The Global Ensemble Prediction System (GEPS) version 7.0 of the Meteorological Service (MSC) of Canada

GEPS 7.0 was implemented at MSC Canadian Meteorological Centre (CMC) operations on December 1st, 2021 (1200 UTC run).

- A technical note describing the latest modifications made to the Global Ensemble Prediction System (GEPS-7.0) is available here:

  http://collaboration.cmc.ec.gc.ca/cmc/cmoi/product_guide/docs/tech_notes/technote_geps-700_e.pdf

- The most recent changes to CMC operational suite of prediction systems are described here:

  https://eccc-msc.github.io/open-data/msc-data/changelog_nwp_en/

- **La version française de ce document est ici:**

  http://collaboration.cmc.ec.gc.ca/cmc/CMOI/product_guide/docs/tech_specifications/tech_specifications_GEPS_7.0.0_f.pdf

The assimilation part of the GEPS is described in section 1 below, while the forecast component is in section 2. Also, some information on the reforecast procedure can be found in section 3. A list of references is included at the end of the document.

1. Data assimilation component

Model version **New**	Global Environmental Multiscale (GEM) model version 5.1.0
Analysis Method **New**	Local Ensemble Transform Kalman Filter (LETKF) (Buehner, 2020) is used to do the analyses to initialize the global ensemble forecasts. A trajectory of 3 to 9 hour forecasts with GEM (Houtekamer et al., 2014; Houtekamer et al., 2009) is used as trial fields to assimilate observations which are not perturbed anymore. An ensemble of 256 trial fields is run with perturbed parameters within the physics by a Stochastic Parameter Perturbation (SPP)(McTaggart-Cowan et al. 2022a &b) (see Appendix A for a list of parameters perturbed in GEPS 7.0). The stochastic kinetic energy back-scattering (SKEB) algorithm (updated version, see section 2) is also used. The time step of these models is 15 minutes. They are subdivided in 8 sub-sets of 32 members. In this upgrade, the cross-validation procedure is changed. Namely, the membership of a sub ensemble is randomly determined with a seed that is different at each analysis time. Also, additional perturbations (with reduced amplitude compared to the previous version) are added to the analysis with homogenous isotropic model error random fields

	(Houtekamer et al. 2009). The length of the assimilation window is 6 hours. The ECMWF-hybrid gain (Houtekamer et al., 2018) approach is modified. In the current upgrade, the uncertainty in the analysis algorithm is sampled by translating LETKF analyses of different members over different - randomly selected -distances to the average of the 4DEnVAR analysis and the mean of the ensemble. As before, the mean position after recentering is identical to the average of the 4DEnVAR analysis and the mean of the ensemble of LETKF analyses. The 4DEnVar analysis is produced on the same model grid as for the LETKF while using the ensemble mean background trajectory from the LETKF as first-guess.
Initialization procedure	Incremental analysis update (IAU) (Bloom et al. 1996, Buehner et al. 2015)
Variables	T, Ps, U, V and q (specific humidity).
Levels **New**	84 hybrid levels. Model lid at 0.1 hPa.
Domain	Global
Grid	Yin-Yang grid at 0.35° uniform resolution (~39 km)
Frequency	Every 6 hours using data ±3 hours at 00, 06, 12 and 18 UTC.
Cut-off time	7 hours for final analyses at 00, 06, 12 and 18 UTC. 3 hours for forecast runs twice a day, at 00 and 12 UTC.Twenty representative members are chosen among the 256 analyses to initialize the medium-range forecasts. The average of this subset of analyses is constrained to be equal to the 256 member analyses ensemble mean. 2 hours for an early forecast run four times a day at 00, 06, 12, 18 UTC. The analyses of subsampled twenty members are used to initialize the 72-hour forecasts. This early forecast run provides analyses and pilot fields for the regional ensemble prediction system.
Processing time ***New***	~25 minutes analysis (with a maximum of 3868 cores) plus ~25 minutes for model integration to produce trials (with 256 x 80 cores) on the supercomputing back-end (banting/daley).
Data used	For LETKF: Radiosonde upper-air, Radiosonde surface, Surface, Aircraft, Satellite wind, oceanic wind Scatterometer, ATOVS level 1b (AMSU-A and AMSU-B/MHS) (GLOBAL and RARS sources), GPS-RO, ATMS, AIRS, IASI, CrIS. For EnVar (in LETKF for recentering) 3 other types of observations (ground-based GPS-RO , CSR, SSMIS) are used in addition to the ones listed above.

