Canada

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1. Summary of highlights

Significant modifications were incorporated into the global and regional data assimilation systems in 2001. First, in January, the regional 3D-Var analysis moved from the standard pressure levels to model levels. At the same time, TOVS/ATOVS radiances from the NOAA-14 and NOAA-15 satellites, as well as wind data from ACARS/AMDAR, were introduced into the regional system. These changes had already been incorporated in the global assimilation system during 2000. Secondly, in June 2001, the level 1b ATOVS dataset (AMSU-A instrument) from NOAA-15 and NOAA-16 replaced the level 1d dataset previously used. Finally, in December 2001, the two assimilation systems were changed to assimilate temperature instead of geopotential data. In addition numerous data sources were added: significant level data from soundings, data from dropsondes, temperatures from aircraft data, additional ATOVS 1B channels (AMSU-A), satwind data (satobs) from GOES satellites. Moreover, a completely revised quality control (QC) algorithms, consisting of a background check and a variational quality control module, have replaced the old QC system which was based on optimum interpolation.

Also in December 2001, the global model was changed with modifications to the subgrid scale orographic scheme, with a low level blocking term added.

The regional model was upgraded in September 2001 with the introduction of a new surface modelling system. This system is now based on a mosaic-type approach that takes into account 4 types of surface in each grid box: vegetated land with possible presence of snow, open water, sea ice and glacier. The land part of the surface system has changed with the use of the so-called Interaction Soil-Biosphere-Atmosphere (ISBA) scheme, instead of the force-restore scheme.

The global medium range Ensemble Prediction System was improved in June 2001 with increased resolution models going from 1.875° to 1.2° horizontal resolution.

The Perfect Prog system has been extended out to day 10 off the operational Global model in January. Work has continued on the development of the Updateable Model Output Statistics (UMOS) postprocessing system. UMOS guidance is now used operationally to generate automated worded forecasts (temperature in May, winds in September). Considerable development has been done on the computer worded forecasts system (SCRIBE).

The chemical tracer model (named Chronos) was introduced in the operational suite in May 2001. This 3D advection-diffusion model with full chemical reaction covers most of North America and runs up to 48 hours. Its main output is tropospheric ozone concentration.

The mesoscale short range model (HIMAP), running at 10 km resolution, had its condensation parameterization scheme upgraded to the Mixed-Phase scheme in February 2001 and is now running twice daily.

The transition to SX-5 of all the operational suite was done in January.

2. Equipment in use at the Centre

CMC Computer Installation - Summary of operational equipment		
Computer	**Memory (Mbytes)**	**Disk (Gbytes)**
2 NEC SX-5/16, 16 cpu	128000	1108
1 NEC SX-4/32 , 32 cpu	8000 (16000 ssd)	800
4 SGI ORIGIN 2000, 4-4-12-16 cpu	1000-2000-3000-4000	1000-800-1000-2300
1 TANDEM Himalaya, S7400, 2 cpu	1024	64
10 SGI ORIGIN 200, 1-3 cpu	512	29-225
27 HP 9000 C110-C180-C360	256-512	6-22
9 HP K200 - K370	256 -512	8-108
5 SGI-Indigo 2XS	64-256	3-20
12 SGI-Indy	128-160	2 - 9
35 SGI 230 -330	256-512	8-20
45 NCD Xterminals	32 - 128	-
1 SGI OCTANE	256	72

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	37,100
- TEMP (500 hPa GZ)	1,150
- TEMP/PILOT (300 hPa UV)	1,275
- DRIFTER	11,300
- AIREP/ADS	3,050
- SATEM	10,300 [1]
- SATOB (including BUFR)	575,000
- SATOB-SST	2,000
- SA/METAR	142,500
- AMDAR/ACARS	99,700
- PIREP	900[1]
- PROFILER	745[1]
- HUMSAT	12,000[2]
- ATOVS (AMSU-A)	675,000
- SSM/I	1,000,000[3]

[1] Not assimilated yet, or no longer assimilated
[2] Locally produced GOES moisture profiles
[3] A third of these are used for ice analyses

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 sent to the WMO Secretariat as well as other major GDPS centres. Similar information is also available locally in near real-time via a data monitoring web site.

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 2001. Monitoring results are distributed directly to national focal points for most countries within RA-IV.

