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On the Need of Orography Filtering in a Semi-Lagrangian Atmospheric Model with a Terrain-Following Vertical Coordinate

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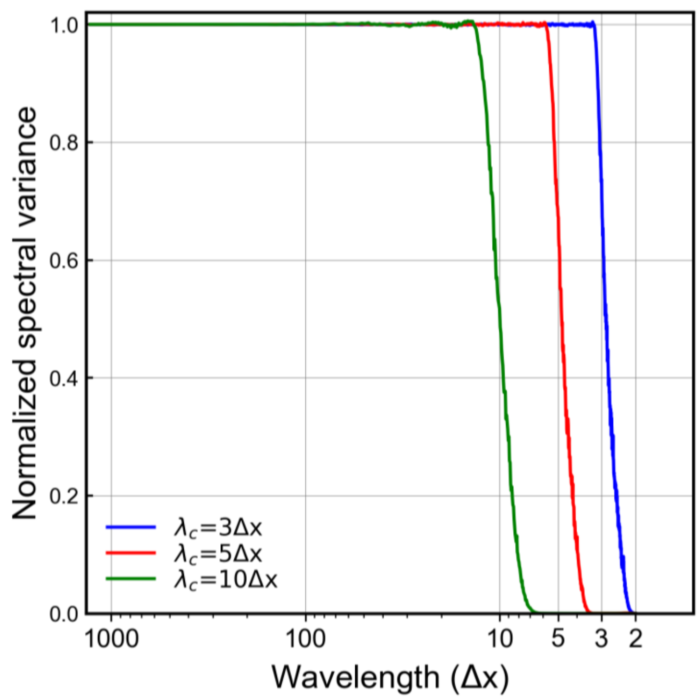
Orographic Filter in GEM

- Increasing the orography resolution in NWP is a global trend.
- ECCC's different GEM-based operational NWP systems are currently obtained with a sharp filter (Zadra 2018).
- The filter is basically a smoothing operator applied to the grid-point space for a small-scale cut-off parameter λ_c.
- For its sharpest configuration, $\lambda_c = N\Delta x$ implies that the variance of $N\Delta x$ wavelength is retained at 50% , while scales smaller than $(N\text{-}1)\Delta x$ are removed.
- Orography generated with $\lambda_c = N\Delta x$ in the filter is referred to as **RC-N** orography in the presentation.



Zadra, A. (2018). Notes on the new low-pass filter for the orography field. Internal Report, RPN-A, Meteorological Research Division, Environment and Climate Change Canada. http://collaboration.cmc.ec.gc.ca/science/rpn/drag_project/documents/topo_lowpass_filter.pdf

Challenges with reduced filter

- ECCC's regional deterministic prediction system (RDPS) is currently employing RC5 filter for orography.
- Moving from RC5 to RC3 filter for orography in RDPS leads to two major numerical issues.

  i. **Increased upper-air noise** (at 250 hPa and above).

  - Due to the orography imprints on the vertical coordinate surfaces due to the terrain-following coordinate system.

  - Can be addressed by faster attenuation of small-scale orography imprints with height with a change in the coordinate definition (Husain et al. 2020).

  ii. **Spurious Warming in the valleys** during winter - particularly in the Canadian Rockies.

  - This is the focus of this presentation.

Husain, S.Z., Girard, C., Separovic, L., Plante, A. and Corvec, S. (2020): On the progressive attenuation of fine-scale orography contributions to the vertical coordinate surfaces within a terrain-following coordinate system. Submitted to the Monthly Weather Review, Currently under review.

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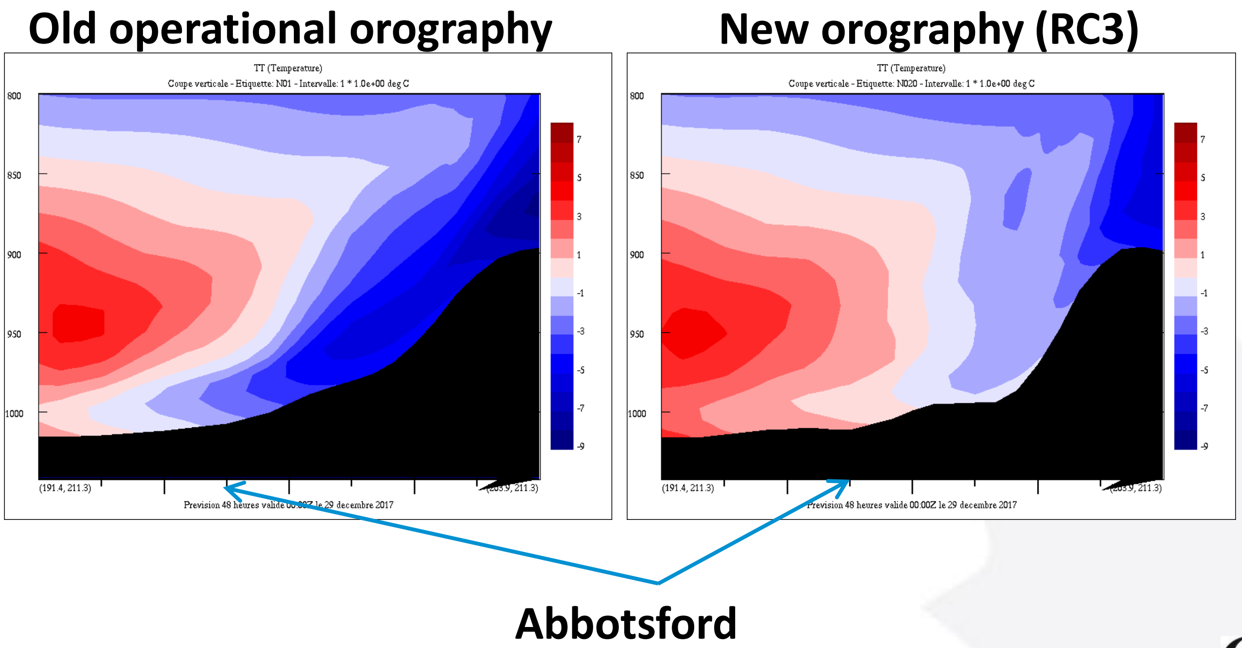
Warming in the valleys

- First indication of a possible problem with RC3 orography in RDPS was reduction in predicted freezing rain accumulation.
- For example, during a freezing rain event in Abbotsford, BC (29 December, 2017) the difference between the RC3 and operational (old – close to RC5) orography was 45 mm to an almost negligible amount.