Ensemble perturbations (new):
• Observations are not perturbed anymore • Homogenous isotropic perturbations are added at the end of the assimilation process (coefficient of 0.26 for the continuous long cut-off cycle and 0.43 for the short cut-off analyses) • The perturbations in the model for the trials are unified for the data assimilation and forecast components of the GEPS. Model uncertainty is now sampled using the SPP and SKEB schemes.

2. Forecast component

Model version *New*	The Global atmosphere-ocean coupled model, in which the Global Environmental Multiscale (GEM) model version 5.1.0 is coupled with the Nucleus for European Modelling of the Ocean model (NEMO, Madec, G. 2008) *version* 3.6 *and the sea ice model* (CICE, Hunke et Lipscomb, 2010) version 4.0.
Initialization **New**	Incremental analysis update (IAU) (Bloom et al. 1996, Buehner et al. 2015)
Formulation	Hydrostatic primitive equations.
Domain	Global
Numerical technique	Finite differences: Arakawa C grid in the horizontal and Charney-Phillips grid in the vertical.
Grid	Yin-Yang grid at 0.35^{o} uniform resolution (~39 km)
Levels **New**	84 hybrid levels. Model lid at 0.1 hPa.
Processing time **New**	Around 1 hour 30 minutes for 16-day forecasts (with 21 x 600 cores) on the supercomputing back-end (banting/daley).
Time integration	Implicit, semi-Lagrangian (3-D), 2 time-level, 900 seconds per time step (Côté et al., 1998a and 1998b).
Prognostic variables	E-W and N-S winds, temperature, specific humidity and logarithm of surface pressure, liquid water content, Turbulent kinetic energy (TKE).
Derived variables	MSL pressure, relative humidity, geopotential height, dew point depression, dew point temperature, QPF, precipitation rate, omega, cloud amount, boundary layer height, relative vorticity

Geophysical variables: ***New***	Surface and deep soil temperature and moisture. Snow depth, snow albedo and snow density: - Derived from analyses, which is done now at GEPS 39km grid instead of GDPS grid, at initial time, Predictive soil variables from ISBA scheme (Noilhan and Planton, 1989; Bélair et al. 2003a and 2003b); Sea ice thickness: - Derived from climatology at initial time, fixed in time Sea surface temperature - Initially from the CMC GIOPS analysis (Smith et al. 2016) and then from the oceanic component of the GEPS. Sea ice cover - Initially from the CMC GIOPS analysis (Smith et al. 2016) and then from the sea-ice component of the GEPS. Orography, surface roughness length (except over water), subgrid-scale orographic parameters for gravity wave drag and low-level blocking, vegetation characteristics, soil thermal and hydraulic coefficients, glaciers fraction - Derived from a variety of geophysical recent data bases using in house software, fixed in time - Sharper filtered topography (ME), produced with a new more scale-selective low-pass filter (McTaggart-Cowan et al., 2019)
Horizontal diffusion	Del-6 on momentum and temperature variables, except Del-2 applied on temperature and momentum variables at the lid (top 4 levels) of the model.
Radiation	Solar and infrared using a correlated-k distribution (CKD) (Li and Barker, 2005).
Surface scheme	Mosaic approach with 4 types: land, water, sea ice and glacier (Bélair et al., 2003a and 2003b).

