Environment and Climate Change Canada   Environnement et Changement climatique Canada

ECMWF ANNUAL SEMINAR 2022
"LAND SURFACE AND OROGRAPHIC DRAG" SESSION

Challenges representing orographic drag in (Canadian) numerical prediction systems

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Canada

OUTLINE

- Brief introduction to orographic drag and its representation in numerical models
- Some international initiatives/projects in past 10 years
- Recent progress and challenges in Canadian models regarding orographic drag, in terms of
  - *model resolution*
  - *system complexity*
  - *forecasting expectations and products*

OROGRAPHIC DRAG

Surface stress/drag

$$\vec{\tau} = (\tau_x, \tau_y)$$

is the force parallel to the surface, per unit area, applied by the earth's surface (all types of surface) on the atmosphere.

In a typical forecast model:

$$\vec{\tau} = \vec{\tau}^{res} + \vec{\tau}^{phy}$$

resolved (dynamics)

$$p_s \vec{\nabla} h_{res}$$

proportional to gradient/slope of resolved orography

parametrized (physics)

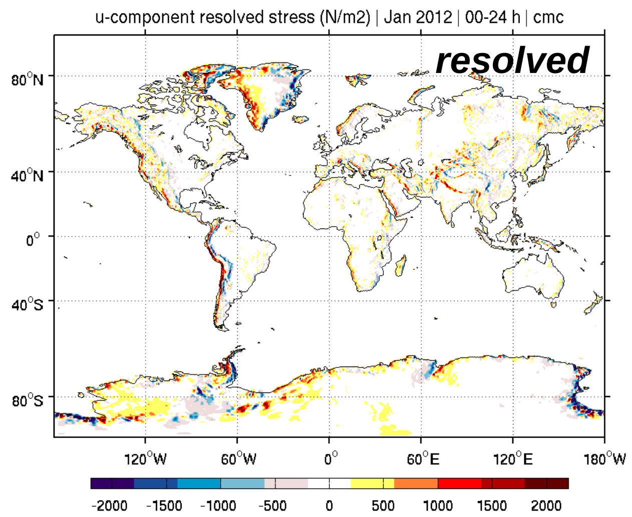
$$\vec{\tau}^{pbl} + \vec{\tau}^{sgo}$$

turbulence over all surfaces (water, ice, land, etc.)

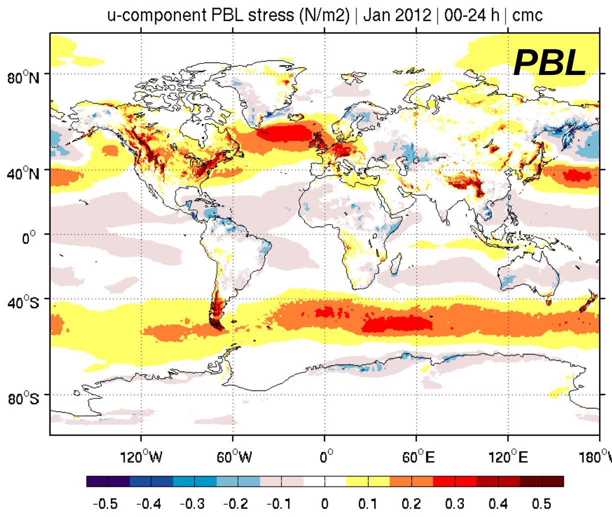
landcover & orography

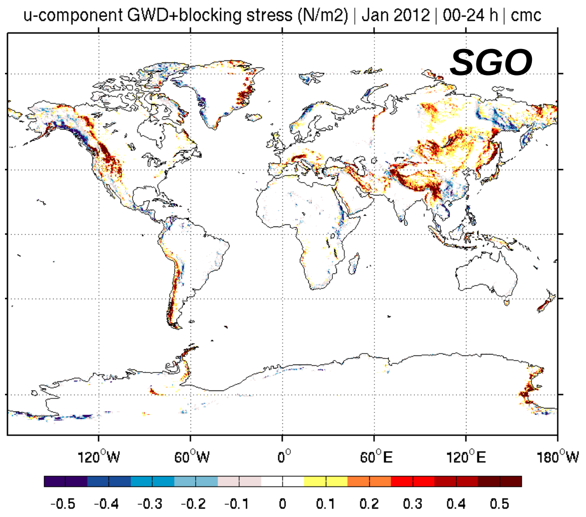
other orographic schemes (e.g. gwd, oro-blocking)

orographic drag



$$\tau_x$$





Examples of a winter-averaged, x-component of surface stress: resolved (top), PBL (bottom left) and SGO (bottom right) components, derived from a global simulation with the Canadian GEM model. (From the WGNE Drag Project report).
https://collaboration.cmc.ec.gc.ca/science/rpn/drag_project/

WGNE* DRAG PROJECT (2013)

https://collaboration.cmc.ec.gc.ca/science/rpn/drag_project/

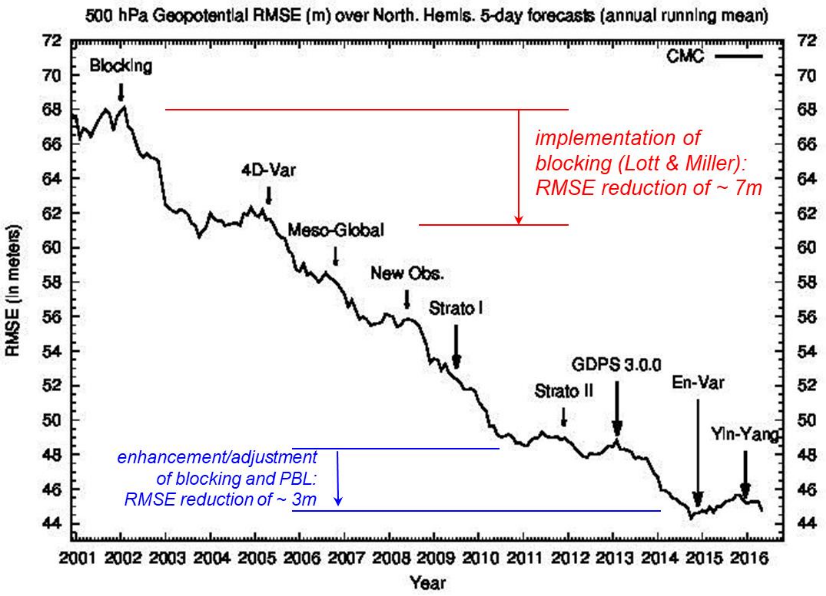
A model inter-comparison of surface drag motivated by

- *sensitivity to and uncertainty in momentum-related schemes, reported by WGNE members*
- *relative scarcity of projects on the subject*

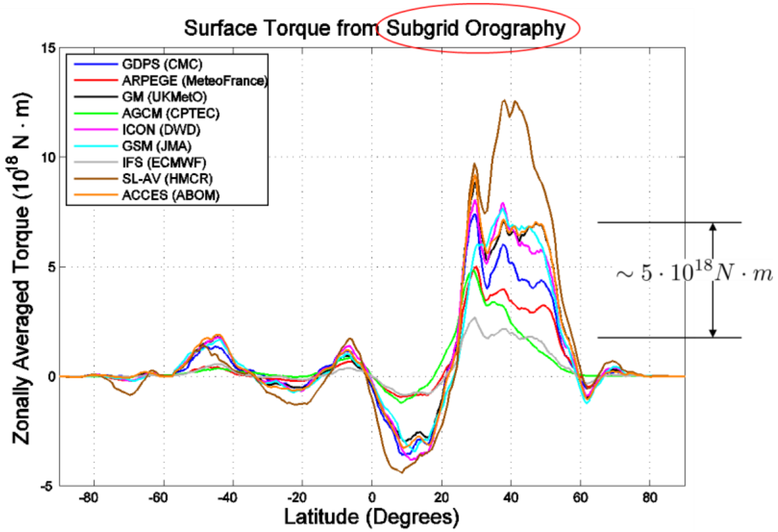
> **Large uncertainty in the partition** of stress between distinct processes over orography (PBL versus SGO)

> Sensitivity to "numerical" details, e.g.
- *how **ancillary data** are generated*
- ***resolution issues**, e.g. definition of "unresolved" / "subgrid scale", and*
- *sensitivity of schemes to horizontal and vertical **discretization***
- *model **dynamics-physics coupling***

> **New guidance needed** to clarify the above issues, e.g.
- *new theoretical insights*
- *new observational data or better use of existing data*
- *numerical experiments (e.g. high resolution simulations)*
- *further collaboration (e.g. inter-comparison projects, bringing together NWP and climate modellers)*



Examples of impact from changes to orographic drag/schemes on Z500 rmse of the Canadian global deterministic prediction system (GDPS)



Example of orographic drag differences among models: intercomparison of winter-averaged, zonally-averaged torque from the subgrid orography scheme.

