Improving Near-Surface Temperature Forecasts in the NCEP Global Forecast System

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May 11, 2017

Motivations:

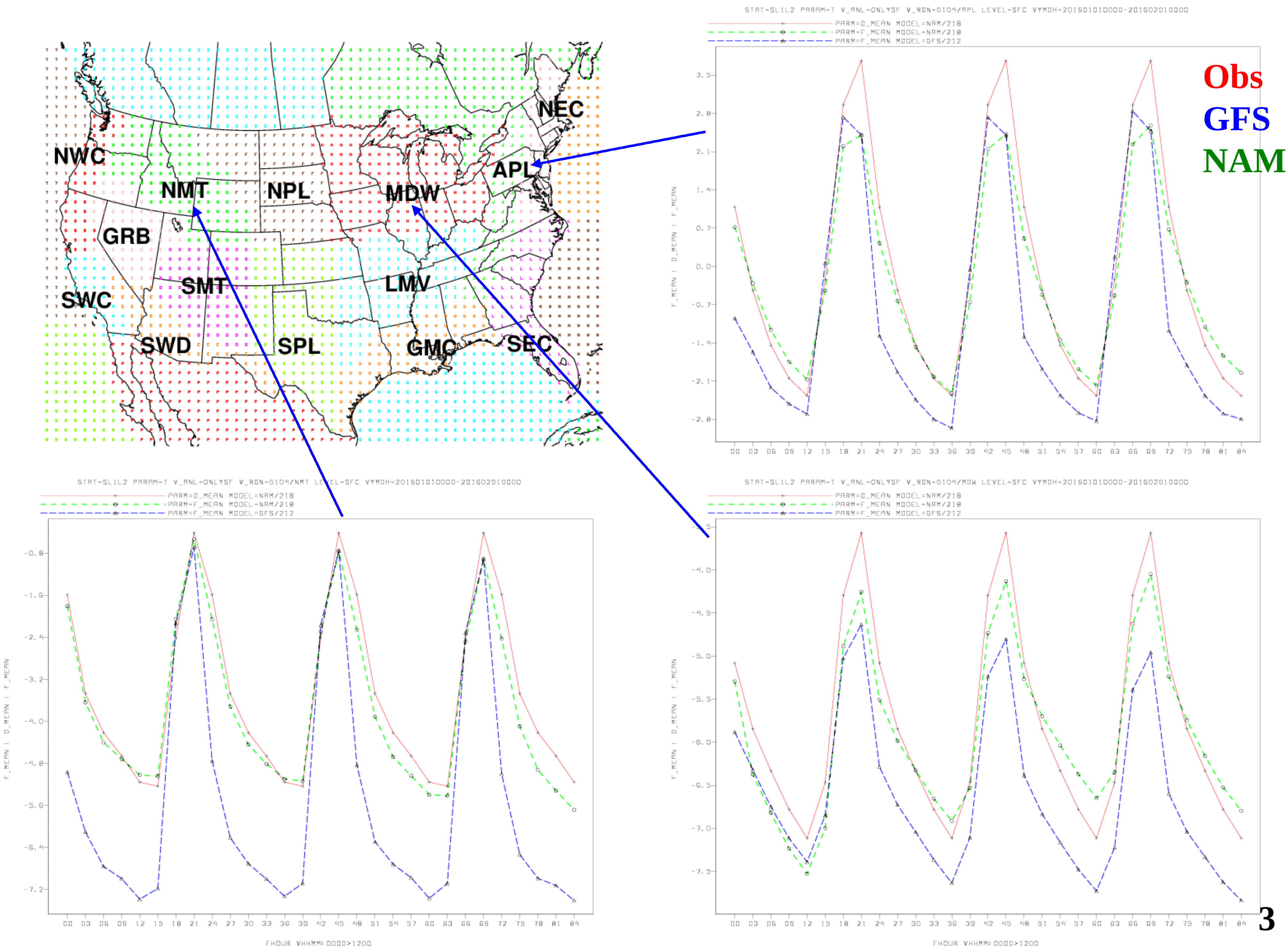
- **What is the problem about GFS surface temperature forecast?**
  - ***One of <u>Top 10</u> problems in the GFS***

    NWS Field Office, NCEP/EMC Model Evaluation Group (MEG)

- **What causes this kind of problem?**
  - ***Understanding of stable boundary layer (SBL) processes***

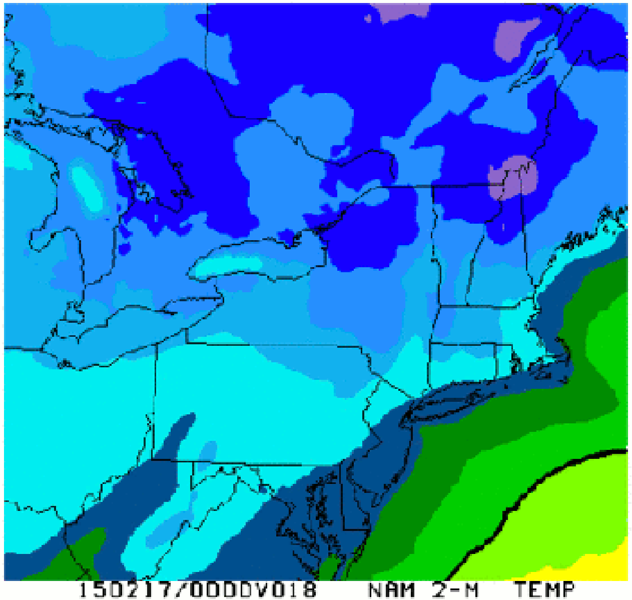
- **How to solve the problem?**
  - ***An approach to fix the problem***

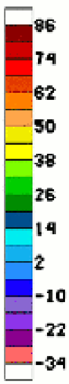
Ops GFS: T2m Forecast Verification Statistics for Jan 2016



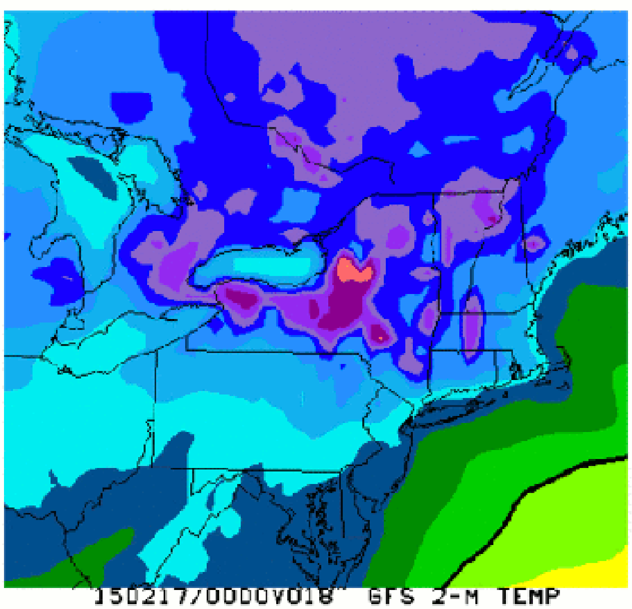
Comparison of T_{2m} (F): NAM, GFS and Obs, 00UTC, 2015-02-17

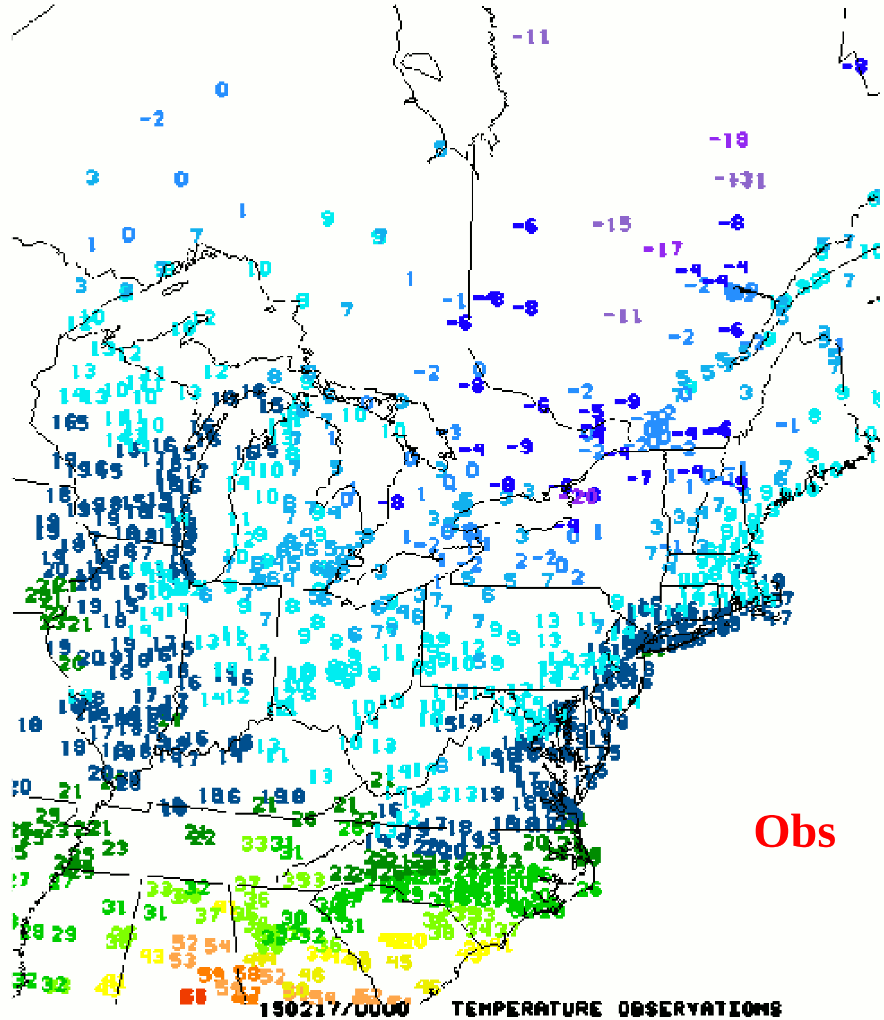
NAM





GFS



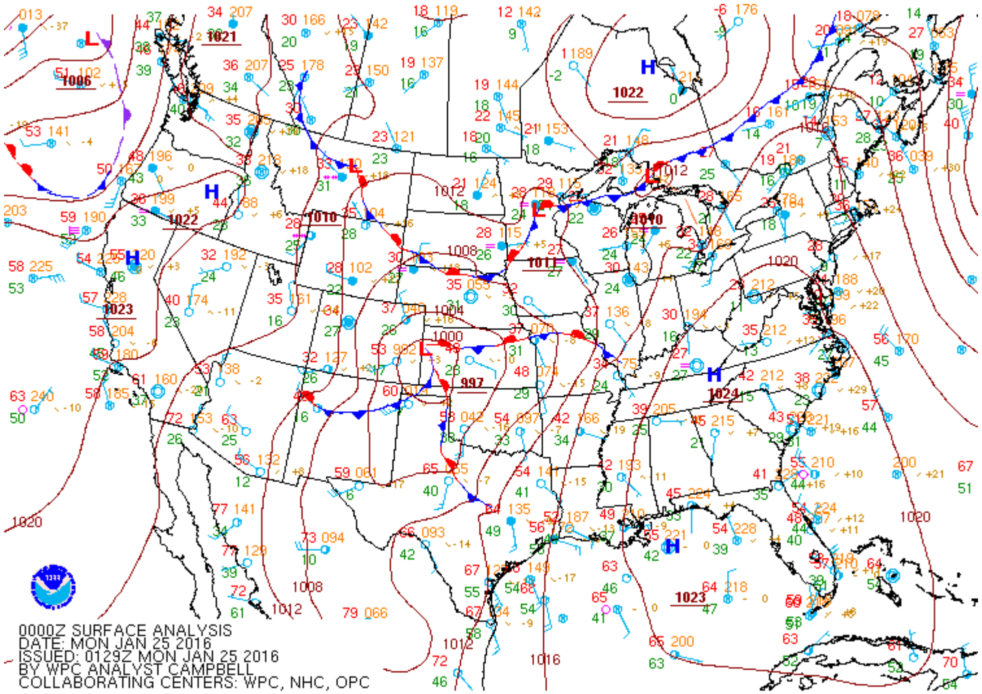


Obs

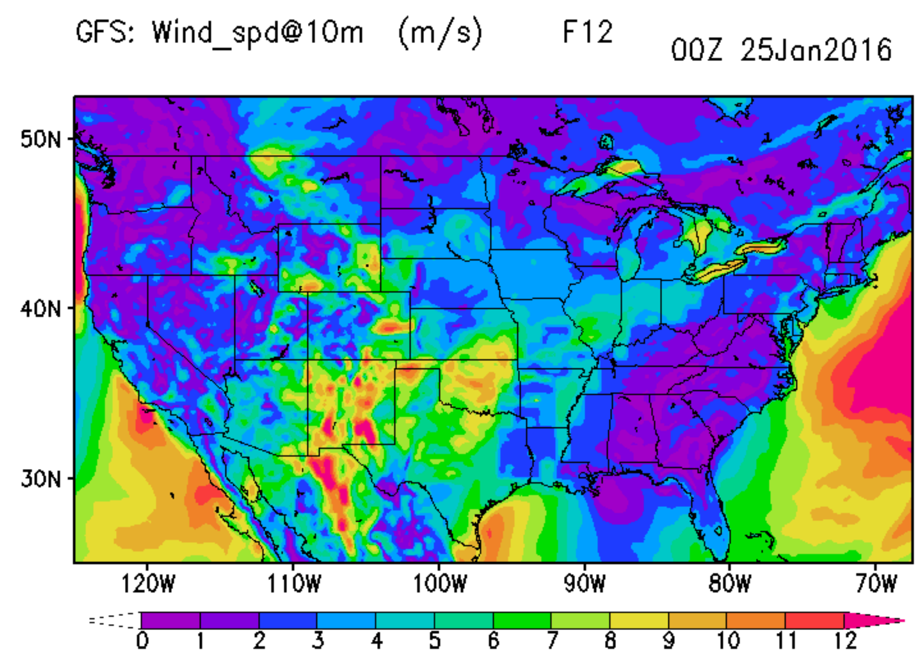
Courtesy Geoffrey Manikin, MEG- 02/19/15

Case 1: Large Cold bias of GFS T2m: Case of 25 Jan 2016

Surface weather map: 00Z 25Jan 2016



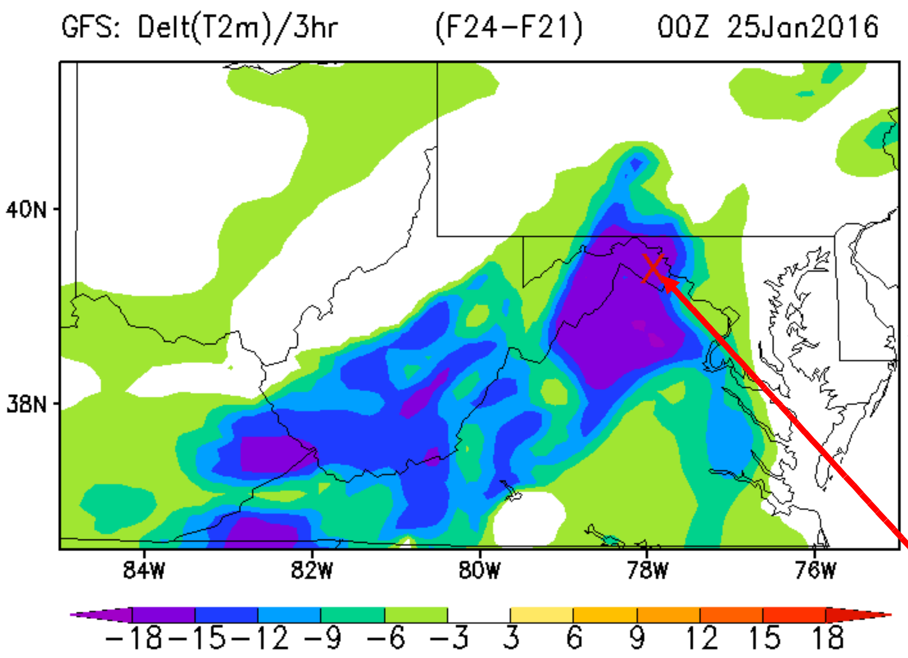
GFS Wind speed at 10m: 00Z 25Jan 2016



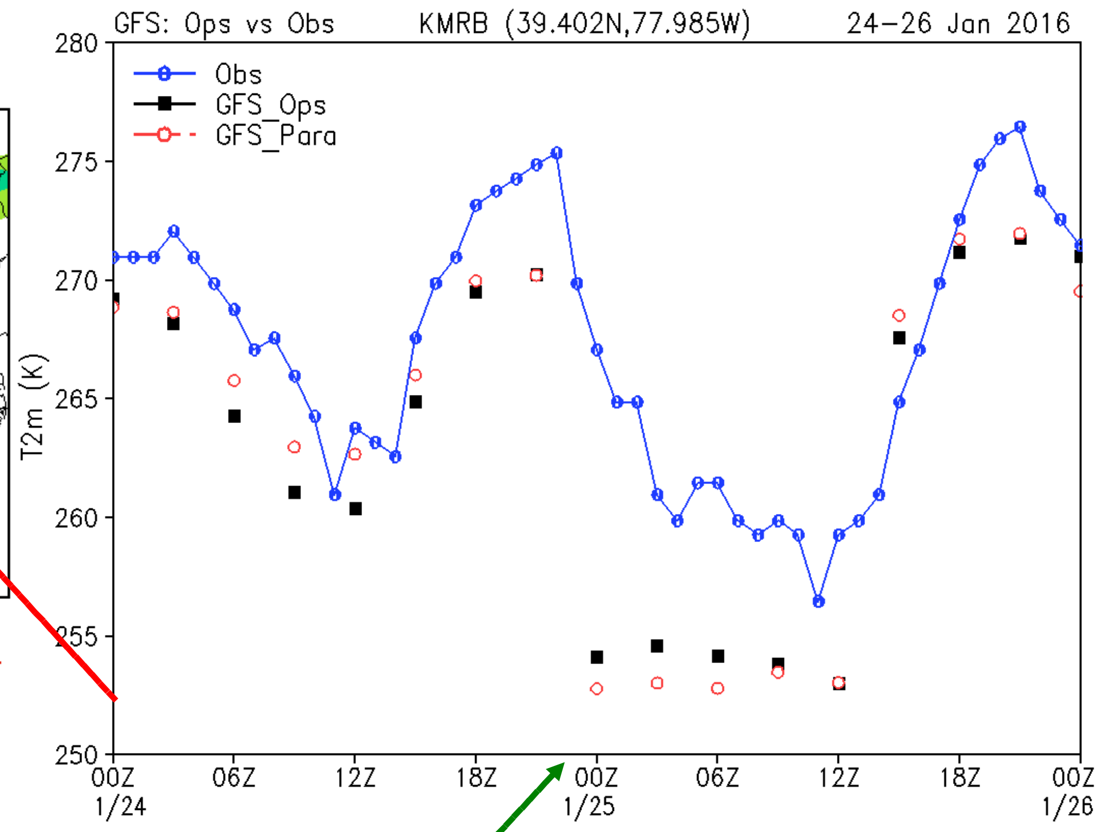
<u>Southeast</u>: High pressure system; Low wind speed less than 2 m/s

GFS/GFSX T2m @ MRB Matinsburg RGNL, WV

00Z 01/24/2016 Cycle



T2m @ KMRB



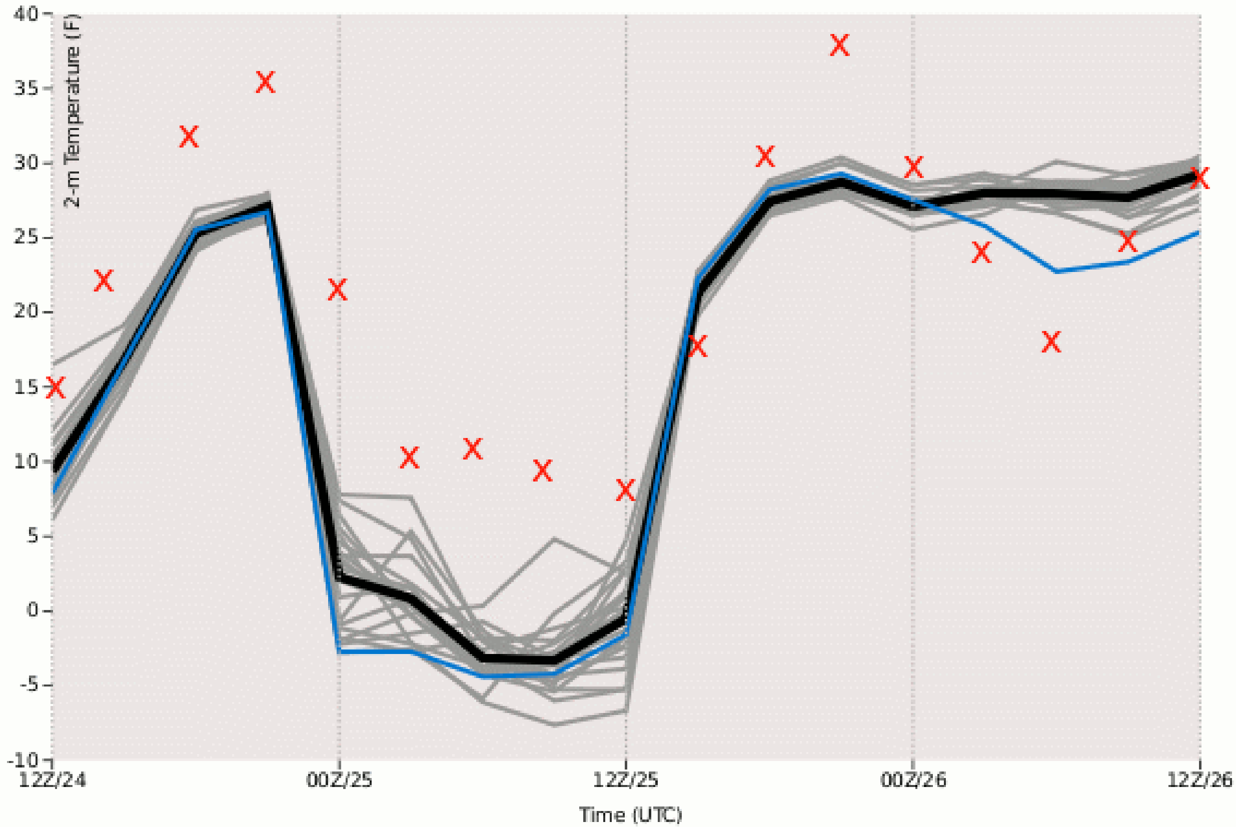
Ops GFS or GFSX: Rapidly cooling up to 15 °C during 3hr;
About 13 degrees of cold bias at 00Z, 25 Jan.
GFSX: Became current operational version on May 11, 2016.