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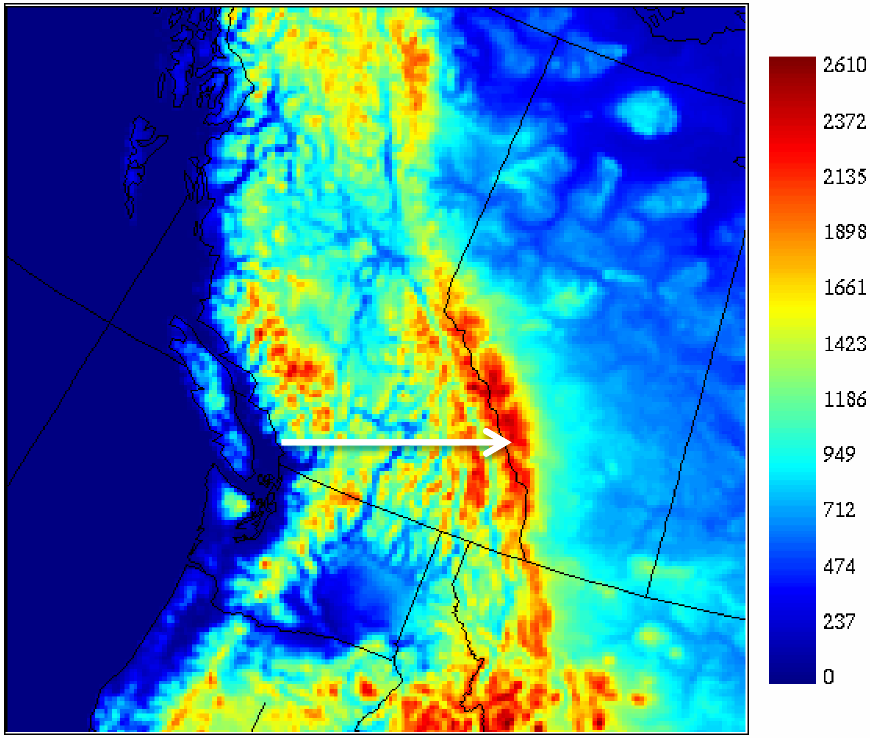
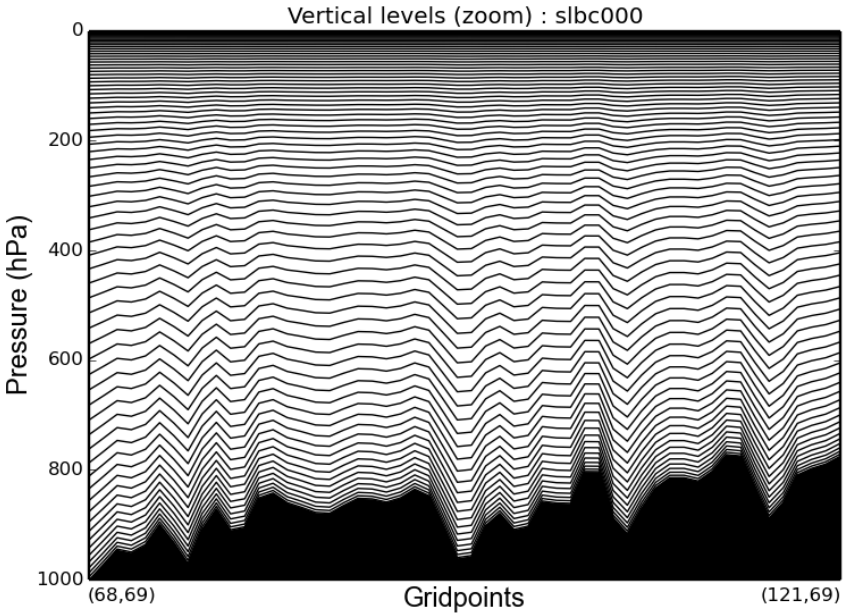
Warming in the valleys

- The issue is studied further by carrying out numerical experiments over a smaller LAM domain covering the Canadian Rockies.
- The valley warming effect can be visualized by comparing temperature along a cross-section (the white line).

Orography with RC3 filter

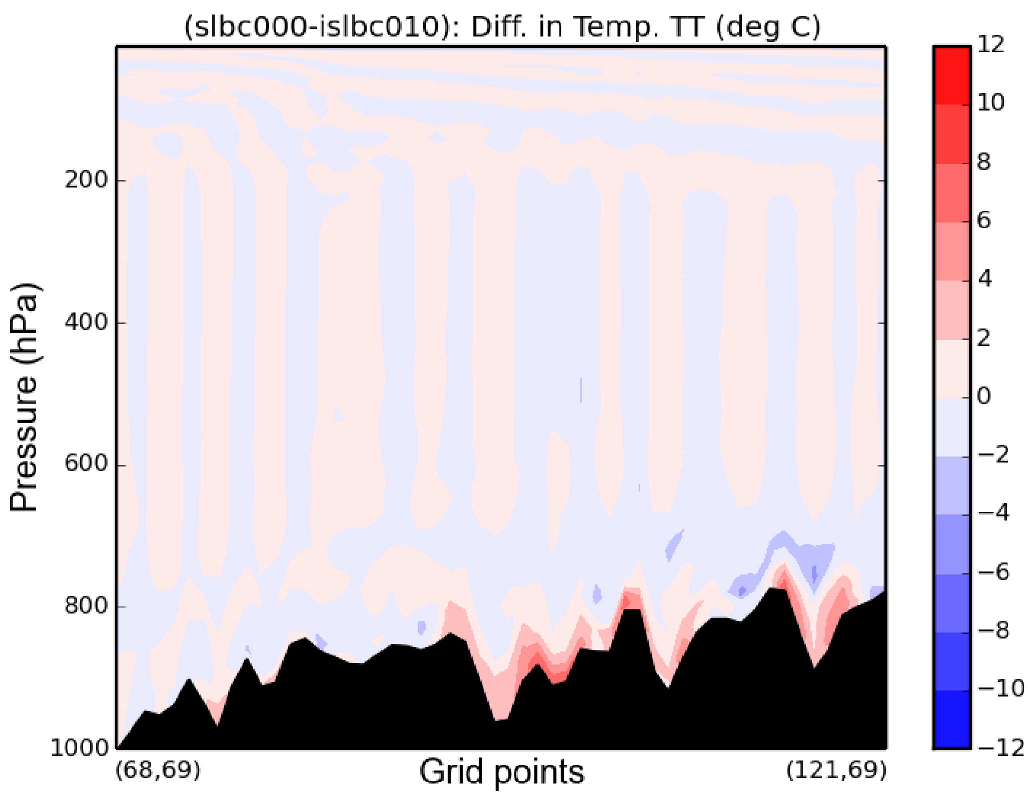




Warming in the valleys

- Vertical cross-section of temperature TT shows the warming in the valleys with RC3 (compared to RC5).
- Simulation initialized at 00Z on 16 January 2017.

$TT_{RC3} - TT_{RC5}$ at 24h



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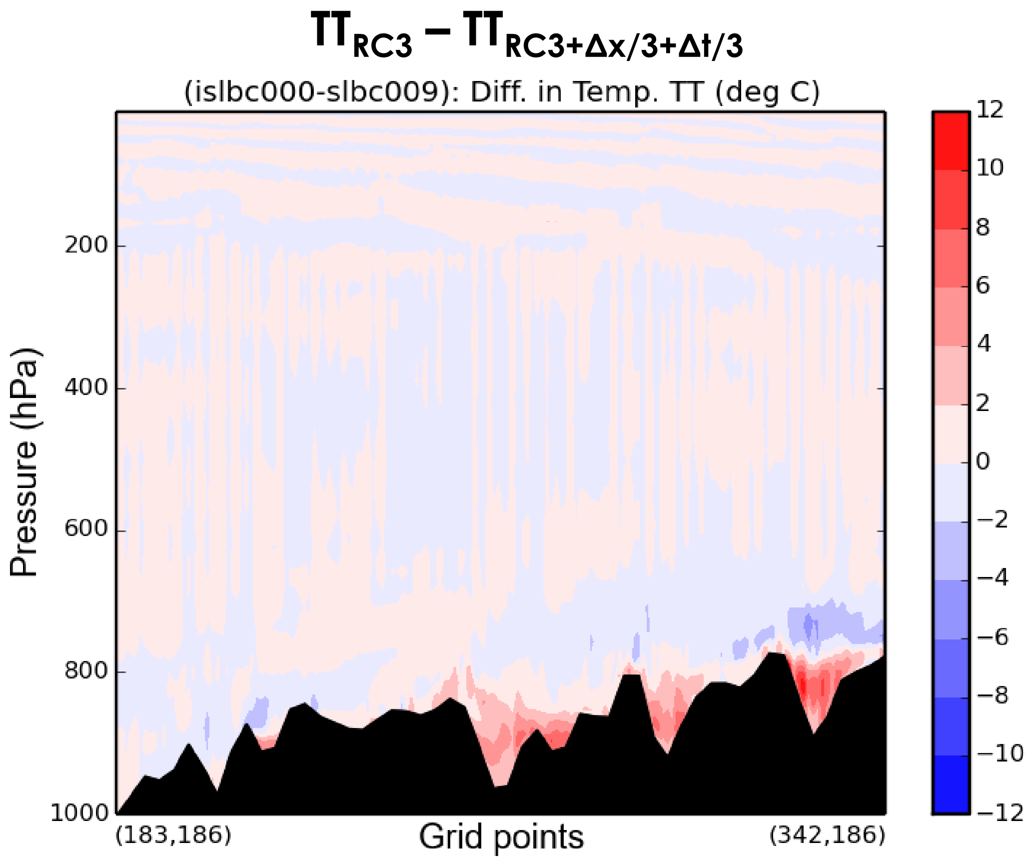
Warming in the valleys

- Similar warming signal is visible, when compared against a run where the spatiotemporal resolution is increased by 3 times.