*** W**orking **G**roup on **N**umerical **E**xperimentation (https://wgne.net/)*
supports numerical experimentation research activities and reports to WMO Research Board

OTHER INITIATIVES

ECMWF/WCRP/WWRP Workshop on
Drag processes and their links to large-scale circulation
12-15 September **2016**, ECMWF
https://www.ecmwf.int/en/learning/workshops-and-seminars/drag-processes-and-their-links-large-scale-circulation

Themes*:*
- representation and uncertainty of drag processes in models across scales
- constraining drag: observations and fine-scale modelling

Intercomparison of orography ancillary fields:
Elvidge et al., JAMES **2019**:
Uncertainty in the representation of orography in weather and climate models and implications for parameterized drag
https://doi.org/10.1029/2019MS001661

WWRP/WCRP TEAMx (since 2020)

*Multi-scale **t**ransport and **e**xchange processes in the **a**tmosphere over **m**ountains – programme and e**x**periment*
(http://www.teamx-programme.org/)

- includes observational campaign and numerical modelling activities for application over mountainous terrain
- more details in following presentation by Annelize van Niekerk

GASS/WGNE COORDE (since 2019)

COnstraining **OR**ographic **D**rag **E**ffects:
A Model Comparison of Resolved and Parametrized Orographic Drag

To investigate the following points w.r.t. orographic drag:

- ***parametrization differences****: how formulations/combinations vary across models*
- ***resolution sensitivity****: how well parametrized drag mimics explicitly resolved orography in high resolution simulations*
- ***forecast error characteristics****:*
    - *which forecast errors are due to drag parametrization errors?*
    - *are these errors systematic across models?*

using a detailed protocol of numerical experiments (low, middle & high resolution; global and regional; with and without parametrized drag).

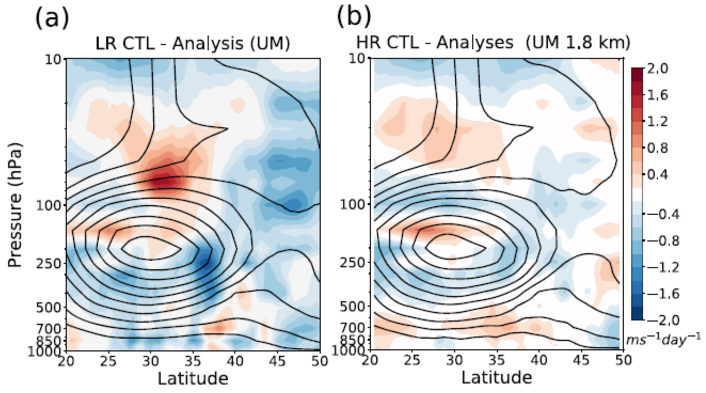


Figure 12. Zonal wind error (model minus analysis) in (a) UM LR CTL and (b) UM 1.8 km HR CTL at the end of the 24 hr forecasts, averaged over the set of 14 forecasts and longitudinally averaged over the ME (shading). Thick black contours are the mean zonal wind in the model, with a 5 ms^{-1} contour interval.

Figure from [van Niekerk et al. 2020, JAMES](https://doi.org/).
Some key points:
- most climate/seasonal resolution models underestimate stratospheric drag
- some climate resolution models overestimate parametrized orographic drag in troposphere

FILTERING THE RESOLVED OROGRAPHY

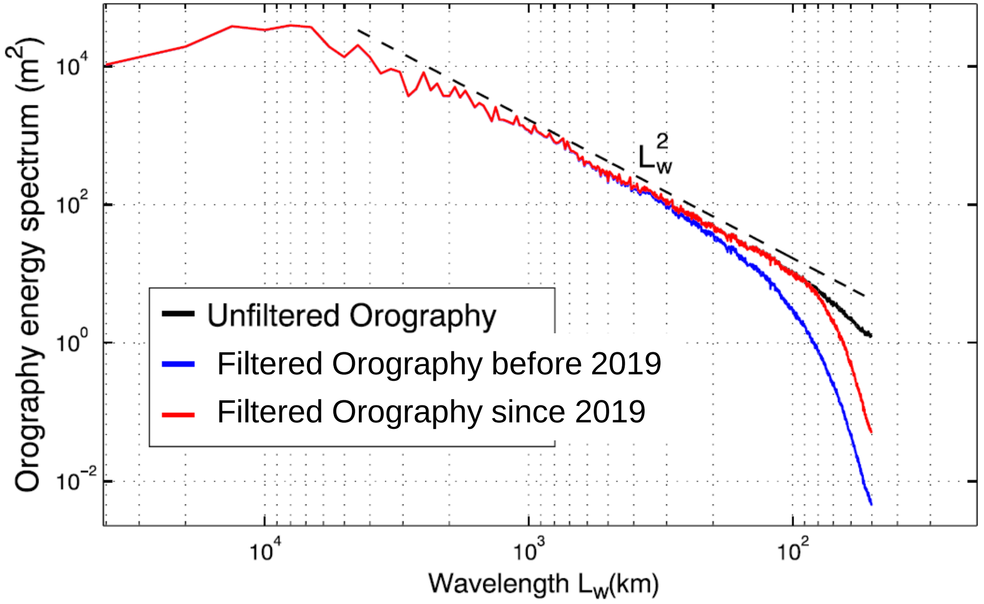
"resolved" orography	h_{res} =	*orography "seen"/used by the model dynamical core*

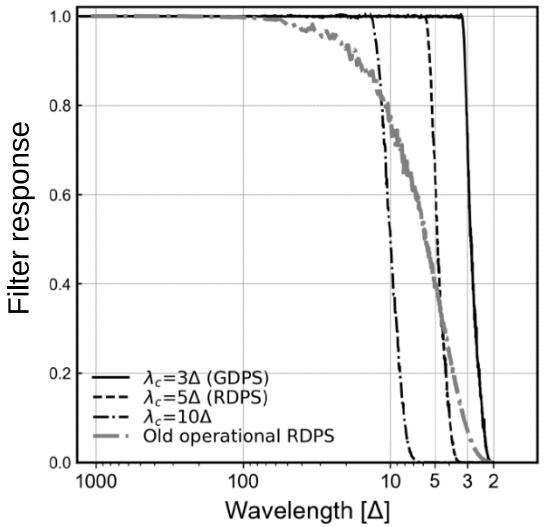
resolved orographic drag/stress : $\vec{\tau}^{res} = p_s \vec{\nabla} h_{res}$

surface pressure (p_s) — ***gradient/slope of of resolved orography*** ($\vec{\nabla} h_{res}$)

- controlling some numerical properties of the dynamical core (e.g. precision, stability) usually requires that the **resolved orography be smoothed to some degree** (i.e. filtering out or attenuating the "smallest scales" of orography may be needed)
- the **"optimal" orography filter** may vary from one dynamical core to the other
- in principle, the definition of unresolved/subgrid orography and the parametrization of the associated processes depend on how the resolved orography is filtered

Source: R. McTaggart-Cowan et al. 2019, JAMES: [Modernization of Atmospheric Physics Parameterization in Canadian NWP]





Figures: A comparison between the resolved orography in the Canadian GEM model and that used by other operational centers* revealed that, until 2019, the smoothing operator attenuated orography with wavelengths up to 20 grid lengths (20 Δx). A filter with a sharper response function was adopted in 2019, with a wavelength cutoff at 3 Δx for the global deterministic model (GDPS) and 5 Δx for the regional deterministic and ensemble systems (RDPS and REPS).

