Government of Canada Gouvernement du Canada

Greyzone in the Great White North: Recent Developments at the Canadian Meteorlogical Centre

Ron McTaggart-Cowan, Ayrton Zadra, Paul Vaillancourt, Leo Separovic, Danahe Paquin-Ricard, Jason Milbrandt, Caroline Jouan and Howard Barker

Canada

Definitions

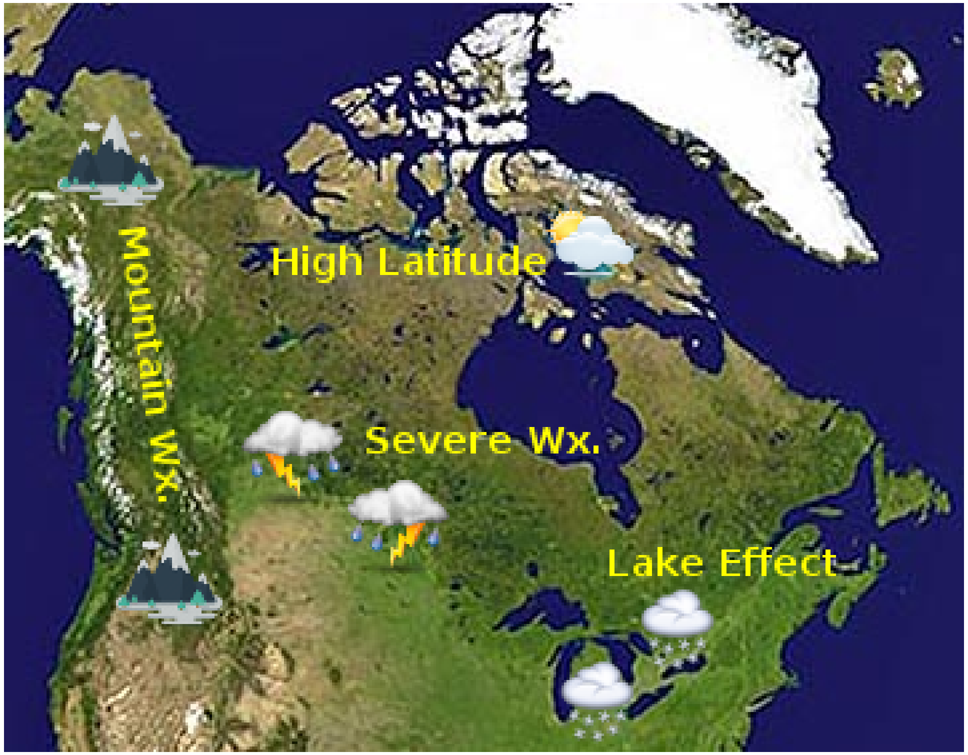
- For this discussion, we adopt a fairly liberal definition for “greyzone”:

> The range of time and space scales over which a parameterization changes from being necessary to detrimental either because the process becomes resolved or the formulation of the closure breaks down

- In addition to the standard interpretation for **horizontal** resolution, this concept applies to **vertical** and **temporal** resolution as well.

Overview

The large variety of potentially high impact weather events in Canada means that different greyzone challenges are faced in different regions.

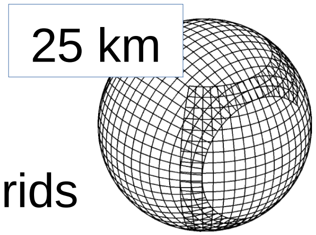


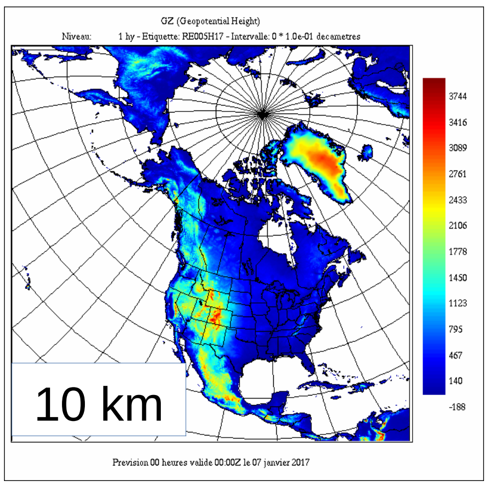
Canadian weather elements associated with current greyzone problems.

- Brief overview of operational NWP systems at CMC
- Mountain meteorology
  - Resolving katabatic flows
  - Orographic filtering and scale separation
- Summer severe weather
  - Representing deep convection at “convection permitting” resolution
  - The need for deep convection at the greyzone boundary
- Lake effect snow bands
  - Semi-resolved and grid-aligned snow bands
- High latitude
  - Impact of low sun angles on shading and reflection

NWP at the Canadian Meteorological Centre

Yin-Yang Global Lat/Lon Grids





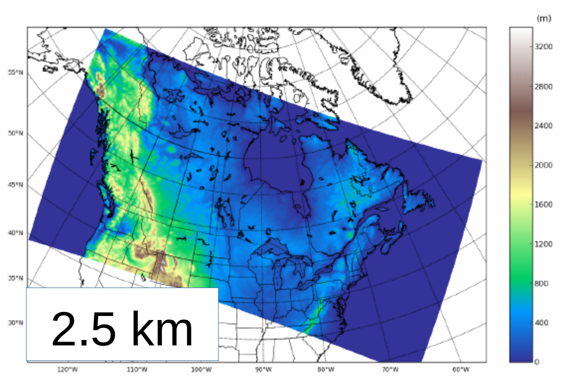


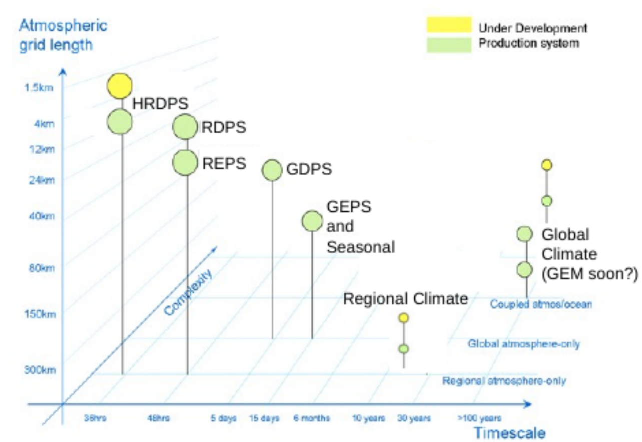
FIG. 1. The HRDPS domain over Canada and northern U.S. Colors represent model topography in meters.

The Global Environmental Multiscale model (GEM; Girard et al. 2014) is used for all NWP activities at the CMC, running at grid spacings from 1° to 2.5 km.

Horizontal greyzone issues become important primarily for the Regional Deterministic Prediction System (RDPS) and the High Resolution Deterministic Prediction System (HRDPS).

Vertical greyzone issues apply to all configurations.

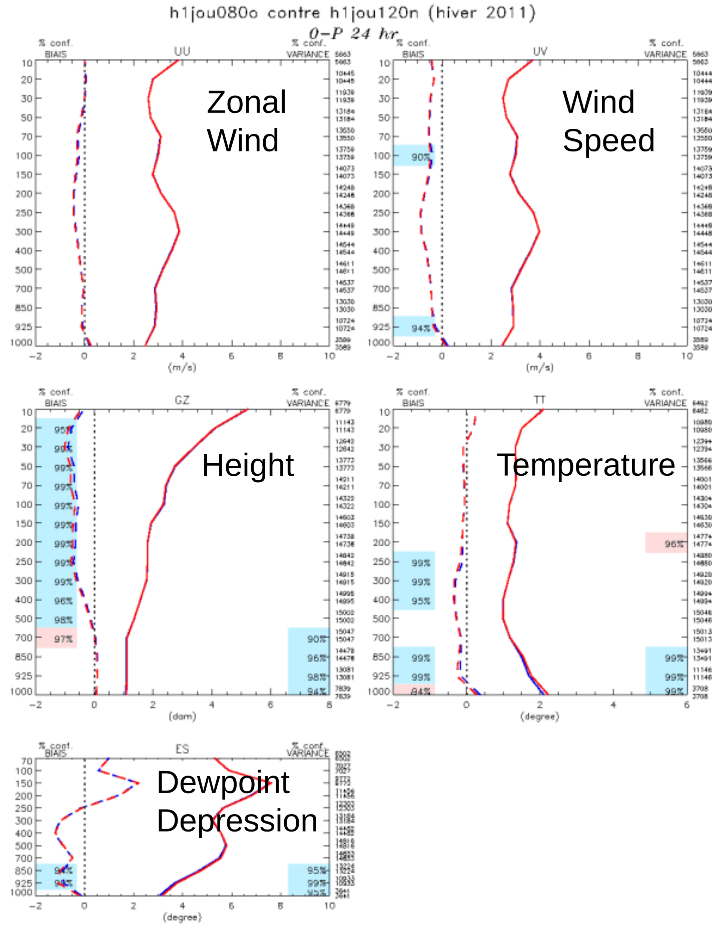
Sample Yin-Yang global grid (top), RDPS model domain (middle) and HRDPS national domain (bottom).



Hierarchy of modelling systems (adapted from the Met Office).

