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Extended-range high-resolution dynamical downscaling over a continental-scale spatial domain with mesoscale simulations

by

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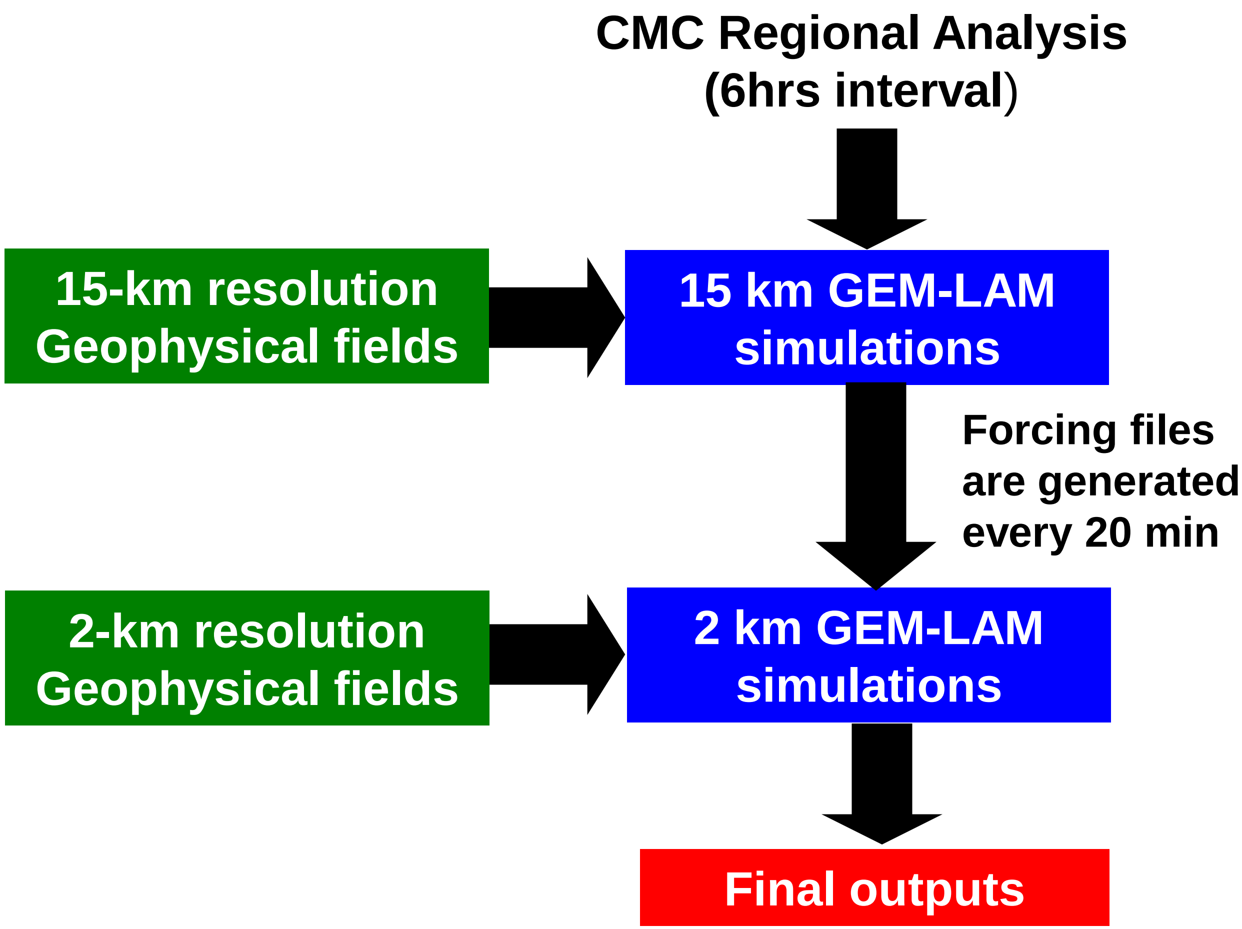
Motivations

- High-resolution multi-year time series of surface-layer meteorological fields are of tremendous interest to weather-dependent energy industries.
- Canadian Wind Energy Association (CanWEA) targets to generate 20% of Canada's electricity from wind by 2025.
- CanWEA has commissioned Pan Canadian Wind Integration Study (PCWIS) to

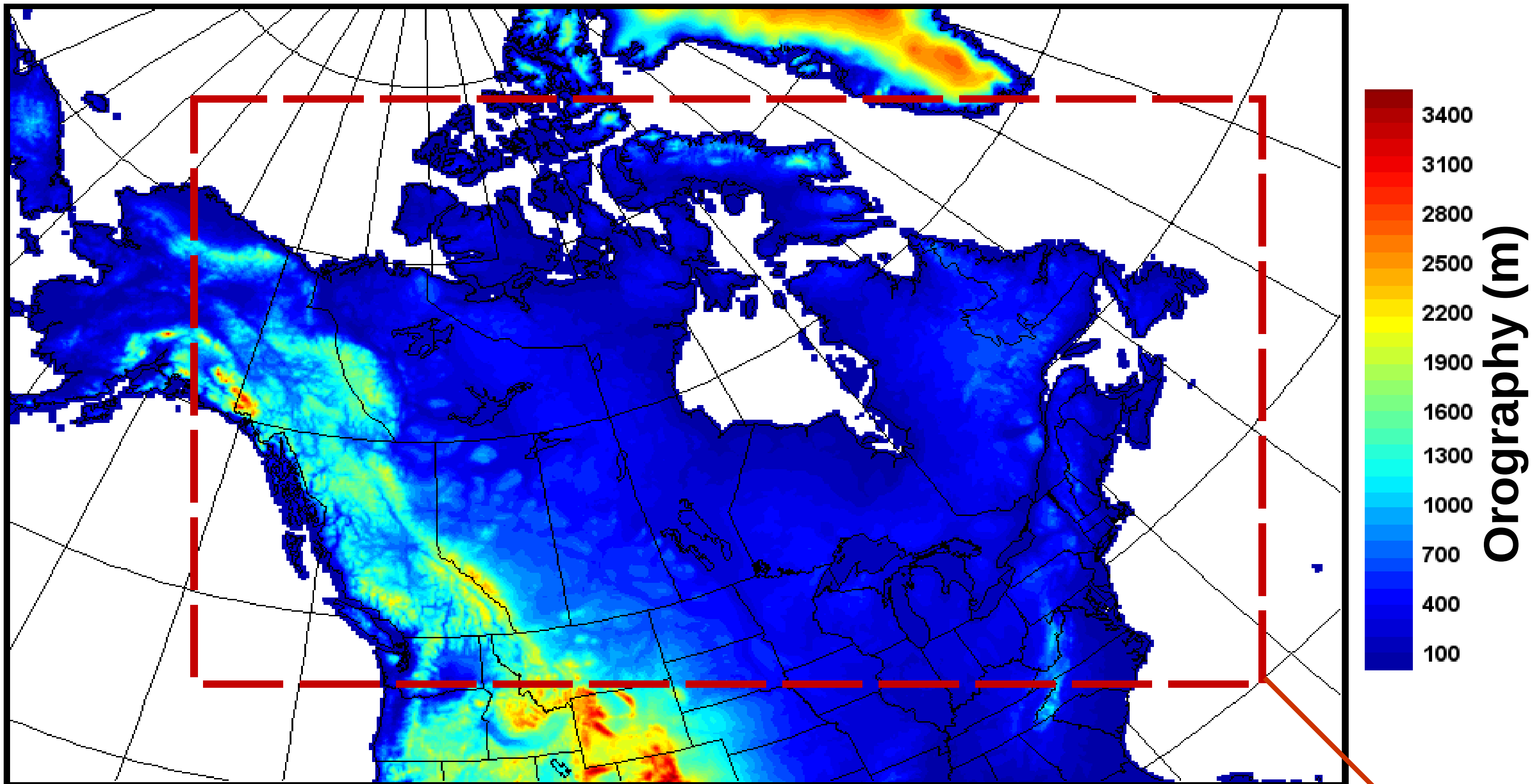
  - analyse multi-year wind speed time series

  - devise plan for large scale wind energy integration
- EC is responsible for generating the time series data for PCWIS.

Basic Dynamical Downscaling Strategy



15-km and 2-km Resolution Simulations Domains



15-km GEM-LAM simulation domain
480x300 grid cells

2-km GEM-LAM simulation domain
3000x1800 grid cells

Issues to be addressed

- Controlling large-scale deviation of the atmosphere (with LAM-15 simulations).
- Addressing deviations of evolving surface fields (with LAM-15 simulations).
- Extending findings of LAM-15 test simulations to LAM-2 simulations.
- Propose optimal configurations for dynamical downscaling.

Atmospheric large-scale deviations:
The biggest challenge

Atmospheric large-scale deviations: The biggest challenge

- Atmospheric large-scales can deviate during dynamical downscaling primarily due to

  - Large spatial domain

  - Extended length of temporal integration

- The problem may be separated into multiple periods of sufficiently small time-frames (e.g. NREL did in the US).

  - May lead to abrupt changes in time-series after temporal blending.

  - Would require additional computational time for spin-up of clouds not present in CMC regional analysis.

Atmospheric large-scale deviations: The biggest challenge

- The problem may be separated into multiple simulations over smaller domains for extended periods (e.g. NREL did in the US).

  - May lead to discontinuities in the meteorological fields along the lateral boundaries of the small domains due to spatial blending.

  - The domains cannot be arbitrarily small for proper development small scales and to avoid small-scale variance deficiency.

- Overall, continuous temporal integration over the entire spatial domain appears to be the most feasible approach, **provided a mechanism is put in place to control large-scale deviations**.

Similarity of scales

- Similarity for a meteorological field Ψ between the model outputs and the driving fields for a simulation time *t* and scale of interest *L*, is computed as

$$P(t,L) = 1 - \frac{\left\langle \left\| \Psi_M(t) - \Psi_D(t) \right\|_L^2 \right\rangle}{\left\langle \left\| \Psi_D(t) - \overline{\Psi_D(t)} \right\|_L^2 \right\rangle}$$

  where < > is spatial average (Storch et al. 2000).

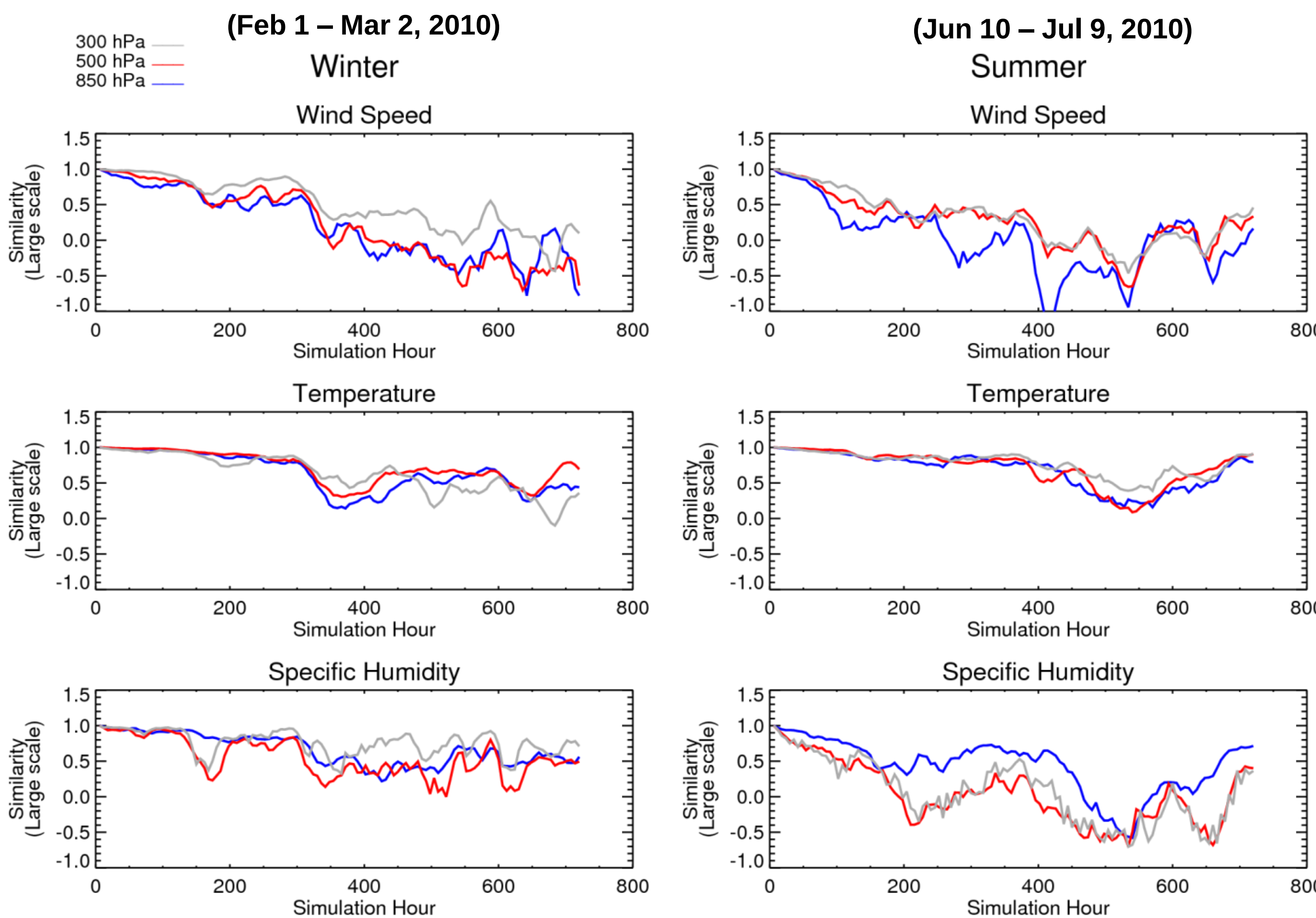
- The length scale *L* is separated using Discrete Cosine Transform based spectral filter.

- For large scales higher degree of similarity is desirable, i.e., *P*(*t*,*L*) should be close to 1.

- Small scales between the driving and the driven fields should ideally be different.

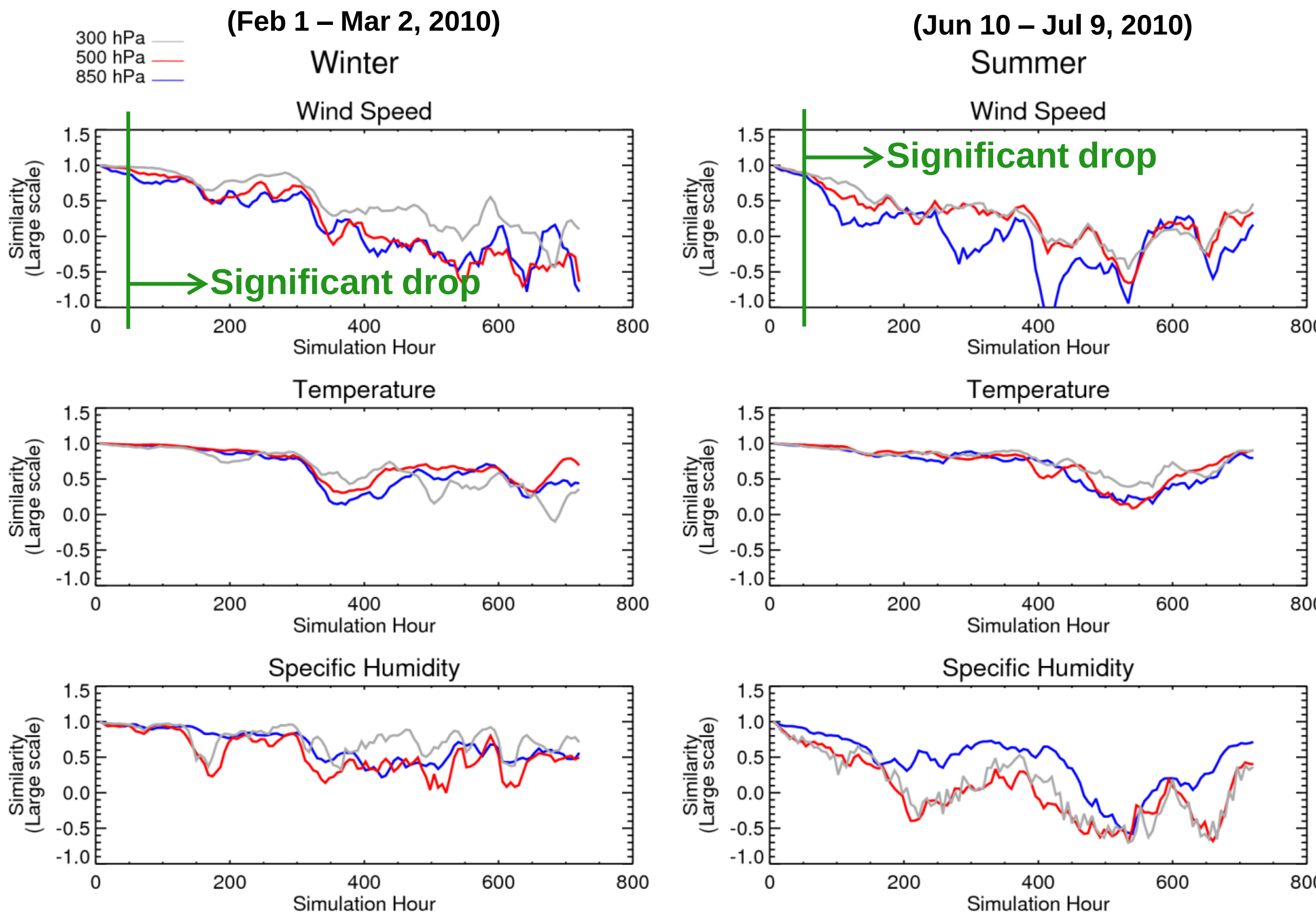
Large-scale similarities between LAM-15 CONTROL and CMC regional analysis

For scales larger than 450 km



Large-scale similarities between LAM-15 CONTROL and CMC regional analysis

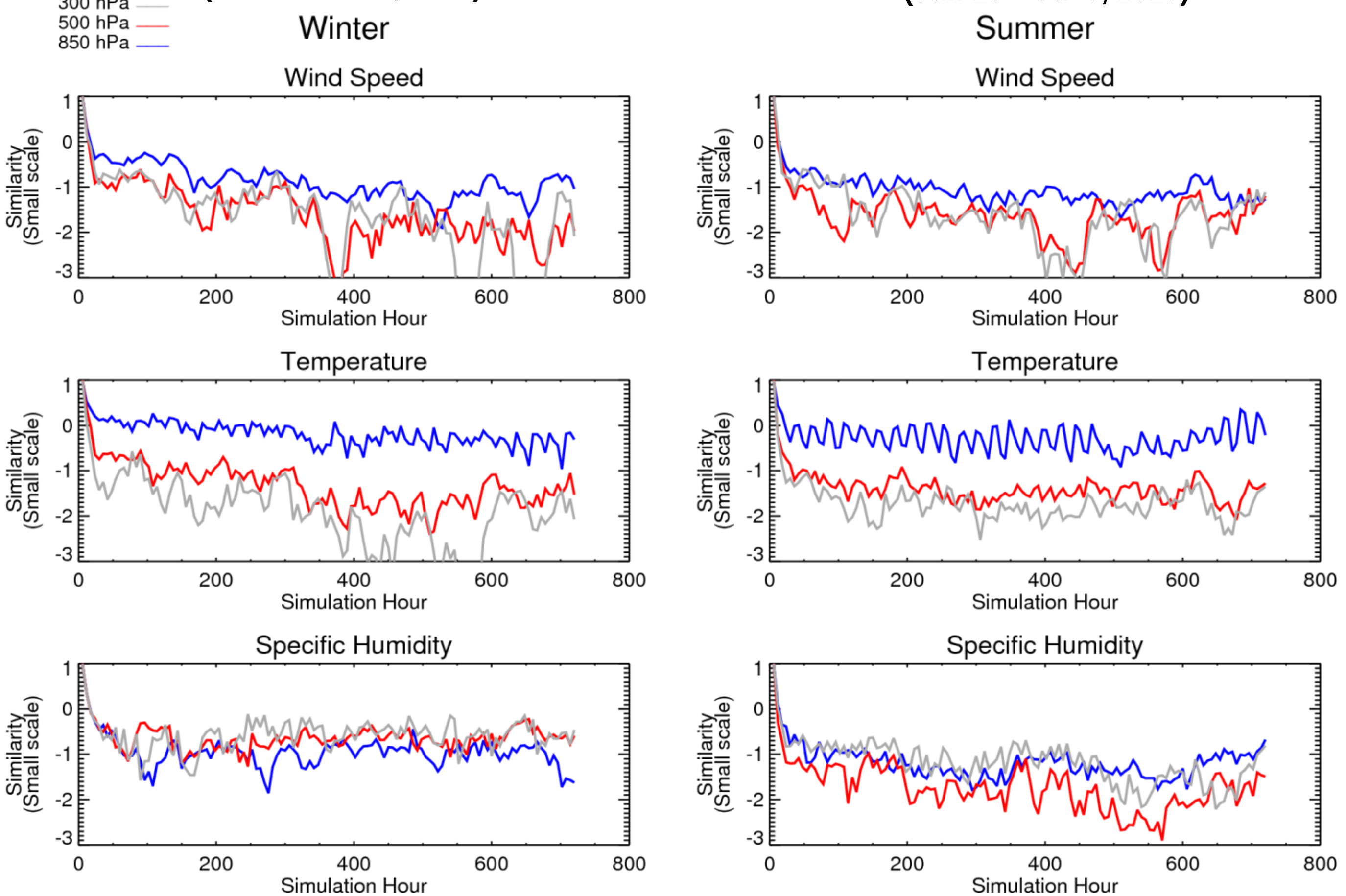
For scales larger than 450 km



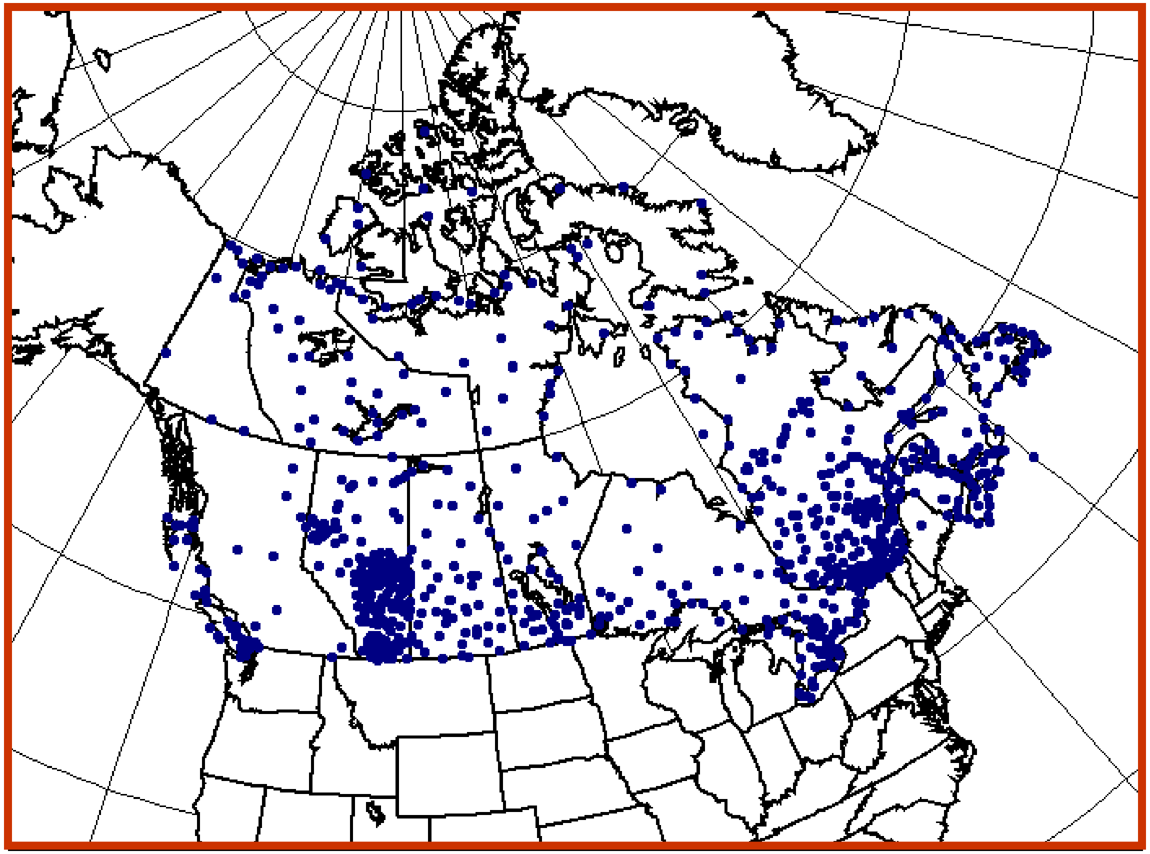
Small-scale similarities between LAM-15 CONTROL and CMC regional analysis

