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The stratospheric extension of the Canadian global weather forecasting system and its impact on tropospheric forecasts

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Recherche en prévision numérique atmosphérique

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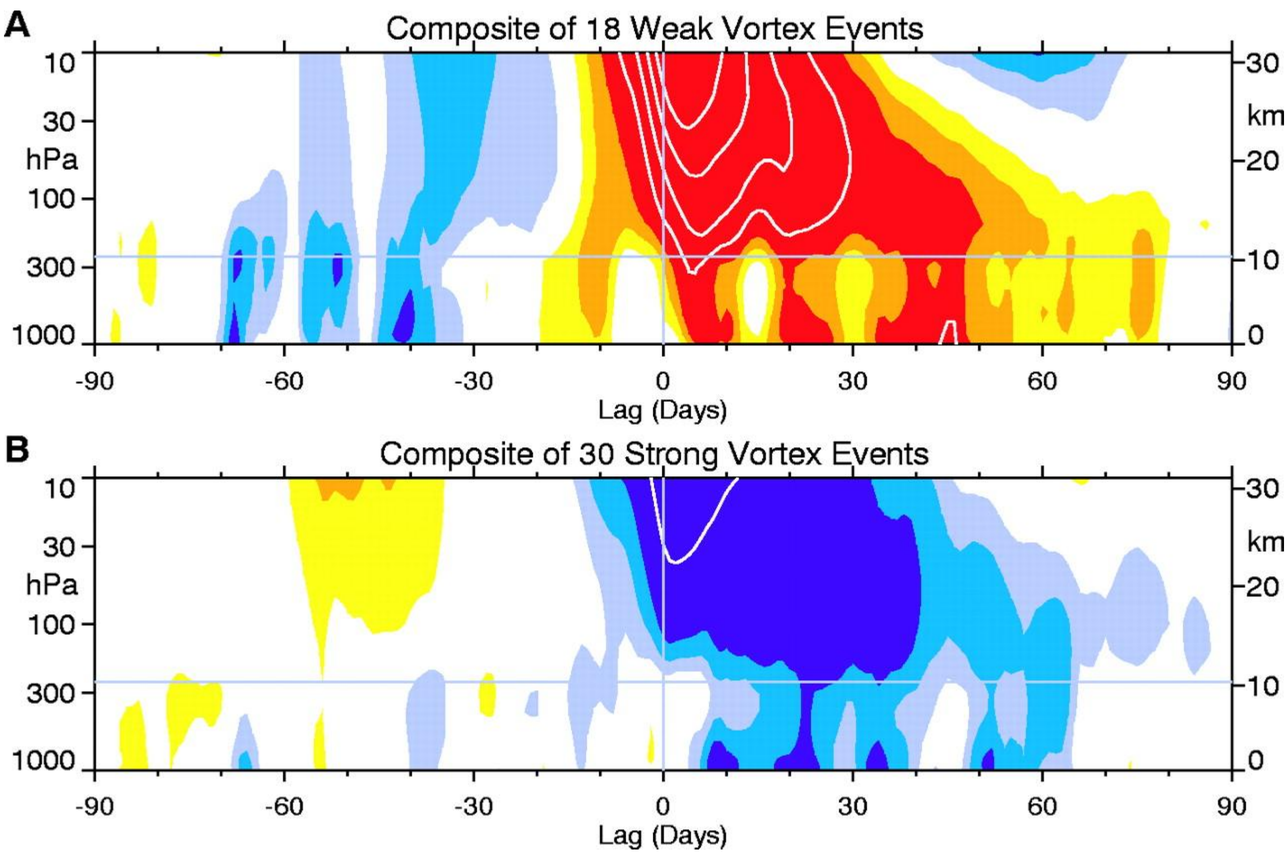
Talk Outline

- Possible ways the stratosphere can impact tropospheric forecasts
  - A question of time scales
- The upgrade of the operational global model at Environment Canada
  - Resolving the stratosphere
  - New assimilated data
  - Scores
- Understanding the improvements in the troposphere
  - Sensitivity experiments
    - Role of observations
    - Role of the model (lid height, parameterizations, etc.)

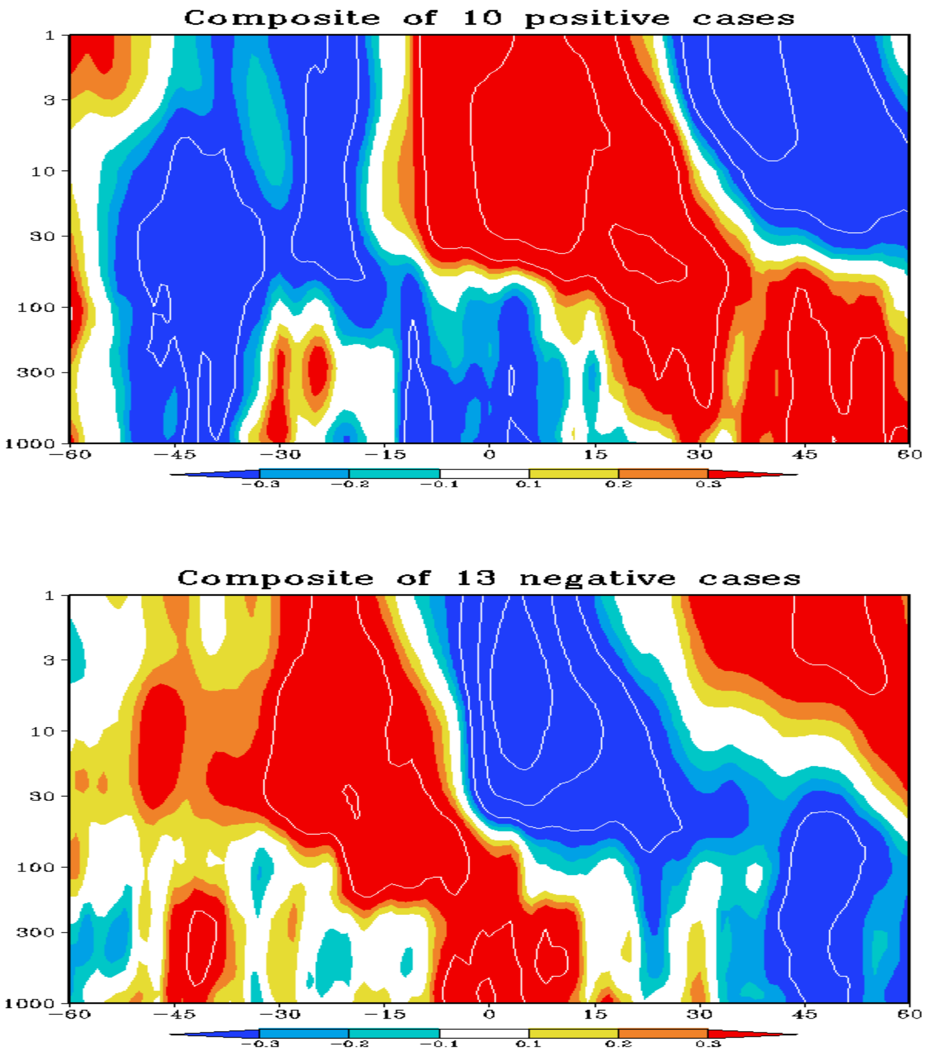
Stratosphere-Troposphere Links (1)



Composites of time-height development of the northern annular mode.

From Baldwin and Dunkerton, *Science 19 October 2001, Vol. 294 no. 5542, pp. 581-584*

Stratosphere-Troposphere Links (2)



Composites of time-height development of the northern annular mode from a free GEM model run.

From Hai Lin, Recherche en prévision numérique, Environment Canada

Stratosphere-Troposphere Links (3)