* See e.g. *Sandu, I., A. Zadra and N. Wedi, 2016: Orographic drag impacts forecast skill.* *[ECMWF Newsletter Issue 150, Winter 2017]*

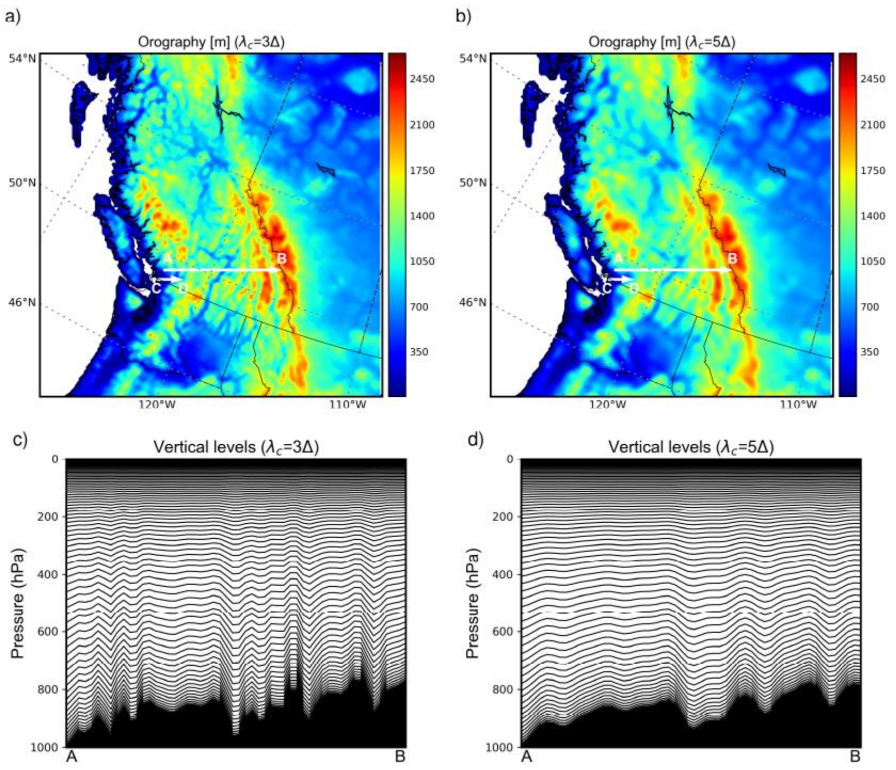
OPTIMAL OROGRAPHY RESOLUTION

From a study by

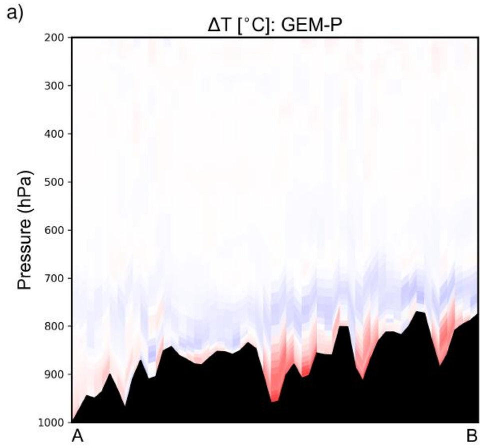
Husain, S.Z., L. Separovic and A. Zadra, 2022:
Optimal fine-scale orographic resolution for numerical weather prediction in the context of effective model resolution
(Submitted to *J. Applied Meteorology and Climatology)*

about issues/errors in the Canadian GEM model:

- **Flow-dependence** (e.g. surface-layer stability): large error can appear in near-surface temperature for flow over orography involving 3Δ (or smaller) length-scales
- **High-impact weather**: in winter, error leads to considerable warming over the valleys; can lead to erroneous predictions of freezing rain
- **Cause**: issue appears to be largely resulting from error in dispersion associated with spatial discretization employed by the model
- **Solution**: error can be eliminated by removing any orographic fine-scale smaller than the optimal orographic resolution which, through a series of experiments, is determined to be around 7~8Δ
- **Recommendations**: optimal orographic resolution is (unsurprisingly) similar to model's effective resolution; attention must be given when stationary forcings in the form of orography are retained at scales below a model's effective resolution



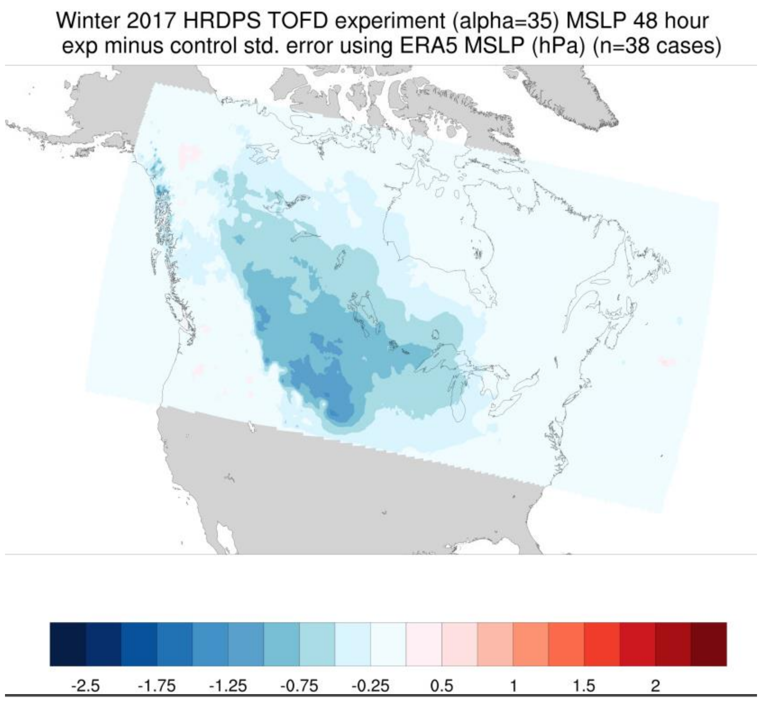
Top: Resolved orography of a test domain over the Canadian Rockies, with nominal resolution Δ = 10km, and two filter cut-offs: (a) λ_c=3Δ and (b) λ_c=5Δ . Bottom: Vertical cross-section including the orography and the model levels along the line denoted by in the upper row figures.



Vertical cross-section of temperature difference for a forecast lead time of 24h between two experiments with orography based on λ_c=3Δ and λ_c=5Δ. The differences represent the mean from 10 winter-time forecasts initialized at 0000 UTC for 10 consecutive days starting on 10-Jan-2017.

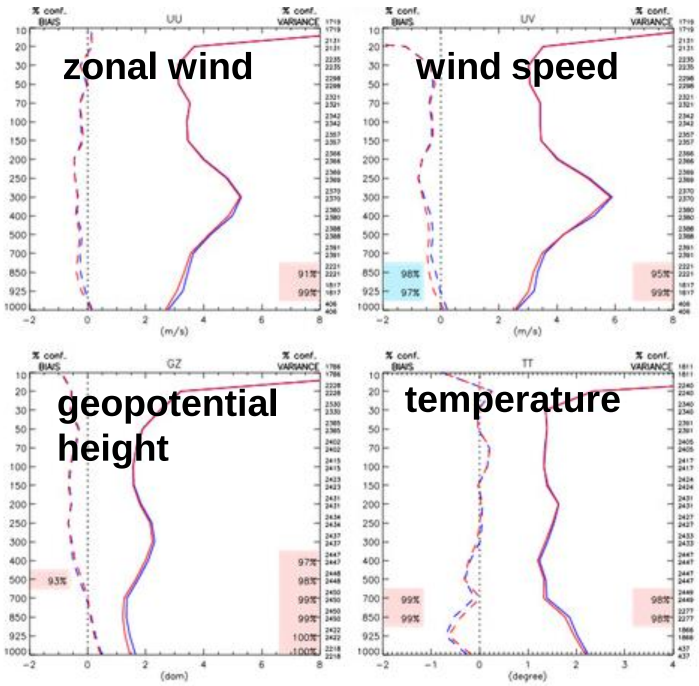
IMPROVEMENTS TO THE REPRESENTATION OF OROGRAPHIC DRAG IN THE CANADIAN HRDPS*

In Dec 2021, the Turbulent Orographic Form Drag (TOFD) scheme** was successfully implemented in the operational HRDPS



Impact of TOFD activation on winter 2017 MSLP forecasts: reduction of stde at t+48h, against ERA5 analyses.

