are tuned based on a calibration technique.
Model Output Statistics (MOS)	An Updateable MOS system (Wilson and Vallée, 2001 and 2002) has been developed and implemented. The system currently provides forecasts for : - Spot time surface temperatures at three-hour intervals between 0 and 48 hour projection times. - Surface wind speed and wind direction at three-hour intervals between 0 and 48 h projection times. - Spot time total sky cover at three-hour intervals in four categories. The system is based on Multiple Discriminant Analysis (MDA)
Diagnostic techniques on direct model output fields	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-h intervals out to 24 hours. These charts constitute the Aviation Package. Forecast charts of buoyant energy, helicity, convective storm severity 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-h intervals out to 24 hours. These charts constitute the Summer Severe Weather Package. Forecast charts of precipitation type (Bourgouin, 2000), 250 hPa contour heights and vorticity, precipitable water, 6-h precipitation amounts, wind chill, surface temperature, thickness values and warm or above freezing layers with bases and tops. The charts are produced at 6-h intervals out to 24 hours. These charts constitute the Winter Severe Weather Package. 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, valid for Today and Tomorrow, constitute the Air Quality Package. Direct model outputs are used to forecast upper air winds and temperatures for aviation purposes. Several parameters interpolated at stations, formatted and transmitted operationally to Regional Offices.
Automated computer worded forecast	A system has been developed and installed 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 1, 2 and 3 (Verret et al., 1993; 1995 and 1997). See the following section Weather element matrices. The system called SCRIBE is being implemented as the main tool for public forecast generation. A prototype version for marine forecasts has also been delivered.
Weather element matrices	Same as section 7.2.4, except the data is valid at projection times between 0 and 48 hours and UMOS guidance is used instead of Perfect Prog one. Supplementary weather element matrices have been developed and implemented in quasi-operational mode. 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 η level 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. The time resolution of these matrices is 3 hours, with projection times out to 48 hours.

7.3.5 High resolution model for short range forecasts (HIMAP)

A high resolution model runs twice a day for 30 hours over two sub-areas of Canada: western Canada and upstream waters; Great Lakes and eastern Canada. This strategy was given the name of High Resolution Model Applications Project (HIMAP, Pellerin et al., 1998). The model used is similar to the unified model described in section 7.3.2; the main differences are:

- the window of uniform grid has a resolution of .09 degrees (~10 km);
- the number of vertical levels are 35 with top of the model at 10 hPa;

- the stable precipitation scheme is the mixed-phase scheme (Tremblay et al. 1996) with the Bourgouin method for precipitation types (Bourgouin, 2000).

The model starts from the 6-hour forecast of the regional model following the 00 UTC and 12 UTC runs. Outputs of surface fields covering the uniform grid area are transmitted in GRIB formats to Canadian Regions. Series of coloured images (including animation) are also made available through the internal Web.

7.4 Specialized forecasts

7.4.1 Environmental Emergency Response model

The CMC is able to provide in real-time air concentrations and surface deposition estimates of airborne pollutants. These fields are obtained from either an Eulerian 3-D long range atmospheric transport/dispersion/deposition model, named the "Canadian Emergency Response Model" or "CANERM", or from a Lagrangian Particle Model, MLDP0. Important applications for this model are the estimation of the concentrations of radionuclides and volcanic ash. Based on this operational capability, the CMC is designed by the WMO as a Regional Specialised Meteorological Centre (RSMC) with specialization in Atmospheric Transport Modelling Products for Environmental Emergency Response. In addition, CMC is designed by the International Civil Aviation Organisation as a Volcanic Ash Advisory Centre (VAAC).

7.4.1.1 Data assimilation, objective analysis and initialization

CANERM and MLDP0 are “off-line” models. Therefore fields of wind, moisture, temperature and geopotential heights must be provided to them. These are obtained either from the Global or the Regional forecast and objective analysis systems. Please refer to the above section 7.2 for more information on these NWP products.

Latitude, longitude and time of the release are necessary input parameters. Estimates of intensity and duration of the release are also required. In the absence of actual source data, the standard default values adopted at the WMO's First International Workshop on Users' Requirements for the Provision of Atmospheric Transport Model Products for Environmental Emergency Response (September 1993) would be used. These are:

- uniform vertical distribution up to 500 m above the ground;
- uniform emission rate during the first 6 hours;
- total pollutant release of 1 arbitrary unit;
- type of radionuclide is Caesium 137.