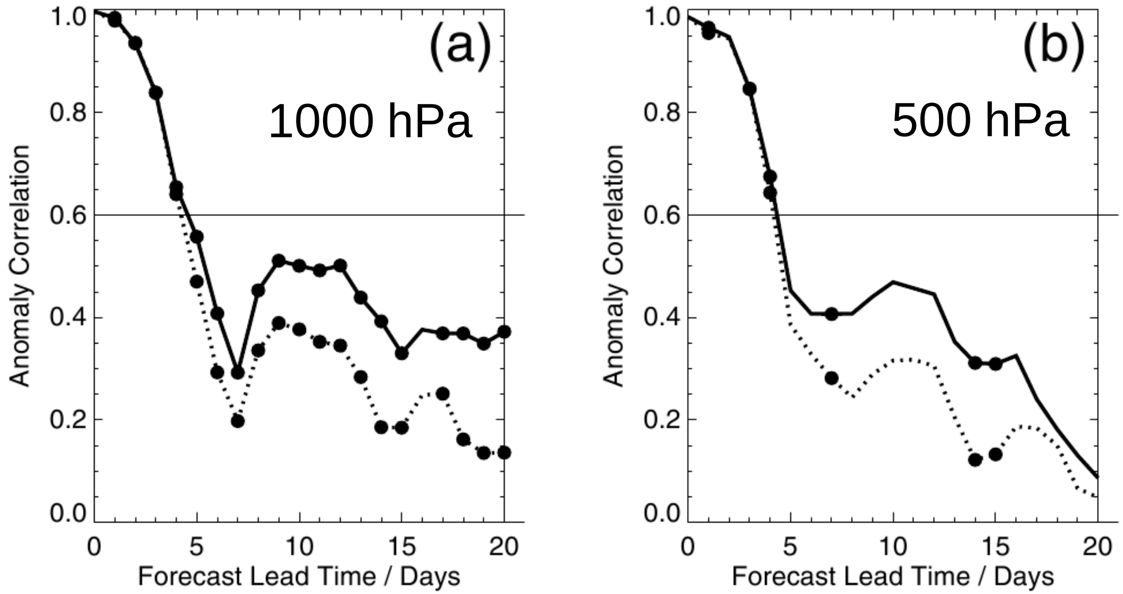
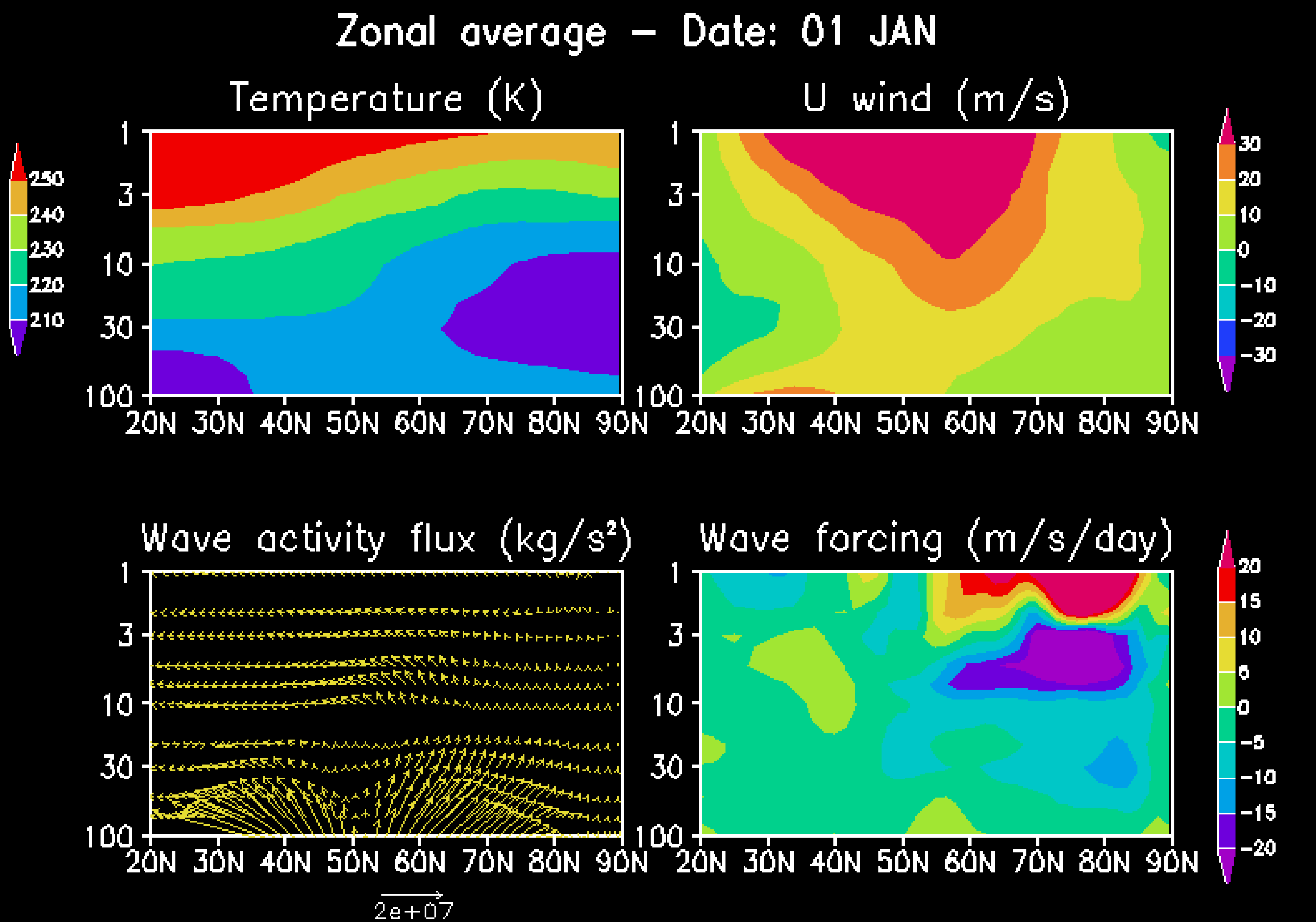


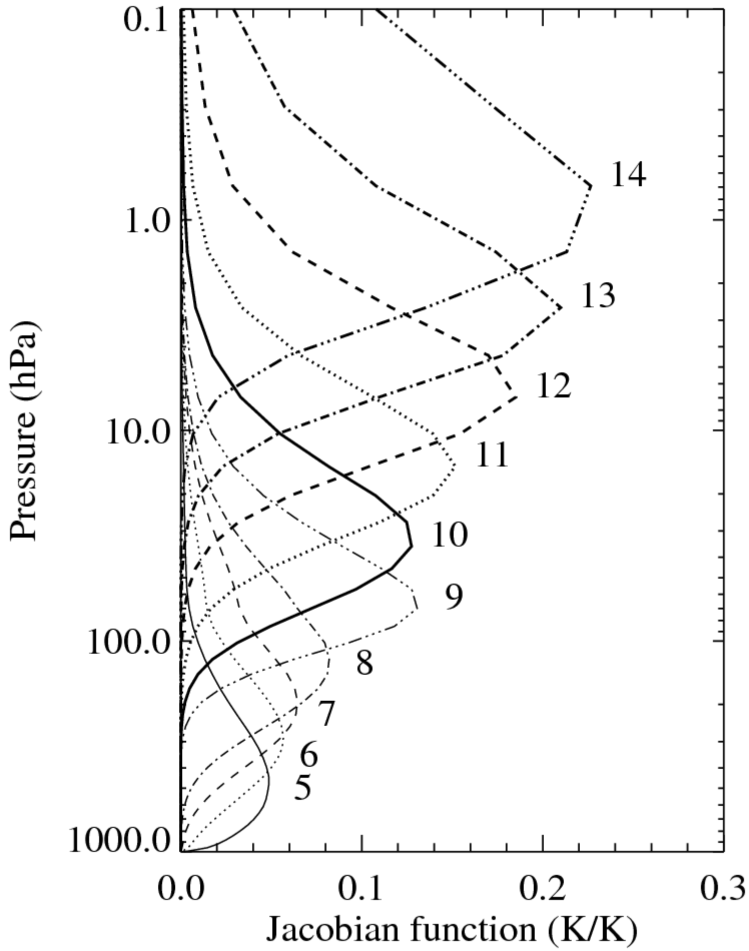
Figure 14. Pooled anomaly correlation coefficient for all case studies at (a) 1000 hPa and (b) 500 hPa. Solid (dotted) line shows anomaly correlation for runs with correct (incorrect) stratospheric initial condition. Circles show forecast times where there is a significant difference in the anomaly correlation between the two sets of runs.

From Charlton, A. J., A. O'Neill, W. A. Lahoz, and A. C. Massacand, 2004: Sensitivity of tropospheric forecasts to stratospheric initial conditions. *Quart. J. Roy. Meteor. Soc.*, **130**, 1771–1792.



Zonal average - Date: 01 JAN
Temperature (K)
U wind (m/s)
Wave activity flux (kg/s²)
Wave forcing (m/s/day)
250
240
230
220
210
30
20
10
0
-10
-20
-30
20
15
10
5
0
-5
-10
-15
-20
1
3
10
30
100
20N 30N 40N 50N 60N 70N 80N 90N
2e+07

Stratosphere-Troposphere Links (4)



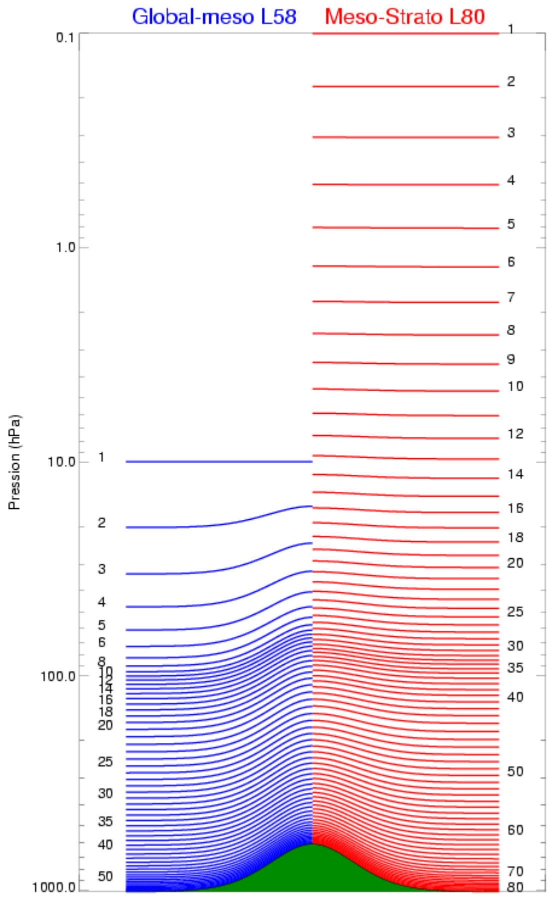
AMSU-A Jacobian functions on the 43 RTTOV levels computed using the US standard atmosphere.

Since **tropospheric peaking channels** also **sense the stratosphere**, assimilation cycles with an improved stratosphere might also result in an improved assimilation of these channels.

EC’s Operational NWP Global Model Resolving the Stratosphere

- First version implemented in June 2009
- Changes to the model:
  - Lid moved from 10 to 0.1 hPa (58 to 80 levels)
  - New radiation scheme (Li and Barker 2005)
  - Introduce non-orographic gravity wave drag scheme (Hines 1997,1998)
  - Introduce methane oxidation scheme (à la ECMWF)
  - New ozone climatology (Paul et al. 1998)
  - Adjusted sponge layers depth and intersity (wth mean zonal component untouched)

Vertical Structure



$$p = A(\eta) + B(\eta)\, p_s$$

$$A(\eta) = [\eta - B(\eta)]\, p_{00}$$

$$B(\eta) = \left(\frac{\eta - \eta_T}{1 - \eta_T} \right)^r$$

$$p_{00} = 800 \text{ hPa}$$

$$r = 1.6$$

Radiation (Li and Barker 2005)

- Valid up to 100 km
- LW calculations scale linearly with number of levels
- 3D interactive treatment of water vapor continuum, CO_2, O_3, N_2O, CH_4, CFC11, CFC12, CFC113, and CFC114
- Use the correlated k-distribution method for absorption/emission of LW and SW-NIR
- Proper treatment of SW and LW spectrum overlap
- Cloud and aerosol infrared scattering
- New and more detailed outputs:
  - Diffuse and direct SW flux (flux on slopes, photosynthesis,solar forecasting)
  - Fluxes over 9 bands in LW, 3 bands in NIR, 9 bands in UV-Vis
  - Clear sky fluxes