Ensemble perturbations for the forecasts (new):

- Forecasts for 20 members (1->20) are produced. They differ in their initial conditions, their physics parameters which are randomly perturbed by SPP (see Appendix A below for a list of parameters perturbed in GEPS 7.0).
- The modified SKEB is also applied with different seeds (Charron et al. 2010). The contribution of the deep convective momentum transfer on the local rate of change of kinetic energy was added to the contributions of the explicit diffusion and parameterized gravity wave drag, as proposed by Shutts (2004), and a parameter controlling the final tendencies produced by the scheme was readjusted to boost its impact on ensemble spread
- Control member 0 is driven by the ensemble mean analysis from recentered LETKF analysis. There is no additional model uncertainty added to the control.
- Each member is initialized with a different set of atmospheric initial conditions from the recentered global LETKF analyses (see section 1). All ensemble members have the same ocean and ice initial conditions from CMC GIOPS analysis.

3. Reforecast system

A reforecast procedure similar to that described in Hagedorn (2008) has been in place since 2015 (see Gagnon et al. 2013b and Gagnon et al. 2014b). As in GEPS 6.1, the reforecast covers 20 years with 4 integration members of 32 days once a week (Thursday 00Z) to generate a historical database of 80 reforecasts for a given date as explained in Gagnon et al. (2014b). The 4 members (instead of 20) are executed to minimize the computational cost. The reforecast system shares almost all the innovations introduced in the 16-day forecasting system, the main ones being the physics update in GEM 5.1.0, and how to quantify the model error and error in the initial conditions. The different atmospheric initial conditions for the 4 members are obtained by adding random isotropic perturbations (see section 3a of Houtekamer et al. 2009) to the ERA5 re-analyzes. As in the medium-range system, the amplitude of random isotropic disturbances is also reduced. Also, as in the 16-day forecast system, the Stochastic Parameter Perturbation (SPP) method replaces the Physics Tendency Perturbation (PTP). The Incremental Analysis Update (IAU) is however not used in the reforecast.

The ocean initial fields come from the ORAS5 ocean reanalysis (Zuo et al. 2015). The sea ice concentration initial fields are the Had2CIS, which was prepared by Woo-Sung Lee of CCCma, who combined the digitized sea ice charts from the Canadian Ice Service (CIS) with the HadISST2.2. The original HadISST2.2 employs an ice chart-based bias correction of the passive microwave record (Titchner and Rayner 2014). The monthly HadISST2.2 data, the digitized CIS weekly sea ice charts over the Arctic region and the weekly CIS "Great Lakes ice charts" over Great Lakes are interpolated to daily data before the combination. The sea ice thickness is interpolated from the monthly ORAS5 data. The near surface air temperature from ERA5 and the snow depth from SPS are used for the initialization of these variables over sea ice in CICE. For the period starting January 2016, the sea ice concentration comes from the CMC GIOPS analysis. As the ORAS5 and the Had2CIS sea ice have a similar climatology as the GIOPS analysis, such change in data source does not cause significant discontinuity in the reforecast behavior.

As in GEPS 6.1, the land surface initial conditions are generated by running the offline Surface Prediction System (SPS; Carrera et al. 2010) but they are now forced with the ERA5 reanalyses. The forcing is also now at the lowest model level, rather than the diagnostic level. This helps with the consistency in surface initial conditions between forecast and reforecast. This off-line system includes a land surface scheme, ISBA (Noilhan & Planton, 1989 and Noilhan and Mahfouf, 1996), as well as a sea ice and a glacier schemes. Each of these schemes is used in the GEM model itself.

Appendix A Description of parameters and algorithms perturbed with the SPP scheme.

The following is a shortened list of Table 3 in the paper by McTaggart-Cowan et al. (2022a). The "Range" column refers to the limits imposed on perturbations' distribution F, the "Time" column to the autocorrelation decay time scale (τ), and the "Shape" column to the parameter controlling the shape of the field distribution (γ=1 implies a uniform distribution and γ=2 a bell-shaped distribution). .