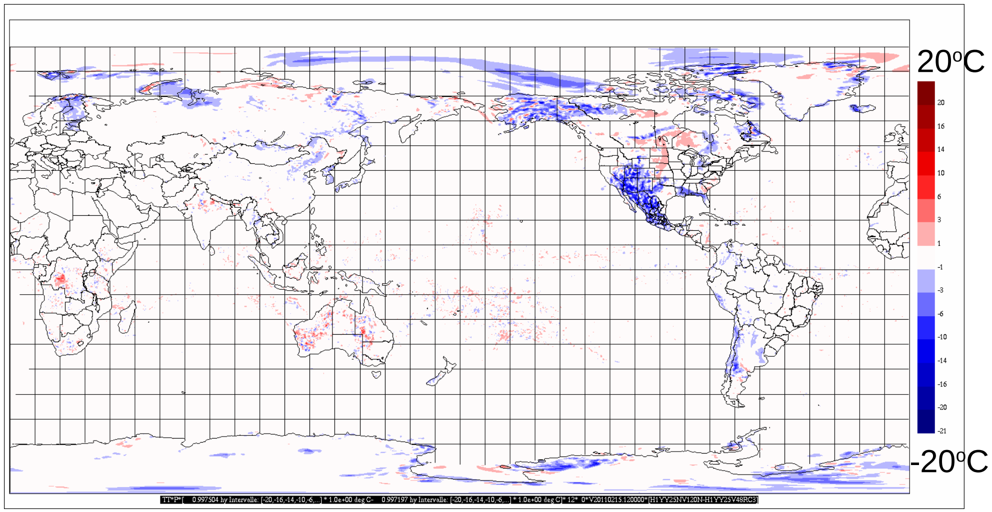
Increasing vertical resolution

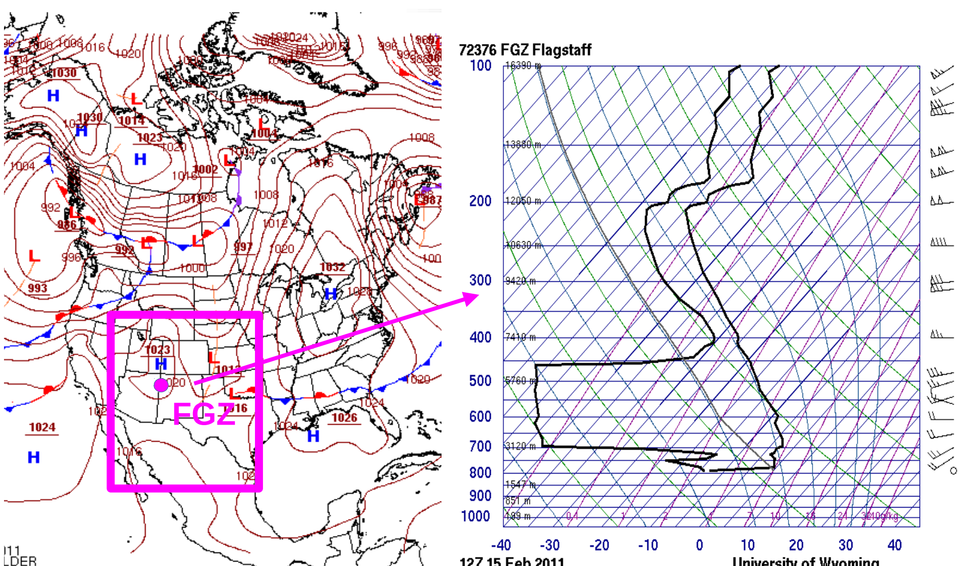
- In all systems at CMC (L80) near-surface vertical resolution is coarse, with the first level at 40 m (20 m thermodynamic)
- An experimental L120 configuration with a lower 10 m level (5 m thermodynamic) yields poor results
- The largest degradations are the result of excessive cooling in mountainous areas overnight



Standard error (solid) and bias (P-O; dashed) against Northern Hemisphere radiosondes after 24 h for a 2-month winter period in the control (blue) and experiment with high vertical resolution (red).

Cooling in Mountainous Regions





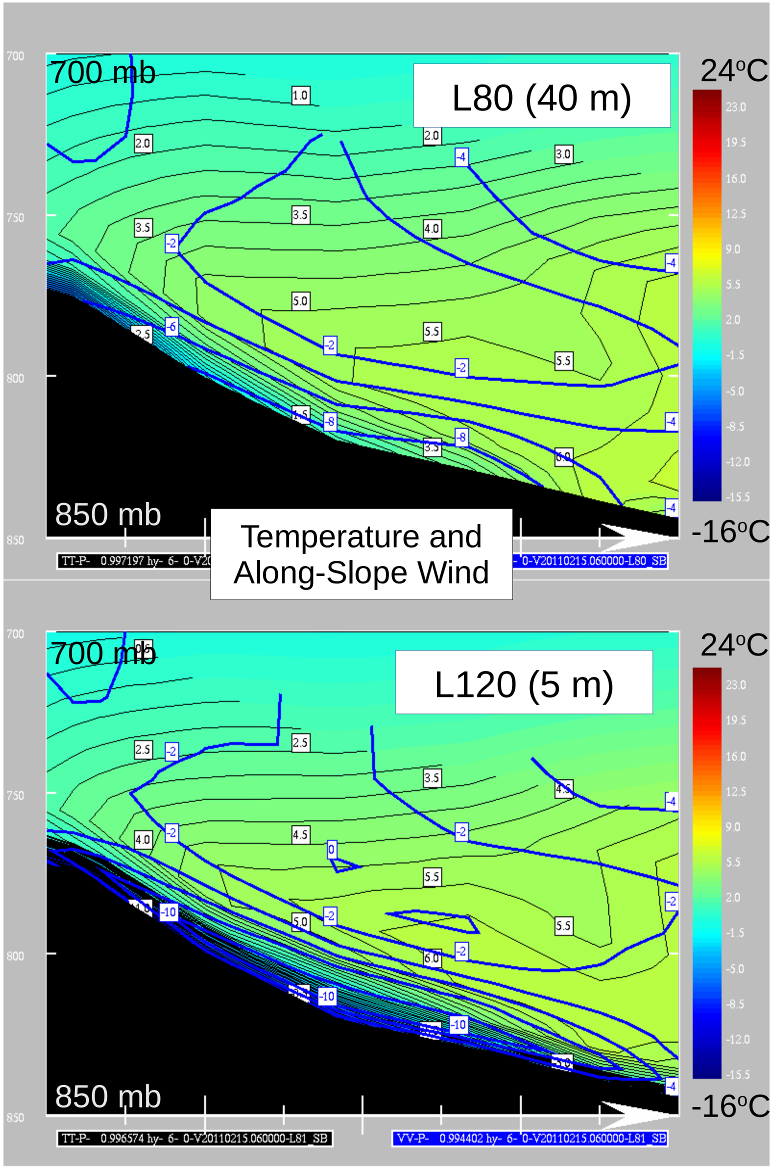
Cooling is most obvious when synoptic forcing is relatively weak.

A representative case is chosen, where widespread cooling at the 20 m level is evident in the L120 configuration.

A strong surface inversion and surface shear is present in the sounding.

Mean 20 m temperature difference (L120-L80) in the 12 h forecast from the 2 month winter period (top; valid 1200 UTC). Analysis for 1200 UTC 15 Feb 2011, with LAM test domain in magenta (left), and the Flagstaff sounding (right) as indicated.

Resolving Katabatic Flows



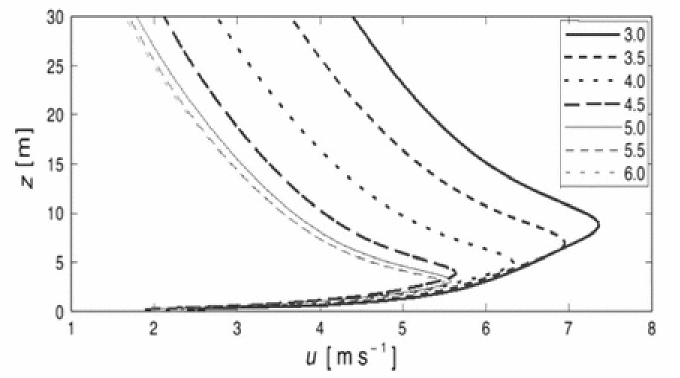
Radiative cooling creates an along-slope pressure gradient that drives a dowslope (katabatic) flow in both configurations.

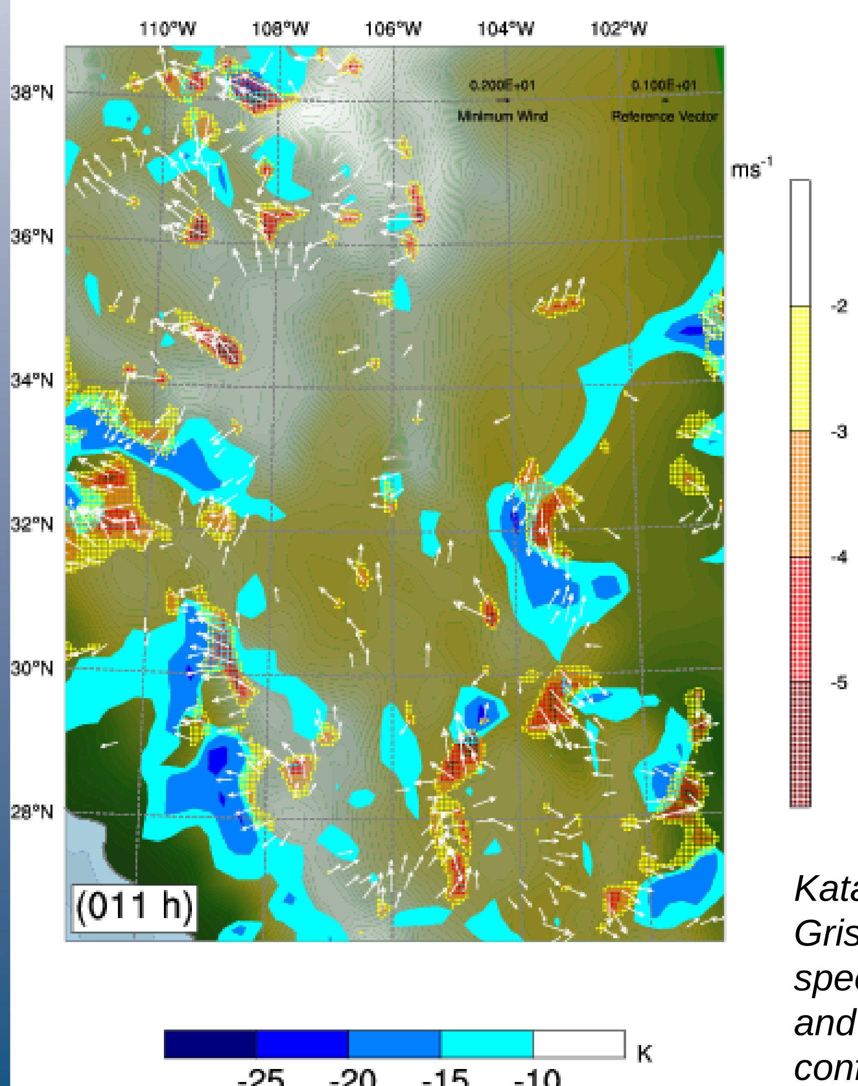
With higher vertical resolution, both the downslope wind speed and cool near-surface temperatures are amplified.