Impact of TOFD on verification against radiosondes (dash line for bias, solid line for stde) at t+48h, for winter 2017 over the model domain: reduction of stde for tropospheric winds, temperature and geopotential. ***no-TOFD*** *vs* ***with-TOFD***



[Material kindly provided by S. Corvec (RPN-A)]

*** H**igh **R**esolution (2.5km) **D**eterministic **P**rediction **S**ystem*

****** *[Beljaars et al. 2004, QJRMS](#)*

IMPROVEMENTS TO THE REPRESENTATION OF OROGRAPHIC DRAG IN THE CANADIAN HRDPS*

Severe winter forecast over British Columbia (BC) in Jan 2020 – a busy month in terms of high impact weather and snow storms:

- *the HRDPS (without TOFD) struggled in forecasting snow in the valleys, with a tendency to break the surface outflow too early and warm up to quickly; many major snow storms were completely missed or under-estimated*
- *with the activation of TOFD, the HRDPS showed a* ***significant improvement in forecasting surface inflow/outflow*** *and therefore snow storms*

Impact on services:

According to forecasters, “ *the improvement of the forecast in Winter on the Pacific coast is very important” :*

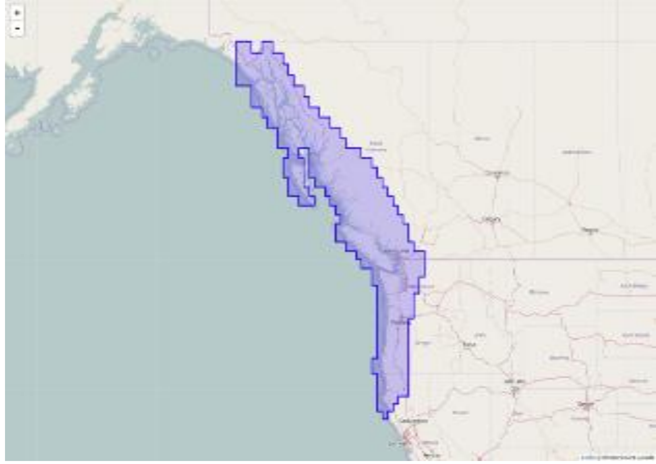
- *major change in the orographic precipitation over BC*
    - *more precip along on the windward side of the Coast Mountains and the coastal valleys*
    - *less precip at the peak of the Coast Mountains, on the leeward side and over the Columbia & Rocky Mountains*
    - *although the new version may have a positive precipitation bias in some narrow valleys due to an incorrect elevation (too high), this change seems to be moving in the right direction*
- *major change/improvement of the winter* ***HIW**** *in the narrow valleys of BC*
    - *more snow, in terms of amounts/fraction/frequency, in the coastal valleys due to a better accuracy in forecasting surface inflow/outflow* ”

**** High Impact Weather***

** **H**igh **R**esolution (2.5km) **D**eterministic **P**rediction **S**ystem*

[Material kindly provided by M. Verville (CMDN)]

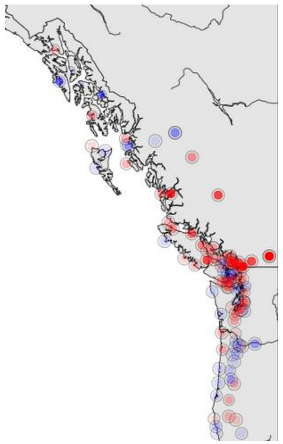
TOFD IMPACT ON WINTER FORECAST OVER THE PACIFIC COAST



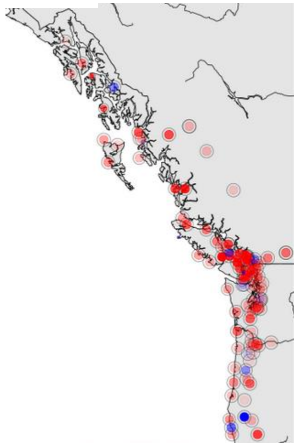
RMSE — Jan-Feb 2020

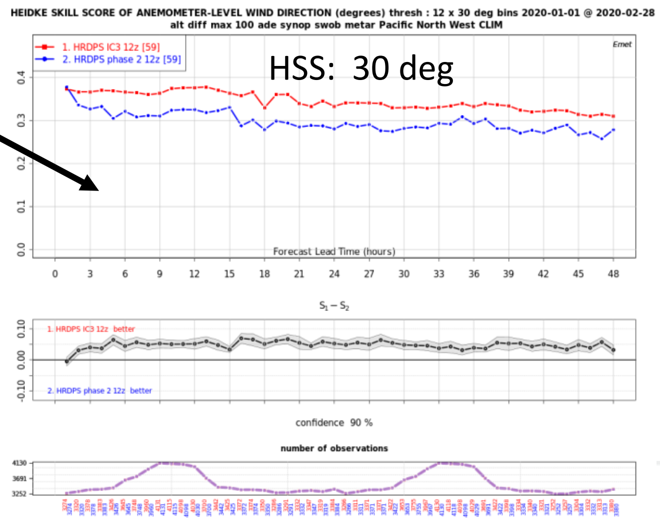
Pacific North West CLIM	TD	1.65%	2.92%	8.74%	9.12%
	TT	1.50%	2.28%	5.76%	5.54%
Pacific North West CLIM	UV	3.74%	4.18%	10.75%	10.47%
Pacific North West CLIM	WD	6.89%	6.52%	16.35%	16.08%
Pacific North West CLIM	PO	0.34%	0.56%	13.52%	10.11%

TT: valid at 00Z (t+24)



TD: valid at 00Z (t+36)



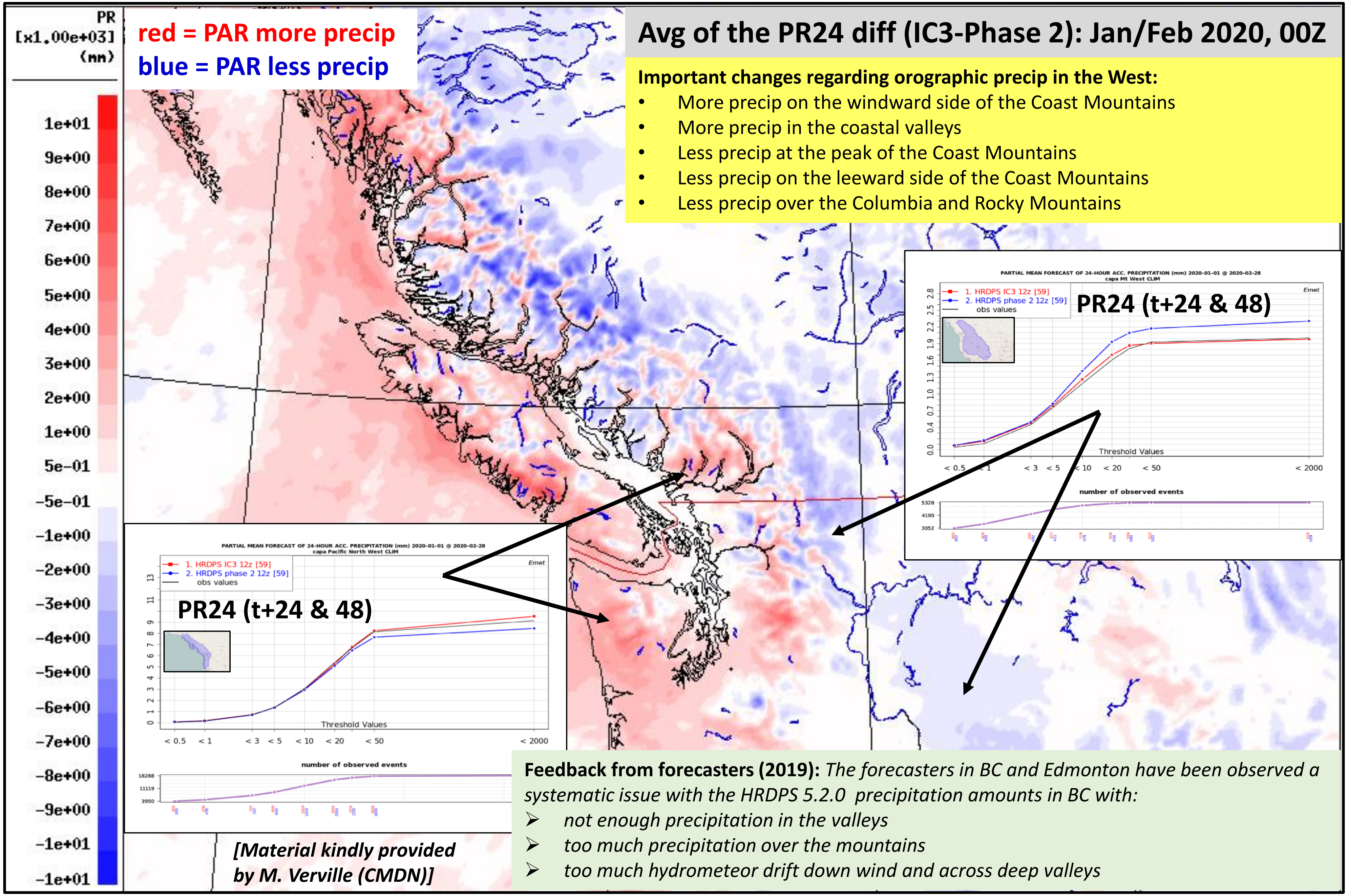


- Scores against surface stations: “improvements in winter over the Pacific coast are quite impressive!”