Name	Description	Type	Application	Range	Time(h)	Shape
adv_rhsint	Order of interpolation for semi-Lagrangian advection	Continuous	Error Model	[-0.4,0.4]	24	2
aero_mult	Aerosol concentration for radiative transfer	Continuous	Factor	[0.5,1.5]	36	1
cond_hcst	Cloud condensate threshold for autoconversion to rain	Continuous	Value	[5,15]x10-3 kgkg-1	36	1
crad_mult	Deep convective cloud radius	Continuous	Factor	[0.5,1.5]	36	1
deeprate	Cloud-rain autoconversion rate in deep convection	Continuous	Value	[0.005,0.015] s^{-1}	36	1
dpdd_mult	Downdraft detrainment depth for deep convection	Continuous	Factor	[0.5,1.5]	36	1
fh_mult	Turbulent surface exchange coefficient in the boundary layer for scalars	Continuous	Factor	[0.5,1.5]	36	1
fm_mult	Turbulent surface exchange coefficient in the boundary layer for momentum	Continuous	Factor	[0.5,1.5]	36	1
fnnreduc	Turbulent flux adjustment for boundary layer clouds	Continuous	Value	[0.5,1.5]	36	1
hu0max	Threshold relative humidity for lowerlevel condensation	Continuous	Value	[0.81,0.99]	36	1
hu0min	Threshold relative humidity for upperlevel condensation	Continuous	Value	[0.75,0.95]	36	1
kfctrig4	Critical vertical motion for deep convection over land	Continuous	Value	[0,0.1] m s^{-1}	36	2
kfctrigwh	Threshold convective velocity scale for high-wind conditions over water	Continuous	Value	[-0.05,0.05] m s^{-1}	36	2
kfctrigwl	Threshold convective velocity scale for low-wind conditions over water	Continuous	Value	[0,0.1] m s^{-1}	36	2
mid_minemf	Trigger threshold for low-CAPE convection	Continuous	Value	[12, 110]x 10^7 kg m s^{-1}	36	1
ml_emod	Boundary layer mixing length scale estimate	Continuous	Error Model	[-2.5,2.5]	36	1

rew_mult	Cloud water droplet radius for radiative transfer	Continuous	Factor	[0.5,1.5]	36	1
rei_mult	Effective cloud ice radius for radiative transfer	Continuous	Factor	[0.5,1.5]	36	1
ricmin	Critical Richardson number for laminar turbulent transition	Continuous	Value	[0,0.5]	36	1
rmscon	Velocity spectrum rms of gravity waves at the launching level	Continuous	Value	[0.2,1.8] m s^{-1}	36	1
sgo_phic	Flow blocking by subgrid-scale orography	Continuous	Value	[0.07,0.27]	36	1.39
tkediff	Turbulent transport of turbulence kinetic energy	Continuous	Factor	[0,2]	36	1

4. References

Bélair, S., J. Mailhot, J.W. Strapp, J.I. MacPherson, 1999: An examination of local versus nonlocal aspects of a TKE-based boundary layer scheme in clear convective conditions. *J. Appl. Met.*, **38**, 1499-1518.

Bélair, S., L.-P. Crevier, J. Mailhot, B. Bilodeau, and Y. Delage, 2003a: Operational implementation of the ISBA land surface scheme in the Canadian regional weather forecast model. Part I: Warm season results. *J. Hydromet.*, **4**, 352-370.

Bélair, S., R. Brown, J. Mailhot, B. Bilodeau, and L.-P. Crevier, 2003b: Operational implementation of the ISBA land surface scheme in the Canadian regional weather forecast model. Part II: Cold season results. *J. Hydromet.*, **4**, 371-386.