7. Forecasting system

7.1 *System run schedule*

The following table summarizes the operational runs at CMC. The core of the operational runs executes in batch on the two NEC SX-5/16. Most of the postprocessing jobs, including CMC products, execute on the front end computer (SGI Origin 2000).

CMC model and upper-air objective analysis run schedule		
R1 (00,12)	Regional GEM model run Regional objective analysis Regional forecast model (24 km) All products available by	00 or 12 UTC data Cut-off time T+1:50 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 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+6:30
G1 (06, 18)	Global early objective analysis	06 or 18 UTC data Cut-off time T+2:00
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 members)	Continuous data assimilation system for 16 members. 10-day forecasts at 150km resolution issued once a day for each members
C1 (00)	CHRONOS model for air quality prediction	48-h forecast
M1 (00)	Global model run (T63)	To 840 h (monthly forecast) for 5 consecutive days before end and middle of month. To 2400 h (seasonal forecast, 3 months) for 6 consecutive days before end of February, May, August and November

Note: There are also runs (not described here) that perform surface objective analyses and update geophysical fields; these are runs G3, G4, G5, G6 and R6.

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 3D-Var. (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.
Processing time	15 minutes plus 3 minutes for trial field model integration on the NEC SX-5.
Data used	GTS data : TEMP, PILOT, SYNOP/SHIP, SATOB, ATOVS level 1b (amsu-a), BUOY, AIREP/AMDAR/ACARS, and locally derived humidity profiles from GOES (HUMSAT).
Bogus	Subjective bogus, as required.

7.2.1.2 Surface

Analysed Surface Fields for the medium range forecasting system

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)
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) the 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 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, 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	Surface temperature and humidity, force-restore method (Deardorff, 1978).
- derived from analyses, fixed in time	Sea surface temperature, snow depth, albedo, deep soil temperature, ice cover.
- derived from climatology, fixed in time	Soil humidity, surface roughness length (except variable over water); soil volume thermal capacity; soil thermal diffusivity.
Horizontal diffusion	None, except del-2 applied near the calculation poles and 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)
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, 1988*a*; Delage, 1988*b*).
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 and 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 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 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 that 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 10 on a daily basis and 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).

Air quality forecast based on a non-linear regression two-stage procedure: classification and regression trees combined with a neuro-fuzzy inference system. Three predictands are available: maximum and average low level ozone concentration over six hour periods and maximum 3-h low level ozone concentration (Burrows, 1998 and Burrows *et al.*, 1998). Forecasts are produced out to 48 hours at 00 UTC and out to 60 hours at 12 UTC.

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 computer worded forecasts

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, 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.

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 800 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; 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; Lefaivre *et al.,* 1997; Plante *et al.* 1999). Eight perturbed analyses are obtained by running independent assimilation cycles that use perturbed sets of observations and are driven by eight different versions of the spectral global model (SEF model T150, Ritchie, 1991). The number of perturbed analyses is doubled as follows: the mean of the analyses is subtracted to the operational analysis and a fraction of this difference is added to the original perturbed analyses. Every day, at 00 UTC, two separate models are used to produce the 10-day forecasts: the SEF model and the GEM model (resolution of 1.2°, Côté *et al.,* 1998*a* and 1998*b*). Each model uses different versions of their physical parameterizations.