7.4.1.2 Models

CANERM is described in Pudykiewicz, 1989. The horizontal and vertical advections in the model are performed using the semi-Lagrangian algorithm of Ritchie, 1987. Diffusion is modelled according to K-theory. The diffusivities are constant in the free atmosphere but have a vertical profile in the boundary layer which is dependent on the state of the surface layer; the vertical diffusivity within the surface layer is approximated using the relations provided by the analytical theory of the surface layer. CANERM simulates wet and dry scavenging, wet and dry deposition and radioactive decay for selected tracers. Wet scavenging is modelled by a simplified statistical parameterization based on the relative humidity. The source term is

modelled by a narrow gaussian distribution to simulate both the release and subgrid scale mixing.
CANERM can be executed in forecast mode up to day 10, using the operational Global forecast model, and up to 2 days using the operational Regional forecast model. CANERM can also be executed in hindcast mode using Global or Regional objective analyses. Presently, three horizontal resolutions are available: a resolution of 150 km on a quasi-hemispheric domain, a movable continental domain with a resolution of 50 km and a mesoscale domain with a resolution of 25 km. CANERM can be run for both the Northern and Southern Hemispheres.

MLDP0 is a Lagrangian Particle Mode described in D'Amours & Malo, 2004. 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. Vertical mixing caused by turbulence is handled through a random displacement equation based on a diffusion coefficient. This coefficient is calculated in terms of a mixing length, stability function, and vertical wind shear.

Lateral mixing is modeled according to a first order Langevin stochastic equation for the unresolved components of the horizontal wind. Dry deposition is modeled in term of a deposition velocity. The deposition rate is calculated by assuming that a particle contributes to the total surface deposition flux in proportion to the tracer material it carries when it is found in a layer adjacent to the ground surface. Wet deposition will occur when a particle is presumed to be in a cloud. The tracer removal rate is proportional to the local cloud fraction.

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 weighing it according to the material amount carried by the particle.

MLDP0 can be executed in configurations similar to those of CANERM; a global configuration also exists. MLDP0 can be executed in inverse (adjoint) mode. The model has been used extensively in this configuration in the context of the WMO-CTBTO cooperation.

7.4.1.3 Numerical Weather Prediction (atmospheric transport/dispersion/deposition) products

Upon request from the appropriate WMO Member Countries Delegated Authorities, the 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 units/m3, for each of the three time periods. The duration of the first time period is between 12 and 24 hours starting at release time. For a release before 12 UTC, it ends at 00 UTC; for a release after 12 UTC, it ends at 12 UTC the next day. The second time

period is the 24 hours following the first time period. The third time period is the 24 hours following the second time period;
- total deposition (wet and dry) in units/m2 from the release time to the end of the third time period.

The standard set of products was agreed upon at the First International Workshop on Users' Requirements for the Provision of Atmospheric Transport Model Products for Environmental Emergency Response. The CMC can also provide charts of air concentration estimates for the surface, 850, 700, 500, 300 and 250 hPa levels as well as total surface deposition estimates, at 3 or 6-hour intervals, if required. All the products can be transmitted by facsimile, in real time, during environmental emergencies.

7.4.2 Ozone and UV index forecasting

The Canadian Global model is used to prepare ozone and UV Index forecast at the 18 hour projection time 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. 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. Correction factors have been added to take into account the snow albedo, elevation and Brerwer angle response.

7.4.3 Wave forecasting

Sea-state forecasts of 48 hours over the Eastern Pacific and Western Atlantic are generated twice a day (00 UTC and 12 UTC) by the WAM (WAve Modeling) model. The Pacific version of the wave model uses the surface level winds from the global model while the Atlantic version uses the regional model wind outputs. Various parameters are plotted on the wave forecast chart (wave height, swell period, swell height and direction, etc.).

7.4.4 Air Quality forecasting

CHRONOS (Canadian Hemispheric and Regional Ozone and NOx System) is a chemical transport model integrated daily over a domain covering the bulk of North America and surrounding waters (Pudykiewicz et al., 1997). The model is run from 00 UTC every day up to 48 hours. It has a horizontal resolution of 21 km and 20 levels in the vertical up to 6 km. The chemical mechanisms used in the simulation include 114 chemical reactions and 47 species. The advection-diffusion equation in the model is solved using semi-Lagrangian algorithm. The model simulates the dry deposition and wet scavenging of chemical tracers. The meteorological inputs used in the simulation of atmospheric chemistry are provided by the Canadian operational regional GEM model. The emissions inventory of chemical species is based on 1995 data and has 21 km resolution for surface emission fields. The emission inventory system takes into consideration the day of the week and the various source types such as mobile, non-mobile, major and minor point sources and biogenic. The initial conditions for the different chemical species are given by the previous 24 hr forecast.