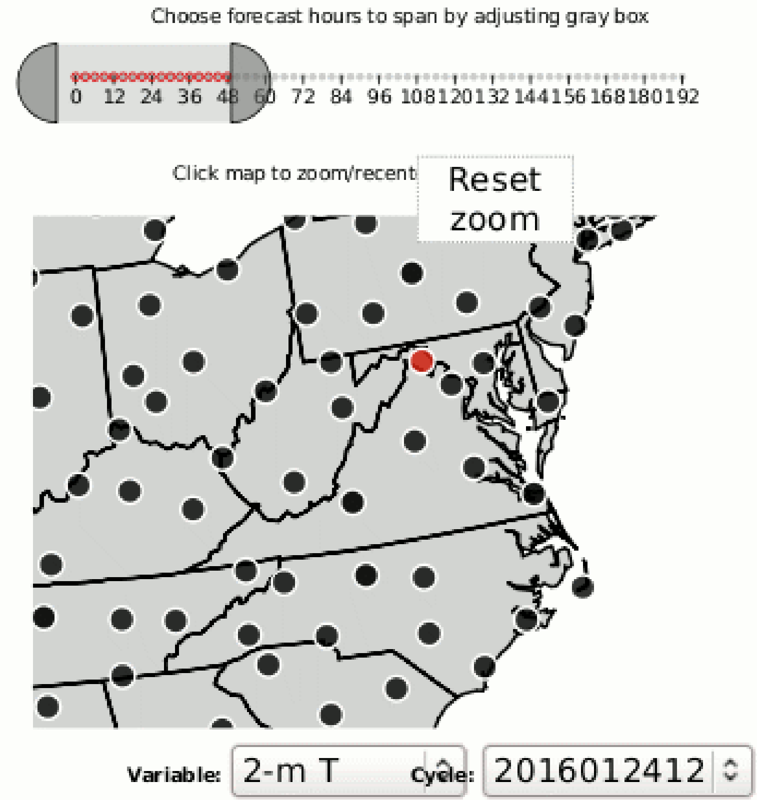
GEFS T2m @ MRB, WV

12Z 24 JAN2016 Cycle

EMC's GEFS plumes for: KMRB

12 UTC 24 January 2016 cycle





-10 | 40 | Set y axis | Reset y axis

start total accumulated QPF at 0 inches when adjusting forecast hours spanned

About the plumes: Data for each station is interpolated from a 0.5-degree grid for both the GEFS (gray lines for control and perturbed members; black for mean) and GFS (blue line). The precipitation-type plot uses the closest gridpoint to each station as opposed to interpolation and does not contain a trace for the GFS. Click on the map to zoom for more stations.

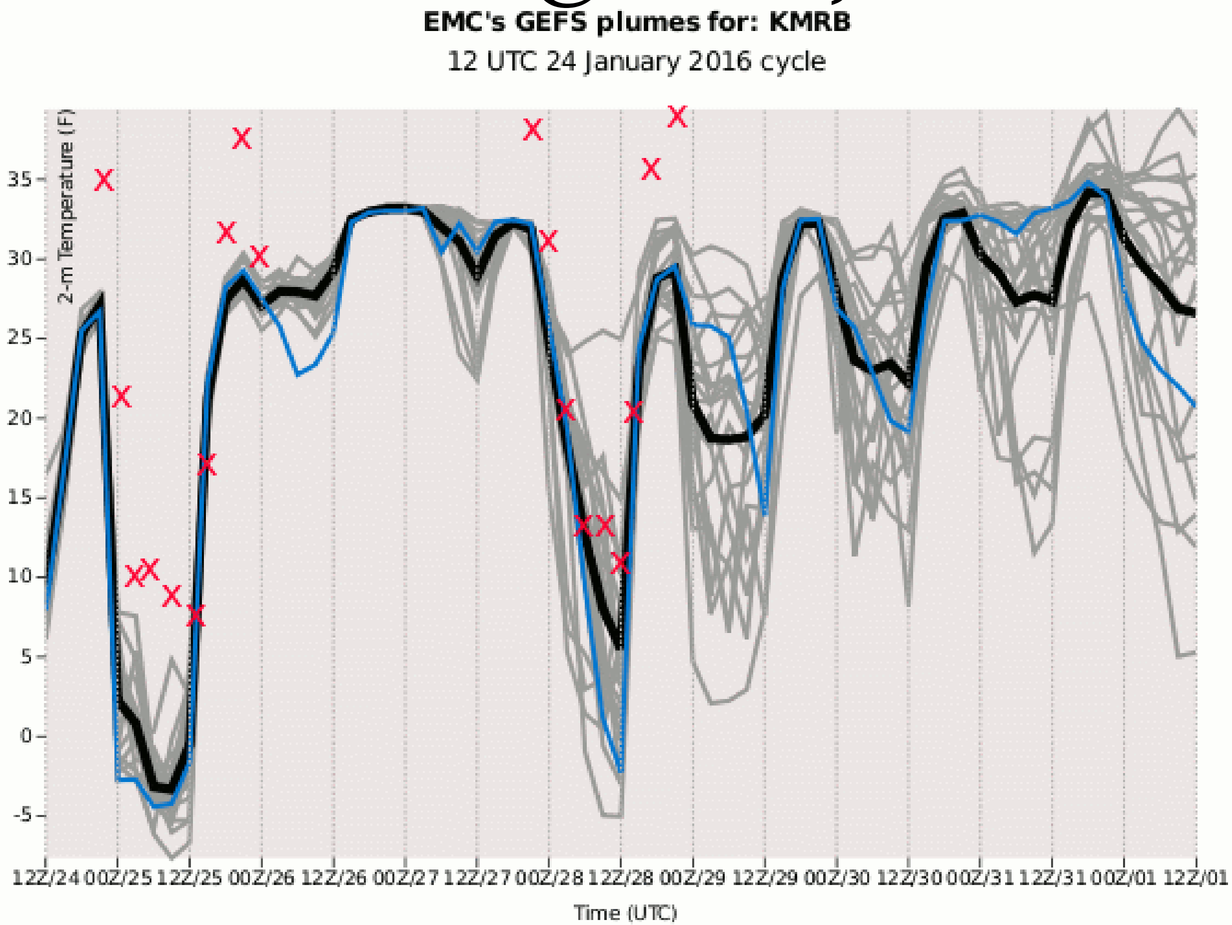
This site is not operational; therefore, data may be missing occasionally.

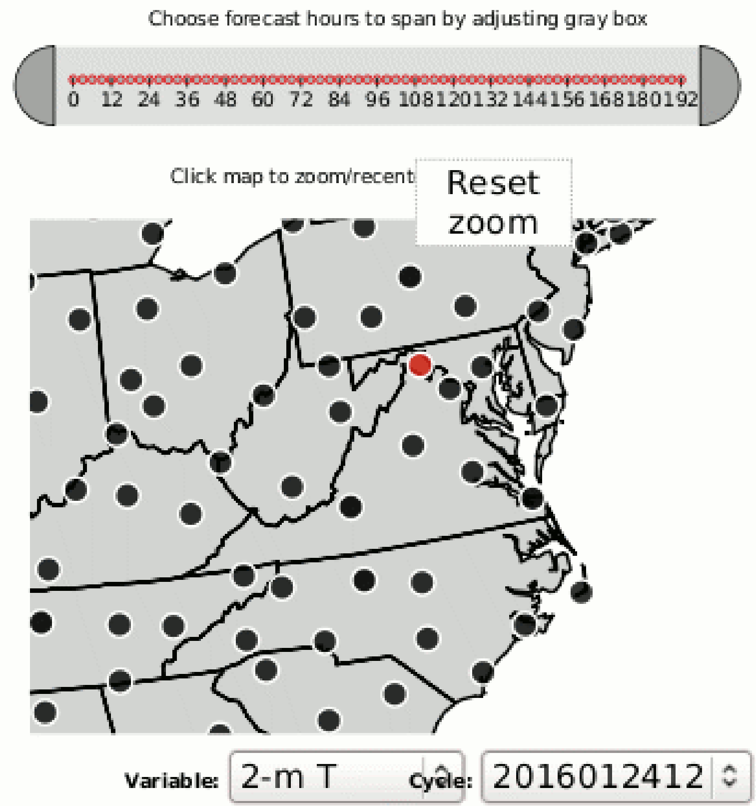
Courtesy Tracey Dorian

x: Observation **Black: GEFS mean** **Blue: Ops GFS**

GEFS T2m @ MRB, WV

12Z 24 JAN2016 Cycle





start total accumulated QPF at 0 inches when adjusting forecast hours spanned

About the plumes: Data for each station is interpolated from a 0.5-degree grid for both the GEFS (gray lines for control and perturbed members; black for mean) and GFS (blue line). The precipitation-type plot uses the closest gridpoint to each station as opposed to interpolation and does not contain a trace for the GFS. Click on the map to zoom for more stations.

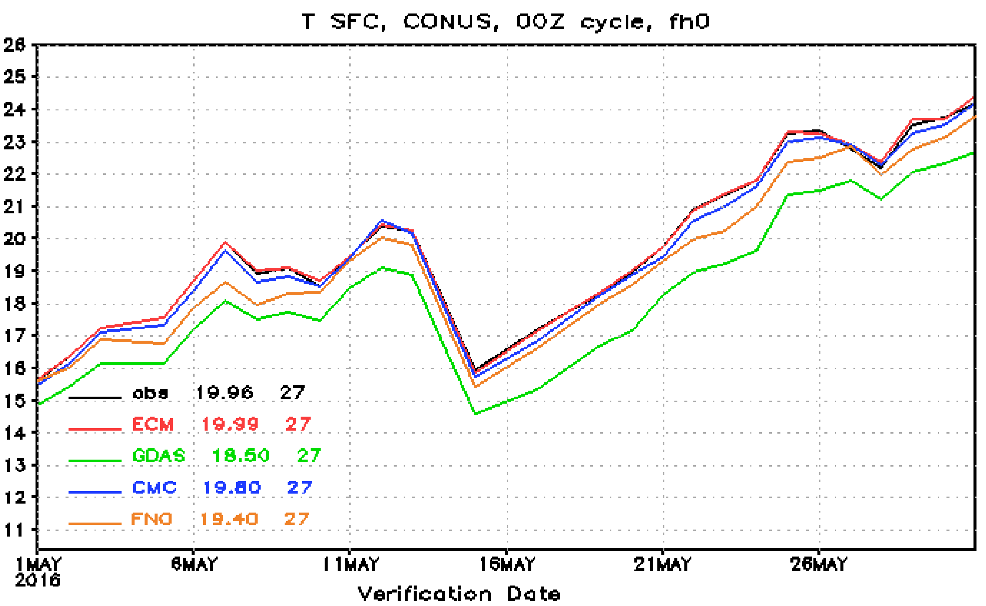
This site is not operational; therefore, data may be missing occasionally.

Courtesy Tracey Dorian

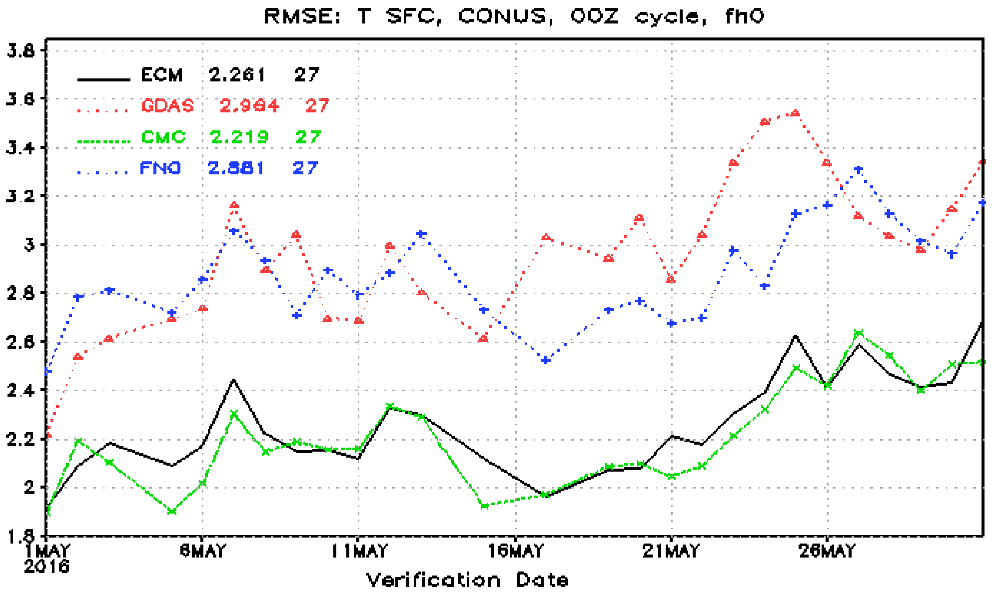
x: Observation **Black: GEFS mean** **Blue: Ops GFS**

Verification of T2m for model analysis (00Z) 1-31 May 2016

BIAS



RMSE



- *GDAS T2m is colder than other models;*
- *GDAS T2m has larger RMSE than ECM and CMC.*

Courtesy Wen Meng

Structure of the Atmosphere Boundary Layer

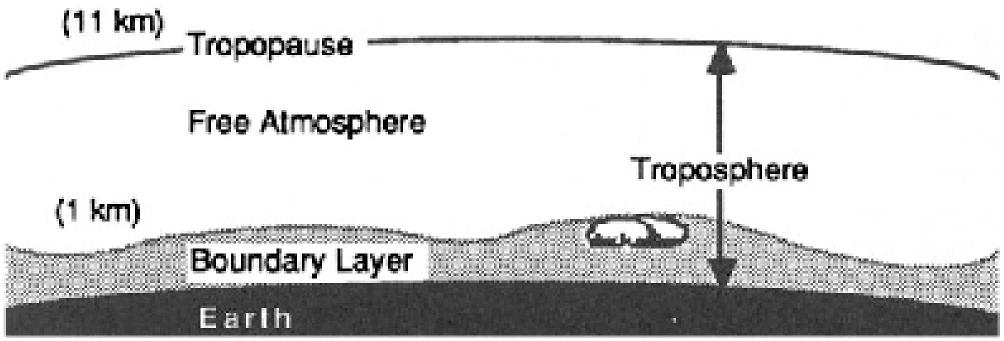


Fig. 2.1 The troposphere and its two parts: the atmospheric boundary layer and the free atmosphere (Stull 2000)

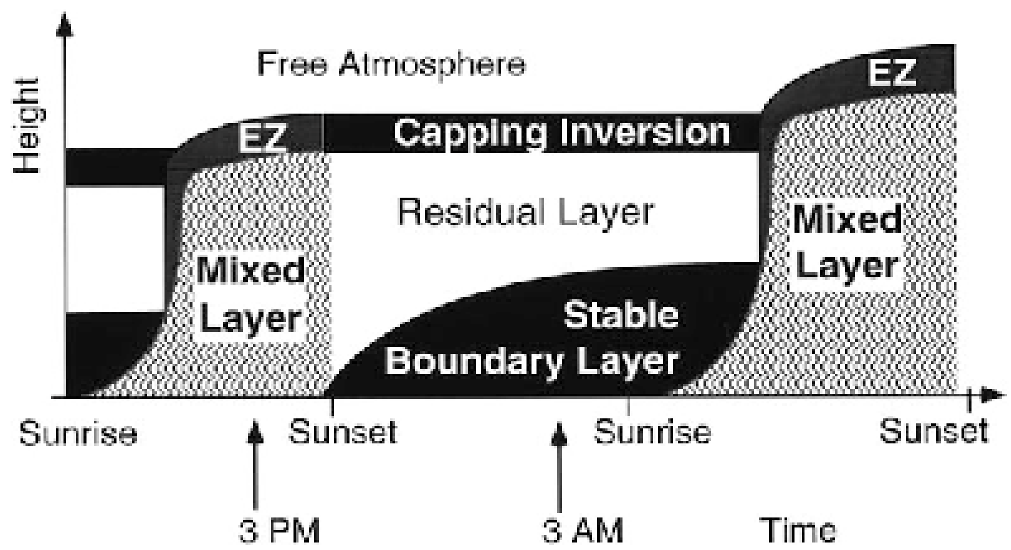
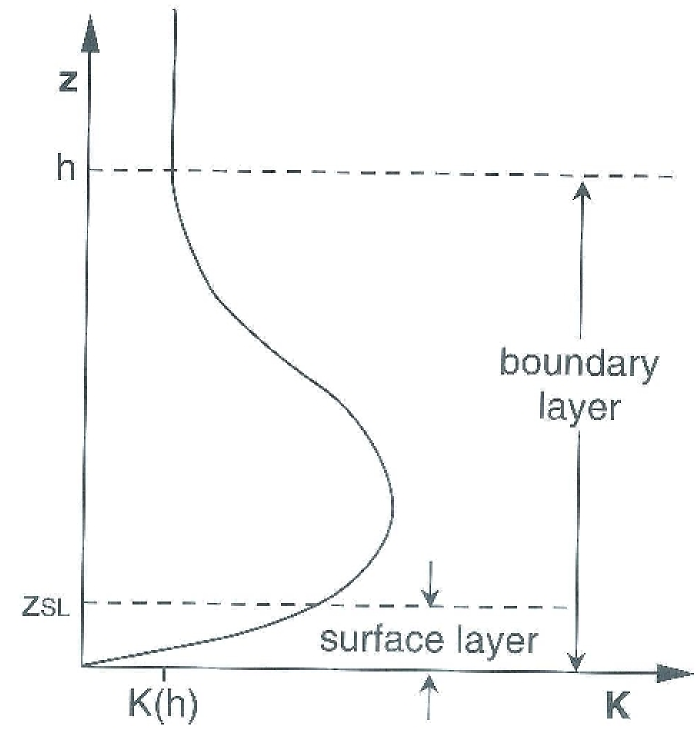


Fig. 2.2 Daily cycle of the structure of the atmospheric boundary layer (Stull 2000), *EZ* Entrainment zone

Stull, 2000



Hong & Pan, 1996

Land-Atmosphere Stable Boundary Layer

Surface Energy Balance:

$(Dn_{SW}\text{-}Up_{SW}) + (Dn_{LW}\text{-}Up_{LW}) = SH + LH + G +$ *Other forcings*

$SH = \rho c_p C_h U_a (T_{sfc} - T_{air})$

$LH = \rho L_v C_q U_a (q_{sfc} - q_{air})$

$G = (K_T/\Delta z)\,(T_{sfc} - T_{soil})$

$Up_{LW} = \varepsilon \sigma_{SB} T_{sfc}^{\,4}$

Other forcings: Sfc pressure, meso motions, gravity wave, etc.

Night-time surface energy budget (No SW; LHF is small so neglected):

(A) Under turbulence: $SH + G \sim Dn_{LW} + Up_{LW}$ **===> quasi-steady state**

(B) Under cessation of turbulence: $G \sim Dn_{LW} + Up_{LW} + (others)$ **===> new state**

The system may reach different equilibrium states !

<u>Consider</u> a clear night, where the surface cools strongly by radiative loss to space. Two possible SBL responses:

***(A) Negative feedback:* To generate downward heat flux ==> compensate radiative surface cooling -----> quasi-stead state**

$T_{sfc}\downarrow$ --> $\Delta T \Uparrow$ --> $SH \Uparrow$ --> $T_{sfc} \Uparrow$

***(B) Positive feedback:* To reduce turbulent fluxes ==> perhaps ultimately to zero -----> different regime (very stable regime)**

$T_{sfc}\downarrow$ --> $\Delta T \Uparrow$ --> $u_* (T_*) \downarrow$ --> $SH\downarrow$ --> $T_{sfc}\downarrow$

Negative feedback: **leading to a quasi-stead state**
Positive feedback: **leading to excessive cooling**

<u>Decoupling:</u> defined as a cessation of turbulent transport between the surface and the atmosphere due to high near surface atmospheric stability. (intermittent) (*discontinuously as a function of external parameters or loss of predictability*)

Monin-Obukov Similarity Theory in GFS (SBL)

$$C_M = k^2/F_M^2 \qquad C_H = k^2/F_M F_H$$

$$\varphi_M = \varphi_H = \frac{1}{2}(1 + \sqrt{1 + 4\alpha\xi}).$$

$$\xi = z/L \qquad L = \frac{\theta}{kg}\frac{u_*^2}{\theta*}$$

$$F_{M,H} = \int_{z_0}^{z} \frac{dz'}{z'} \varphi_{M,H}(z'/L)$$

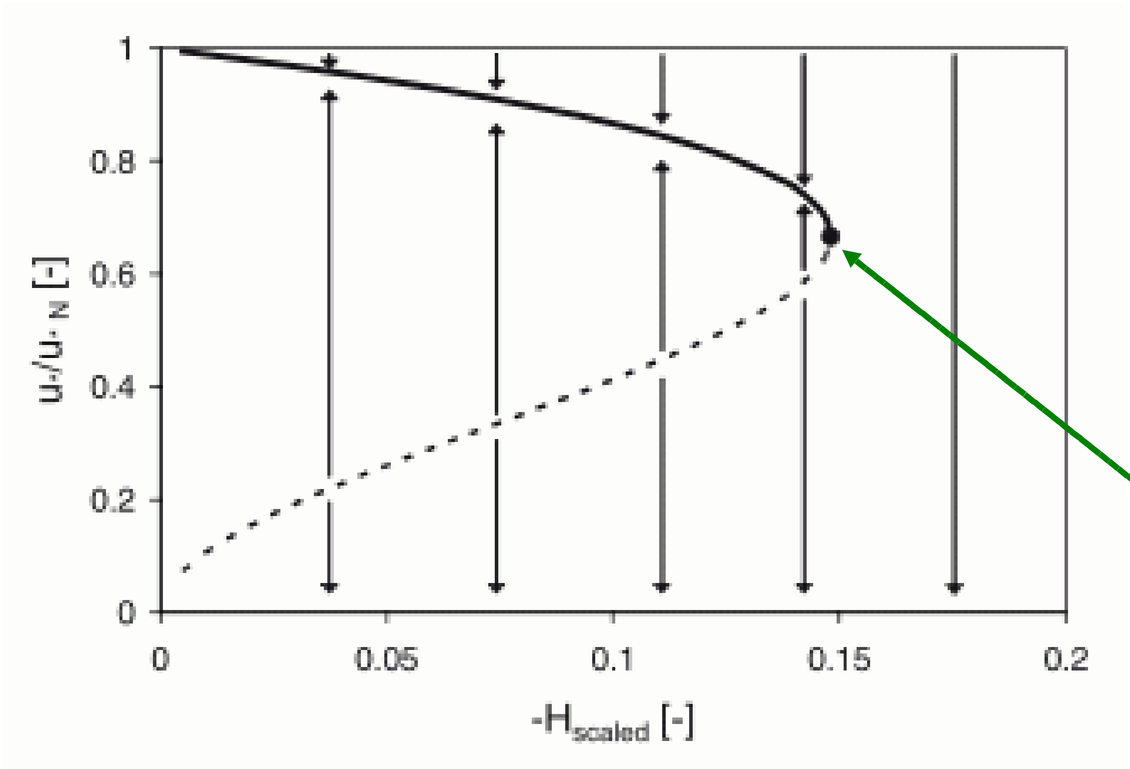
$$F_{M,H} = ln\frac{z}{z_{0M,H}} - \psi_{M,H}(\frac{z}{L}; \frac{z_{0M,H}}{L}),$$

$$\psi_{M,H} = \sqrt{1 + 4\alpha\xi_{0M,H}} - \sqrt{1 + 4\alpha\xi} + ln\frac{\sqrt{1+4\alpha\xi}+1}{\sqrt{1+4\alpha\xi_{0M,H}}+1}$$

$$\xi_{0M,H} = z_{0M,H}/L.$$

The flux-profile has no limitation of a finite critical bulk Richardson number throughout a continuous range of the stable regime.