Stronger wind shear across the surface layer enhances turbulent fluxes and ensures that cooling is transmitted to the atmosphere.

Typical cross-section of temperature (colours) and along-slope winds (blue contours, with negative values downslope) in the L80 (top) and L120 (bottom) configurations.

Resolving Katabatic Flows





Low level jets in katabatic flows peak at 5-10 m, coincident with the lowest level in the L120 run.

Enhanced downsloping is associated with cold pool formation when vertical resolution is increased.

Katabatic flow speeds by slope angle in LES (top; Grisogono and Alexen (2012)). Downslope low level jet speeds at 20m (arrows), enhanced flow (warm colours) and cold pools (cold colours) for the L120-L80 configurations. Model orography is plotted in background green/grey colours for reference.

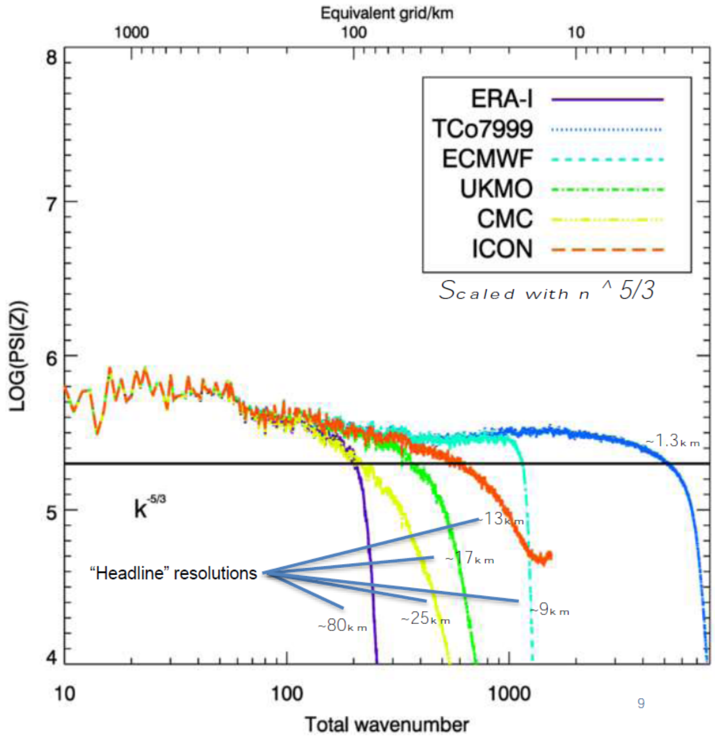
Resolving Katabatic Flows

- With a deep surface layer, operational configurations do not resolve the shallow drainage flows; instead, they rely on surface layer stability functions for fluxes.
- At such coarse vertical resolutions, NWP systems may require parameterization of these flows (Haiden and Whiteman 2005): GEM does not have such a scheme
- With a 5-m level, the model begins to develop an under-resolved density-driven feature but yields overly intense cold pools in valleys

Vertical Greyzone: What near-surface vertical resolution is needed to fully resolve katabatic flows, eliminating the need for parameterization via stability functions or a dedicated scheme?

Terrain Resolution

- The orography in the operational GEM configurations is heavily filtered to avoid the generation of fine-scale structures that may be under-resolved
- However, our current filter appears to be overly pessimistic regarding the effective resolution of the model (Vosper et al. 2016), leaving too much of the terrain variance to subgrid parameterizations

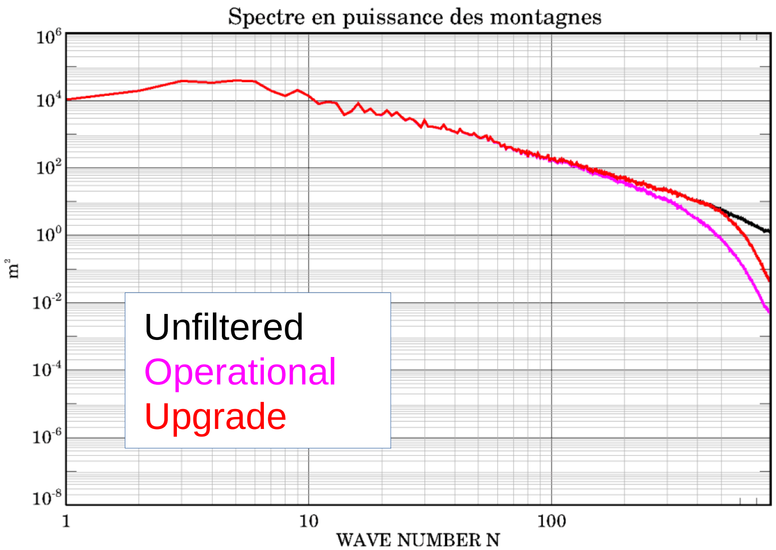


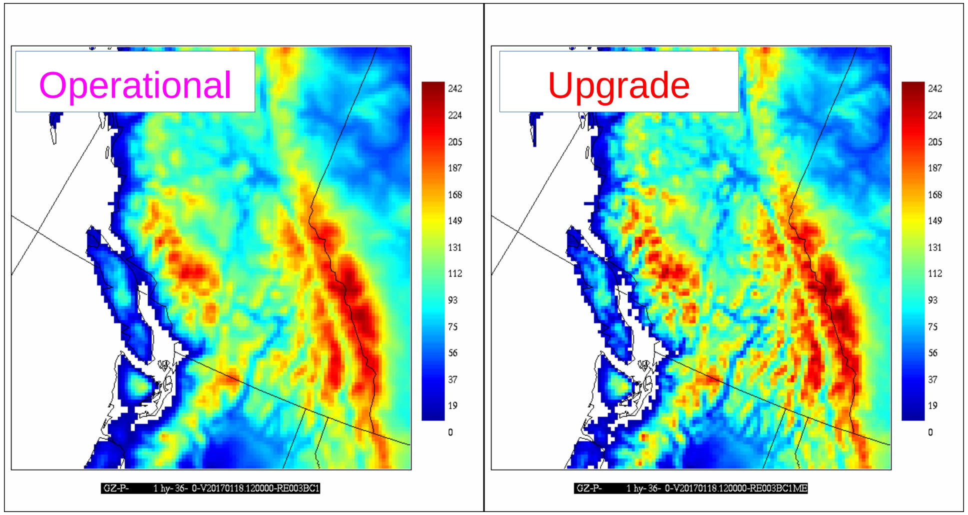
Resolved orographic spectra from various operational global models running at different nominal resolutions (generated by Malardel et al., obtained via Wedi (2016)).

Terrain Resolution

As part of an upcoming upgrade:

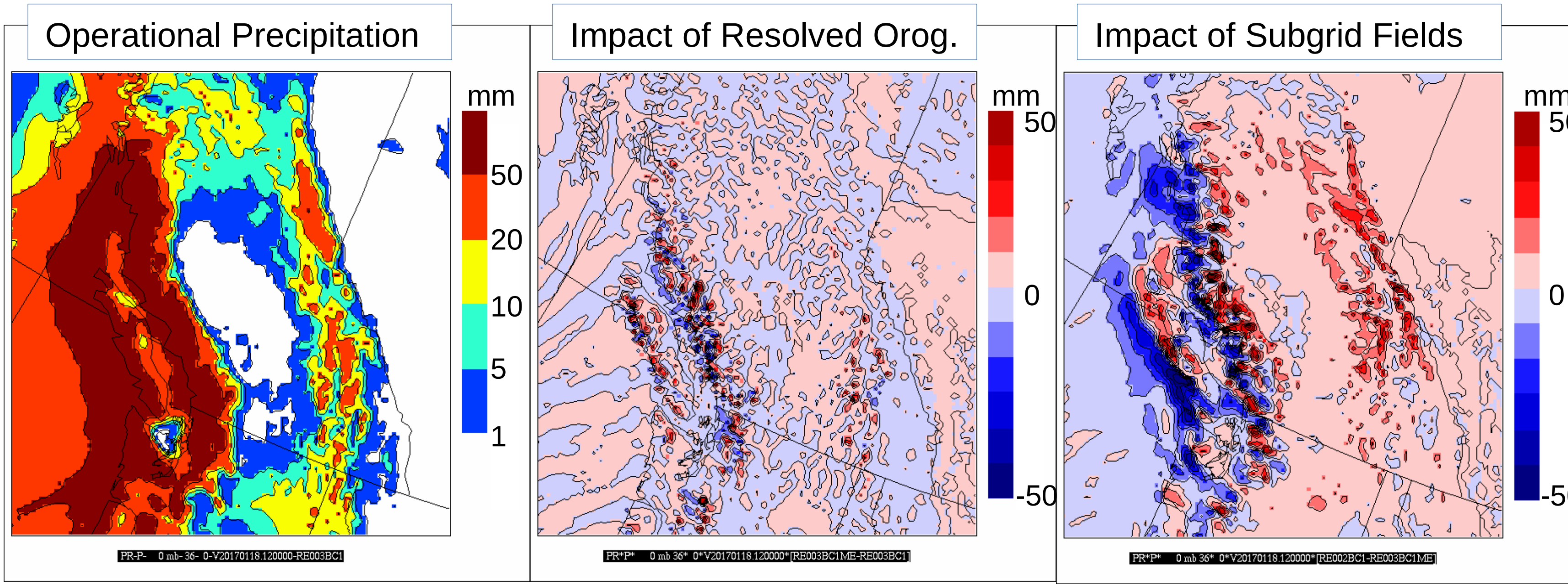
- A much sharper filter is used to increase the fraction of resolve orography
- Subgrid fields are computed to a cutoff of 5 km, with the remaining variance assigned to roughness for surface flux calculations





Power spectrum of resolved orography in the original database and configurations as indicated in the legend (left), with operational and upgrade resolved orography fields to the right (dam).