Part of the significant improvement in wind direction scores is due to a more accurate forecasts of surface inflow/outflow in costal valleys (attributed to the TOFD scheme)

[Material kindly provided by M. Verville (CMDN)]

Avg of the PR24 diff (IC3-Phase 2): Jan/Feb 2020, 00Z



Important changes regarding orographic precip in the West:

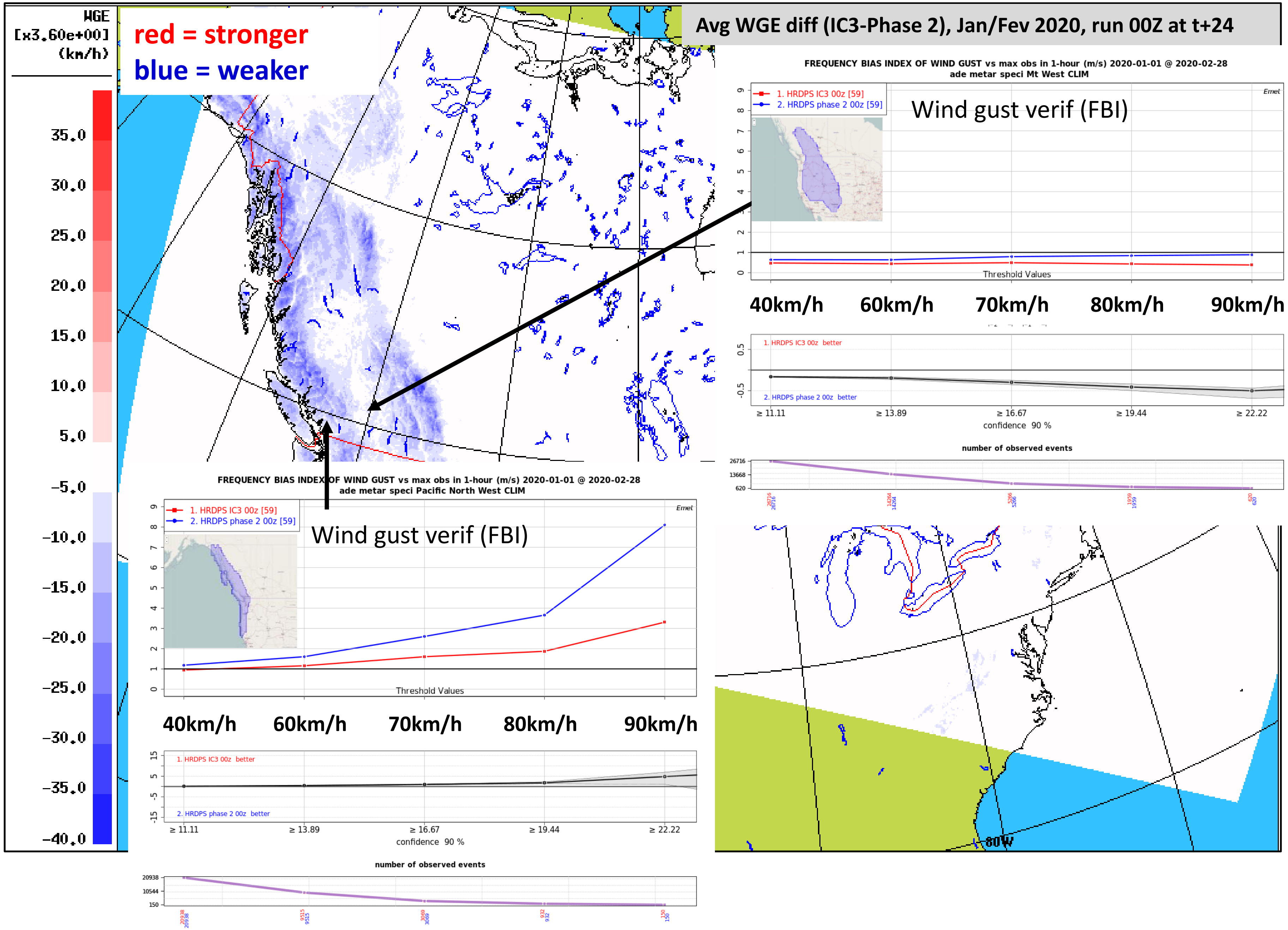
- More precip on the windward side of the Coast Mountains
- More precip in the coastal valleys
- Less precip at the peak of the Coast Mountains
- Less precip on the leeward side of the Coast Mountains
- Less precip over the Columbia and Rocky Mountains

Feedback from forecasters (2019): *The forecasters in BC and Edmonton have been observed a systematic issue with the HRDPS 5.2.0 precipitation amounts in BC with:*

- ➢ *not enough precipitation in the valleys*
- ➢ *too much precipitation over the mountains*
- ➢ *too much hydrometeor drift down wind and across deep valleys*

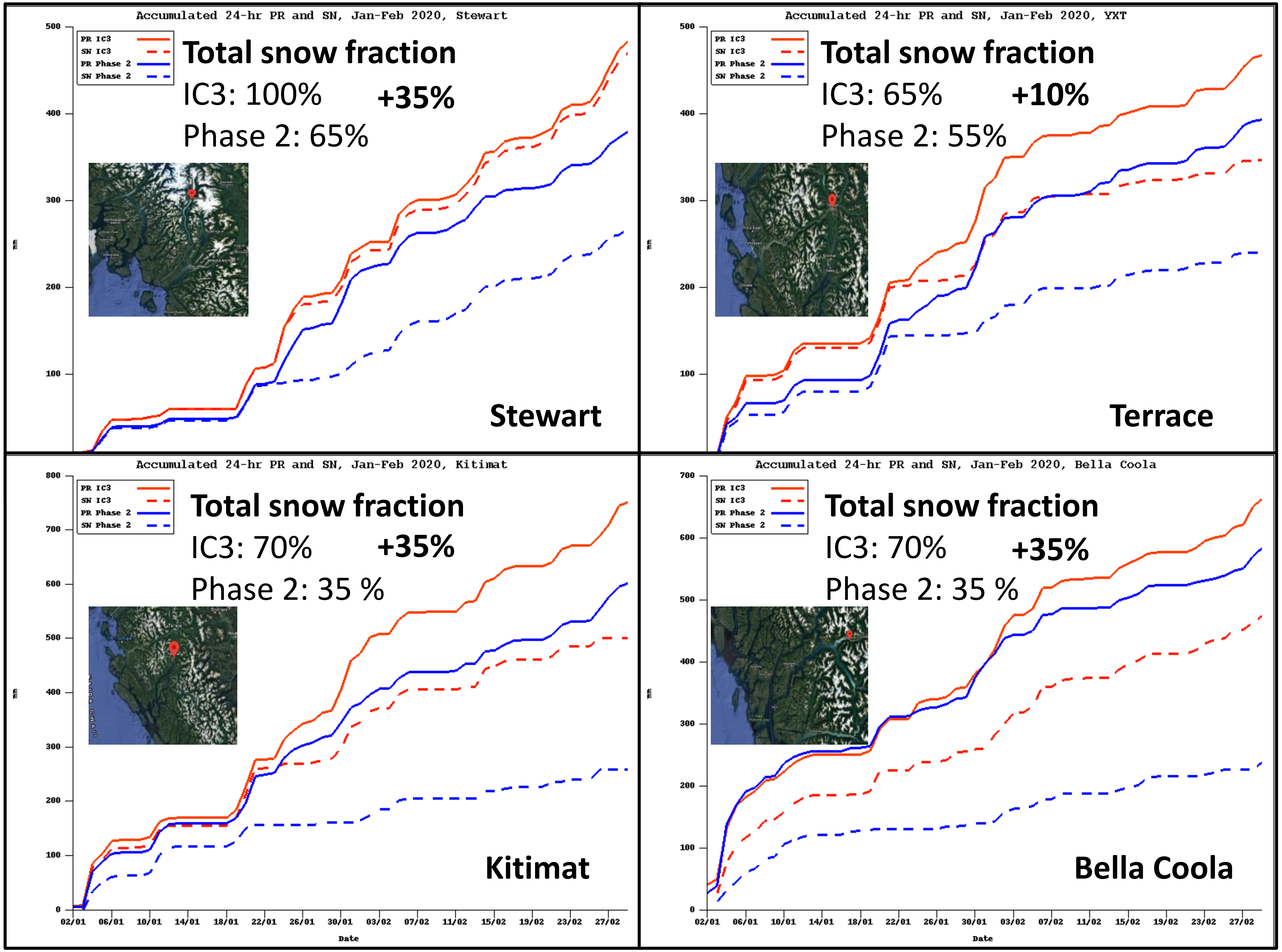
[Material kindly provided by M. Verville (CMDN)]