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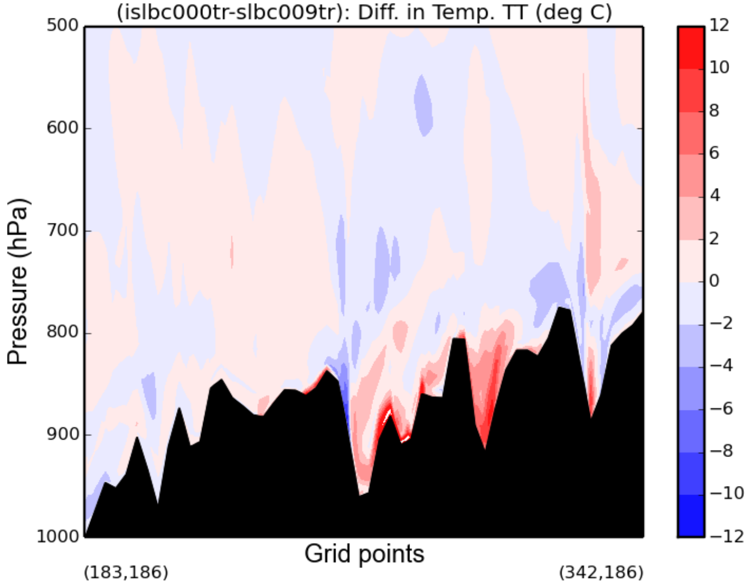
Warming in the valleys

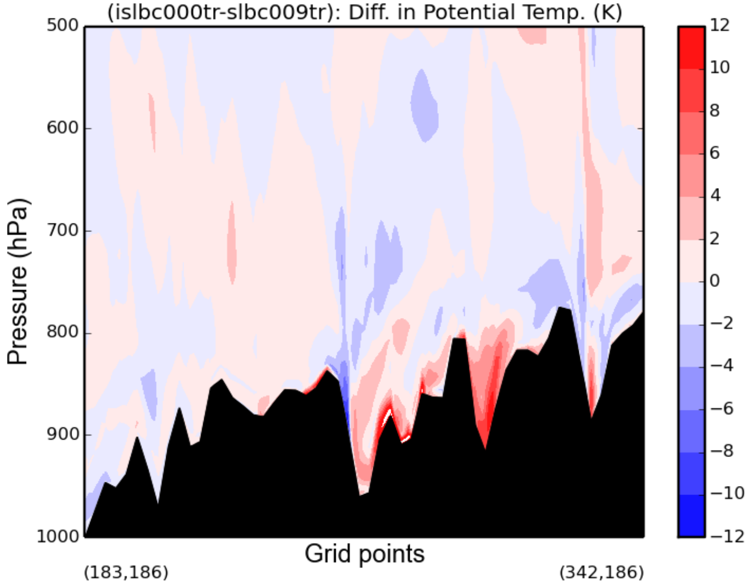
- When the tests (RC3 and RC3+Δt/3+Δx/3) are repeated without physics, the valley warming signal is reproduced.
- So, the warming is primarily attributable to dynamics.

$Var_{RC3} - Var_{RC3+\Delta x/3+\Delta t/3}$

Temperature, TT



Potential Temp., TH



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Pertinent Questions

- Effective resolution of numerical models, i.e., the smallest scales that are fully resolved with sufficient accuracy, is considerably coarser than the Nyquist limit.
- Skamarock (2004) found the effective resolution for NWP models to be at a range of 6-8Δ (from KE spectra).
- Other studies made similar conclusions.

- This leads to some important pertinent questions.
  - What is the role of GEM's effective resolution in this issue?
  - Can we learn more about the issue by studying simpler problems in one and two-dimensions?

Skamarock WC. (2004): Evaluating mesoscale NWP models using kinetic energy spectra. Mon. Weather Rev., 132: 3019–3032.

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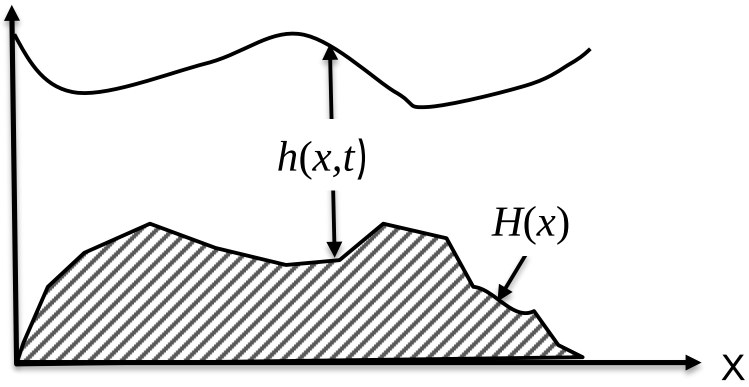
1D Shallow Water Problem

- In the absence of Coriolis force the 1-dimensional shallow water equations have the form

  $$\frac{d\phi}{dt} + \phi\frac{\partial u}{\partial x} = 0,$$

  $$\frac{du}{dt} + \frac{\partial \phi}{\partial x} + g\frac{\partial H}{\partial x} = 0,$$

  where $\phi = gh$.



- A 1D SWE model is developed that employs a numerical approach very similar to GEM, i.e.

  - 2-time-leve iterative implicit approach, and

  - semi-Lagrangian treatment for advection.

- Periodic horizontal boundary conditions are applied.

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1D Shallow Water Problem

- The test problem consists of orography defined using the following relation

$$H(x) = 0.5h_m\left[1 - \cos\left(\pi\frac{x}{a}\right)\right]\delta_{x_c}$$

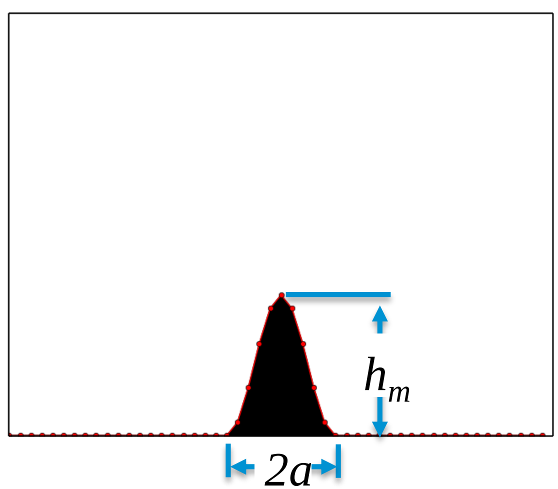
where $\delta_{x_c} = \begin{cases} 1\ if\ x_c - a \leq x \leq x_c + a \\ 0\ for\ other\ values\ of\ x \end{cases}$

with h_m being the height of the mountain,

the width of the mountain given by $L = 2a$ and

x_c is the center of the computational domain.

