Negative Water Vapor in the GFS: Causes and Solutions

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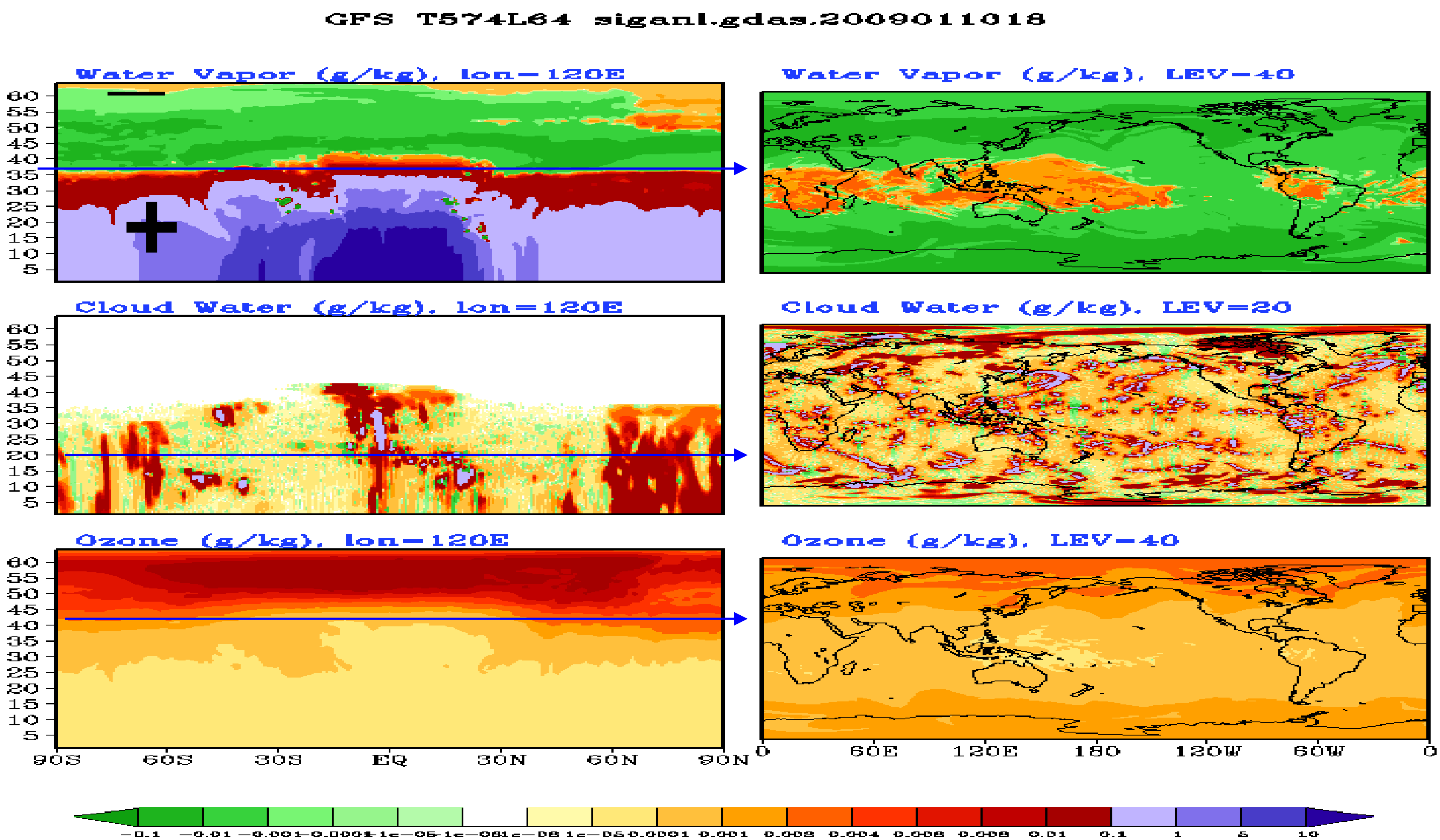
August 13, 2009

Negative Tracers in the GFS



It has long been noticed that negative water vapor and negative cloud water exist in the NCEP GFS

Causes of Negative Water Vapor

1. **Vertical advection**
2. **Data assimilation**
3. **Spectral transform**
4. **Borrowing by cloud water**
5. **SAS Convection**

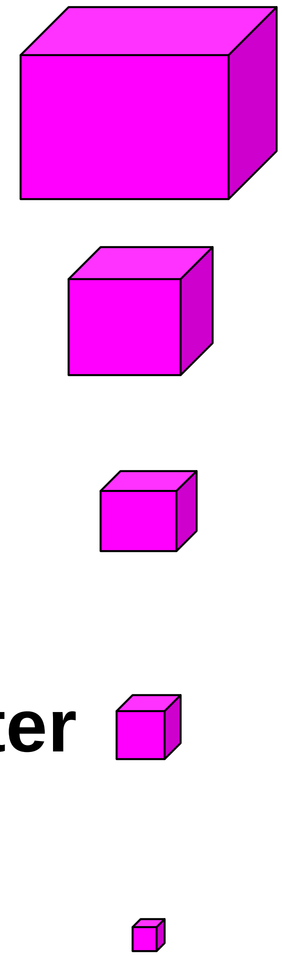


illustration of relative importance

5. SAS Convection

In SAS (sascnv_v.f)

Q1(I,k) = Q1(I,k) + DELLAQ(I,k) * XMB(I) * DT2

XMB is the mass flux at cloud base

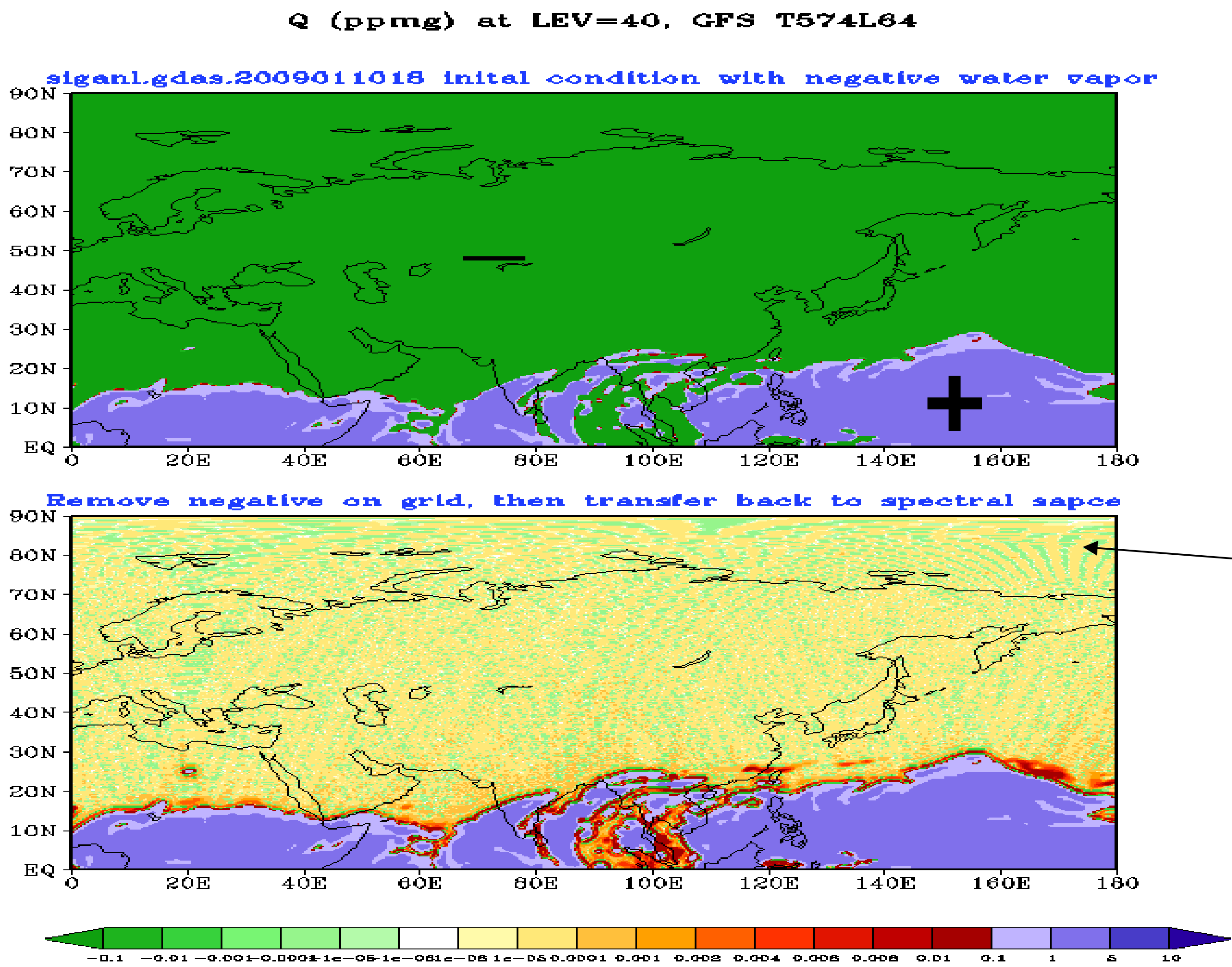
Moorthi wrote:

"Actually, the culprit is "**DELLAQ**" which really is "Eta dq/dz" term. This is the vertical advection term through mass-flux. Since the vertical discretization used is centered, it can produce negative values. If you want to adjust, then you need to **adjust "DELLAQ" to be positive definite**."

So far no changes have been made to SAS to address this issue.

However, it's contribution is negligibly small compared to others.

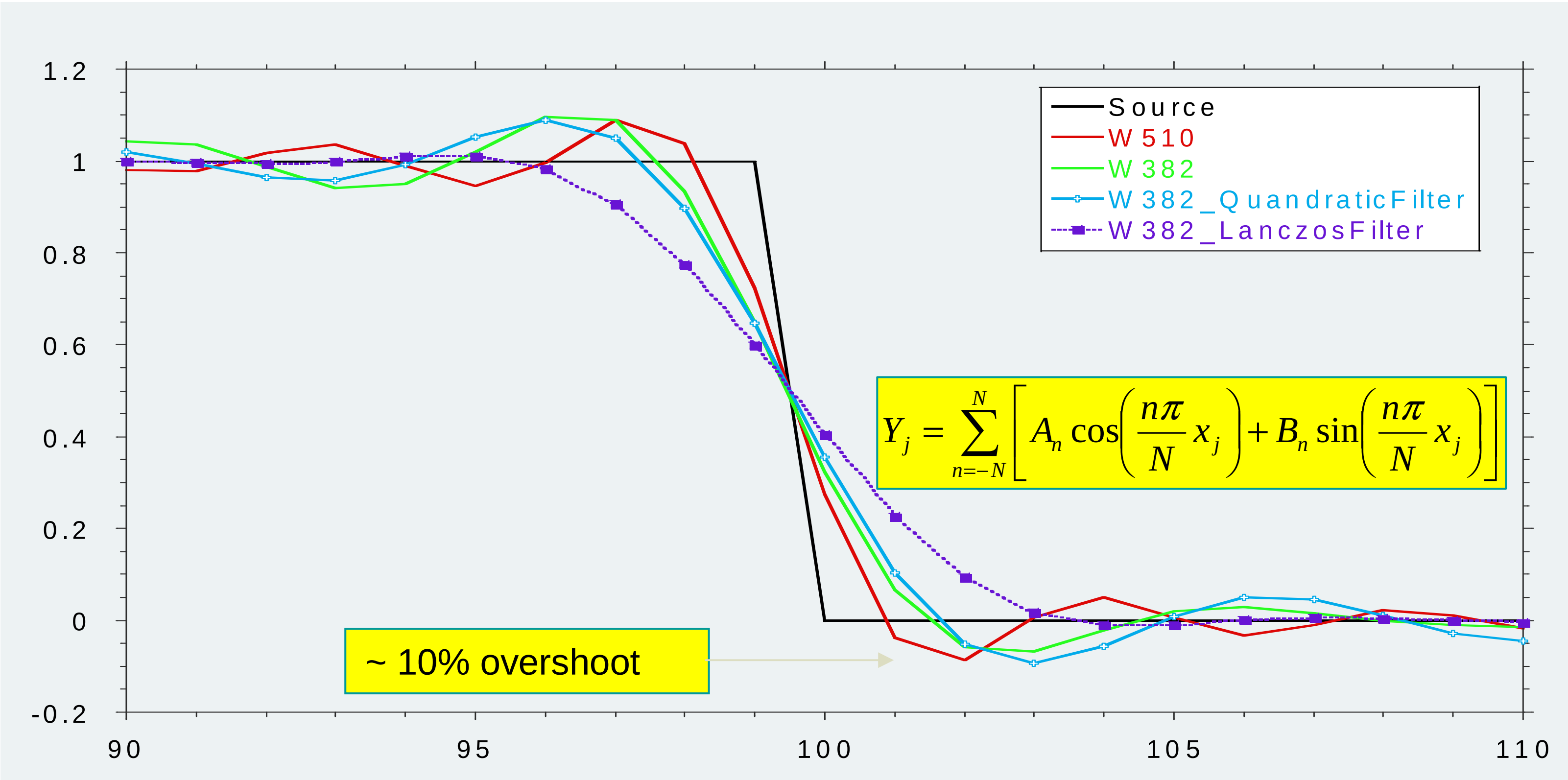
3. Spectral Transform



Set negative to zero, then run spectral transform

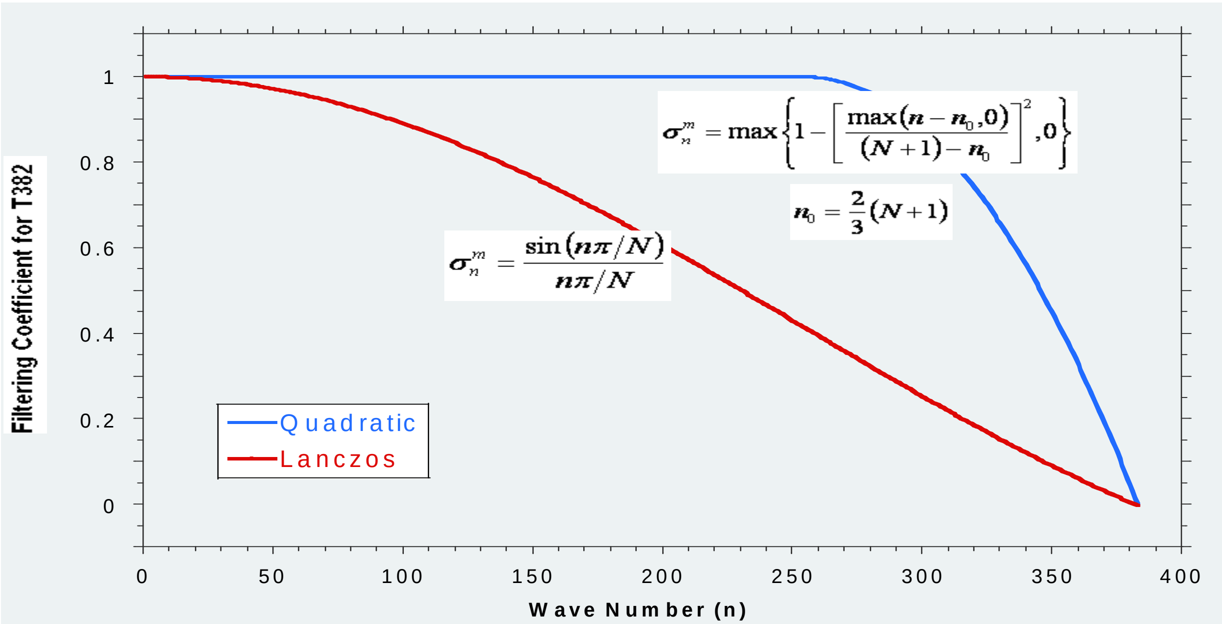
Gibbs

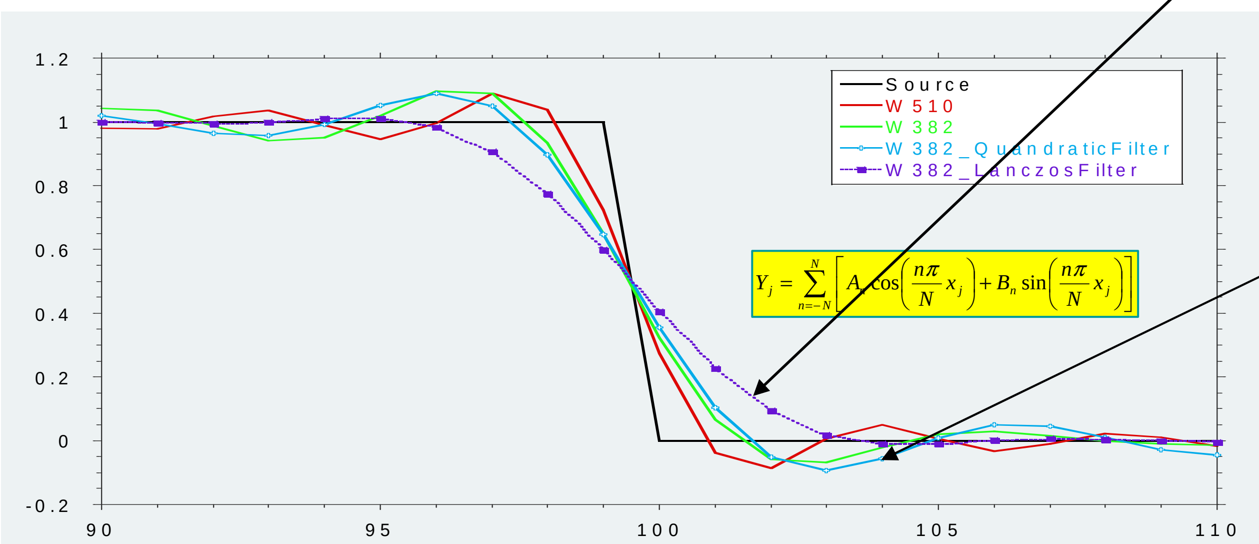
Of very small magnitude ~$\mathbf{10^{-11}}$ (g/g)



illustration

1. Spectral transform (truncation) produces Gibbs at points with discontinuity. In spectral models negative water vapor will always exist if it is included in the spectral transform.
2. The Gibbs becomes smaller in models with higher spectral resolution (compare W510 and W382)





Filters can be used to reduce the impact of Gibbs, however:

Lanczos Filter: is effective for reducing the Gibbs, but has large impact on long waves.