EC's Operational NWP Global Model Resolving the Stratosphere

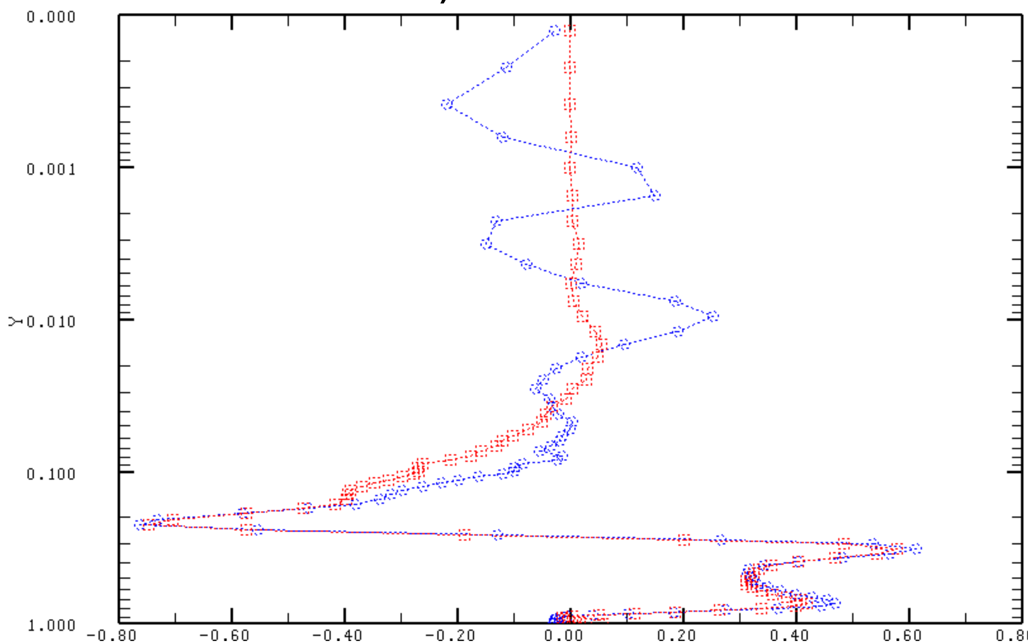
- Changes to the 4D-Var assimilation:
  - New background error statistics in the middle atmosphere
  - New data: AMSU-A channels 11-14
  - New data: GPSRO 30-40 km altitude
  - Revised background error variances for AMSU-A ch. 9-10
  - Dynamic bias correction (except AMSU-A ch. 11-14)

New background error covariances

- Background error covariances from "NMC method" recomputed with the stratospheric version of the model
- Vertical correlations for balanced temperature are localized with Schur product (also cross-term between T and winds)

<u>Figure</u>: Analysis increment of temperature from only aircraft data (no data above ~200hPa) using: **old** and **new approach.**

Also, variances were recomputed.

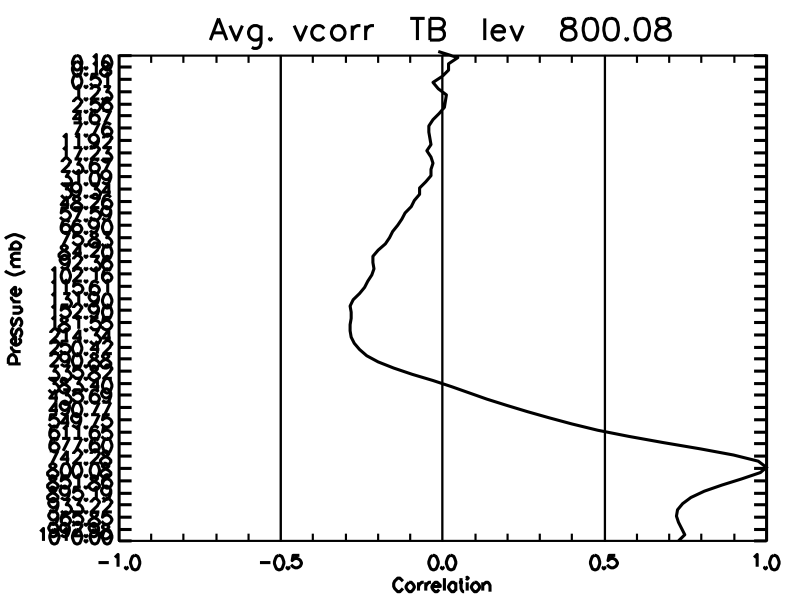


T_b correlation with vertical localization

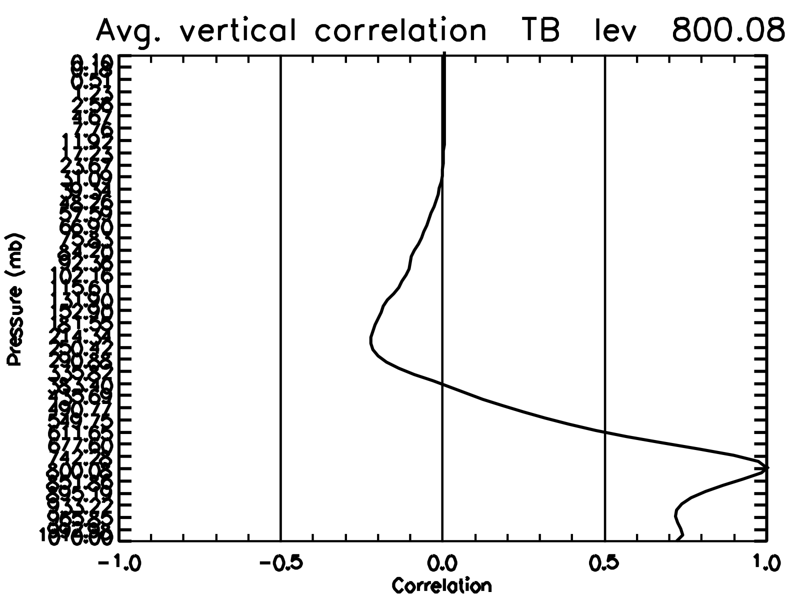
Localization applied to all analysis variables, including T_b

Localization by multiplying with a "Gaussian" function eliminates long-range correlations, while preserving the local correlations

Original correlation



Correlation with localization



New background error variances

- Variances adjusted to be consistent with MLS retrieved temperatures and radiosonde T and U, except above 1 hPa where T variances reduced to avoid problems

Impact of new variances

(from 3D-Var experiments with new vs. old variances)

Winter: Neutral, except slightly negative for mass at day 4 in NH

Summer: Positive for mass and wind in extra-tropics

Bias correction characteristics

- Dynamical: updated every 6-h using last 15-day statistics
- Multiple linear regression. Generalized to use any choice of predictors
- For AMSU, first removes scan bias, than uses 4 air mass predictors: GZ 1-10, 5-50, 250-500 and 500-1000 hPa
- Static correction applied to AMSU-A channels 11-14 to avoid drift in 6h (trial) forecast away from the observations
- For IR, uses observation itself: bias = (O-P) = a BTobs + b
- Allows weighting: more weight near radiosondes

GPS-Radio Occultation

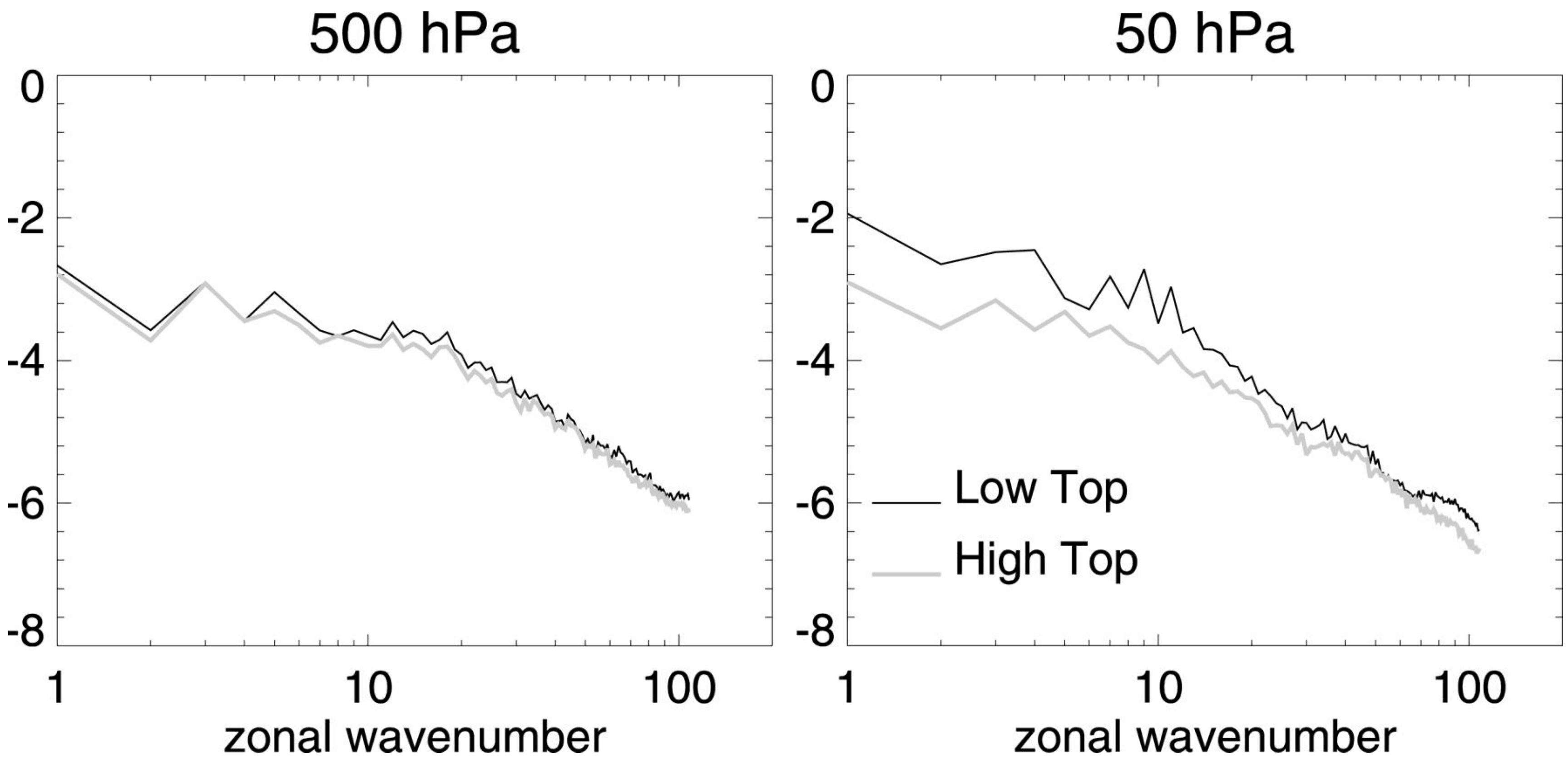
- Refractivity profiles assimilated from 4 to 40 km (~3 hPa) and at least 1 km above surface

- Satellites at time of tests:
  - CHAMP (1 satellite, aft antenna, ~150 profiles/day)
  - GRACE (1 satellite, aft antenna, ~150 profiles/day)
  - COSMIC (6 satellites, fwd & aft antennae, ~1500 profiles/day)