The current operational output of CHRONOS consists of hourly concentrations of ozone, $PM_{2.5}$ and PM_{10}. The current version of the system considers only sulphate and secondary organic aerosols. Post-processing is performed on these outputs to provide users with maximum, mean and 3-hourly running mean data of tropospheric ozone per 6 hours slice. The outputs are available on the world wide web as alphanumerical point forecasts for a selection of cities across Canada. Also on the web (http://www.msc-smc.ec.gc.ca/aq_smog/chronos_e.cfm), maps of maximum values for ozone and aerosol species are available, providing a better spatial representation of the different chemical variables predicted. The maps are also available on the vizaweb internally.

7.5 Extended range forecasts (10-30 days)

Ten-day temperature anomaly forecasts (Verret et al., 1998) are generated once a day and fifteen-day temperature anomaly forecasts are generated once a week using a perfect prog approach from the medium-range model described in section 7.2.2.

Monthly temperature forecasts based on numerical weather prediction techniques are issued at the beginning and mid-month of every month. Two ensembles of 6 runs, obtained from 24-hour time lag, are produced: 6 from the Global Environmental Multiscale (GEM) model of Recherche en prevision numérique (RPN) (Côté et al., 1998a and 1998b) (1.875° with 50 levels in the vertical) and 6 from the atmospheric general circulation model second generation (AGCM2) of the Canadian Climate Centre for modelling and analysis (CCCma) (McFarlane et al., 1992) (T32 L10). Both models use the same initial operational analyses. SST anomalies observed over the previous 30 days are added to climatological values over the period; snow is relaxed towards climatology at the end of the first month, except for the AGCM2, where it is a prognostic variable.
Direct model surface temperature outputs ensemble means are averaged over the 30-day period and subtracted from model climatology obtained from a 26-year hindcast period (see section 7.6). The final deterministic forecasts are generated from the normalized average of both model ensemble means. These temperature anomalies are then normalised by the model standard deviation multiplied by 0.43 (to get equiprobable classes) and categorised in above, below and normal categories. Charts are produced, showing above normal, below normal and near normal temperature categories. Monthly forecast products are available on the Internet (Web address http://weatheroffice.ec.gc.ca/saisons/index_e.html).

7.6 Long range forecasts (seasonal forecasts)

7.6.1 Season 1 forecasts (zero lead time)

Season 1 forecasts are produced using a numerical approach (Derome et al., 2001). The approach is identical to the monthly forecast one described in section 7.5 . Maps are similar to those used in monthly forecasts: 3 categories, separated using the 0.43 standard deviation of observed climatology. The temperature and precipitation forecasts are produced using direct model outputs. The two ensemble means of forecasts are subtracted from their respective models' climatologies, and normalised by models' standard deviations. These normalised forecasts are then added, divided by two and used to produce a map, categorised in 3 categories, using the 0.43 value for separation. Skill maps of temperature and precipitation, as obtained over the 26 years of historical runs, are shown for each of the 4 seasonal forecasts periods.

The probabilistic forecasts are done by counting members in each of the three possible forecast categories: below normal, near normal and above normal. The probabilistic forecasts are not calibrated but a reliability diagram with error bars is provided with each forecast.

The model outputs for the season 1 are now available in real time on Internet via the CCCma web site. The monthly and seasonal means for 7 fields for the 2 operational models (CCCma AGCM2 and RPN GEM) can be downloaded. Data from both the operational and the hindcast runs are available. The operational forecast data can be accessed at http://www.cccma.bc.gc.ca/data/cmc/cmc.shtml while the hindcast data are located at http://www.cccma.bc.ec.gc.ca/data/hfp/hfp.shtml

7.6.2 Season 2, 3 and 4 forecasts

Seasonal forecasts with lead times of 3, 6 and 9 months are produced, using a Canonical Correlation Analysis technique (Shabbar and Barnston, 1996). The technique uses the SST anomalies observed over the last year to predict temperature and precipitation anomalies at Canadian stations (51 for temperatures, 69 for precipitation) for the following 3 seasons. Maps of above, normal and below temperature and precipitation are produced. These are accompanied by skill maps, as obtained from cross-validation over a 40-year period.