Quandratic Filter: preserves long waves, but is not effective for removing Gibbs.

4. Borrowing by Cloud Water

In subroutine precpd.f
(precipitation process from suspended cloud water/ice)

! move water from vapor to liquid should the liquid amount be negative

```
   do i = 1, im
      if (cwm(i,k) .lt. 0.) then
        q(i,k)   = q(i,k) + cwm(i,k)
        t(i,k)   = t(i,k) - elwv * rcp * cwm(i,k)
        cwm(i,k) = 0.
      endif
    enddo
```

This step creates negative water vapor if
1. q <= 0
2. 0 < q < abs(cwm)

Modified subroutine precpd.f (thanks to Moorthi)

The borrowing is allowed only if :

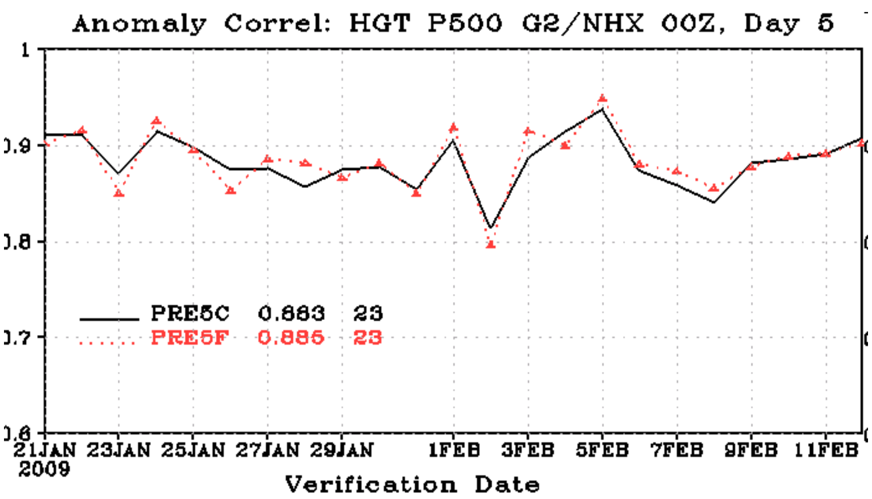
1. water vapor itself is positive and
2. the borrowing is limited to the available amount of water vapor

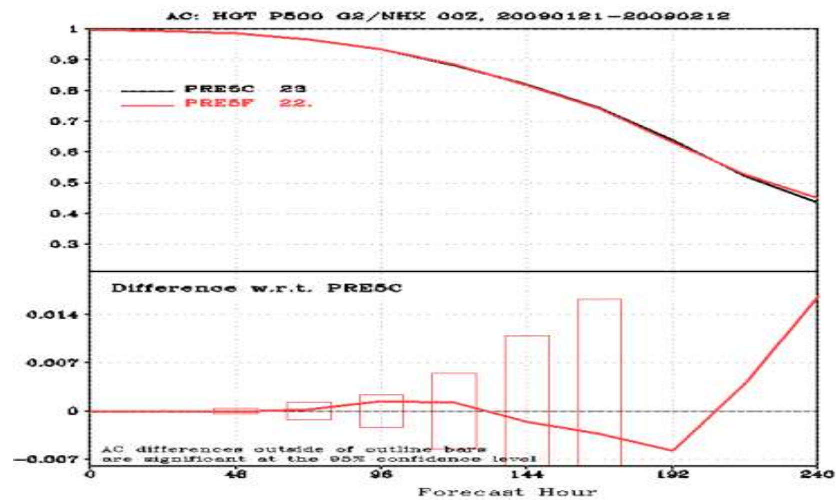
```
do i = 1, im
  if (cwm(i,k) < 0.) then
    tem      = q(i,k) + cwm(i,k)
    if (tem >= 0.0) then
      q(i,k)   = tem
      t(i,k)   = t(i,k) - elwv * rcp * cwm(i,k)
      cwm(i,k) = 0.
    elseif (q(i,k) > 0.0) then
      cwm(i,k) = tem
      t(i,k)   = t(i,k) + elwv * rcp * q(i,k)
      q(i,k)   = 0.0
    endif
  endif
enddo
```

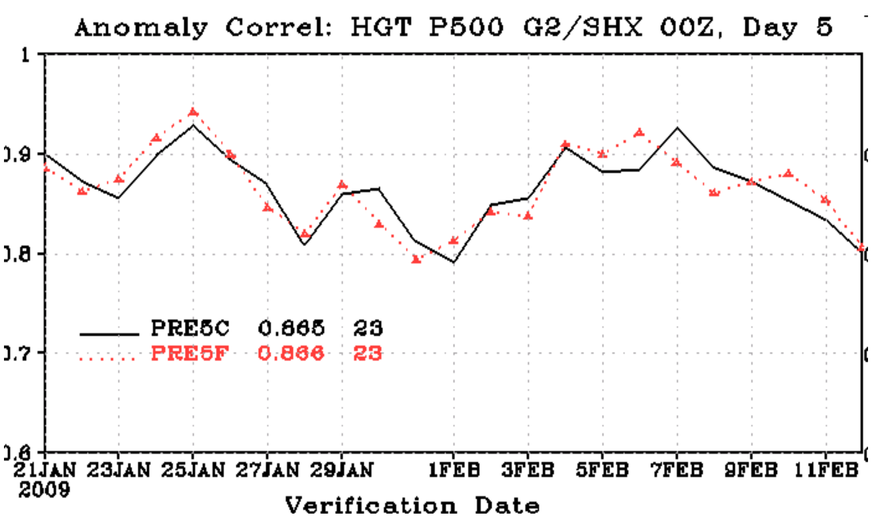
T574L64 Sensitivity Test on Cloud Water Borrowing

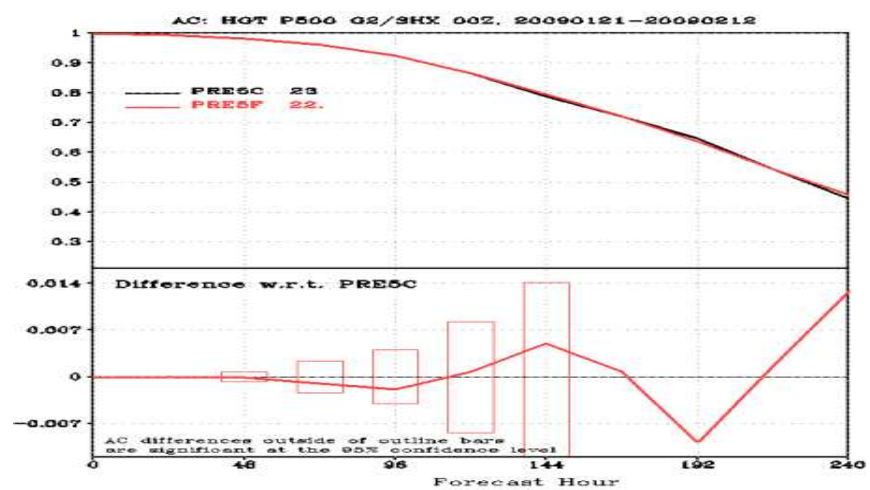
http://www.emc.ncep.noaa.gov/gmb/wx24fy/vsdb_glopara/pre5f/

10Jan2009 ~ 12Feb2009









T574L64 Sensitivity Test on Cloud Water Borrowing

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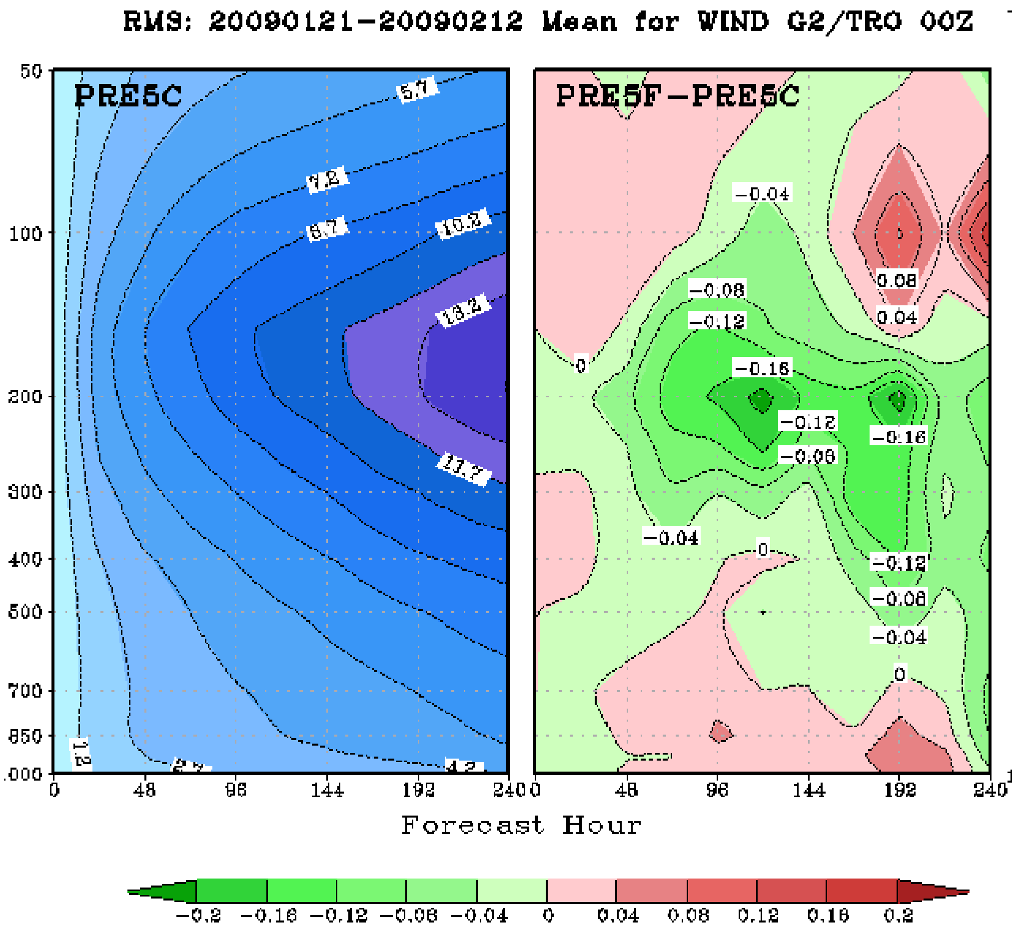
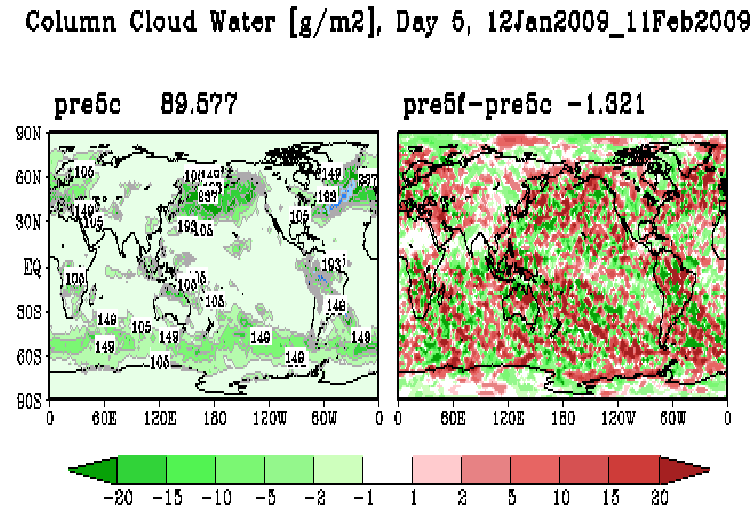




Conclusion:

The change in precpd.f shows no significant impact on the model's forecast skills

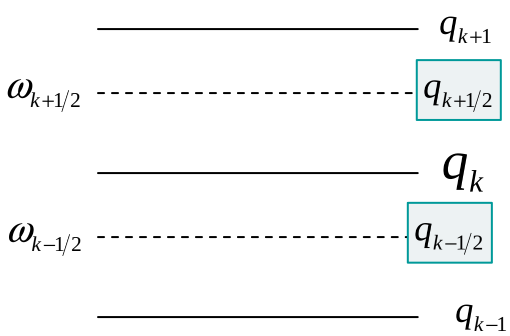
1. Vertical Advection

- The vertical advection scheme of tracers in the current GFS is central in space and leap-frog in time. It is not positive definite and can produce negative tracers. This is the major source of negative water vapor in the GFS.

- A **positive-definite** vertical advection scheme, the Van-Leer **flux-limited** scheme, is adopted. It is combined with a **new time-integration** method to eliminate negative water vapor from vertical advection in the current *Eulerain* GFS.

- Semi-Lagrangian is also positive definite. The future semi-Lagrangian GFS does not need the above Van-Leer flux-limited scheme.

Vertical Advection of Tracers: Current GFS Scheme



$$\frac{\partial q}{\partial t} = -\omega\frac{\partial q}{\partial p} = -\left(\frac{\partial \omega q}{\partial p} - q\frac{\partial \omega}{\partial p}\right)$$

Flux form conserves mass

$$A_k = \frac{1}{\Delta p_k}\left(\omega_{k-\frac{1}{2}} q_{k-\frac{1}{2}} - \omega_{k+\frac{1}{2}} q_{k+\frac{1}{2}}\right) - \frac{1}{\Delta p_k} q_k \left(\omega_{k-\frac{1}{2}} - \omega_{k+\frac{1}{2}}\right)$$

$$\Delta p_k = p_{k-\frac{1}{2}} - p_{k+\frac{1}{2}}$$

Currently GFS uses central differencing in space and leap-frog in time.

$$q_{k-\frac{1}{2}} = \frac{1}{2}\left(q_{k-1} + q_k\right)$$

$$A_k = \frac{1}{2\Delta p_k}\left(\omega_{k-\frac{1}{2}}\left(q_{k-1} - q_k\right) + \omega_{k+\frac{1}{2}}\left(q_k - q_{k+1}\right)\right)$$

The scheme is not positively definite for tracers and may produce negative tracers.

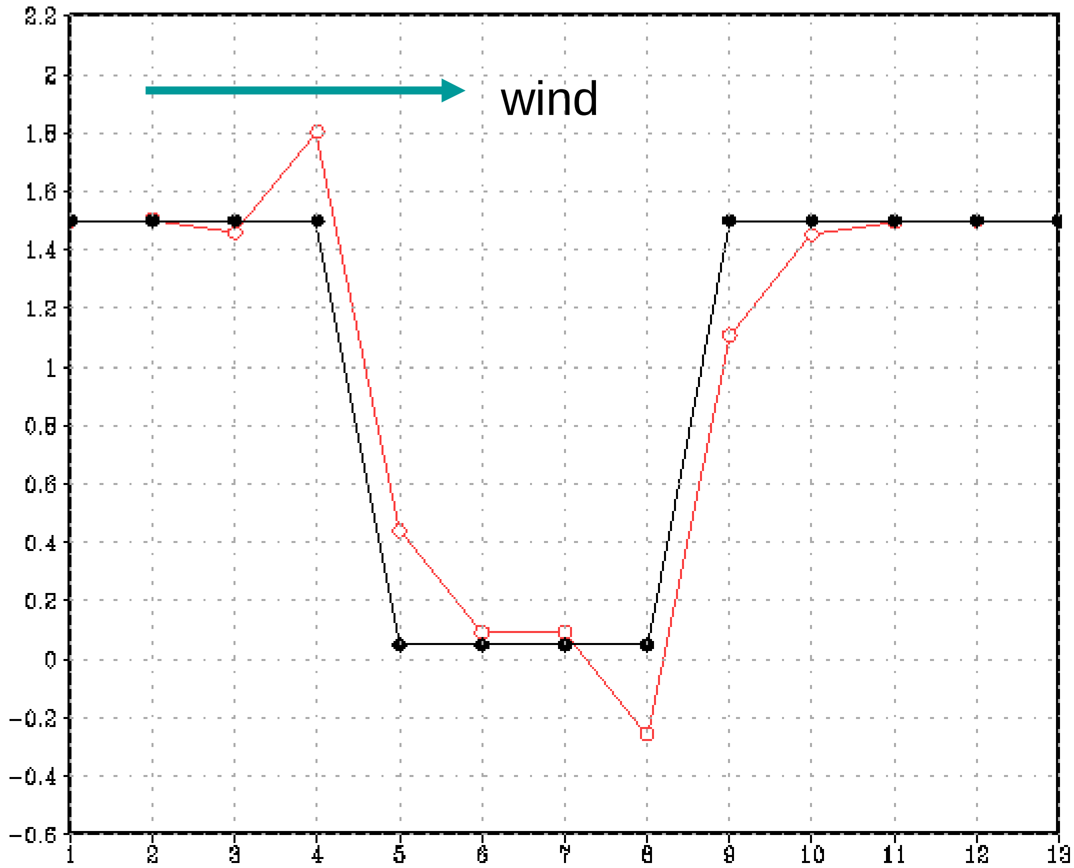
$$q_k^{n+1} = q_k^{n-1} - 2\Delta t \cdot A_k^n$$

Vertical Advection of Tracers: Current GFS Scheme

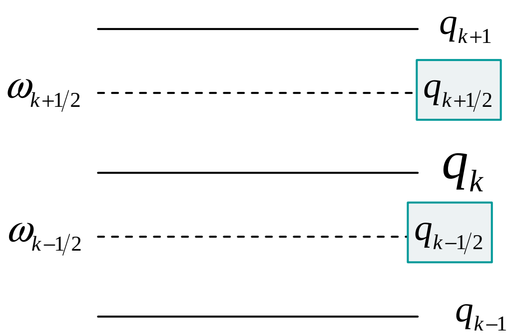
Idealized case:

Black: Initial distribution

Red: after a few steps of advection



Vertical Advection of Tracers: Upwind Scheme



$$\frac{\partial q}{\partial t} = -\omega \frac{\partial q}{\partial p} = -\left(\frac{\partial \omega q}{\partial p} - q \frac{\partial \omega}{\partial p} \right)$$

Flux form conserves mass

$$A_k = \frac{1}{\Delta p_k} \left(\omega_{k-\frac{1}{2}} q_{k-\frac{1}{2}} - \omega_{k+\frac{1}{2}} q_{k+\frac{1}{2}} \right) - \frac{1}{\Delta p_k} q_k \left(\omega_{k-\frac{1}{2}} - \omega_{k+\frac{1}{2}} \right)$$

For computational stability, upwind-in-space scheme must use forward-in-time integration.