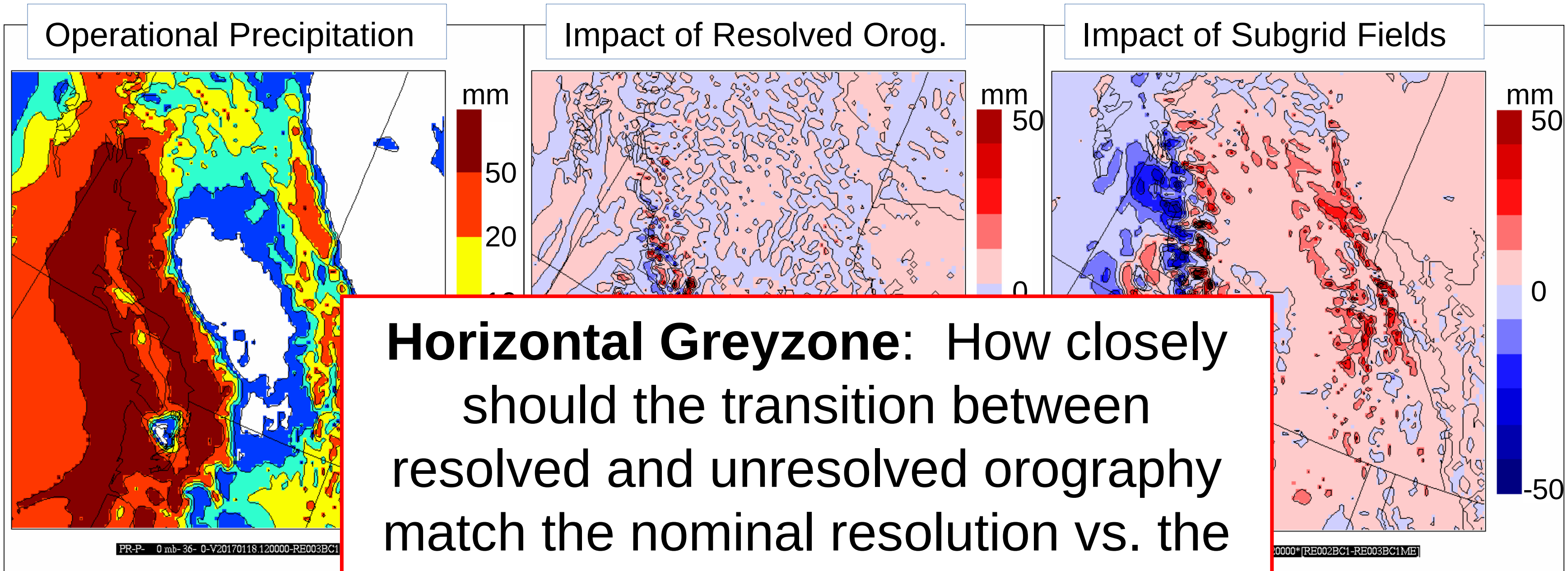
Terrain Resolution



Precipitation accumulation after 36 h for a 10 km model initialized at 0000 UTC 17 January 2017 (left), and differences induced using the updated resolved orography and the updated subgriscale fields.

- Additional lee-side snow accumulation is primarily the result of reduced subgrid variance, which reduces the impact of parameterized blocking
- Enhanced hydrometeor drift has a positive impact in this case

Terrain Resolution



Horizontal Greyzone: How closely should the transition between resolved and unresolved orography match the nominal resolution vs. the effective resolution of the model?

Precipitation accumula… …nuary 2017 (left), and differences induced using the updated resolved orography and the updated subgriscale fields.

- Additional lee-side snow accumulation is primarily the result of reduced subgrid variance, which reduces the impact of parameterized blocking
- Enhanced hydrometeor drift has a positive impact in this case

Convection at High Resolution

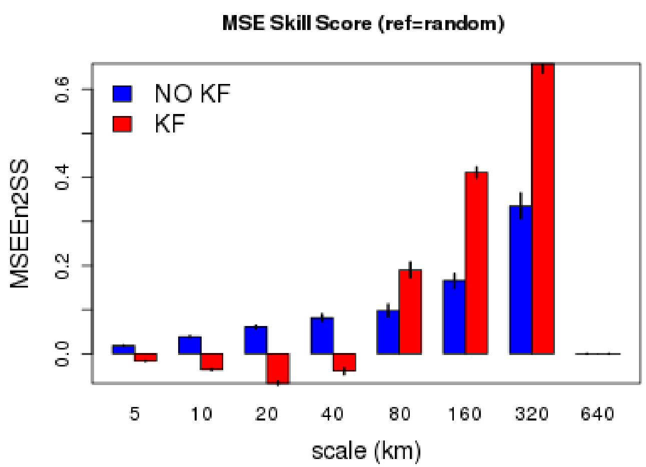
- The 2.5 km grid spacing of the High Resolution Deterministic Prediction System (HRDPS) places it at the lower edge of the convective greyzone, however, forecasters noted:
  - Late onset and overly intense precipitation
  - Disorganized spatial structures compared to radar
- As of 2015, the Kain and Fritsch (1990) convective parameterization scheme (CPS) is used with:
  - An elevated trigger condition (limits activity)
  - reduced cloud depth (2 km) and radius (500 m)
  - Rapid adjustment time scale (30 min)
- The CPS stabilizes and triggers explicit scheme via detrainment: only ~10% of domain-total precipitation comes from the CPS

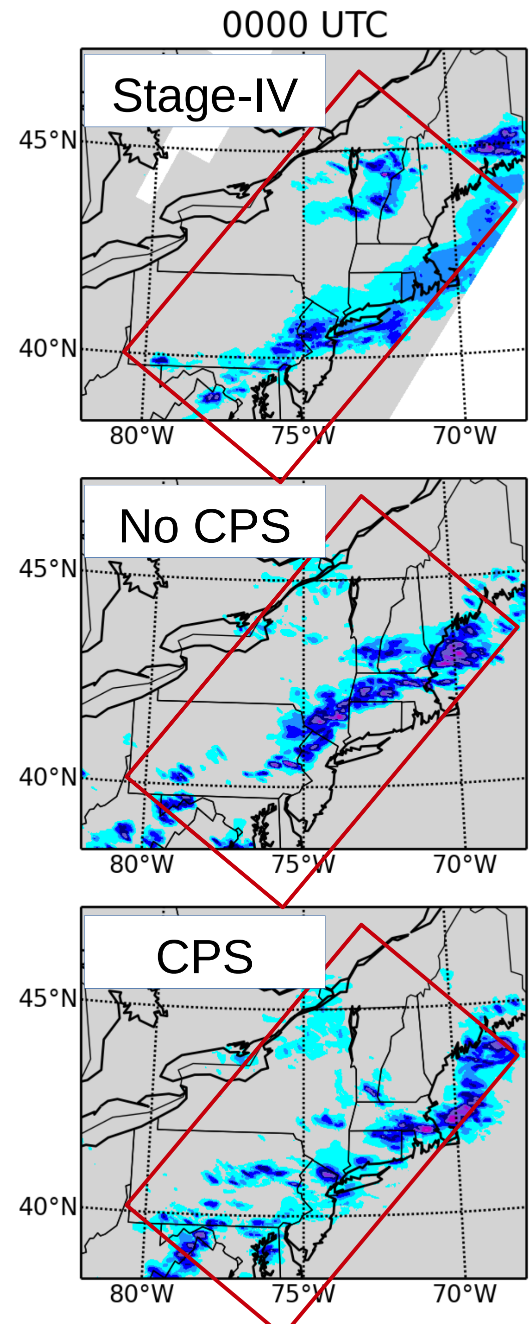
Convection at High Resolution

With the CPS active, precipitation patterns improve compared to Stage-IV analyses:

- Reduce size of over-predicted regions
- Increase squall line propagation speed

Skill increase is most noticeable in the mesoscale, consistent with improved squall line organization when the CPS is active.



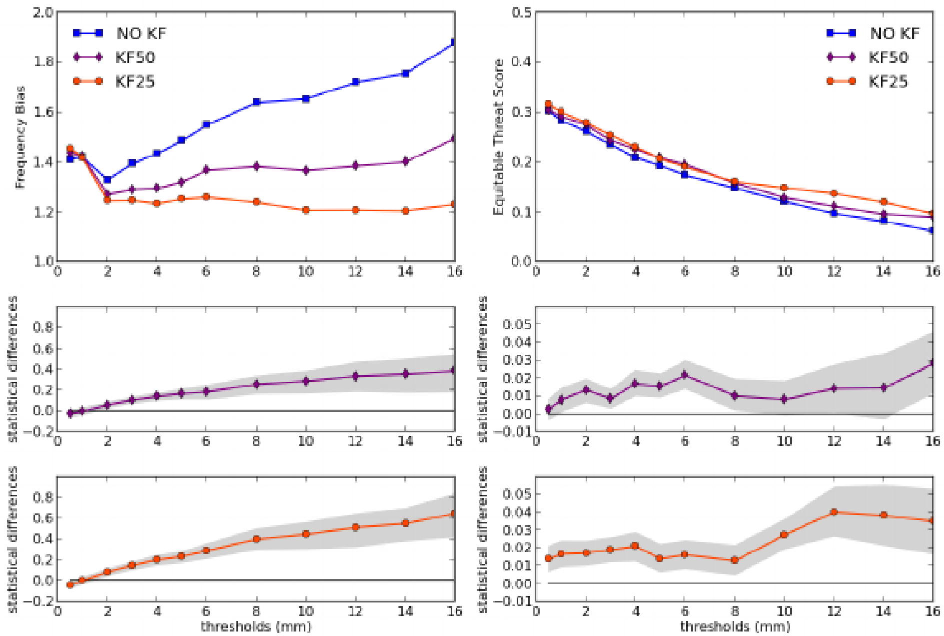


Hourly accumulated precipitation for 0000 UTC 10 June 2011 from the Stage-IV analysis (top), and HRDPS runs without (middle) and with (bottom) the CPS active. Scale-dependent precipitation skill score (above) is based on the work of Casati et al. (2015).

Convection at High Resolution

Use of a CPS leads to a systematic reduction in QPF, with the biggest reductions in the large-accumulation bins.

A modest improvement in the threat score implies that precipitation structure improvements also extend beyond the case study.



Day-1 precipitation forecast scores for the HRDPS over 80 summer cases for 2014. Frequency bias (left) and equitable threat score (ETS; right) are plotted by threshold, with the significance of differences shown for each experiment below the main panels.