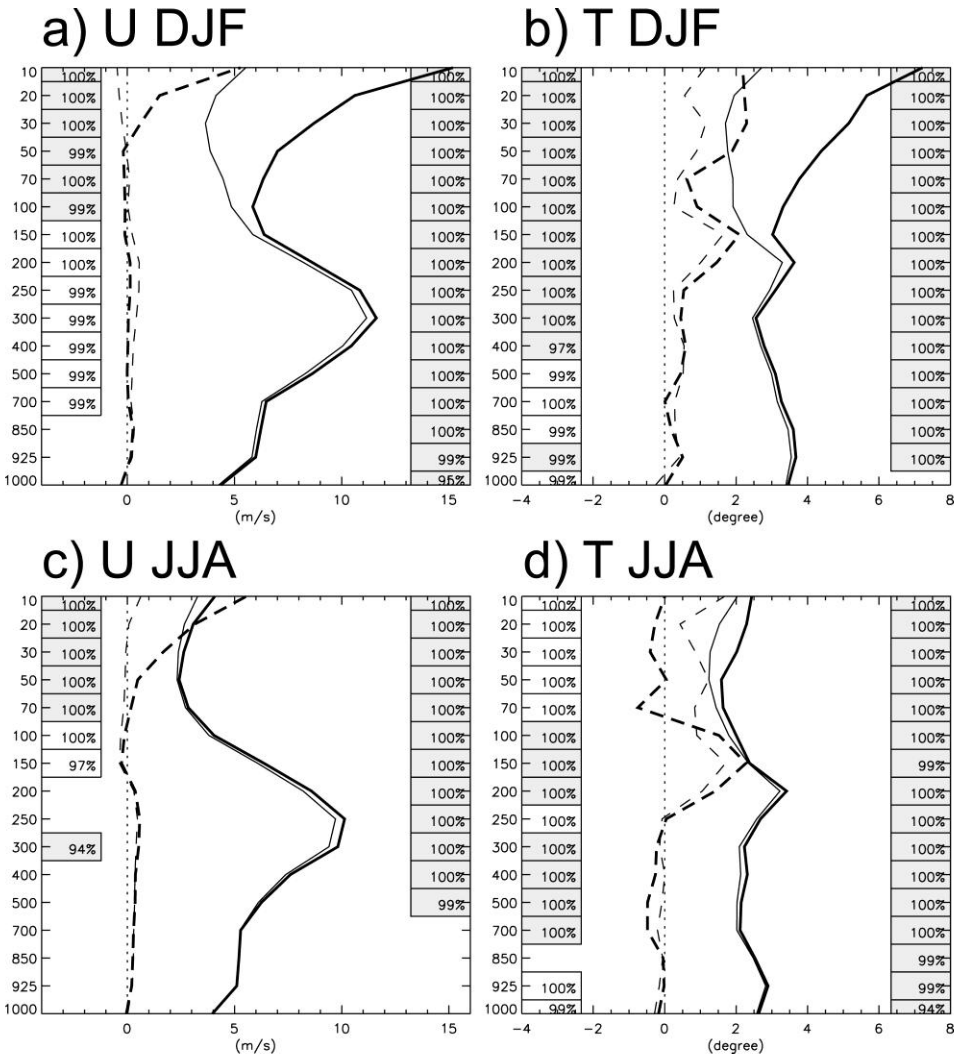
- Each profile contributes ~40 data vertically (vertical thinning at 1 km)
- Assumed non-biased (based on accurate clocks, 10^{-14} seconds)
- Observation error small: 0.7% (10-20 km) to 3-4% at 40 km, assigned dynamically

Mean temperature analysis increments

One month in winter



Results against Radiosondes



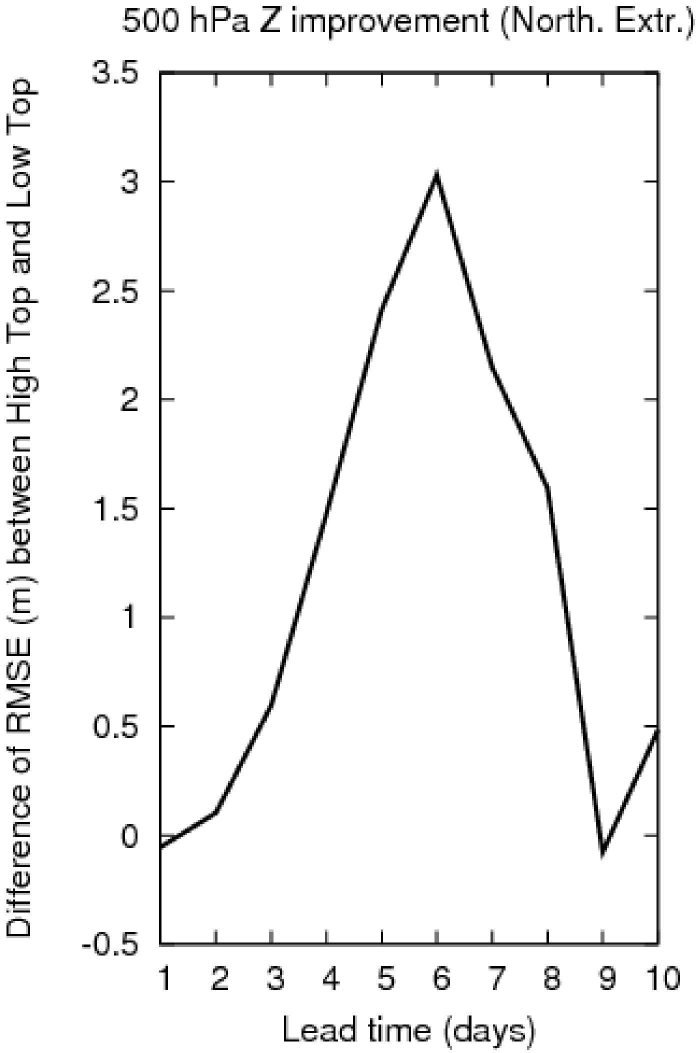
5-day forecasts

Solid: RMS error
Dashed: Bias

Shown for the **northern hemisphere**.

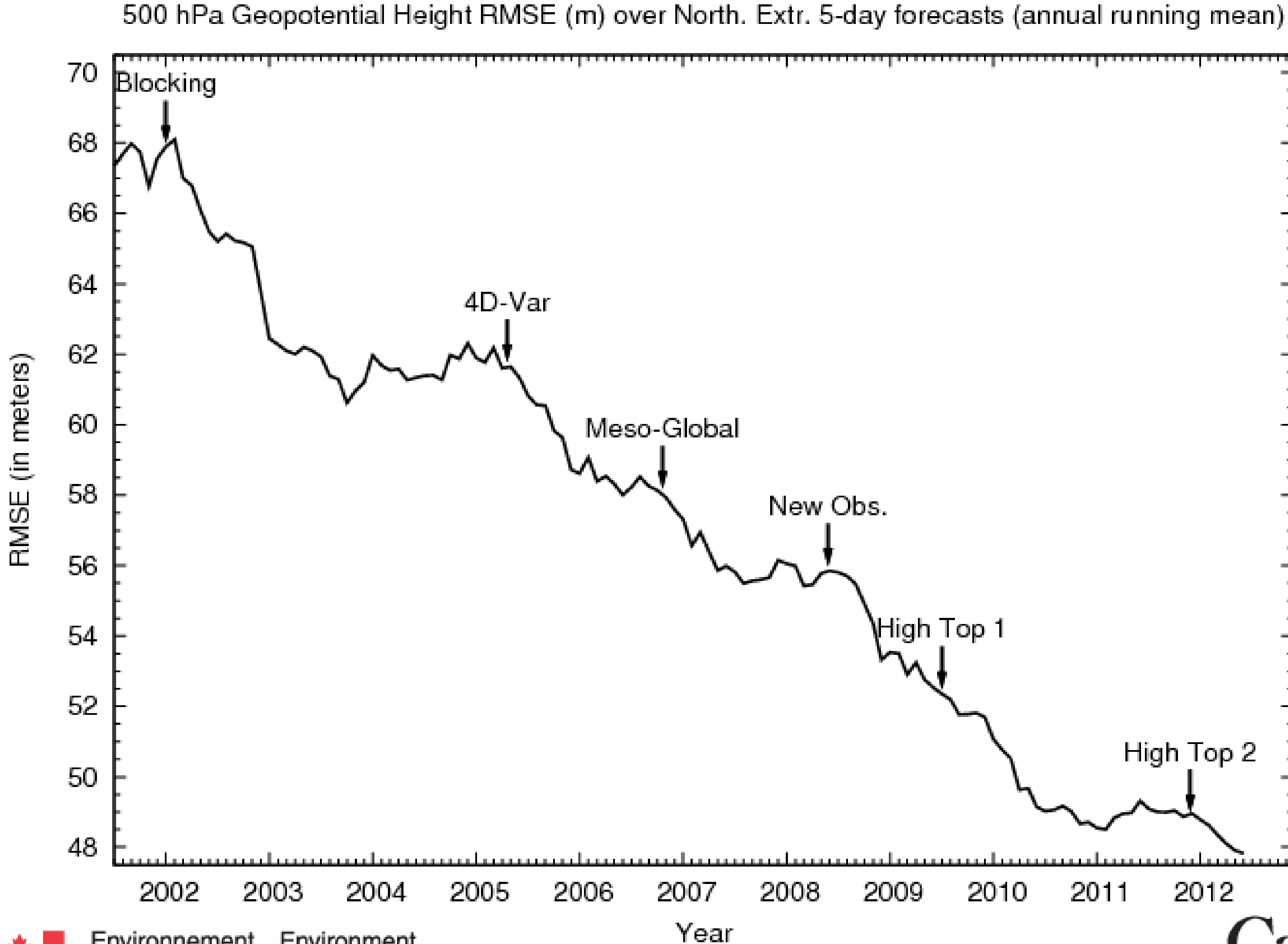
Results similar in the southern hemisphere, but DJF ←→ JJA.

Results against Radiosondes



Improvements of RMS forecast error during operational parallel run (26 March --- 17 June 2009).