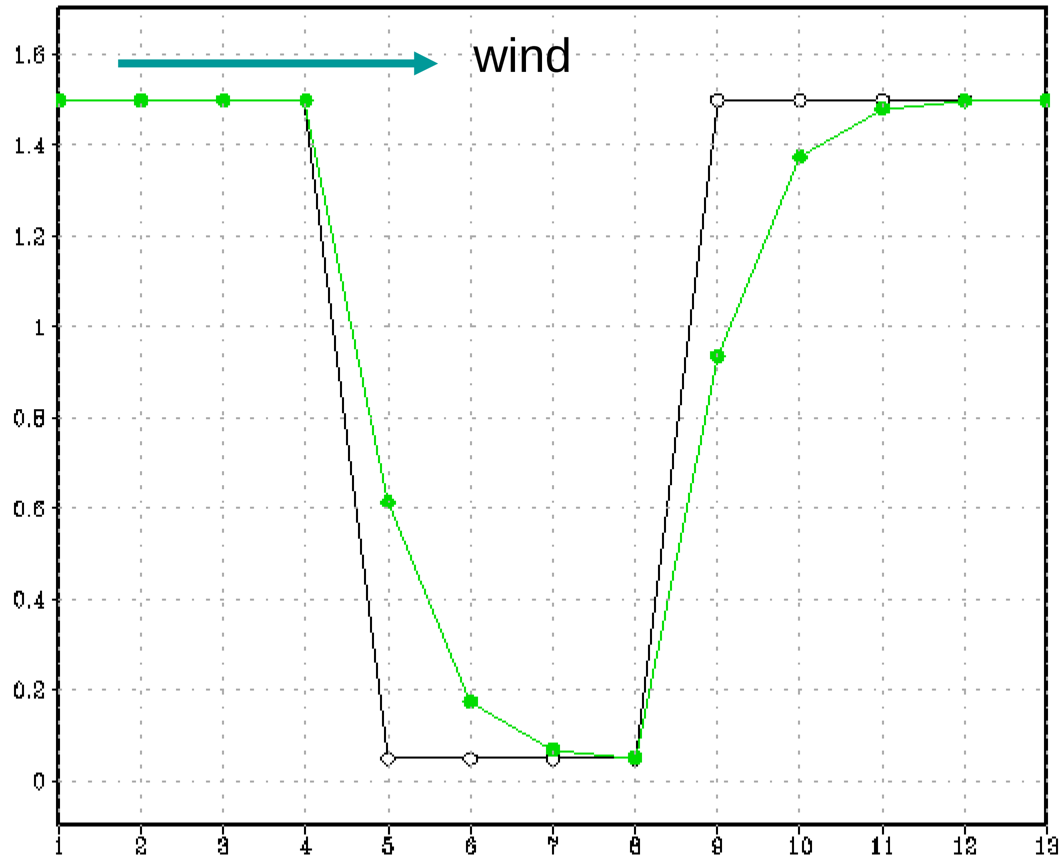
$$q_{k-\frac{1}{2}} = \begin{cases} q_{k-1} & \text{if } \omega_{k-1/2} < 0 \\ q_k & \text{if } \omega_{k-1/2} \geq 0 \end{cases}$$

$$q_k^{n+1} = q_k^n - \Delta t \cdot A_k^n$$

Vertical Advection of Tracers: Upwind

Idealized case

Up-wind scheme does not produce negative tracers, but has been known to be rather diffusive. It also requires a change in the GFS time integration scheme



Vertical Advection of Tracers: Flux-Limited Scheme

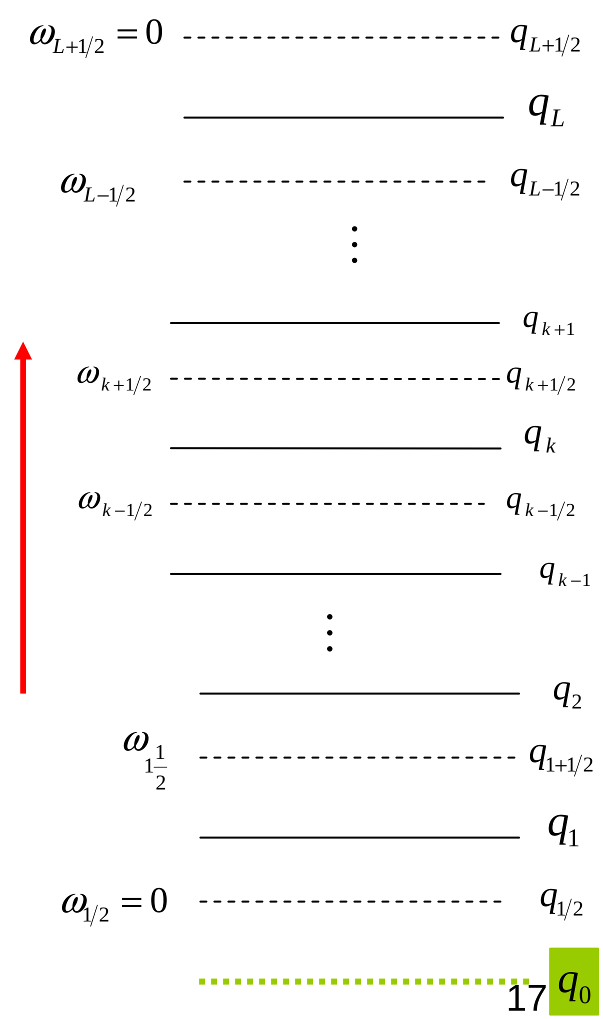
if $\omega_{k-1/2} < 0$ $\quad q_{k-1/2} = q_{k-1} + \Phi^{-}_{k-1}\left(q^{H}_{k-1/2} - q_{k-1}\right)$ $\quad$ Thuburn (1993)

$$q^{H}_{k-1/2} = \frac{1}{2}\left(q_k + q_{k-1}\right)$$

$$\Phi^{-}_{k-1} = \frac{r^{-}_{k-1} + \left|r^{-}_{k-1}\right|}{1 + \left|r^{-}_{k-1}\right|}$$

Van Leer (1974) Limiter, anti-diffusive term

$$r^{-}_{k-1} = \frac{q_{k-2} - q_{k-1}}{q_{k-1} - q_k} = \frac{\Delta q_{k-2}}{\Delta q_{k-1}}$$



Special boundary conditions

for $k = 1$ $\quad \omega_{1/2} q_{1/2} = 0$ $\quad$ since $\quad \omega_{1/2} = 0$

for $k = 2$

$$q_{3/2} = q_1 + \Phi^{-}_{1}\left(q^{H}_{3/2} - q_1\right)$$

$$\Phi^{-}_{1} = \frac{r^{-}_{1} + \left|r^{-}_{1}\right|}{1 + \left|r^{-}_{1}\right|} \qquad r^{-}_{1} = \frac{q_0 - q_1}{q_1 - q_2} = \frac{\Delta q_0}{\Delta q_1}$$

$$q_0 = \begin{cases} \max\left(0, 2q_1 - q_2\right) & \text{if } q_1 \geq 0 \\ \min\left(0, 2q_1 - q_2\right) & \text{if } q_1 < 0 \end{cases}$$

Vertical Advection of Tracers: Flux-Limited Scheme

if $\omega_{k-1/2} \geq 0$

$$q_{k-1/2} = q_k + \Phi_k^+ \left(q_{k-1/2}^H - q_k \right)$$

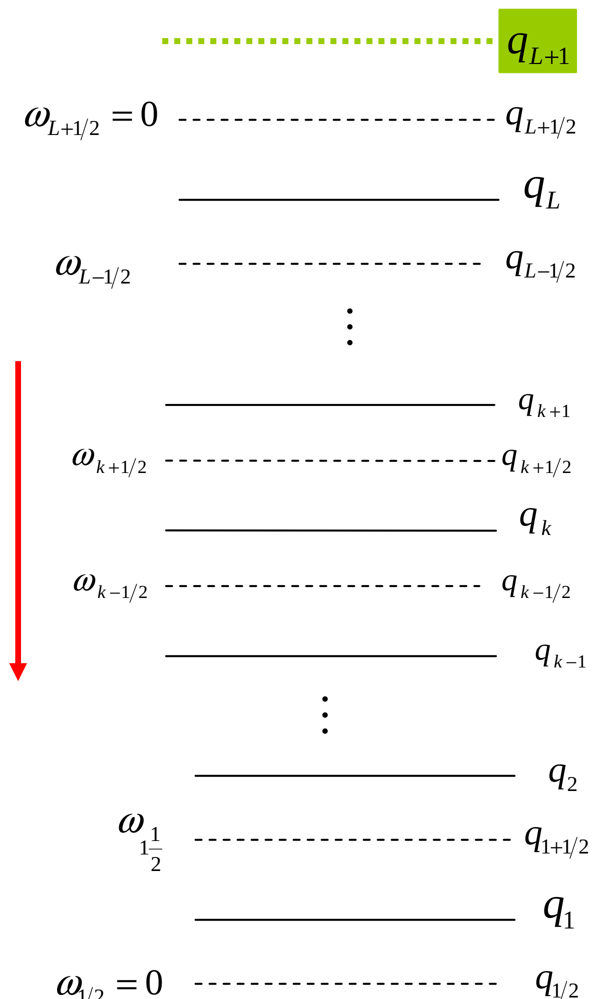
Thuburn (1993)

$$q_{k-1/2}^H = \frac{1}{2}\left(q_k + q_{k-1} \right)$$

$$\Phi_k^+ = \frac{r_k^+ + \left| r_k^+ \right|}{1 + \left| r_k^+ \right|}$$

Van Leer (1974) Limiter, anti-diffusive term

$$r_k^+ = \frac{q_k - q_{k+1}}{q_{k-1} - q_k} = \frac{\Delta q_k}{\Delta q_{k-1}}$$



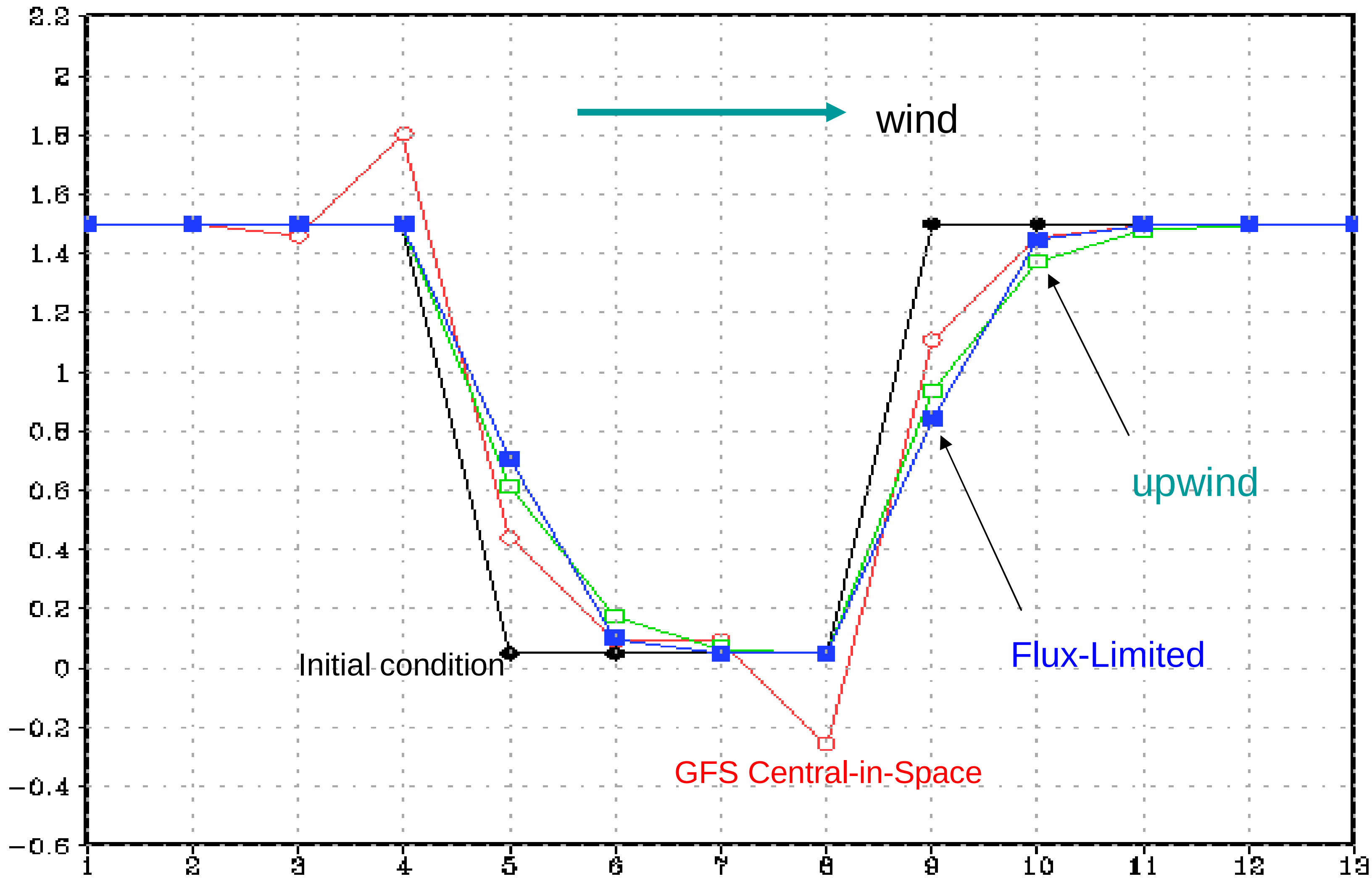
Special boundary condition for $k = \mathrm{L}$

$$q_{L-1/2} = q_L + \Phi_L^+ \left(q_{L-1/2}^H - q_L \right)$$

$$\Phi_L^+ = \frac{r_L^+ + \left| r_L^+ \right|}{1 + \left| r_L^+ \right|} \qquad r_L^+ = \frac{q_L - q_{L+1}}{q_{L-1} - q_L} = \frac{\Delta q_L}{\Delta q_{L-1}}$$

$$q_{L+1} = \begin{cases} \max \left(0\,,\ 2\,q_L - q_{L-1} \right) & \text{if} \quad q_L \geq 0 \\ \min \left(0\,,\ 2\,q_L - q_{L-1} \right) & \text{if} \quad q_L < 0 \end{cases}$$

Vertical Advection of Tracers: Idealized Case Study



Horizontal + Vertical Advection of Tracers: Computational Instability

Current GFS, leap-frog in time and central in space

$$\frac{\partial q}{\partial t} = -\vec{V}_h \cdot \nabla_h q - \omega \frac{\partial q}{\partial p} = -B_k^n - A_k^n$$

$$q_k^{n+1} = q_k^{n-1} - 2\Delta t \cdot B_k^n - 2\Delta t \cdot A_k^n$$

B_k^n horizontal advection, computed in spectral form

A_k^n vertical advection, computed in finite-difference form with **central** differencing in space

The scheme is stable as long as the CFL condition is satisfied, but it is **not positively defined for tracers.**

If leap-frog time integration is combined with upwind or flux-limited scheme in space, the advection becomes **unconditionally unstable**.