Bélair, S., J. Mailhot, C. Girard, and P. Vaillancourt, 2005: Boundary-layer and shallow cumulus clouds in a medium-range forecast of a large-scale weather system. *Mon.Wea. Rev.*, **133**, 1938-1960.

Bélair, S., M. Roch, A-M. Leduc, P.A. Vaillancourt, S. Laroche, and J. Mailhot, 2009: Medium-range quantitative precipitation forecasts from Canada's new 33-km deterministic global operational system. *Wea. Forecasting*, **24**, 690-708.

Benoît, R., J. Côté and J. Mailhot, 1989: Inclusion of a TKE boundary layer parameterization in the Canadian regional finite-element model. *Mon. Wea. Rev.*, **117**, 1726-1750.

Bernier, N. B., and S. Bélair, 2012: High horizontal and vertical resolution limited-area model: Near-surface and wind energy forecast applications, *J. Appl. Meteorol. Climatol.*, **51**, 1061–1078.

Blackadar, A. K. 1962: The Vertical Distribution of Wind and Turbulent Exchange in a Neutral Atmosphere, Journal of Geophysical Research, **67**, No. 8, 1962, pp. 3095-3102.

Bloom, S. C., L. L. Takacs, A. M. da Silva, and D. Ledvina, 1996: Data assimilation using incremental analysis updates. *Mon. Wea. Rev.*, 124, 1256–1271.

Bougeault, P. and P. Lacarrère, 1989: Parameterization of orography-induced turbulence in a meso-beta-scale model. *Mon. Wea. Rev.*, **117**, 1872-1890.

Buehner, M., R. McTaggart-Cowan, A. Beaulne, C. Charette, L. Garand, S. Heilliette, E. Lapalme, S. Laroche, S. R. Macpherson, J. Morneau and A. Zadra, 2015: Implementation of Deterministic Weather Forecasting Systems based on Ensemble-Variational Data Assimilation at Environment Canada. Part I: The Global System. *Mon. Wea. Rev.* **143**, 2532-2559. Carrera, M. L., S. Bélair, V. Fortin, B. Bilodeau, D. Charpentier, and I. Doré, 2010: Evaluation of snowpack simulations over the Canadian Rockies with an experimental hydrometeorological modeling system, *J. Hydrometeorol.*, **11**, 1123–1140.

Buehner, M. (2020) Local ensemble transform Kalman filter with cross validataion. *Monthly Weather Review*, **148**, 2265– 2282.

Carrera, M. L., S. Bélair, V. Fortin, B. Bilodeau, D. Charpentier, and I. Doré (2010), Evaluation of snowpack simulations over the Canadian Rockies with an experimental hydrometeorological modeling system, J. Hydrometeorol., **11**, 1123–1140.Charron, M., R.

Charron, M., G. Pellerin, L. Spacek, P. L. Houtekamer, N. Gagnon, H. L. Mitchell, L. Michelin, 2010: Toward Random Sampling of Model Error in the Canadian Ensemble Prediction System, *Mon. Wea. Rev.*, **138**, 1877-1901.

Côté, J., S. Gravel, A. Méthot, A. Patoine, M. Roch and A. Staniforth, 1998a: The Operational CMC-MRB Global Environmental Multiscale (GEM) Model: Part I - Design Considerations and Formulation, *Mon. Wea. Rev.*, **126**, 1373-1395.

Côté, J., J.-G. Desmarais, S. Gravel, A. Méthot, A. Patoine, M. Roch and A. Staniforth, 1998b: The Operational CMC-MRB Global Environmental Multiscale (GEM) Model: Part II - Results, *Mon. Wea. Rev.,* **126**, 1397-1418.

Deacu, D., Fortin, V., Klyszejko, E., Spence, C., Blanken, P.D. 2012. Predicting the Net Basin Supply to the Great Lakes with a Hydrometeorological Model. *Journal of Hydrometeorology*, **13**, 1739–1759.