Negative feedback / positive feedback in SBL



Van de Wiel et al.

turning point

Bifurcation diagram: Turbulence vs cooling rates.

Linear stability analysis: Stable/unstable equilibrium states

$$z/L < z/L|_M = \ln(z/z_0)/[2*\alpha*(1-z_0/z)]$$

Here z0 is the momentum roughness length, and α=5.

Hopf Bifurcation

Van de Wiel et al.

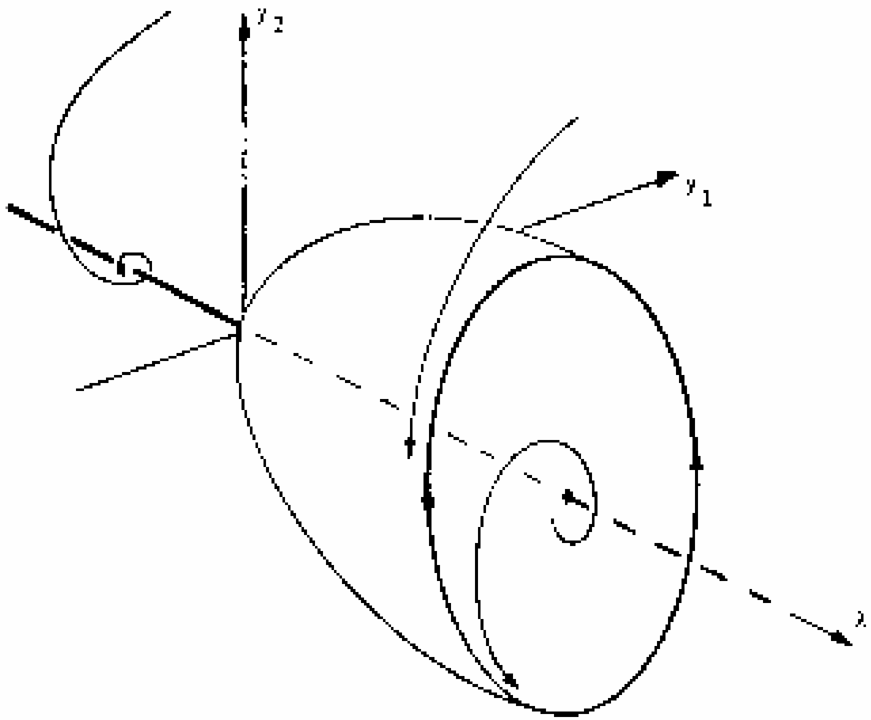


FIG. F1. Example of a Hopf bifurcation (see Seydel 1988). The limiting behavior from the trajectories near the equilibrium line change from a stable into a cyclic solution, when the critical value of a parameter λ_{crit} is passed (λ_{crit} is located at the intersect of the three axes).

Hopf Bifurcation

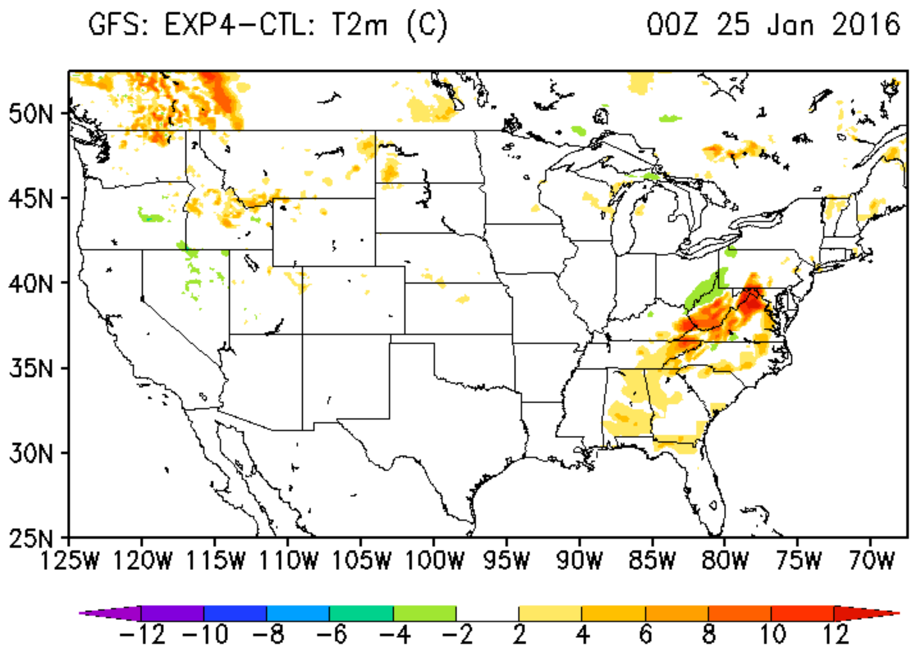
A system with two coupled nonlinear ordinary differential equations:

$$dy_1/dt = f_1(y_1, y_2, \lambda)$$
$$dy_2/dt = f_2(y_1, y_2, \lambda)$$

$\lambda < \lambda_{crit}$: numerical stable;

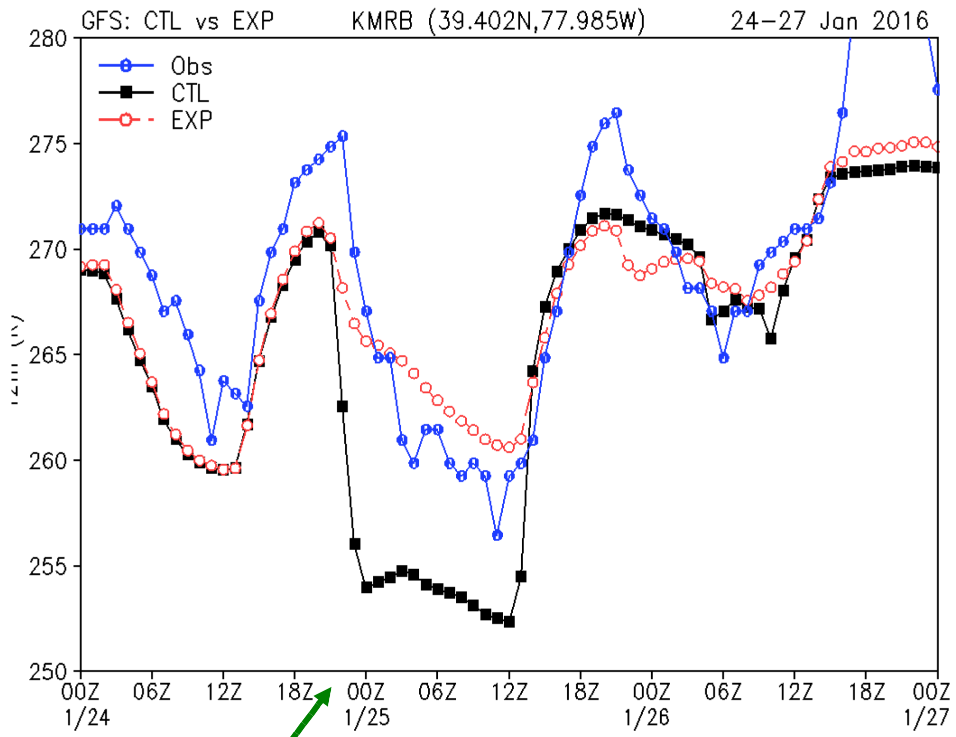
$\lambda > \lambda_{crit}$: numerical unstable.

Case 1: GFS Test: T2m 00Z, 2016-01-24 Cycle



GFS Test: Increase T_{2m} and reduce cold bias

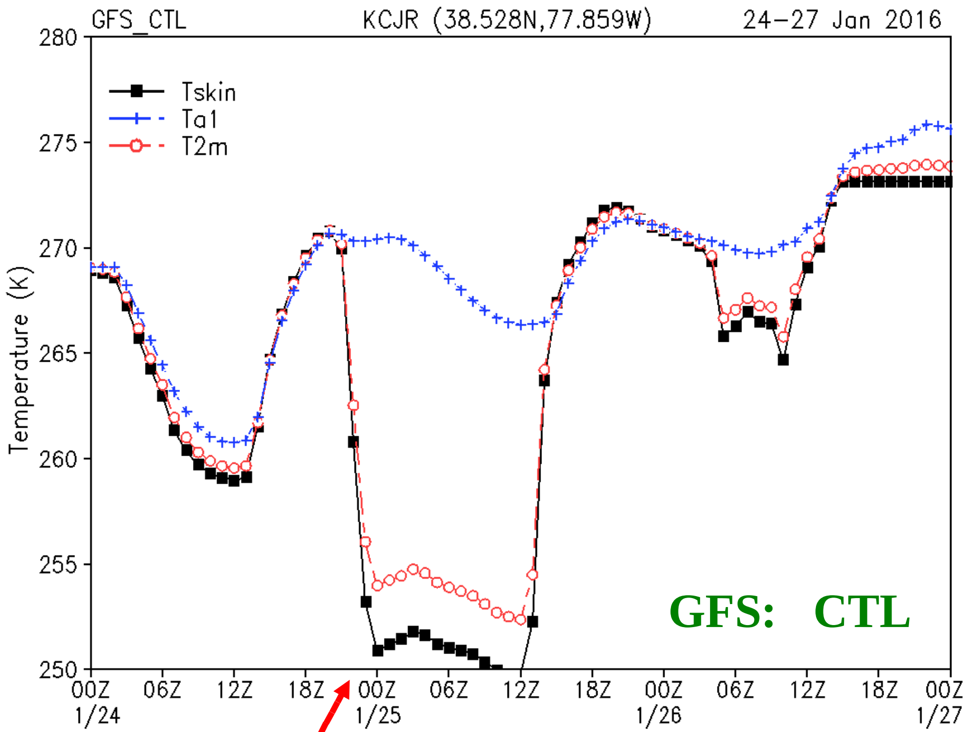
T2m @ MRB Matinsburg RGNL, WV

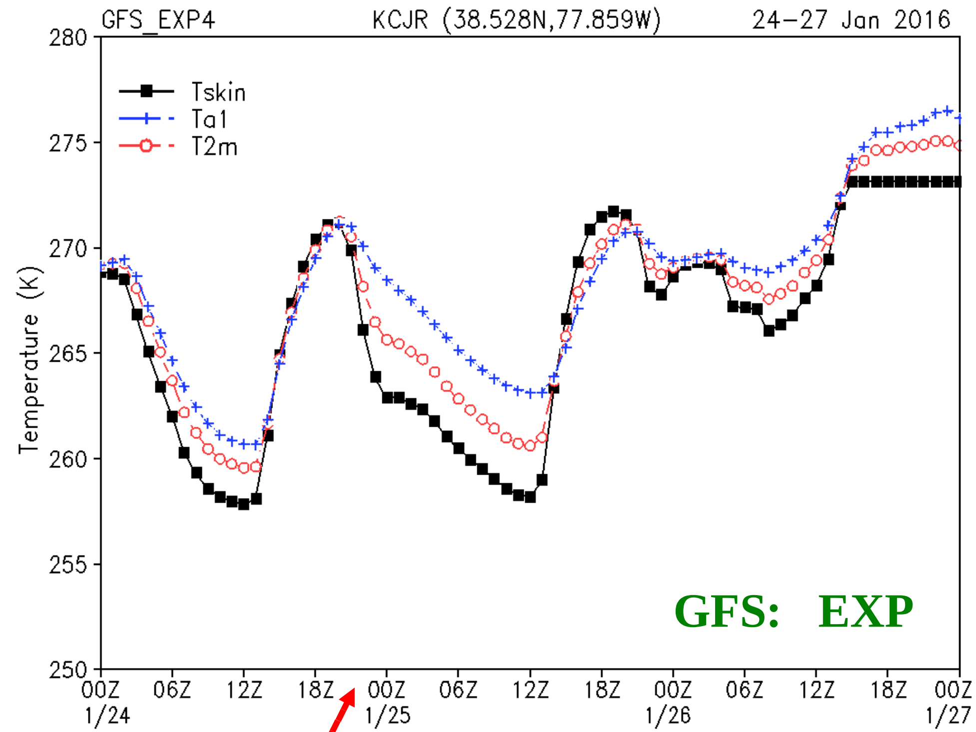


CTL: Rapidly cooling more than 15 °C during 3hr;
EXP: Substantially improved

GFS Test: T1, T2m and Tskin @ MRB

T1: Temperature at the lowest model level (Blue); T2m: Red; Tskin: Black





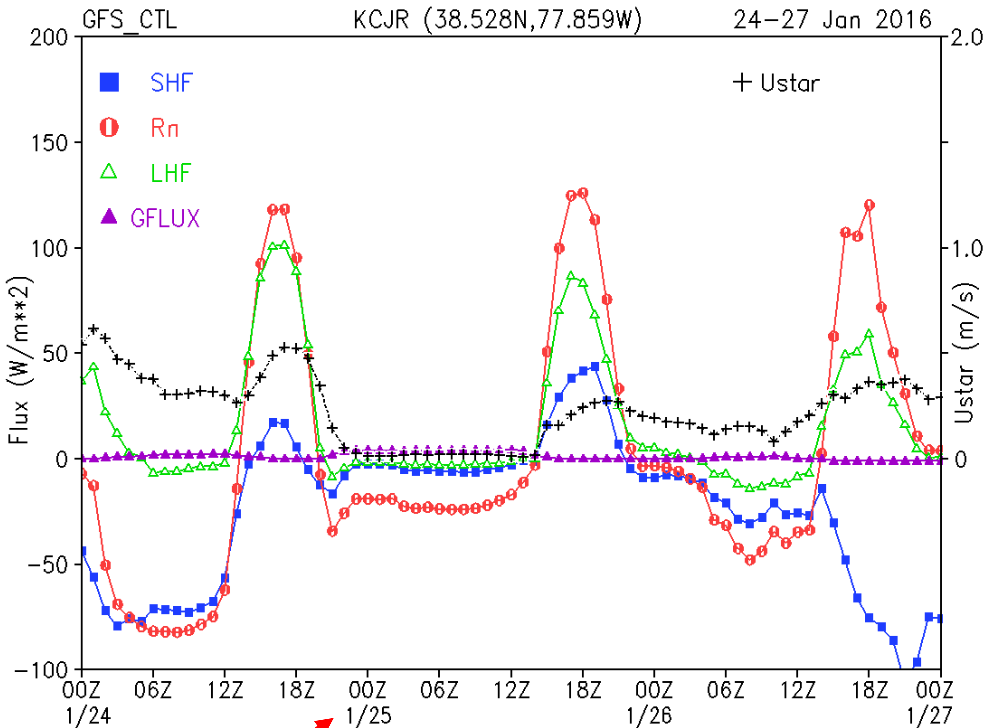
Rapidly cooling: Decoupled

Improvement

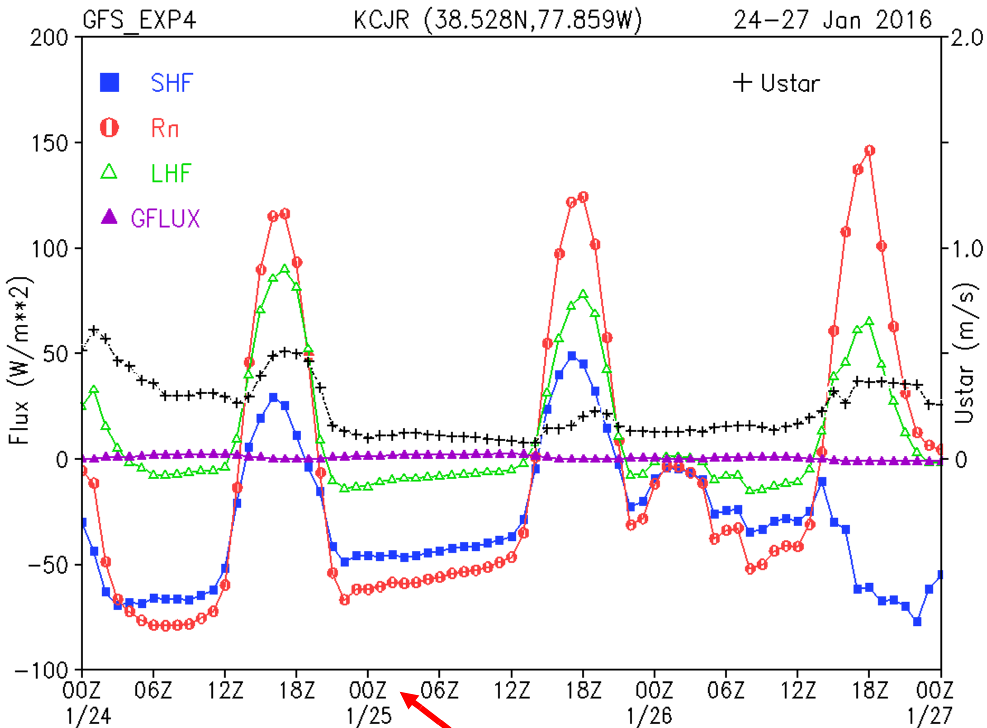
CTL: ***Large difference between T1 and T2m (or Tskin) during a period of nighttime on 1/25.***
EXP: ***Substantially improved not only T2m, but also Tskin and T1.***

GFS Test: Surface Fluxes and Ustar @ MRB

GFS: CTL



GFS: Test



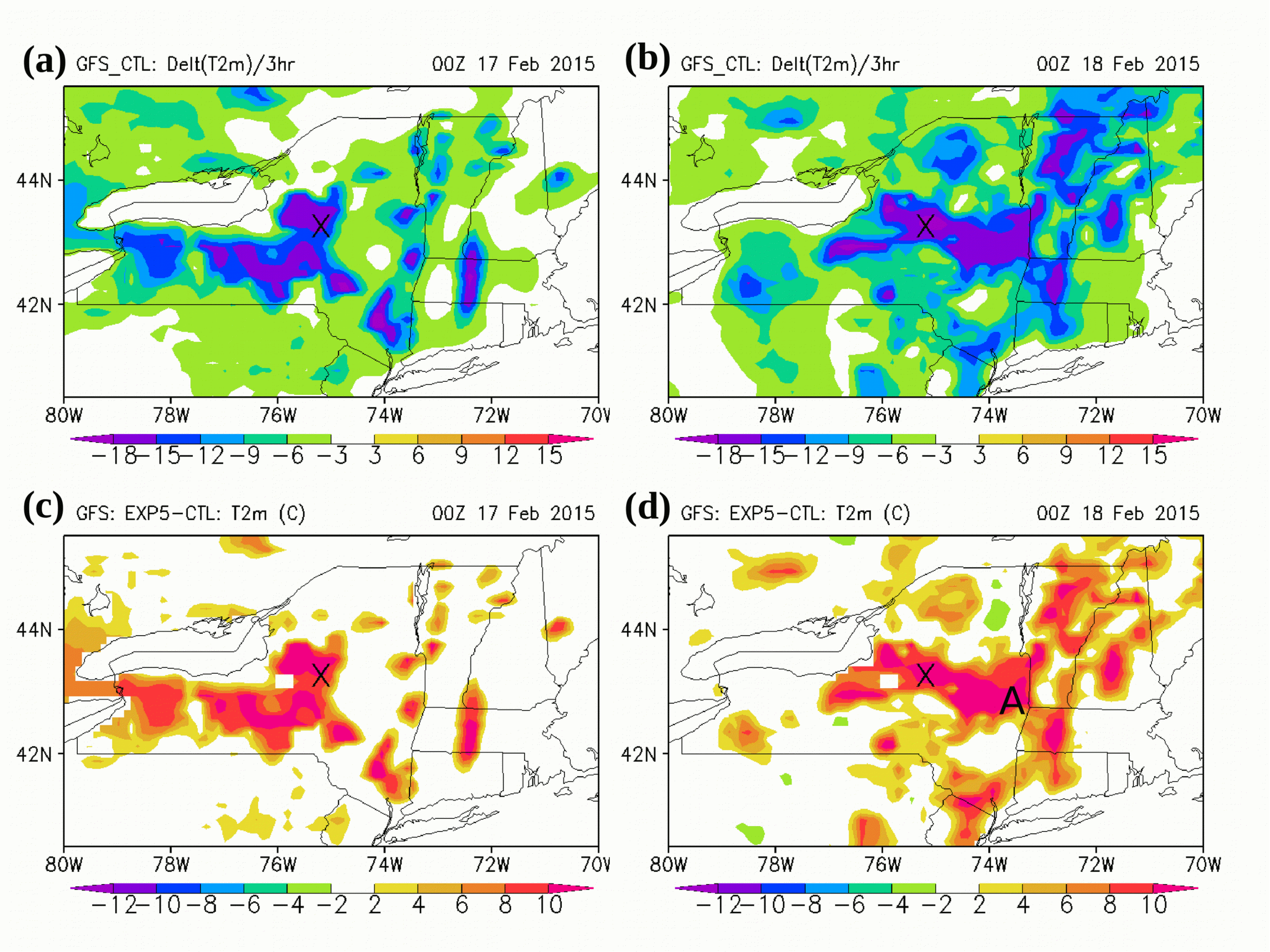
Under weak turbulence

Cessation of turbulence: SHF, Ustar → 0

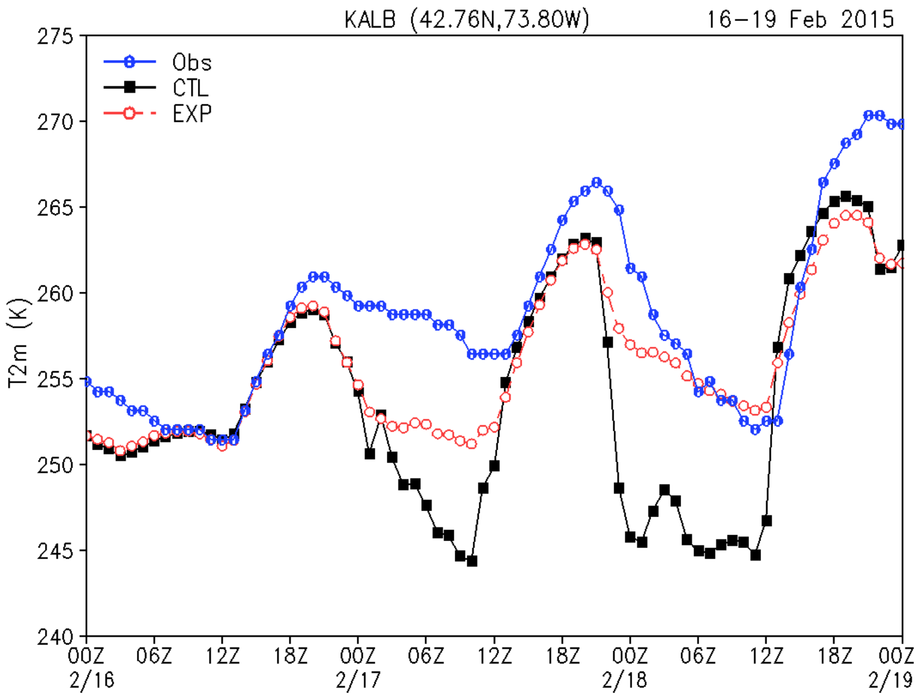
SHF: Sensible heat flux; **Rn: Net downward radiation;**