Historical Perspective on the Improvement

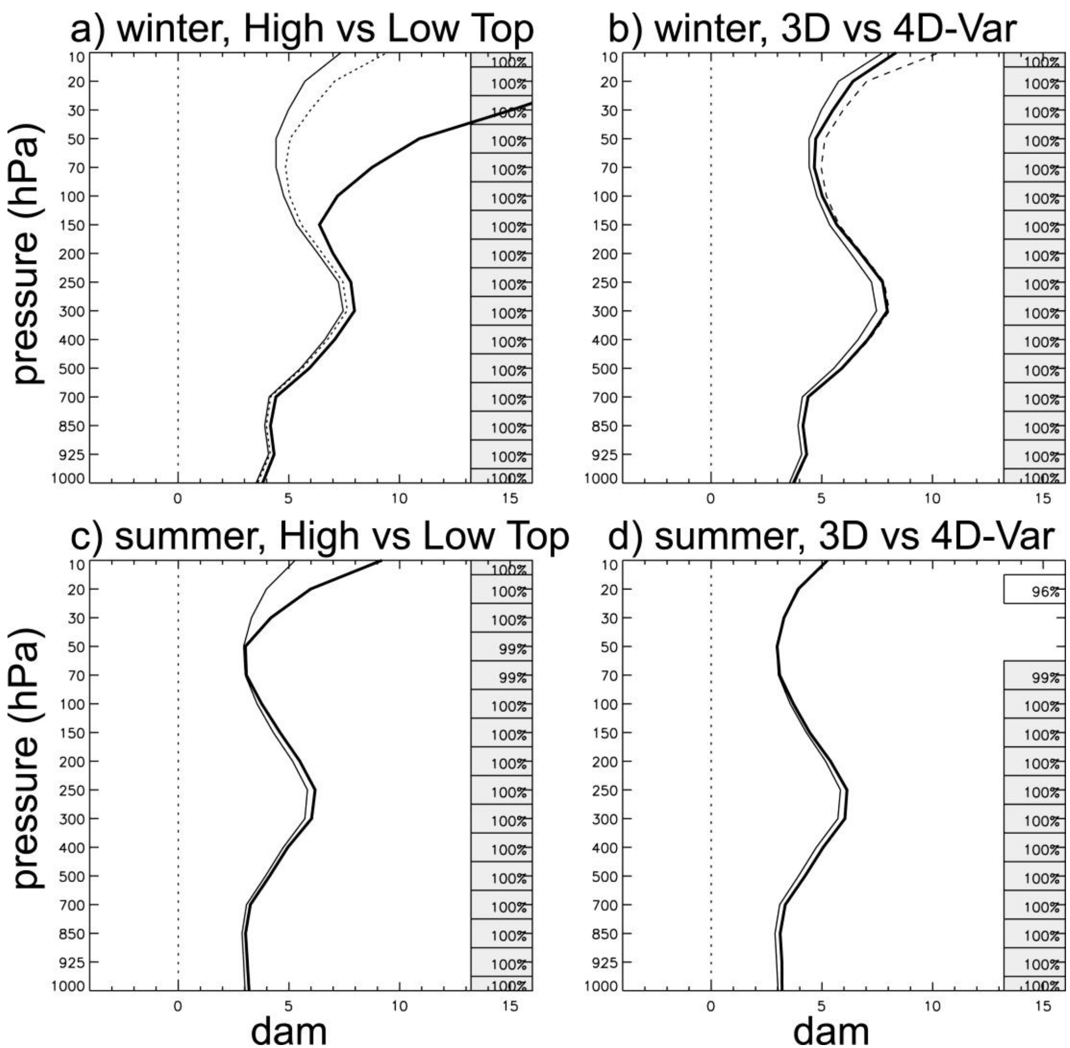


Attribution of Improvements

- Sensitivity experiments to better understand the origin of the improvements
  - Role of the additional stratospheric observations?
  - Lid position on improving
    - Stratospheric forecasts
    - Tropospheric forecasts?
  - Role of other model changes (new radiation scheme, sponge layer, etc.)?

- Are the improvements due to
  - better initial conditions?
  - better model to perform the forecasts?

Attribution of Improvements



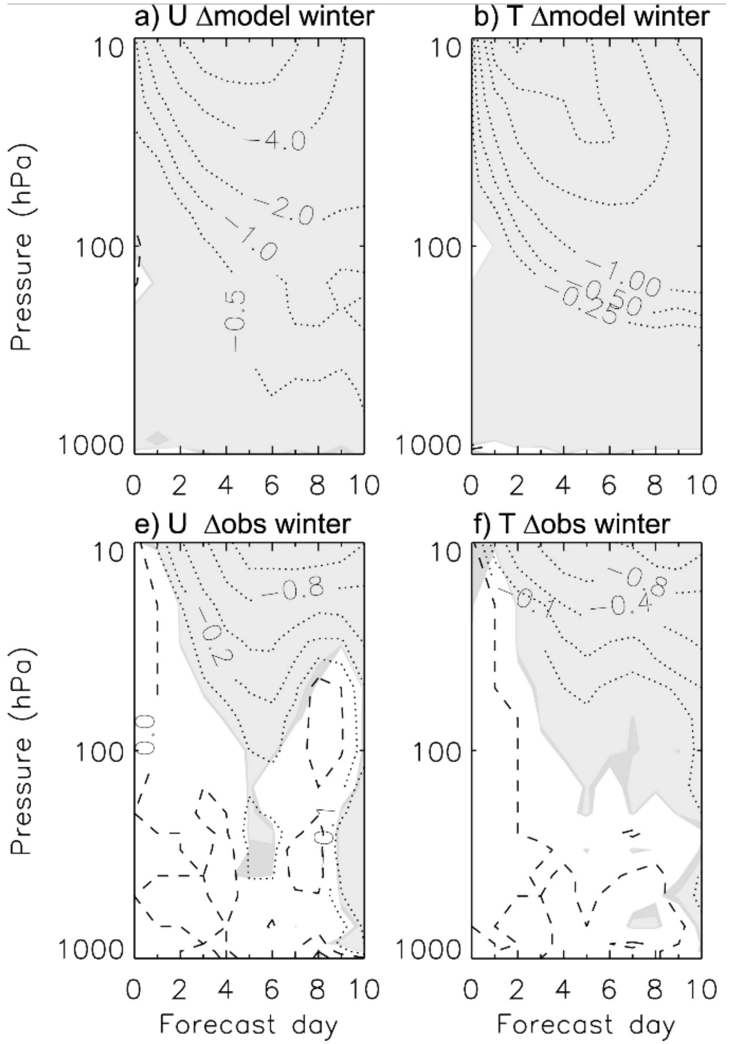
RMS 5-day forecast error for height against radiosondes.

Left panels:
Thick: Low top
Thin: High top
Dotted: High top minus additional stratospheric obs.

Right panels:
Thick: High top with 3D-Var
Thin: High top with 4D-Var
Dashed: High top with 3D-Var minus additional stratospheric obs.

Similar signal with 3D- and 4D-Var.

Attribution of Improvements



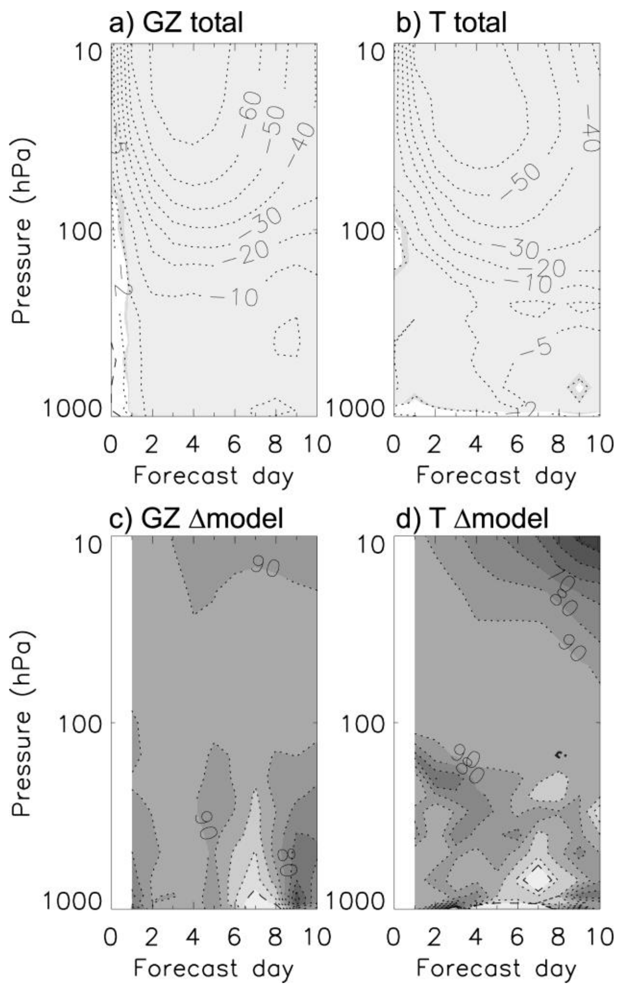
Differences in STD forecast error for zonal wind (m/s) and temperature (K) against radiosondes in northern extratropics.

Upper panels:
Differences due to model changes only (same observation network)

Lower panels:
Differences due to added stratospheric observations only (same model)

Impact of changes obtained with DA cycling

Attribution of Improvements



Percent reduction in STD forecast error for geopotential height and temperature against radiosondes in northern extratropics in winter.