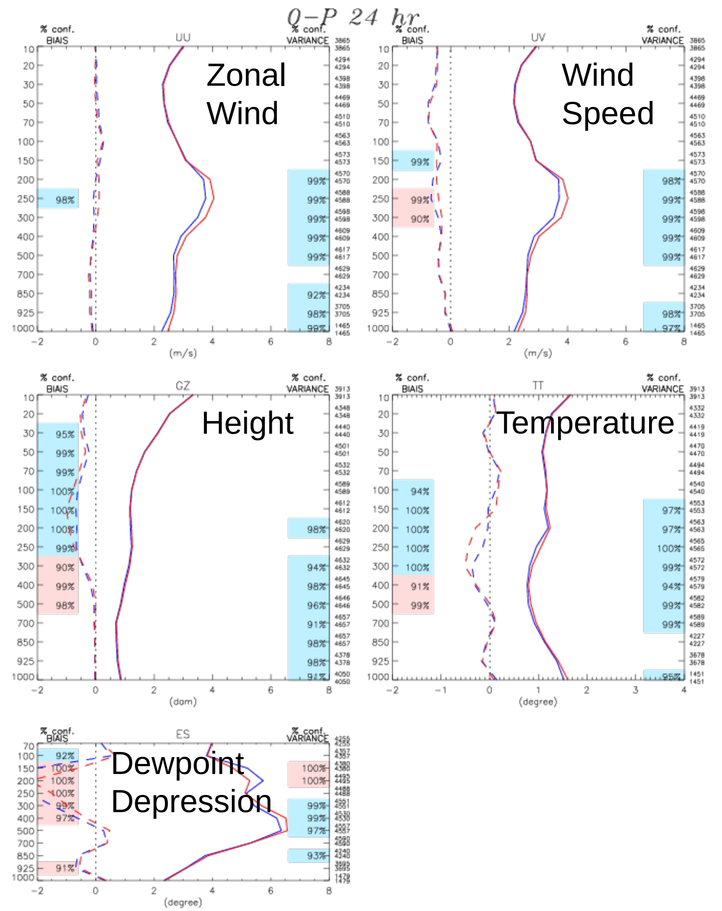
Horizontal Greyzone: Even at “convection permitting” grid spacings where CPS assumptions are questionable, use of a CPS appears to be beneficial.

No-Convection at Intermediate Resolution

The inverse test is used to assess the need for a CPS in the relatively low resolution (10 km grid spacing) Regional Deterministic Prediction System (RDPS).

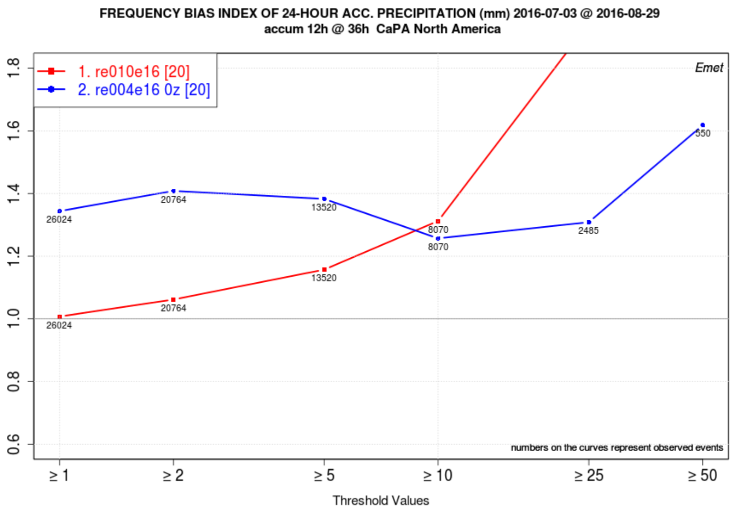
The RDPS relies heavily on the convective parameterization:

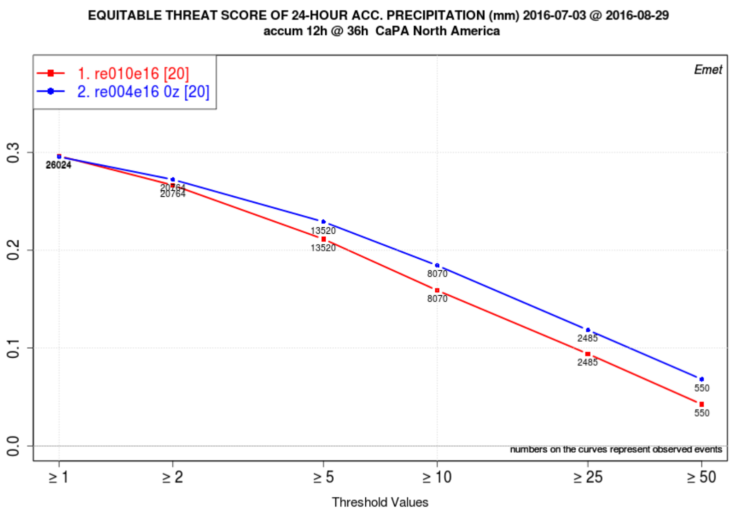
- Effective resolution extends into the mesoscale .
- Simple condensation scheme (Sunqvist et al. 1991; stratiform-only) compared to the HRDPS P3 scheme (Morrison and Milbrandt 2015).



Standard error (solid) and bias (P-0; dashed) against North American radiosondes after 24 h for a 2-month winter period in the control (blue) and experiment without the K-F CPS (red).

No-Convection at Intermediate Resolution



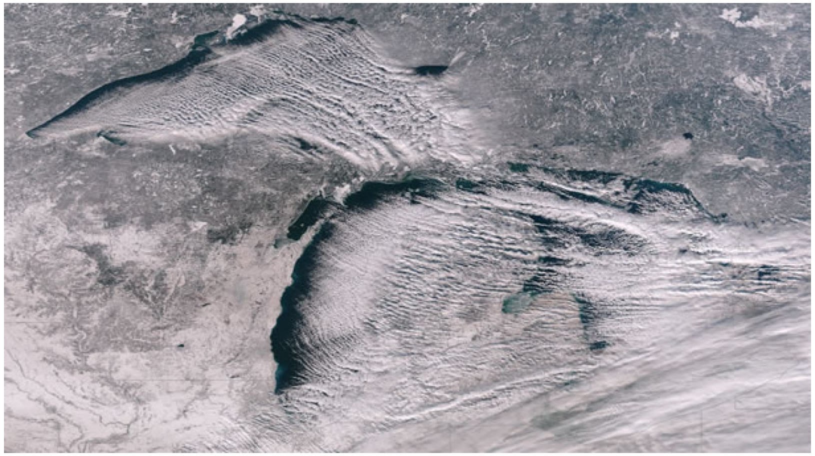


Without a CPS, the frequency bias develops a strong positive slope, with most precipitation falling in extremely intense pockets that are not well predicted.

Horizontal Greyzone: Despite being close to the convective greyzone borderline, the skill of the 10-km RDPS depends on the presence of parameterized convection.

Frequency bias and ETS for a set of 20 summer 2016 cases in the RDPS using an experimental configuration (blue) and the same configuration with the Kain-Fritsch CPS off (red).

Lake Effect Snow Bands



Lake effect snow event over the Great Lakes on 11 Dec 2013 (NASA).

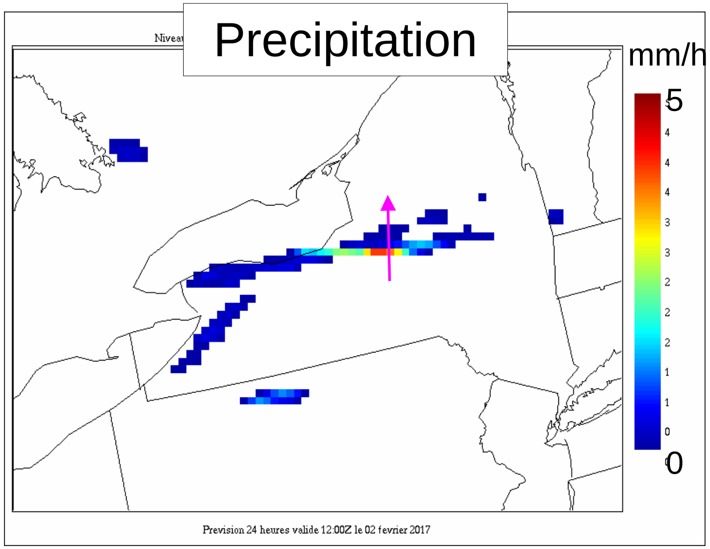
- Lake effect snow has large impacts near the Great Lakes:
  - 24-h accumulations >1m
  - Zero visibility for road travel and aviation
- Lake effect bands tend to form in regions of lower-level conditionally instability, with a sharp inversion aloft
- Horizontal scales in the bands are highly anisotropic:
  - Along-streamer length scale up to 500 km
  - Cross-streamer length scale as small as several km
- Snow bands are predicted by the RDPS (10 km): many are well predicted, but others are unphysically aligned with the underlying model grid (numerical streamers)

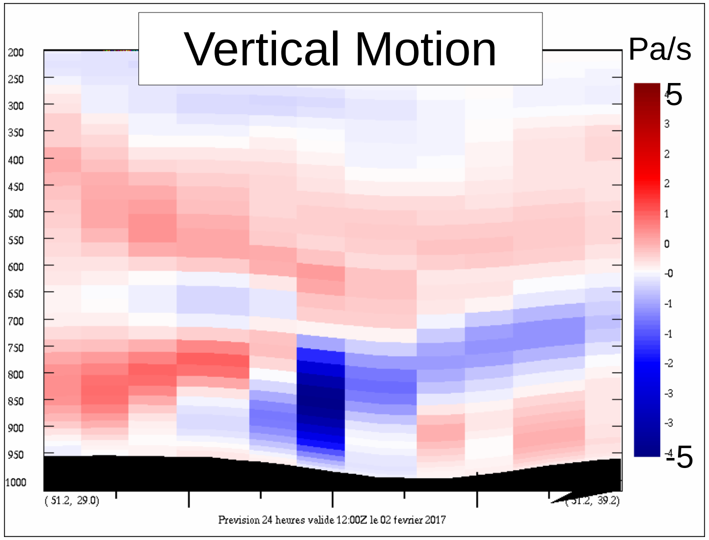
Lake Effect Snow Bands

With a 10 km grid spacing, the primary snow band in the middle of this observed lake effect event is aligned with the model grid.