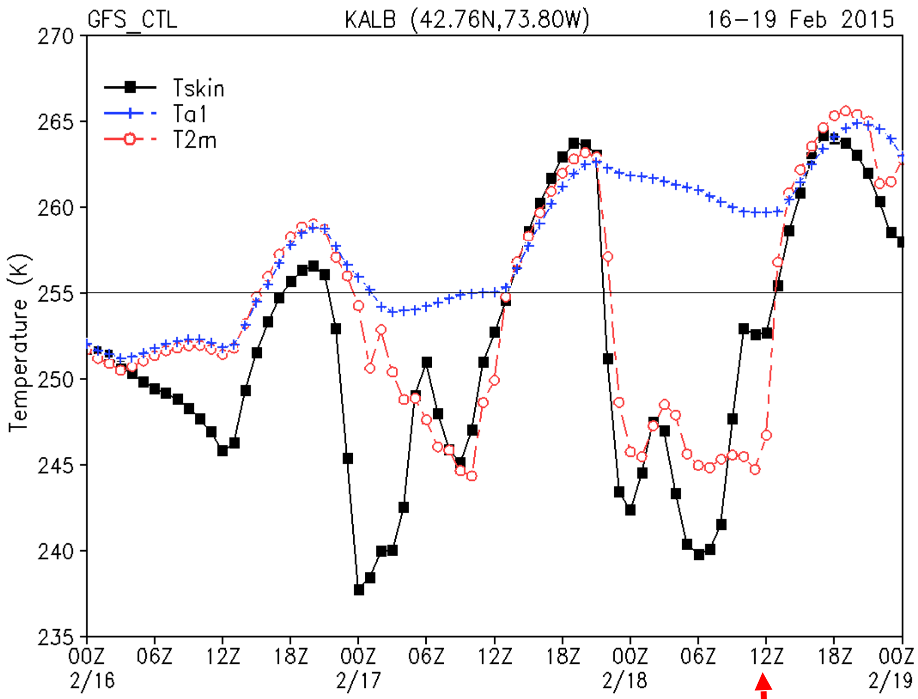
LHF: Latent heat flux; **GFLUX: Soil heat flux;** **Ustar: Friction velocity**

Case 2: GFS Test: T2m 00Z, 2015-02-16 Cycle

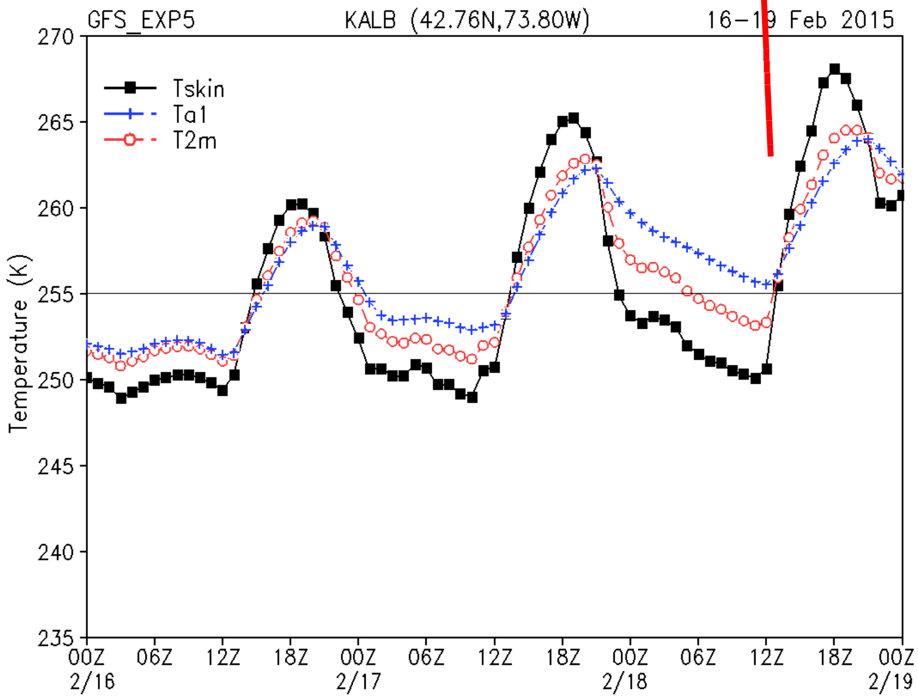


GFS Test: T1, T2m and Tskin @ KALB





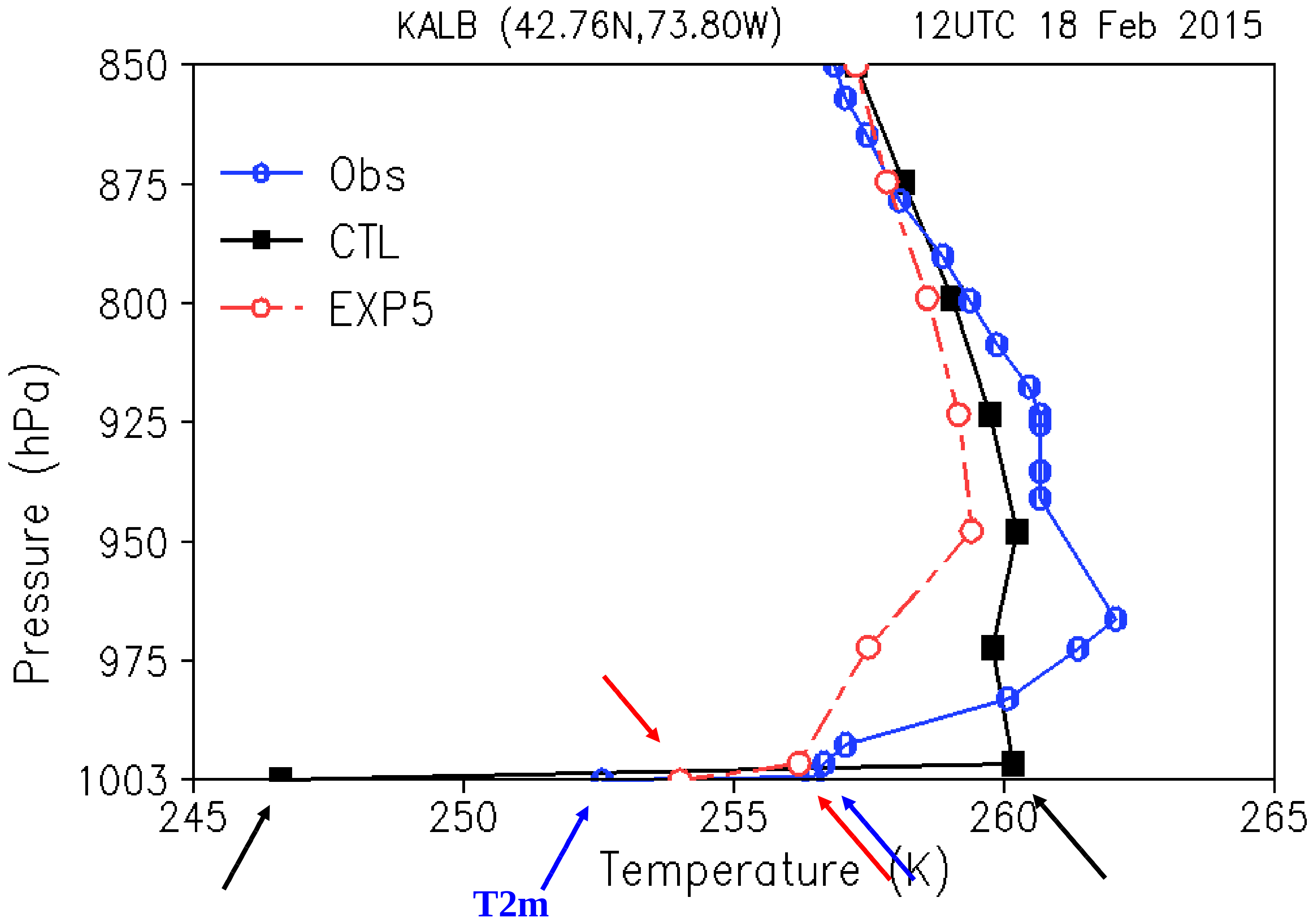
Rapidly cooling: Decoupled



CTL: ***Large difference between T1 and T2m (or Tskin) during a period of nighttime on 1/25.***

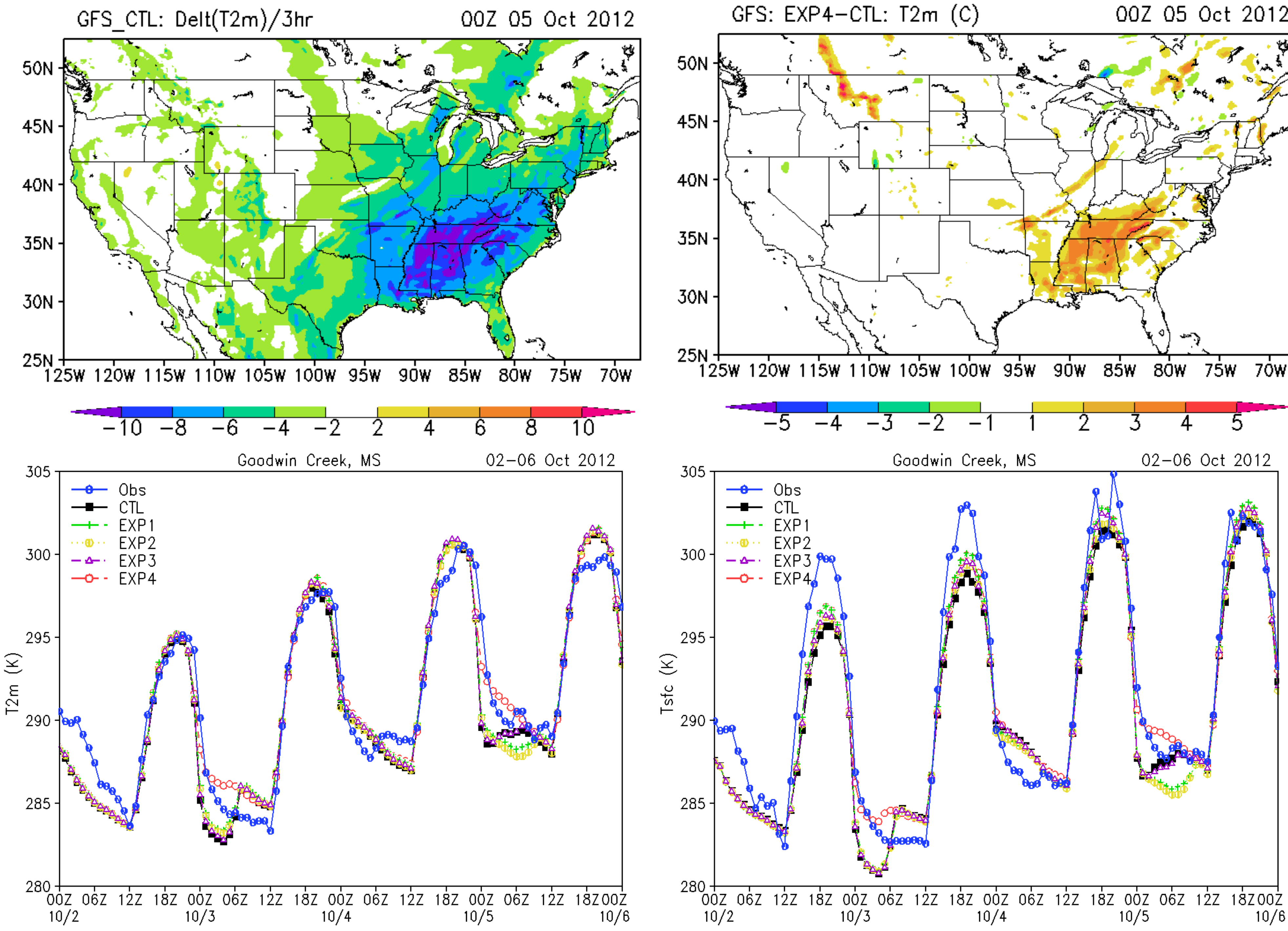
EXP: ***Substantially improved not only T2m, but also Tskin and T1.***

GFS Test: Temperature profiles @ KALB



<u>CTL:</u> ***Little downward heat transport (atmos-->land) during the night decoupling period results in accumulation of exess heat and as a result, the warm bias exists above the first model level.***

Case 3: GFS Test: T2m 00Z, 2012-10-05 Cycle



GFS Test: Autumn season

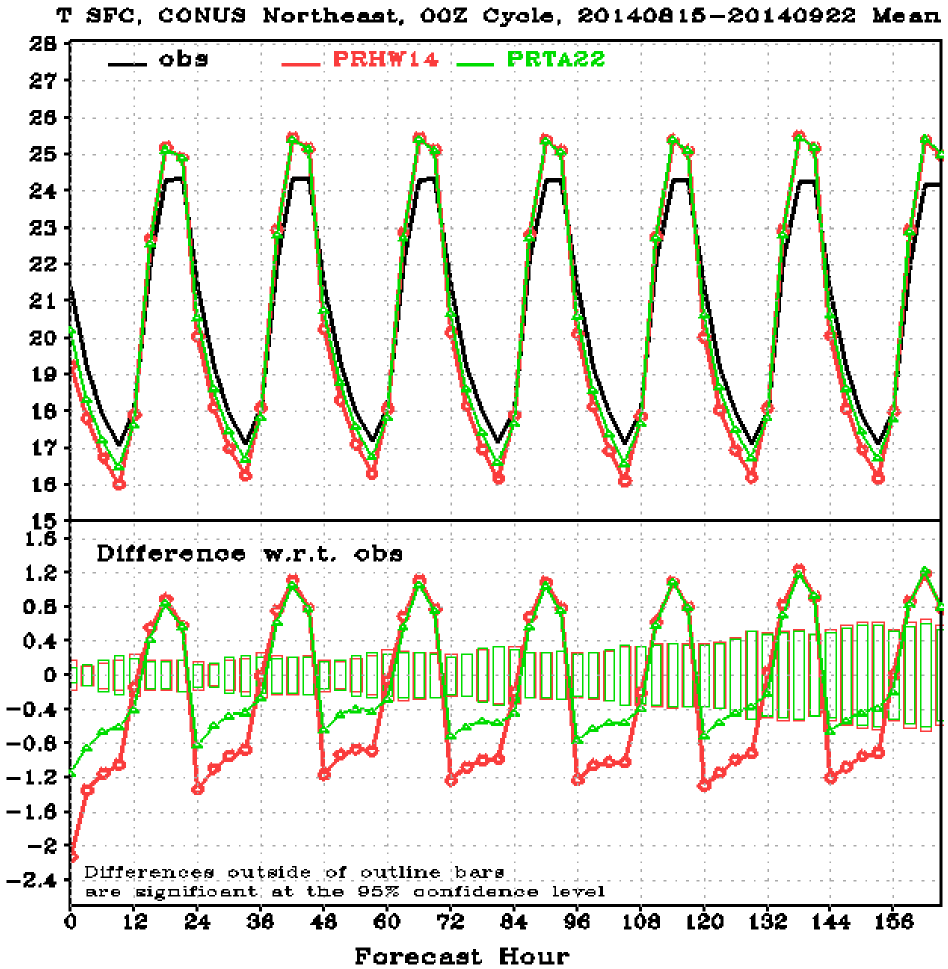
GFS: **T1534; Free forecast at each 00Z cycle**

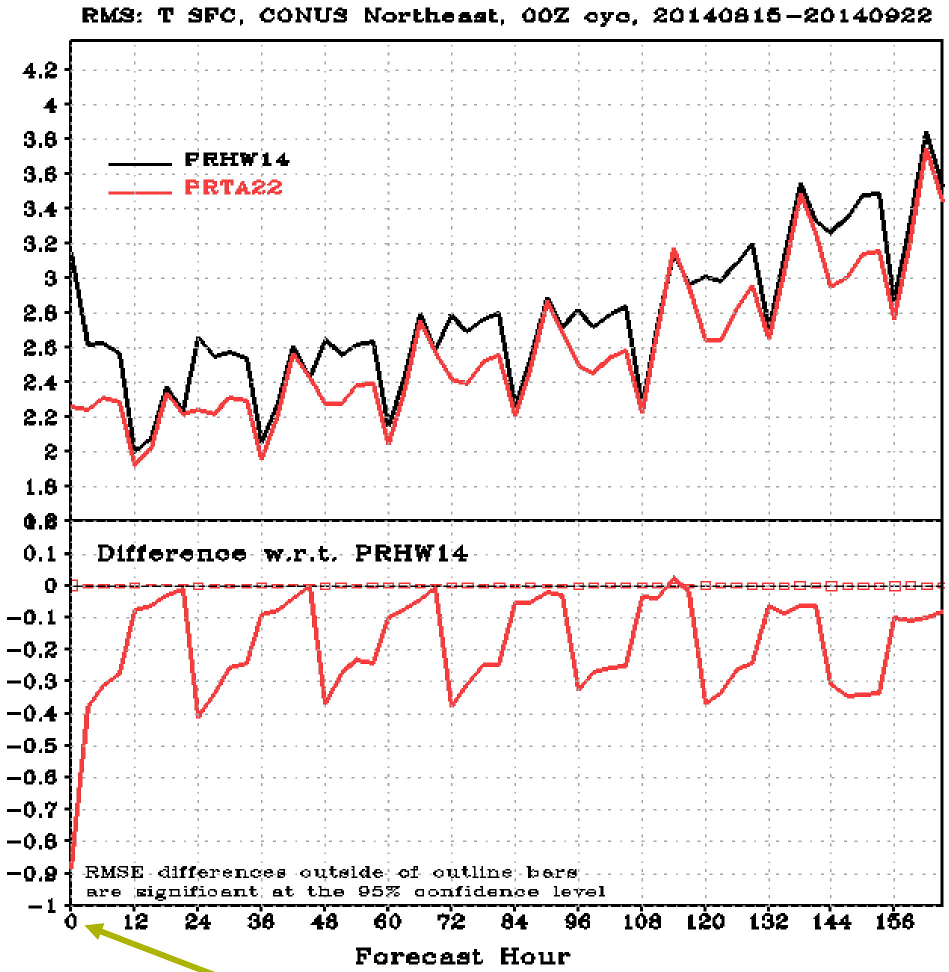
Case: **Aug.15 – Sep.22, 2014**

There are several cases for T_{2m} rapidly cooling late afternoon

Results: **prhw14 vs prta22 (test)**

Surface temperature and its RMSE Northeast

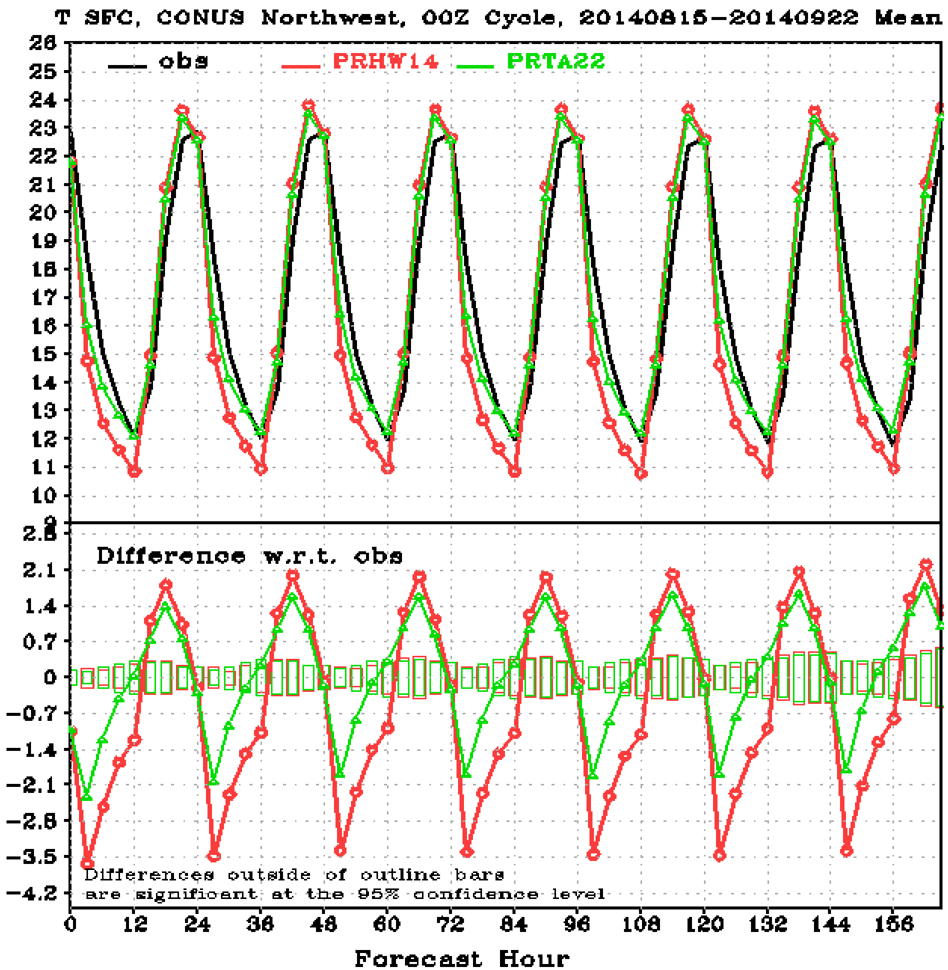


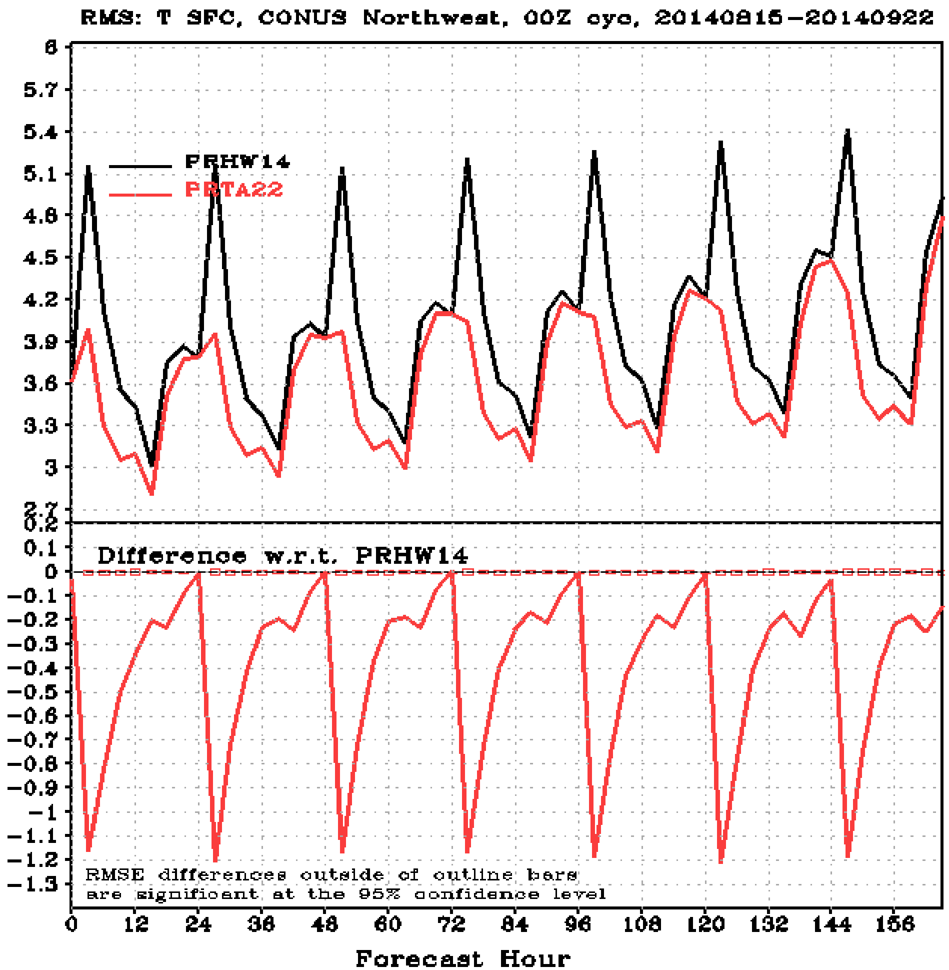


T2m at t=0 ?