Winter forecast in BC – Sustained/Gust wind speed



- The is a significant reduction of the 10-m sustained and gust wind speed and in BC
- This reduction seems to be positive on the west side of the Coast Mountains and negative on the east side

[Material kindly provided by M. Verville (CMDN)]



PR24 and SN24 summation for Jan and Feb 2020

PR24
SN24

Higher amounts of SN forecasted by IC3 in these coastal valleys are not just related to higher amounts of total precipitation, but also an higher fraction of snow

no-TOFD vs ***with-TOFD***

[Material kindly provided by M. Verville (CMDN)]

STOCHASTIC PARAMETER PERTURBATIONS (SPP) OF SUBGRID OROGRAPHY (SGO) SCHEME

R. McTaggart-Cowan et al. 2022, MWR:
Using Stochastically Perturbed Parameterizations to Represent Model Uncertainty Part I: Implementation and Parameter Sensitivity

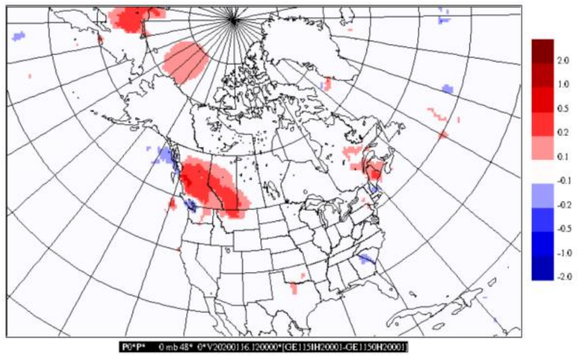
- in Dec 2021, **SPP** was implemented in the Canadian **operational** ensemble prediction system
- one of the 20+ perturbed parameters is the **orographic blocking** “critical phase” H_{nc} (eq. 9 in Lott & Miller 1997) used to calculate the vertical distribution of the drag

Figures kindly provided by L. Separovic (RPN-A):

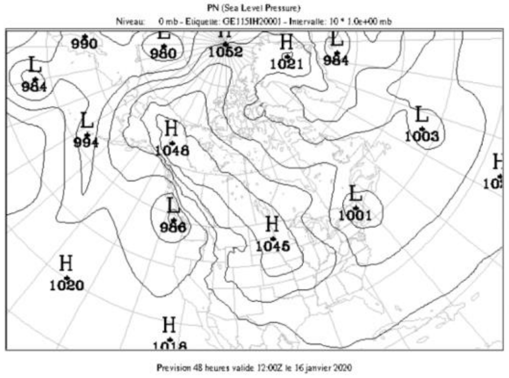
- example of impact from SGO parameter perturbations
- SGO SPP fractional contribution to ensemble spread is localized bellow 700 hPa and impacts temperature and surface pressure
- synoptic situation is shown in the upper right panel
- ensemble mean error for T-850hPa is very large (up to 8K) over the southern Prairies