For scales smaller than 450 km

(Feb 1 – Mar 2, 2010) **(Jun 10 – Jul 9, 2010)**



Estimating the impact on screen-level scores

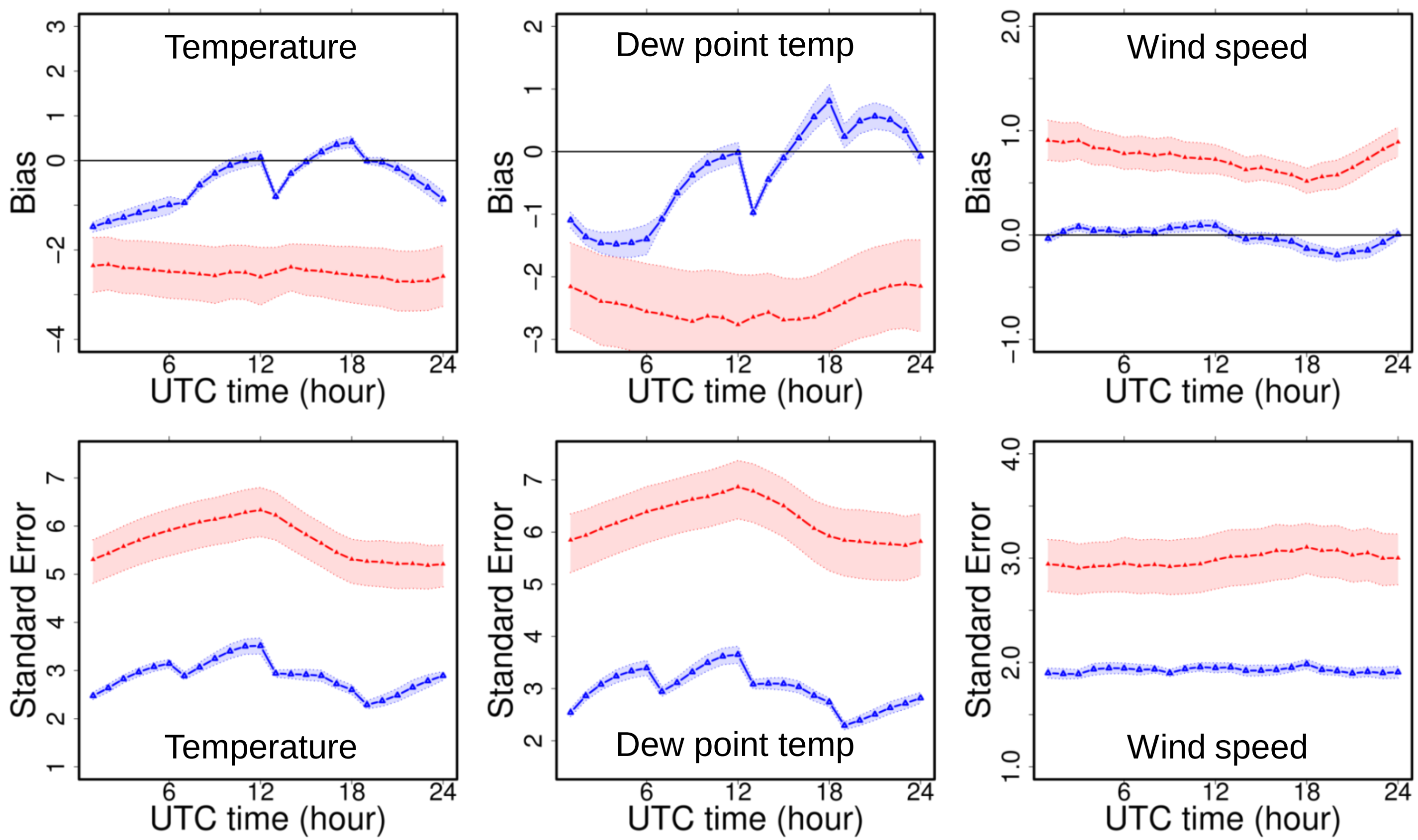


- Total number of stations is 898.
- Only Canadian stations are included for evaluation.
- 100 m elevation difference permitted between model and observation.
- Statistical analyses using **USTAT** (Marcel Vallée).

Screen-level scores

REG FORECAST
LAM-15 CONTROL

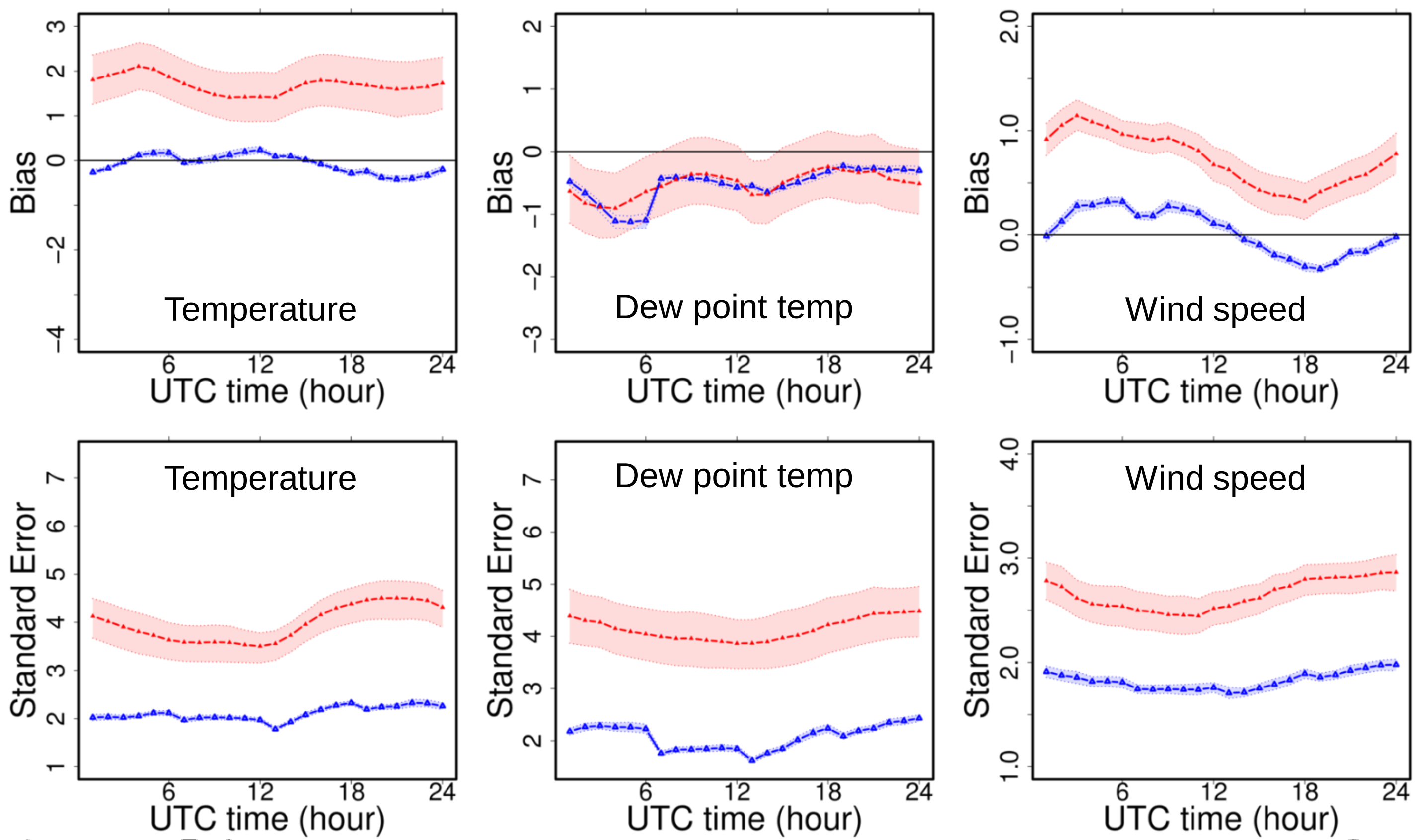
Winter (Feb 1 – Mar 2, 2010)



Screen-level scores

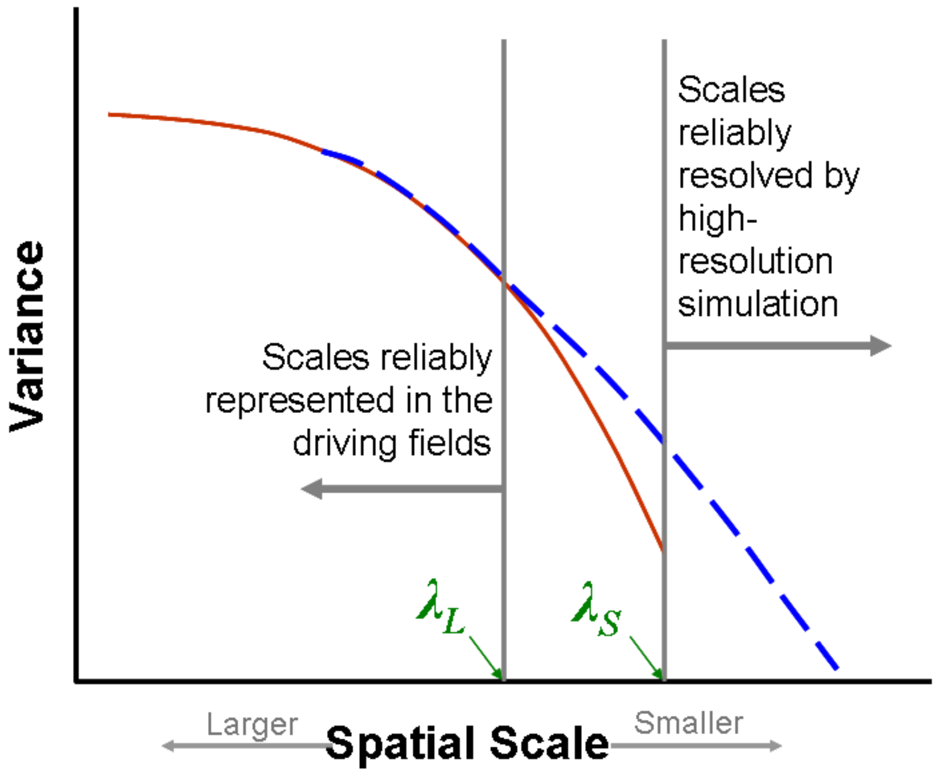
REG FORECAST
LAM-15 CONTROL

Summer (Jun 10 – Jul 9, 2010)



Controlling large-scale deviations: Some basic assumptions

- Smaller scales are preconditioned by the large-scales.
- Large-scale features of the driving field (CMC analysis for LAM-15, and LAM-15 outputs for LAM-2) are assumed to be more reliable.
- Influence of smaller scales on the large scales are insignificant.



Selection of nudging parameters: Nudging length scale

- Selection of nudging length scales λ_L and λ_S requires

- Comparison of variance spectra of analysis and model fields

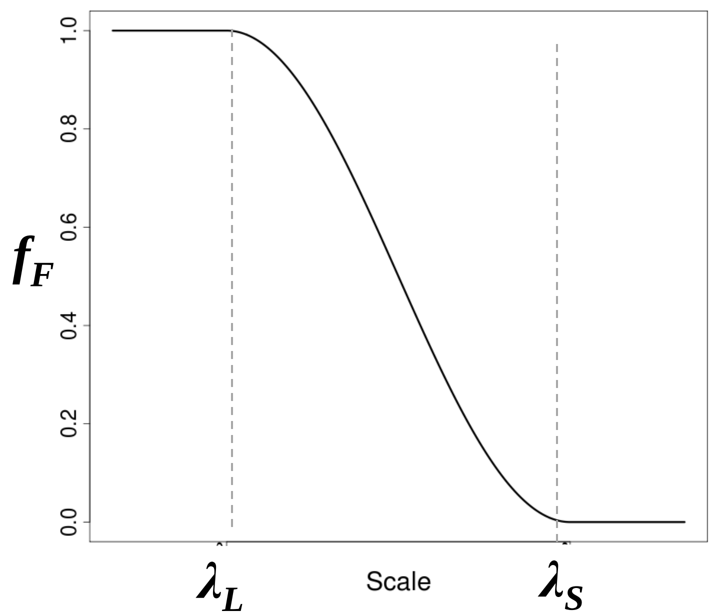
- A soft/gradual cut-off of scales between λ_L and λ_S

- Filter applied on the 2D DCT to obtain the DCT of the filtered field

$$F_F(m,n) = F(m,n)\, f_F(m,n)$$

2D DCT: $F(m,n)$

2D filter: $f_F(m,n)$



- It's followed by inverse DCT.

Controlling large-scale deviations: Nudging of simulation outputs

- A meteorological field Ψ at a given vertical level is nudged using the following relation

Nudging term

$$\Psi_M = \Psi_M + \frac{\beta(\zeta)}{\tau(t)} \left[\Psi_D - \Psi_M \right]_L$$

Vertical profile of nudging

Spatial scale of interest

Mesoscale simulation output

Driving field

Relaxation time

Controlling large-scale deviations: Nudging of simulation outputs

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Nudging term

$$\Psi_M = \Psi_M + \frac{\beta(\zeta)}{\tau(t)}\left[\Psi_D - \Psi_M\right]_L$$

Vertical profile of nudging

Spatial scale of interest defined by λ_L and λ_S.

Mesoscale simulation output

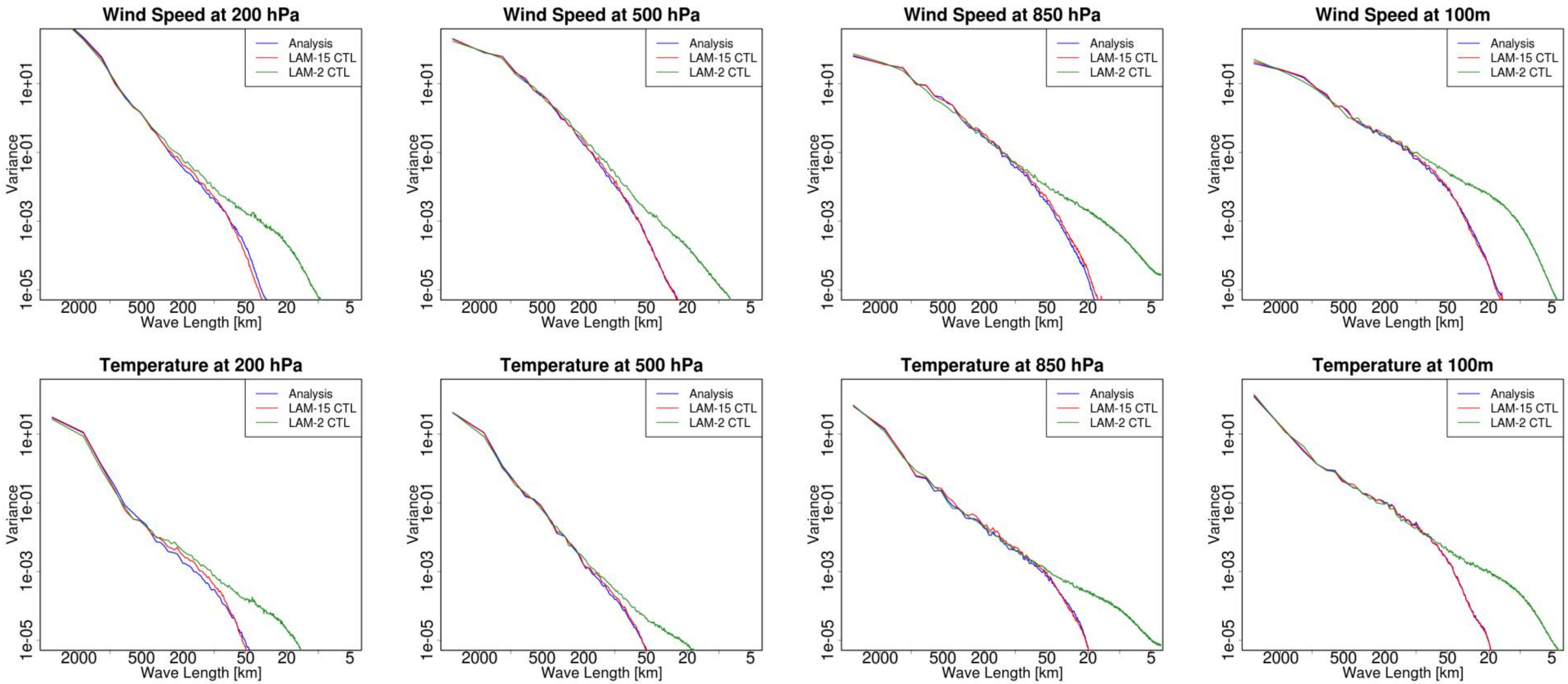
Driving field

Relaxation time

- Nudging term is expanded in the spectral space to have better control over scale selection for retaining.
- Spectral decomposition is based on 2D DCT.

Variance Spectra
Averaged over two days (Feb 1-2, 2010)

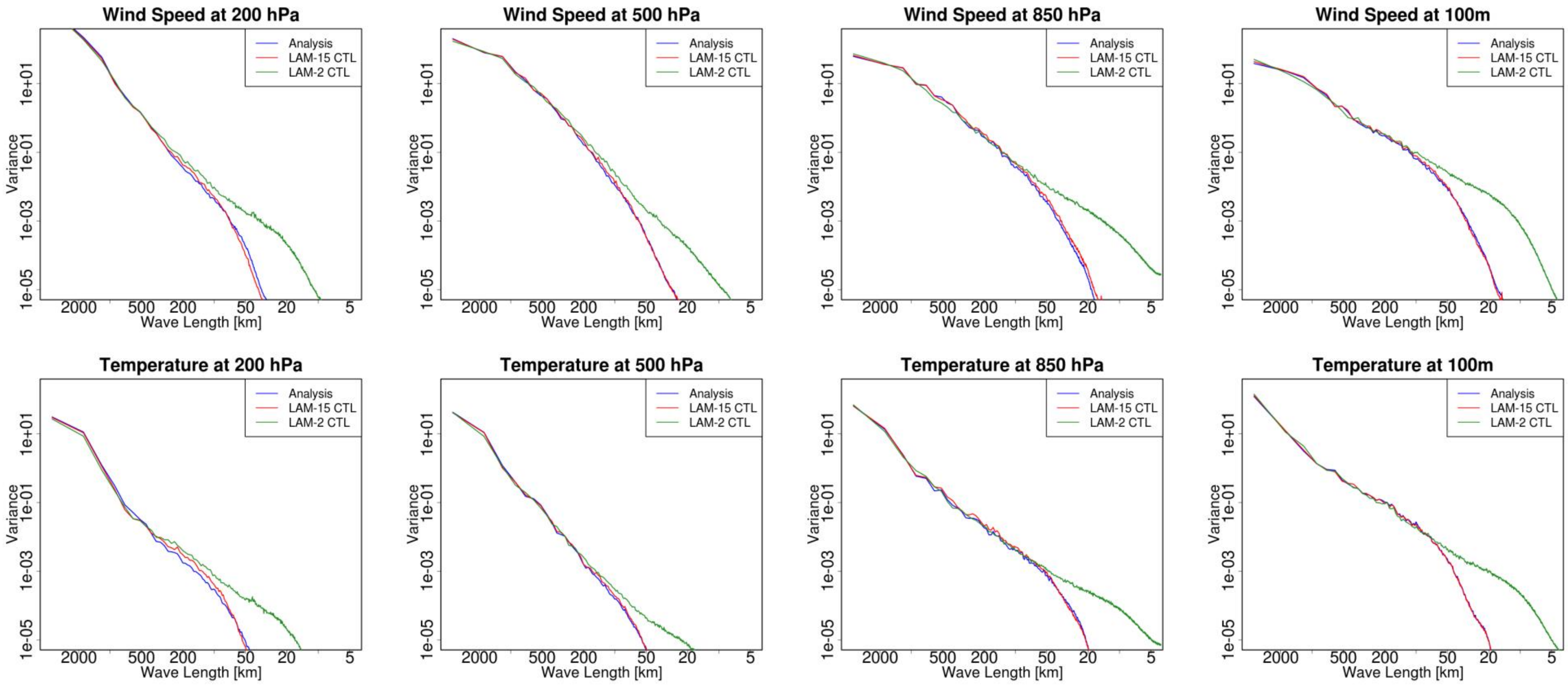
CMC Regional Analysis
LAM-15 CONTROL
LAM-2 CONTROL



Variance Spectra
Averaged over two days (Feb 1-2, 2010)

CMC Regional Analysis
LAM-15 CONTROL
LAM-2 CONTROL

$$\lambda_S = 100km, \ \lambda_L = 300km$$



Sensitivity of different nudging parameters

- Sensitivity tests are conducted to identify an optimal nudging strategy by investigating

  - Different nudging vertical profiles $\beta(\zeta)$

  - Different temporal relaxations $\tau(t)$

  - Different nudging length scales, λ_S and λ_L

- Only temperature and horizontal wind are nudged.
- Different test configurations are denoted as follows