$10\Delta x$ mountain



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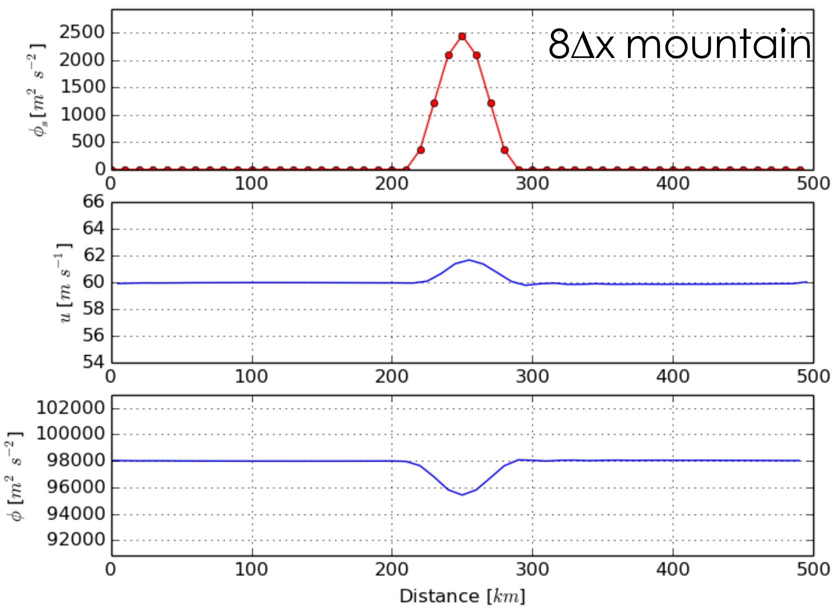
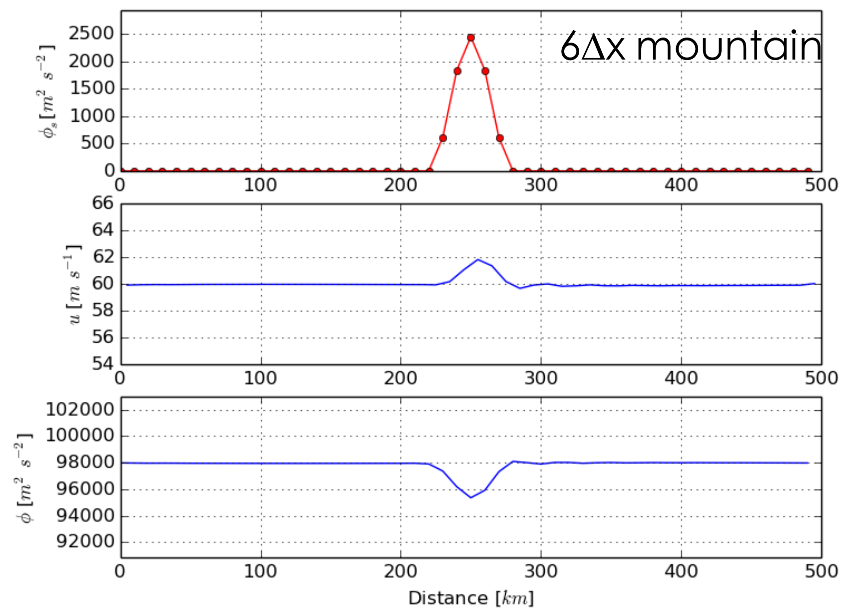
1D Shallow Water Problem

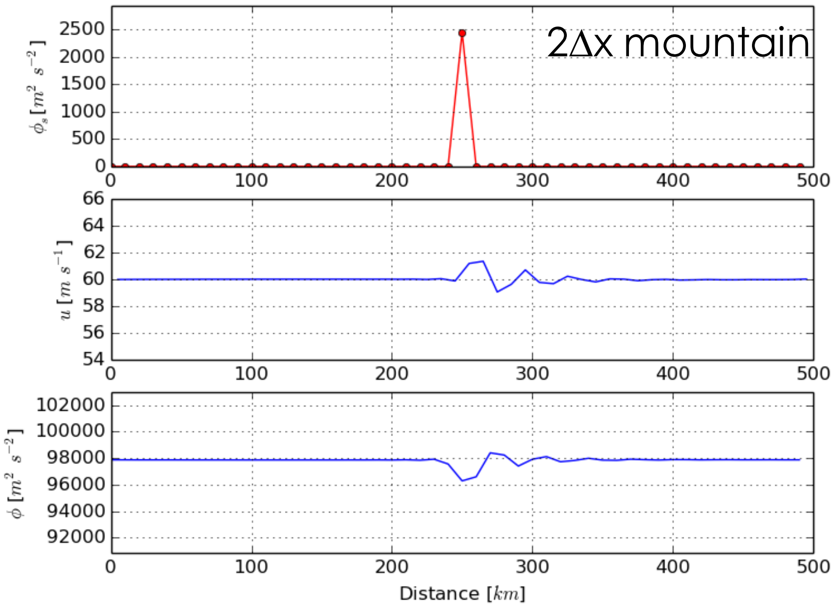
- The test problem is based on incoming wind speed u=60 m s^{-1}, h_m=500 m, Δx=10 km, and Δt=100 s.
- Steady-state solutions for $n\Delta x$ mountains (for n=2,4,6,8, etc.) are computed.
- Solutions (u and ϕ) for both 8Δx (left) and 6Δx (right) mountains are characterized by symmetry around the mountain (which conforms to previous study results by others).

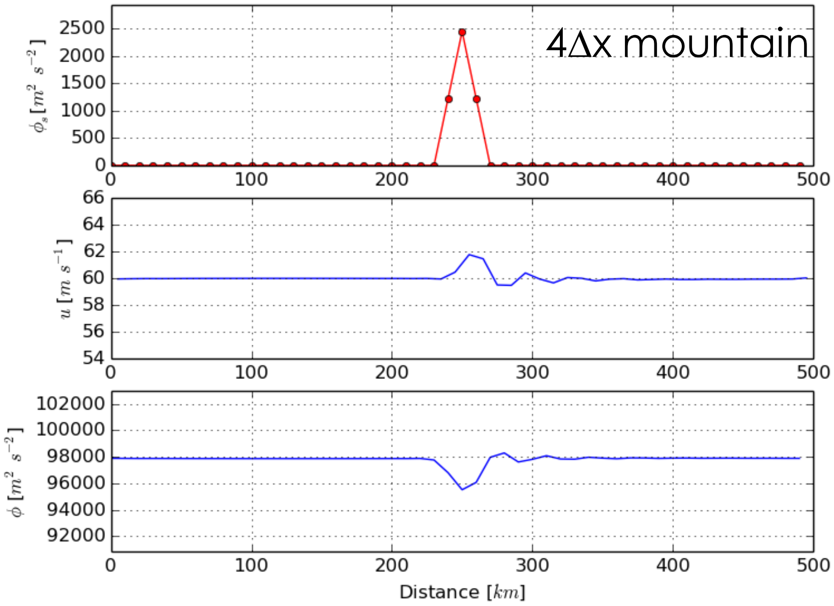




1D Shallow Water Problem

- Solutions (u and ϕ) for both $2\Delta x$ (left) and $4\Delta x$ (right) mountains suffer from lack of symmetry and distortions on the lee-side of the mountain.
- Inaccurate dispersion as well damping from semi-Lagrangian treatment are among reasons of error.





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2D Valley Problem

- In order to study the issue further a two-dimensional test case was constructed within GEM (using slab-symmetry).
- The test problem consists of orography defined using the following relation

  $$H(x) = 0.5h_m\left[1+\cos\left(\pi\frac{x}{a}\right)\right]\delta_{x_c}$$

  where

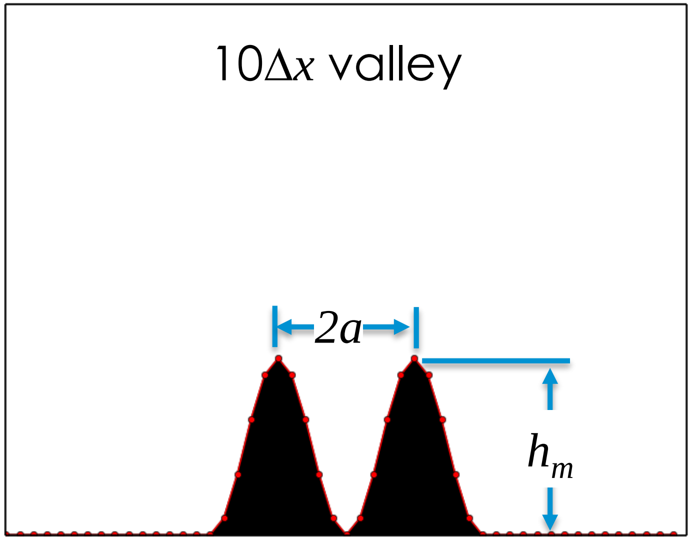
  $$\delta_{x_c} = \begin{cases} 1 \; if \; x_c - 2a \le x \le x_c + 2a \\ 0 \; for \; other \; values \; of \; x \end{cases}$$

  with

  h_m being the valley depth,

  $L = 2a$ is the valley width, and

  x_c is the center of the domain.