Dee, D. P., and Co-authors, 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q.J.R. Meteorol. Soc.*, **137**: 553–597.

Delage, Y., 1988a: The position of the lowest levels in the boundary layer of atmospheric circulation models. *Atmos.-Ocean*, **26**, 329-340.

Delage, Y., 1988b: A parameterization of the stable atmospheric boundary layer. *Boundary-Layer Meteor.*, **43**, 365-381.

Erfani, A., and Co-authors, 2013: The New Regional Ensemble prediction System at 15 km horizontal grid spacing (REPS 2.0.1) Canadian Meteorological Centre Technical Note. [Available on request from Environment Canada, Centre Météorologique Canadien, division du développement, 2121 route Transcanadienne, 4e étage, Dorval, Québec, H9P1J3 or via the following web site :

http://collaboration.cmc.ec.gc.ca/cmc/CMOI/product_guide/docs/lib/technote_reps201_20131204_e.pdf

Fillion, L., H. L. Mitchell, H. Ritchie and A. Staniforth, 1995: The impact of a digital filter finalization technique in a global data assimilation system, *Tellus*, **47A**, 304-323.

Gagnon, N., and Co-authors, 2013a: Improvements to the Global Ensemble Prediction System (GEPS) from version 2.0.3 to version 3.0.0. Canadian Meteorological Centre Technical Note. [Available on request from Environment Canada, Centre Météorologique Canadien, division du développement, 2121 route Transcanadienne, 4e étage, Dorval, Québec, H9P1J3 or via the following web site :

http://collaboration.cmc.ec.gc.ca/cmc/CMOI/product_guide/docs/lib/op_systems/doc_opchanges/technote_geps300_20130213_e.pdf

Gagnon, N., and Co-authors, 2013b: Improvements to the Global Ensemble Prediction System (GEPS) from version 3.0.0 to version 3.1.0. Canadian Meteorological Centre Technical Note. [Available on request from Environment Canada, Centre Météorologique Canadien, division du développement, 2121 route Transcanadienne, 4e étage, Dorval, Québec, H9P1J3 or via the following web site :

http://collaboration.cmc.ec.gc.ca/cmc/CMOI/product_guide/docs/lib/technote_geps310_20131204_e.pdf

Gagnon, N., and Co-authors, 2014: Improvements to the Global Ensemble Prediction System (GEPS) from version 3.1.0 to version 4.0.0. Canadian Meteorological Centre Technical Note. [Available on request from Environment Canada, Centre Météorologique Canadien, division du développement, 2121 route Transcanadienne, 4e étage, Dorval, Québec, H9P1J3 or via the following web site :

http://collaboration.cmc.ec.gc.ca/cmc/cmoi/product_guide/docs/lib/technote_geps-400_20141118_e.pdf

Gagnon, N., and Co-authors, 2014b: Improvements to the Global Ensemble Prediction System (GEPS) reforecast system from version 3.1.0 to version 4.0.0. Canadian Meteorological Centre Technical Note. [Available on request from Environment Canada, Centre Météorologique Canadien, division du développement, 2121 route Transcanadienne, 4e étage, Dorval, Québec, H9P1J3 or via the following web site :

http://collaboration.cmc.ec.gc.ca/cmc/cmoi/product_guide/docs/lib/Tech_Note_GEPS400_reforecast_v1.1_E.pdf

Gagnon, N., and Co-authors, 2015: Improvements to the Global Ensemble Prediction System (GEPS) from version 4.0.1 to version 4.1.1. Canadian Meteorological Centre Technical Note. [Available on request from Environment Canada, Centre Météorologique Canadien, division du développement, 2121 route Transcanadienne, 4e étage, Dorval, Québec, H9P1J3 or via the following web site :

http://collaboration.cmc.ec.gc.ca/cmc/CMOI/product_guide/docs/lib/technote_geps-411_20151215_e.pdf.