Horizontal + Vertical Advection of Tracers: Computational Instability

Flux-Limited Horizontally-Filtered Scheme, **forward in time**

$$\frac{\partial q}{\partial t} = -\vec{V}_h \cdot \nabla_h q - \omega \frac{\partial q}{\partial p} = -B_k^n - A_k^n$$

$$q_k^{n+1} = q_k^n - \Delta t \cdot B_k^{n+\frac{1}{2}} - \Delta t \cdot A_k^n$$

$$B_k^{n+\frac{1}{2}} = \left(\frac{3}{2} + \varepsilon\right) B_k^n - \left(\frac{1}{2} + \varepsilon\right) B_k^{n-1}$$

Adam-Bashforth filter

B_k^n horizontal advection, computed in spectral form with **central** differencing in space

A_k^n vertical advection, computed in finite-difference form with **flux-limited** scheme in space

Still unstable after about 30 days of integration

Horizontal + Vertical Advection of Tracers: Computational Instability

Flux-Limited Vertically-Filtered Scheme, **central in time**

$$\frac{\partial q}{\partial t} = -\vec{V}_h \cdot \nabla_h q - \omega \frac{\partial q}{\partial p} = -B_k^n - A_k^n$$

$$q_k^{n+1} = q_k^{n-1} - 2\Delta t \cdot B_k^n - \Delta t \cdot A_k^{n*}$$

$$A_k^{n*} = \frac{1}{2}\left(A_k^n + A_k^{n-1}\right)$$

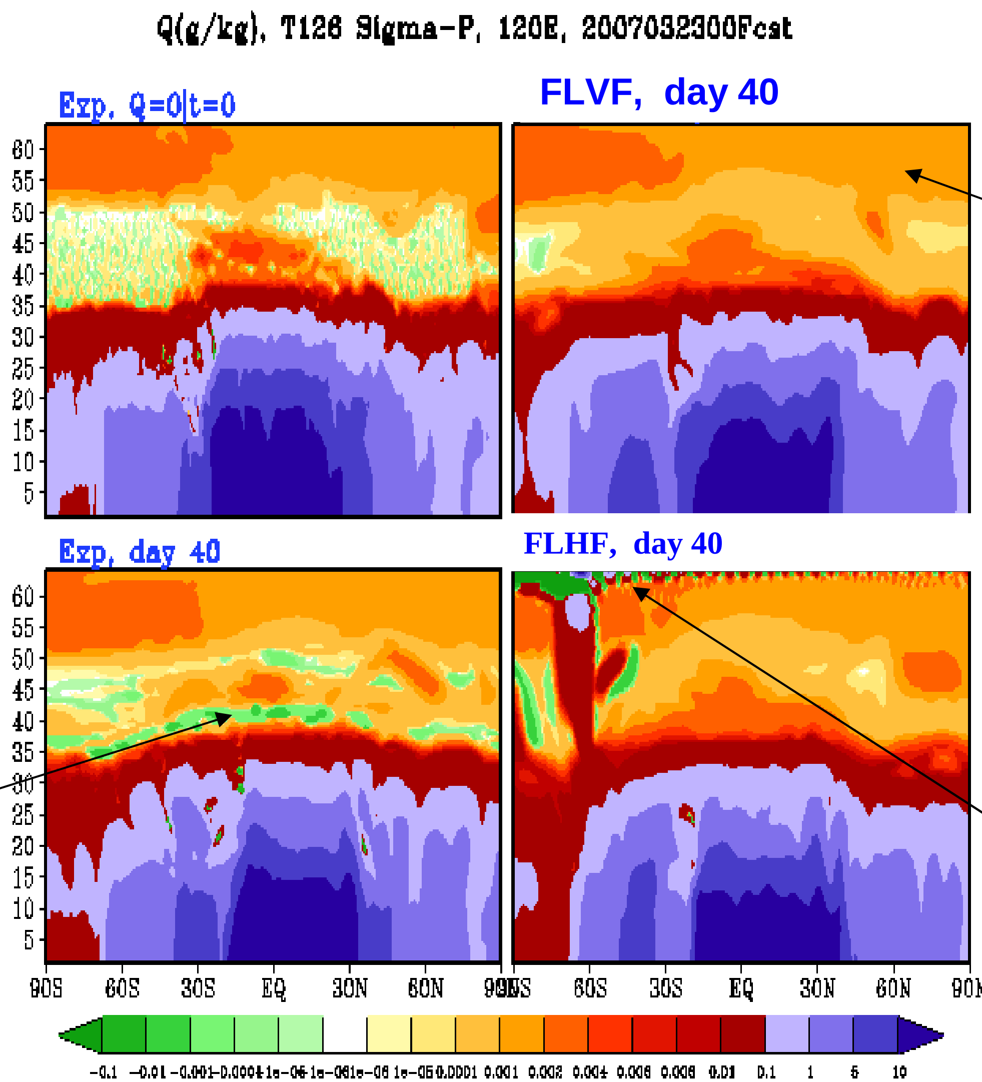
New method **thanks to Henry Juang**

B_k^n horizontal advection, computed in spectral form with **central** differencing in space

A_k^n vertical advection, computed in finite-difference form with **flux-limited** scheme in space

Stable ! A 150-day integration of GFS T126 encountered no problem

GFS T126L64 Climate Runs, Forecasts without Data Assimilation



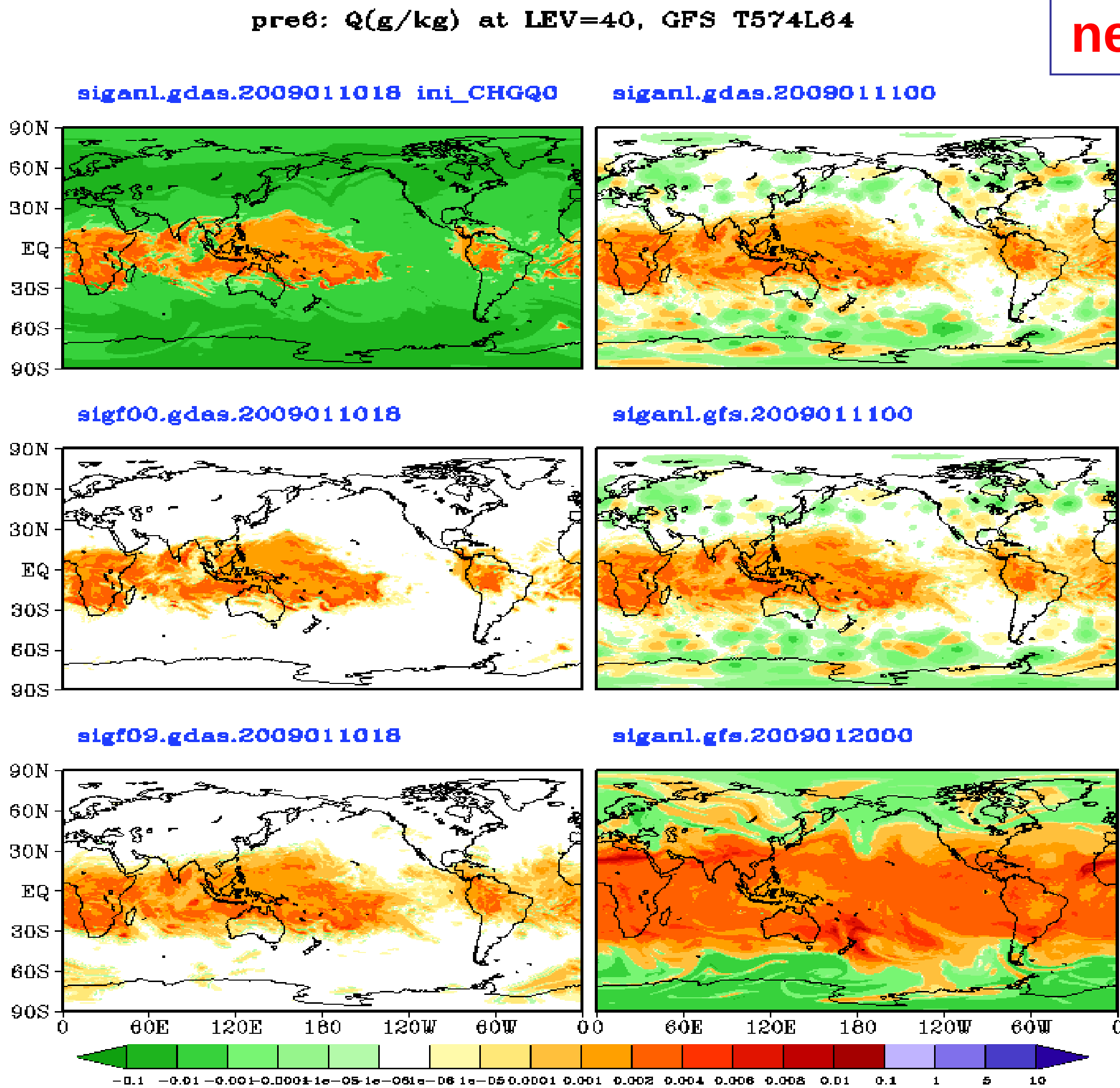
Flux-Limited Vertically-Filtered Scheme: flux-limited in space and central in time. The scheme is stable, and does not generate negative tracers.

GFS Cntl: negative tracers

Flux-Limited Horizontally-Filtered (Adams-Bashforth) Scheme: flux-limited in space and forward in time. Unstable for “climate” runs.

GFS T574L64 Test with Data Assimilation

GSI also produces negative water vapor



Initial condition
2009011018 cycle

Next GDAS cycle
After **GSI anal** step

Run CHGRES, remove negative q

Next GFS cycle
After **GSI anal** step

9 hours of GDAS fcst, with the Flux-Limited Scheme and modified precpd.f

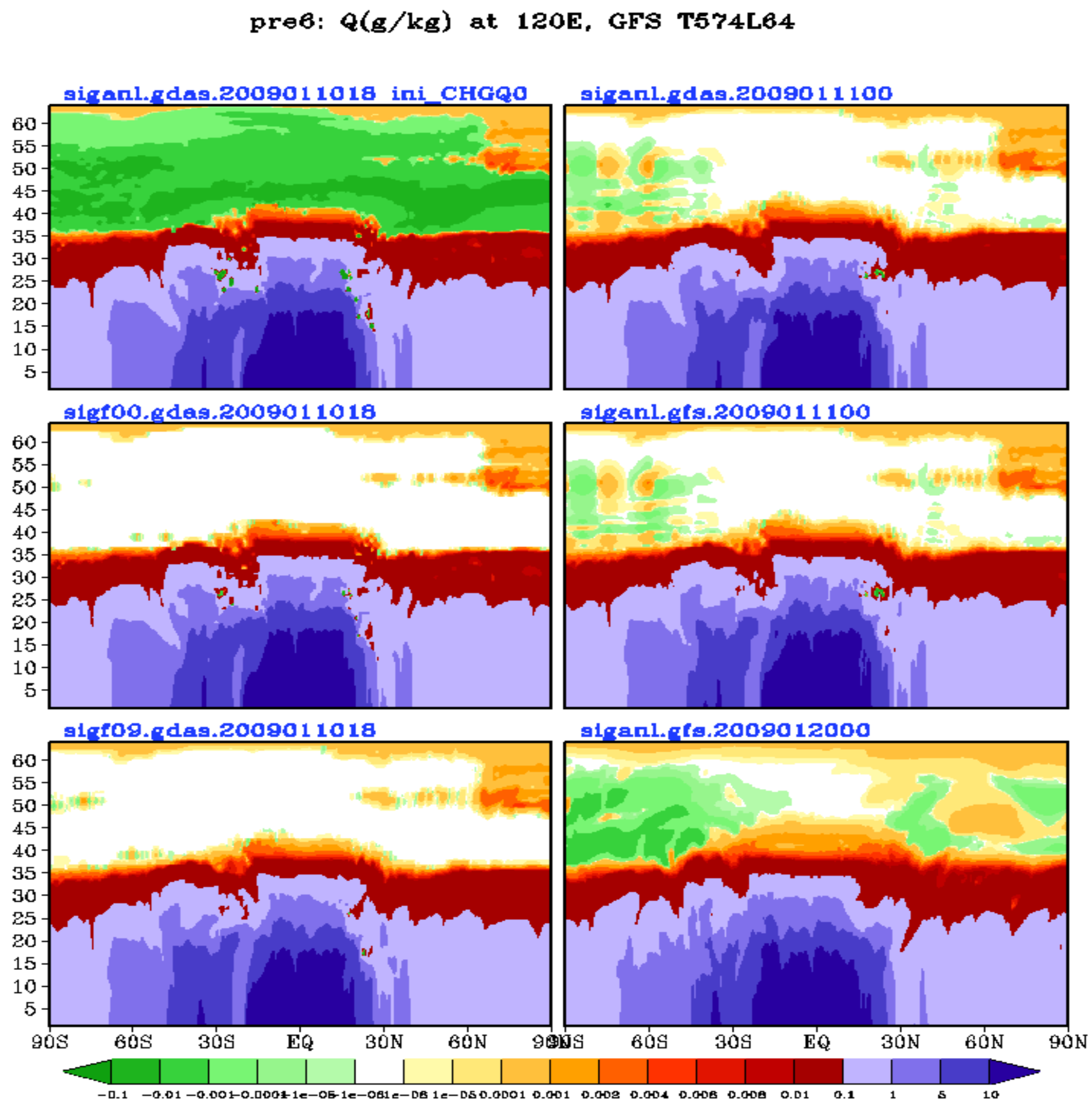
After 10 days of cycling

GFS T574L64 Test with Data Assimilation

Initial condition
2009011018 cycle

Run CHGRES, remove negative q

9 hours of GDAS fcst, with the Flux-Limited Scheme and modified precpd.f



Next GDAS cycle
After **GSI anal** step

Next GFS cycle
After **GSI anal** step

After 10 days of cycling

GSI also produces negative water vapor

2. GSI Data Assimilation

GSI also produces negative water vapor

Jim Jung and Russ Treadon suggested to tune the following two parameters in GSI exglobal_analysis.sh.sms script

Current default:	factqmin=0.005,	factqmax=0.005
New values:	factqmin=30	factqmax=10

Russ wrote: The two parameters represent weighting factors which scale the negative moisture (factqmin) and supersaturated moisture (factqmax) penalty terms. The larger either factor is, the larger the contribution from this penalty term. Setting either parameter to zero turns off the given moisture constraint penalty term. The negative and supersaturated moisture penalty terms are a summation of the squared value of all negative or saturated RH values in the 3d analysis grid. The factqmin (factqmax) term multiplies each product in the sum.

Jim Jung Wrote: I tried several values (orders of magnitude) for both factqmax and factqmin. Factqmax was set to a value that generates about the same number of supersaturated points as are in the 24 hour forecast has. Factqmin is much more difficult. If you have a lot of negative moisture points, a large factqmin can stop convergence. I expect both factqmax and factqmin will have to be re-tested as changes are made to the moisture field.