N# T# S#

- **S#**: **Nudging scale**
- **T#**: **Temporal relaxation**
- **N#**: **Nudging vertical profile**

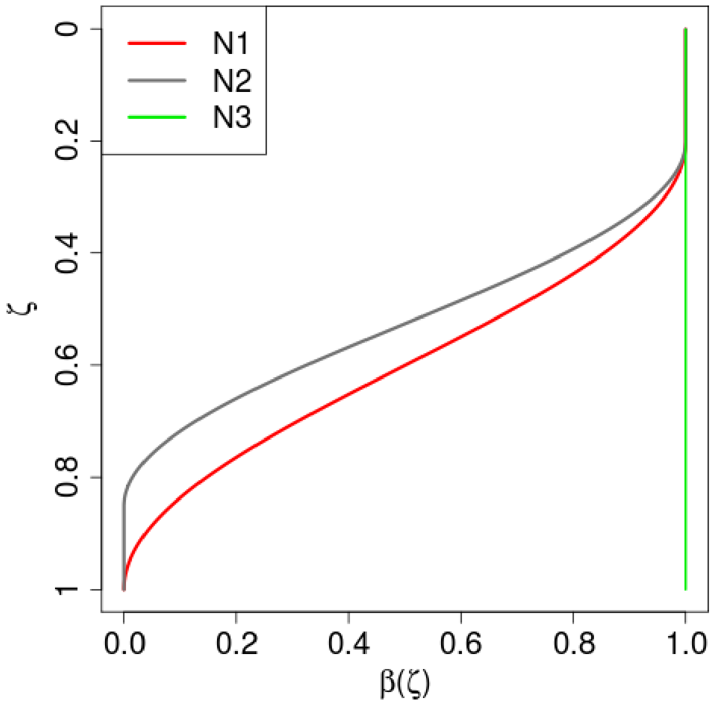
Different nudging vertical profiles

- General profile shape is given by

$$\beta(\zeta)=\begin{cases}0 & if\ \zeta>\zeta_B\\ 1 & if\zeta<\zeta_T\\ f(\zeta) & if\ \zeta_T<\zeta<\zeta_B\end{cases}$$

where

$$f(\zeta)=\left[\cos\left\{\frac{\pi}{2}\frac{\zeta-\zeta_T}{\zeta_B-\zeta_T}\right\}\right]^2$$



Different temporal relaxations

- General form: $\tau = \dfrac{t_R}{\Delta t\, \omega(t)}$

  Relaxation time scale (t_R)

  Temporal weighting function ($\omega(t)$)

  where $\omega(t) = [\cos\{\pi n \Delta t / t_D\}]^m$ with m=0,2,4,6,…

  Time interval between two consecutive driving fields (t_D)

- T1: Constant weak relaxation

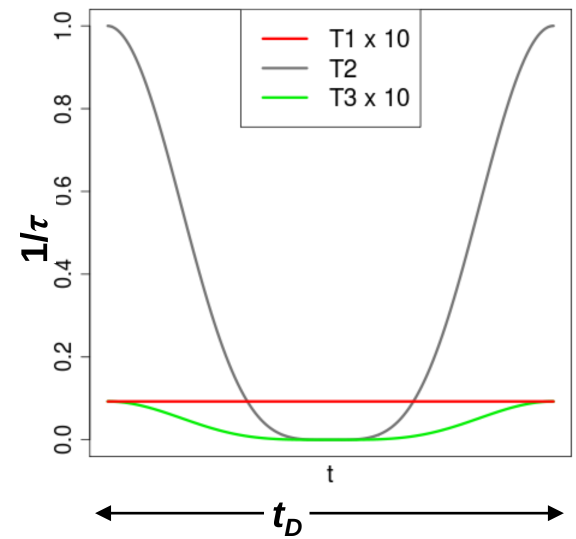
  $t_R = t_D$ and m=0, i.e., $\omega(t)$=1

- T2: Variable strong relaxation

  $t_R = \Delta t$ and m=2

- T3: Variable weak relaxation

  $t_R = t_D$ and m=2



Different nudging length scales

- S1:

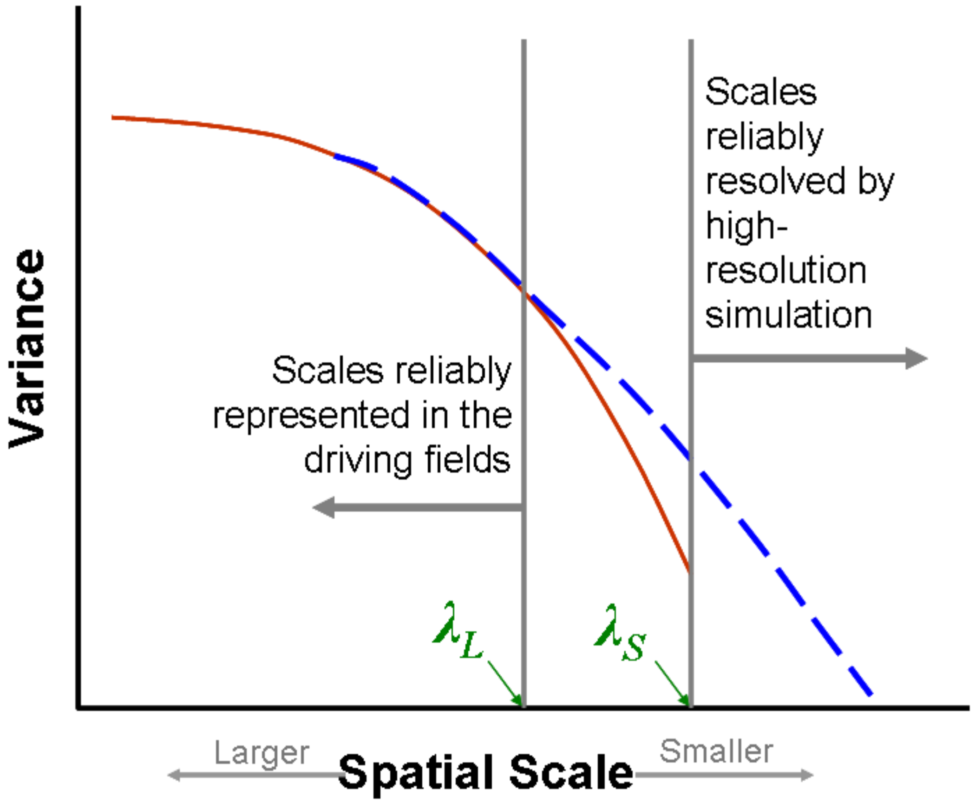
  λ_S =100 km and λ_L=300 km

- S2:

  λ_S =225 km and λ_L=450 km

- S3:

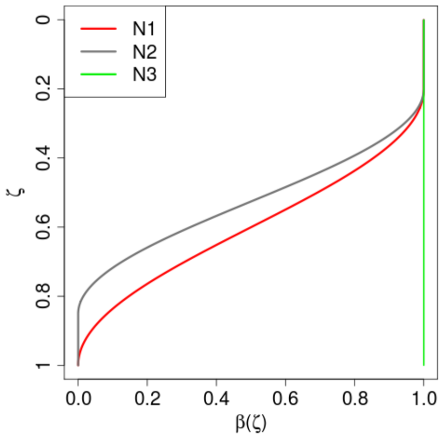
  λ_S =350 km and λ_L=700 km

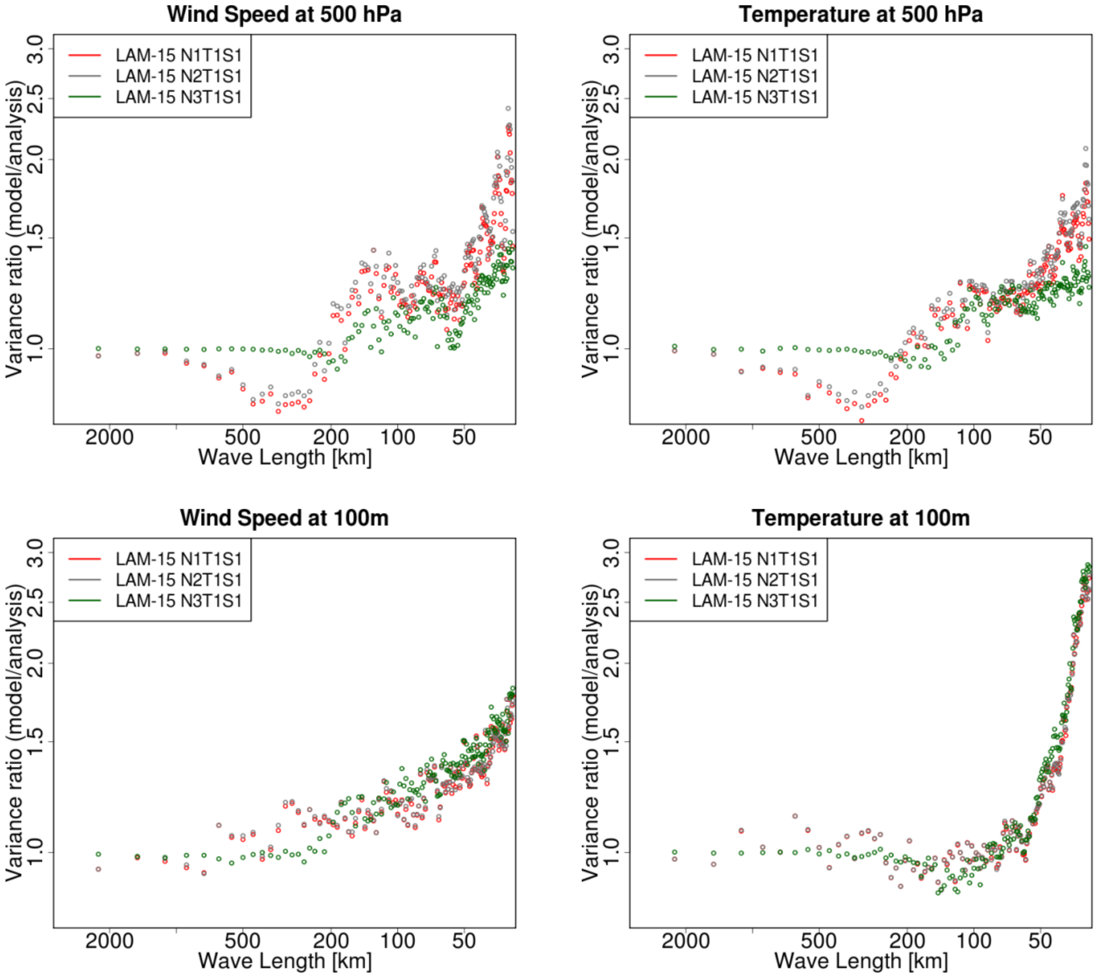


Sensitivity: Nudging vertical profile
Variance ratio (LAM-15/Analysis)

Winter
Feb 1 – Mar 2, 2010

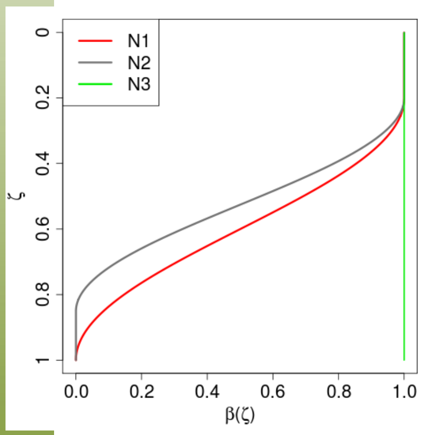
LAM-15 N1T1S1
LAM-15 N2T1S1
LAM-15 N3T1S1





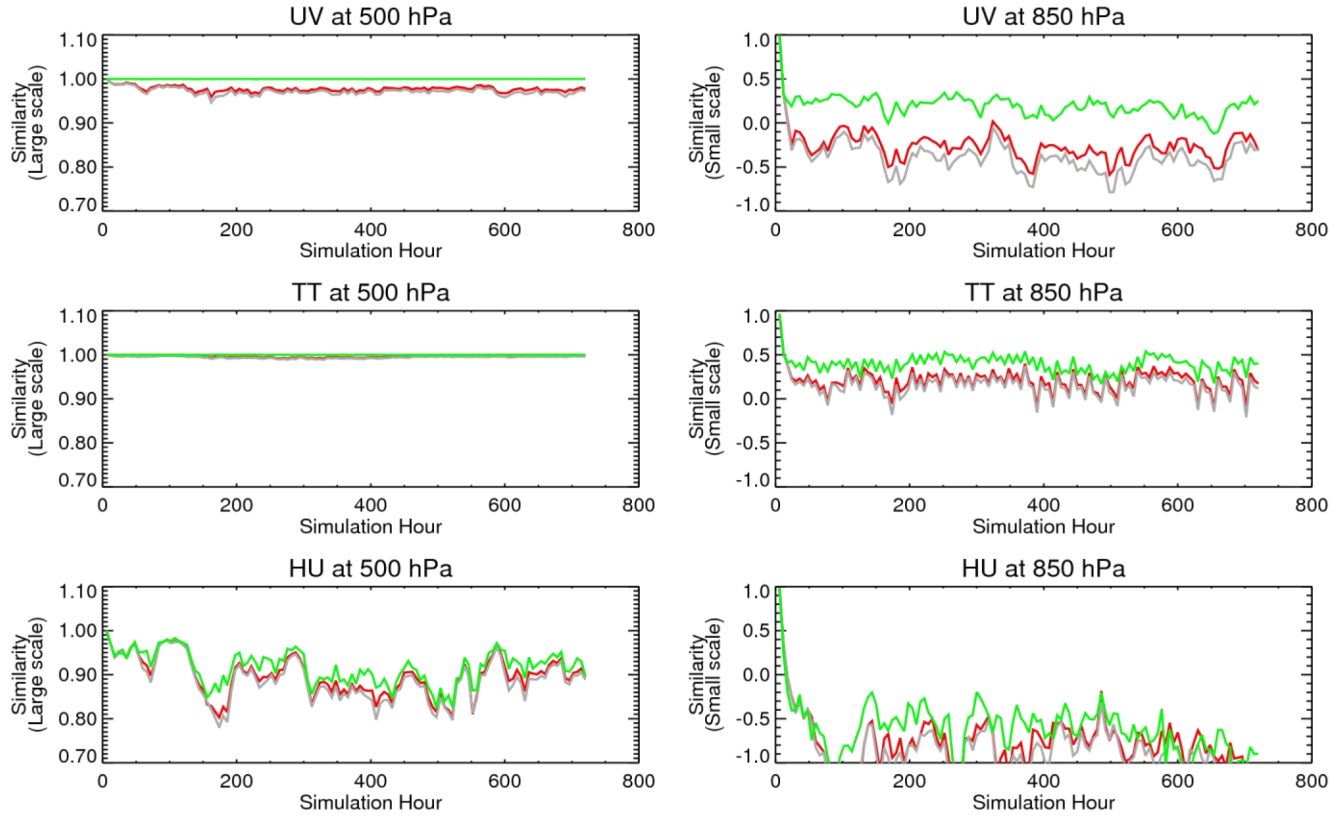
Sensitivity: Nudging vertical profile
Similarity

LAM-15 N1T1S1
LAM-15 N2T1S1
LAM-15 N3T1S1



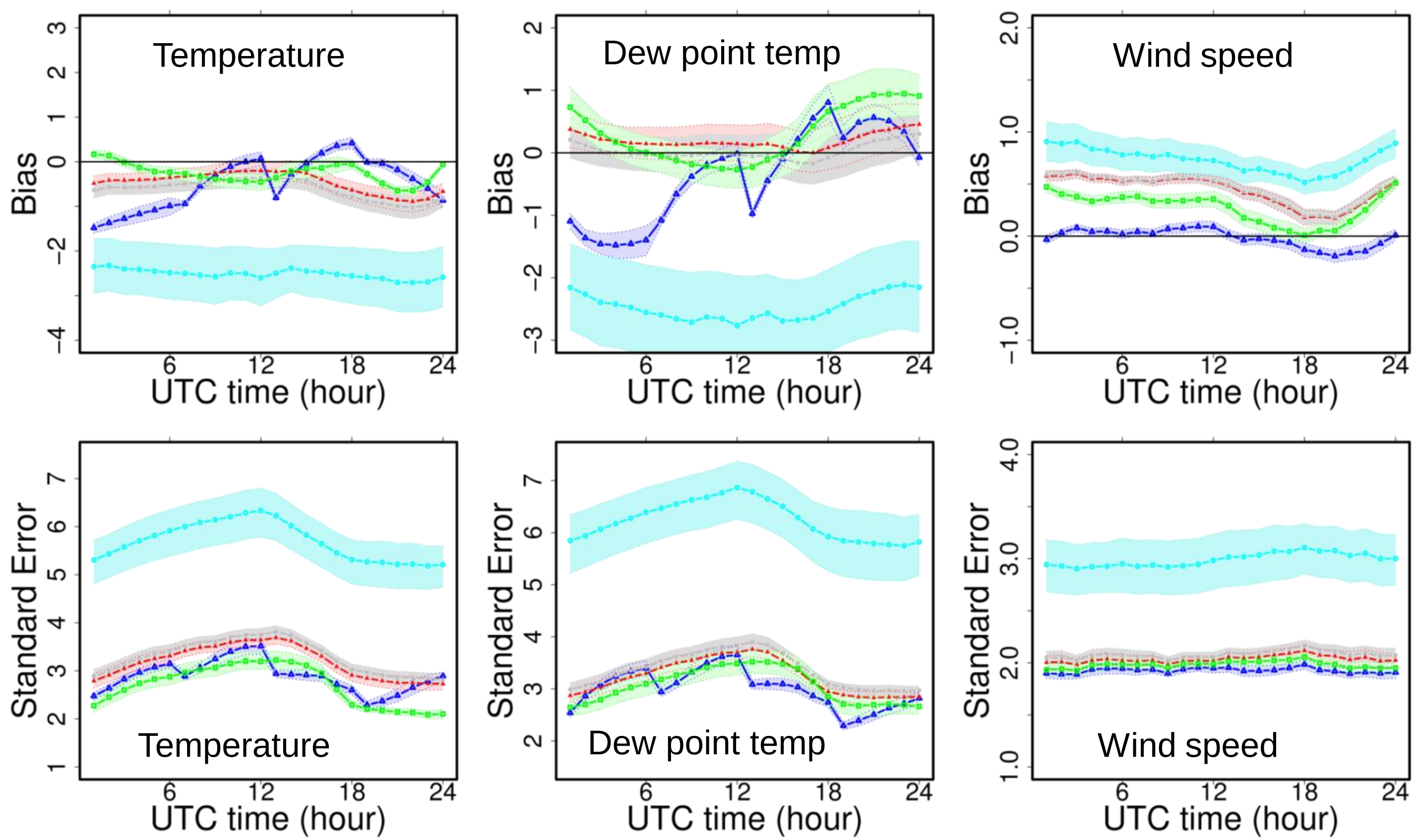
Winter (Feb 1 – Mar 2, 2010)

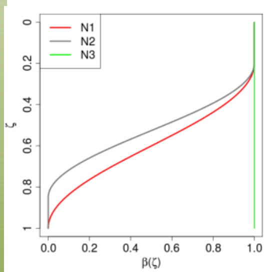
Large scales (at 500 hPa) **Small scales (at 850 hPa)**



Sensitivity: Nudging vertical profile
Screen-level scores

Winter (Feb 1 – Mar 2, 2010)



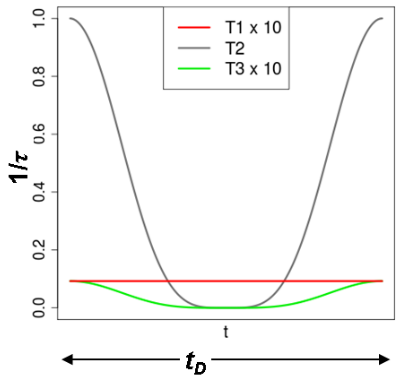


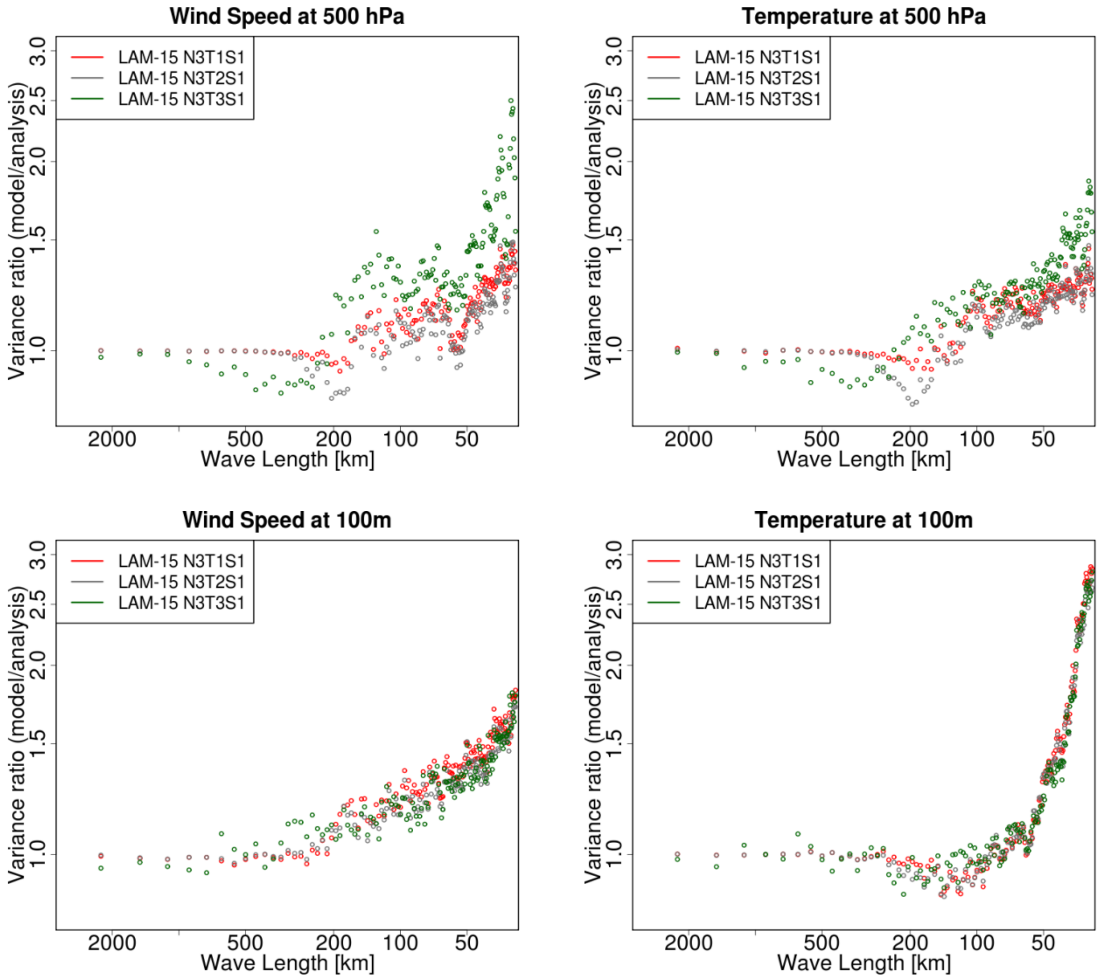
- Overall N3 is selected as optimal for the next tests.