Upper panels:
Total percent reduction of Low top vs High top systems

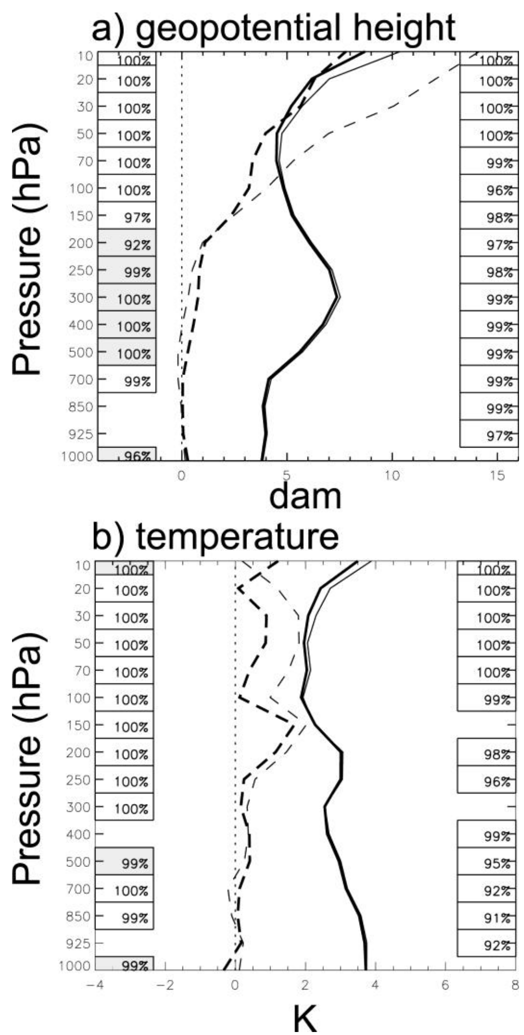
Lower panels:
Percent reduction due to model changes only (same observation network without additional stratospheric observations)

Impact of changes obtained with DA cycling

Attribution of Improvements

- To separate the role of improved initial conditions to that of the medium-range forecast model:
  - Perform sensitivity experiments with the same set of initial conditions (from High top system)
  - Revert step be step to Low top model components
    - Old radiation
    - Old sponge layer
    - Old vertical grid spacing above 100 hPa
    - Old vertical coordinate (eta)
    - Lid height at 10 hPa

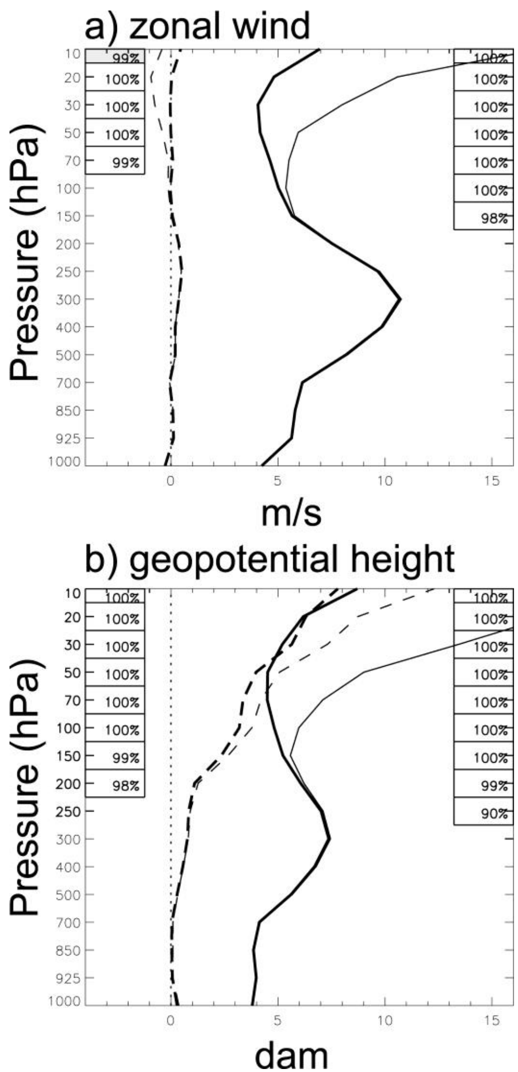
Improvements Due to the Radiation Scheme



The Li and Barker (2005) scheme slightly contributes to improve scores in the stratosphere and troposphere.

However, it contributes to only **20%** of 5-day forecast improvements when comparing High top and Low top systems, with given initial conditions.

Improvements Due to the Higher Lid



Putting the lid at 0.1 hPa explains a very large part of the stratospheric improvements.

However, it **does not contribute** to improve the troposphere for 5-day forecasts with given initial conditions.

Improvements Due to Other Model Changes

- With given initial conditions, reverting back to:
  - old sponge layer (depth and intensity)
  - old vertical grid spacing above 100 hPa
  - old vertical coordinate (eta)

  did not produce any changes in tropospheric scores in the troposphere.

- We hypothesize that **tropospheric** improvements are vastly due to **improvements to the initial conditions**.

Conclusions (1)

- Most of the stratospheric and tropospheric forecast improvement is obtained without the extra observations in the upper stratosphere.
- These observations further improve forecasts in the winter hemisphere, but not in the summer hemisphere.
- Large improvements in stratospheric forecast skill are found to be due to the higher lid height of the new model.

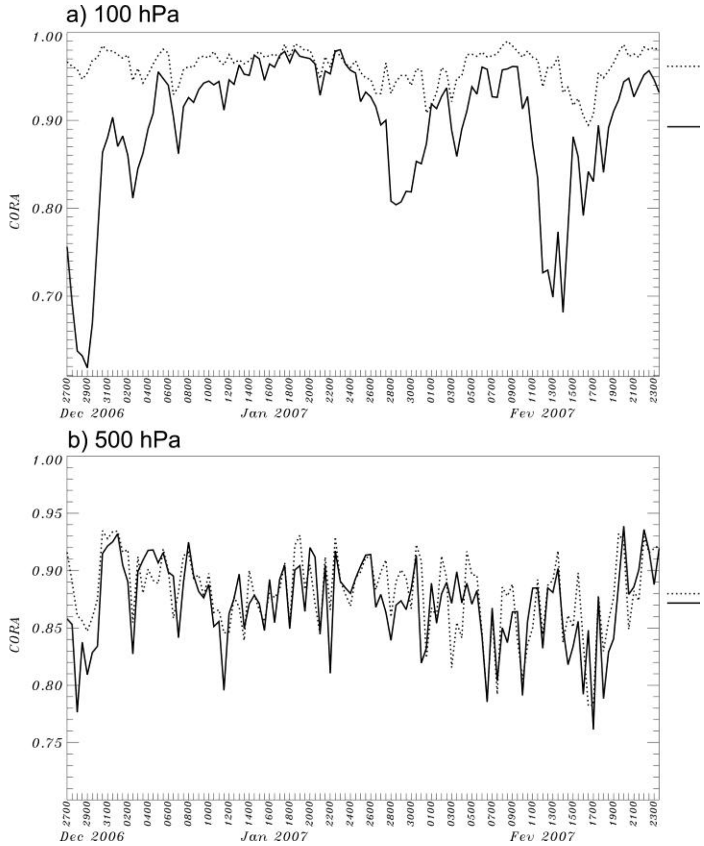
Conclusions (2)

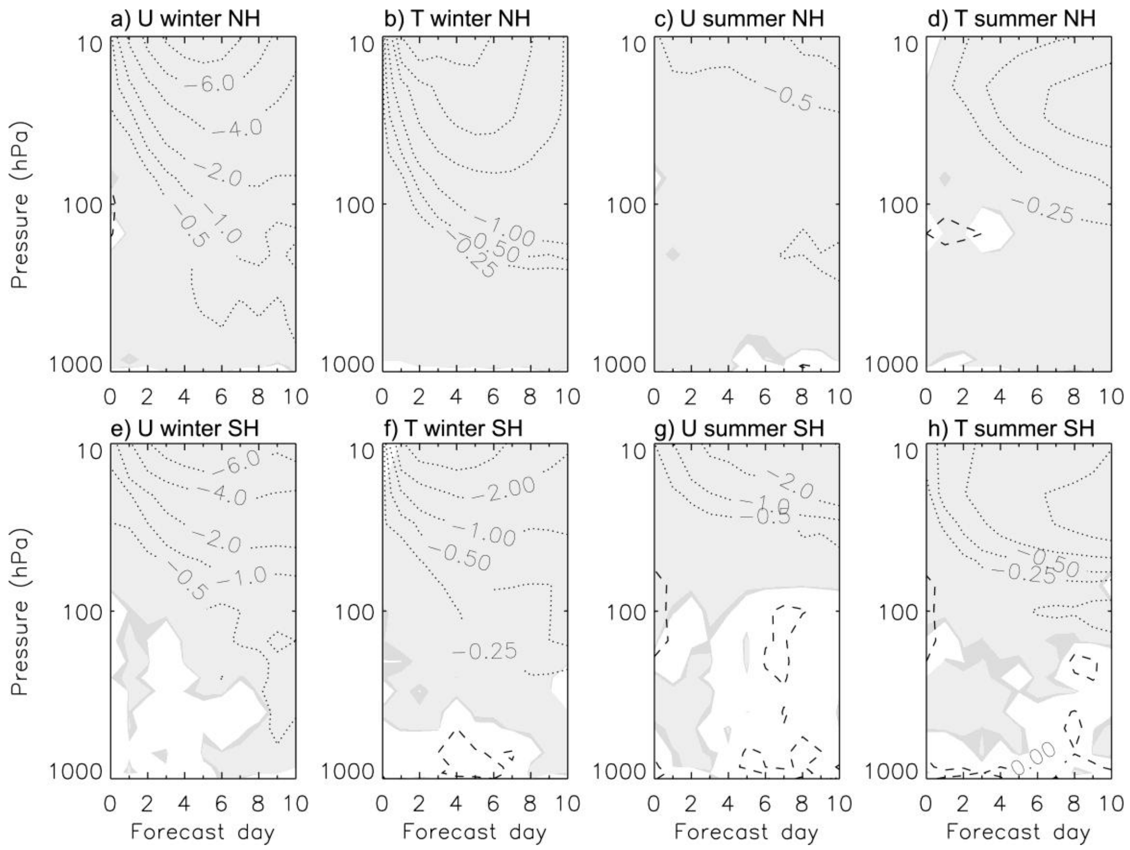
- The new radiation scheme helps to improve tropospheric forecasts. However, the degree of improvement seen in tropospheric forecast skill could not be explained with these purely forecast experiments.

- We hypothesize that the cycling of a better model and assimilation provide improved initial conditions, resulting in improved forecasts.