Case of 14-Jan-2020 12Z, t+48h

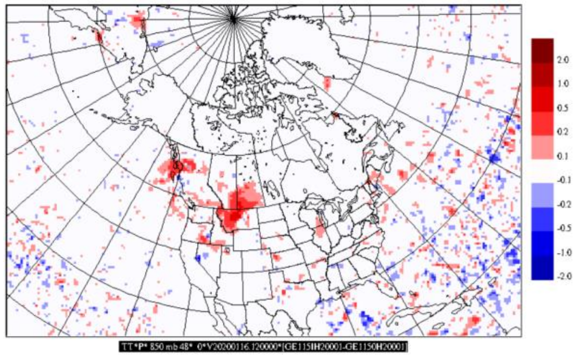
Ens. spread in Psurf



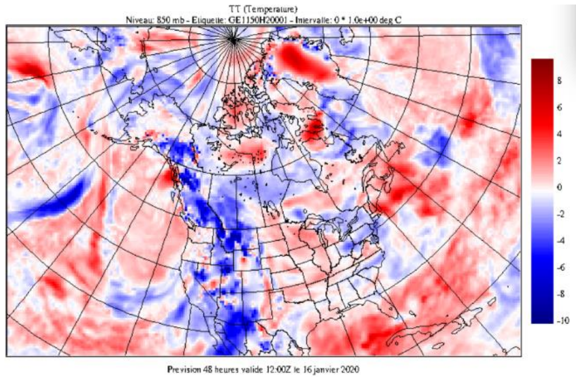
Ens. mean SLP



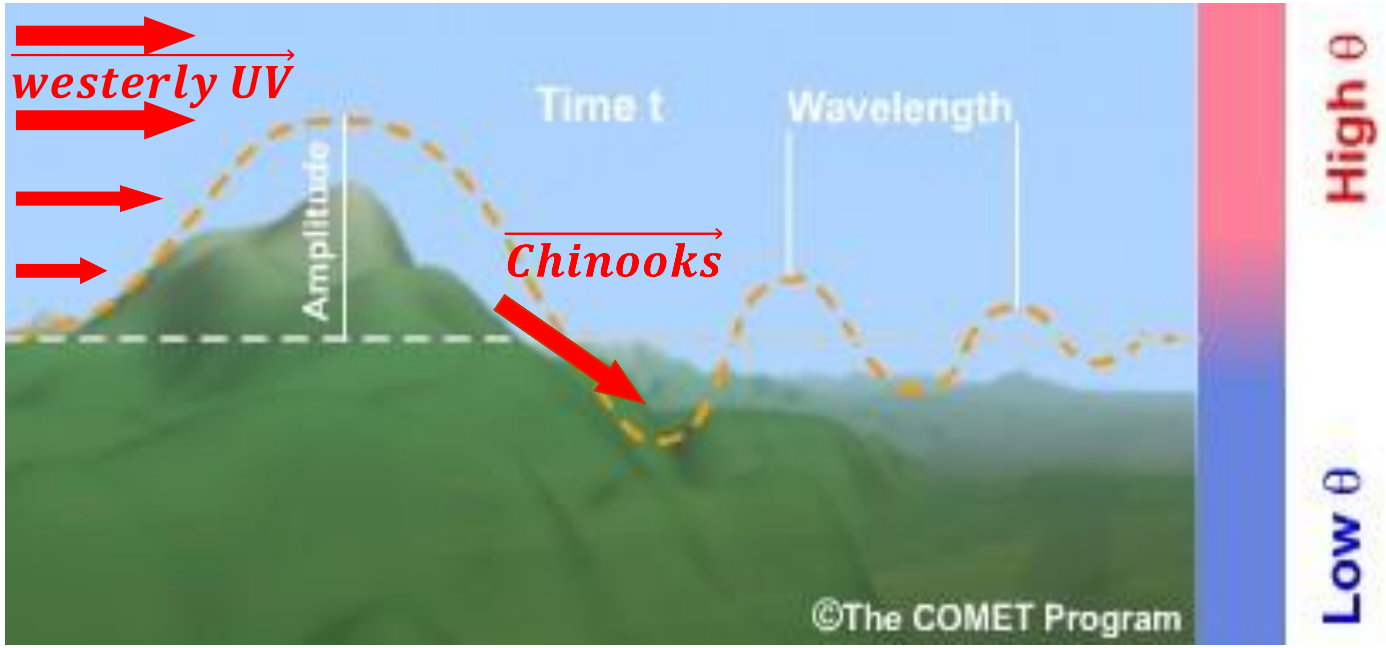
Ens. spread in T-850hPa



Ens. mean error T-850hPa



HIGH-IMPACT WEATHER: CHALLENGES WITH CHINOOKS

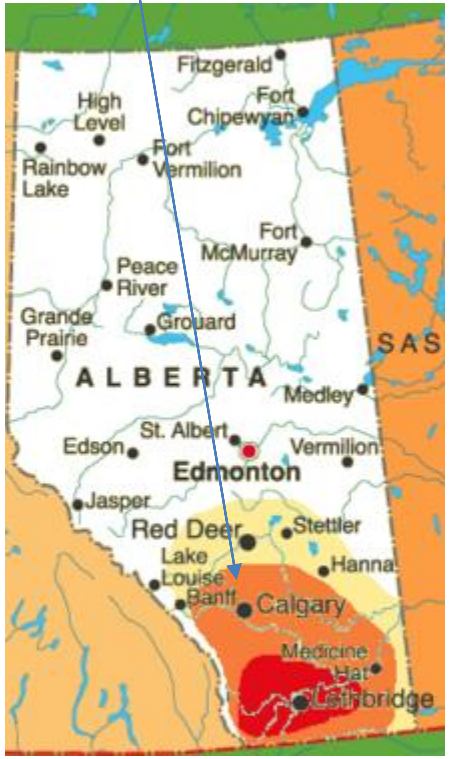


Chinooks are a Föhn Winds, i.e. a rain shadow winds resulting from the subsequent adiabatic warming of air which has dropped most of its moisture on windward slopes (orographic lift). The air on the leeward slopes then becomes warmer than equivalent elevations on the windward slopes.

The onset of Chinooks arises with the replacement of an arctic air mass by a maritime air mass over the Rockies. The warmer air setting over the Rockies creates favorable conditions for Mountain Wave (MW) activity. This triggers a downslope flow on the leeward side of the Rockies, which increases surface temperatures through adiabatic warming. MWs also generate a buoyancy oscillation (orange dotted line) on the downwind side. Chinook Winds have a gusty nature and often reach values up to 120 km/h.

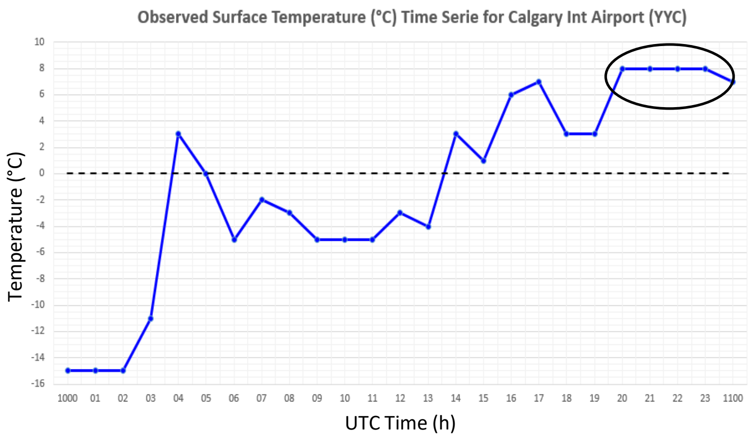
Various cases reported of significant errors near-surface temperature predicted by the HRDPS, near Calgary, Alberta, during Chinook events. Errors were not eliminated by the activation of TOFD. Issue if currently under investigation…

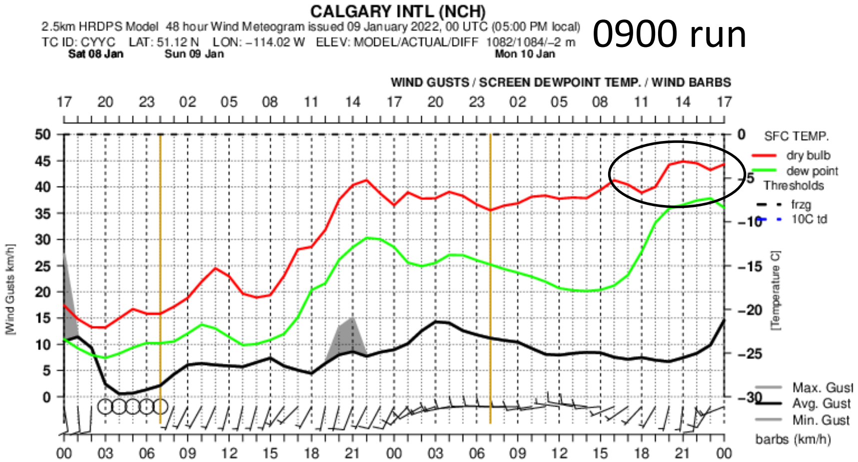
Chinooks are more frequent over Southeastern Alberta

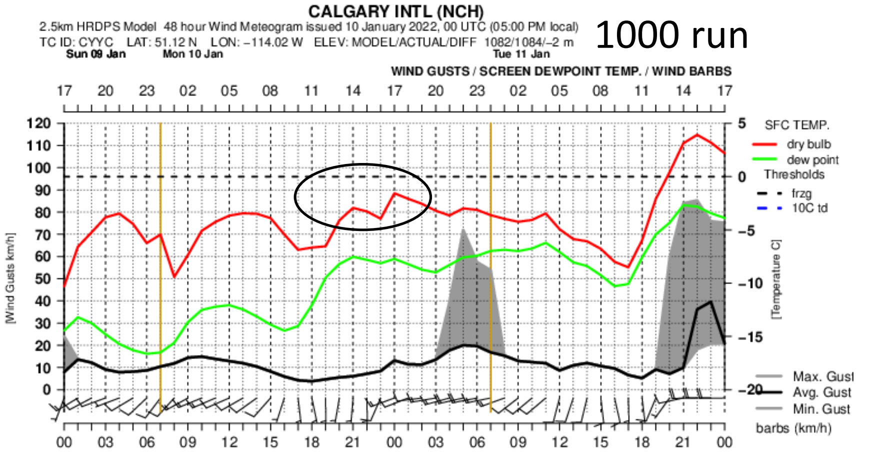


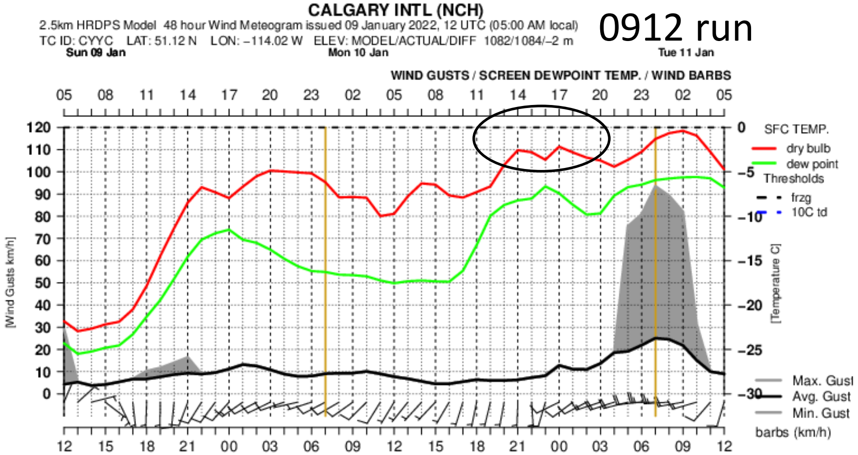
[Material kindly provided by M. Verville and M. Powers Jr(CMDN)]