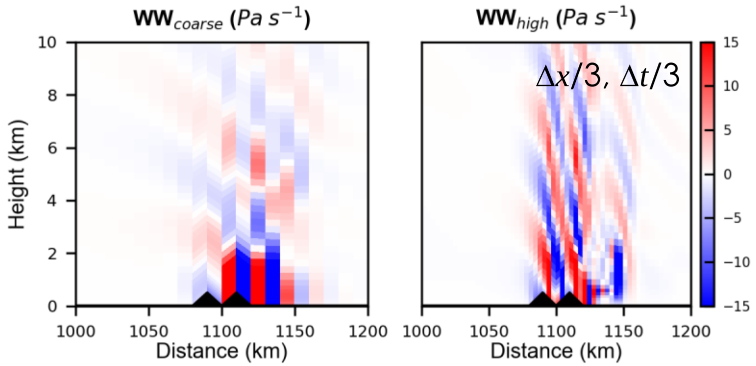
- Further information on test configuration is provided in the appendix.

2D Valley Problem

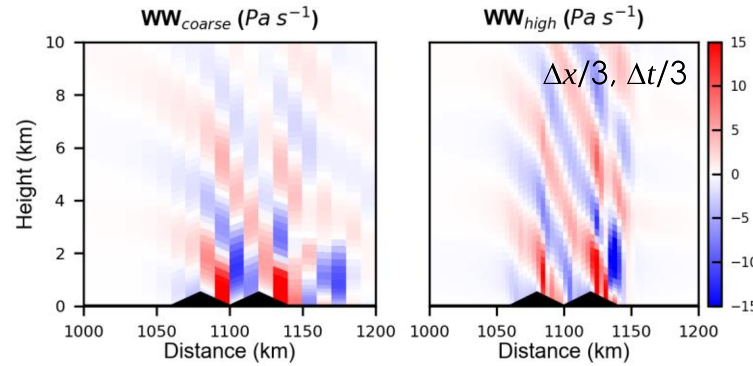
- Supercritical condition ($Fr = 1.5 \;\, with\, u = 15\, ms^{-1}, h_m = 500\, m$)

Vertical motion, WW (Pa s^{-1})

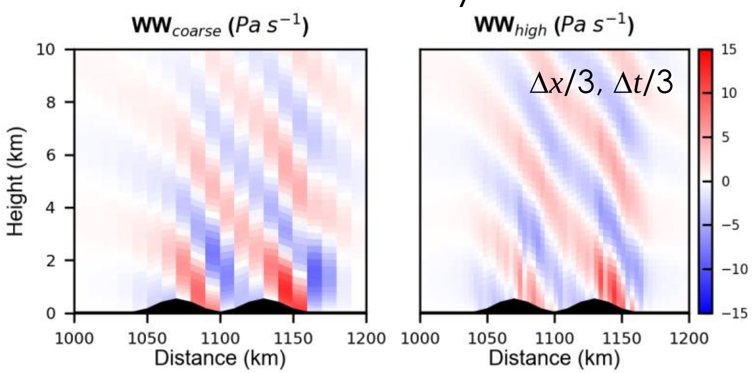
2Δx valley



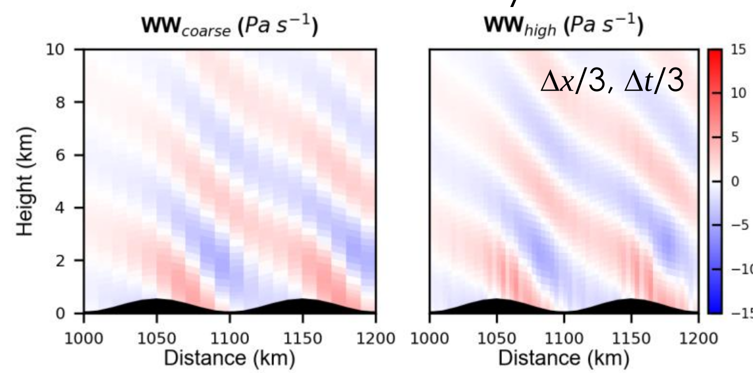
4Δx valley



6Δx valley



10Δx valley



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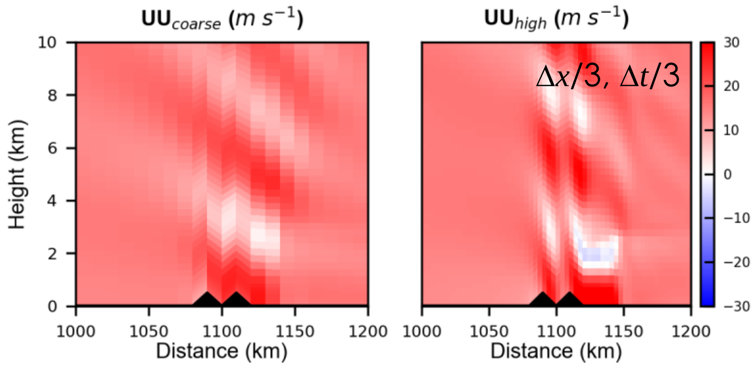
2D Valley Problem

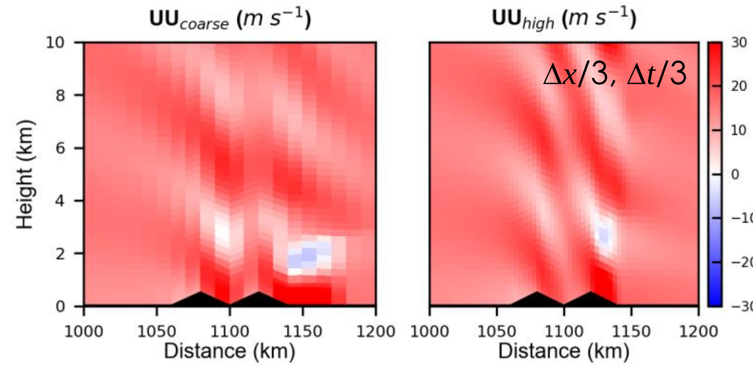
- Supercritical condition ($Fr = 1.5 \;\; with \; u = 15 \, ms^{-1}, h_m = 500 \, m$)

Horizontal wind, UU (m s^{-1})

