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

Weizhong Zheng\textsuperscript{1,2} and Michael Ek\textsuperscript{1}

\textsuperscript{1}NOAA/NCEP/Environmental Modeling Center(EMC), USA
\textsuperscript{2}IMSG@NOAA/NCEP/EMC, USA

Email: Weizhong.Zheng@noaa.gov

Acknowledges: Helin Wei, Jesse Meng, Jongil Han, Ruiyu Sun, Fanglin Yang, Geoffrey Manikin, Glenn White, Mark Iredell and Ken Mitchell

May 11, 2017
Motivations:

- What is the problem about GFS surface temperature forecast?
  - One of Top 10 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
Comparison of $T_{2m}$ (F): NAM, GFS and Obs, 00UTC, 2015-02-17

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

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

EMC's GEFS plumes for: KMBR
12 UTC 24 January 2016 cycle

Choose forecast hours to span by adjusting gray box

Click map to zoom/recent
Reset zoom

Variable: 2-m T  Cycle: 2016012412

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.

x: Observation  Black: GEFS mean  Blue: Ops GFS

Courtesy Tracey Dorian
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.

x: Observation   Black: GEFS mean   Blue: Ops GFS

Courtesy Tracey Dorian
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

Hong & Pan, 1996
Land-Atmosphere Stable Boundary Layer

**Surface Energy Balance:**

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

\[ SH = \rho c_p C_h U_a (T_{sfc} - T_{air}) \]
\[ LH = \rho L_v C_q U_a (q_{sfc} - q_{air}) \]
\[ G = (K_T/Δz) (T_{sfc} - T_{soil}) \]
\[ Up_{LW} = \varepsilon \sigma_{SB} T_{sfc}^4 \]

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

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

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

(B) Under cessation of turbulence: \( G \sim Dn_{LW} + Up_{LW} + \text{(others)} \implies \) new state

The system may reach different equilibrium states!
Consider 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
\[ T_{sfc} \downarrow \rightarrow \Delta T \uparrow \rightarrow SH \uparrow \rightarrow T_{sfc} \uparrow \]

(B) **Positive feedback:** To reduce turbulent fluxes ==> perhaps ultimately to zero -----> different regime (very stable regime)
\[ T_{sfc} \downarrow \rightarrow \Delta T \uparrow \rightarrow u_\ast (T_\ast) \downarrow \rightarrow SH \downarrow \rightarrow T_{sfc} \downarrow \]

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

**Decoupling:** 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)

\[ C_M = \frac{k^2}{F_M^2} \quad C_H = \frac{k^2}{F_M F_H} \]

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

\[ \zeta = z/L \quad L = \frac{\theta}{k g} \frac{u_*^2}{\theta_*} \]

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

\[ F_{M,H} = \ln \frac{z}{z_{0M,H}} - \psi_{M,H} \left( \frac{z}{z_{0M,H}} \right) \]

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

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

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

Bifurcation diagram: Turbulence vs cooling rates.
Linear stability analysis: Stable/unstable equilibrium states

\[ z/L < z/L \big|_M = \ln(z/z_0)/\left[2*\alpha*(1-z_0/z)\right] \]
Here \( z_0 \) is the momentum roughness length, and \( \alpha = 5 \).
Hopf Bifurcation

A system with two coupled nonlinear ordinary differential equations:

\[
\frac{dy_1}{dt} = f_1(y_1, y_2, \lambda)
\]
\[
\frac{dy_2}{dt} = f_2(y_1, y_2, \lambda)
\]

\(\lambda < \lambda_{\text{crit}}\) : numerical stable;
\(\lambda > \lambda_{\text{crit}}\) : numerical unstable.

Van de Wiel et al.
Case 1: GFS Test: T2m 00Z, 2016-01-24 Cycle

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

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

**GFS Test**:  T1, T2m and Tskin @ MRB

**GFS**:  CTL
**GFS**:  EXP

**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: Surface Fluxes and Ustar @ MRB

GFS: CTL

GFS: Test

Cessation of turbulence: SHF, Ustar $\to 0$

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

CTL: Little downward heat transport (atmos-->land) during the night decoupling period results in accumulation of excess heat and as a result, the warm bias exists above the first model level.
Case 3: GFS Test: T2m

GFS_CTL: Delt(T2m)/3hr

00Z 05 Oct 2012

GFS: EXP4–CTL: T2m (C)

00Z 05 Oct 2012

Goodwin Creek, MS

02–06 Oct 2012

T2m (K)

Obs
CTL
EXP1
EXP2
EXP3
EXP4

T5fc (K)

Obs
CTL
EXP1
EXP2
EXP3
EXP4
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

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

T2m at t=0?
Surface temperature and its RMSE  

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

Reduced cold bias and RMSE afternoon and nighttime (~0.4 °C)
Autumn: Temperature fits to Obs: Bias and RMSE

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

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).
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

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

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

Reduced temperature bias and RMSE near the surface
Winter: Moisture fits to Obs: Bias and RMSE

Reduced moisture bias and RMSE near the surface in North America
Improved scores for light and medium precipitation and reduced their bias.
NEMS Case: GFS/NEMS T2m @ GEG  Spokane Airport, WA

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

GFS: T2m forecast > 12 °C temperature drop in 3 hours.
NEMS Case: GFS/NEMS T2m @ GEG  Spokane Airport, WA

T2m: GFS vs NEMS

wspd@10m: GFS vs NEMS

Weak wind: 1/26 – 1/29

Courtesy Glenn white for the obs.

Courtesy Corey Guastini & Tracey Dorian for the plume diagrams

http://www.emc.ncep.noaa.gov/mmb/cguastini/gfsx/EMCGFSXplum...
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?