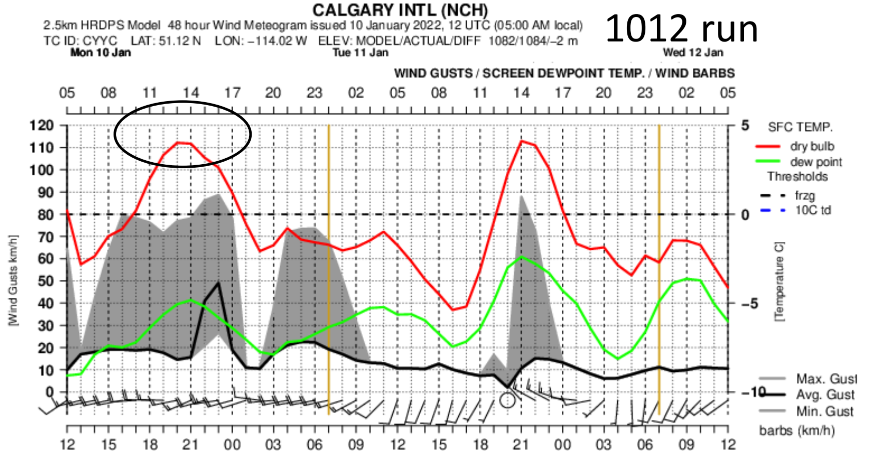
HRDPS Performance for Calgary – Chinook event of Jan. 10th











- Similar issues in HRDPS surface temperature forecast were seen with different lead times (48h, 36h, 24h and 12h)
- HRDPS 2022011012 run had the best forecast for Calgary, but still had a cold bias of 4-5°C
- **NOTE**: HRDPS was able to reproduce the upper level synoptic pattern for the event (500mb, 700mb), but issues in the HRDPS forecast increased closer to the surface – Not shown here

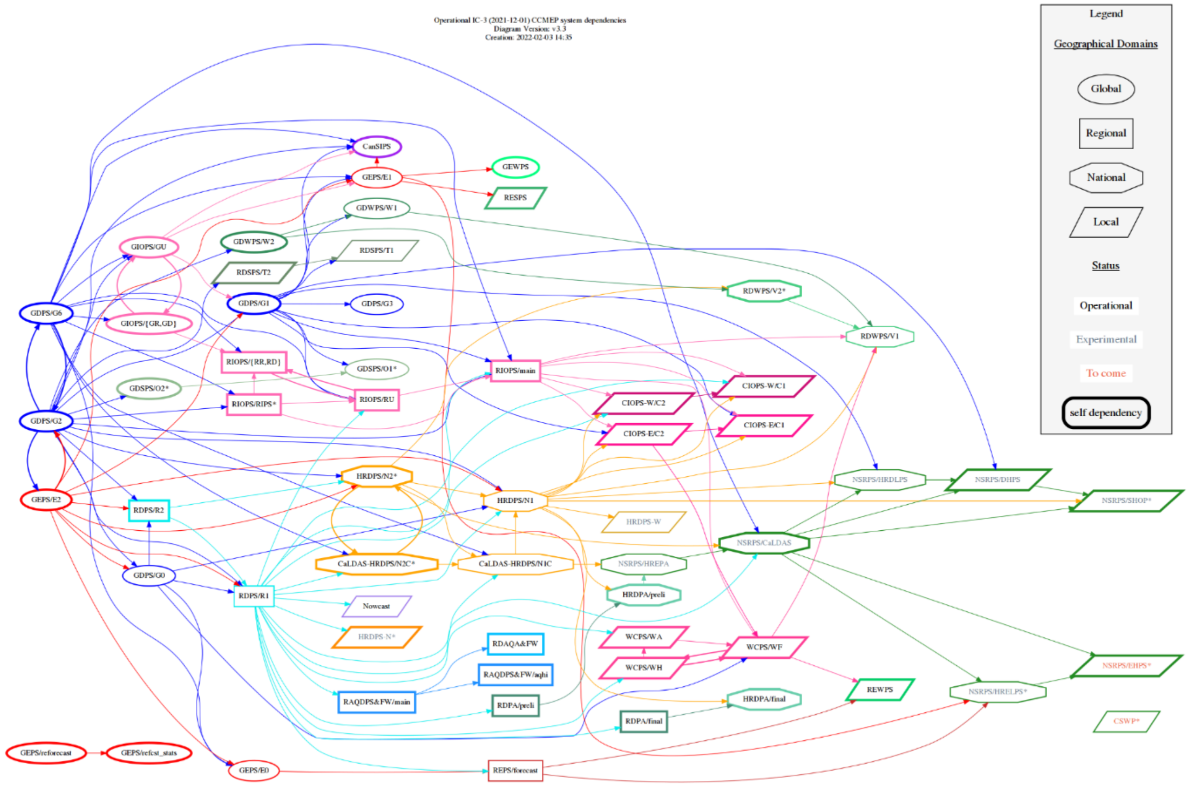
[Material kindly provided by M. Verville and M. Powers Jr(CMDN)]

CHALLENGES RELATED TO RESOLUTION AND INCREASING COMPLEXITY

- in the year 2000*, the Canadian Meteorological Centre services were mainly based on **3** systems
  - *global deterministic (res. 100km)*
  - *regional deterministic (res. 25km)*
  - *global ensemble*

- in Dec 2021 (see diagram):
  - ***31** systems (global, continental, national, regional)*
  - *resolution range: from 40km to 1km and finer*
  - *deterministic and ensemble*
  - *atmospheric and environmental (ocean, seaice, waves, hydrology, urban); some coupled*
  - *188 dependencies*
  - ***orography** plays a role in many of these systems => increasing need for seamless representation of orographic processes*

Diagram of systems dependencies as of Dec 2021,
produced by the Canadian Integration and Software Infrastructure Standardisation unit (CMDI)



** when I started working at the Canadian Centre*

CHALLENGES RELATED TO RESOLUTION AND INCREASING COMPLEXITY

Example of resolution issue probably related to orography processes, reported by D. Deacu (CMDE):

Based on results from the **High Resolution Ensemble Land Surface Prediction System** (HRELPS) designed to

- *produce daily 16-day and weekly 32-day high-resolution (2.5-km) ensemble forecasts of surface and near-surface variables*
- *provide high quality input fields to ensemble hydrological systems*

Atmospheric forcings are provided by REPS (10km) up to 72h leadtime, and GEPS (40km) at later leadtimes – note that both systems went through a major upgrade in Dec 2021.

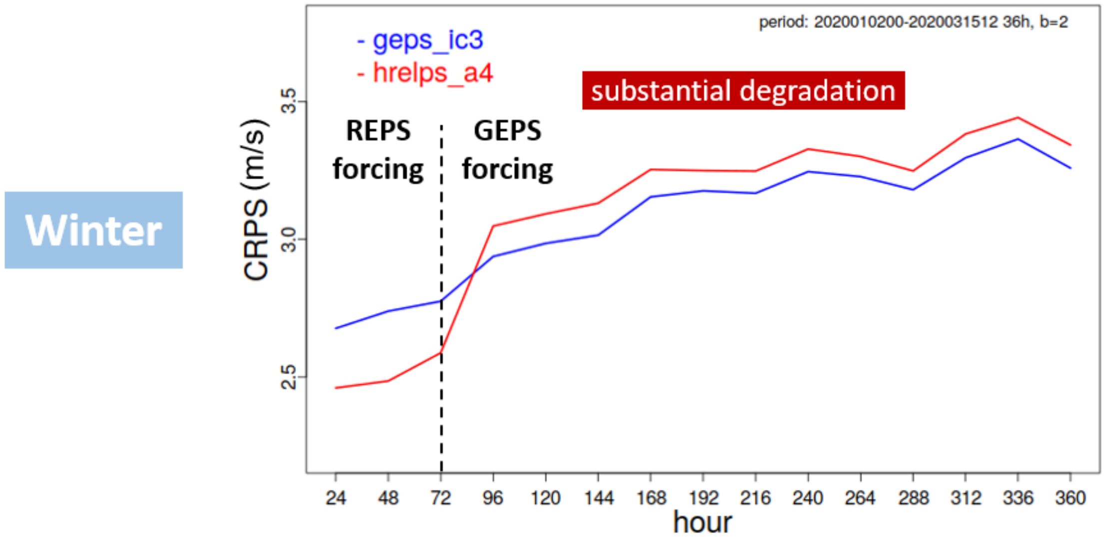


Figure kindly provided by D. Deacu (CMDE): Comparison of 10-m wind CRPS (winter 2020) of the HRELPS in before (blue) and after (red) changes implemented in Dec 2021. Cause of degradation (and possible solution) are currently under investigation.

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THANK YOU / MERCI !

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