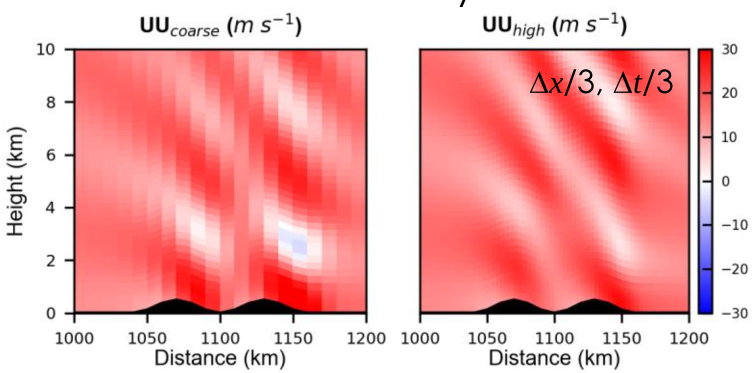
2Δx valley



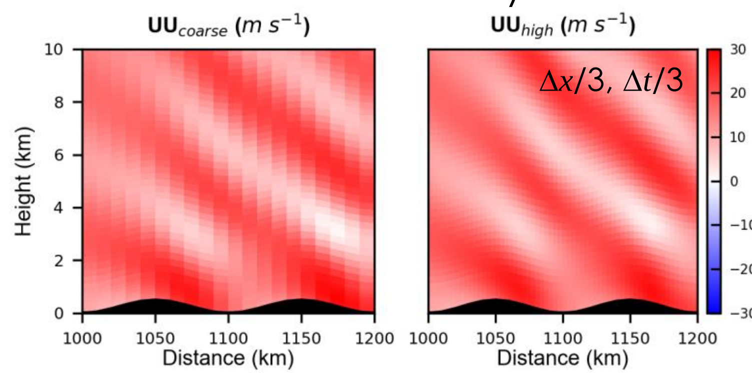
4Δx valley



6Δx valley



10Δx valley

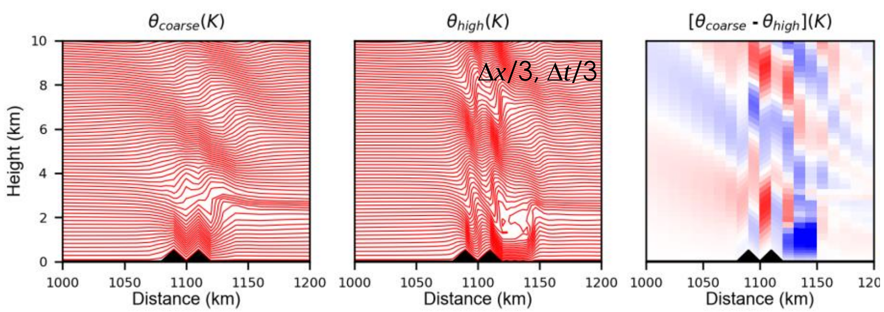


2D Valley Problem

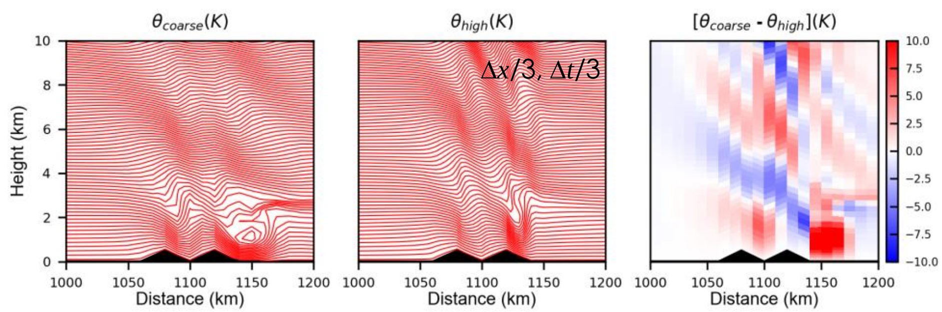
- Supercritical condition ($Fr = 1.5\ with\ u = 15\ ms^{-1}, h_m = 500\ m$)

Potential Temp., θ (K)

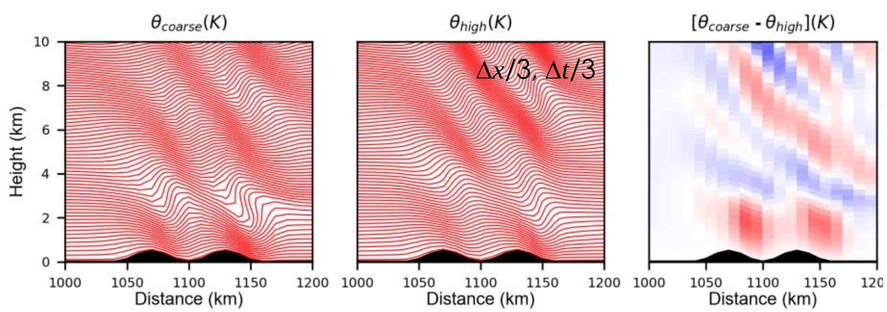
2Δx valley



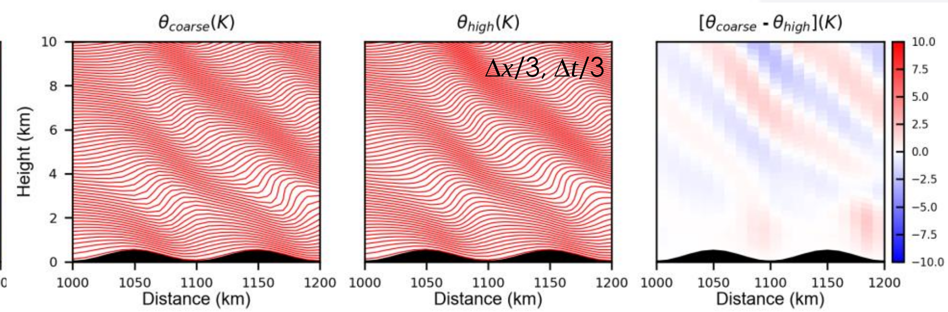
4Δx valley



6Δx valley



10Δx valley



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Conclusions

- The objective was to identify which scales to retain in orography for NWP using GEM as a reference model.
- Scales smaller than $6\Delta x$ are found to be under-resolved, and therefore, model predictions at these scales can be quite inaccurate (due to dispersion error, damping of the finest scales by semi-Lagrangian treatment, etc.).
- A combination of factors – (i) inaccurate flow representation at the finest scales, (ii) near-surface atmospheric stability , and (iii) near-surface wind speed – can collectively lead to a spurious secondary signal like "valley warming" during winter.
- In the context of GEM, **$6\Delta x$ and smaller scales in the orography are undesirable**.
- The problem is likely to be sensitive to the numerical details of an NWP model, and therefore careful investigation is required when higher resolution orography (with respect to the model grid resolution) is pursued with other models.

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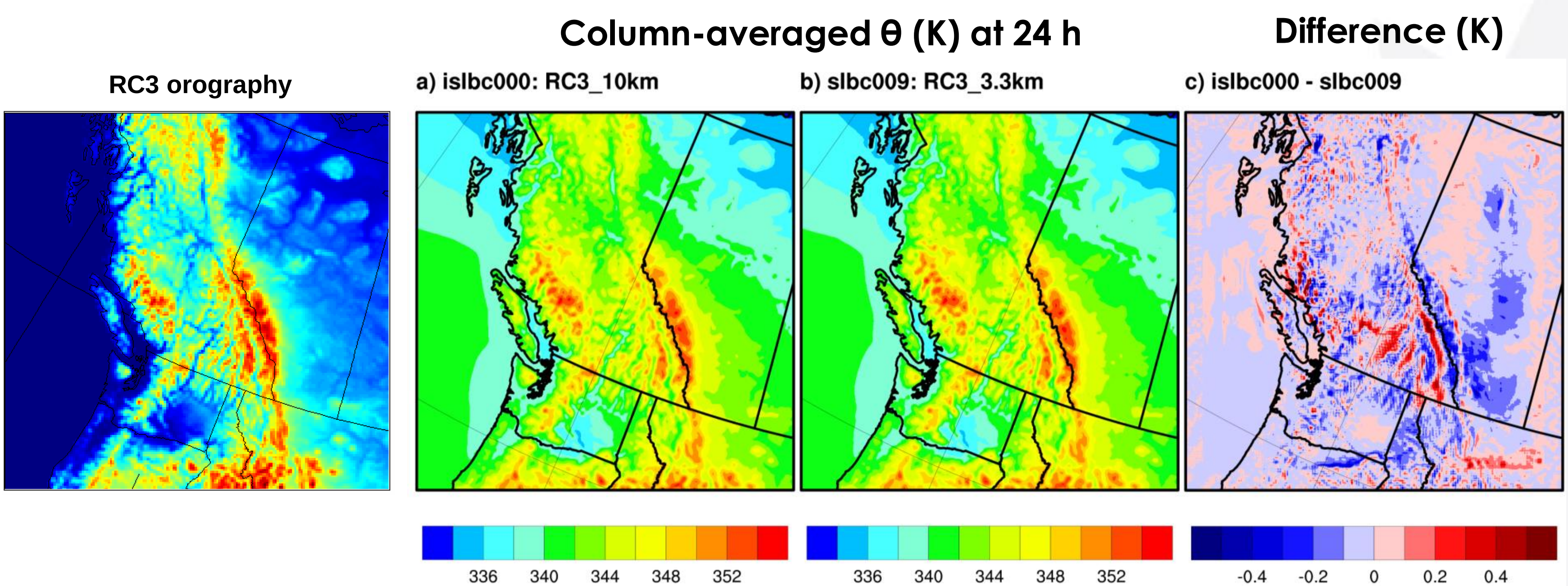
Appendix