Sensitivity: Temporal relaxation
Variance ratio (LAM-15/Analysis)

Winter
Feb 1 – Mar 2, 2010

LAM-15 N3T1S1
LAM-15 N3T2S1
LAM-15 N3T3S1

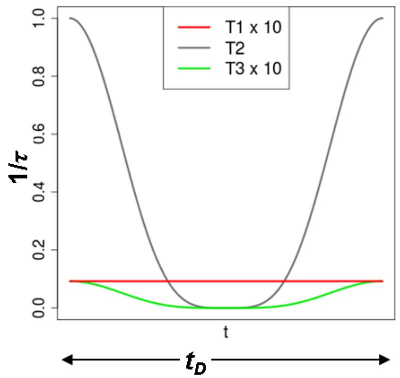


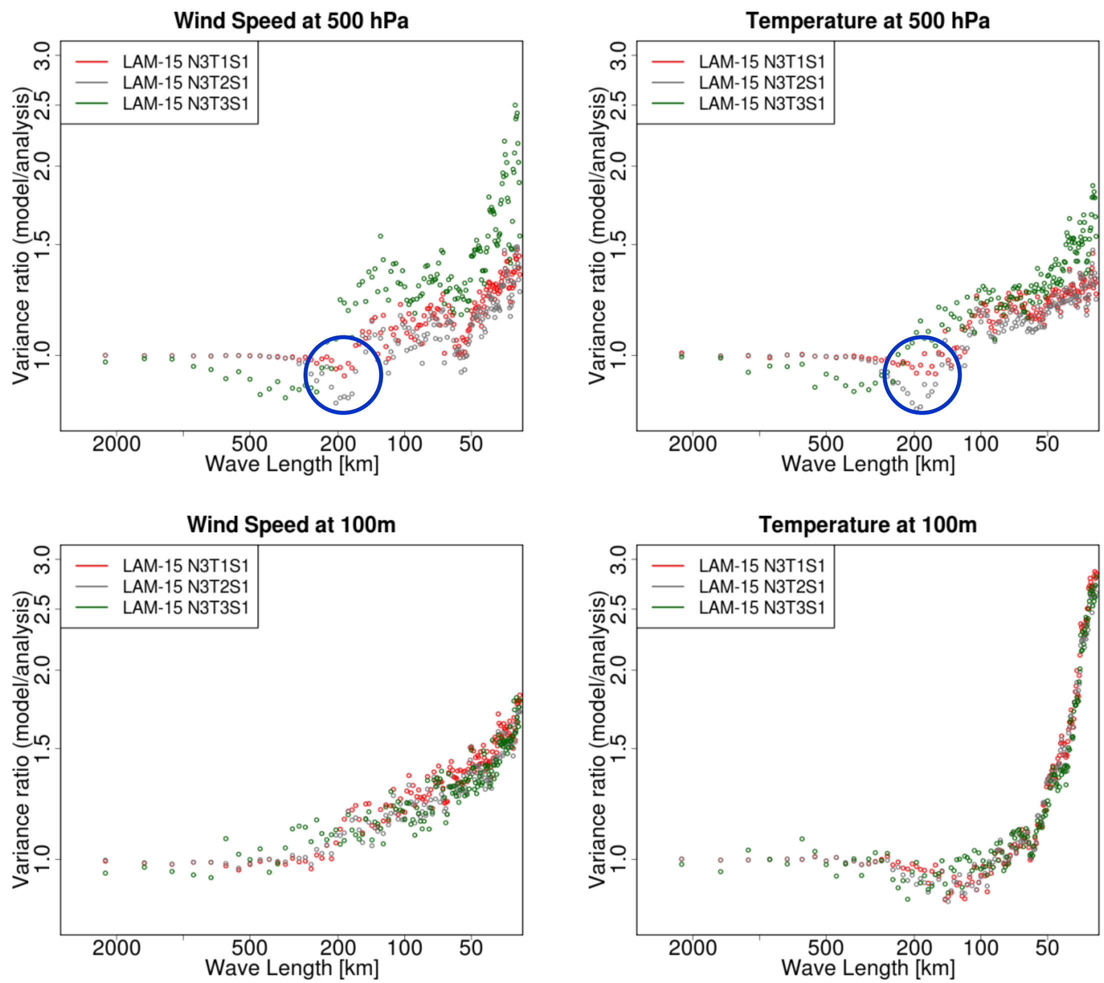


Sensitivity: Temporal relaxation
Variance ratio (LAM-15/Analysis)

Winter
Feb 1 – Mar 2, 2010

LAM-15 N3T1S1
LAM-15 N3T2S1
LAM-15 N3T3S1



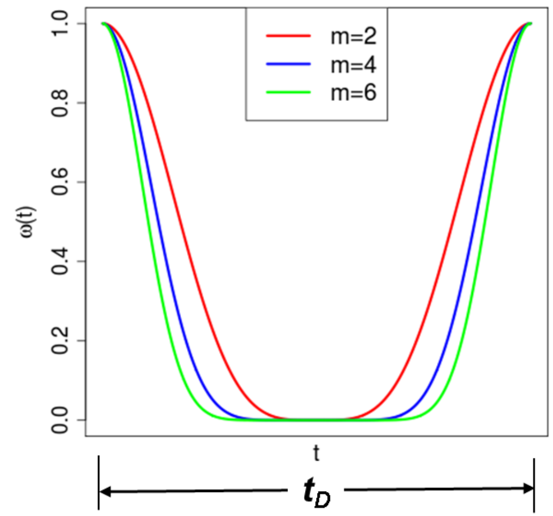


Addressing variance deficiency

- Strong nudging only at times when driving fields are available

  - May lead to abrupt changes in time series.

  - Increasing *m* will have similar impact.

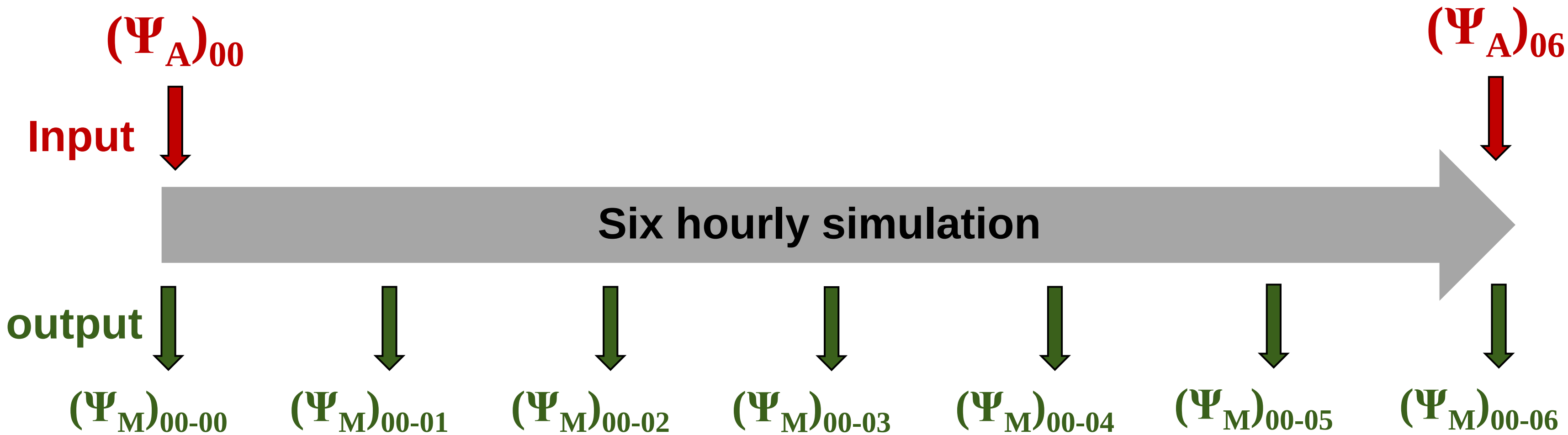


- Computing hourly analysis estimates from RDPS outputs or by running LAM-15 simulations.

  - More effective but computationally expensive.

Addressing variance deficiency

Estimating hourly equivalent of analysis



Error, $\varepsilon_{00\text{-}06} = (\Psi_M)_{00\text{-}06} - (\Psi_A)_{06}$

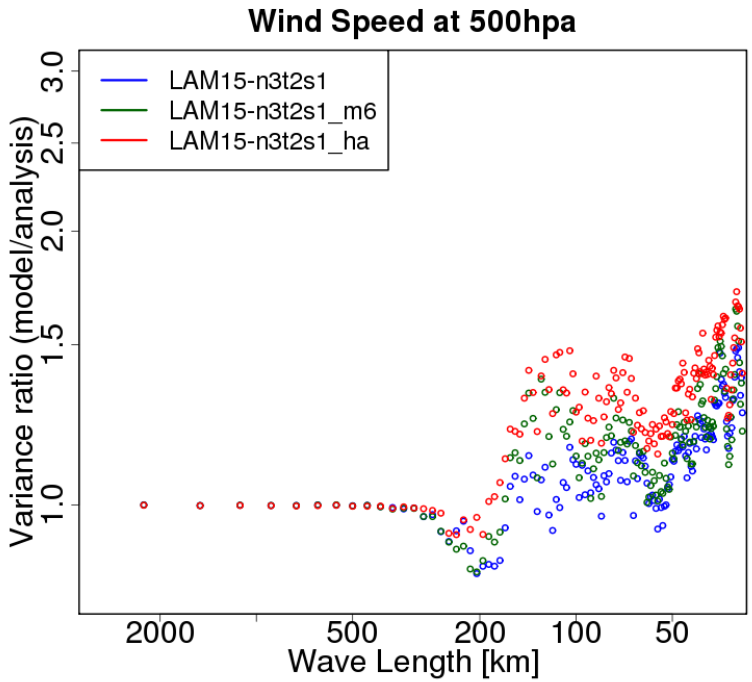
For linear growth of error, $\varepsilon_{00\text{-}0N} = (N/6)\ \varepsilon_{00\text{-}06}$

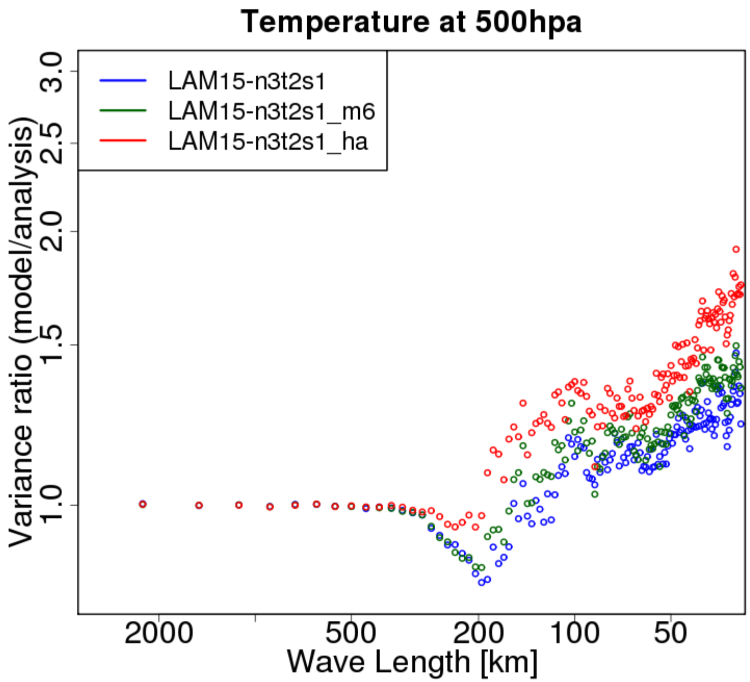
Therefore, hourly analysis estimate, $(\Psi_A)_{0N} = (\Psi_M)_{00\text{-}0N} - \varepsilon_{00\text{-}0N}$

Addressing variance deficiency
Comparison of different approaches

LAM-15 N3T2S1
LAM-15 N3T2S2_M6 [with m=6]
LAM-15 N3T2S3_HA [with hourly analysis estimates]

Averaged over five days (Feb 1 -5, 2010)

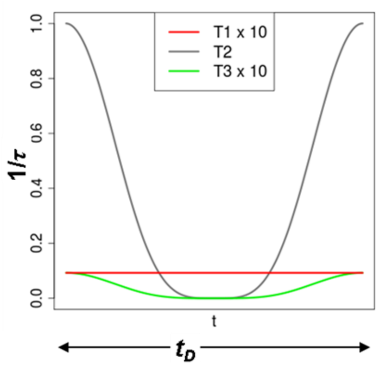


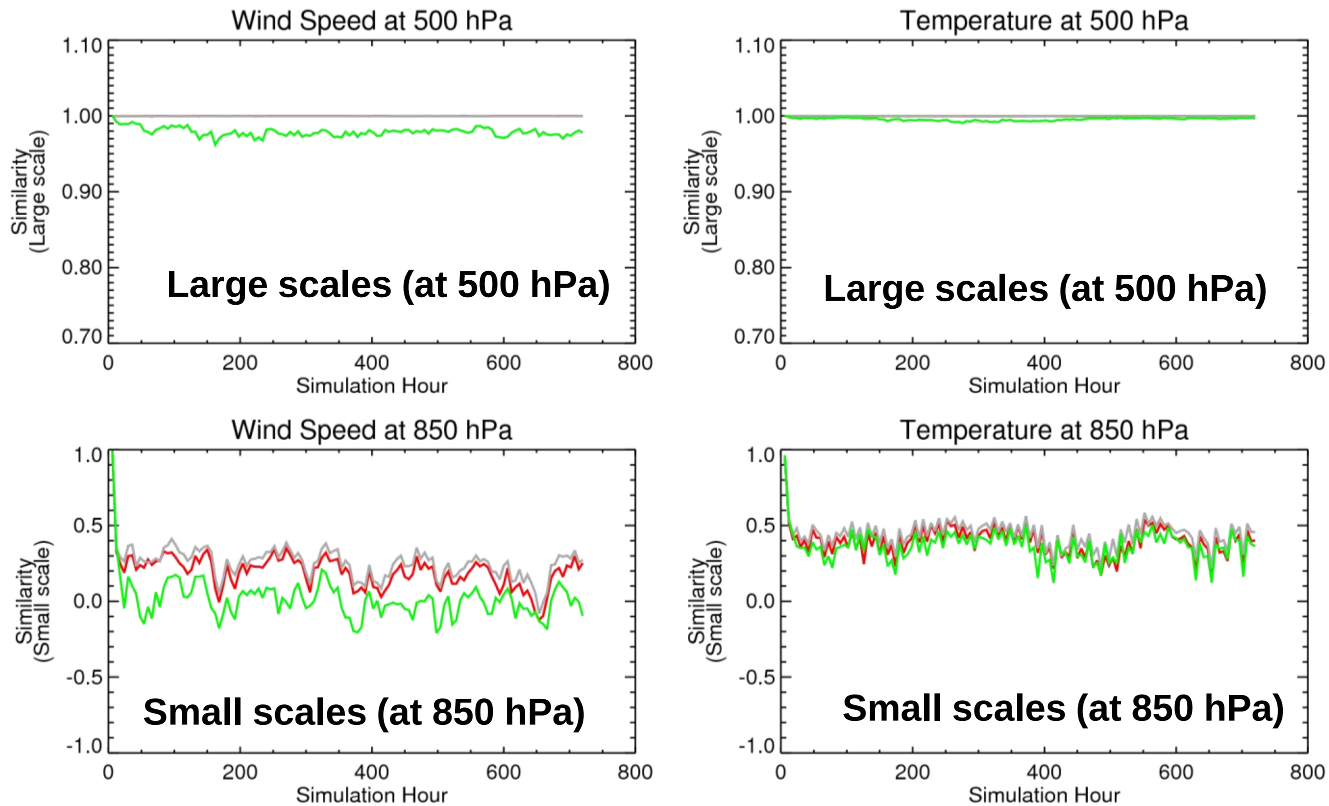


Sensitivity: Temporal relaxation
Similarity

LAM-15 N3T1S1
LAM-15 N3T2S1
LAM-15 N3T3S1

Winter (Feb 1 – Mar 2, 2010)

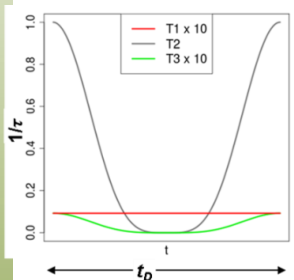




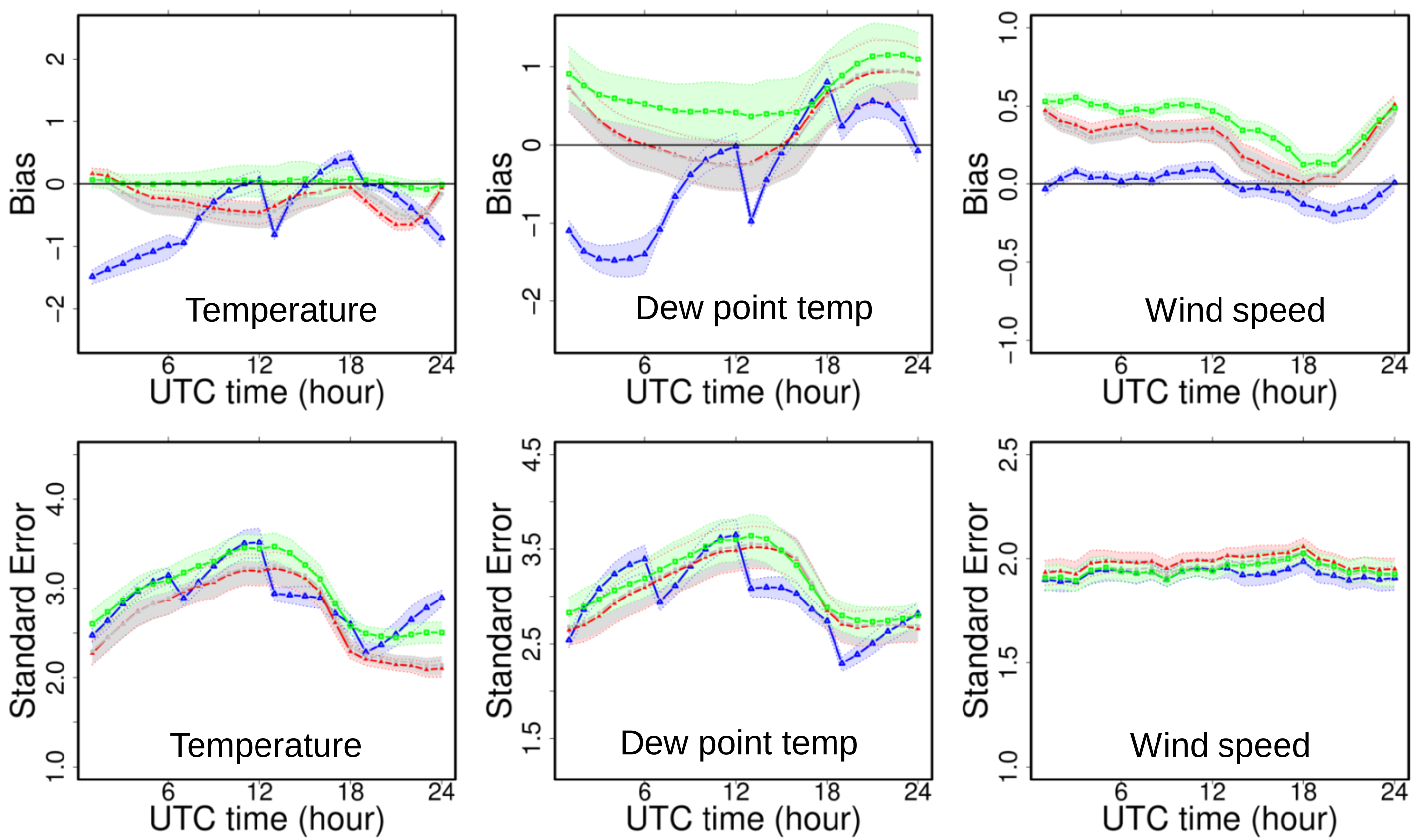
Sensitivity: Temporal relaxation

Screen-level scores

REG FORECAST
LAM-15 N3T1S1
LAM-15 N3T2S1
LAM-15 N3T3S1



Winter (Feb 1 – Mar 2, 2010)

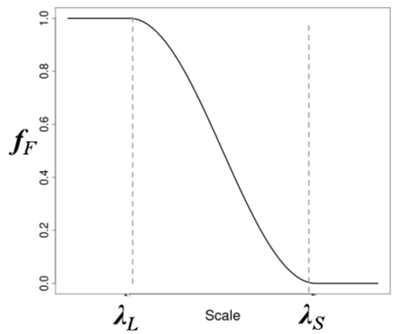


- **Overall N3T2 is selected for further tests**

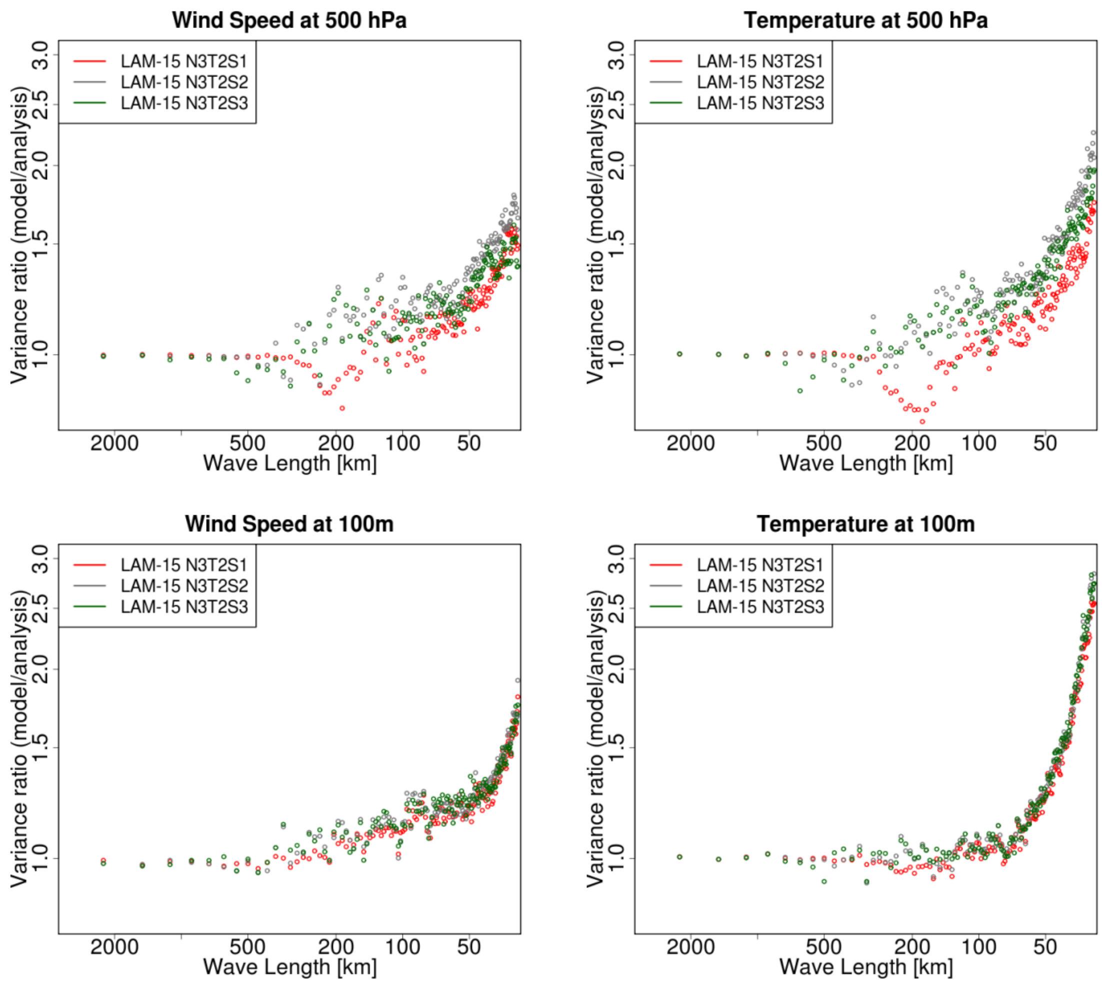
Sensitivity: Nudging length scale
Variance ratio (LAM-15/Analysis)