Reduced cold bias and RMSE afternoon and nighttime (~0.5 °C)

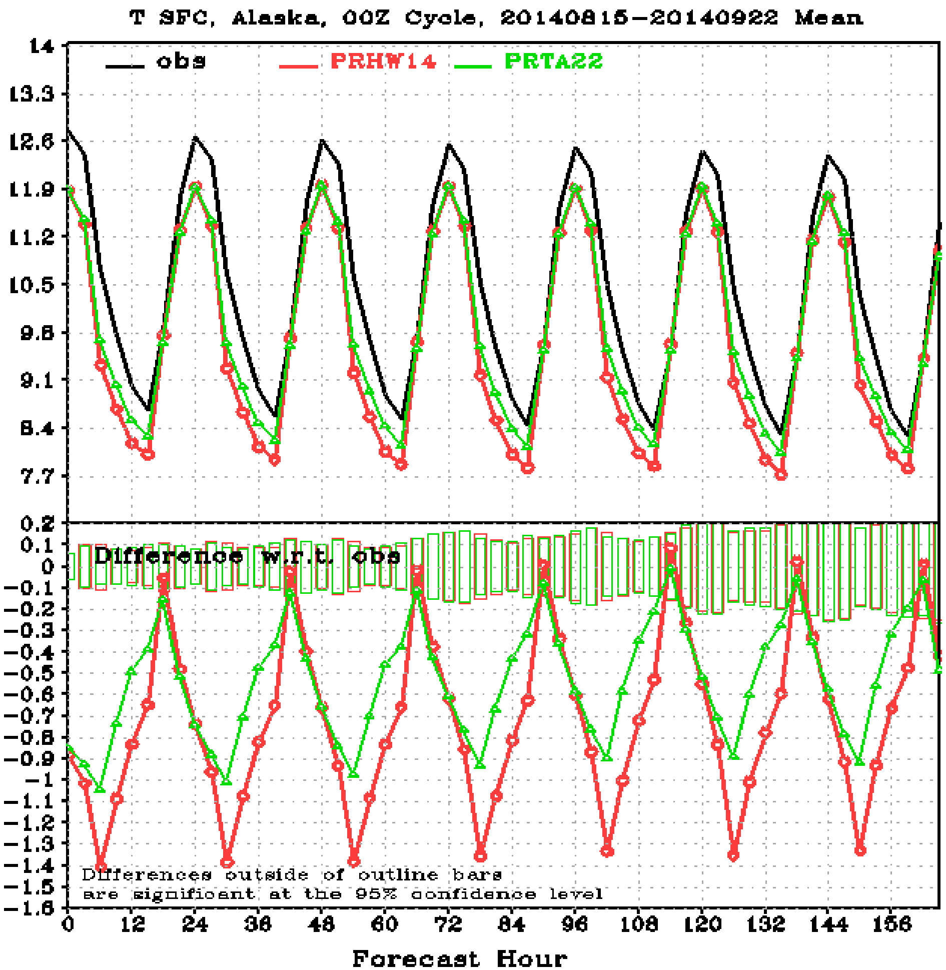
Surface temperature and its RMSE Northwest

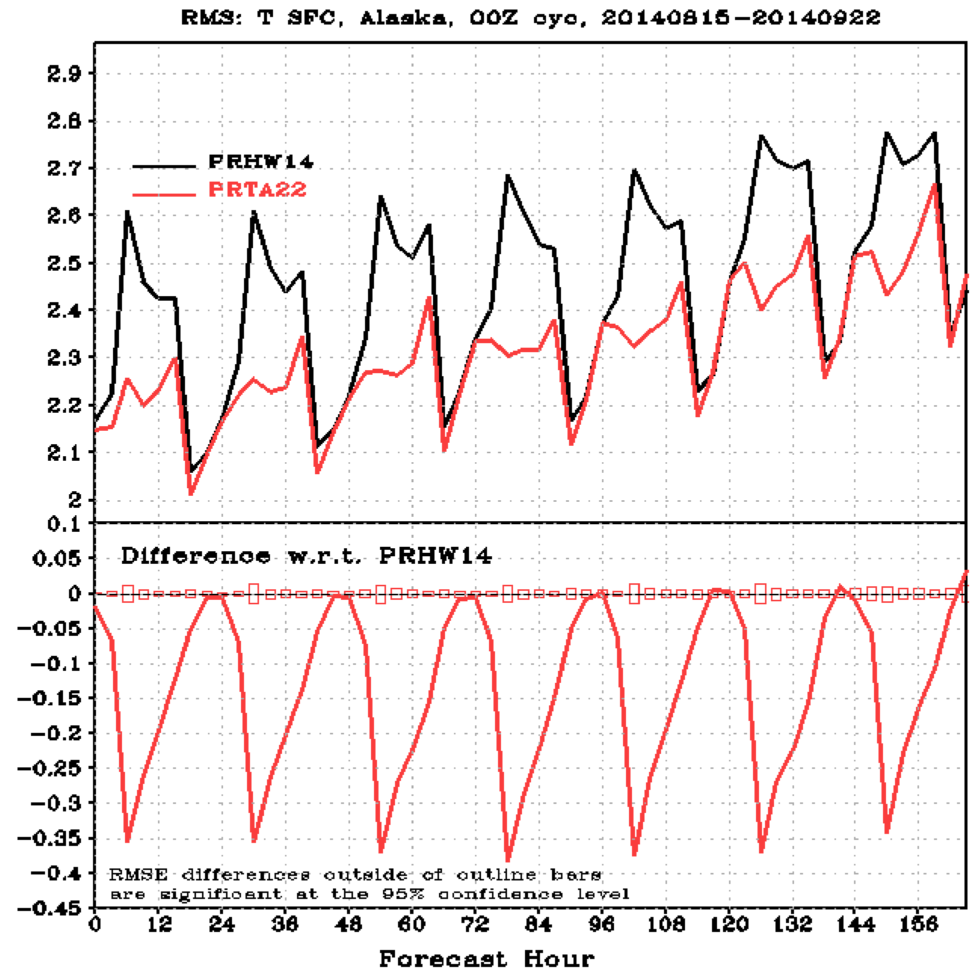




Reduced warm bias in the morning and cold bias in the afternoon (1.5 °C);
Reduced RMSE afternoon and nighttime up to 1.2 °C .

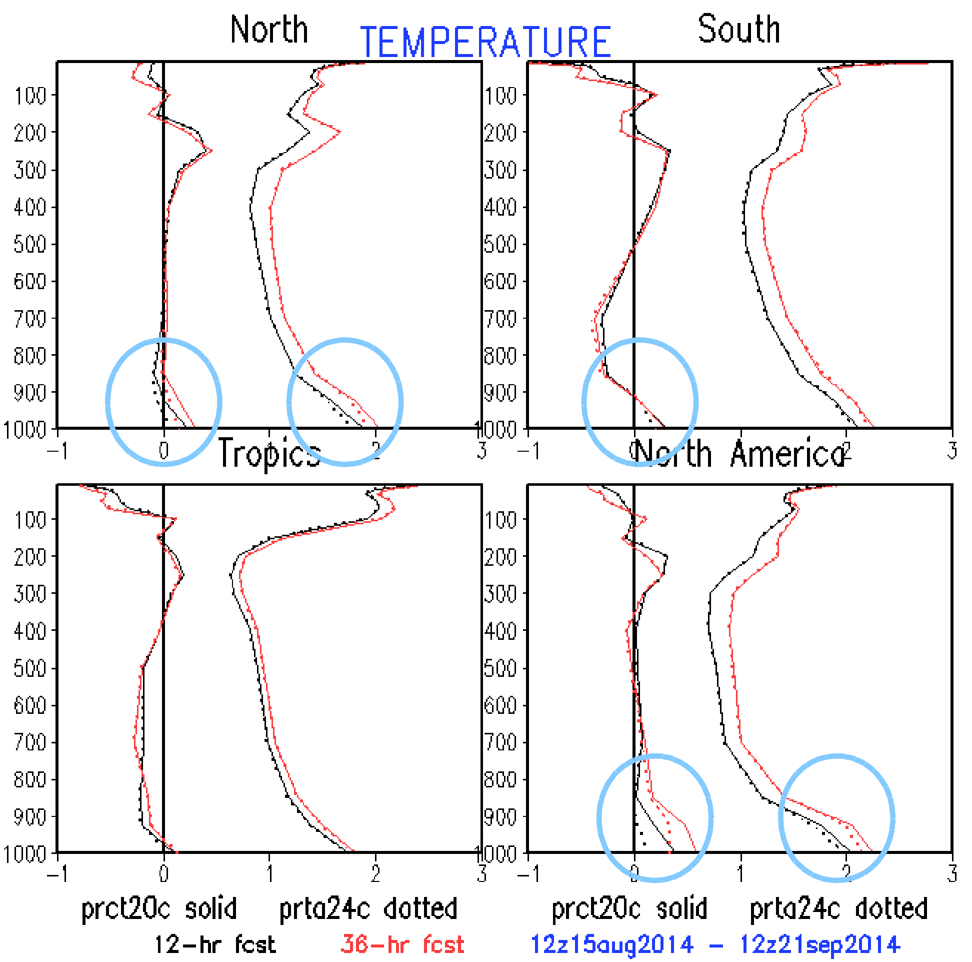
Surface temperature and its RMSE Alaska



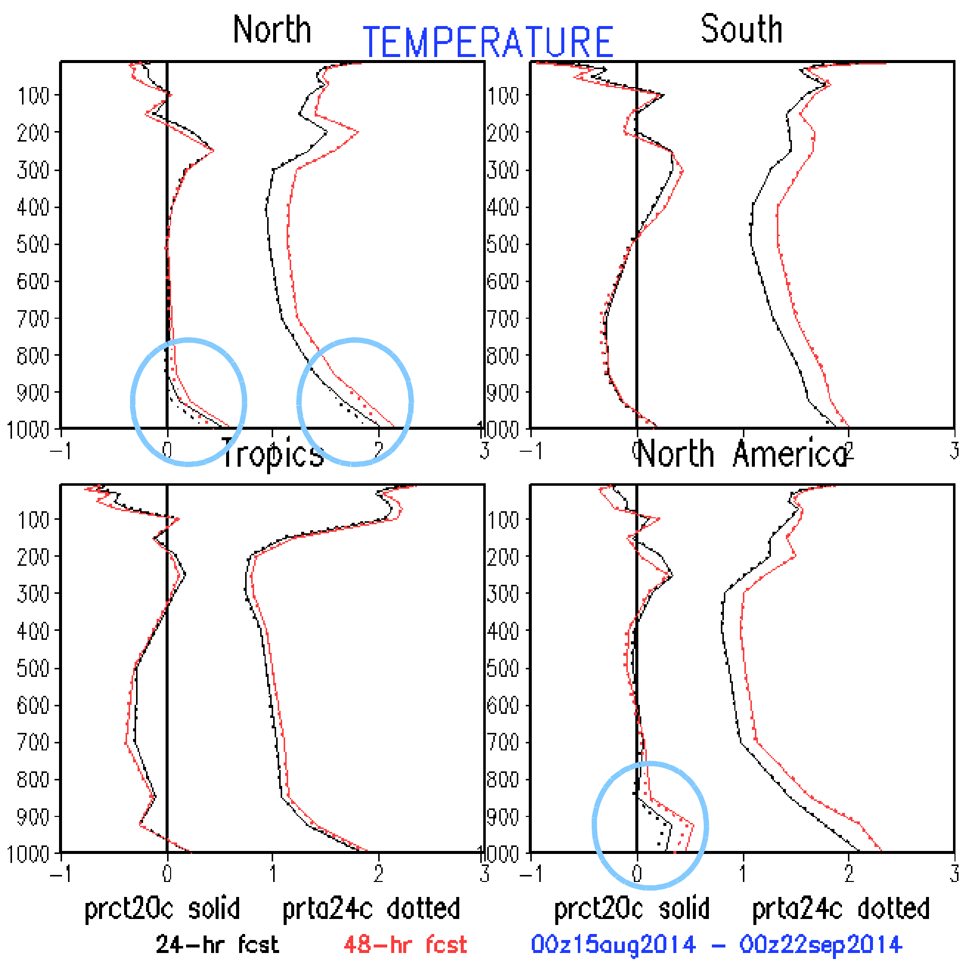


Reduced cold bias and RMSE afternoon and nighttime (~0.4 °C)

Autumn: Temperature fits to Obs: Bias and RMSE



12/36-hr fcst



24/48-hr fcst

Reduced temperature bias and RMSE near the surface in North America

GFS Test: Winter season

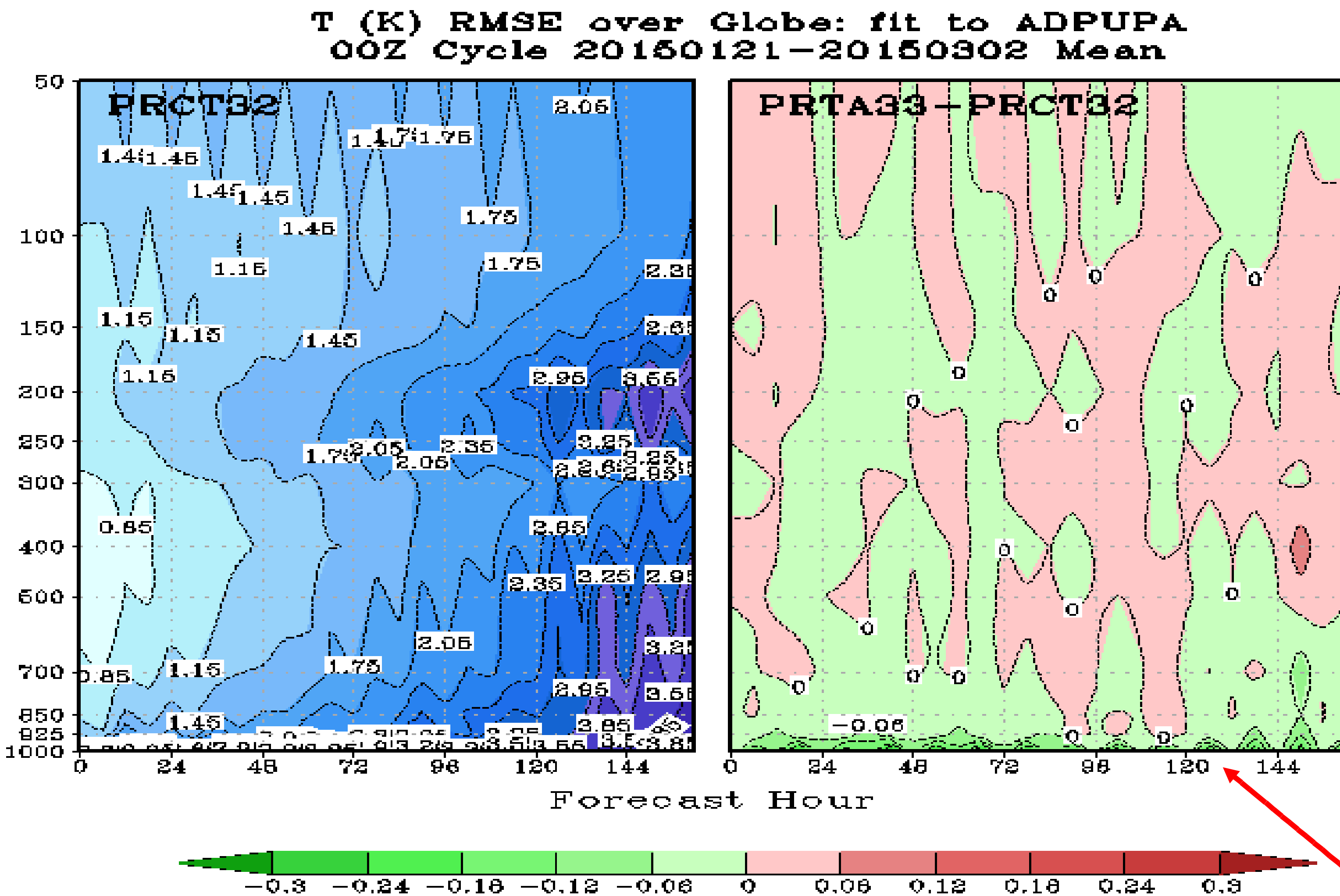
GFS: **T1534; Free forecast at each 00Z cycle**

Cases: **Jan.21 – Mar.02, 2015; Winter season**

There are several cases for T_{2m} rapidly cooling late afternoon

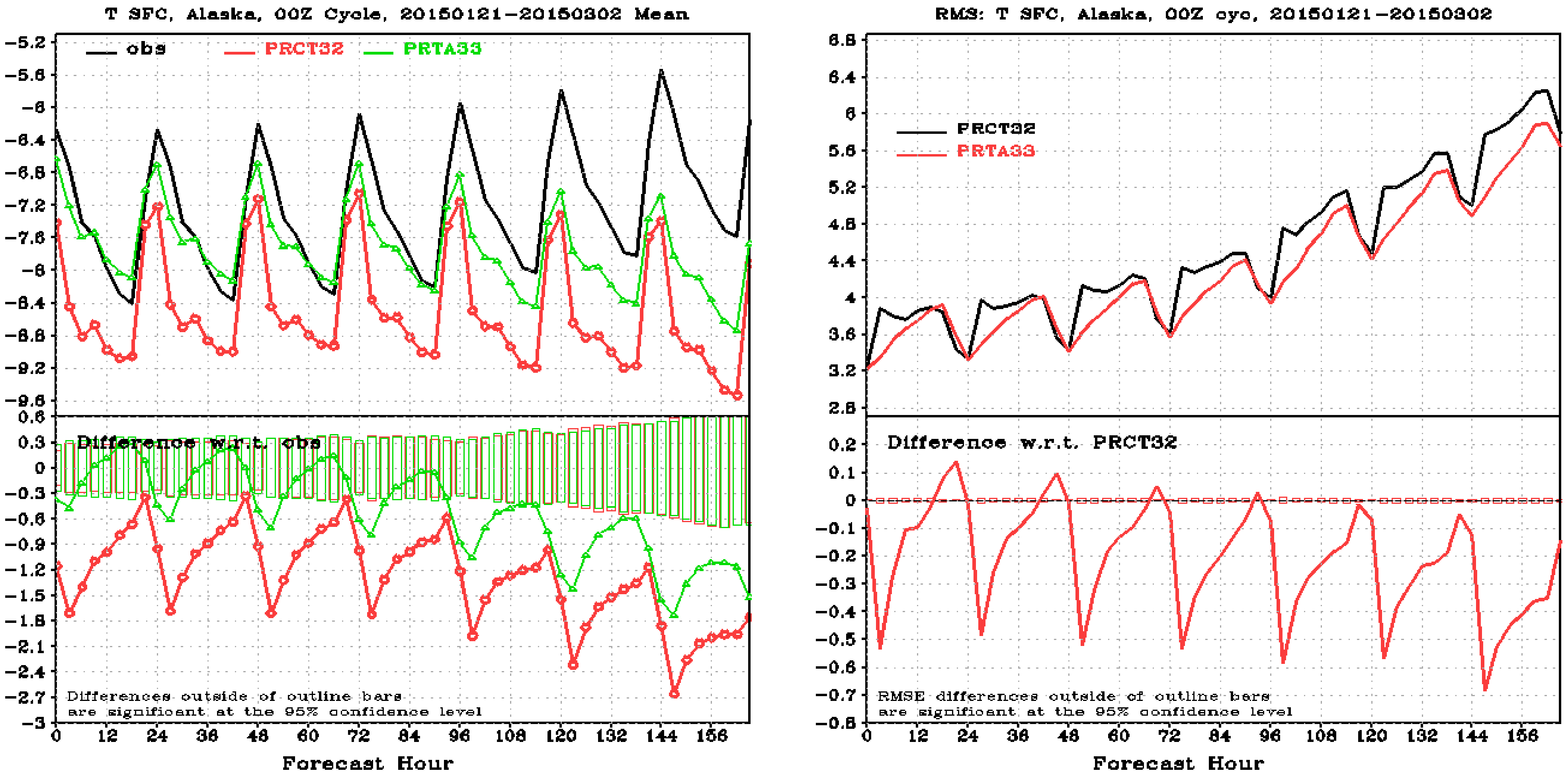
Results: **prct32 (CTL) and prta33 (EXP)**