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

7.3 *Short-range forecasting systems (0-48 hours)*

7.3.1 Data assimilation and objective analysis

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 (28 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 are performed using the high resolution grid of the GEM model. The 3D-Var 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 model.
Domain	Global.
Grid	The analysis is done spectrally at T108 using a 400x200 gaussian grid. Results are interpolated on a version of the GEM model's global variable resolution grid: 24 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). The first two analyses of each spin-up (00 UTC, 06 UTC and 12 UTC, 18 UTC) have a cut-off time of 5h30. The final analysis of each spin-up (00 UTC and 12 UTC) has a cut-off of 1h50. 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 NEC SX-5.
Data used	GTS data : TEMP, PILOT, SYNOP/SHIP, SATOB, ATOVS level 1b (amsu-a), BUOY, AIREP/AMDAR/ACARS, and locally derived humidity profiles from GOES (HUMSAT).
Bogus	Subjective bogus, as required.
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	353 x 415 variable resolution on latitude-longitude grid having a uniform .22 degree (~24 km) window covering North America and adjacent oceans.
Levels	28 hybrid levels (0, .010, .020, .040, .061, .091, .131, .177, .222, .273, .328, .384, .444, .500, .555, .611, .666, .722, .773, .818, .859, .894, .925, .950, .970, .985, .995, 1.00); 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, 720 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, 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	Surface and deep soil temperatures, surface and deep soil humidity ISBA scheme (Noilhan and Planton 1989); sea ice thickness, snow depth, snow albedo
- derived from analyses, fixed in time	Sea surface temperature, ice cover
- derived from climatology, fixed in time	Surface roughness length (except variable over water); soil volume thermal capacity; soil thermal diffusivity.
Horizontal diffusion	del-2 applied to all history carrying variables.
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	Nil.
Radiation	Solar and infrared modulated by clouds (Garand, 1983; Garand and Mailhot, 1990; Yu *et al.*, 1996).
Surface fluxes	Momentum, heat and moisture based on similarity theory.
Boundary layer fluxes	Based on turbulent kinetic energy (Benoît *et al.*, 1989; Delage, 1988*a*; Delage, 1988*b*).
Shallow convection	Turbulent fluxes in partially saturated air (Girard, personal communication).
Stable precipitation	Sundqvist scheme (Sundqvist *et al.*, 1989).
Convective precipitation	Fritsch-Chappell scheme (Fritsch and Chappell, 1980; Bélair *et al.,* 2000) in the uniform grid, mass flux type (Wagneur, 1991) in the variable grid.

7.3.3 Numerical Weather Prediction Products

7.3.3.1 Analysis

A series of classic analysis products are available in electronic or chart form (i.e. surface analysis of snow and cover, 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. A myriad 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 (Vallée *et al.*, 1998) has been developed and implemented. The system currently provides forecasts for :

- 6-h probability of precipitation forecasts at all projection times between 0 and 48 hours at 674 Canadian locations.

- 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.

Development work is being done to expand the set of weather element guidance to include 12-h probability of precipitation and sky cover.

Diagnostic techniques on direct model output fields

Charts of forecast icing (Tremblay *et al.*, 1995), turbulence (Elrod, 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 output 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 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). See the following section Weather element matrices.

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 forecast (HIMAP)

A high resolution model is run 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 the same unified model described in section 7.3.2, except for the following differences:

- the window of uniform grid has a resolution of .09 degrees (~10 km);
- the number of vertical levels is 35 with top of the model at 10 hPa;
- the convection scheme is the Kain-Fritsch scheme (Kain and Fritsch, 1990, Kain and Fritsch, 1993);
- the stable precipitation scheme is the mixed-phase scheme (Tremblay et al 1996) with the Bourgouin method for precipitation types (Bourgouin, 2000).

The model is started 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 *Specialised 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 a 3-D long range atmospheric transport/dispersion/deposition model, named the "Canadian Emergency Response Model" or "CANERM". The main applications for this model have been for estimating concentrations of radionuclides and volcanic ash. Based on this operational capability, the CMC has been 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 has been designed by the ICAO as a Volcanic Ash Advisory Centre (VAAC).

7.4.1.1 Data assimilation, objective analysis and initialization

Fields of wind, moisture, temperature and geopotential heights must be provided to CANERM. 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 for CANERM. 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 Model

CANERM was developed by Janusz Pudykiewicz of Environment Canada and is described in Pudykiewicz, 1989. The horizontal and vertical advection 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 executed in both the Northern and the Southern Hemispheres.

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 Unit-s/m^3, 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/m^2 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. In addition, CMC is designed by the ICAO as a Volcanic Ash Advisory Centre (VAAC).

7.4.2 *Ozone and UV index forecast*

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.

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 forecast

7.4.4.1 CANFIS

The Canadian Meteorological Centre produces low level ozone concentration forecasts in support for the regional air quality program (Burrows *et al*, 1997). Dynamic-statistical forecast models provide a low cost solution to the problem of producing forecast of environmental variables such as low level ozone concentration, and can give a good trade-off between significance and precision in return for substantially lower computer resource requirements. Most environmental variables have a non-linear dependencies on predictors in part or all of their distribution. recent non-linear regression techniques allow for a significant increase in accuracy of dynamic-statistical models compared to traditional linear regression methods. One of these is Classification and regression Trees (CART) (Brieman *et al*, 1984), another is the Neuro-Fuzzy Inference System (NFIS) (Chiu, 1994). Both CART and NFIS are capable if modelling en entire predictand data distribution, including the tails, with better accuracy than linear regression and with fewer predictors. Given a learning data base of matched predictand and predictors, CART regression produces a non-parametric, non-linear, tree-based, piece-wise continuous model of the predictand data. It uses a variance minimizing algorithm which optimizes the task of predictor selection, often greatly reducing initial data dimensionality. NFIS first reduces initial data dimensionality by a procedure known as subtractive clustering which finds vector cluster centers, but it does not of itself eliminate predictors. Overlapping coverage in predictor space is enhanced by allowing a Gaussian membership function to apply for each component of clusters. Coefficients for a continuous predictand response model bases on the fuzzified cluster centers are then obtained by least-squares estimation procedure.