Summer
Jun 10 – Jul 9, 2010

LAM-15 N3T2S1
LAM-15 N3T2S2
LAM-15 N3T2S3



S1: λ_S =100 km, λ_L=300 km
S2: λ_S =225 km, λ_L=450 km
S3: λ_S =350 km, λ_L=700 km



Sensitivity: Nudging length scale
Similarity

LAM-15 N3T2S1
LAM-15 N3T2S2
LAM-15 N3T2S3

S1:
λ_S =100 km, λ_L=300 km
S2:
λ_S =225 km, λ_L=450 km
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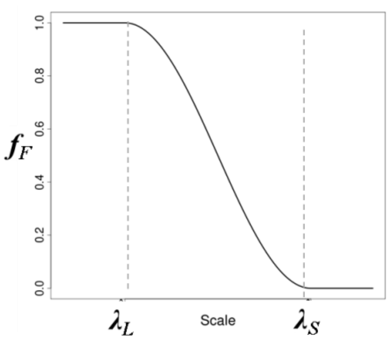
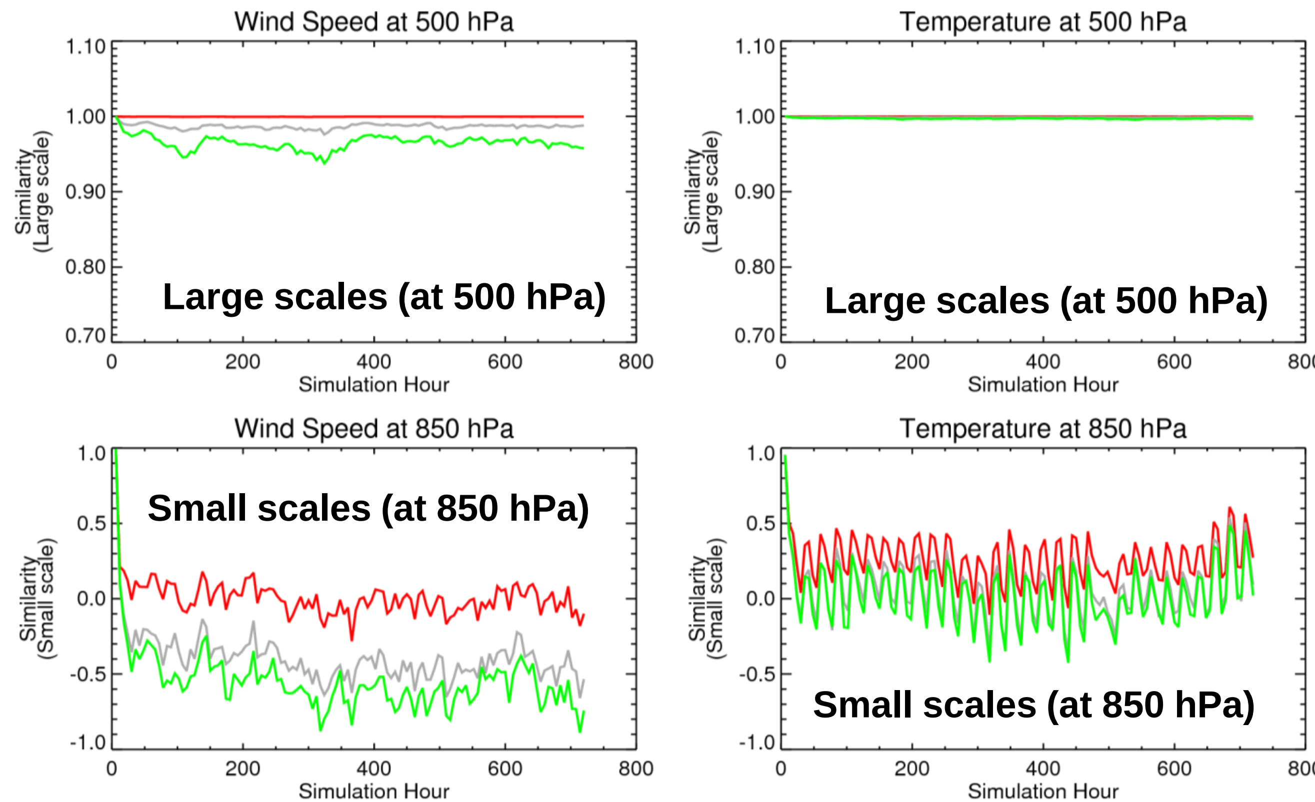


Summer (Jun 10 – Jul 9, 2010)



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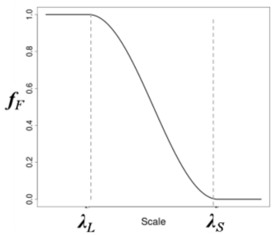
Canada

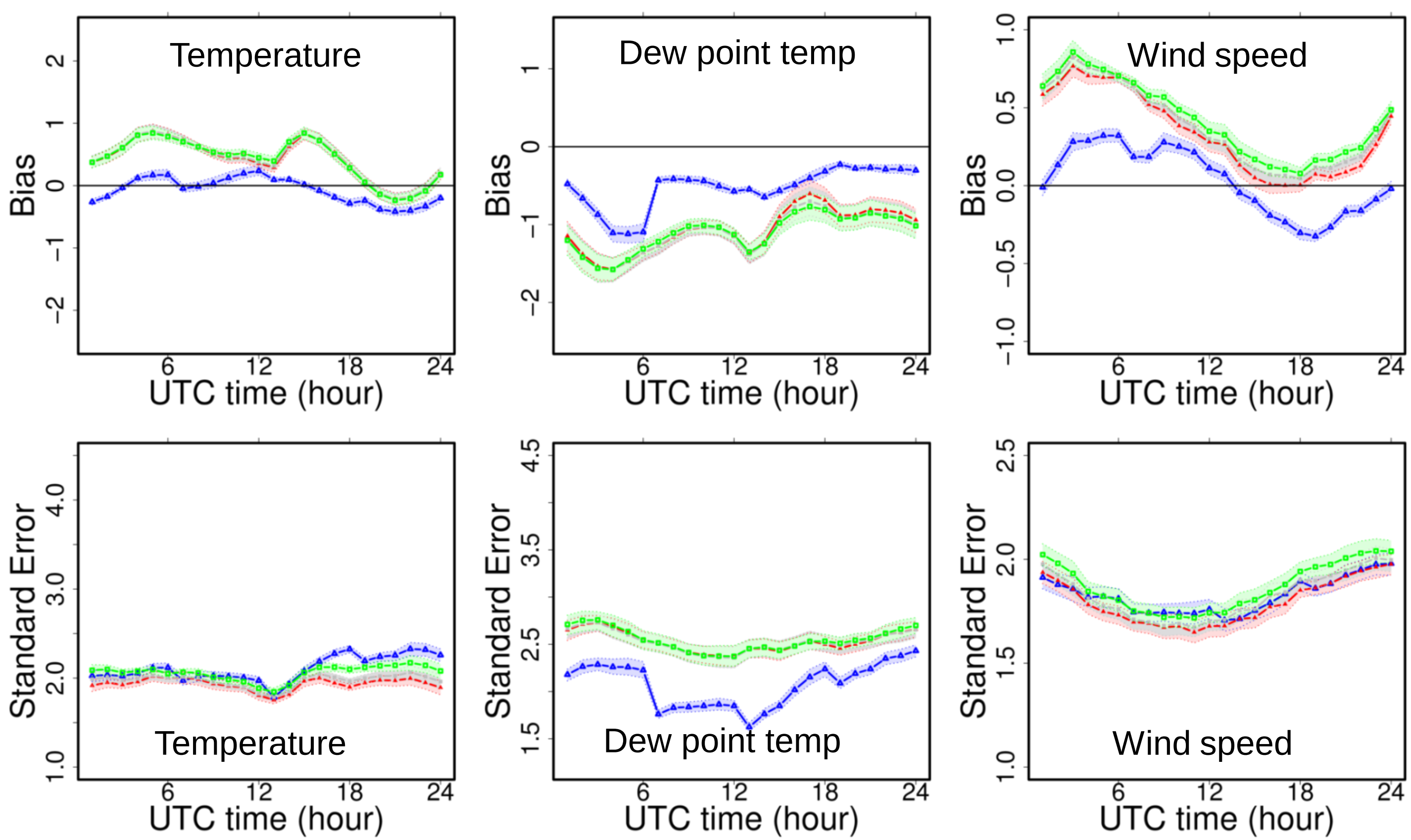
Sensitivity: Nudging length scale

Screen-level scores

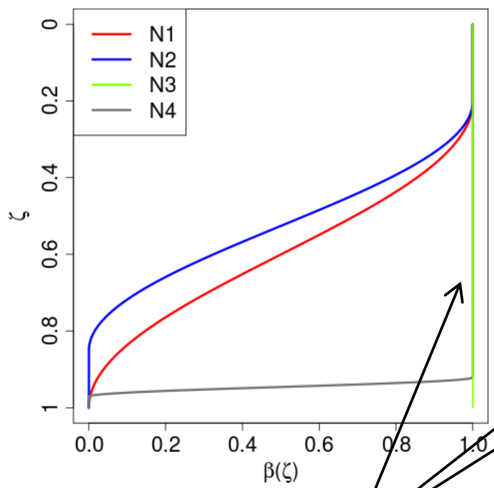
REG FORECAST
LAM-15 N3T2S1
LAM-15 N3T2S2
LAM-15 N3T2S3

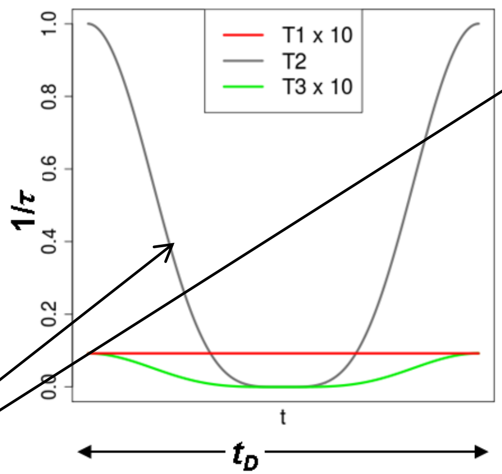


Summer (Jun 10 – Jul 9, 2010)



LAM-15 simulations
Overall comparison





S1: λ_S =100 km, λ_L=300 km

S2: λ_S =225 km, λ_L=450 km

S3: λ_S =350 km, λ_L=700 km

- Overall **N3T2S1**, i.e., uniform nudging vertical profile and with variable strong relaxation and nudging length scales defined by λ_S=100 km and λ_L=300 km, is found to be **optimal for LAM-15 simulation**.

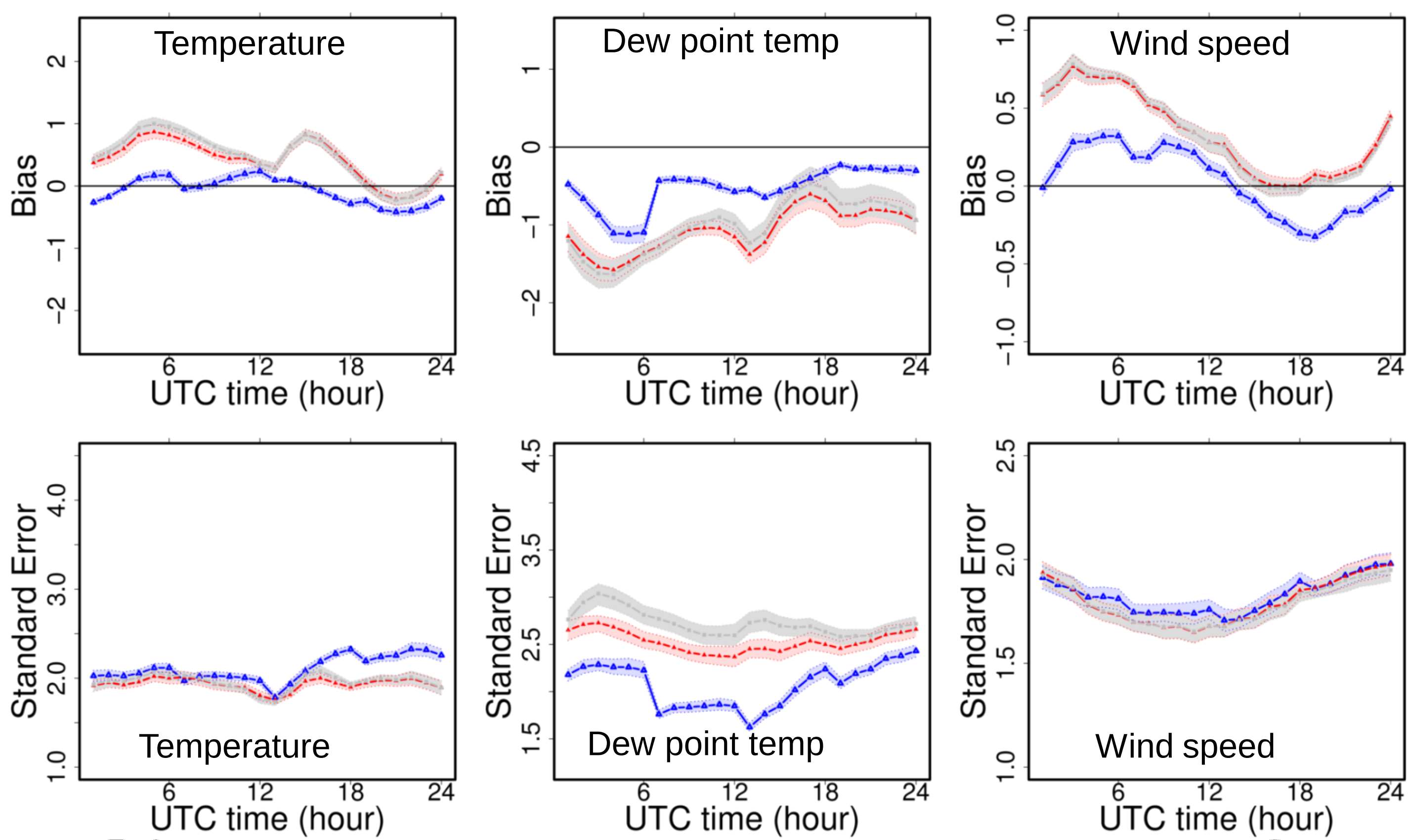
Deviations in the evolving surface fields: Another challenge

Deviations in the evolving surface fields: Another challenge

REG FORECAST
LAM-15 N3T2S1
LAM-15 N3T2S1_EXT

N3T2S1_EXT was initialized 4 months earlier

Summer (Jun 10 – Jul 9, 2010)



Deviations in the evolving surface fields: Another challenge

- Prognostically evolving surface fields (e.g. soil moisture, surface temperature, snow-conditions) may deviate from their expected values due to accumulation of error.
- This may lead to erroneous surface induced fluxes and inaccurate prediction of surface-layer meteorology.

Deviations in the evolving surface fields: Another challenge

- Prognostically evolving surface fields (e.g. soil moisture, surface temperature, snow-conditions) may deviate from their expected values due to accumulation of error.
- This may lead to erroneous surface induced fluxes and inaccurate prediction of surface-layer meteorology.
- Any evolving surface field, Φ, at a given time step can be readjusted using the following relation

Readjustment

$$\Phi_M = \Phi_M + \gamma_F \left[\Phi_R - \Phi_M\right]$$

Model simulated field

Reference field

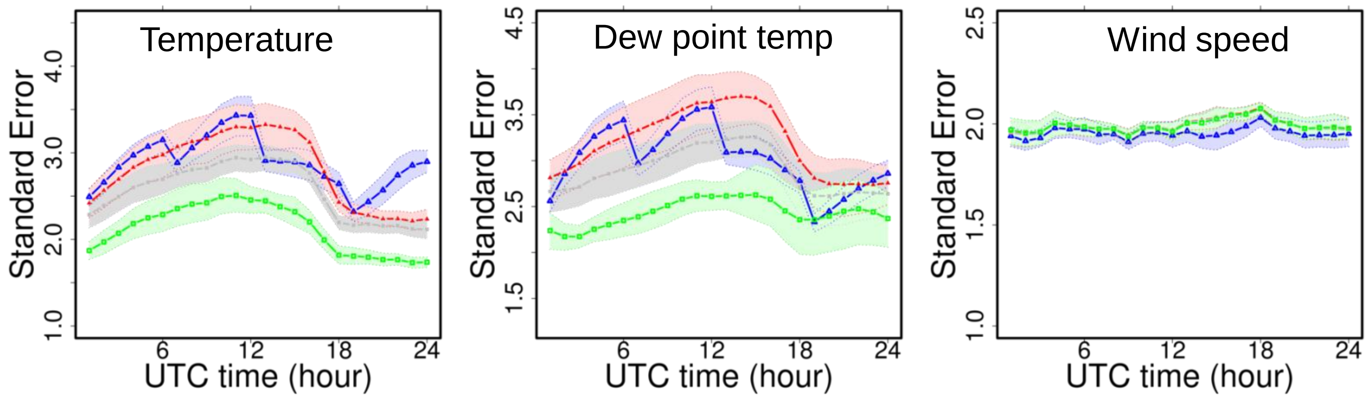
Relaxation factor

Impact of surface nudging
Screen-level score

Surface fields for nudging: Surface temperature, soil moisture, and snow-conditions (snow depth and density)

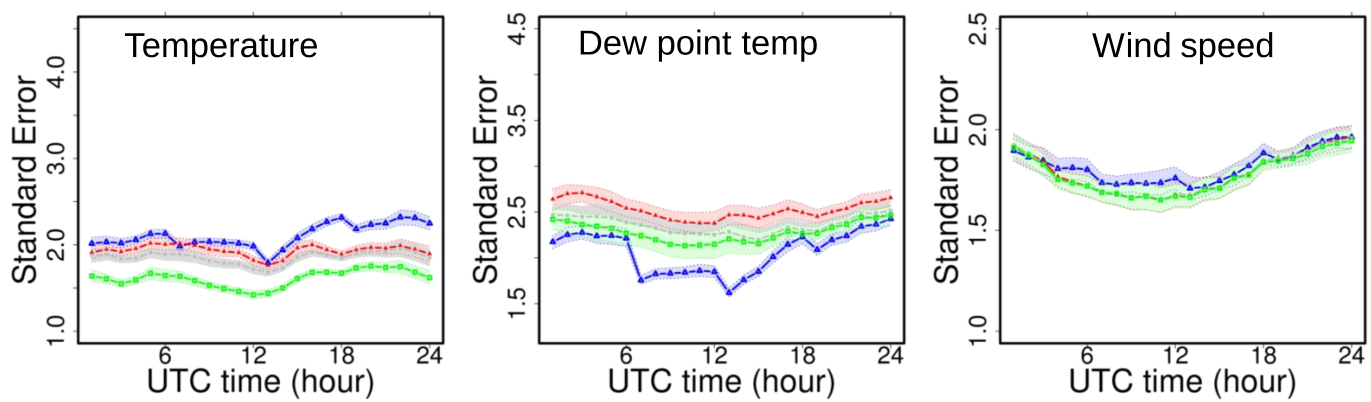
a) Winter

REG FORECAST
LAM-15 N3T2S1
LAM-15 N3T2S1_SPS
(with γ_F=0.01)
LAM-15 N3T2S1_SPSV3
(with γ_F=0.25)



b) Summer

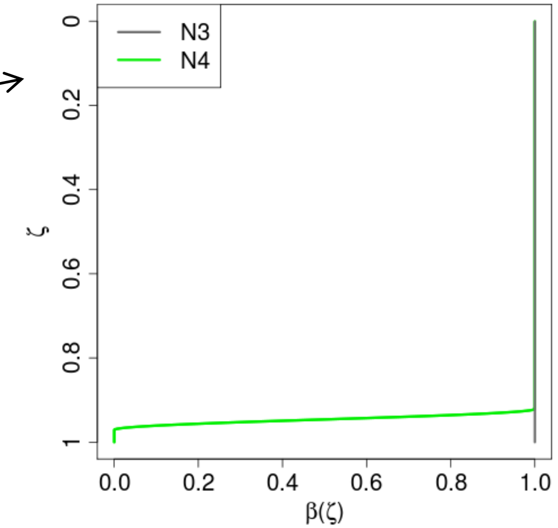
REG FORECAST
LAM-15 N3T2S1
LAM-15 N3T2S1_SPS
(with γ_F=0.01)
LAM-15 N3T2S1_SPSV3
(with γ_F=0.25)



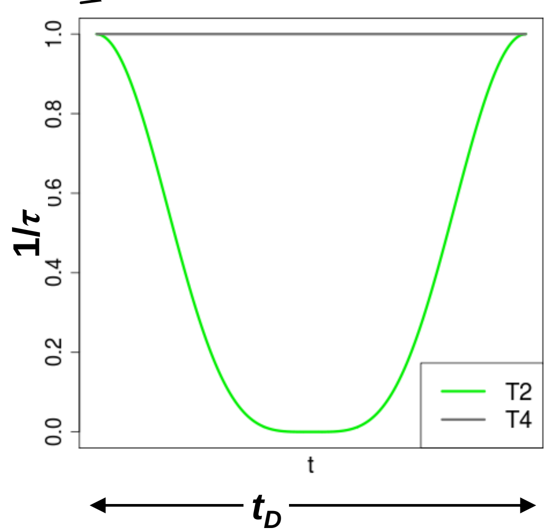
Extension to 2 km GEM-LAM simulations

Extension to LAM-2 simulations
Experiment configurations

- **Period:** **Winter (Feb 5 -18, 2010)**
- **Vertical profiles:**
  - **- N3 (uniform)**
  - **- N4 (steep gradient in surface-layer)**