Temperature fits to Obs: RMSE Global



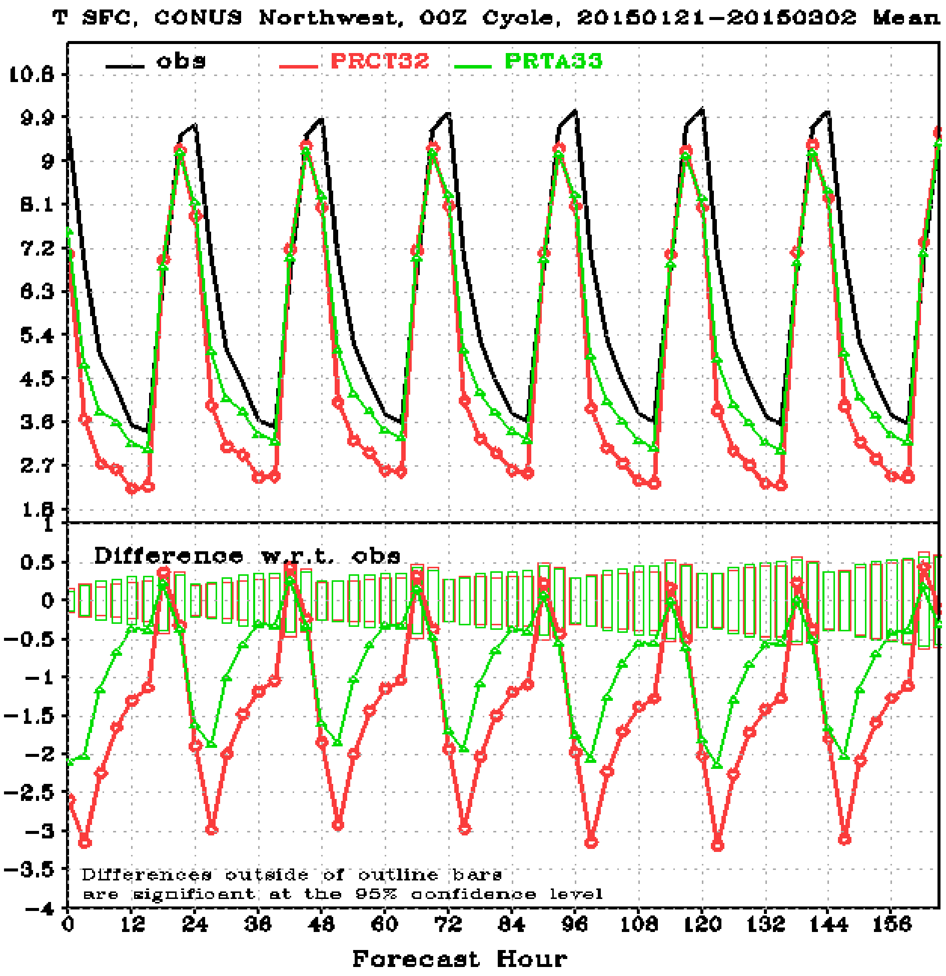
Reduced RMSE near the surface

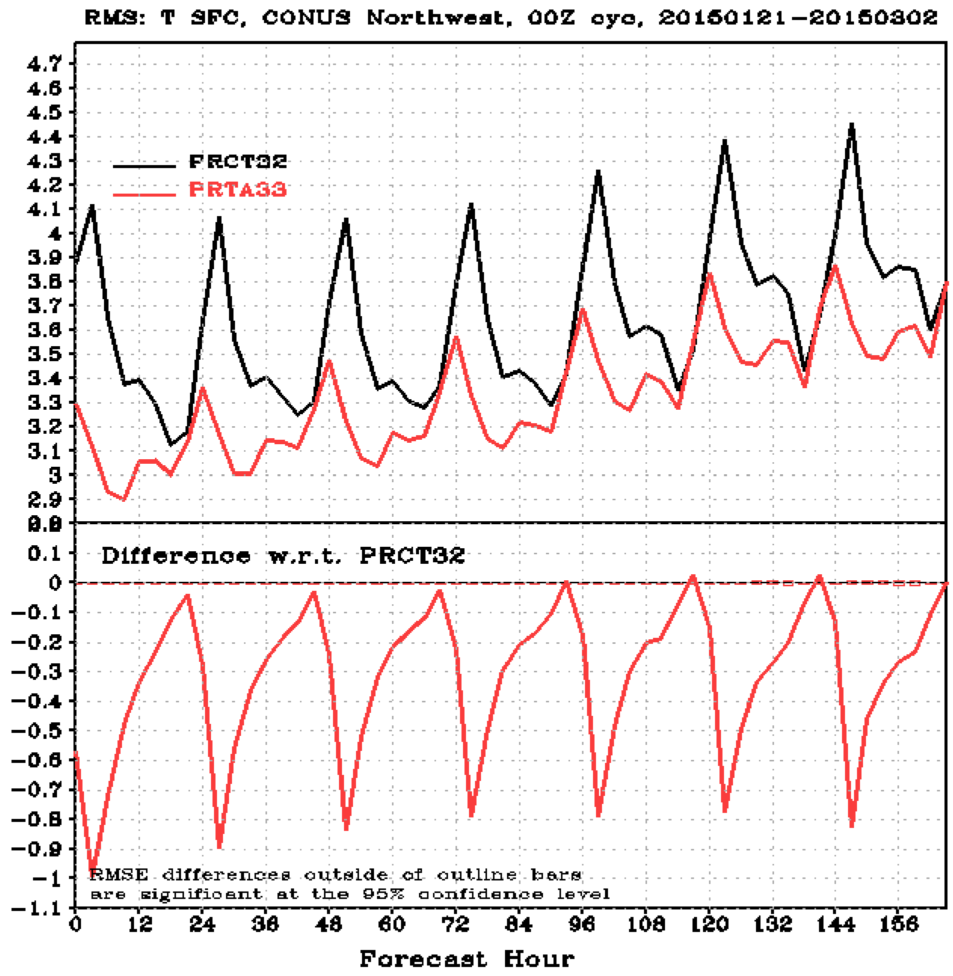
Surface temperature and its RMSE Alaska



Reduced cold bias(~1 °C) and RMSE (~0.5 °C) afternoon and nighttime.

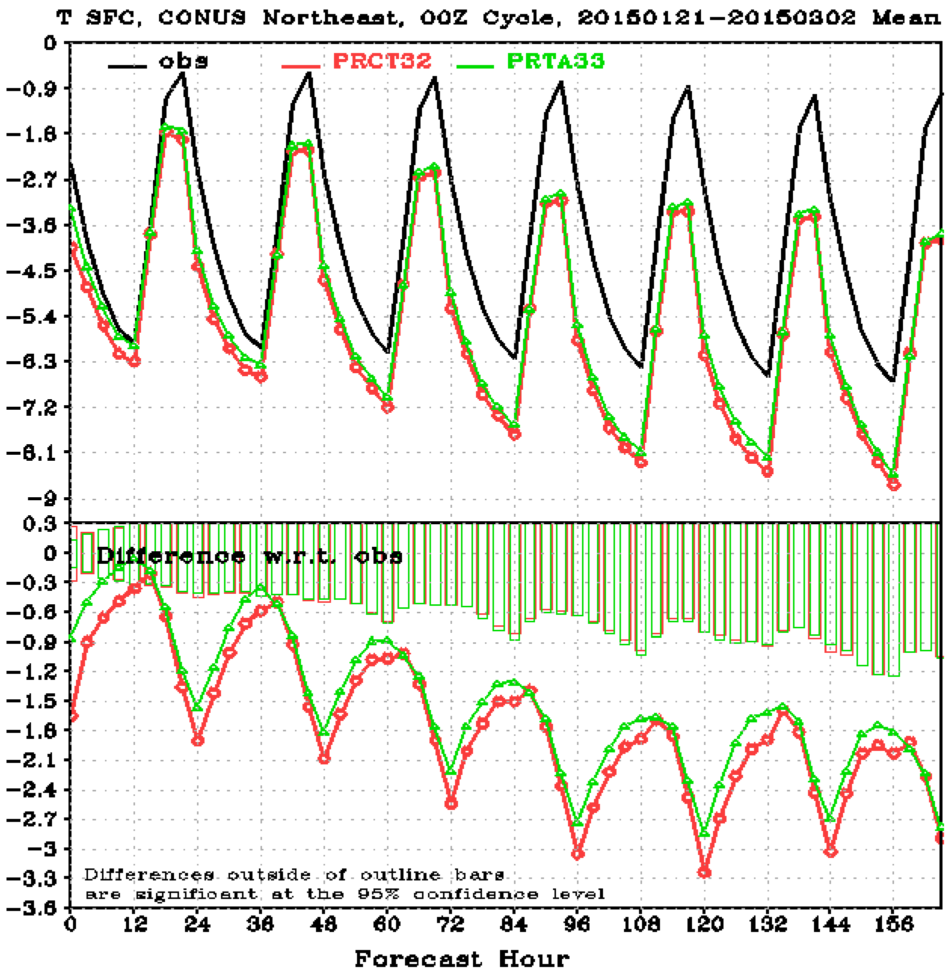
Surface temperature and its RMSE   Northwest

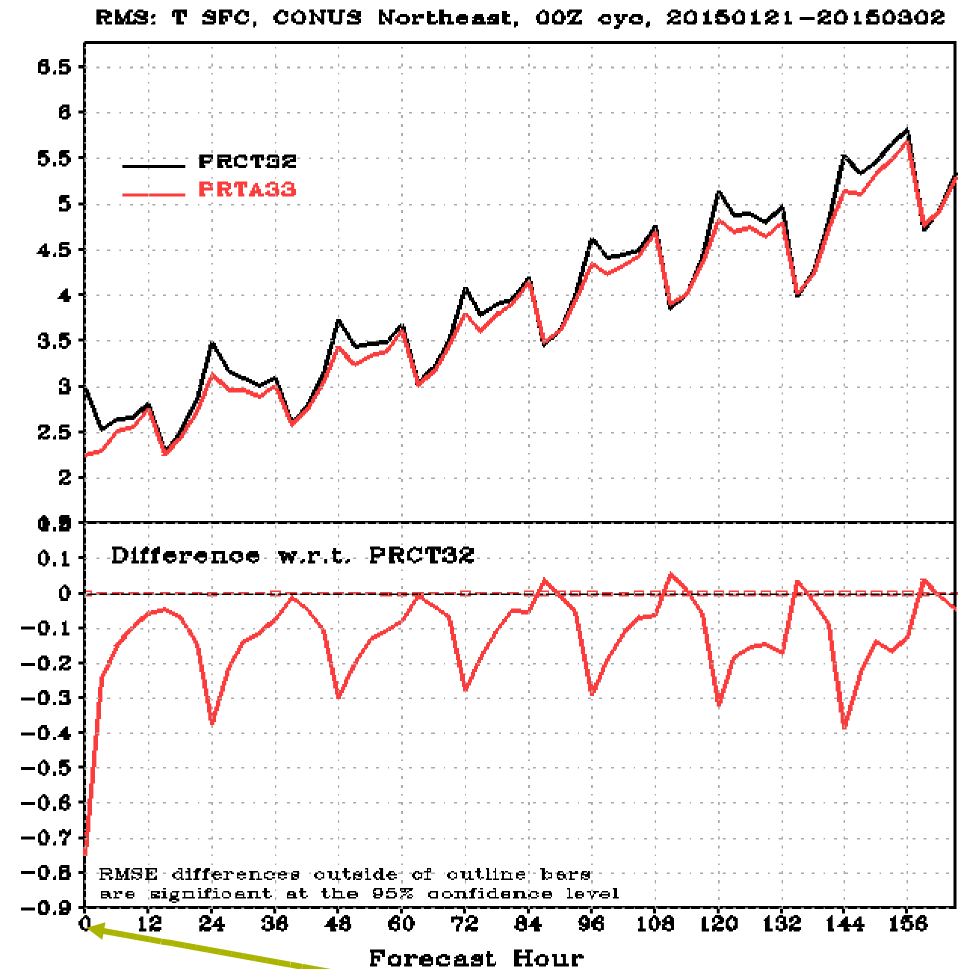




Reduced cold bias afternoon and nighttime (~ 1.2 °C);
Reduced RMSE afternoon and nighttime up to 1.0 °C (~ 25% RMSE).

Surface temperature and its RMSE Northeast



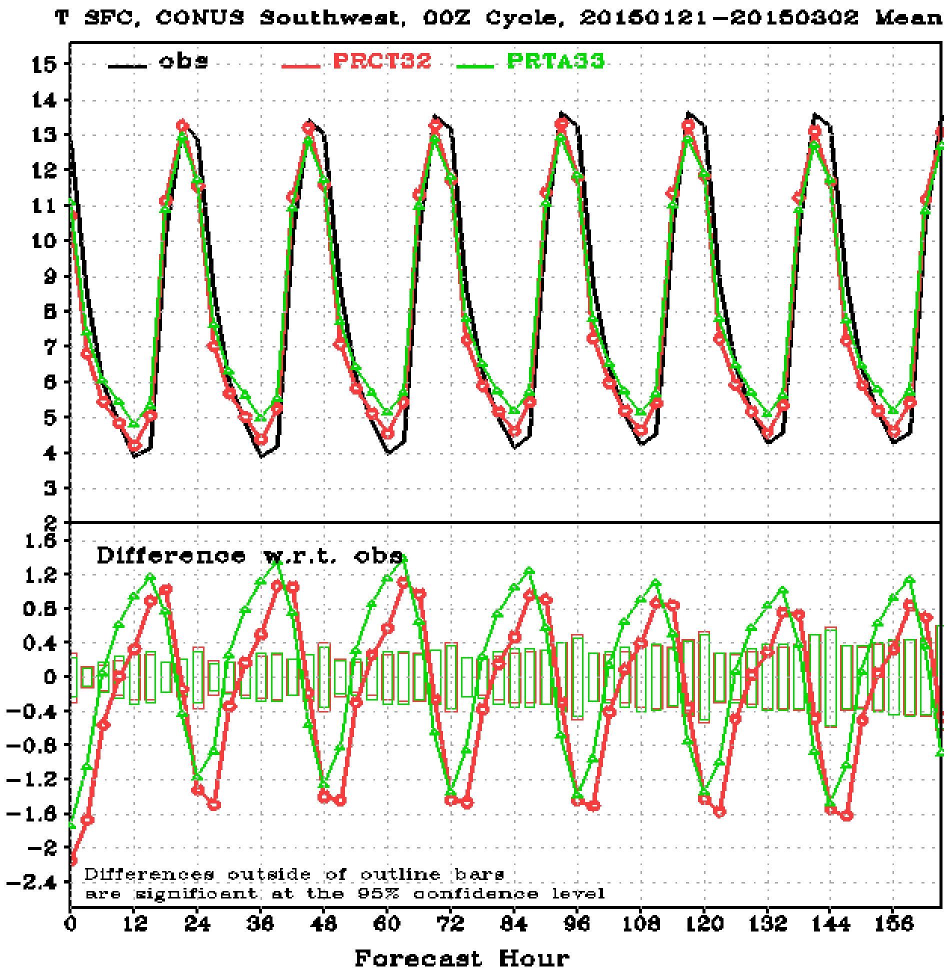


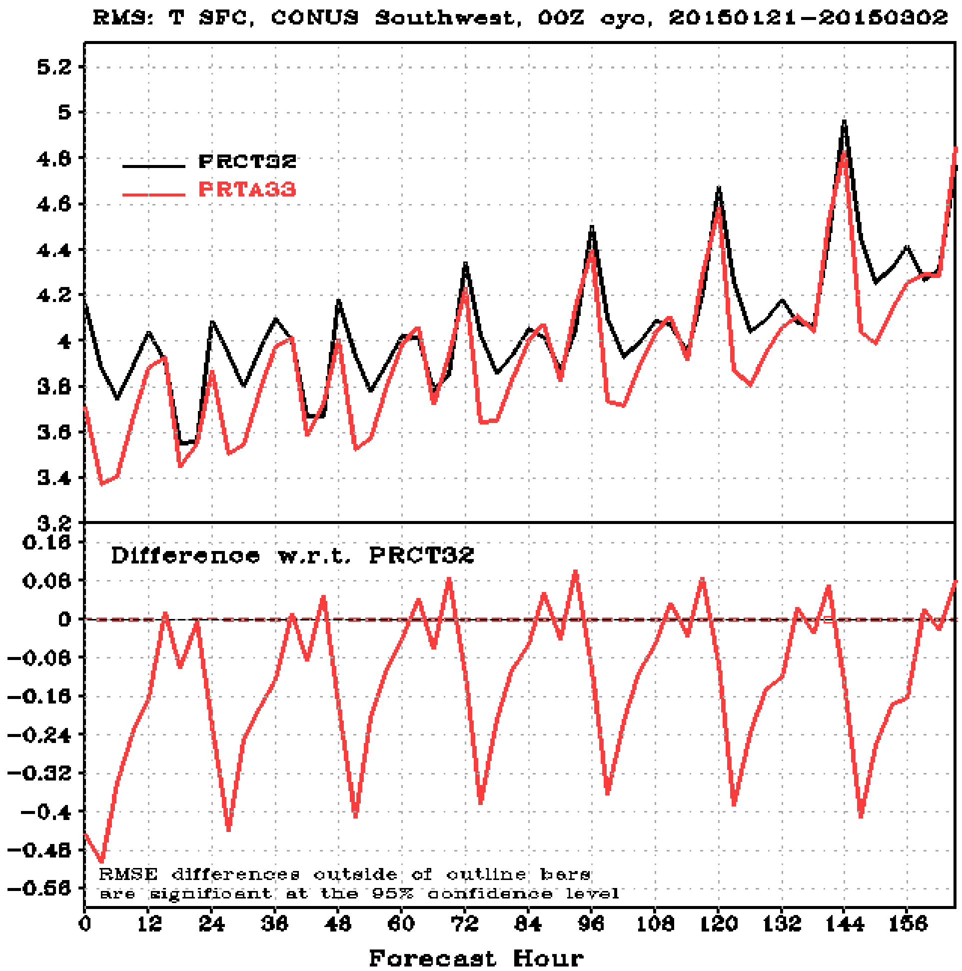
T2m at t=0 ?

Reduced cold bias and RMSE afternoon and nighttime (~ 0.5 °C)

New land data sets (e.g., snow albedo) can reduce this kind of errors (cold trend).

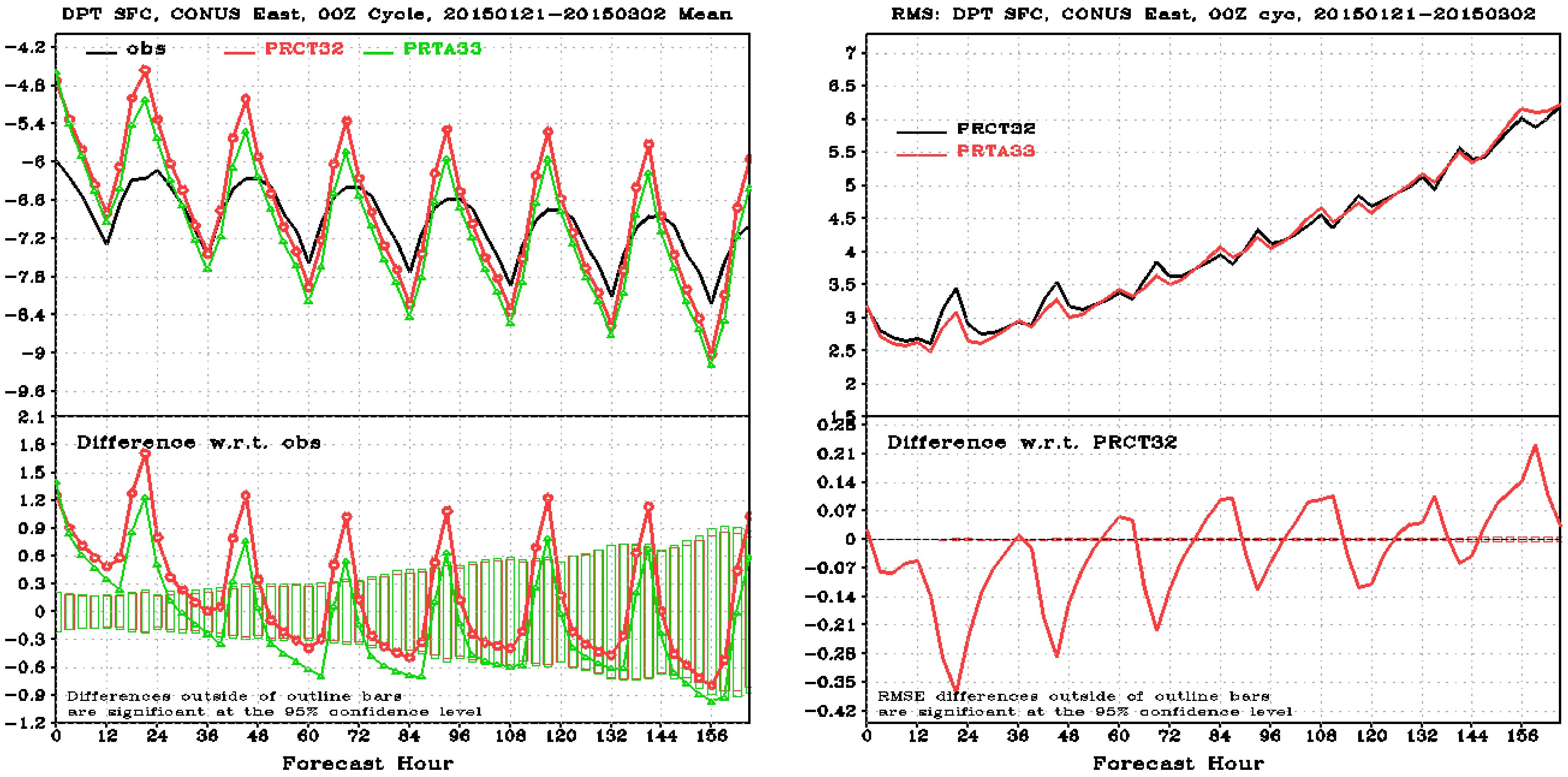
Surface temperature and its RMSE Southwest





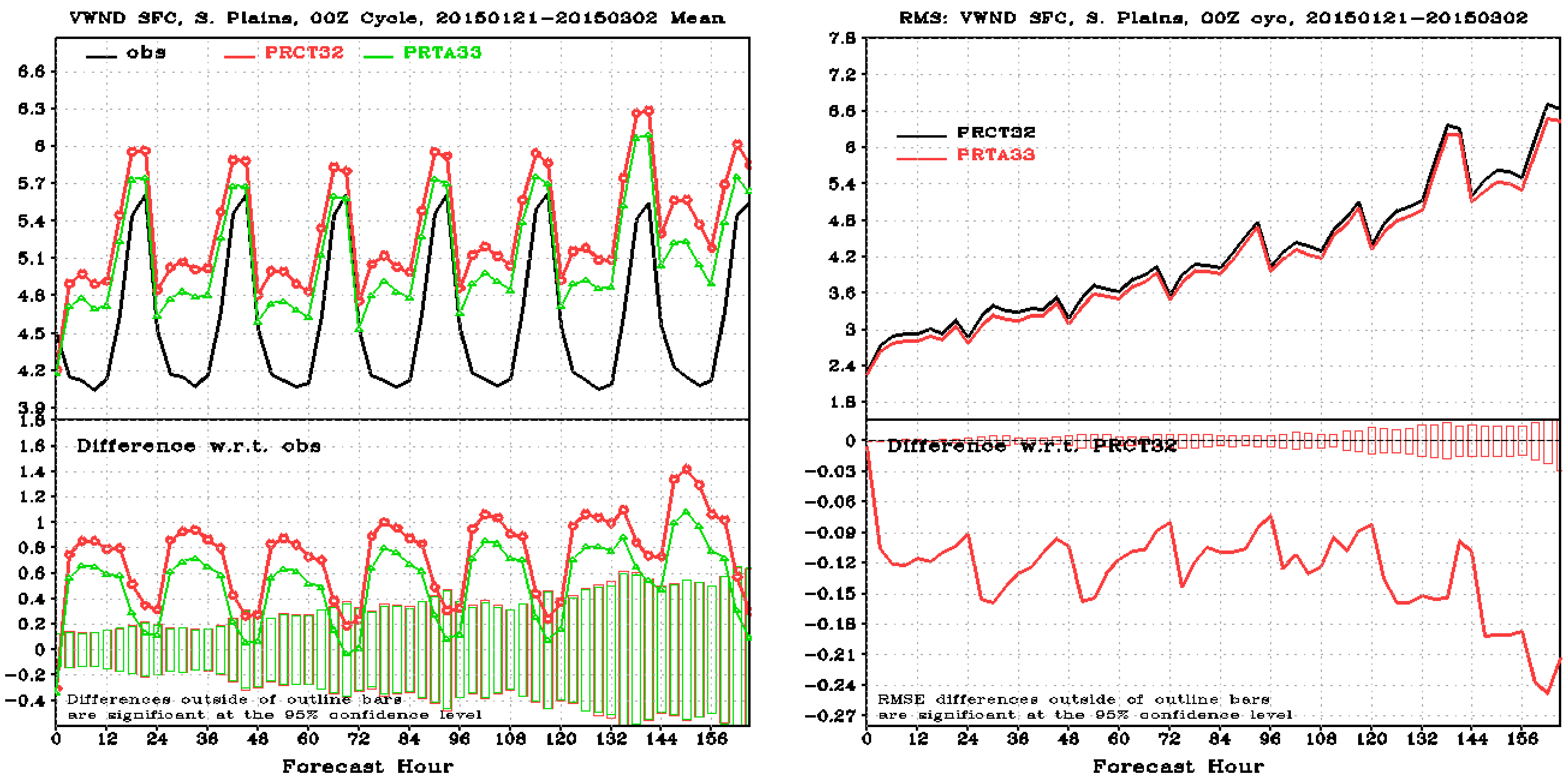
Reduced cold bias afternoon but got a little warm bias during nighttime; Reduced RMSE afternoon and nighttime up to 0.4 °C (~ 10% RMSE).