GFS T574L64 Test with GSI Tuning

factqmin=30 factqmax=10

Initial condition 2009011018 cycle

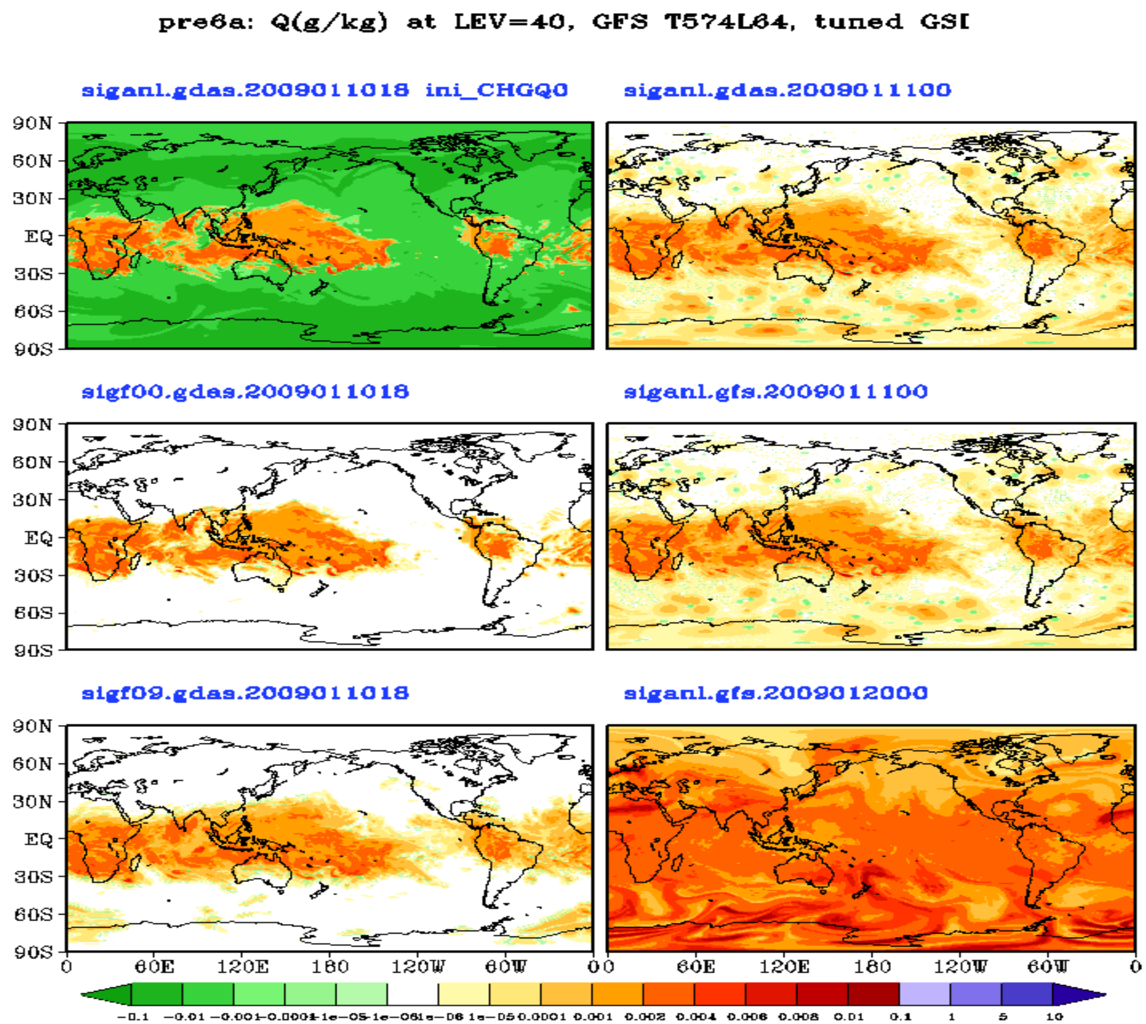
Next GDAS cycle After **GSI anal** step

Run CHGRES, remove negative q

Next GFS cycle After **GSI anal** step

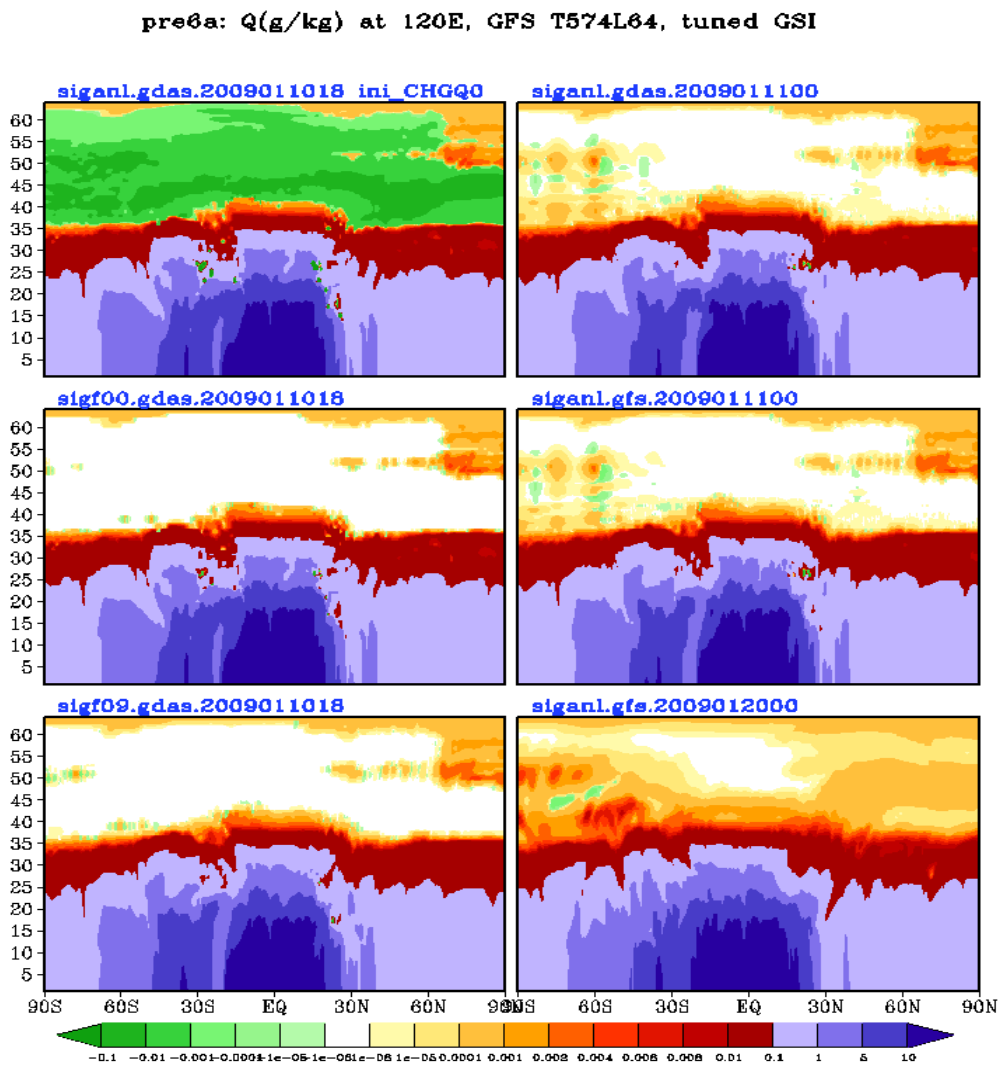
9 hours of GDAS fcst, with the Flux-Limited Scheme and modified precpd.f

After 10 days of cycling



GFS T574L64 Test with GSI Tuning

factqmin=30 factqmax=10



Initial condition
2009011018 cycle

Run CHGRES, remove negative q

9 hours of GDAS fcst, with the Flux-Limited Scheme and modified precpd.f

Next GDAS cycle
After **GSI anal** step

Next GFS cycle
After **GSI anal** step

After 10 days of cycling

GFS T574L64 Parallel Experiments

11 Jan 2009 ~ 28 Feb 2009, with data assimilation

Pre5e: the latest T574L64 Eulerian GFS

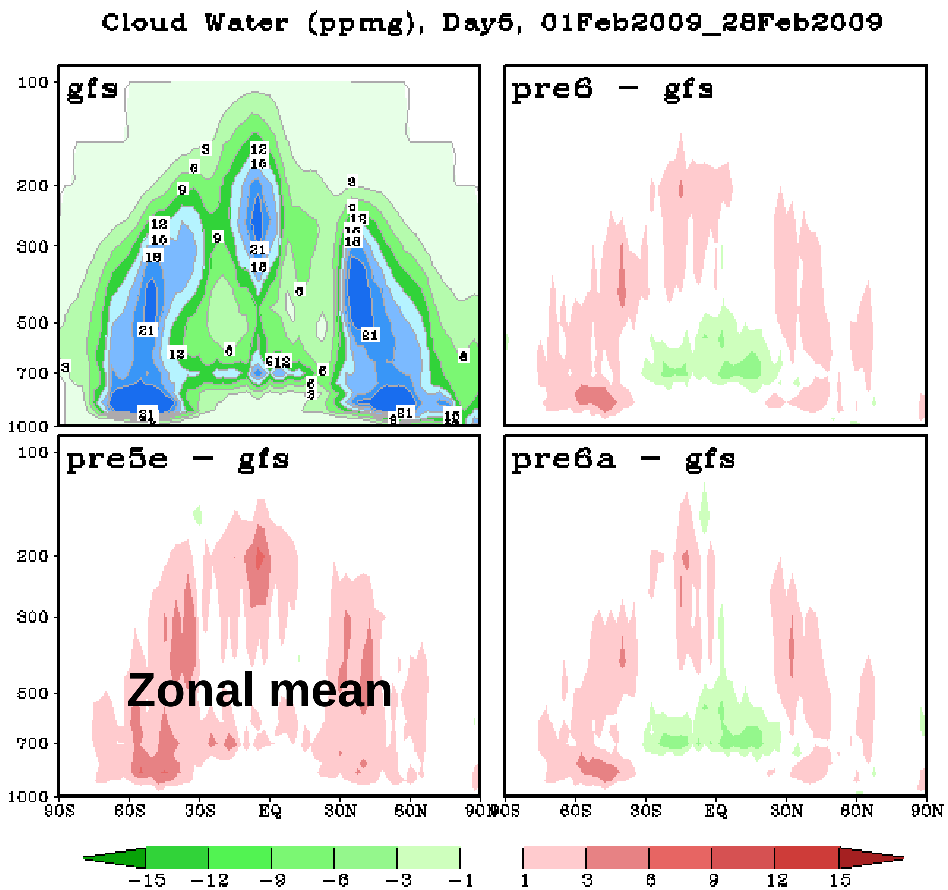
Pre6: as pre5e, except with Flux-Limited Vertical Advection + new precpd.f

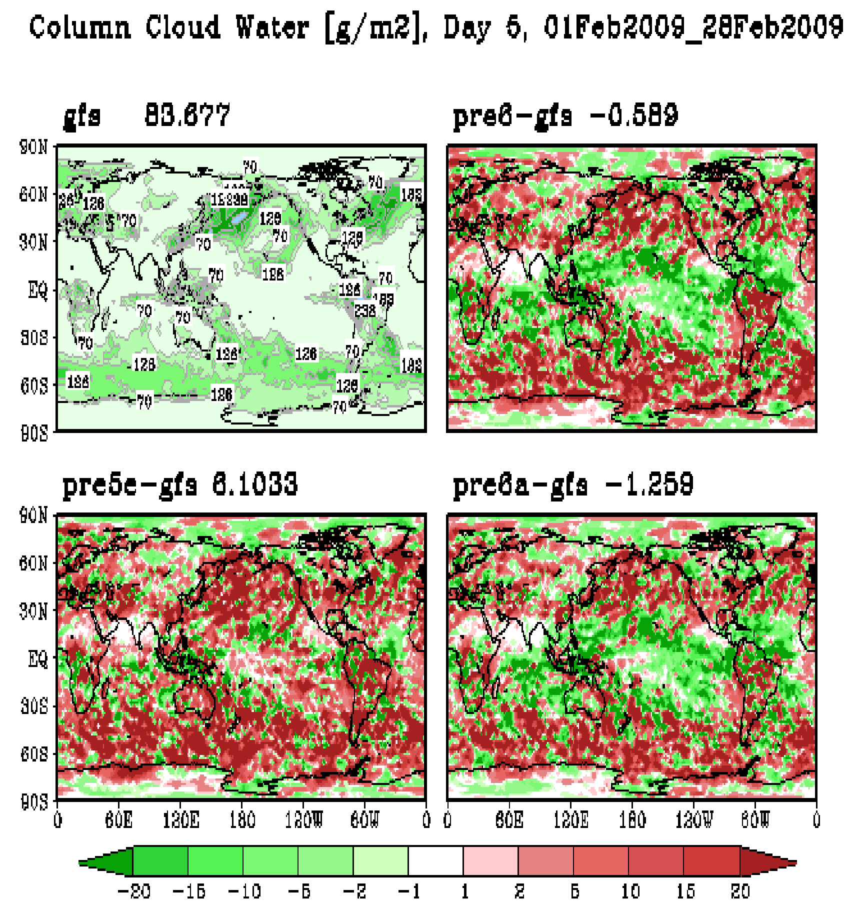
Pre6a: as pre6, except with tuned GSI factqmin and factqmax

http://www.emc.ncep.noaa.gov/gmb/wx24fy/vsdb_glopara/pre6/
http://www.emc.ncep.noaa.gov/gmb/wx24fy/vsdb_glopara/pre6a/

Cloud Water

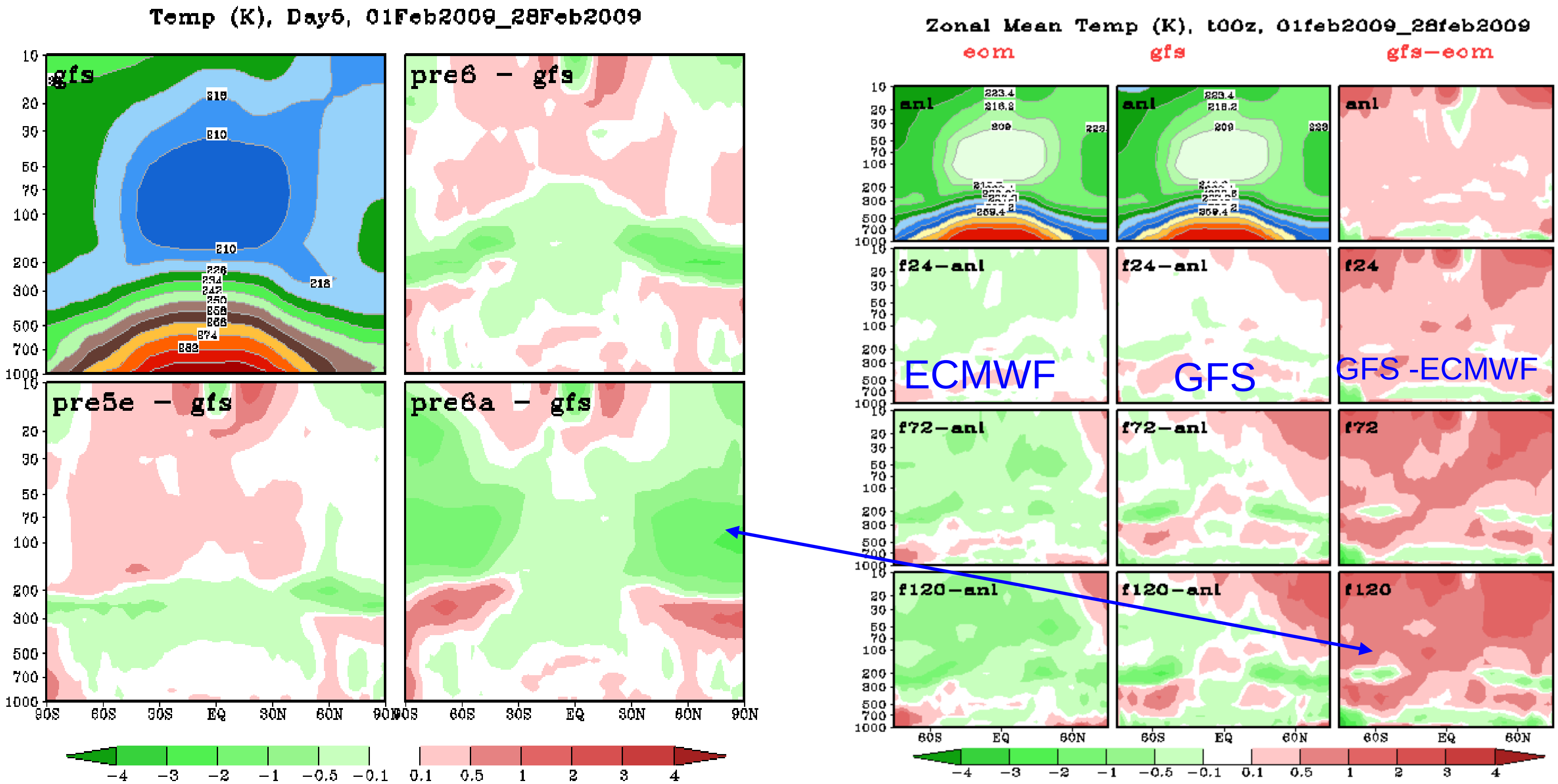
Pre6 – pre5e = - 6.69





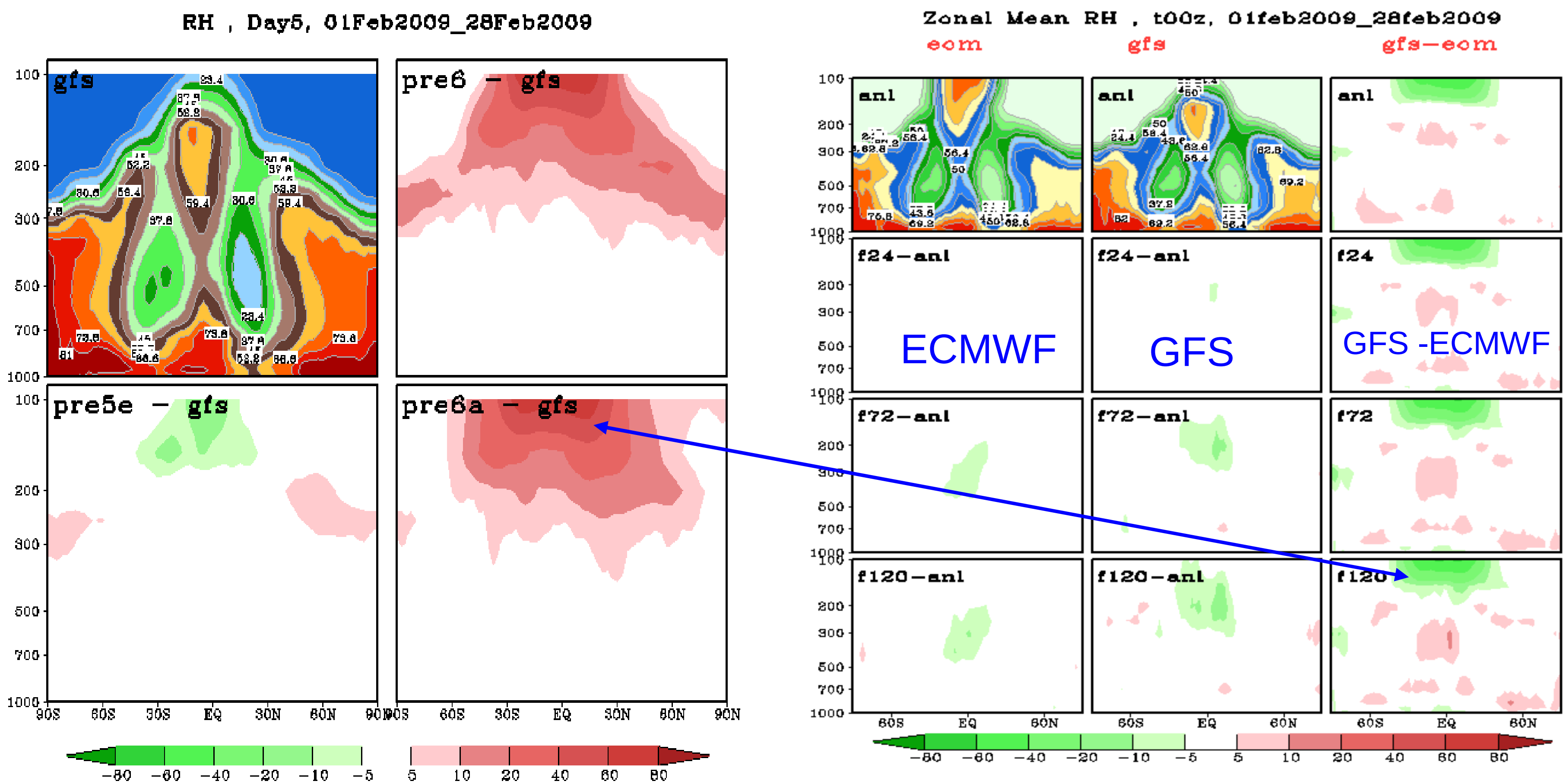
- Higher resolution GFS (T574) has more cloud water
- Flux-limited scheme **reduces** cloud water, especially in the tropical lower troposphere.