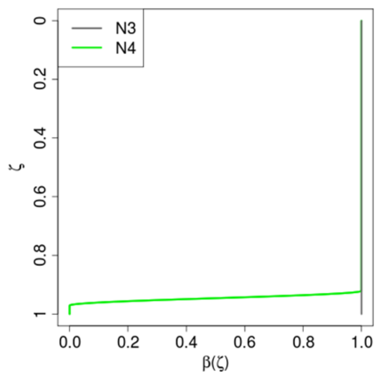


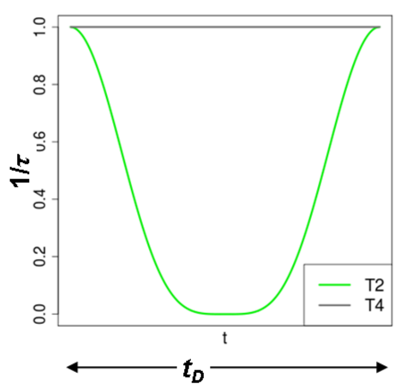
- **Temporal relaxation:**
  - **- T2**
  - **- T4 ($t_R=\Delta t$, $m=0$, i.e. $\tau=1$)**



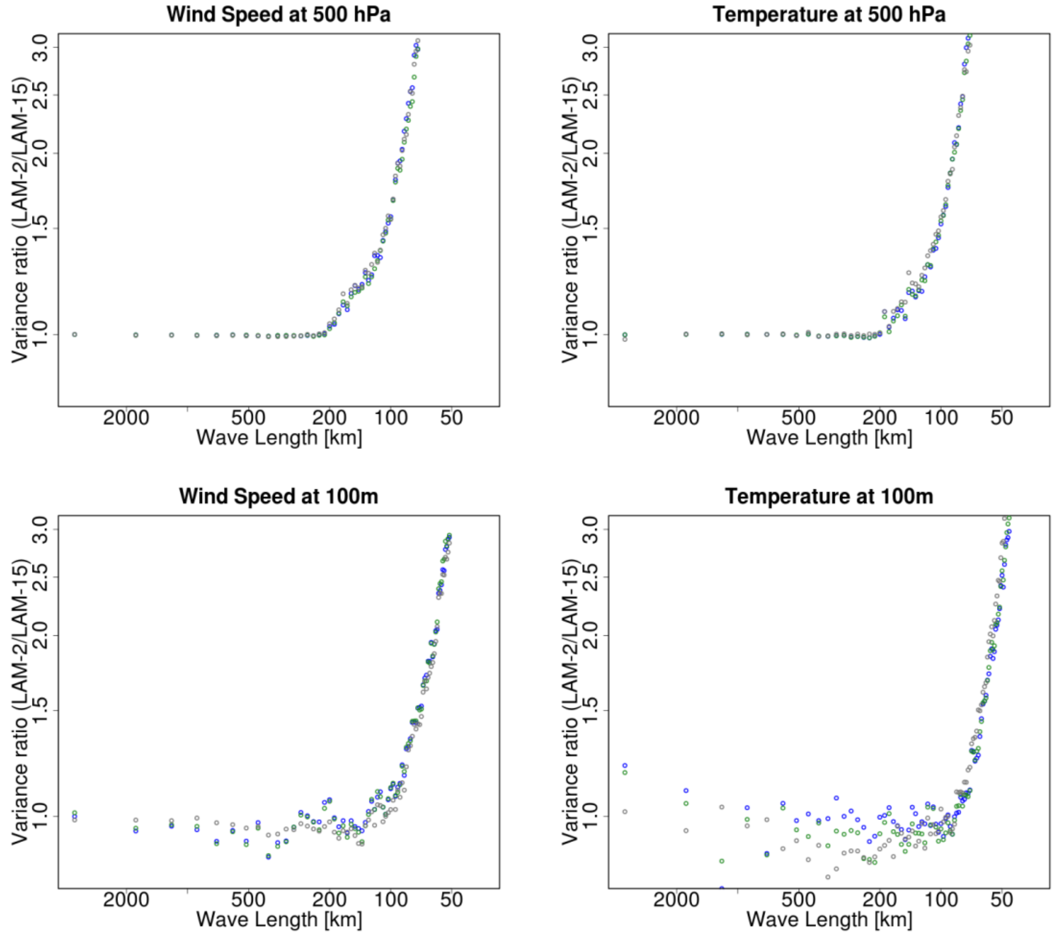
Extension to LAM-2 simulations
Variance ratio (LAM-2/LAM-15)

LAM-2 N4T2S1
LAM-2 N4T2S1_SPSV3
LAM-2 N3T4S1_SPSV3





For winter (Feb 5 – 18, 2010)



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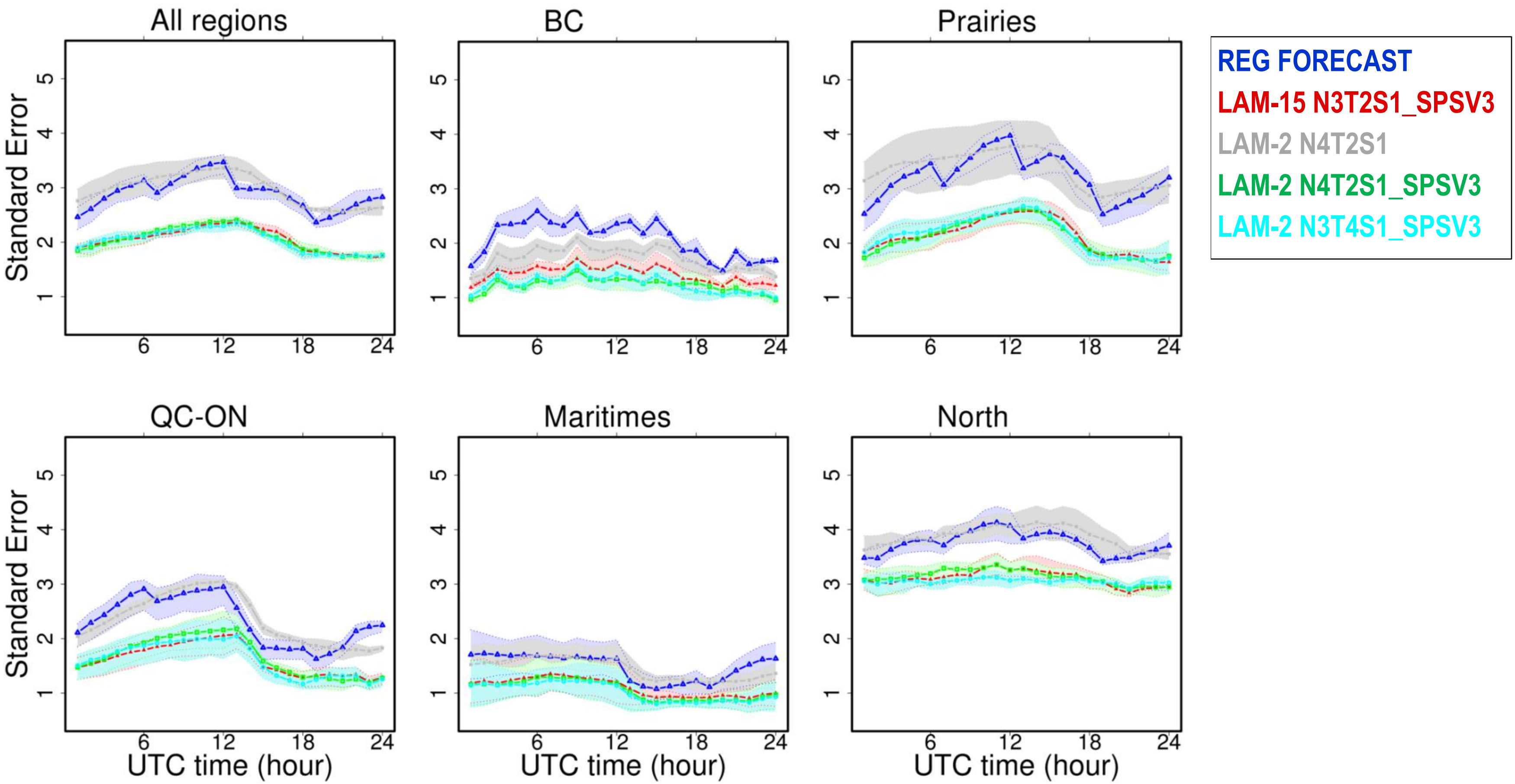
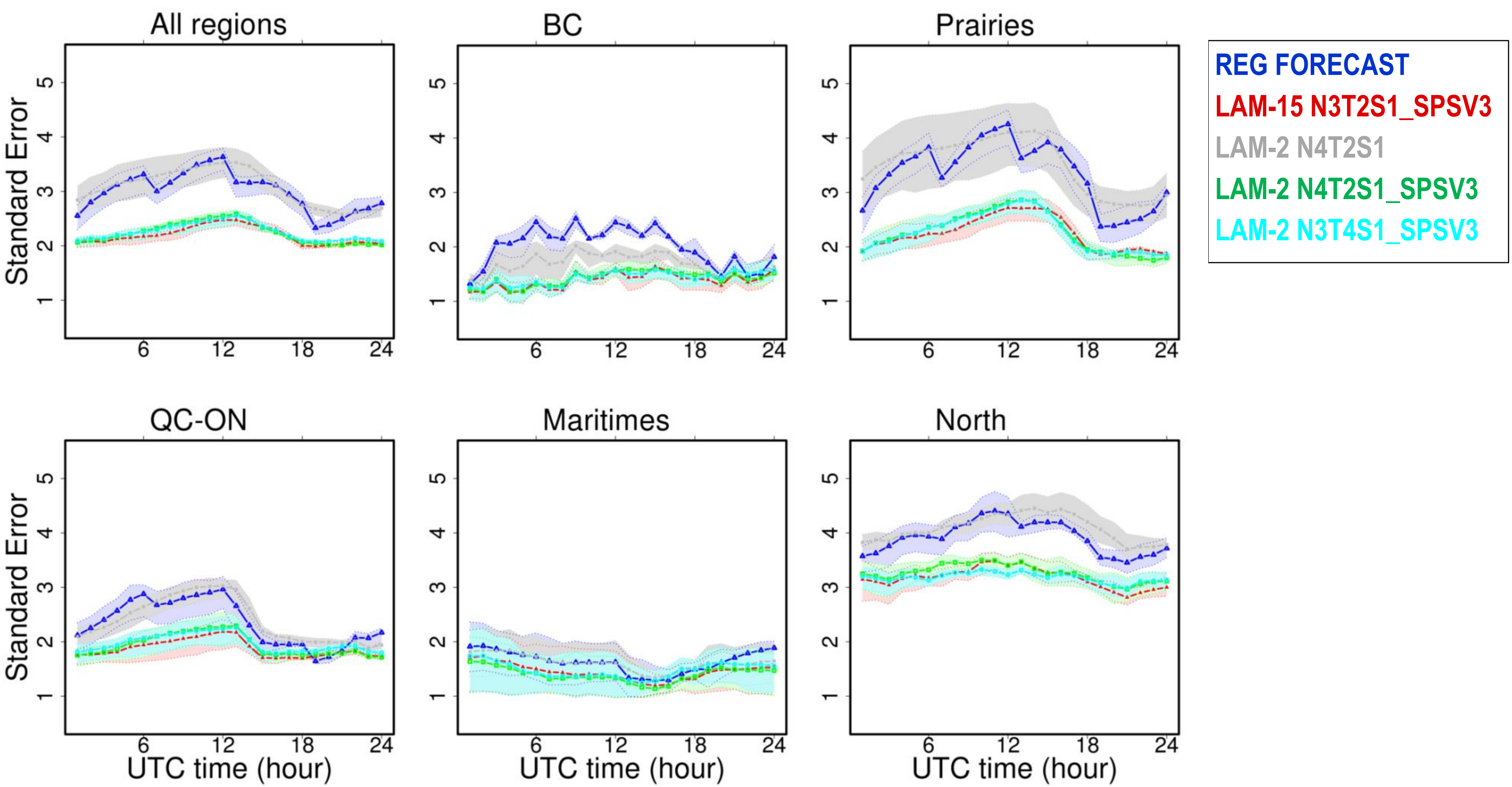
Extension to LAM-2 simulations
Screen-level scores

Temperature (Feb 5 – 18, 2010)



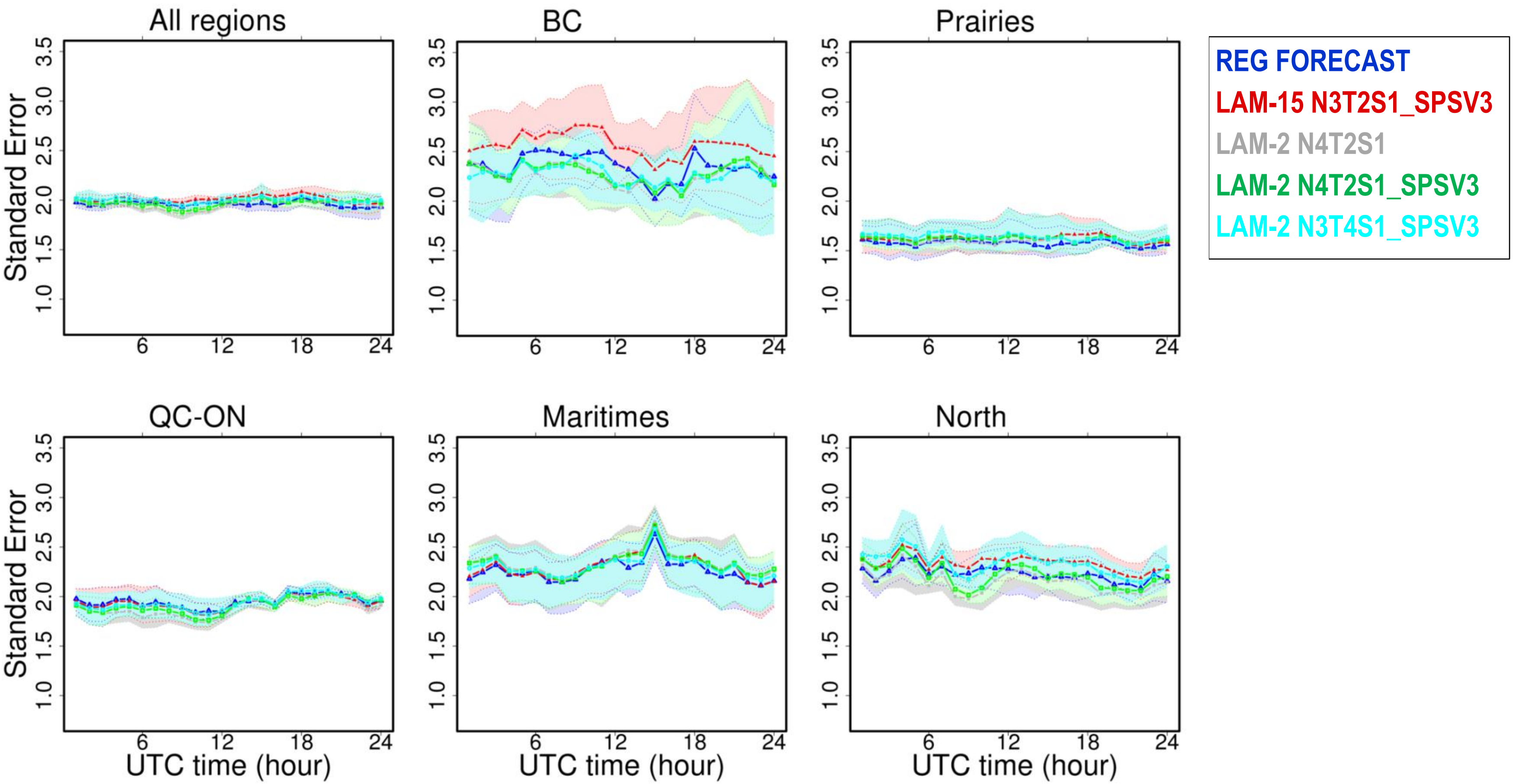
Extension to LAM-2 simulations
Screen-level scores

Dew point temperature (Feb 5 – 18, 2010)



Extension to LAM-2 simulations
Screen-level scores

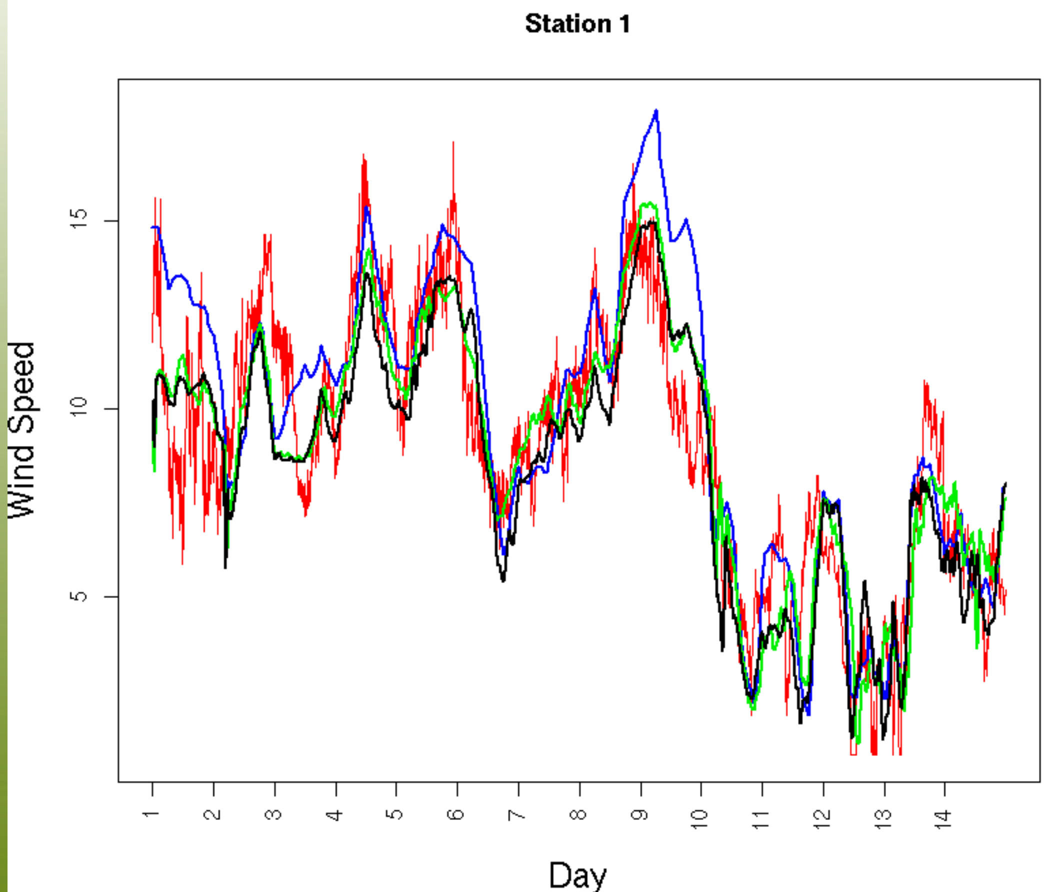
Wind speed (Feb 5 – 18, 2010)



Evaluation of LAM-15 and LAM-2 generated time series against observations from wind turbine locations

Extension to LAM-2 simulations
Time series at 80 m

Wind speed at Station 1 (Feb 5-18, 2010)



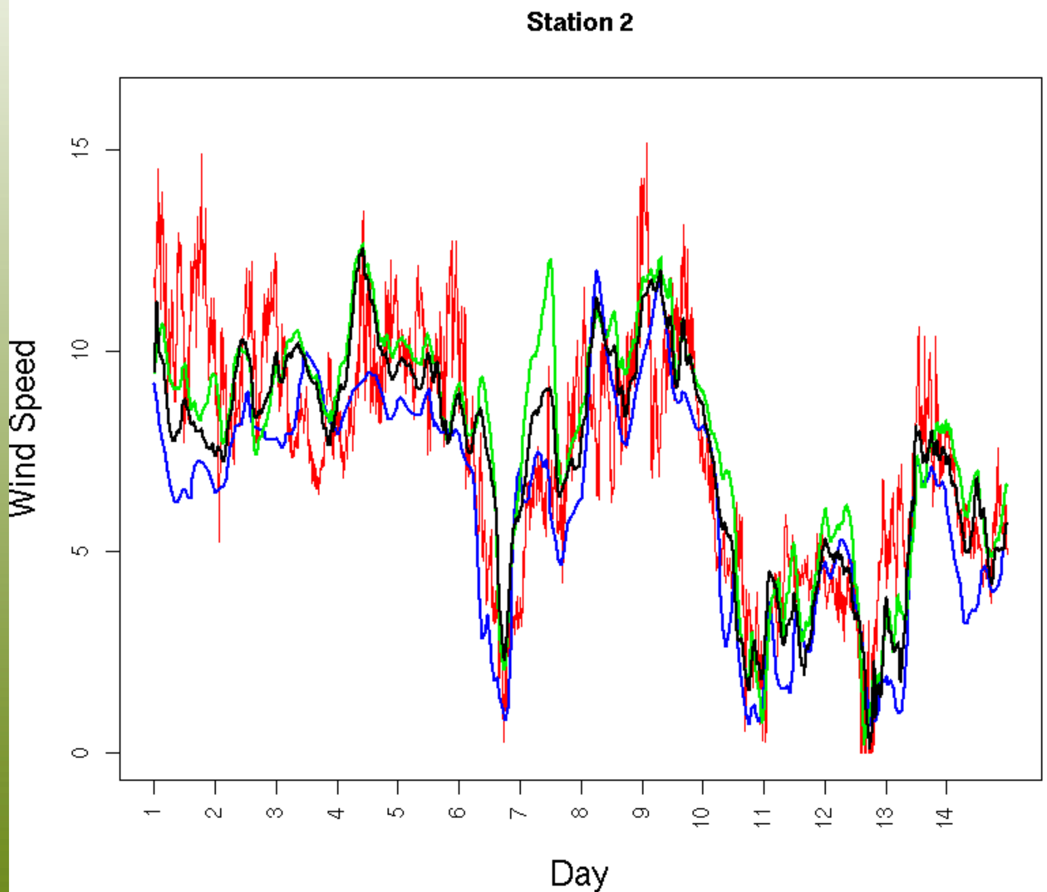
Observation
LAM-15 N3T2S1_SPSV3
LAM-2 N4T2S1_SPSV3
LAM-2 N3T4S1_SPSV3

	OBS	LAM-15	LAM-2	
			N3T4S1	N4T2S1
Variance	11.8	15.4	11.0	11.0
Bias		0.7	-0.5	-0.1
SE		2.1	1.7	1.7
Correlation		0.85	0.87	0.88

Both LAM-2 simulations are better than LAM-15.