Surface dew point temp and its RMSE   CONUS East



Reduced wet bias and RMSE afternoon and nighttime (~0.35 °C)

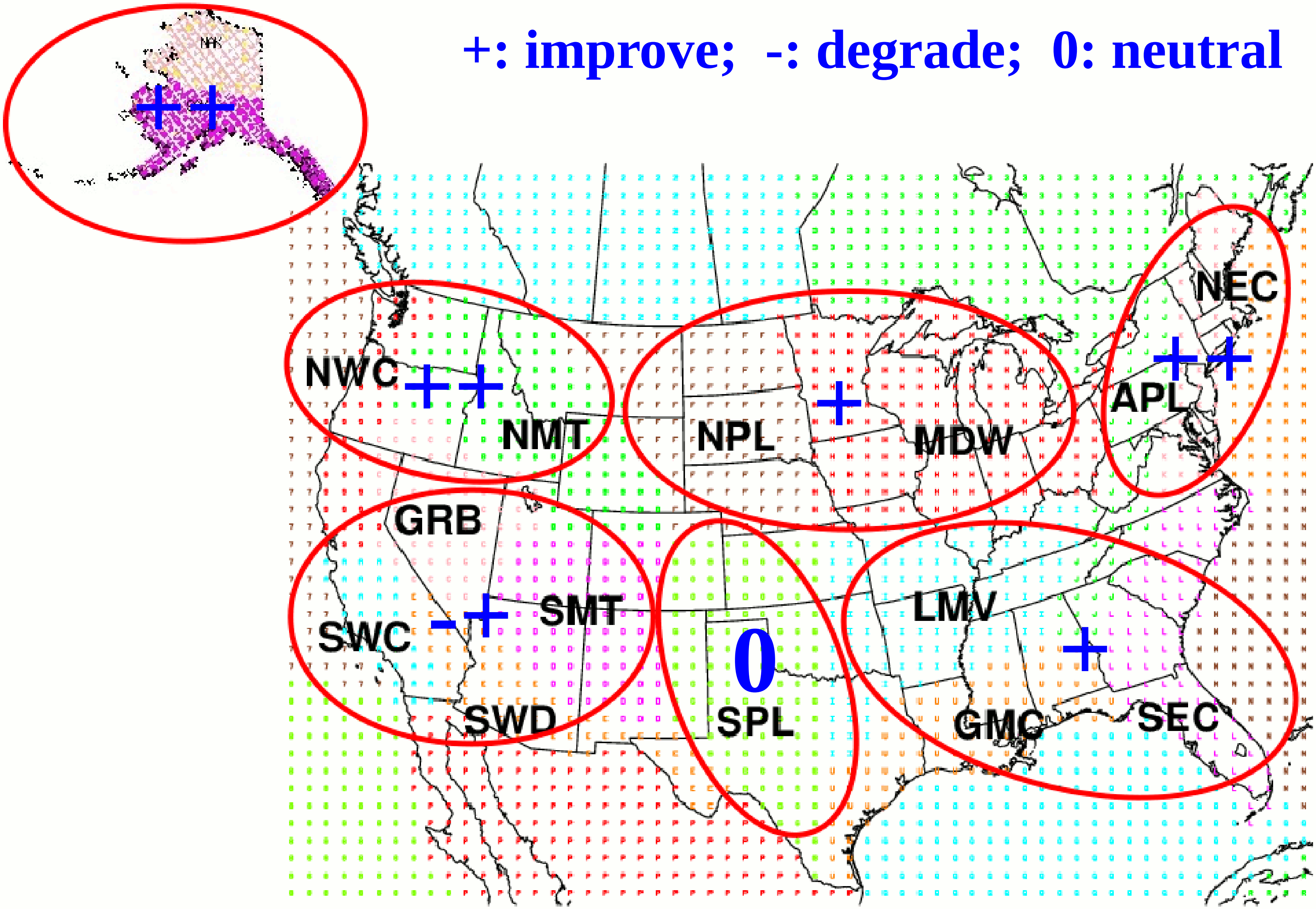
Surface wind speed and its RMSE South Plains



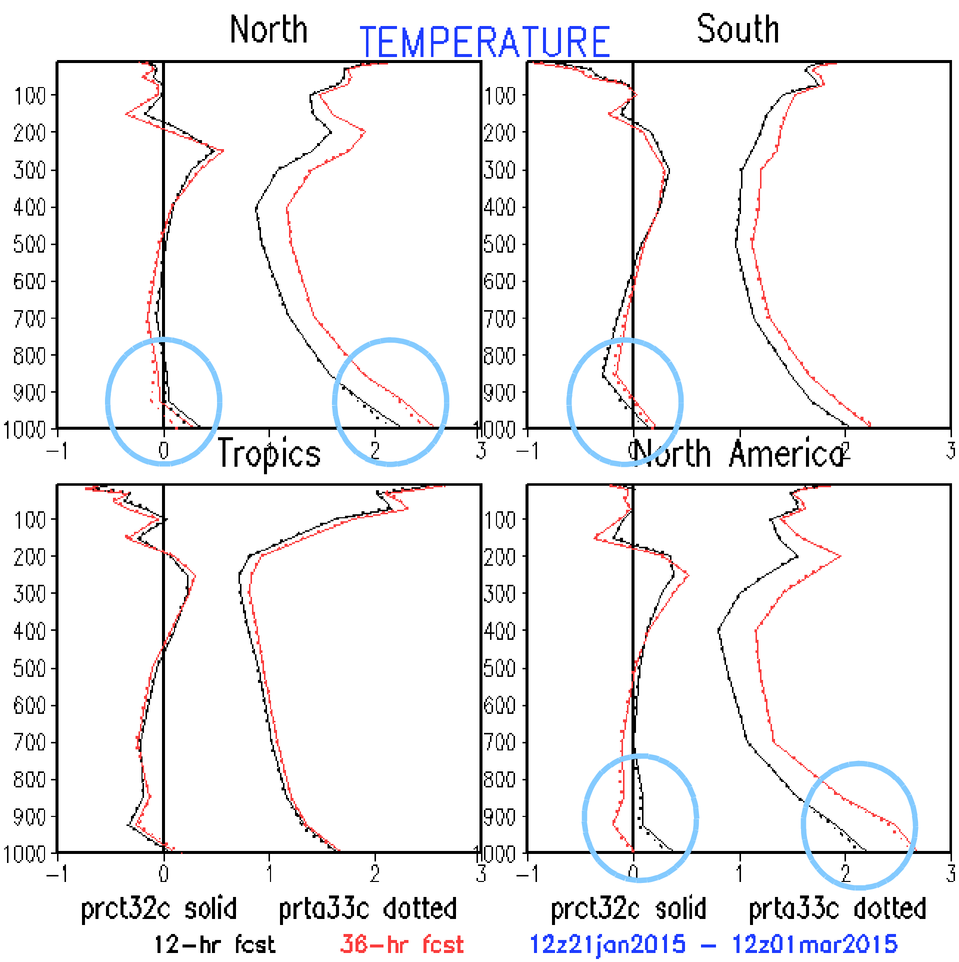
Reduced high wind speed bias and RMSE daytime and nighttime.

Forecast Verification Statistics (FVS) regions (Win)