Zonal Mean Temperature



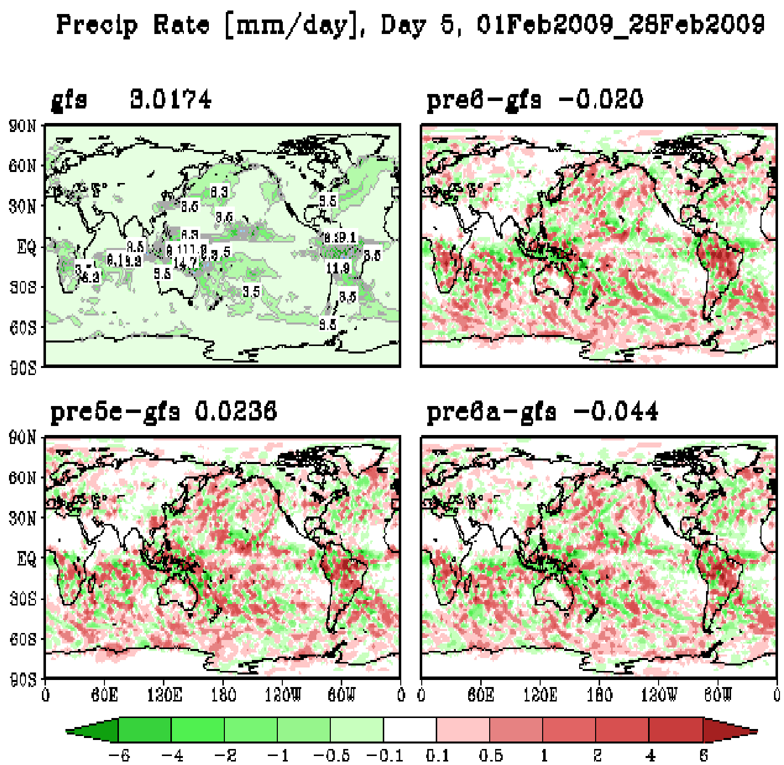
- Removing negative moisture **cools** the stratosphere. **Jim Jung** also found similar response in his experiments.
- Current GFS is always warmer than ECMWF in the stratosphere.

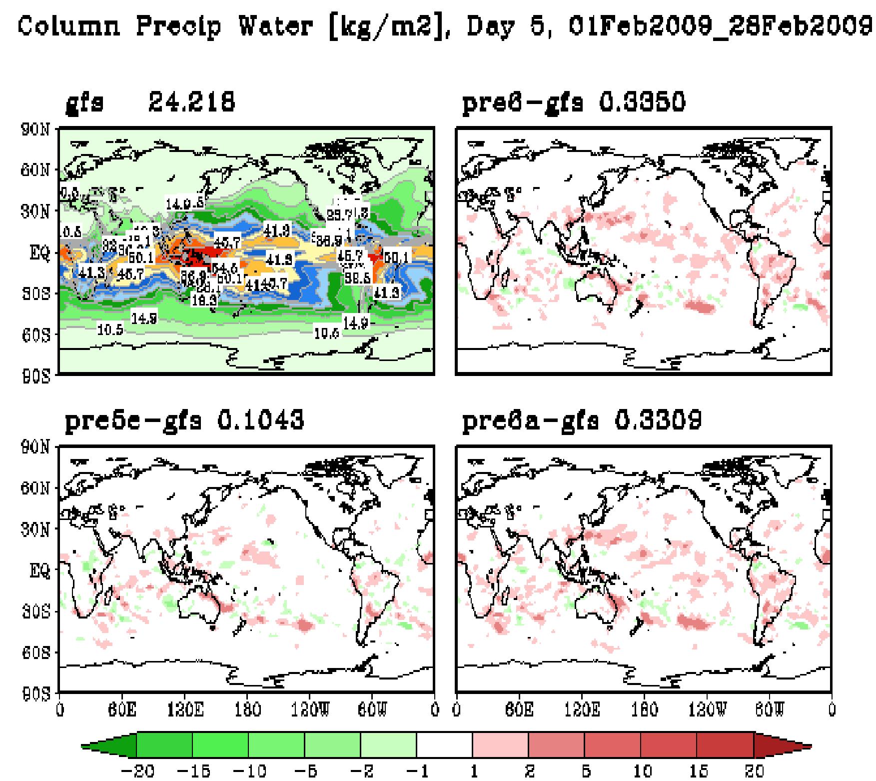
Zonal Mean RH



- Removing negative moisture **increase RH** near the tropical tropopause (lower T + higher q).
- This change actually moves the GFS closer to the ECMWF model

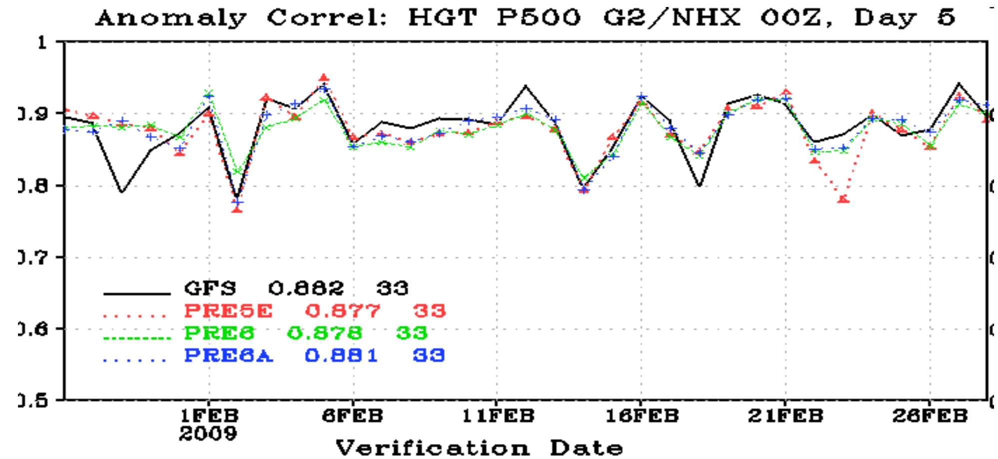
Rainfall and Precipitable Water

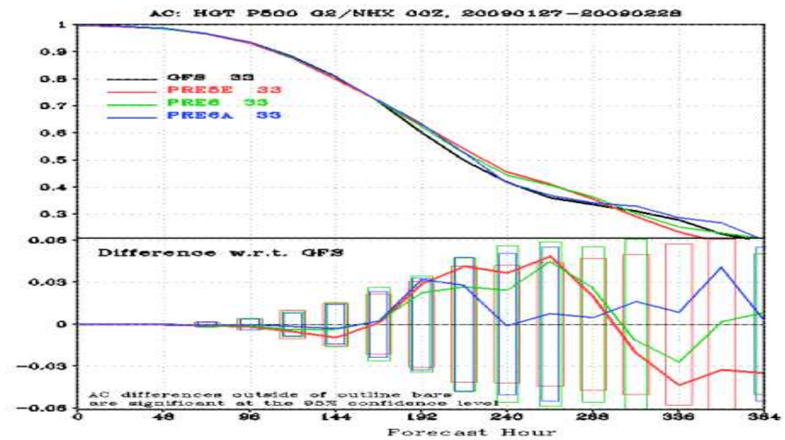


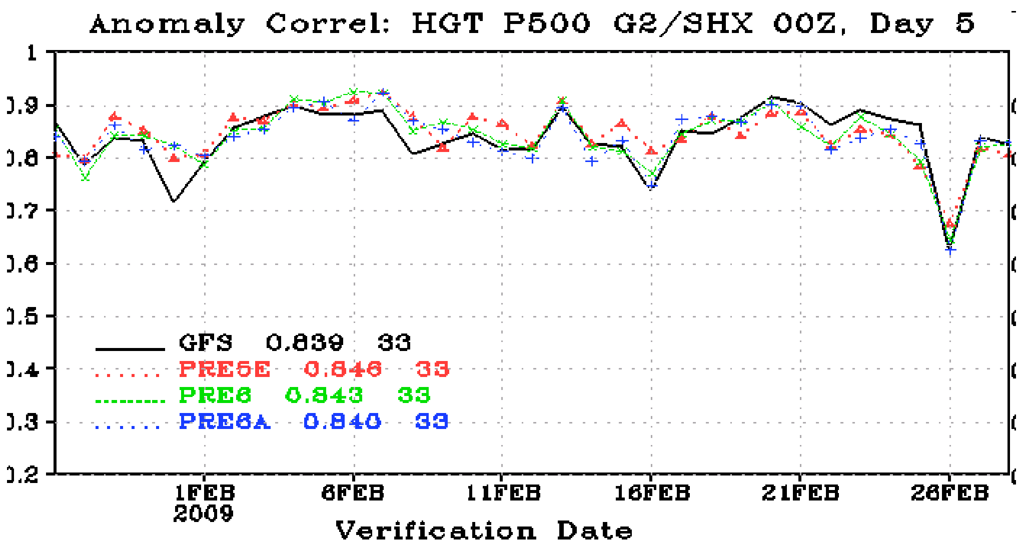


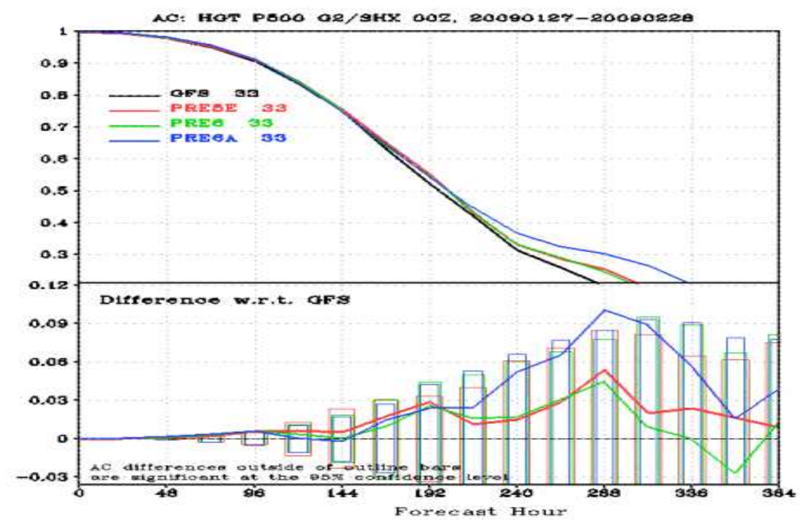
- Removing negative moisture **reduces precip** **rate, and** **increase precipitable water**