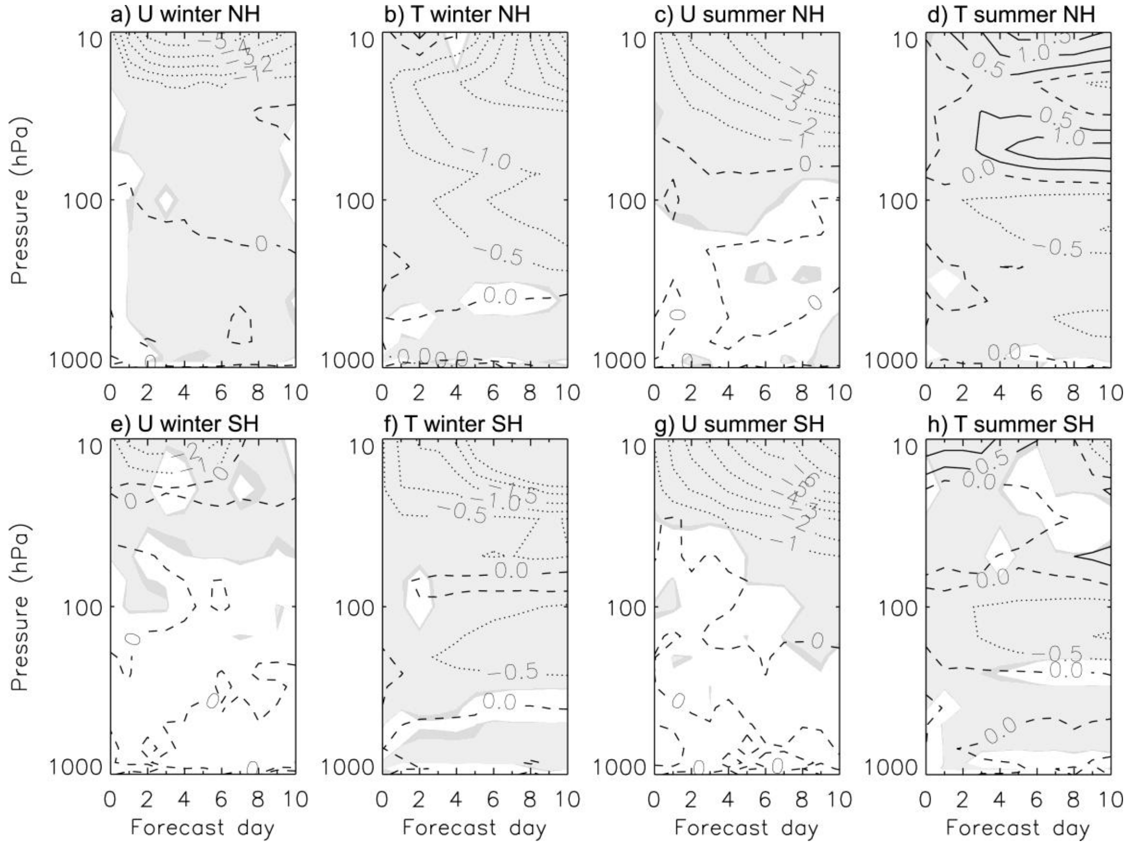
Reference

Charron, M., S. Polavarapu, M. Buehner, P. A. Vaillancourt, C. Charette, M. Roch, J. Morneau, L. Garand, J. M. Aparicio, S. MacPherson, S. Pellerin, J. St-James, and S. Heilliette, 2012: The stratospheric extension of the Canadian global deterministic medium-range weather forecasting system and its impact on tropospheric forecasts. *Mon. Wea. Rev.*, **140**, 1924–1944.

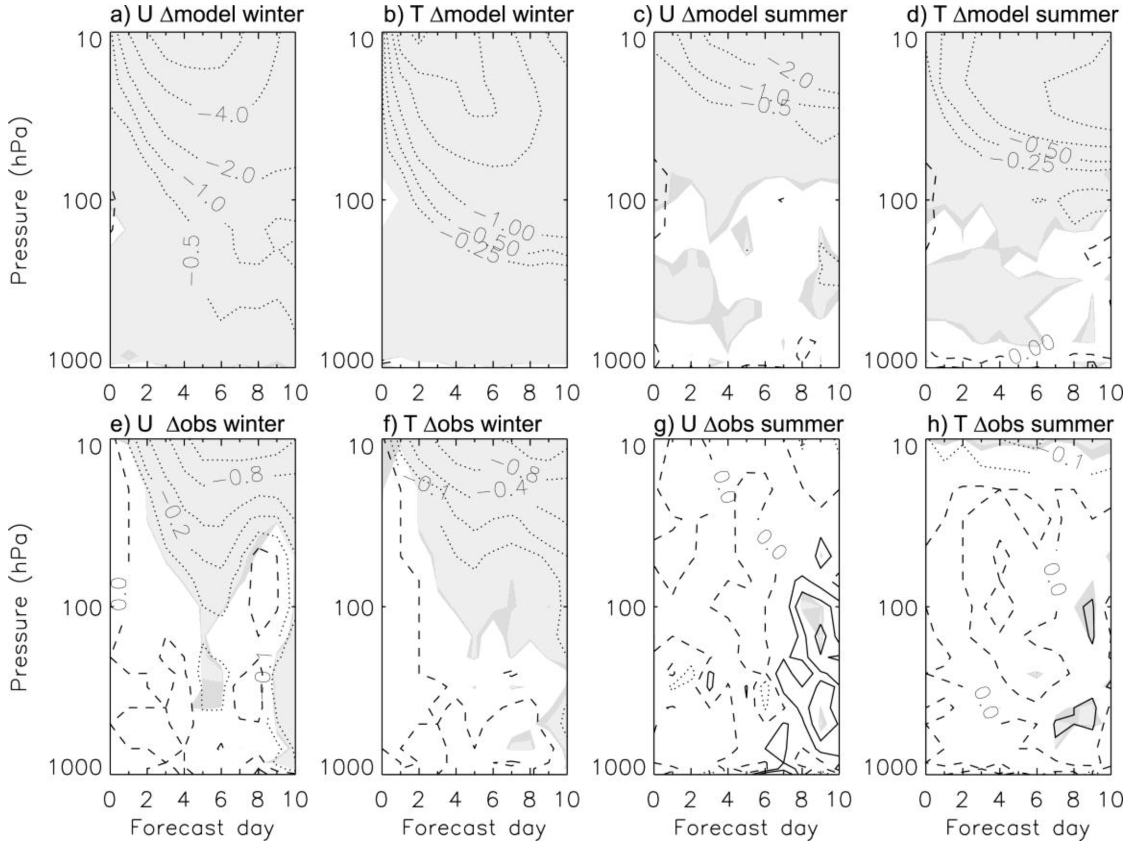

a) 100 hPa
CORA
Dec 2006
Jan 2007
Fev 2007
b) 500 hPa
CORA
Dec 2006
Jan 2007
Fev 2007



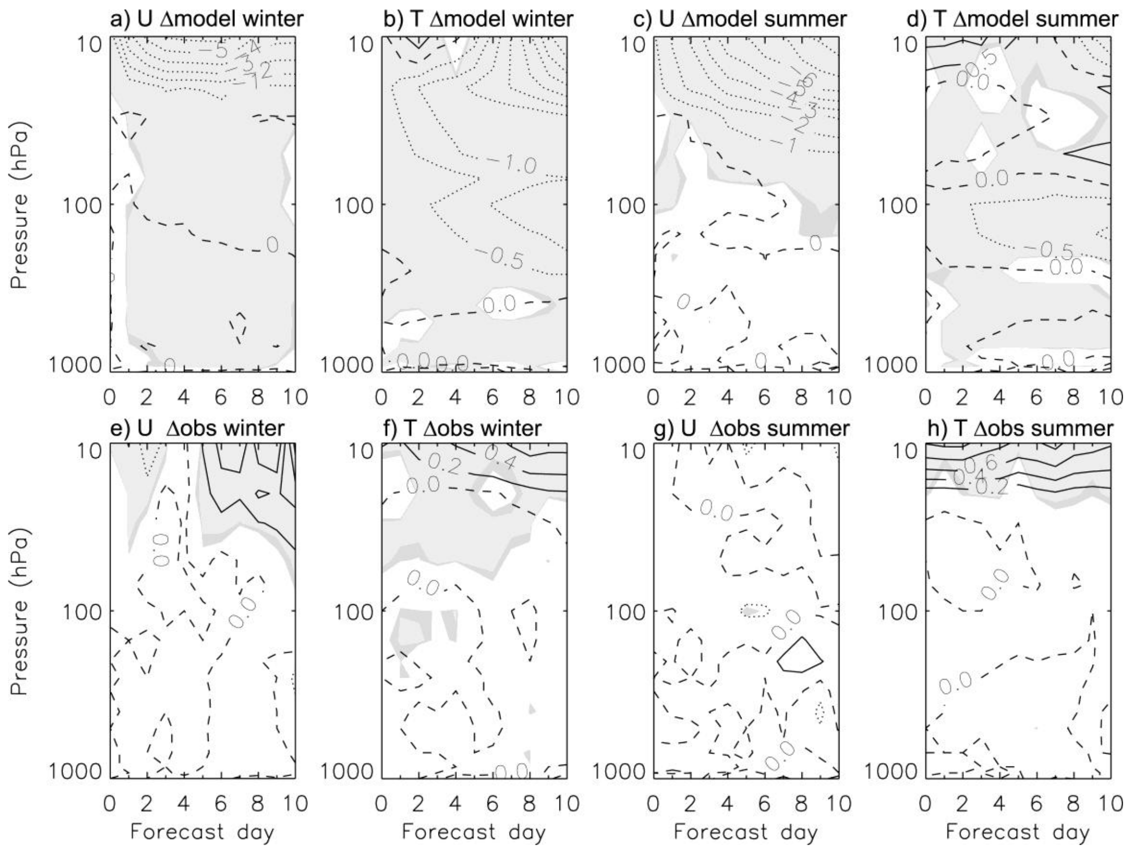
a) U winter NH
b) T winter NH
c) U summer NH
d) T summer NH
e) U winter SH
f) T winter SH
g) U summer SH
h) T summer SH
Pressure (hPa)
Forecast day