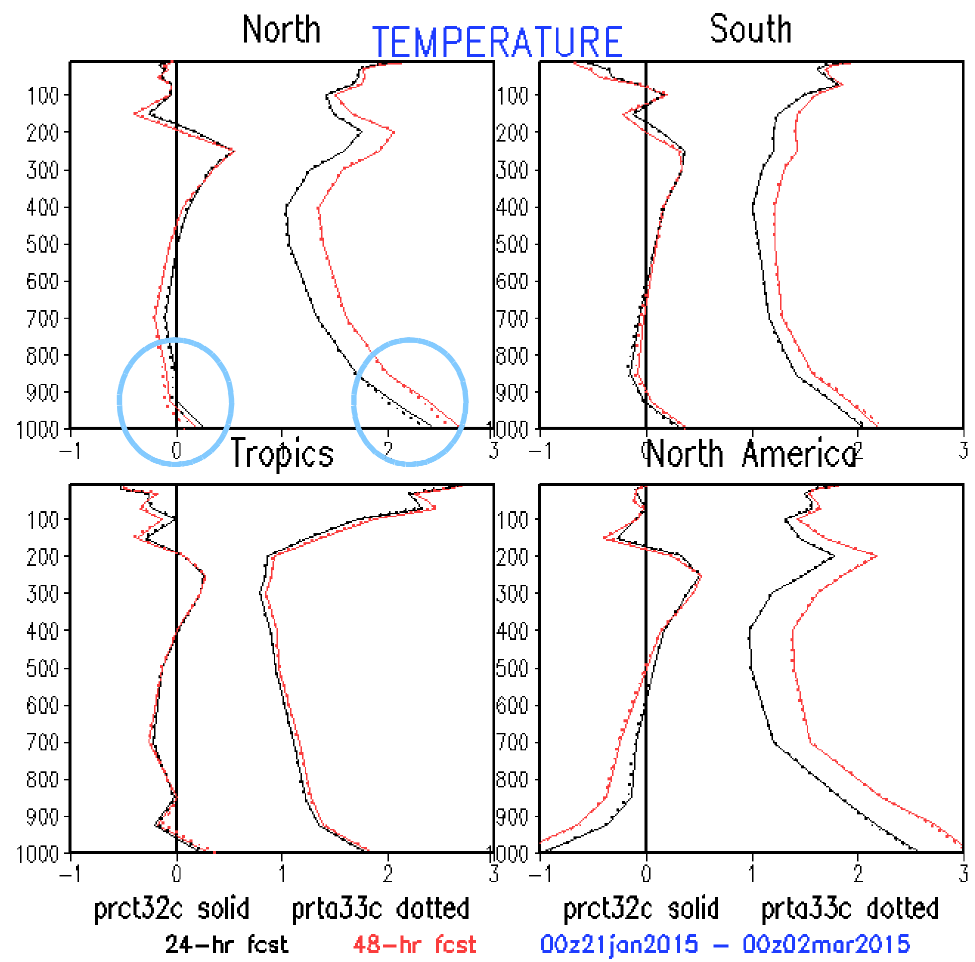
+: improve; -: degrade; 0: neutral



Winter: Temperature fits to Obs: Bias and RMSE



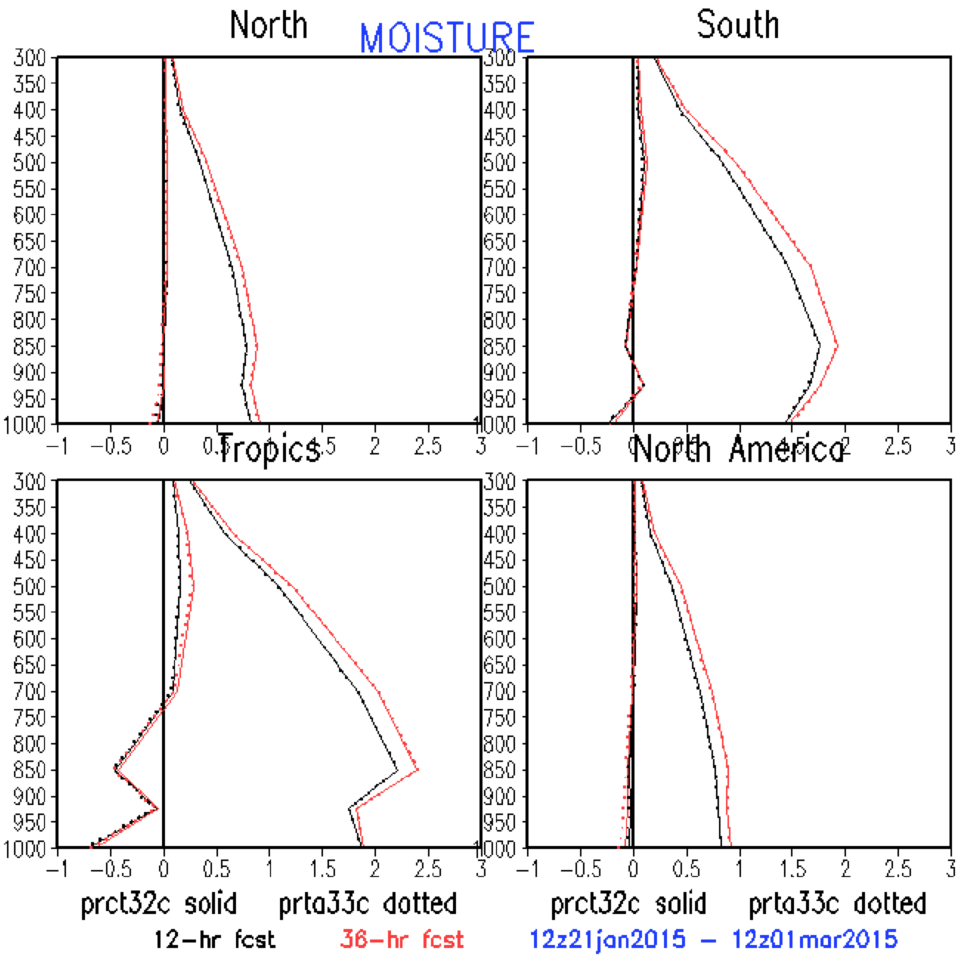
12/36-hr fcst



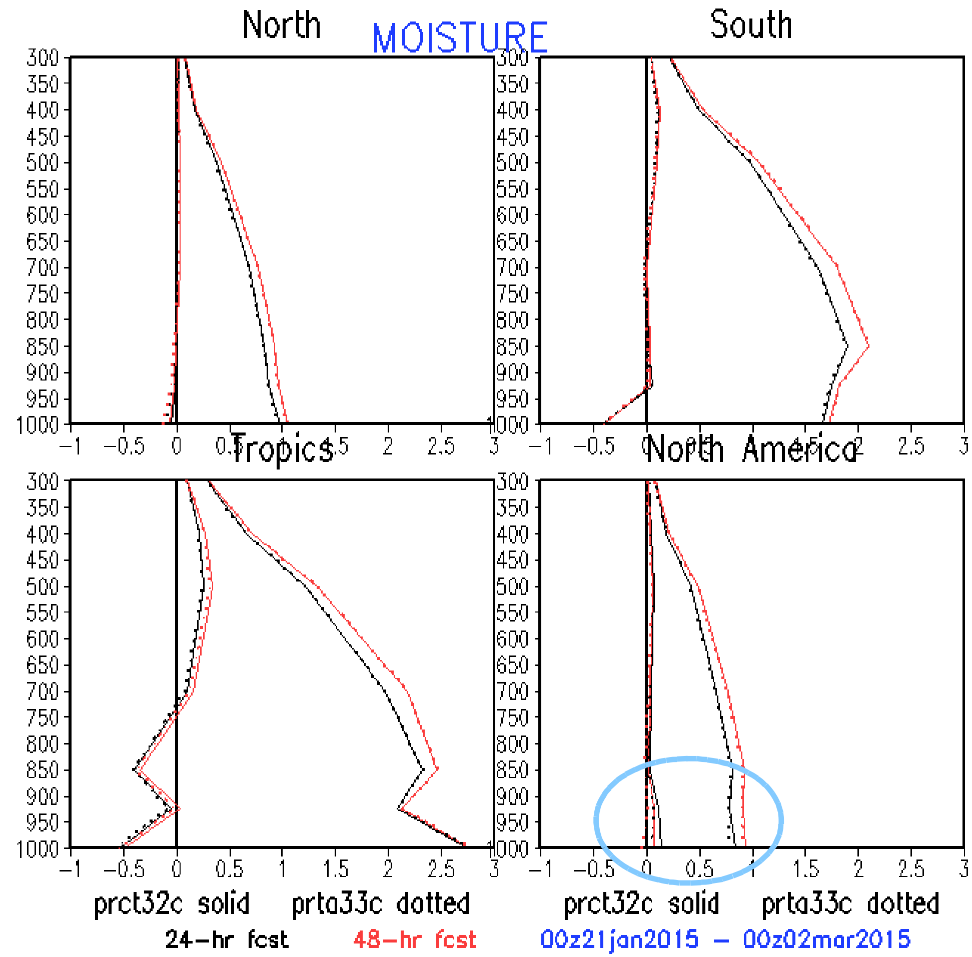
24/48-hr fcst

Reduced temperature bias and RMSE near the surface

Winter: Moisture fits to Obs: Bias and RMSE



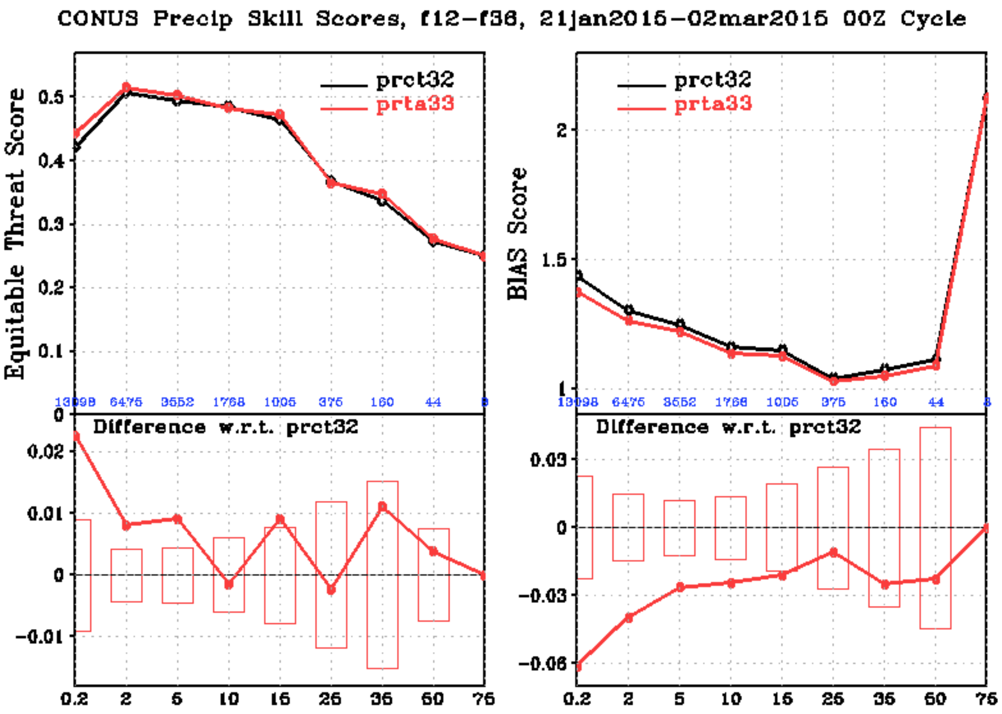
12/36-hr fcst

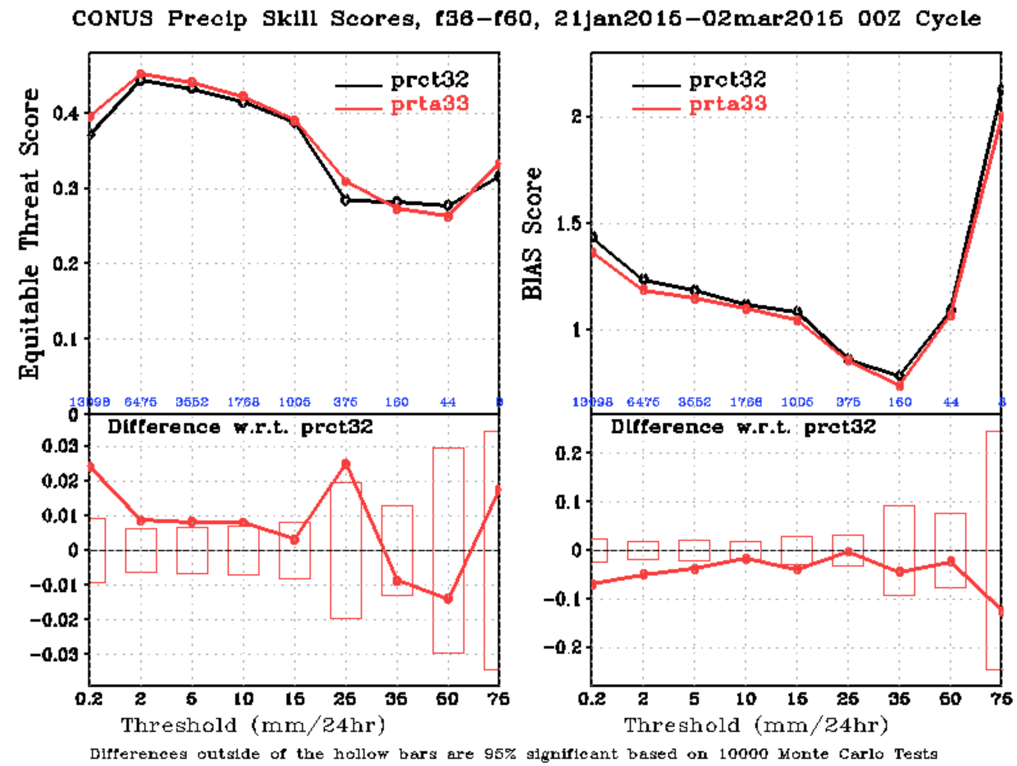


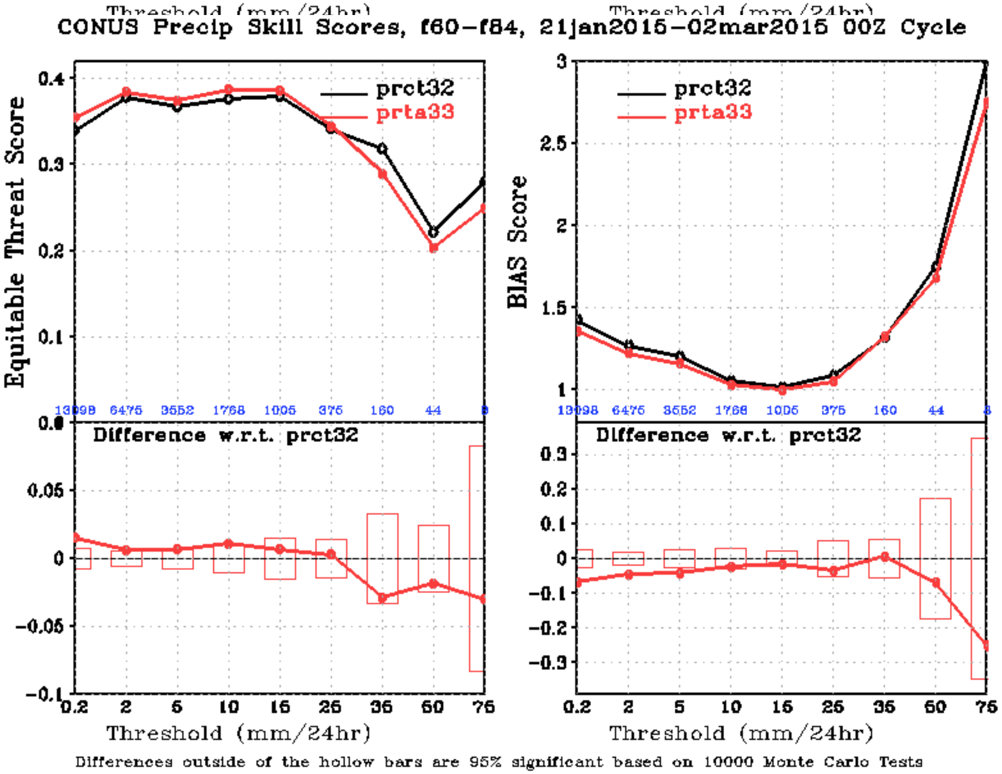
24/48-hr fcst

Reduced moisture bias and RMSE near the surface in North America

Precipitation Skill Scores over CONUS: f12-f36, f36-f60, f60-f84

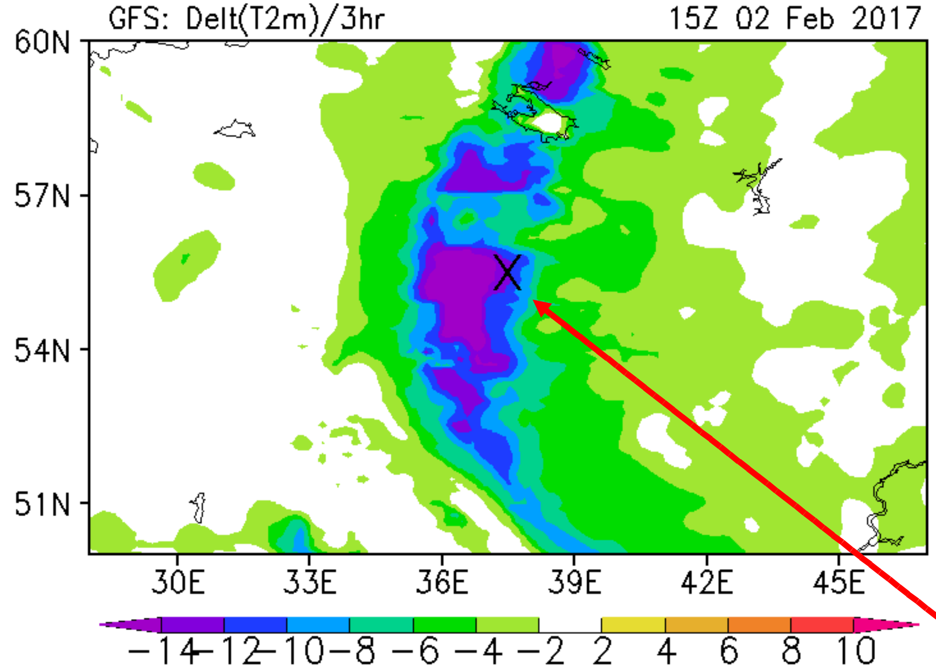


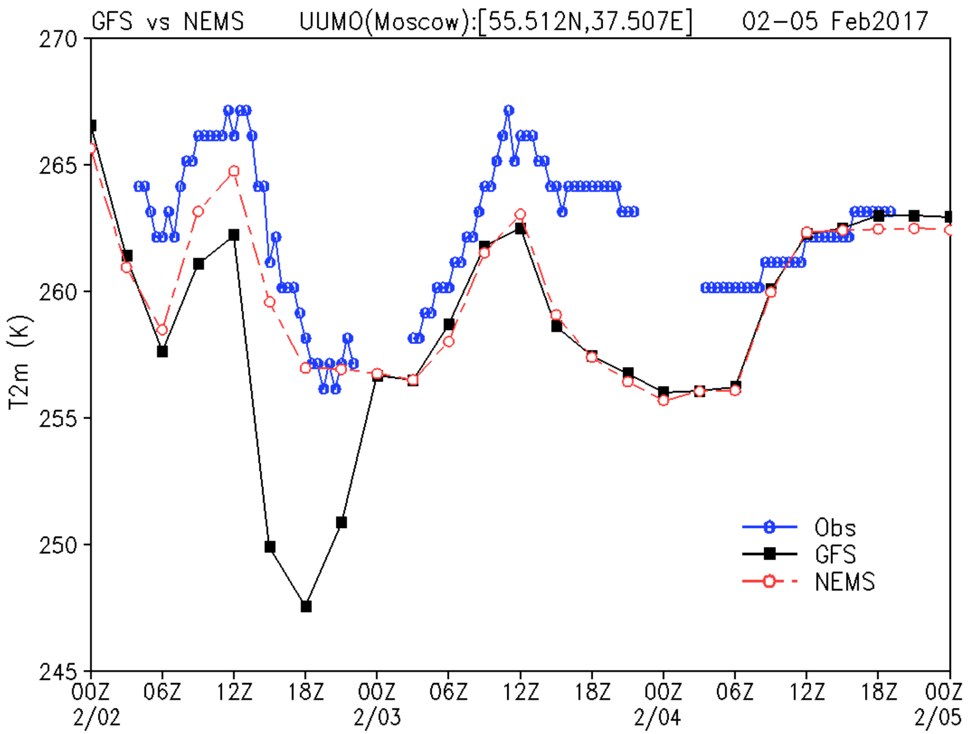


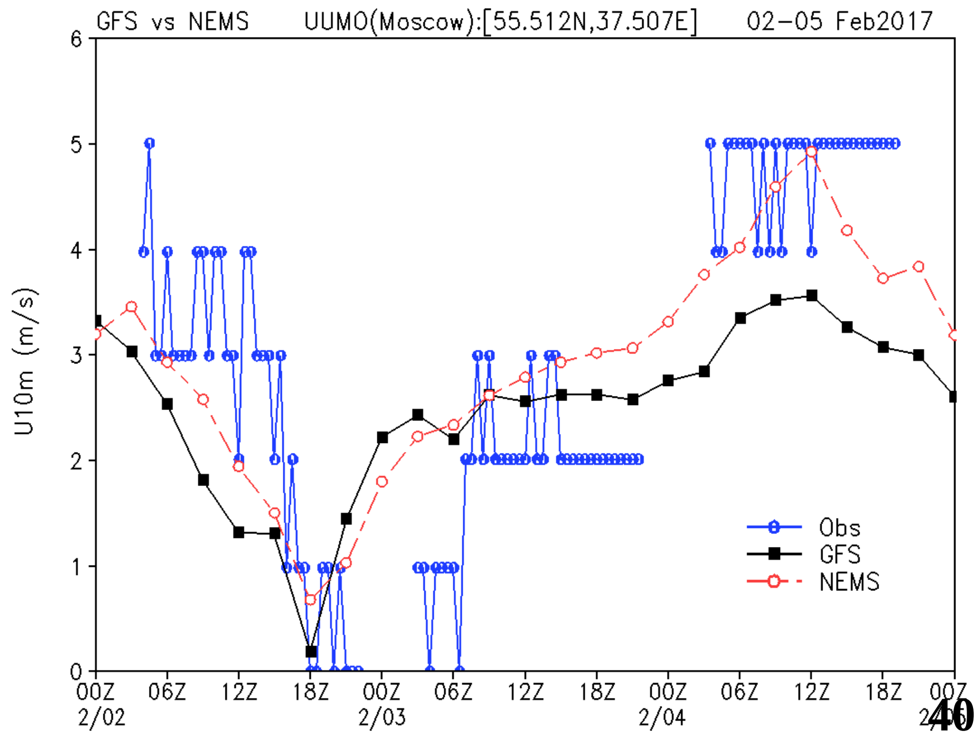


Improved scores for light and medium precipitation and reduced their bias.

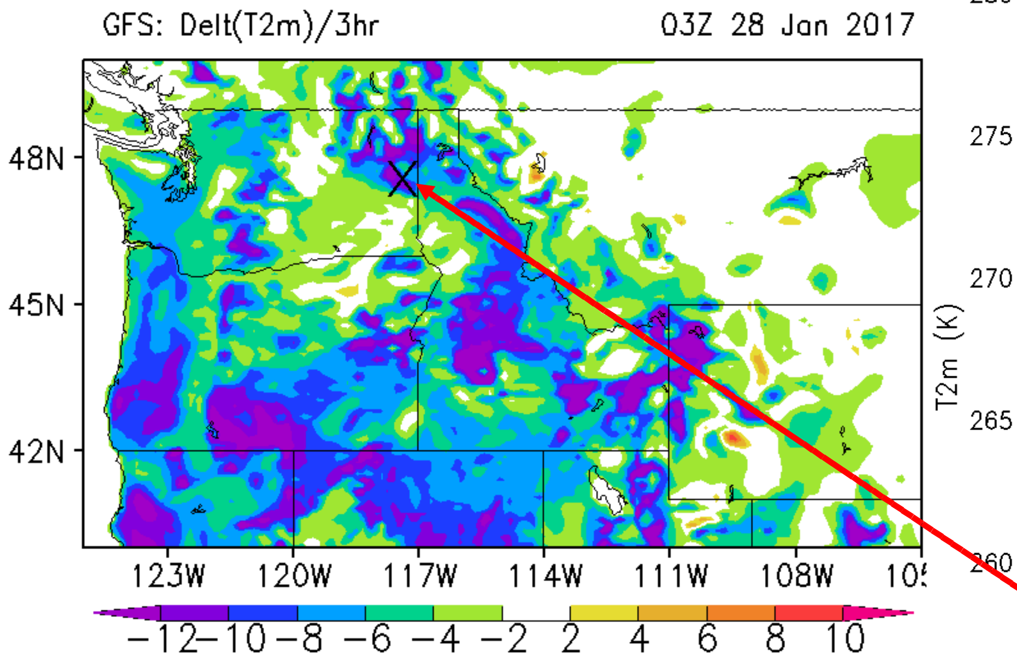
NEMS Case: GFS/NEMS T2m @ UUMO Moscow, Russia



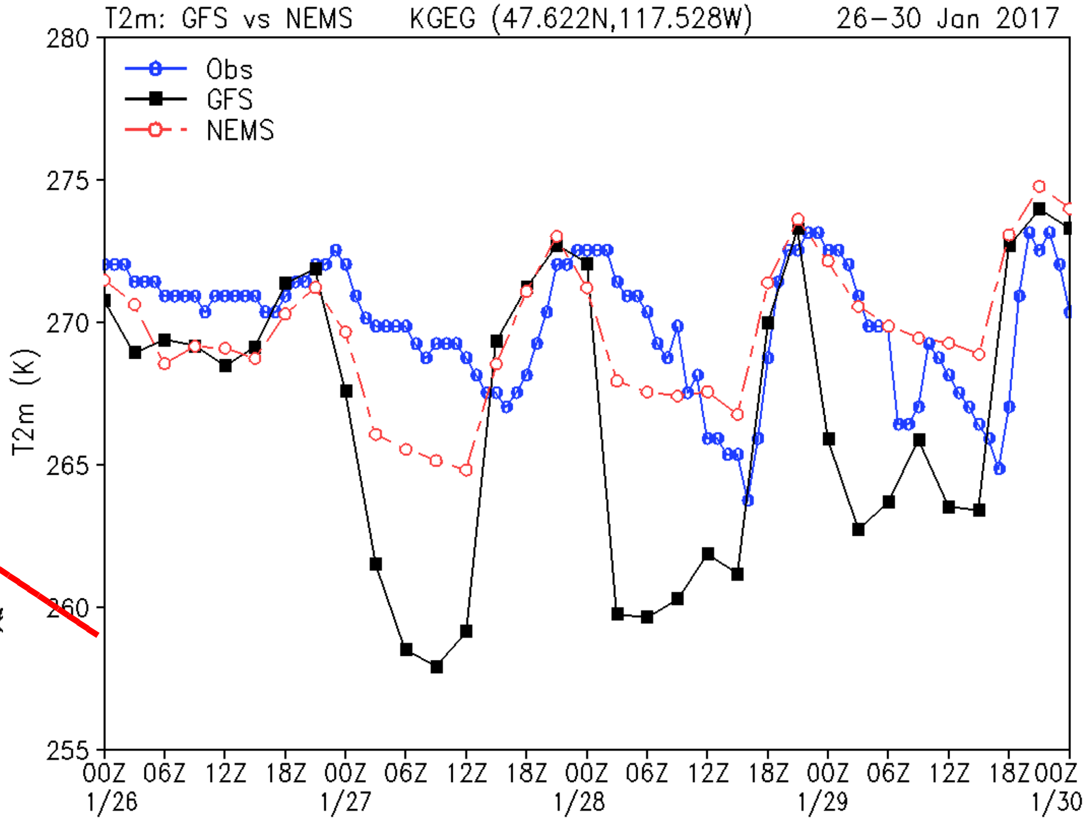




NEMS Case: GFS/NEMS T2m @ GEG Spokane Airport, WA



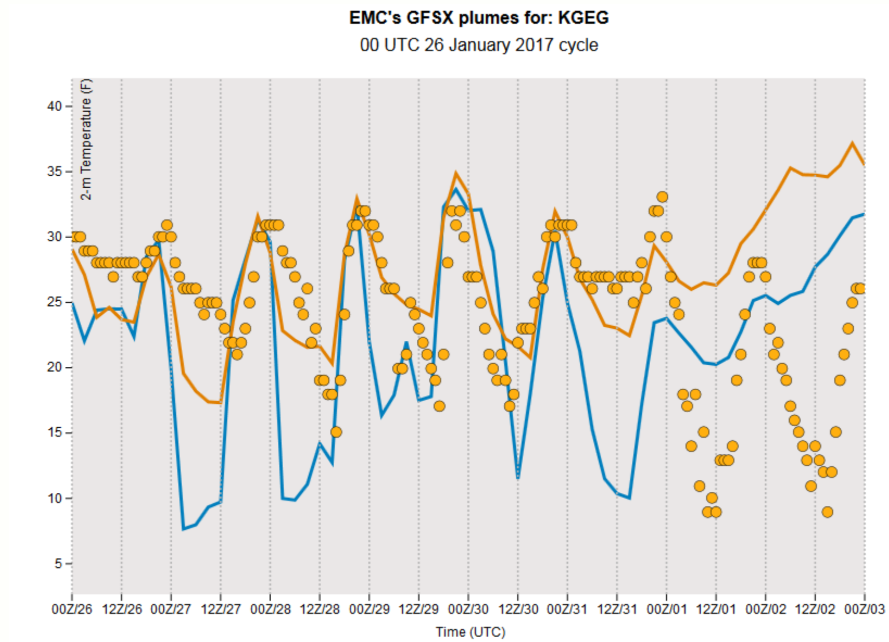
GFS: **T2m forecast > 12 C temperature drop in 3 hours.**

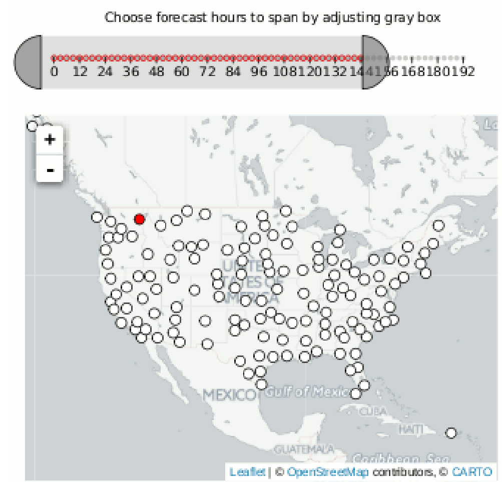


GFS: Rapidly cooling more than 12 °C during 3hr;
NEMS: Substantially improved around sunset.

NEMS Case: GFS/NEMS T2m @ GEG Spokane Airport, WA

00Z 01/26/2017 Cycle: 1/26 – 2/1





Courtesy Glenn white for the obs.

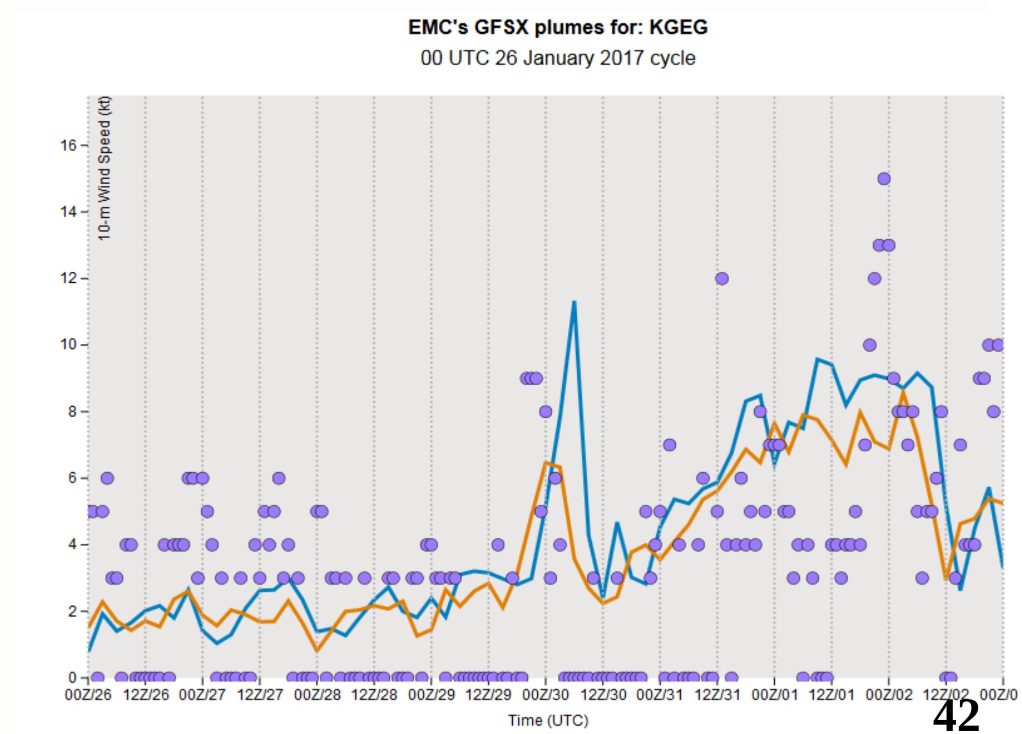
y min y max Set y axis Reset y axis

T2m: GFS vs NEMS

About the plumes: Data for each station is interpolated from a 0.5-degree grid for both the GFS (blue) and GFSX (orange). All observed data are derived from hourly station reports. Zoom for more CONUS stations.

This site is not operational; therefore, data will be missing occasionally. The contact for this site is corey.guastini@noaa.gov

Courtesy Corey Guastini &Tracey Dorian for the plume diagrams



wspd@10m: GFS vs NEMS

Weak wind: 1/26 – 1/29

Summary/Discussion

- **The GFS T2m excessive cold bias is closely related to the positive/negative feedback between the land and the atmosphere under stable conditions.**

- **The modifications were proposed to fix the T2m cold bias, which prevented the coupling system from decoupling.**

- **The case study for snow-free or snow pack indicates the modifications can remove the excessive cold biases of T2m and Tskin, and temperature at the first model level was also improved.**

- **The tests for the medium range GFS free forecasts demonstrate the modifications can substantially reduce the T2m cold bias in the late afternoon and nighttime, except for the Southwest region where the sensitivity tests show a little warm bias during nighttime but again reduce RMSE.**

- **We plan to include these modifications in next upgrade operational NEMS GFS model in 2017.**

- **In the future, new land data sets (e.g. veg/soil types, new GVF, albedo, etc.) will be updated in the model and expect to further reduction of T2m bias.**

Thank You !

Any questions/comments?