500-hPa HGT AC



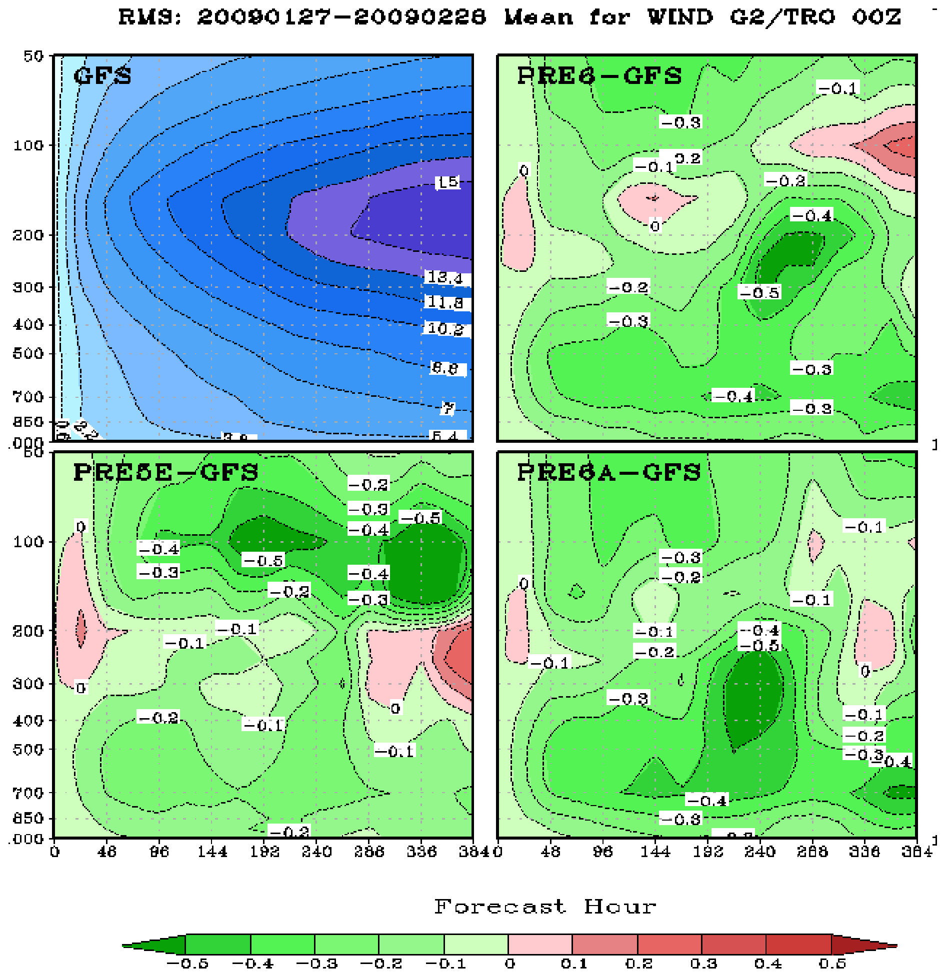


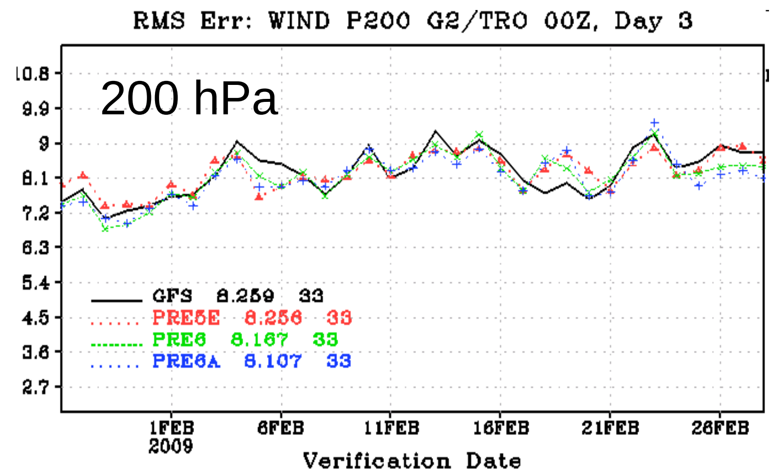


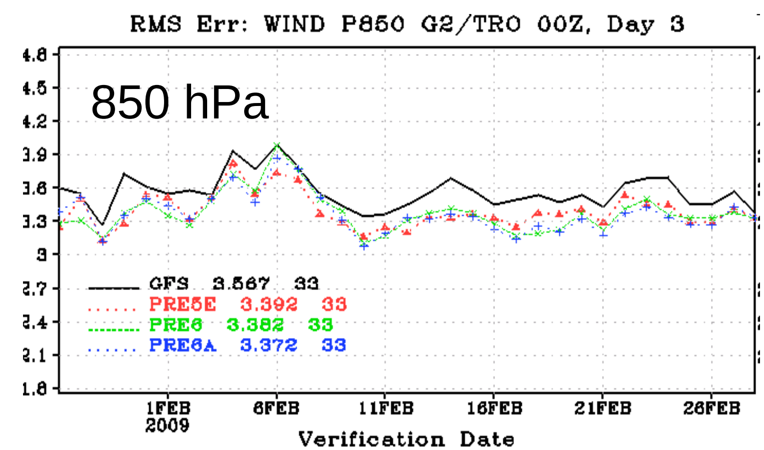


- No significant differences in week one, slightly better in week two

Tropical Wind RMSE

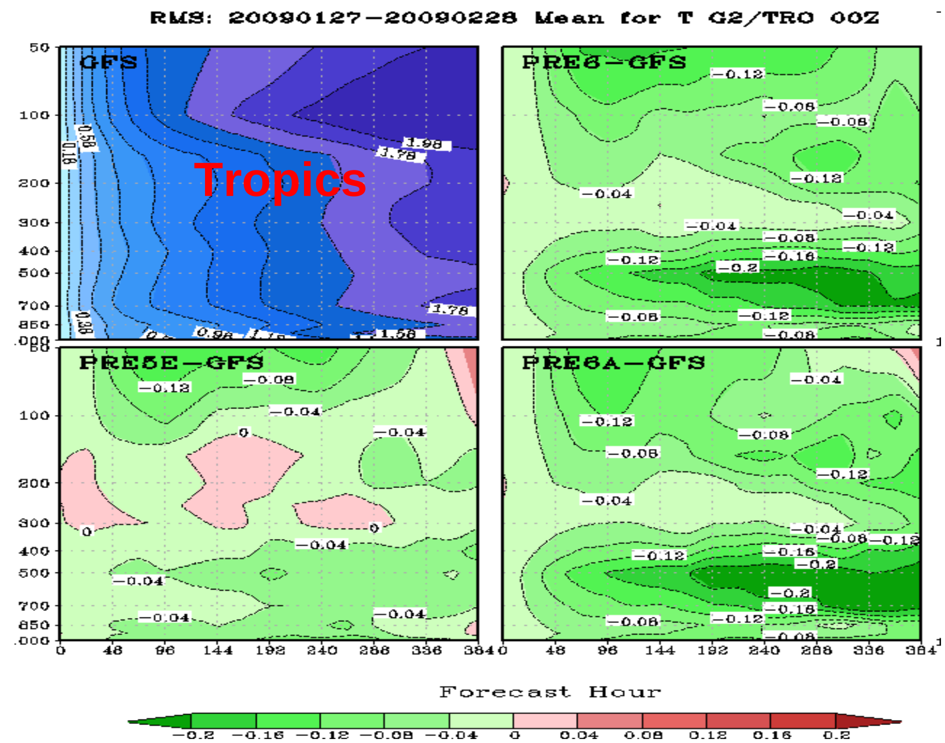




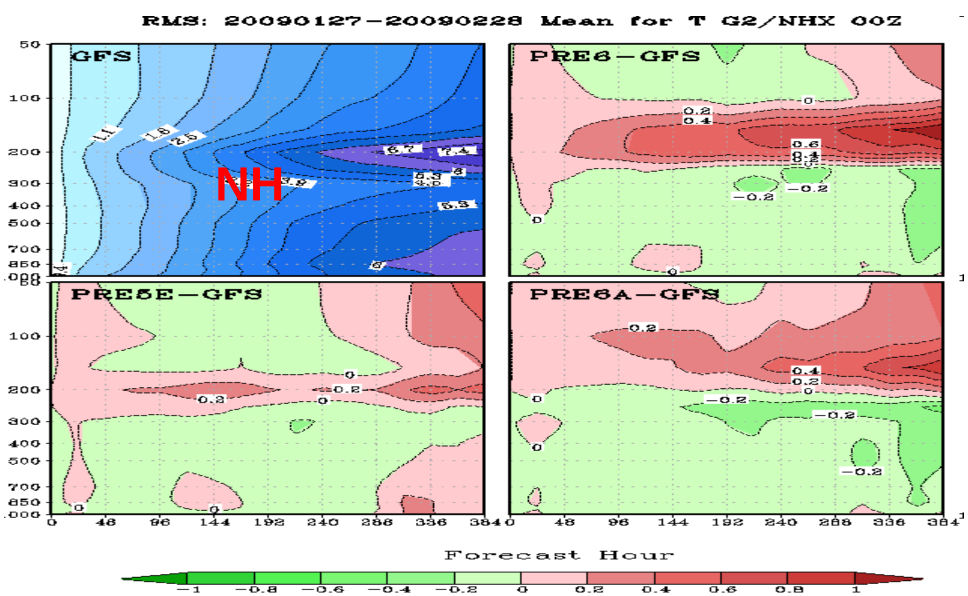


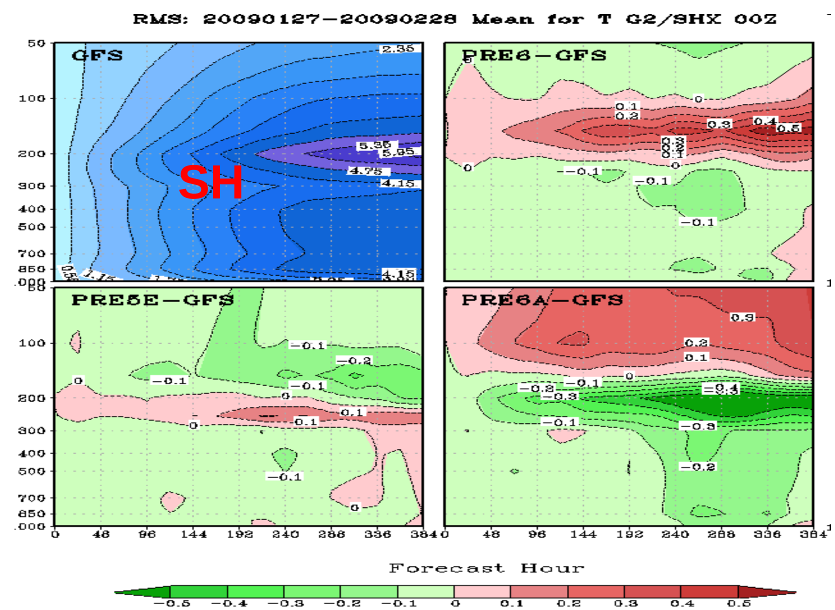
- All T574 runs have smaller tropical wind RMSE than the current operational GFS
- Removing negative moisture further reduced wind RMSE in the lower tropical troposphere, but increased wind RMSE near 100 hPa.

Temperature RMSE

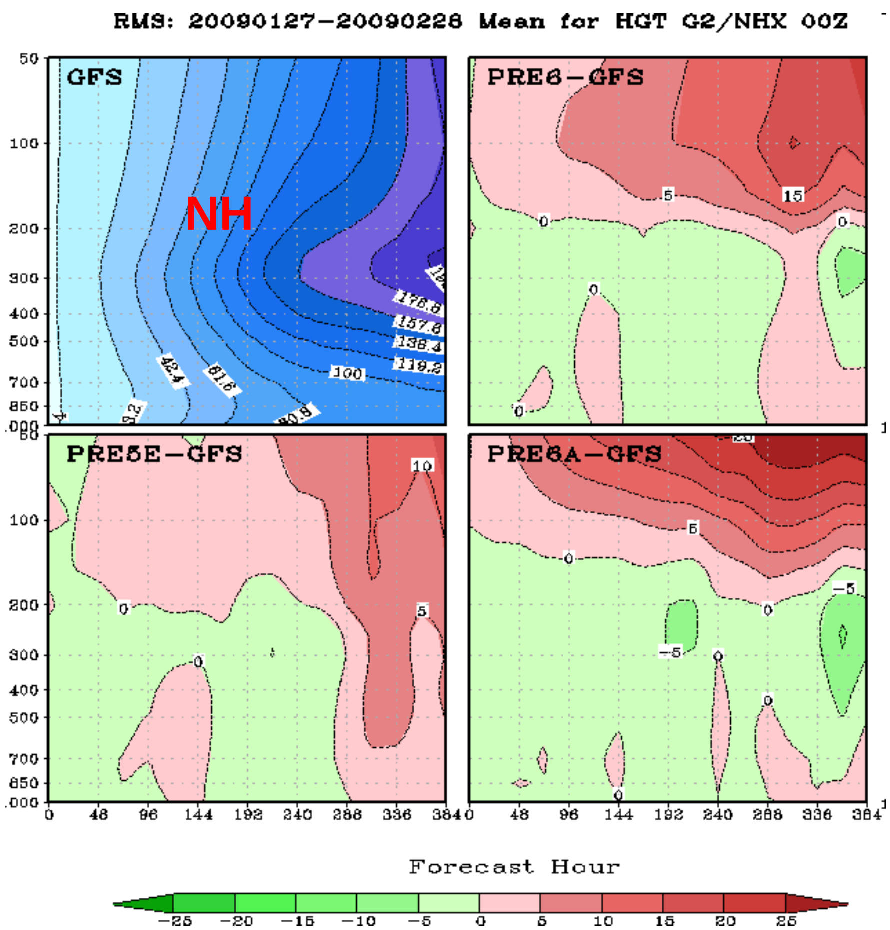


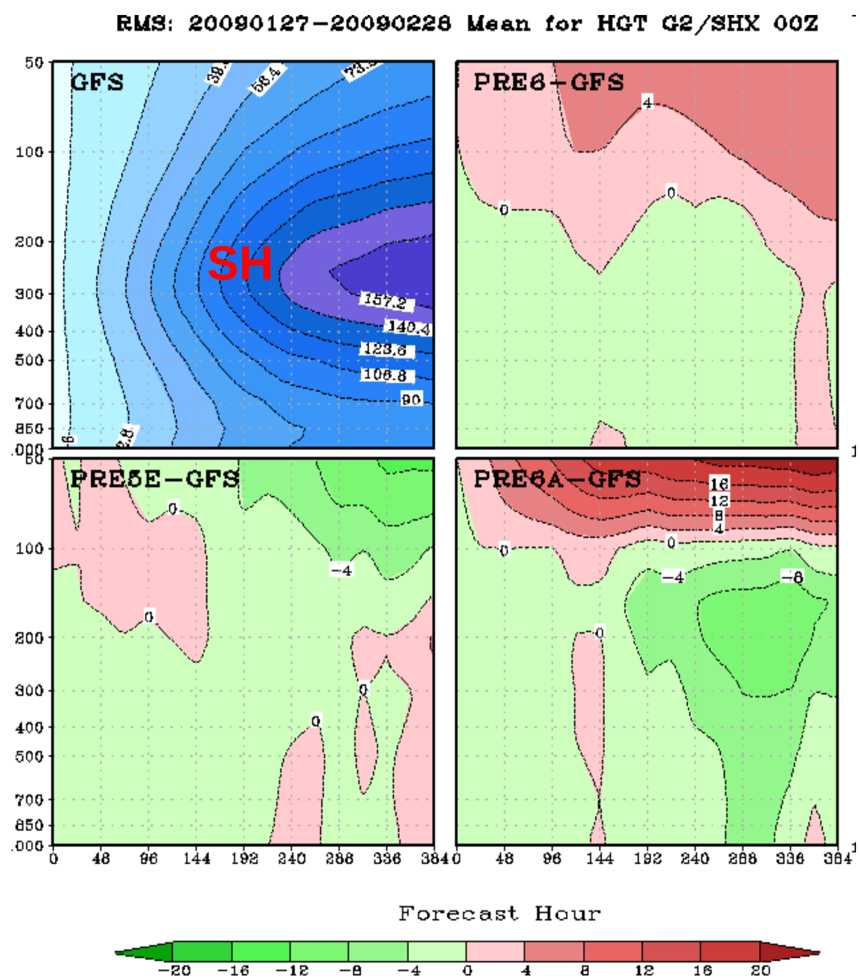
- Reduced RMSE in the tropics
- Increased NH and SH RMSE near the tropopause





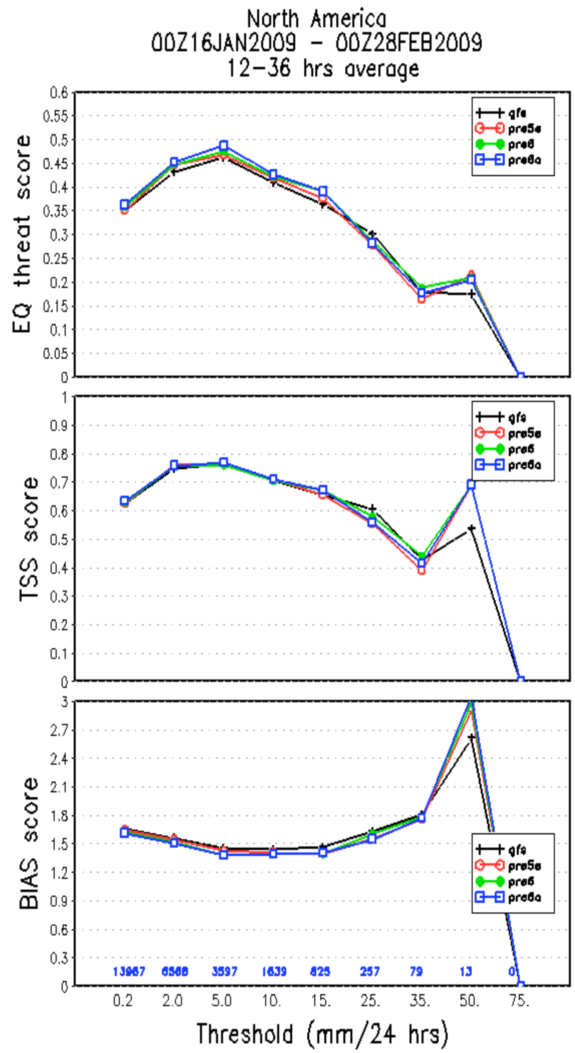
Height RMSE

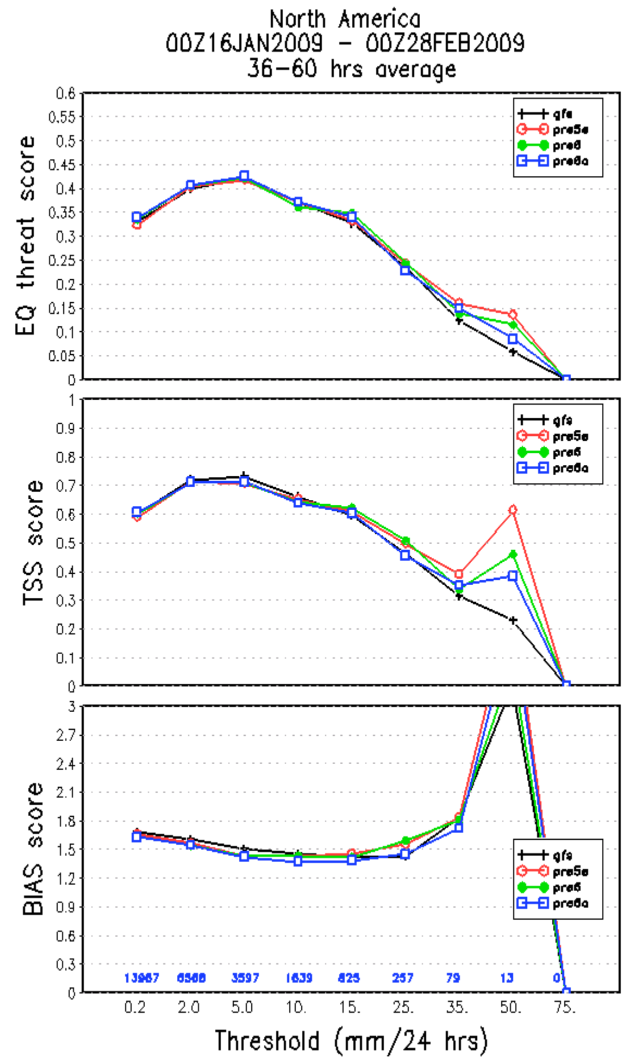


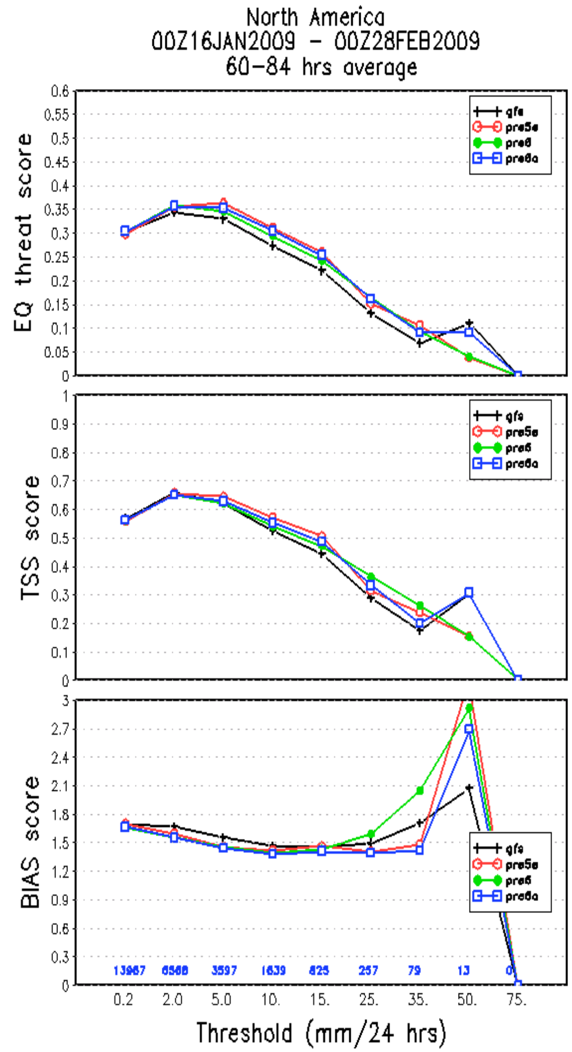


Removing negative moisture increased stratospheric HGT RMSE in both the Northern and Southern hemisphere