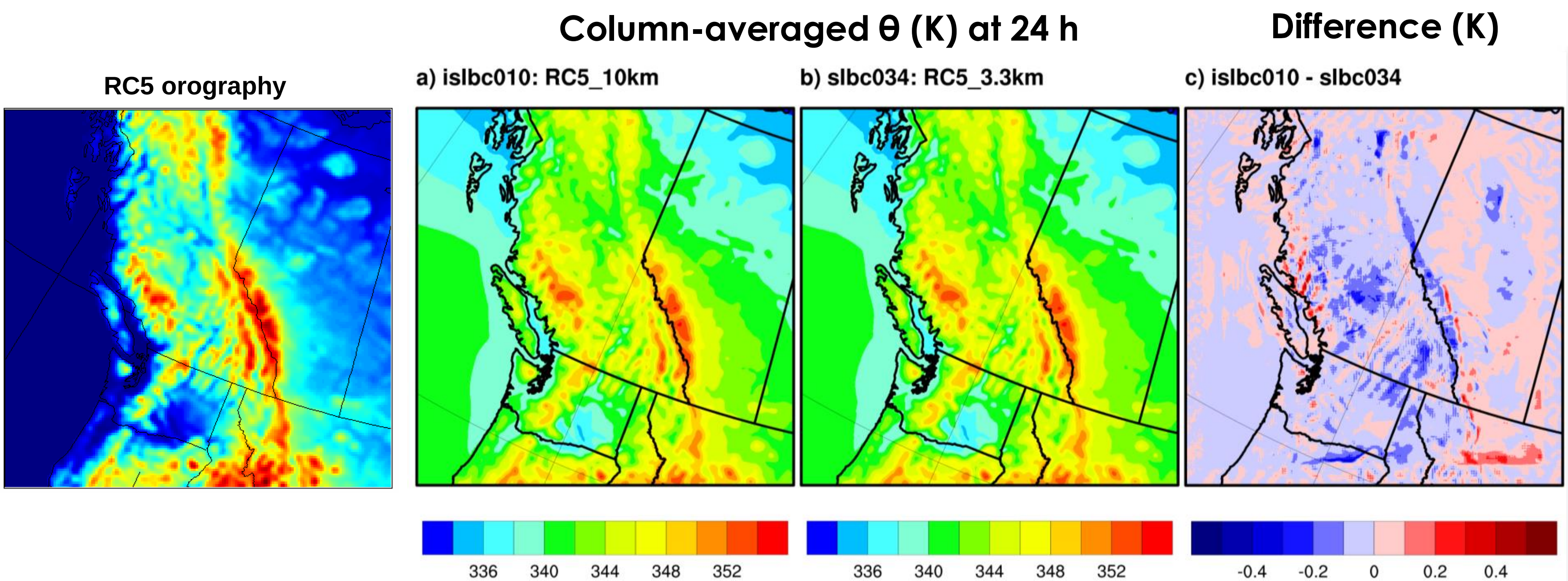
Warming in the valleys

- 2-D maps of column-integrated weighted-average of potential temperature are constructed.
- Net warming along the valleys is widespread with **RC3** filter.
- Also, there is cooling over the mountain tops and away to the east from the Rockies.
- However, domain-average potential temperature does not reveal any (significant) net warming/cooling with RC3.



Warming in the valleys

- For orography with the **RC5** filter the warming signal is largely eliminated.
- Also, the cooling over the mountains and away to the east are substantially reduced.



2D Valley Problem

- In order to have better alignment with the RDPS experiments
  - coarse and high resolution configurations employ 10-km (Δt=300s) and 3.333-km (Δt=100s), respectively,
  - vertical levels near surface (first 9 levels) are set to identical values, and
  - the vertical resolution above those is set to 250m so that the vertical absorption layer at the model top designed for other pre-existing theoretical cases can be readily applied.
- The definition of the valley chosen for this test case is a good representation of the actual valleys within the 3D model.
- The test problem involves flow under stable conditions (with N=0.02 s^{-1}, constant with height).
- Only supercritical case results ($Fr > 1.0$ where $Fr = u/(Nh_m)$) are presented (as the winter-time valley conditions are mostly supercritical).

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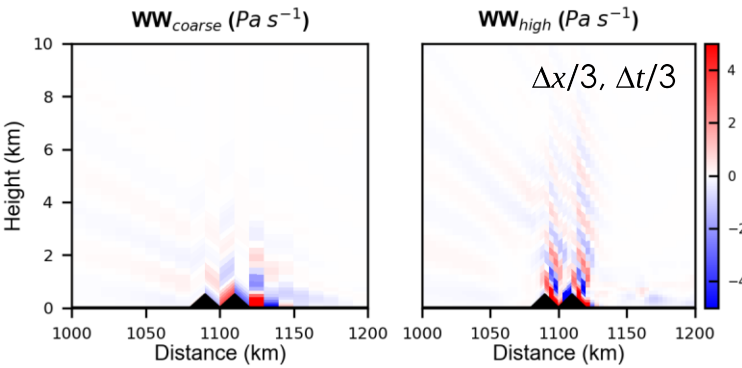
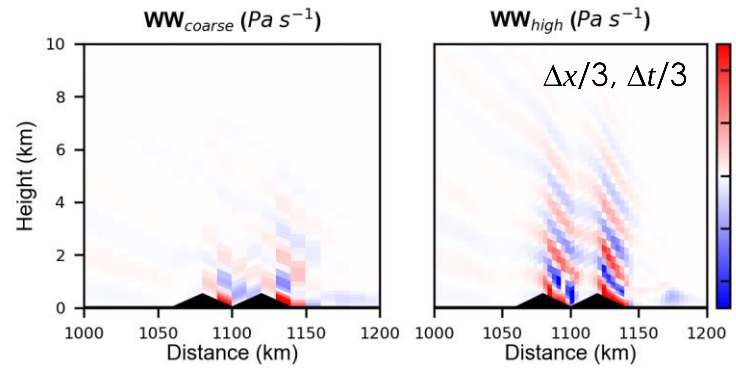
2D Valley Problem

- Subcritical condition ($Fr = 0.5 \;\; with \; u = 5 \, ms^{-1}, h_m = 500 \, m$)
- Results after 6 hours of simulation.