Extension to LAM-2 simulations
Time series at 80 m

Wind speed at Station 2 (Feb 5-18, 2010)



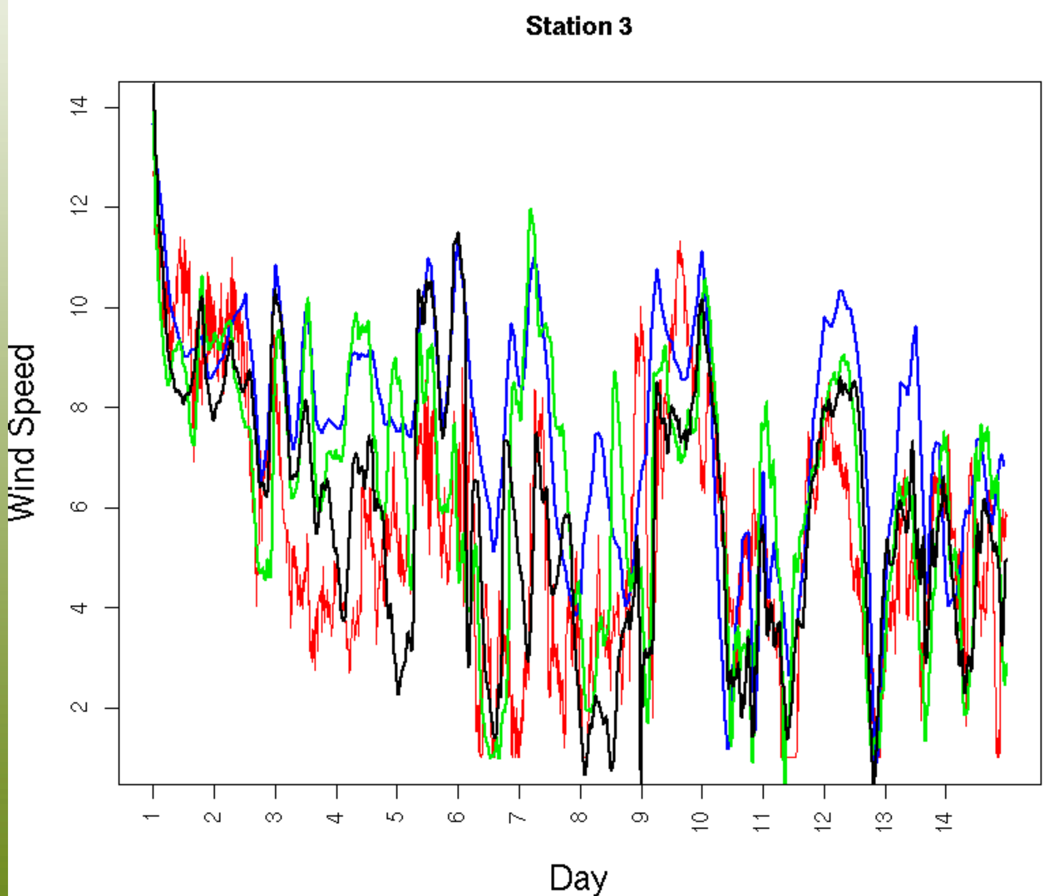
Observation
LAM-15 N3T2S1_SPSV3
LAM-2 N4T2S1_SPSV3
LAM-2 N3T4S1_SPSV3

	OBS	LAM-15	LAM-2	
			N3T4S1	N4T2S1
Variance	8.5	7.6	7.4	8.0
Bias		-1.2	-0.1	0.3
SE		2.0	1.8	1.9
Correlation		0.76	0.80	0.78

Both LAM-2 simulations are better than LAM-15.

Extension to LAM-2 simulations
Time series at 80 m

Wind speed at Station 3 (Feb 5-18, 2010)

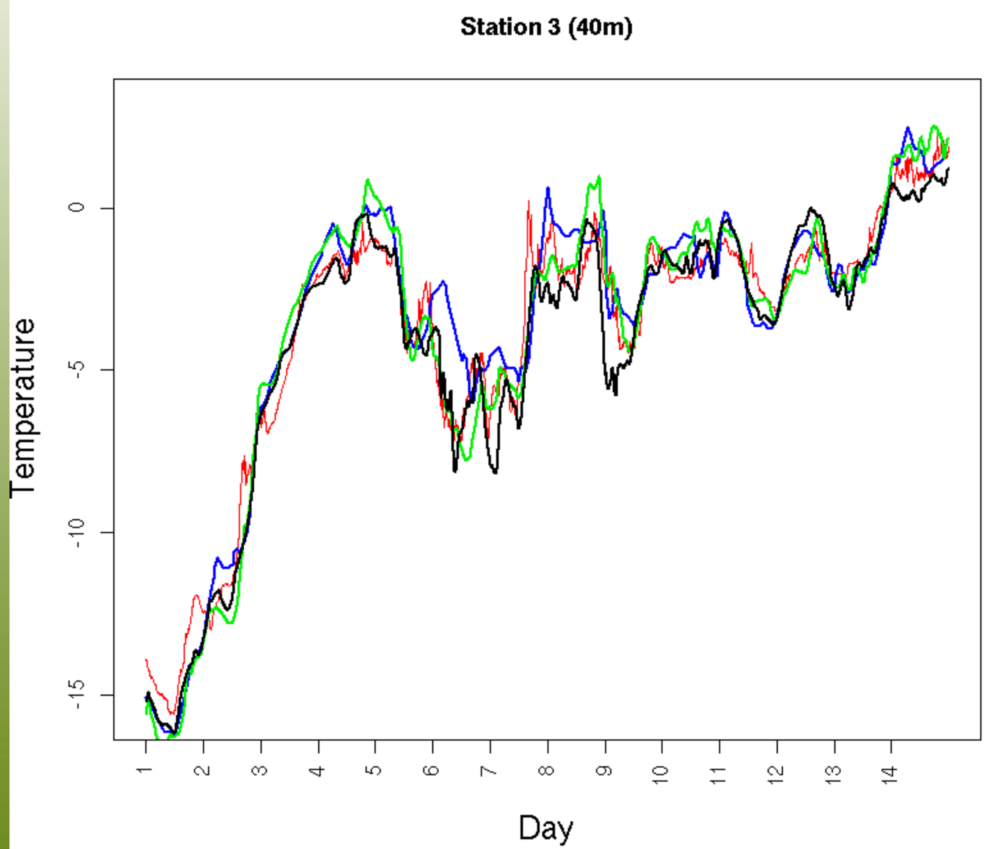


	OBS	LAM-15	LAM-2	
			N3T4S1	N4T2S1
Variance	6.4	5.4	6.8	6.5
Bias		2.0	0.4	0.9
SE		2.3	2.1	2.5
Correlation		0.56	0.66	0.53

LAM-2 N3T4S1 is better than LAM-15 and other LAM-2.

Extension to LAM-2 simulations
Time series at 40 m and 80 m

Temperature at Station 3 (Feb 5-18, 2010)



Observation
LAM-15 N3T2S1_SPSV3
LAM-2 N4T2S1_SPSV3
LAM-2 N3T4S1_SPSV3

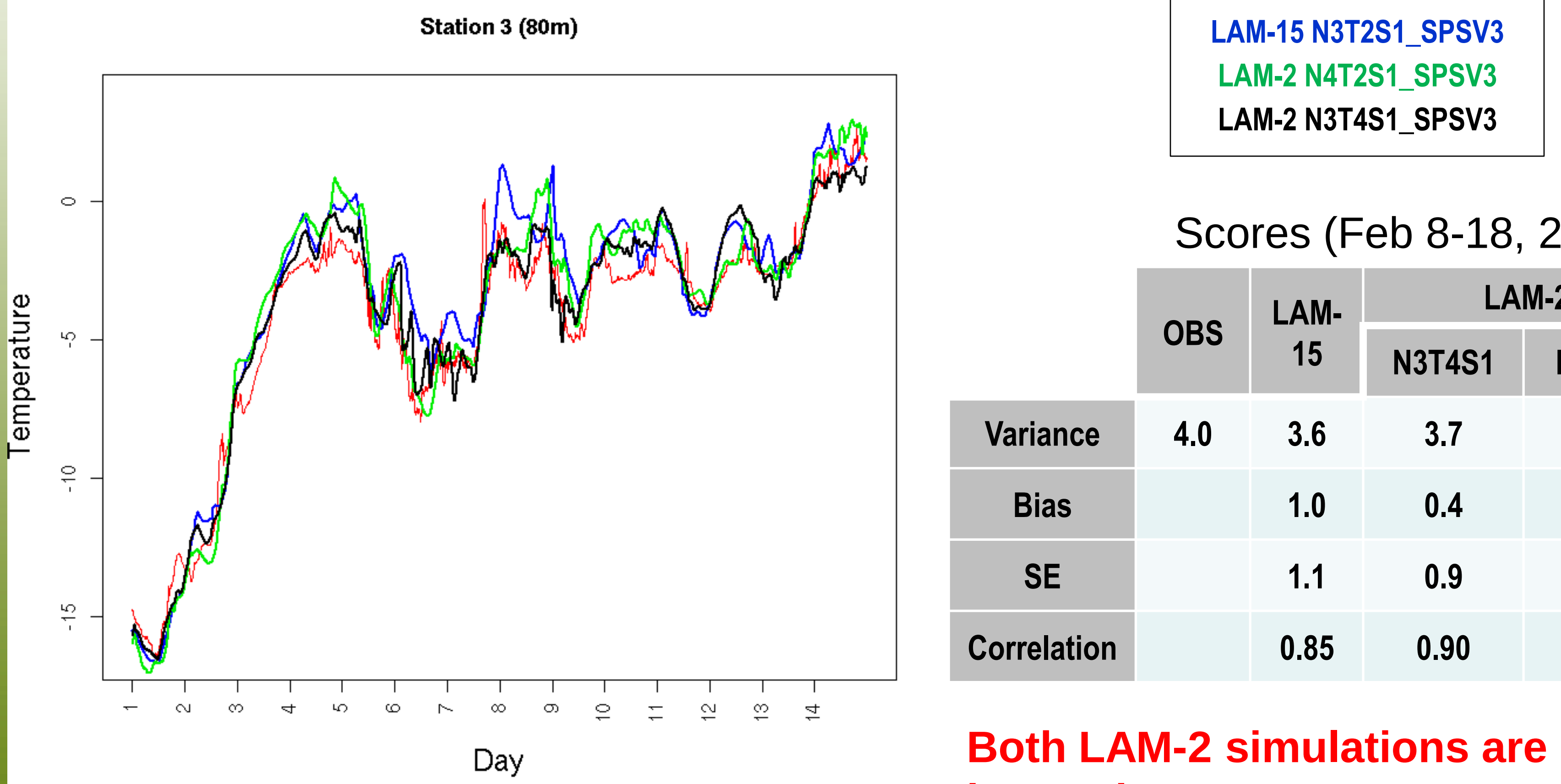
Scores (Feb 8-18, 2010)

	OBS	LAM-15	LAM-2	
			N3T4S1	N4T2S1
Variance	3.8	3.3	4.4	5.1
Bias		0.4	-0.3	0.2
SE		1.1	0.9	0.8
Correlation		0.84	0.91	0.93

Both LAM-2 simulations are slightly better than LAM-15.

Extension to LAM-2 simulations
Time series at 80 m above surface

Temperature at Station 3 (Feb 5-18, 2010)



Scores (Feb 8-18, 2010)

	OBS	LAM-15	LAM-2	
			N3T4S1	N4T2S1
Variance	4.0	3.6	3.7	5.2
Bias		1.0	0.4	0.7
SE		1.1	0.9	0.9
Correlation		0.85	0.90	0.92

Both LAM-2 simulations are better than LAM-15.

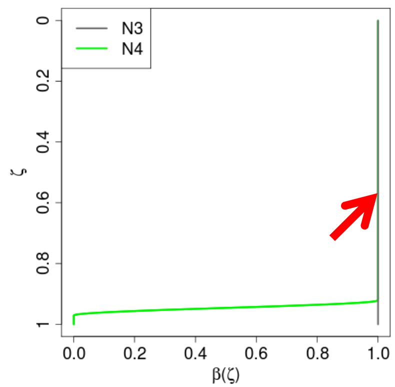
LAM-2 simulations
Overall comparison

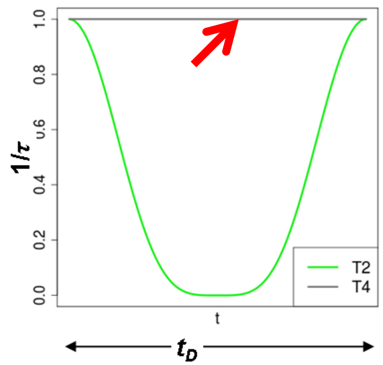
- Both N3T4S1 and N4T2S1 LAM-2 configurations lead to comparable scores.
- LAM-2 N3T4S1 results in better score compared to LAM-15 simulation

  - for all stations

  - for both wind and temperature

- Overall **N3T4S1**, i.e., uniform nudging vertical profile and with constant temporal relaxation (τ=1), is found to be **optimal for LAM-2 simulation**.





Summary

- Spectral nudging of atmosphere
  - Maintains large-scale similarities
  - Does not suppress small scales significantly
  - Restricts substantial deviations of the evolving surface fields
- Uniform nudging vertical profile is found to be optimal.
- Surface nudging towards SPS fields
  - Significantly improves screen-level temperature and dew point.
  - Neutral for screen-level wind
- 2-km simulations in general improves statistical scores at 40 m and 80 m above surface.

Acknowledgements

- Stephane Bélair – for his valuable advice regarding the land-surface component of the project.
- Marcel Vallée – for the USTAT package.
- Minwei Qian – for providing the basic frame work of spectral nudging.
- Michel Desgane – for his valuable advice.
- Yosvany Martinez – for all the help at all stages of the project.
- Marco Carrera – for all the encouragement and advice.
- Laurent Chardon – for helping us at different stages to setup and execute GEM in the new Linux cluster.
- Shared Services – for their invaluable support to this day.
- ecoEII – for funding of the ongoing project.

Thank You

Future Work

- Impact of dynamical downscaling on sub-kilometer GEM-LAM simulations over both large and smaller spatial domains may be investigated.

Objectives of the project

- Produce multi-year surface-layer meteorological fields.
- Spatial coverage: Canadian territory (south of 70º N)
- Grid spacing: 2 km
- Time coverage: 2008 – 2010 (possible extension up to 2012)
- Output frequency: 10 min (for mandatory fields)
- Output fields (mandatory):

  Wind speed and direction, air temperature, specific humidity at 80, 100, and 120 m above ground level, and surface pressure.
- Output fields (additional):

  Incoming solar radiation, cloud water content, precipitation amount and type, etc.

Downscaling Methodologies

- Mainly three types
  - Dynamical downscaling
  - Statistical downscaling
  - Mixed statistical-dynamical downscaling

Dynamical downscaling

- Based on atmospheric model simulations.
- Resolves various dynamical and physical atmospheric processes.
- Outputs of coarse-resolution atmospheric simulation drive higher resolution limited-area simulations
- Adds and improves small-scale features in the meteorological fields.
- Often involve multiple stages of simulations.
- Computationally expensive.

Downscaling Methodologies

Statistical downscaling

- Based on statistical equations (e.g., regression, neural networks, etc.).
- Converts coarse-resolution atmospheric fields from global climate or atmospheric models to high-resolution limited-area fields.
- Can improve model bias without significant computational effort.
- More emphasis on long-term climate statistics.
- Large error may appear in day-to-day or hour-to-hour outputs.
- Limited to regions with access to historical observations from meteorological stations.

Downscaling Methodologies

Mixed statistical-dynamical downscaling

- First dynamically downscales predefined large-scale weather patterns in the coarse-resolution fields.
- Mean downscaled variables are obtained through weighted average of mesoscale model simulated values of each weather type and their occurrence frequencies.
- Lower computational cost compared to dynamical downscaling.
- Usually provides mean downscaled fields and not suitable for time series generation.
- Recent schemes based on empirical orthogonal functions are capable of time series generation, but restricted by temporal frequency of coarse-resolution fields.

List of physical parameteritzation

Physical process	Parameterization scheme
Radiation	CCCMARAD (Li and Barker 2005)
Land surface	ISBA (Noilhan and Planton 1989; Bélair et al. 2003)
Deep convection	Kain and Fritsch 1990 (Only for 15-km simulations)
Shallow convection	Kuo transient (Kuo et al. 1965; Bélair et al. 2005)
Mixing length	Blackadar
Boundary layer turbulence	MOISTKE
Condensation	Sundqvist et al.1989

Some important configurations

- Model lid at 10 hPa for both LAM-15 and LAM-2
- First momentum level 10 m agl
- First few mom levels: 10, 30, 50, 80, 120, 216 m agl
- First few therm levels: 5, 20, 40, 65, 100m agl
- Non-hydrostatic: 10 min (for mandatory fields)
- Vertical sponge layer (4 for LAM-15, 6 for LAM-2)
- Radiation calculation every 30 min for both
- Limit snow depth to 10cm over sea ice
- Used filtered topography and variable topography

GenPhysX configurations

- **TOPO:** CDED250 (~90 m *Canada*)
  SRTM (~90 m *-60.0<lat<+60.0*)
  USGS (~900 m *Global*)
- **MASK:** GLOBCOVER (~300 m *lat>-65.0*)
- **VEG:** USGS (~900 m *Global*)
- **SOIL:** USDA (~1 km *USA*)
  AGRC (~10 km *Canada*)
  FAO (~1 degree *Global*)

Selection of nudging parameters: Nudging length scale

- The 2D DCT of the filtered field is obtained as

$$F_F(m,n) = F(m,n)\, f_F(m,n)$$

where

$$f_F(m,n) = \begin{cases} 0.0 & \text{if } \hat{\alpha} \ge \Delta / \lambda_S \\ \left[\cos\left(\dfrac{\pi}{2} \dfrac{\hat{\alpha}\lambda_L / \Delta - 1}{\lambda_L / \lambda_S - 1} \right) \right]^2 & \text{if } \Delta / \lambda_S > \hat{\alpha} \ge \Delta / \lambda_L \\ 1.0 & \text{if } \hat{\alpha} < \Delta / \lambda_L \end{cases}$$

2D wave number ($\hat{\alpha}$)

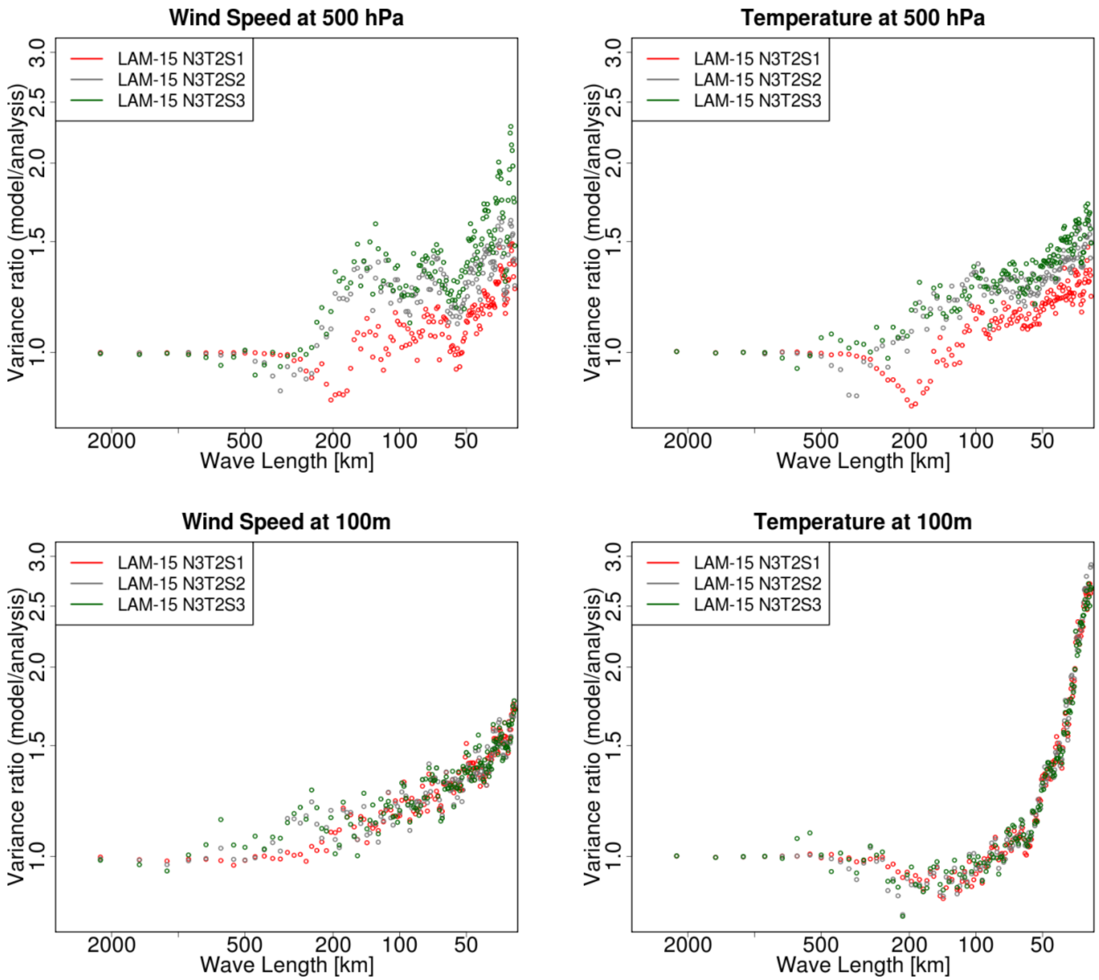
Grid spacing (Δ)

Cutoff wavelengths (λ_S, λ_L)