Geleyn, J.-F. 1985: On a Simple, Parameter-Free Partition between Moistening and Precipitation in the Kuo Scheme., Mon. Wea. Rev., 113, 405-407.

Hagedorn R. 2008: Using the ECMWF reforecast dataset to calibrate EPS forecasts. *ECMWF Newsletter* **117**: 8–13.

Hamill, T. M., R. Hagedorn, J. S. Whitaker, 2008: Probabilistic Forecast Calibration Using ECMWF and GFS Ensemble Reforecasts. Part II: Precipitation. *Mon. Wea. Rev.*, **136**, 2620–2632.

Houtekamer, P. L., M. Buehner and M. De La Chevrotière, 2018: Using the hybrid gain algorithm to sample data assimilation uncertainty. *Q. J. R. Meteorol. Soc.*, 1-22.

Houtekamer, P.L., Mitchell H. L. and Deng X. 2009: Model Error Representation in an Operational Ensemble Kalman Filter, *Mon. Wea. Rev.*, **137**, 2126-2143.

Houtekamer, P. L., X. Deng, H. L. Mitchell, S.-J. Baek and N. Gagnon, 2014: Higher resolution in an operational ensemble Kalman filter, Mon. Wea. Rev, 142, 1143-1162.

HUNKE, E.C., et W.H. LIPSCOMB. CICE: the Los Alamos sea ice model, documentation and *software user's manual, Version 4.1*, Los Alamos (Nouveau-Mexique), Los Alamos National Laboratory, 2010, (rapport technique LA-CC-06-012).

Ioannidou, L., W. Yu, and S. Bélair, 2014: Forecasting of surface winds over Eastern Canada using the Canadian offline land surface modeling system, *J. Appl. Meteorol. Climatol*., **53**, 1760–1774, doi:10.1175/JAMC-D-12-0284.1.

Kain, J. S. and J. M. Fritsch, 1990: A one-dimensional entraining / detraining plume model and its application in convective parameterization. *J. Atmos. Sci.*, **47**, 2784-2802.

Kain, J. S. and J. M. Fritsch, 1993: Convective parameterization for mesoscale models: The Kain-Fritsch scheme. The representation of cumulus convection in numerical models. *Meteor. Monogr*., **27**, Amer. Meteor. Soc., 165-170.

Li, J. and H. W. Barker, 2005: A radiation algorithm with correlated k-distribution. Part I: local thermal equilibrium. *J. Atmos. Sci*., **62**, 286-309.

Li, X. M. Charron, L. Spacek, and G. Candille, 2008: A regional ensemble prediction system based on the moist targeted singular vectors and stochastic parameter perturbations. *Mon. Wea. Rev.*, **136**, 443-462.

Lott, F., and M. Miller, 1997: A new sub-grid scale orographic drag parameterization; its testing in the ECMWF model. *Quart. J. Roy. Meteor. Soc*., **123**, 101-127.

Madec, G. (2008). NEMO ocean engine (Tech. Rep. 27). Paris, France: Note du Pole de modelisation, Institut Pierre - Simon Laplace.

Mailhot, Jocelyn et al: Scientific Description of RPN Physics Library - Version 3.6. Recherche en Prévision Numérique, Meteorological Service of Canada, Dorval, Québec, Canada.

McFarlane, N.A., 1987 : The effect of orographically excited gravity wave drag on the general circulation of the lower stratosphere and troposphere. *J. Atmos. Sci*., **44**, 1775-1800.

McFarlane, N.A., C. Girard and D.W. Shantz, 1987: Reduction of systematic errors in NWP and General Circulation models by parameterized gravity wave drag. Short and Medium-Range Numerical Weather Prediction, Collection of Papers Presented at the WMO/IUGG NWP Symposium, 4-8 August 1986, Tokyo, 713-728.