The vertical circulation associated with the band is very strong, with associated near-surface convergence.

The feature in this simulation appears to be occurring at the 2-Δx limit of the model, well below its effective resolution.





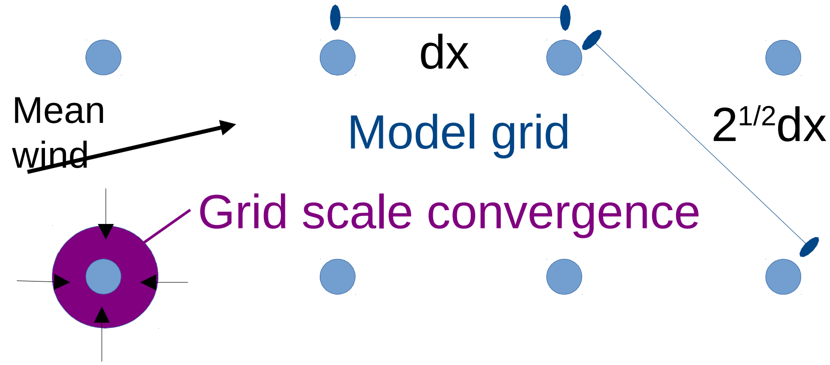
Precipitation rate after 24-h in a 10 km run initialized at 1200 UTC 1 February 2017 (top), and vertical motion along the indicated cross-section (bottom).

Under-Resolved Bands

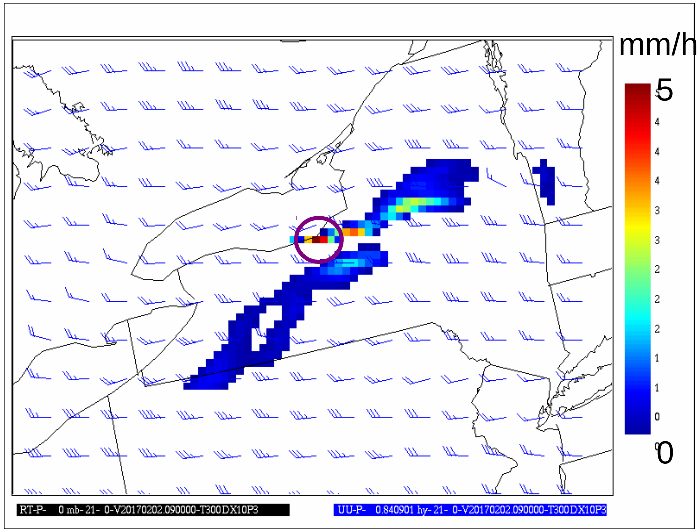
For an under-resolved process, a grid-scale forcing will elicit a grid-scale response that tends to propagate in the direction of highest resolution.

As model resolution increases, the primary band is able to break away from grid alignment.

However, secondary bands begin to appear, with cross-band scales that were fully unresolved (parameterized) at lower resolutions.



Snow band initiation at a point



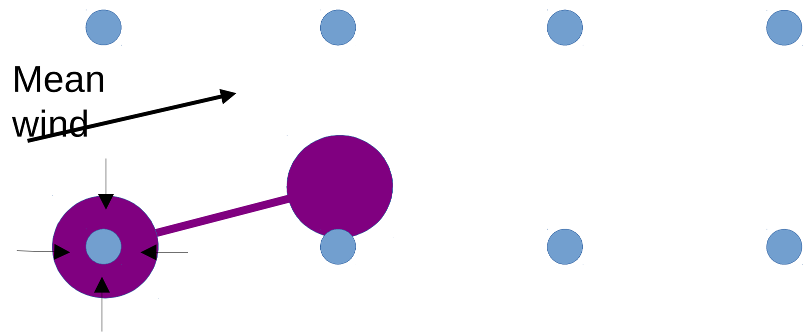
Schematic of possible numerical streamer mechanism (top). Precipitation rate at 22 h, with ~850 mb wind barbs plotted in knots (bottom).

Under-Resolved Bands

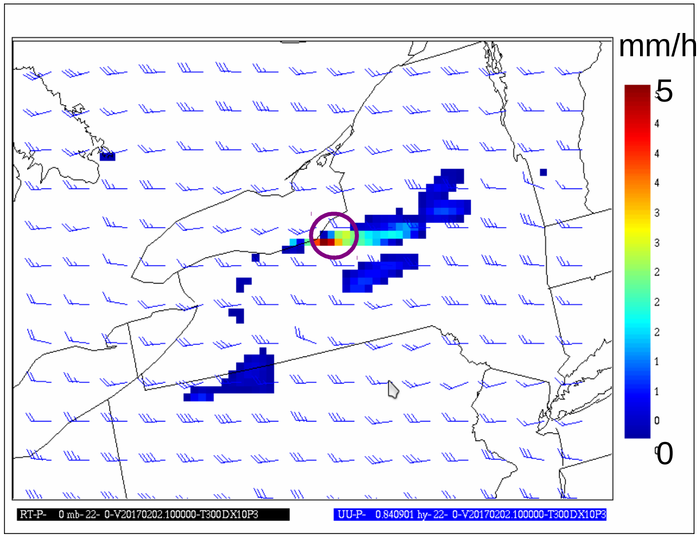
For an under-resolved process, a grid-scale forcing will elicit a grid-scale response that tends to propagate in the direction of highest resolution.

As model resolution increases, the primary band is able to break away from grid alignment.

However, secondary bands begin to appear, with cross-band scales that were fully unresolved (parameterized) at lower resolutions.



Advection in near-parallel flow



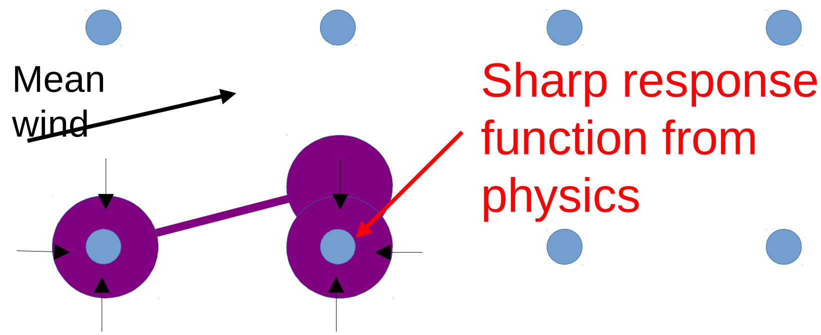
Schematic of possible numerical streamer mechanism (top). Precipitation rate at 23 h, with ~850 mb wind barbs plotted in knots (bottom).

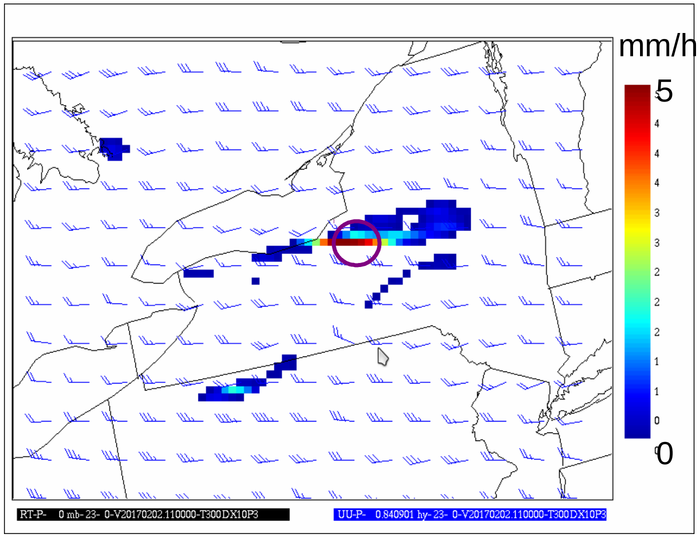
Under-Resolved Bands

For an under-resolved process, a grid-scale forcing will elicit a grid-scale response that tends to propagate in the direction of highest resolution.

As model resolution increases, the primary band is able to break away from grid alignment.

However, secondary bands begin to appear, with cross-band scales that were fully unresolved (parameterized) at lower resolutions.

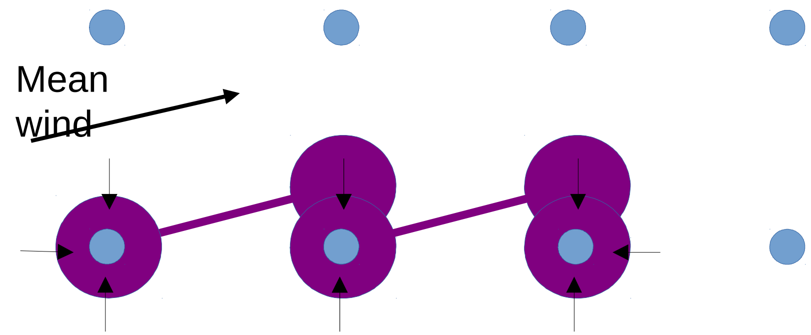




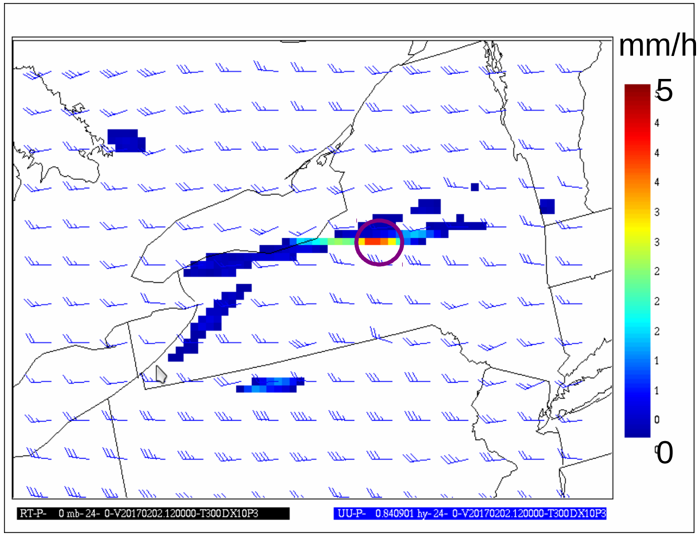
Schematic of possible numerical streamer mechanism (top). Precipitation rate at 23 h, with ~850 mb wind barbs plotted in knots (bottom).