Sensitivity: Nudging length scale
Variance Spectra

Winter
Feb 1 – Mar 2, 2010

LAM-15 N3T2S1
LAM-15 N3T2S2
LAM-15 N3T2S3

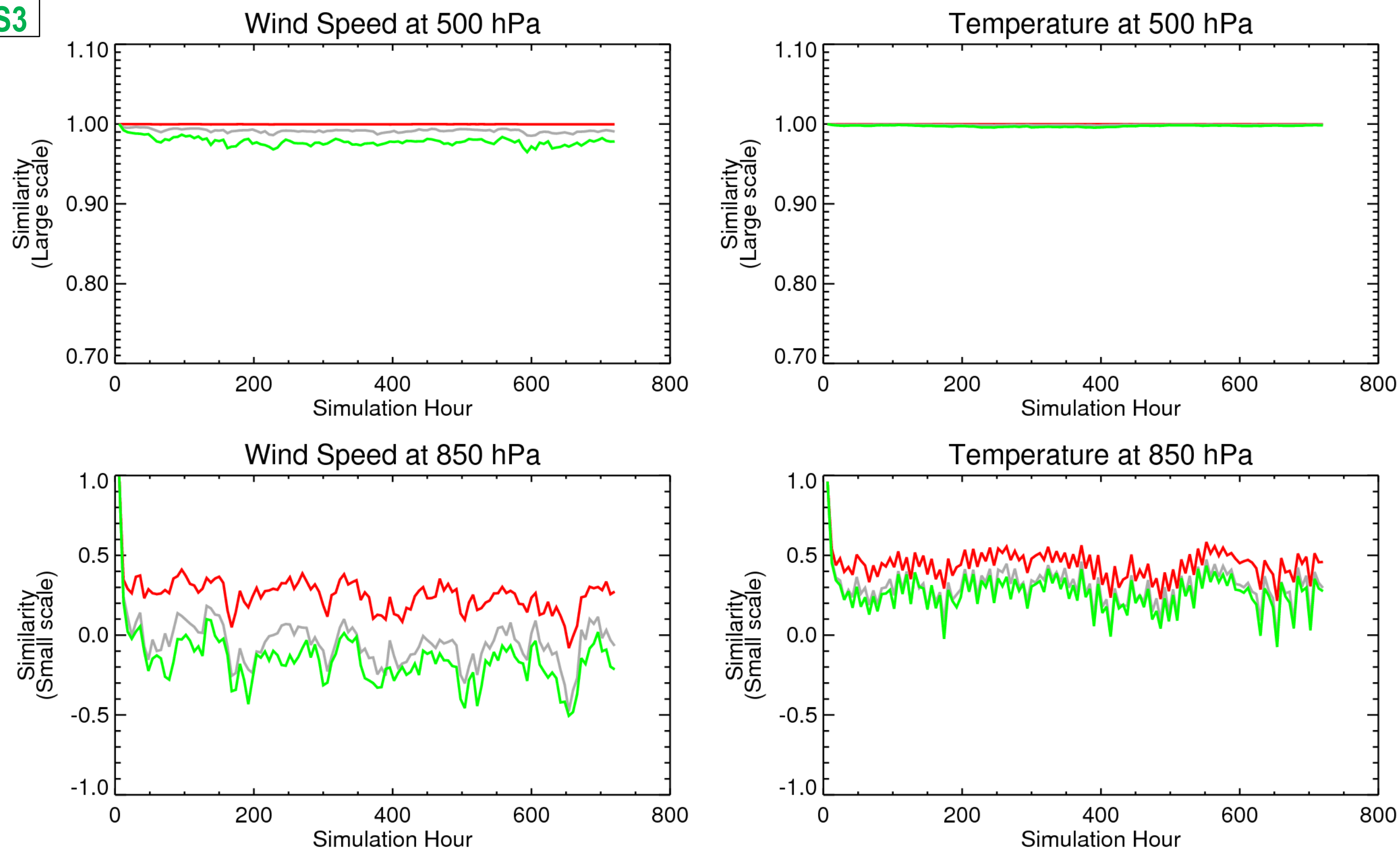


Sensitivity: Nudging length scale

Similarity

LAM-15 N3T2S1
LAM-15 N3T2S2
LAM-15 N3T2S3

Winter (Feb 1 – Mar 2, 2010)



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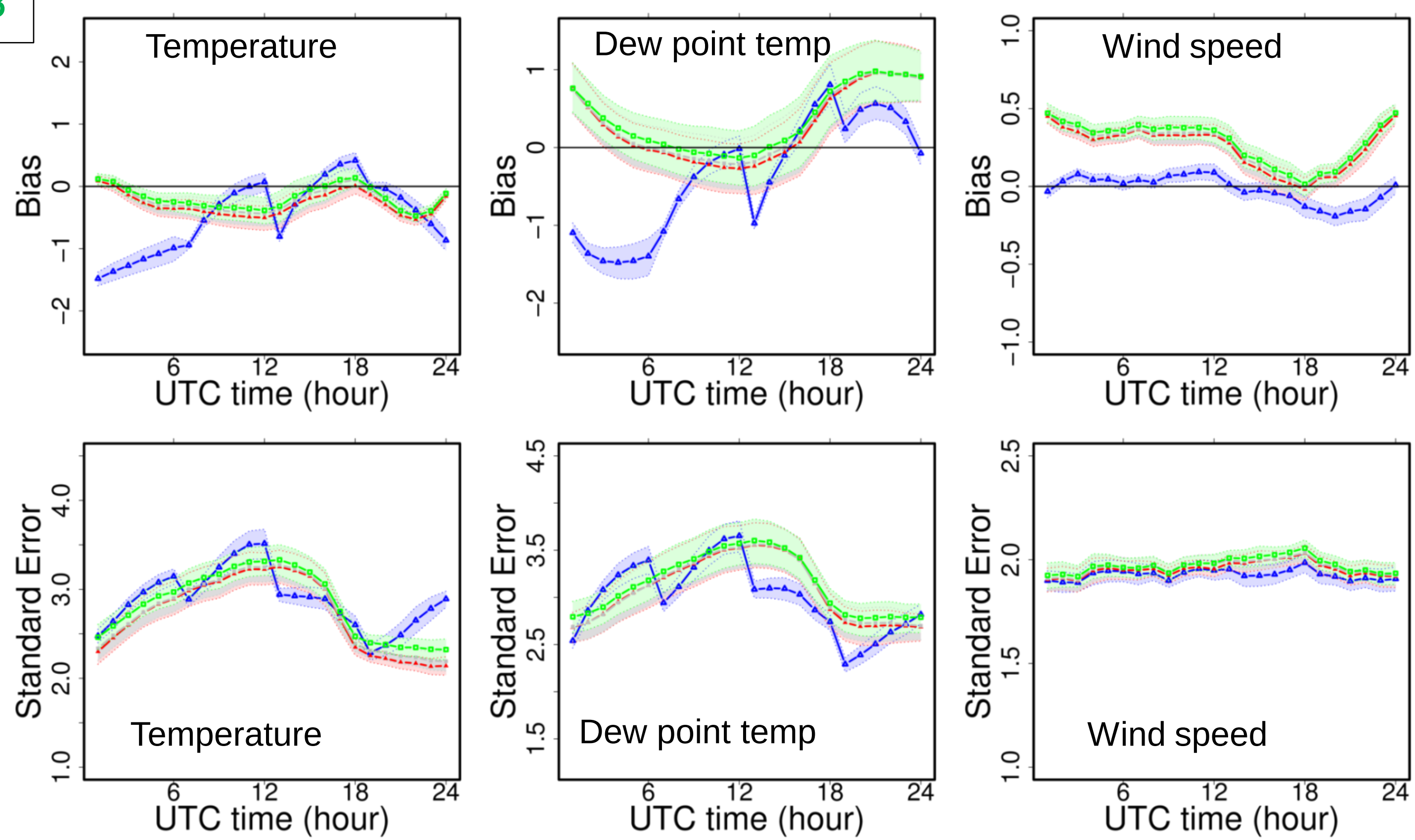
Canada

Sensitivity: Nudging length scale
Screen-level scores

REG FORECAST
LAM-15 N3T2S1
LAM-15 N3T2S2
LAM-15 N3T2S3

Winter (Feb 1 – Mar 2, 2010)

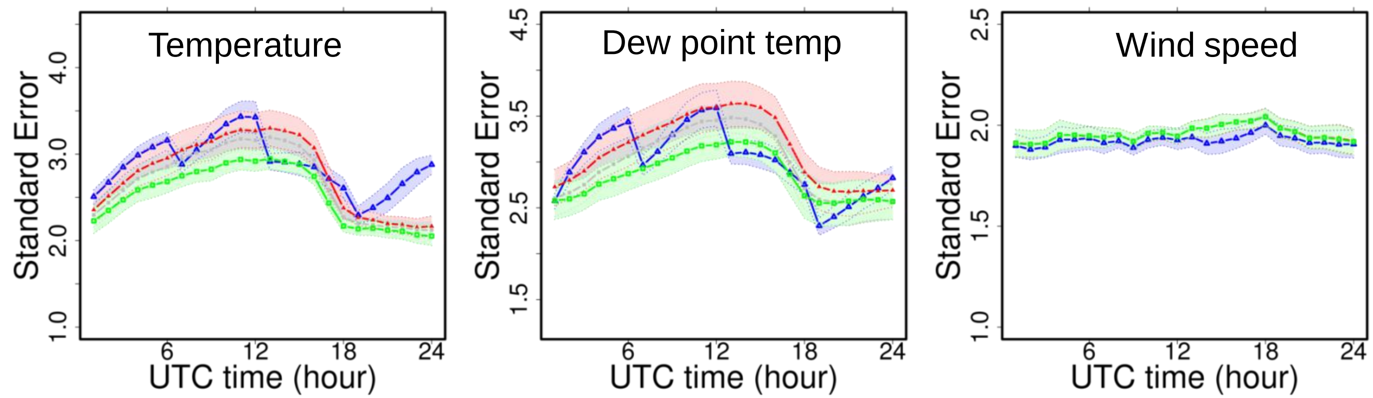


Impact of surface nudging
Screen-level score

<u>SPS vs Analysis as reference</u>

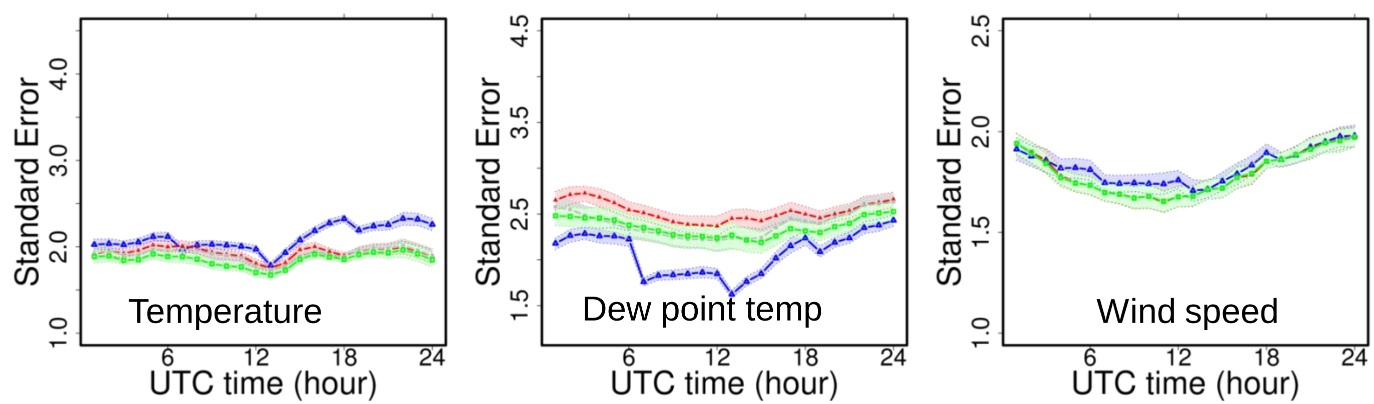
a) Winter

REG FORECAST
LAM-15 N3T2S1
LAM-15 N3T2S1_ANA
LAM-15 N3T2S1_SPS



b) Summer

REG FORECAST
LAM-15 N3T2S1
LAM-15 N3T2S1_ANA
LAM-15 N3T2S1_SPS

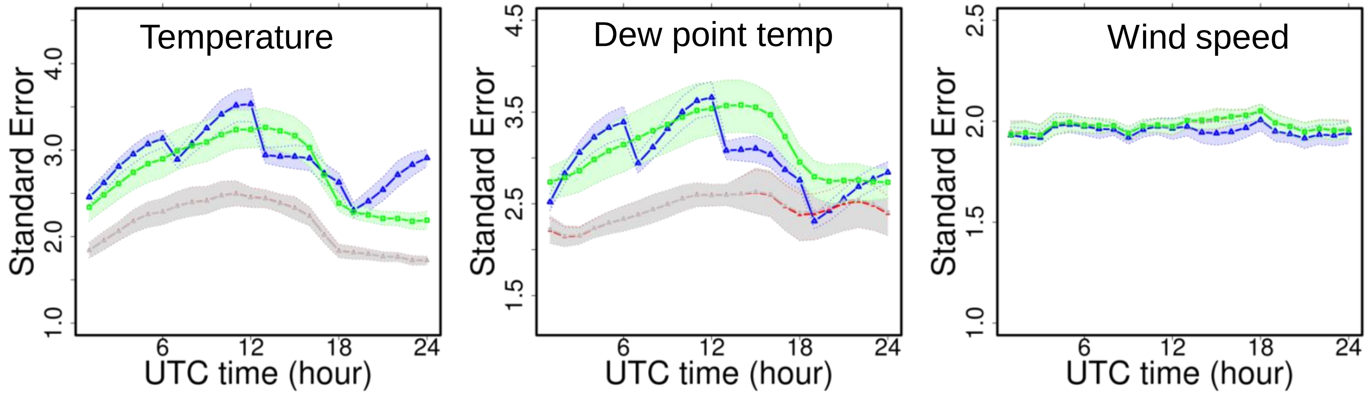


Impact of surface nudging
Screen-level score

Sensitivity of surface fields for nudging

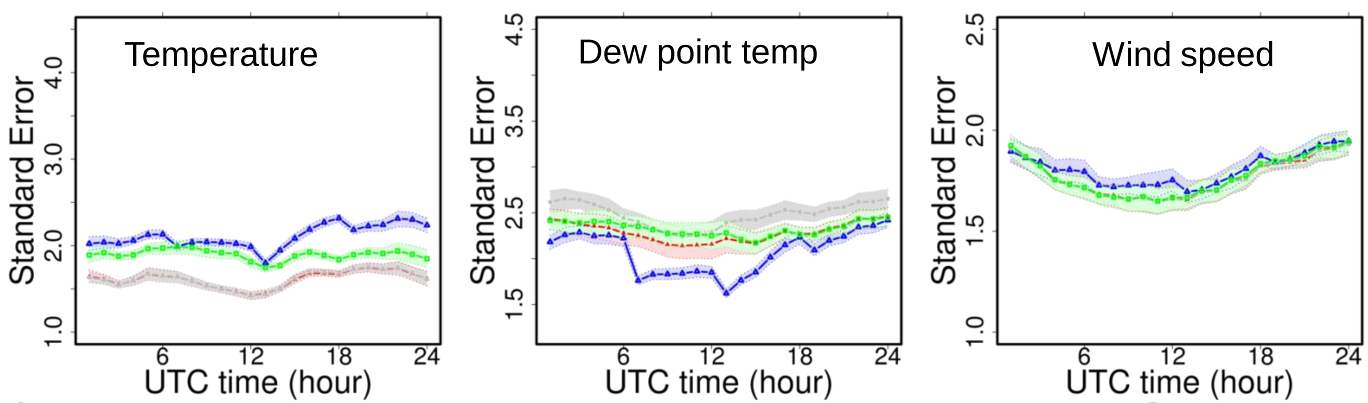
a) Winter

REG FORECAST
LAM-15 N3T2S1_SPSV3
N3T2S1_SPSV3_ST
N3T2S1_SPSV3_SD-DN



b) Summer

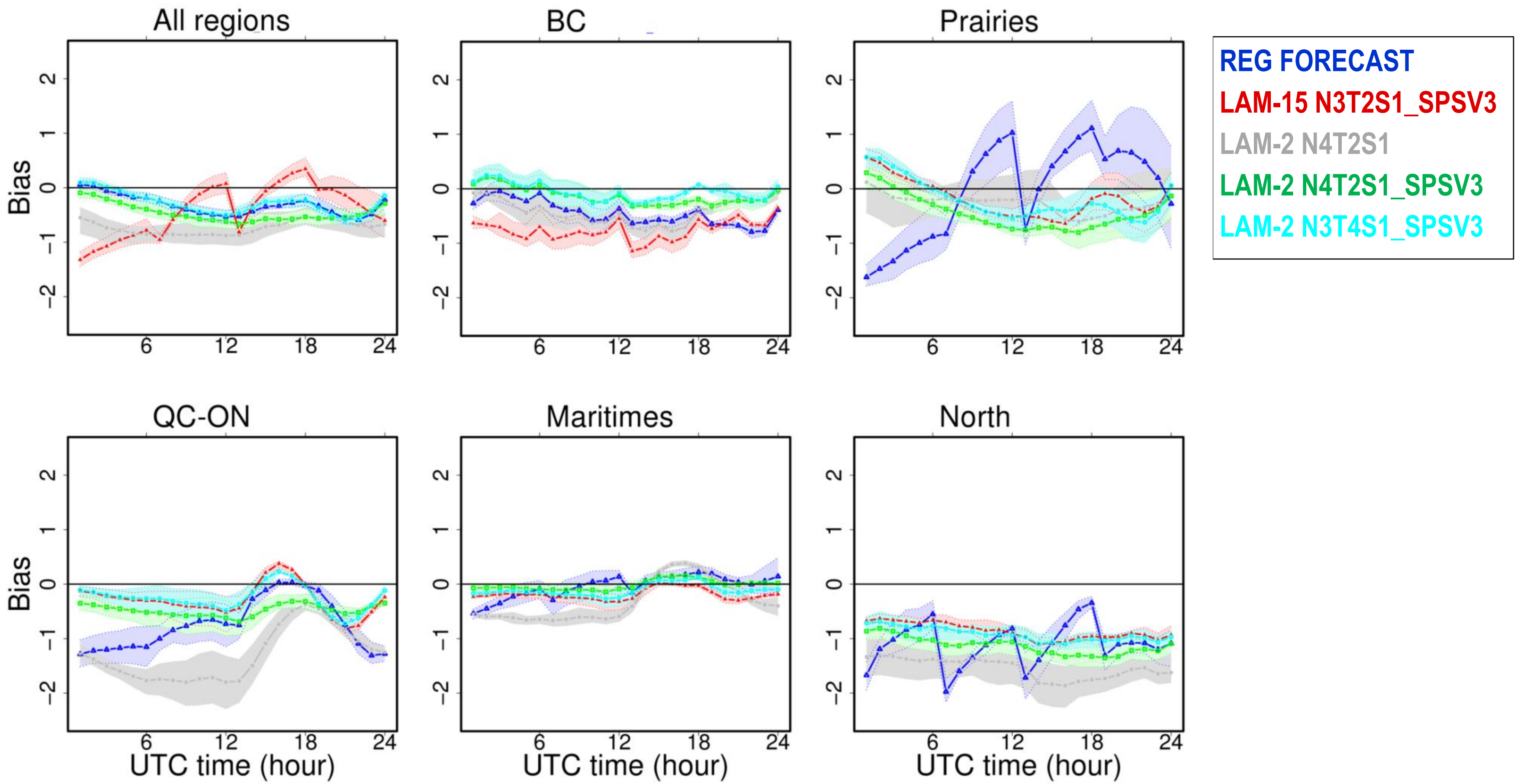
REG FORECAST
LAM-15 N3T2S1_SPSV3
N3T2S1_SPSV3_ST
N3T2S1_SPSV3_SM



Extension to LAM-2 simulations

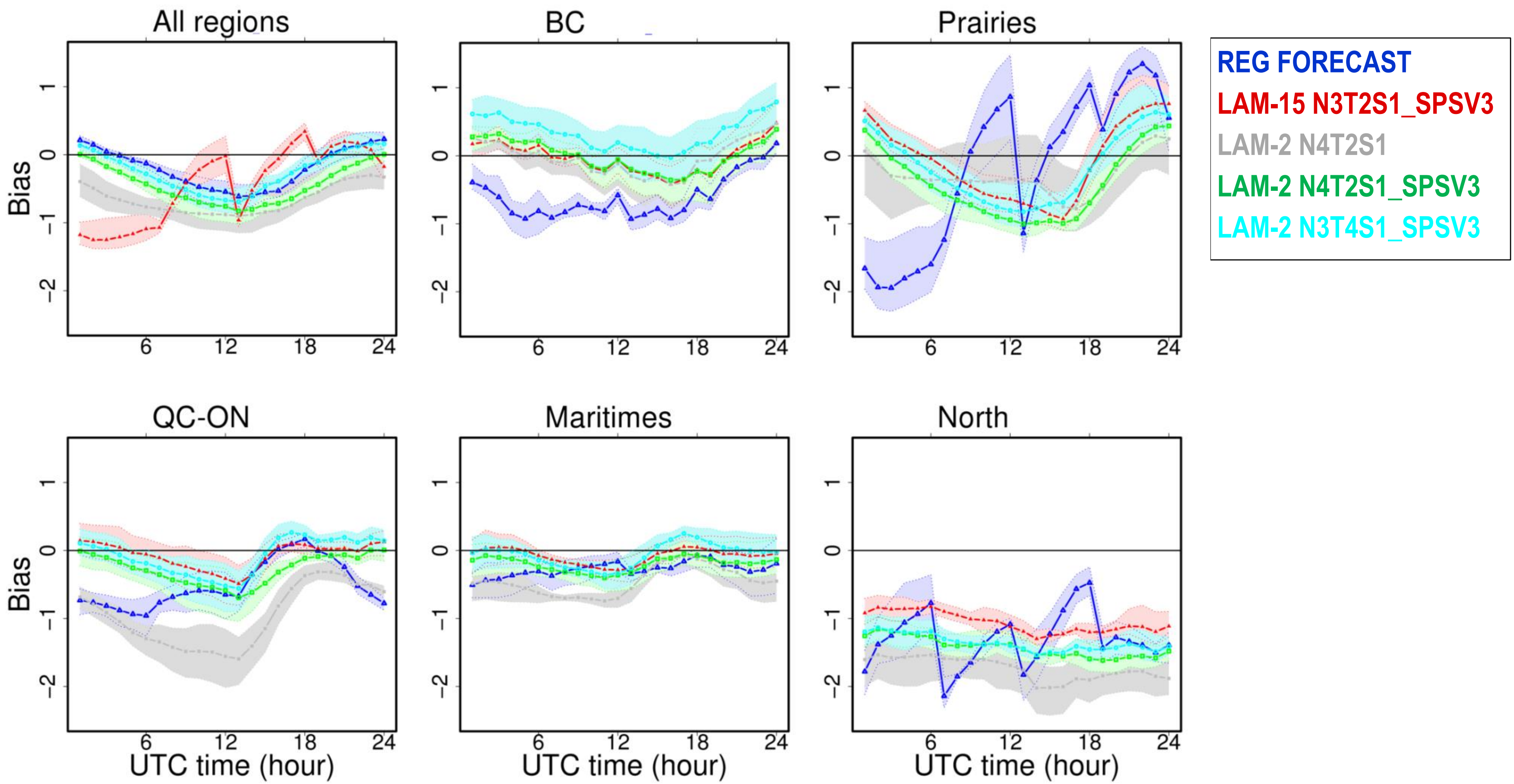
Screen-level scores

Temperature in winter (Feb 5 – 18, 2010)



Extension to LAM-2 simulations
Screen-level scores

Dew point temperature in winter (Feb 5 – 18, 2010)



Extension to LAM-2 simulations

Screen-level scores

Wind speed in winter (Feb 5 – 18, 2010)