McTaggart-Cowan, R., P. A. Vaillancourt, A. Zadra, S. Chamberland, M. Charron, S. Corvec, J. A. Milbrandt, D. Paquin-Ricard, A. Patoine, M. Roch, L. Separovic, J., Yang, 2019: Modernization of Atmospheric Physics Parameterization in Canadian NWP. J. Adv. Model. Earth Syst., doi:https://doi.org/10.1029/2019MS001781.

McTaggart-Cowan, R., L. Separovic, R. Aider, M. Charron, M. Desgagné, P. L. Houtekamer, D. Paquin-Ricard, P. Vaillancourt and A. Zadra, 2022a: Using stochastic parameter perturbations to represent model uncertainty, part I: implementation and parameter sensitivity. TBD

McTaggart-Cowan, R., L. Separovic, M. Charron, D. Xingxiu, N. Gagnon, P. L. Houtekamer and A. Patoine, 2022b: Using stochastic parameter perturbations to represent model uncertainty, part II: Comparison with existing techniques in an operational ensemble. TBD

McTaggart-Cowan, R. and A. Zadra, 2015: Richardson Number Hysteresis in a Boundary Layer Parametrization. *Mon. Wea. Rev*. **143**, 1232–1258.

Noilhan, J. and S. Planton 1989: A simple parameterization of land surface processes for meteorological models, *Mon. Wea. Rev.*, **117**, 536-549.

Noilhan, J., and J. F. Mahfouf, 1996: The ISBA land surface parameterisation scheme, Global Planet. Change, **13**, 145–159.

Pudykiewicz, J., R. Benoit, and J. Mailhot, 1992: Inclusion and verification of a predictive cloud water scheme in a regional weather prediction model. *Mon. Wea. Rev.*, **120**, 612-626.

Separovic, L., S. Z. Husain, W. Yu, and D. Fernig (2014), High-resolution surface analysis for extended-range downscaling with limited-area atmospheric models, *J. Geophys. Res. Atmos.*, **119**, 13,651–13,682, doi:10.1002/2014JD022387.

Shutts, G. (2005), A kinetic energy backscatter algorithm for use in ensemble prediction systems. *Q.J.R. Meteorol. Soc.*, **131**: 3079–3102. doi: 10.1256/qj.04.106

Smith, G.C., F. Roy, M. Reszka, D. Surcel Colan, Z. He, D. Deacu, J.-M. Belanger, S. Skachko, Y. Liu, F. Dupont, J.-F. Lemieux, C. Beaudoin, B. Tranchant, M. Drévillon, G. Garric, C.-E. Testut, J.-M. Lellouche, P. Pellerin, H. Ritchie, Y. Lu, F. Davidson, M. Buehner, M. Lajoie and A. Caya, 2016: Sea ice Forecast Verification in the Canadian Global Ice Ocean Prediction System. Quart. J. Roy. Met. Soc., **142**, 659–671, doi: 10.1002/qj.2555.

Sundqvist, H., E. Berge and J. E. Kristjansson, 1989: Condensation and cloud parameterization studies with a mesoscale numerical weather prediction model. *Mon. Wea. Rev.*, **117**, 1641-1657.

Vaillancourt P. and co-authors, 2012: Improvements to the Regional Deterministic Prediction System (RDPS) from version 2.0.0 to version 3.0.0 Canadian Meteorological Centre Technical Note. Available via the following web site :

http://collaboration.cmc.ec.gc.ca/cmc/cmoi/product_guide/docs/lib/op_systems/doc_opchanges/technote_rdps300_20121003_e.pdf

Zadra, A., M. Roch, S. Laroche and M. Charron, 2003: The Subgrid scale Orographic Blocking Parameterization of the GEM Model, *Atmos. Ocean*, **41**, 151-170.

Zuo, H., Balmaseda, M. A. and Mogensen, K., 2015. The new eddy-permitting ORAP5 ocean reanalysis: description, evaluation and uncertainties in climate signals. Climate Dynamics, 10.1007/s00382-015-2675-1.

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