Under-Resolved Bands

For an under-resolved process, a grid-scale forcing will elicit a grid-scale response that tends to propagate in the direction of highest resolution.
As model resolution increases, the primary band is able to break away from grid alignment.
However, secondary bands begin to appear, with cross-band scales that were fully unresolved (parameterized) at lower resolutions.

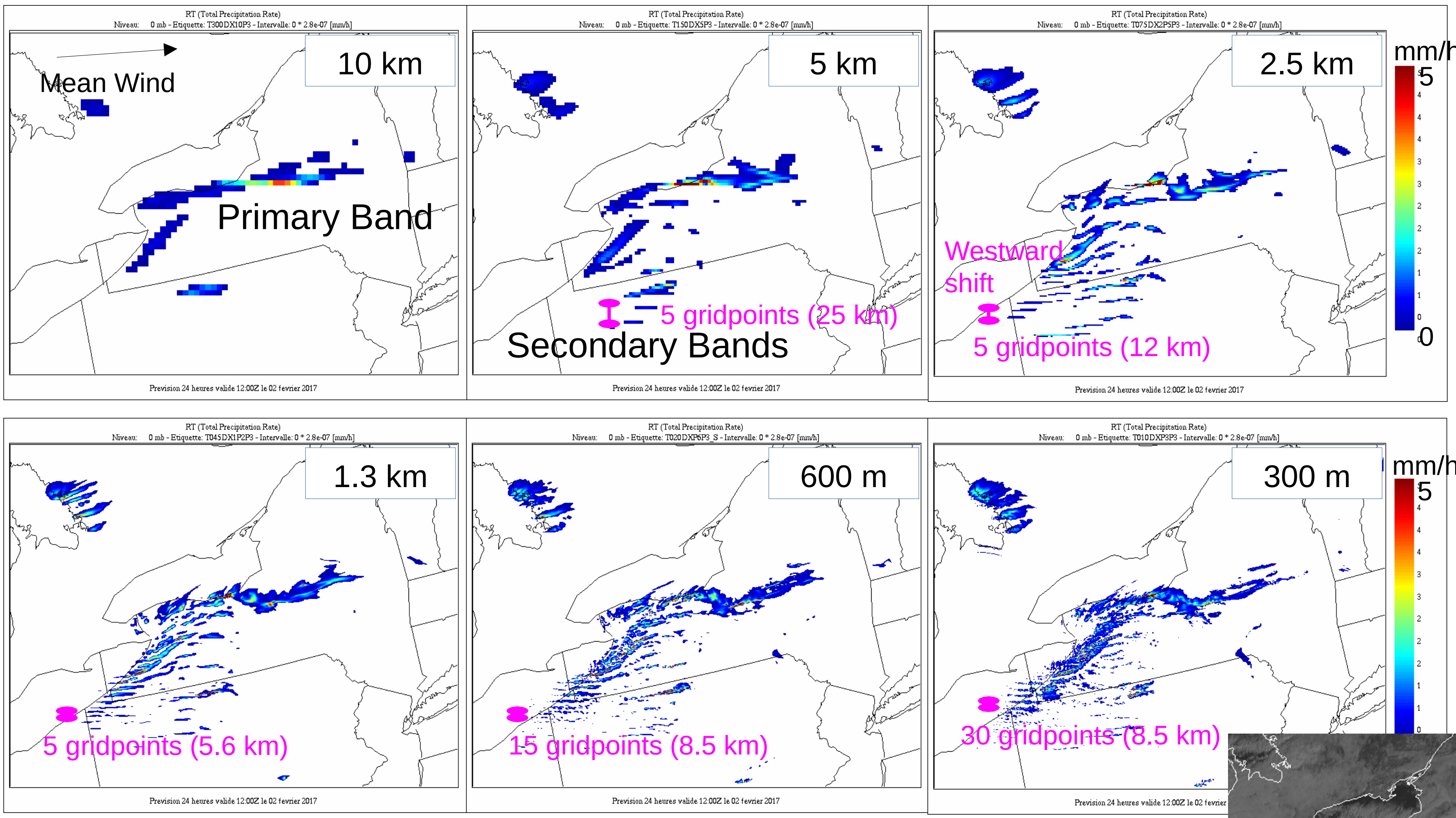


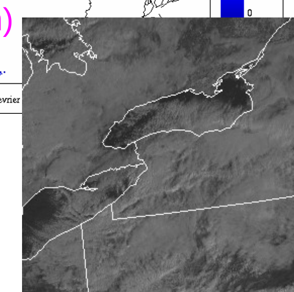
Grid-aligned process forms band



Schematic of possible numerical streamer mechanism (top). Precipitation rate at 24 h, with ~850 mb wind barbs plotted in knots (bottom).

Lake Effect Snow Band Representation





Precipitation rates after 24 h valid 1200 UTC 2 Feb 2017, with grid spacings as indicated on the panels above. Visible satellite image valid at 1400 UTC inset on lower right.

Resolution of Lake Effect Snow Bands

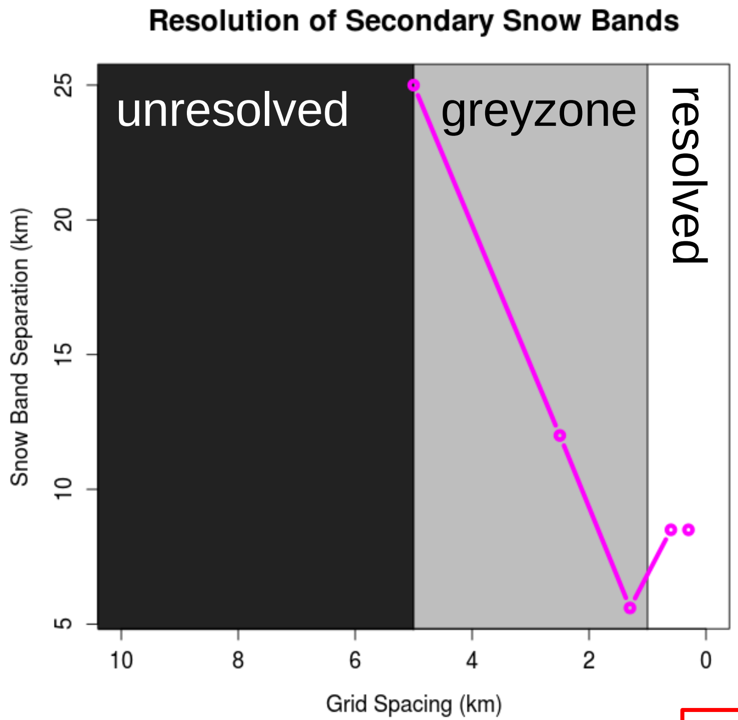
Grid Spacing	Primary Band	Secondary Bands
>15 km	Unresolved (parameterized)	Unresolved (parameterized)
5-10 km	**Under-resolved (grid alignment)**	Unresolved (shifted)
1.3-2.5 km	Resolved	**Under-resolved (grid alignment) (5Δx spacing)**
< 600 m	Resolved	Resolved

Summary of snow streamer representation at varying grid spacings. Greyzones are identified with bold text.

Band alignment with the model grid occurs only for under-resolved features.

Combined with the late triggering of the secondary streamer (eastward shift), parameterization of snow bands is currently insufficient.

Secondary Band Separation



Lateral separation distance between secondary snow bands as a function of model grid spacing, with process resolution transitions annotated for reference.

The separation distance of the secondary bands stabilizes at 8 km for grids spacings < 1 km.

This is consistent with an effective model resolution on the order of 7dx for these features, with under-resolution creating an undershoot on the 1.3 km grid (separation 5dx).

Horizontal Greyzone: Problems of band triggering and grid alignment persist across a range of intermediate grid spacings, with a convergence to a resolved solution only at < 1km.

Radiative Transfer at High Resolution

Underlying assumptions for all radiative transfer (RT) models used in NWP and climate models:

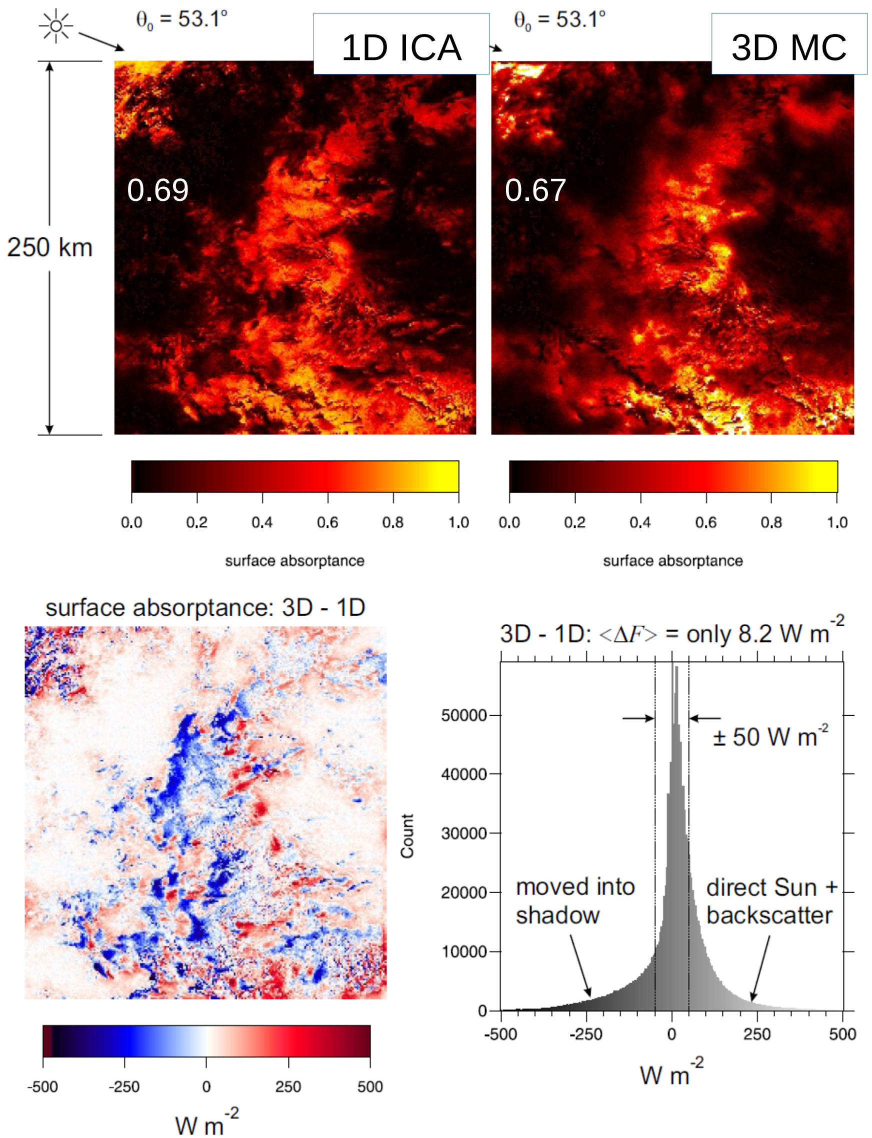
- Plane parallel (variations only perpendicular)
- Horizontally homogeneous optical properties