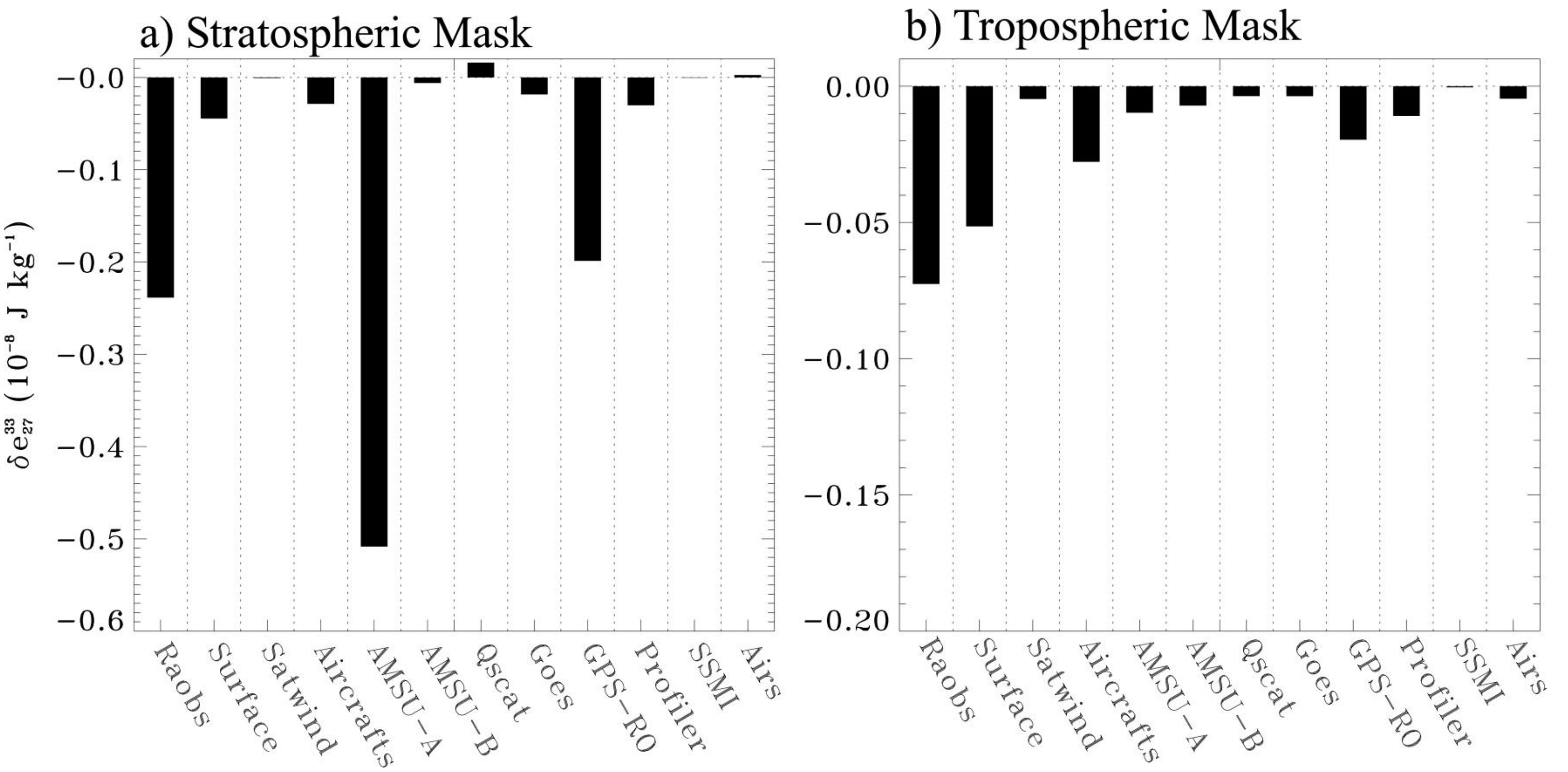


a) U winter NH
b) T winter NH
c) U summer NH
d) T summer NH
e) U winter SH
f) T winter SH
g) U summer SH
h) T summer SH
Pressure (hPa)
Forecast day

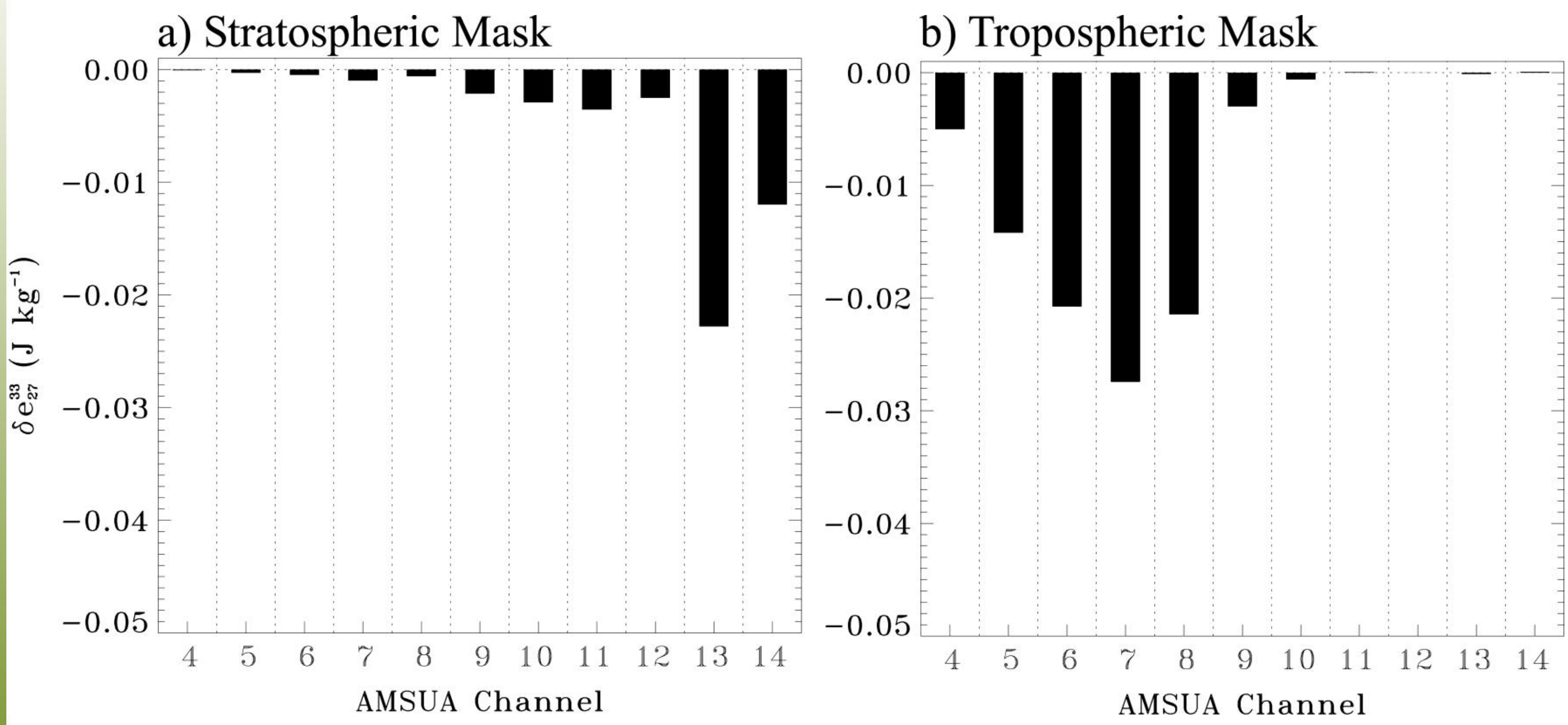


a) U Δmodel winter
b) T Δmodel winter
c) U Δmodel summer
d) T Δmodel summer
e) U Δobs winter
f) T Δobs winter
g) U Δobs summer
h) T Δobs summer
Pressure (hPa)
Forecast day


a) U Δmodel winter
b) T Δmodel winter
c) U Δmodel summer
d) T Δmodel summer
e) U Δobs winter
f) T Δobs winter
g) U Δobs summer
h) T Δobs summer
Pressure (hPa)
Forecast day



a) Stratospheric Mask
b) Tropospheric Mask
δe$^{33}_{27}$ (10^{-8} J kg^{-1})
−0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
0.00
−0.05
−0.10
−0.15
−0.20
Raobs
Surface
Satwind
Aircrafts
AMSU−A
AMSU−B
Qscat
Goes
GPS−RO
Profiler
SSMI
Airs



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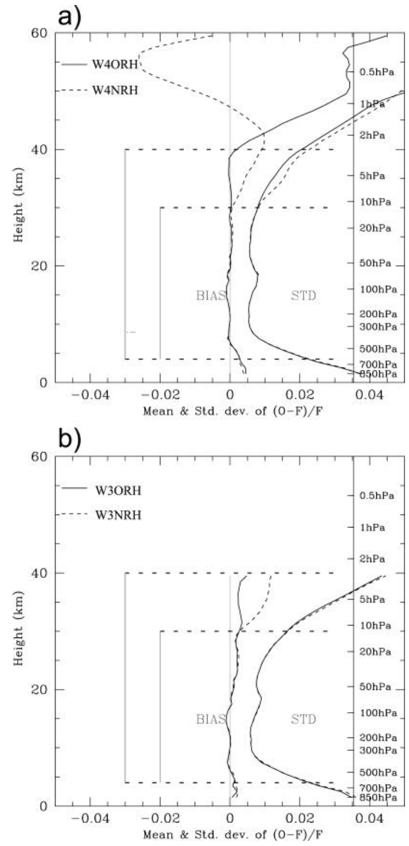

a)
W4ORH
W4NRH
BIAS
STD
Height (km)
Mean & Std. dev. of (O−F)/F
0.5hPa
1hPa
2hPa
5hPa
10hPa
20hPa
50hPa
100hPa
200hPa
300hPa
500hPa
700hPa
850hPa
b)
W3ORH
W3NRH
BIAS
STD
Height (km)
Mean & Std. dev. of (O−F)/F

	Low-top model	High-top model
No. of horizontal grid points	800 × 600	800 × 600
Vertical coordinate	Normalized σ	Hybrid
No. of vertical levels	58	80
Lid position	10 hPa	0.1 hPa
Sponge layer below lid (∇_H^2)	Four levels, acts on full fields	Six levels, acts on departure from zonal means
Tropical sponge near lid $\left[\frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho K \frac{\partial \mathbf{u}}{\partial z}\right)\right]$	Four levels, K (at lid) = 450 $m^2 s^{-1}$ down to 0 at 50 hPa	Eight levels, K (at lid) = 50 $m^2 s^{-1}$ down to 0 at 3 hPa
Radiation scheme	Fouquart/Bonnel+Garand	Li and Barker (2005)
Nonorographic gravity wave drag scheme	None	Hines (1997a,b)
Methane oxidation	None	Simple relaxation
Ozone climatology	Kita and Sumi (1986)	Paul et al. (1998) below 0.3 hPa, HALOE above 0.15 hPa, transition between 0.3 and 0.15 hPa
Total relative computational cost	1.0	1.5

Expt	Assimilation scheme	Extra observations	Reduced observation errors	Model
W4ORH	4DVAR	AMSU-A 11–14 GPSRO 30–40 km	AMSU-A 9 and 10	High top
W4NRH	4DVAR		AMSU-A 9 and 10	High top
W4NNH	4DVAR			High top
W4NNL	4DVAR			Low top
W3ORH	3DVAR (FGAT)	AMSU-A 11–14 GPSRO 30–40 km	AMSU-A 9 and 10	High top
W3NRH	3DVAR (FGAT)		AMSU-A 9 and 10	High top

Expt	Assimilation scheme	Extra observations	Reduced observation errors	Model
S4ORH	4DVAR	AMSU-A 11–14 GPSRO 30–40 km	AMSU-A 9 and 10	High top
S4NNL	4DVAR			Low top
S3ORH	3DVAR (FGAT)	AMSU-A 11–14 GPSRO 30–40 km	AMSU-A 9 and 10	High top