CANFIS is a two-stage data modelling technique combining the strength of CART to optimize selection of predictors from a large pool of potential predictors, with the modelling strength of NFIS. A CANFIS model requires minimal computer time to run. It will be used to produce models for ground level ozone, particulates, and other pollutants at more than 100 sites in Canada. The models will be used in a Perfect Prog forecast mode twice daily. Upstream and local Lagrangian meteorological and emissions predictors will be produced from 72-hour back-trajectories calculated at 925 hPa with the operational Global model.

The primary contributors to occurrences of high levels of ground level ozone are photochemical reaction involving ozone and NOx/VOC precursors of ozone. Ozone and its precursors can be produced locally and also transported to a site from upwind locations. Knowledge of airmass properties and pollution emissions locally and upwind from a site are essential for prediction of ground level ozone. Predictors for a dynamic-statistical model should involve both local and upwind meteorology and NOx/VOC emissions. Many potential predictors should be included, then the most relevant for a site are selected by the CANFIS procedure.

A database of hourly ground level ozone observations matched with a large pool of potential predictors was gathered for the years 1980-1994 for more than 100 sites in Canada to develop the dynamic-statistical model. Three predictands are forecast for each 6-hour period ending at 00, 06, 12 and 18 UTC. These are maximum 3-hour running average ground level ozone concentration in each 6-hour period, maximum ozone and average ozone concentration.

To build the predictors, 1988 emissions of NOx/VOC for point, area, and mobile sources in eastern North America were summed on a 20 km grid, stratified by four seasons, and by day of week. A three-dimensional 72-hour back trajectory starting from 925 hPa was run from each site at 00, 06, 12 and 18 UTC every day to calculate upwind predictors. Emissions at hourly trajectory locations are assumed to be injected into the air and are summed every 6 hours along the trajectory, with a grand sum over the entire trajectory. The combination of maximum temperatures and emissions predictors for the precious two days along the trajectories serve as surrogate for the process of injecting a load of pollution and ozone into an airmass upwind of a site and transporting it to the site. There are two predictors that are themselves estimated along the trajectories: maximum temperature and occurrence of precipitation. These predictors are estimated for two reasons: the trajectory locations may often not be near a meteorological observation site, so an observed value may not be available; they must be forecast for the day of validity at the site in the national operational model, either from 00 or 12 UTC runs the current day.

The system is driven by the Canadian operational Global model.

7.4.4.2 CHRONOS

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 night up to 48 hours. It has a horizontal resolution of 21 km and 20 levels in the vertical up to 4 km. The chemical mechanism used in the simulation has 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 input employed in the simulation of atmospheric chemistry is provided by the Canadian operational regional GEM model. The emissions inventory of chemical species is based on 1990 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 and aerosol species. 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 alpha numerical 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, allowing the user to have a better spatial representation of the different chemical variables predicted.

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 once a week using a perfect prog approach from the medium-range model described at section 7.2.2.

Monthly temperature forecasts based on numerical weather prediction techniques, are issued at the beginning and mid-month of every month. An ensemble of 5 runs, obtained from 24-hour time lag, is produced. The model used is very similar to the former operational spectral global model (Ritchie, 1991), except it has lower horizontal resolution (T63 L23) and has evolving geophysical forcing: the anomalies (analysis-climatology) of sea surface temperature (SST) and snow, observed during the previous 30 days, are added to the daily climatology during the integration. 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). These temperature anomalies are then normalised by the model standard deviation multiplied by .43 (to get equiprobable classes) and categorised in above, below and normal classes. 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)*

Seasonal forecasts are issued 4 times a year (at the beginning of March, June, September and December). Seasonal products are distributed internationally and nationally through Internet (address http://weatheroffice.ec.gc.ca/saisons/index_e.html on the Web). They are also distributed nationally on the National Telecommunications System and to selected users by facsimile and made available on electronic bulletin boards. The charts are accompanied by a verification chart giving the performance of the forecast over the hindcast period. Also, verification charts, showing the previous season's prediction and a preliminary analysis of the observed anomaly, are provided.