8 Verification of prognostic products

Objective verification of the operational numerical models is carried out continuously at the CMC. S1 skill scores, biases and root mean square errors are produced for the Canadian verification area. A monthly verification summary is produced and distributed to our clients.

A verification system following the WMO/CBS recommendations was implemented in 1987. Results are routinely exchanged with the other participating NWP centres. The table on the following page is a summary of the CMC verification scores for 2004 according to the recommended format. Since 1994, CMC has exchanged these verification scores electronically with other NWP centres, which has allowed a more comprehensive comparison of NWP models from the various centres.

Verification summary - 2004
Canadian Meteorological Centre
Global Environmental Multiscale (GEM) Model (0.9 deg. L28)
Verification against analysis

Area	Parameters	T+24h		T+72h		T+120h	
		00UTC	12UTC	00UTC	12UTC	00UTC	12UTC
N. Hemisphere	RMSE (m) GZ 500 hPa	12.3	12.5	31.5	31.9	57.5	58.1
	RMSVE (m/s) Wind 250 hPa	5.0	5.1	10.6	10.7	16.1	16.2
Tropics	RMSVE (m/s) Wind 850 hPa	2.7	2.6	4.3	4.3	5.2	5.2
	RMSVE (m/s) Wind 250 hPa	4.9	5.0	8.4	8.4	10.6	10.6
S. Hemisphere	RMSE (m) GZ 500 hPa	18.5	18.5	43.8	43.5	74.5	73.8
	RMSVE (m/s) Wind 250 hPa	5.6	5.6	11.8	11.7	17.9	17.7

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	13.0	12.5	31.5	31.8	56.6	56.8
	RMSVE (m/s) Wind 250 hPa	6.9	6.7	12.5	12.2	18.2	17.8
Europe	RMSE (m) GZ 500 hPa	14.9	14.2	33.8	32.5	61.5	62.8
	RMSVE (m/s) Wind 250 hPa	6.2	6.0	11.7	11.5	18.2	18.2
Asia	RMSE (m) GZ 500 hPa	15.4	15.5	30.7	32.3	50.1	52.9
	RMSVE (m/s) Wind 250 hPa	6.5	6.7	11.4	11.9	15.9	16.6
Australia - N.Z.	RMSE (m) GZ 500 hPa	15.3	15.7	26.7	27.7	43.7	47.2
	RMSVE (m/s) Wind 250 hPa	6.6	6.6	11.0	10.9	16.0	15.9
Tropics	RMSVE (m/s) Wind 850 hPa	4.3	4.2	5.4	5.3	6.2	6.0
	RMSVE (m/s) Wind 250 hPa	6.3	6.3	8.5	8.9	10.5	10.9
N. Hemisphere	RMSE (m) GZ 500 hPa	15.2	14.7	34.5	34.4	61.5	62.3
	RMSVE (m/s) Wind 250 hPa	6.4	6.4	11.8	11.7	17.5	17.4
S. Hemisphere	RMSE (m) GZ 500 hPa	17.1	17.9	33.0	34.4	54.4	57.3
	RMSVE (m/s) Wind 250 hPa	6.8	7.1	11.6	11.8	16.9	17.3

9 Plans for the future

The 4DVar assimilation will replace the 3DVar for the global data assimilation system.

The global model horizontal resolution will be increased to 40 km with improved physics schemes.

An improved version of the wave model (WAM) will be introduced running at a resolution of 0.5 degrees.

SCRIBE will be the main tool for public and marine forecast preparation in MSC.

A new updated version of Perfect Prog will be implemented in the global prediction system.

The UMOS set of guidance will be expanded to include cloud and probability of precipitation.

The ensemble forecasts will be extended from 10 to 15 days. As well, a full 12Z run will be added to the current 00Z run.

USA and Canada will share ensemble forecasts and develop joint products over North America.

HIMAP 10km model forecasts will be replaced by a series of higher resolution (2.5km) model executions from a limited area modeling strategy of the GEM model.

2 new models (SEF and GCM-3) will be added to seasonal forecasts system which already uses GEM and GCM-2.

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