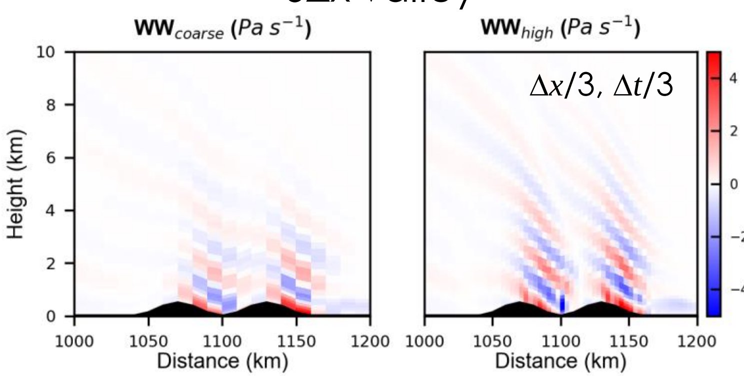
2Δx valley



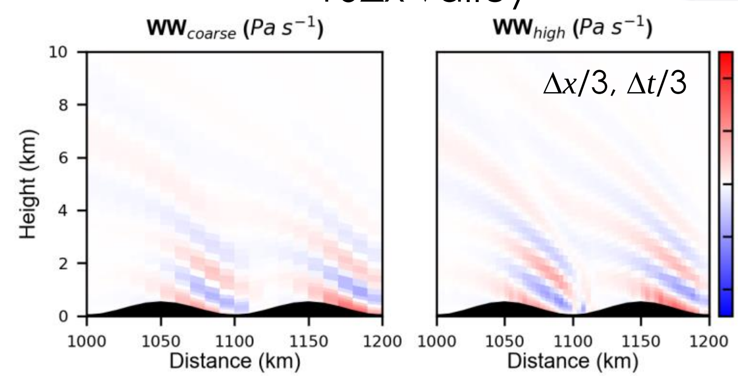
4Δx valley



6Δx valley



10Δx valley



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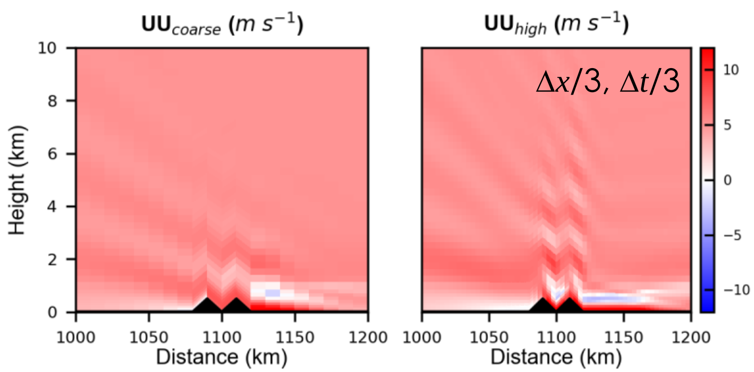
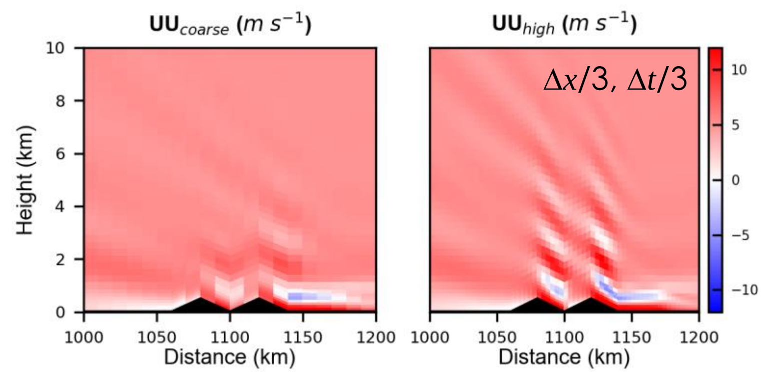
2D Valley Problem

- Subcritical condition ($Fr = 0.5\ \ with\ u = 5\ ms^{-1}, h_m = 500\ m$)

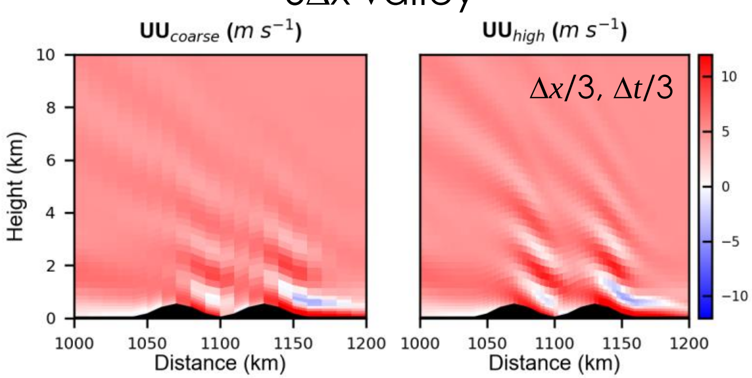
2Δx valley



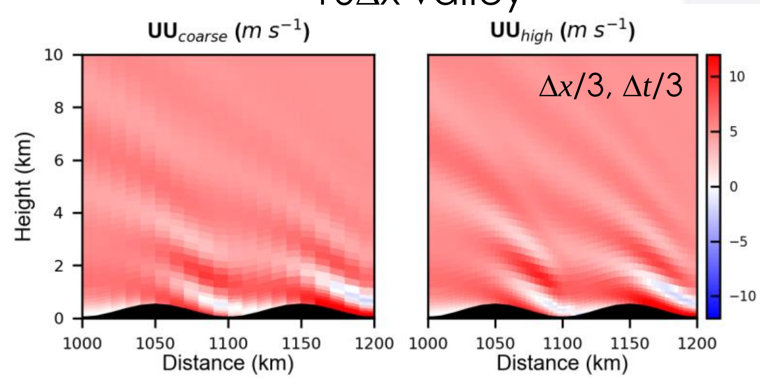
4Δx valley



6Δx valley



10Δx valley



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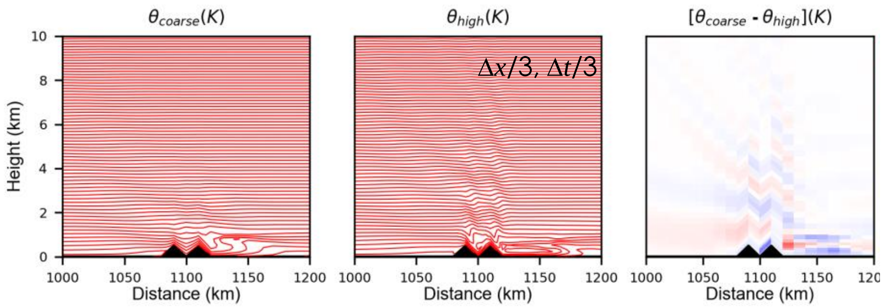
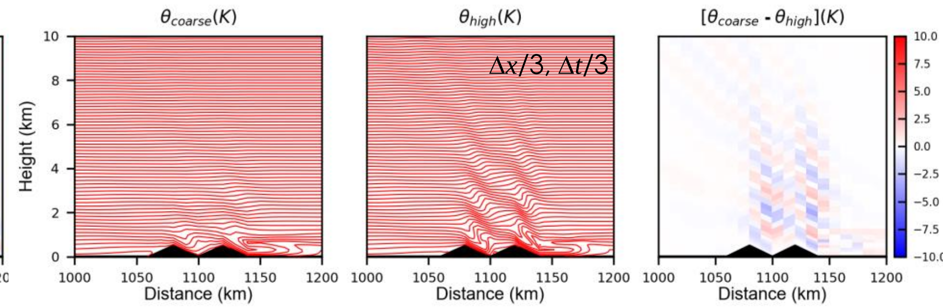
2D Valley Problem

- Subcritical condition ($Fr = 0.5 \;\; with\, u = 5\, ms^{-1}, h_m = 500\, m$)

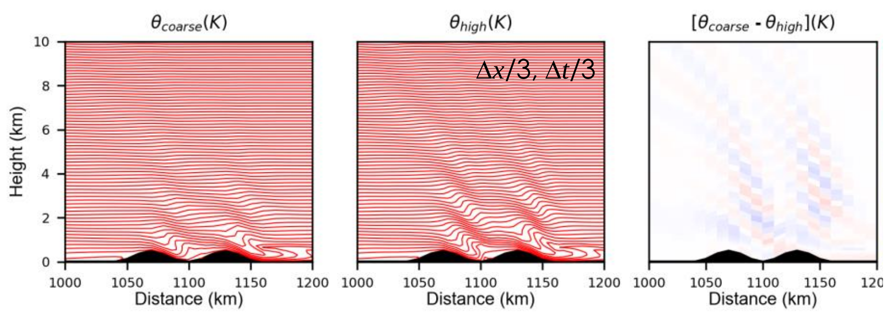
2Δx valley



4Δx valley



6Δx valley



10Δx valley