7.6.1 Season 1 forecasts (zero lead time)

Season 1 forecasts are produced using a numerical approach (Derome *et al.,* 2001). Two ensembles of 6 runs, obtained from 24-hour time lag, are produced: 6 from the T63 L23 model described in section 7.5, 6 from a general circulation model (GCM) (McFarlane *et al.,* 1992) (T32 L10). Both models use the same initial operational analyses. SST anomalies, that have been 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 GCM, where it is a prognostic variable. A simple statistical linear regression equations relates the 1000-500 hPa thickness anomalies (forecast minus model climatology) to surface temperature anomalies, using regression coefficients for 90-day forecasts. Maps are similar to monthly ones: 3 classes, separated using the .43 standard deviation of observed climatology. The precipitation forecast is produced using a more direct approach: the two ensemble means of forecast precipitation 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 classes, using the .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.

7.6.2 Season 2, 3 and 4 forecasts

Seasonal forecasts at lead time 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. Verifications of prognostic products

The objective verification of the operational numerical models is done on a continuing basis. S1 skill scores, bias and root mean square error 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 has been implemented in 1987. Results are regularly exchanged with the other participating centres. The table on the following page is a summary of the verification scores for 2001 according to the recommended format. Since 1994, CMC began an electronic exchange of these verification scores with other NWP centres. This electronic exchange proved to be very useful and results from various operational NWP models can now be compared much more easily and thoroughly.

Verification summary - 2001
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 RMSVE (m/s) Wind 250 hPa	14.0 5.5	14.0 5.6	36.9 11.6	36.5 11.5	64.4 17.0	
Tropics	RMSVE (m/s) Wind 850 hPa RMSVE (m/s) Wind 250 hPa	2.7 5.3	2.7 5.3	4.4 9.0	4.4 9.0	5.3 11.1	
S. Hemisphere	RMSE (m) GZ 500 hPa RMSVE (m/s) Wind 250 hPa	21.6 6.2	21.6 6.3	51.4 13.0	51.6 13.1	80.1 18.5	

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 RMSVE (m/s) Wind 250 hPa	15.4 7.3	16.2 7.3	37.3 14.1	38.3 13.9	63.6 19.8	
Europe	RMSE (m) GZ 500 hPa RMSVE (m/s) Wind 250 hPa	15.3 6.6	14.4 6.3	35.3 12.0	34.4 11.8	68.5 19.0	
Asia	RMSE (m) GZ 500 hPa RMSVE (m/s) Wind 250 hPa	14.9 7.2	15.3 7.3	32.5 12.0	33.0 12.3	55.0 16.4	
Australia - N.Z.	RMSE (m) GZ 500 hPa RMSVE (m/s) Wind 250 hPa	13.4 7.1	13.8 7.3	28.3 12.0	30.3 12.1	45.0 16.8	
Tropics	RMSVE (m/s) Wind 850 hPa RMSVE (m/s) Wind 250 hPa	4.5 6.7	4.4 6.7	5.6 9.0	5.4 9.3	6.5 10.9	
N. Hemisphere	RMSE (m) GZ 500 hPa RMSVE (m/s) Wind 250 hPa	16.1 6.9	16.2 6.9	38.3 12.8	38.5 12.7	68.0 18.5	
S. Hemisphere	RMSE (m) GZ 500 hPa RMSVE (m/s) Wind 250 hPa	18.0 7.7	20.0 8.2	38.0 13.2	41.9 13.5	58.5 18.3	

9. Plans for the future

The regional model resolution will be increased to 15 km resolution with improved physics schemes.

The global model will have improvements to its physics (surface scheme) and to its vertical resolution (top higher than 10 hPa with a hybrid coordinate system).

Additional type of observations (additional AMSU-A channels above 10 hPa, some AMSU-B channels, radiances for IR channels: HIRS, GOES, AIRS) and surface wind data (SSM/I, QuikScat) will be incorporated into both assimilation systems. Canadian AMDAR data should become available during 2002 and will be assimilated.

The UMOS guidance will be completed. Development work will be initiated to update the Perfect Prog statistical guidance system.

Particulate matter treatment will be added to the air quality model.

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