$$\frac{\partial \begin{smallmatrix}\text{optical}\\\text{properties}\end{smallmatrix}}{\partial x} = \frac{\partial \begin{smallmatrix}\text{optical}\\\text{properties}\end{smallmatrix}}{\partial y} = \frac{\partial I}{\partial x} = \frac{\partial I}{\partial y} = 0$$

These approximations are extreme and incorrect, particularly for high resolution systems: 3D RT is needed

Examples of cloud shadowing effects for deep convection (top) and a stratocumulus deck (bottom).

3D Radiative Transfer

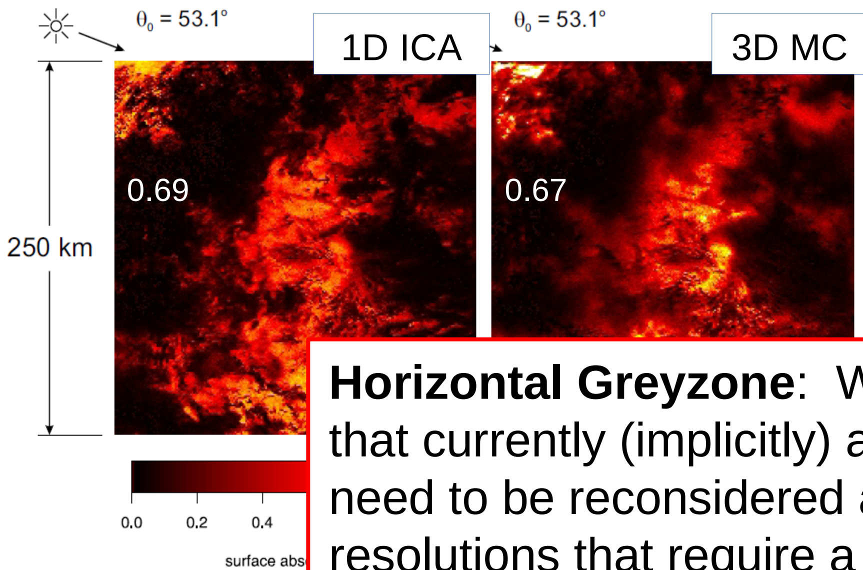


At low sun angles (e.g. high latitudes), the effects of shadowing and reflection from lateral faces can be important to surface heating.

The Monte Carlo (MC) approach can adopted efficiently for a relatively small number of photons, bringing it closer to applicability for NWP.

Results from a 0.25 km GEM simulation for 16 May 2015 over French Guiana for surface absorption (top) with 1D (left) and 3D (right) RT. Difference is shown on lower-level, along with the PDE of differences for the full domain (lower-right).

3D Radiative Transfer



At low sun angles (e.g. high latitudes), the effects of shadowing and reflection from lateral faces can be

heating.

C)

ted

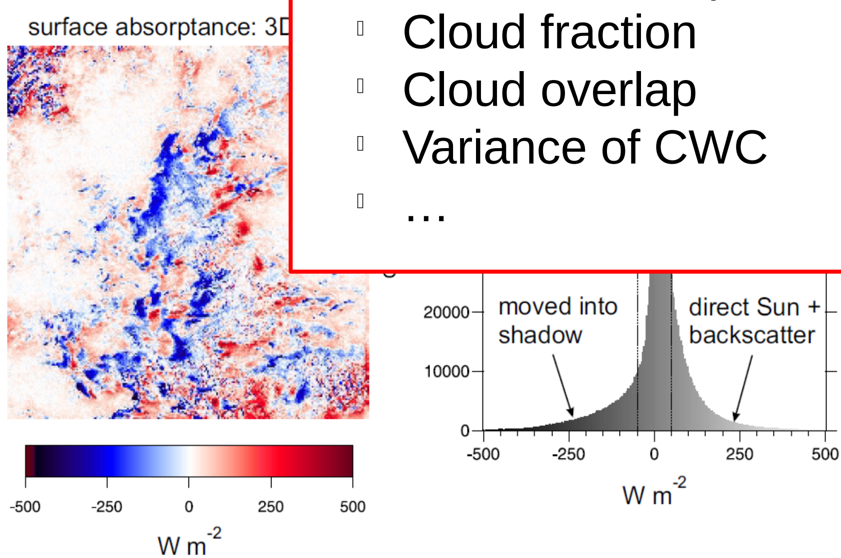
ively

otons,

P.

Horizontal Greyzone: What optical properties that currently (implicitly) account for 3D effects, need to be reconsidered as we move into resolutions that require a 3D RT solution?

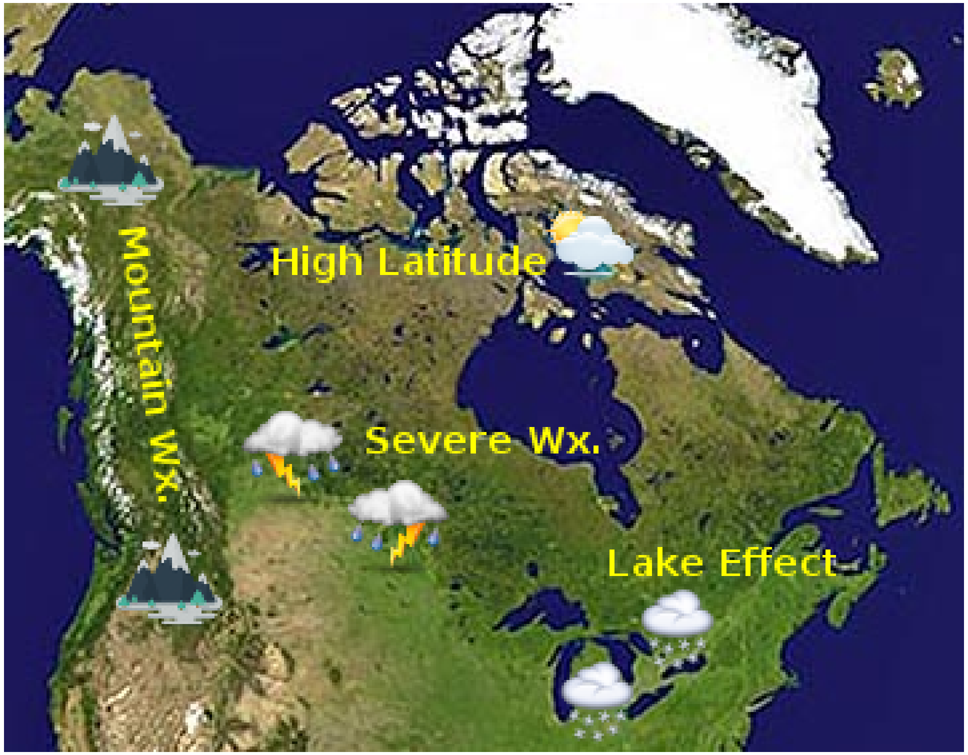
- Cloud fraction
- Cloud overlap
- Variance of CWC
- …



Results from a 0.25 km GEM simulation for 16 May 2015 over French Guiana for surface absorption (top) with 1D (left) and 3D (right) RT. Difference is shown on lower-level, along with the PDE of differences for the full domain (lower-right).

Discussion

Different greyzones for distinct classes of high impact weather create a challenge when developing a national solution for Canadian NWP.



Canadian weather elements associated with current greyzone problems.

Mountain Greyzone

- At high vertical resolution, katabatic flows is partially resolved
  - Lowest level set to 10 m
- Terrain must be treated in comparison with the effective model resolution
  - Increase resolved component

Severe Weather Greyzone

- Use of a CPS at 2.5 km appears to improve squall line organization
  - Use a CPS at high resolution
- Use of a CPS at 10 km is essential for guidance quality
  - Update microphysics to P3

Lake Effect Greyzone

- Cascade of greyzones between 10 and <1 km depending on snow band width scales
  - Consider changes to shallow convection or diffusion

High Latitude Greyzone

- Low sun angles amplify impact of shading and reflection
  - Moving towards 3D RT

References

Casati, B., A. Glazer, J. Milbrandt and V. Fortin, 2015: An intensity-scale skill score to assess the added value of enhanced resolution. *NCAR Seminar Series*, Boulder, Colorado.

Girard, C., and Coauthors, 2014: Staggered vertical discretization of the Canadian Environmental Multiscale (GEM) model using a coordiante of the log-hydrostatic-pressure type. *Mon. Wea. Rev.*, **142**, 1183-1196.

Haiden, T. and C. D. Whiteman, 2005: Katabatic flow mechanisms on a low-angle slope. *J. Appl. Met.*, 44, 113-126.

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

Morrison, H. and J. A. Milbrandt, 2015: Parameterization of cloud microphysics based on the prediction of bulk ice particle properties. Part I: scheme description and idealized tests. *J. Atmos. Sci.*, **72**, 287-311.

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

Vosper, S. B., A. R. Brown, and S. Webster, 2016: Orographic drag on islands in the NWP mountain grey zone. *Quart. J. Roy. Meteor. Soc.*, **142**, 3128-3137.