CONUS Precip Skill Scores

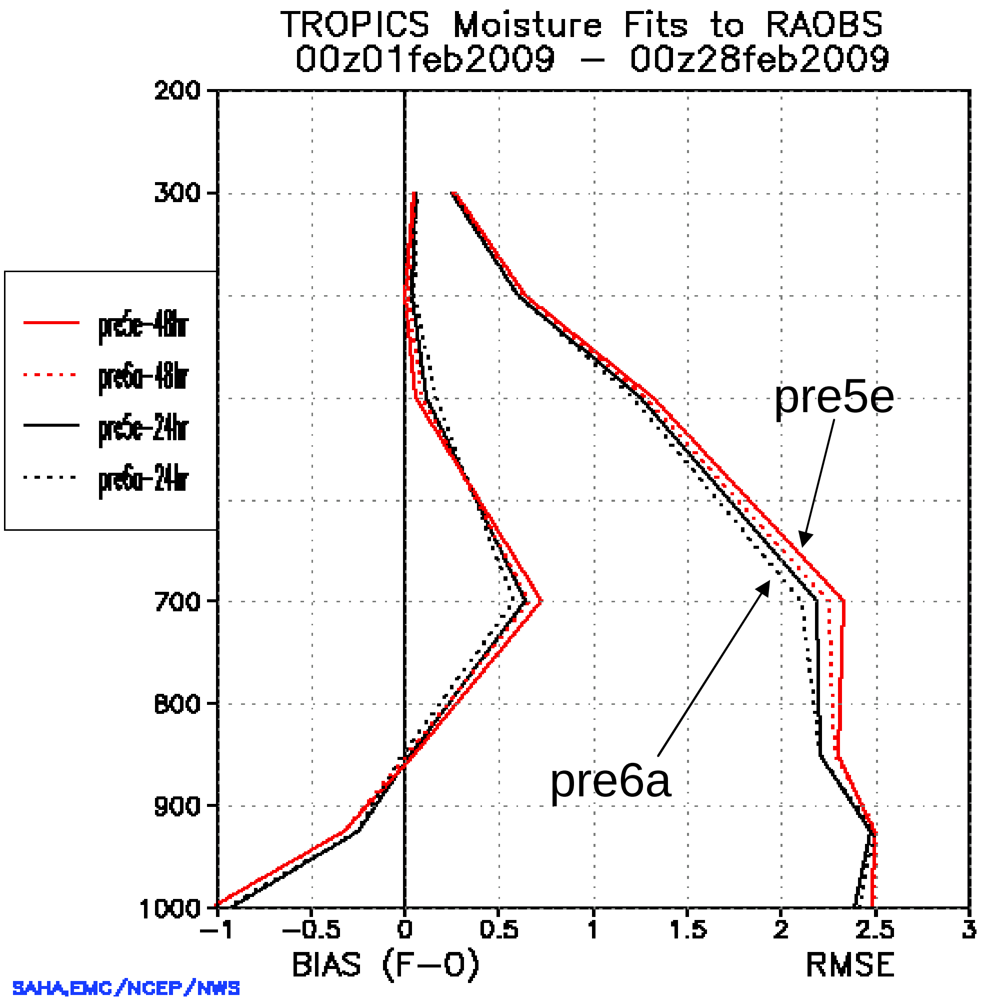


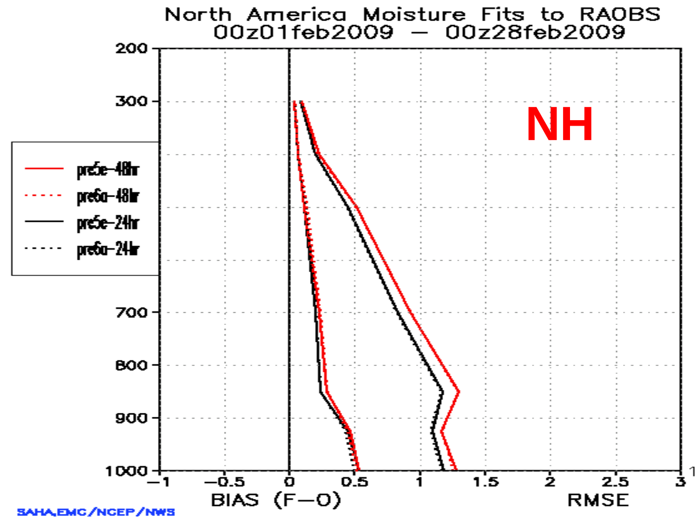


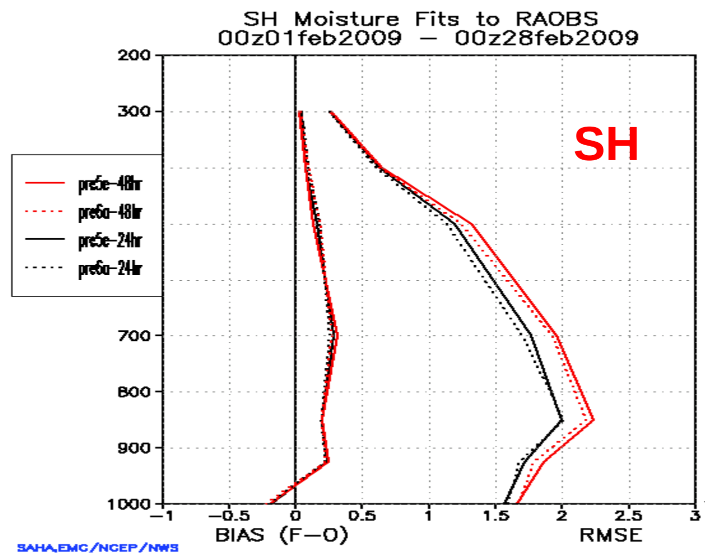


No much difference. All T574 runs are slightly better than the operational T382

Fit-to-Obs: Moisture

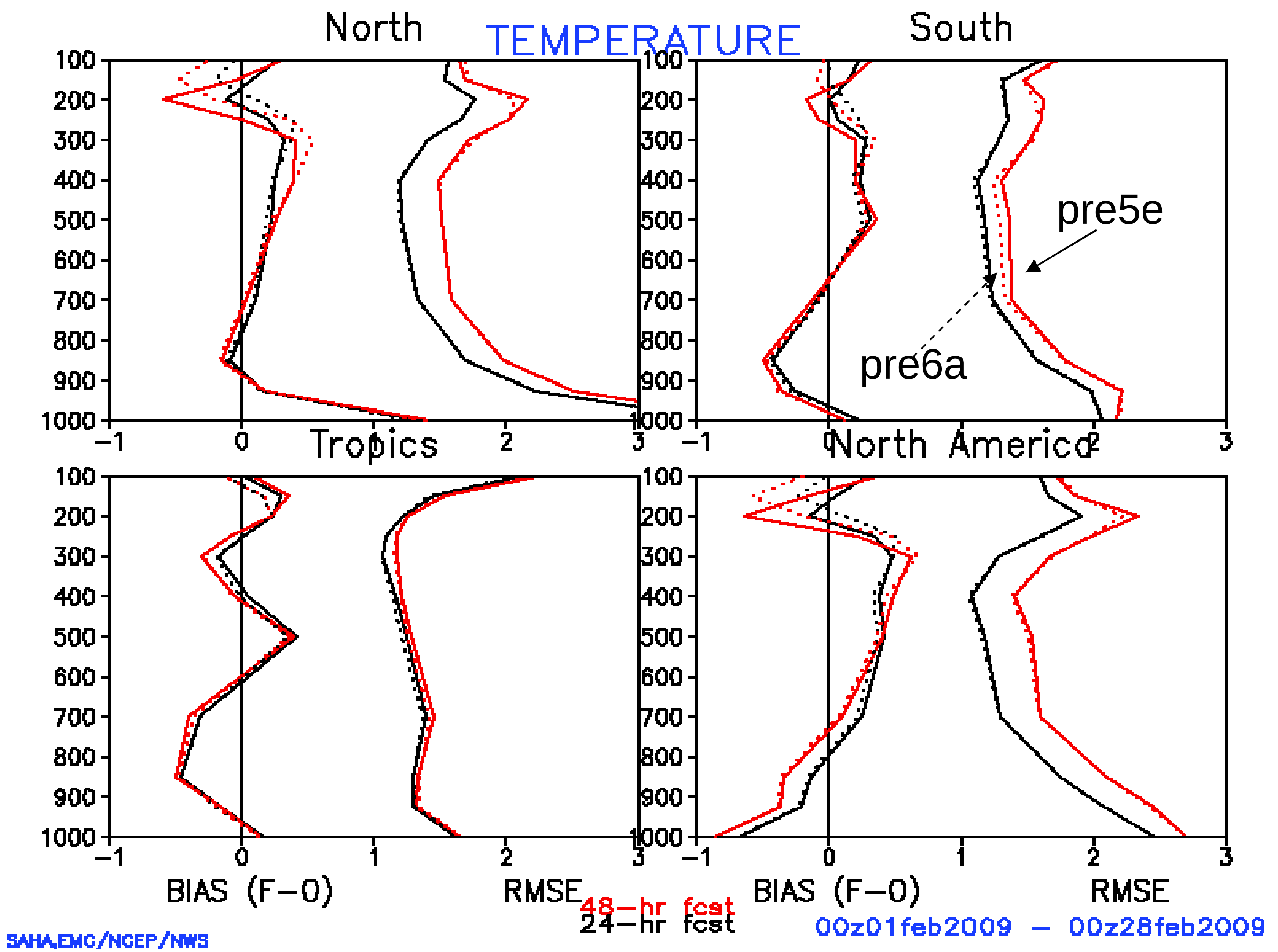






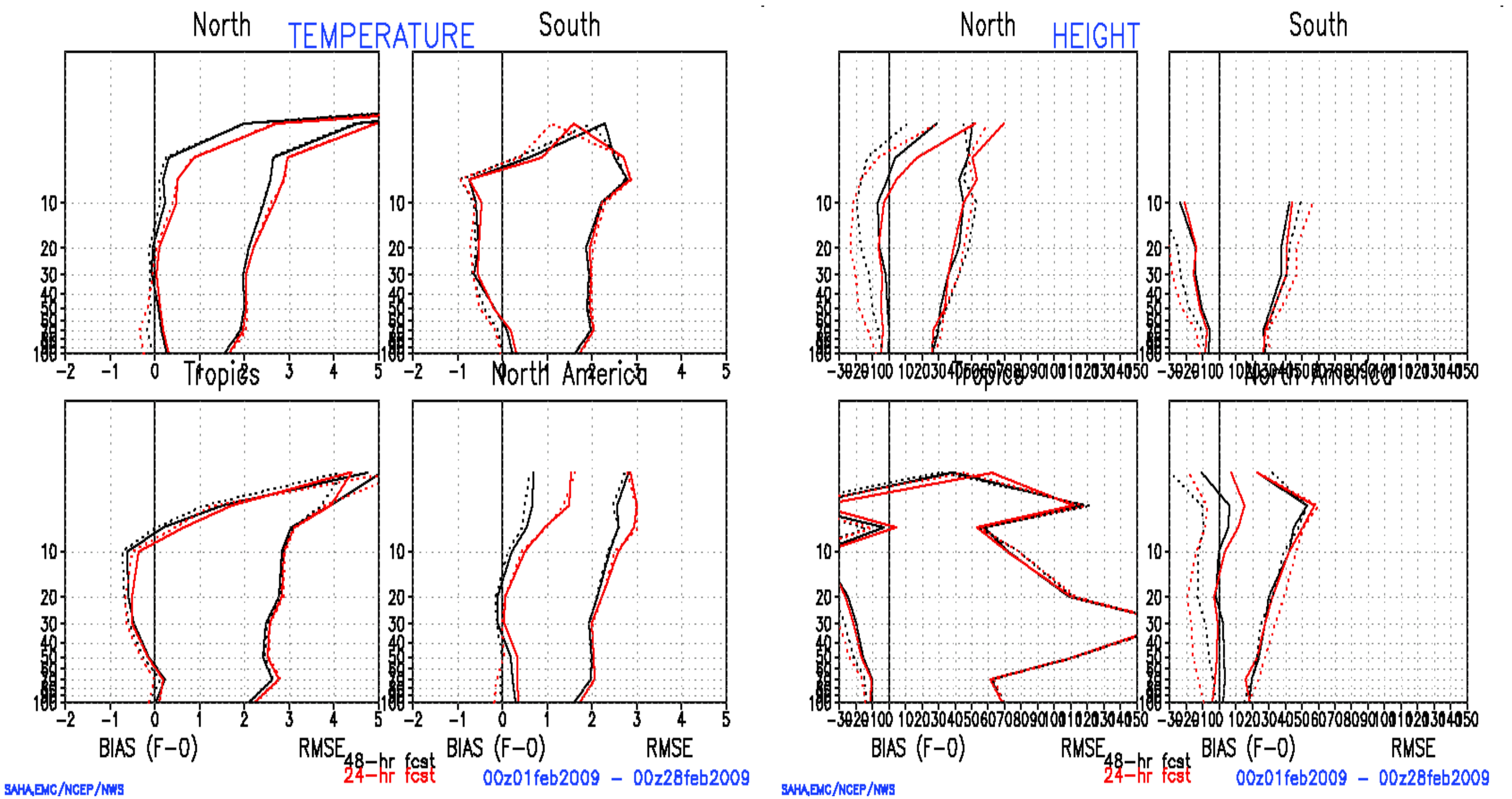
- Removing negative moisture reduced moisture bias and RMSE in the tropics and SH.

Fit-to-Obs: Troposphere Temperature



Not much difference except near the tropopause.

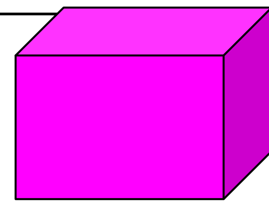
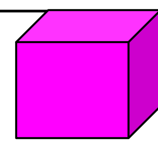
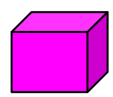
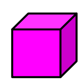
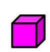
Fit-to-Obs: Stratosphere Temperature and Height



Slightly colder stratosphere
Larger height bias and RMSE

Unbroken lines: pre5e T574 control
Dotted lines: pre6a T574 exp

Summary: Negative Water Vapor in the GFS

Causes	*Importance*	*Solutions*
Vertical Advection		1. Semi-Lagrangian 2. Flux-Limited Positive-Definite Scheme for current Eulerian GFS
GSI Analysis		Tuning factqmin and factqmax
Spectral Transform		*1. Semi-Lagrangian GFS: running tracers on grid, no spectral transform* *2. Eulerian GFS: no solution yet.*
Cloud Water Borrowing		Limiting the borrowing to available amount of water vapor
SAS Mass-Flux		*Remains to be resolved*

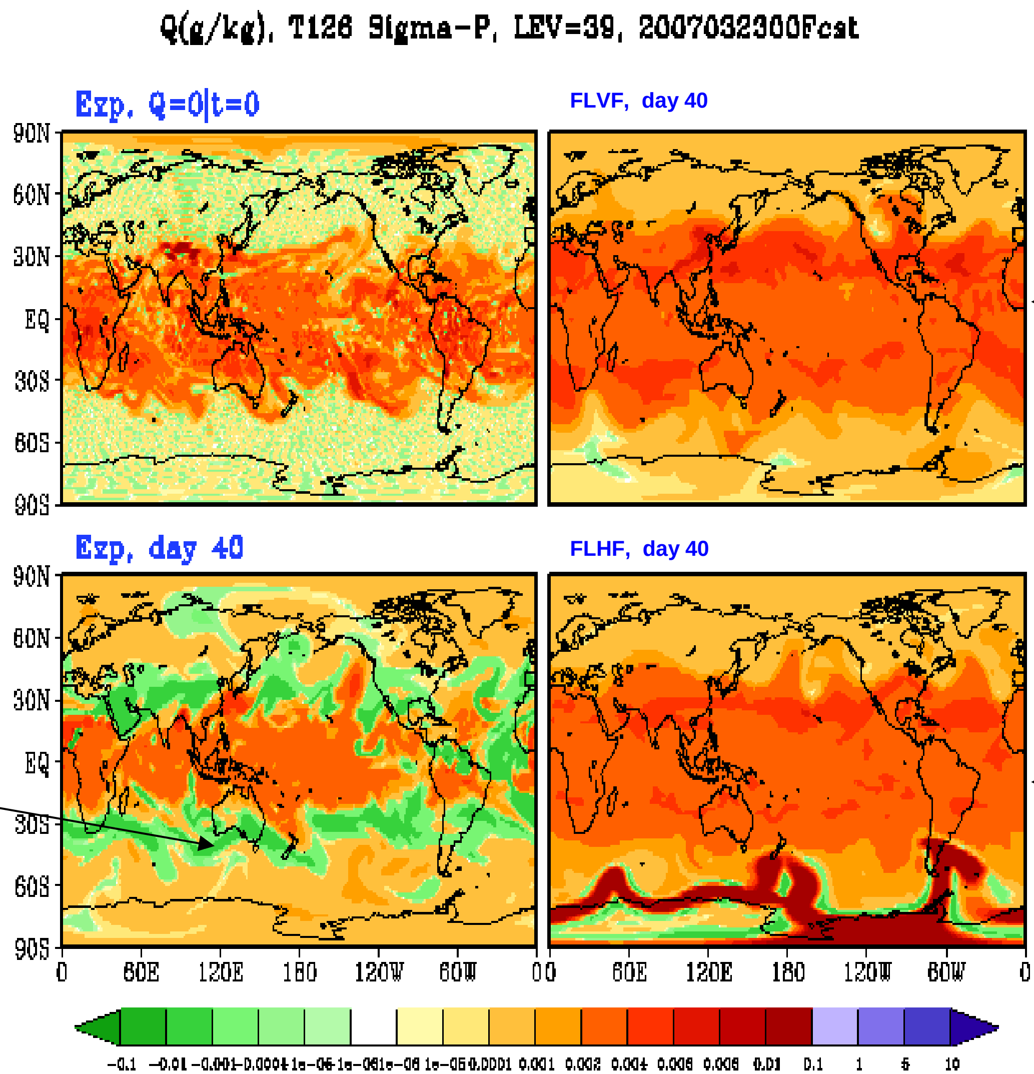
Conclusion

- The causes of negative water vapor in the GFS were identified. New schemes were proposed to reduce and/or remove negative tracers.

- T574L64 parallel experiments showed that removing negative moisture
  - (over) cooled the stratosphere, drew GFS closer to the ECMWF
  - (over) Increased RH near the tropical tropopause, drew GFS closer to the ECMWF
  - Improved moisture fit to observations in the tropics and SH
  - Reduced (increased) wind RMSE in the tropical lower (upper) troposphere
  - Reduced tropical temperature RMSE, but increased mid-latitude stratospheric temperature RMSE
  - Increased HGT RMSE in the lower stratosphere

- Q: Will a recalculation of the GSI bias correction help reduce the HGT and Temp RMSE in the stratosphere?

Flux-Limited Schemes

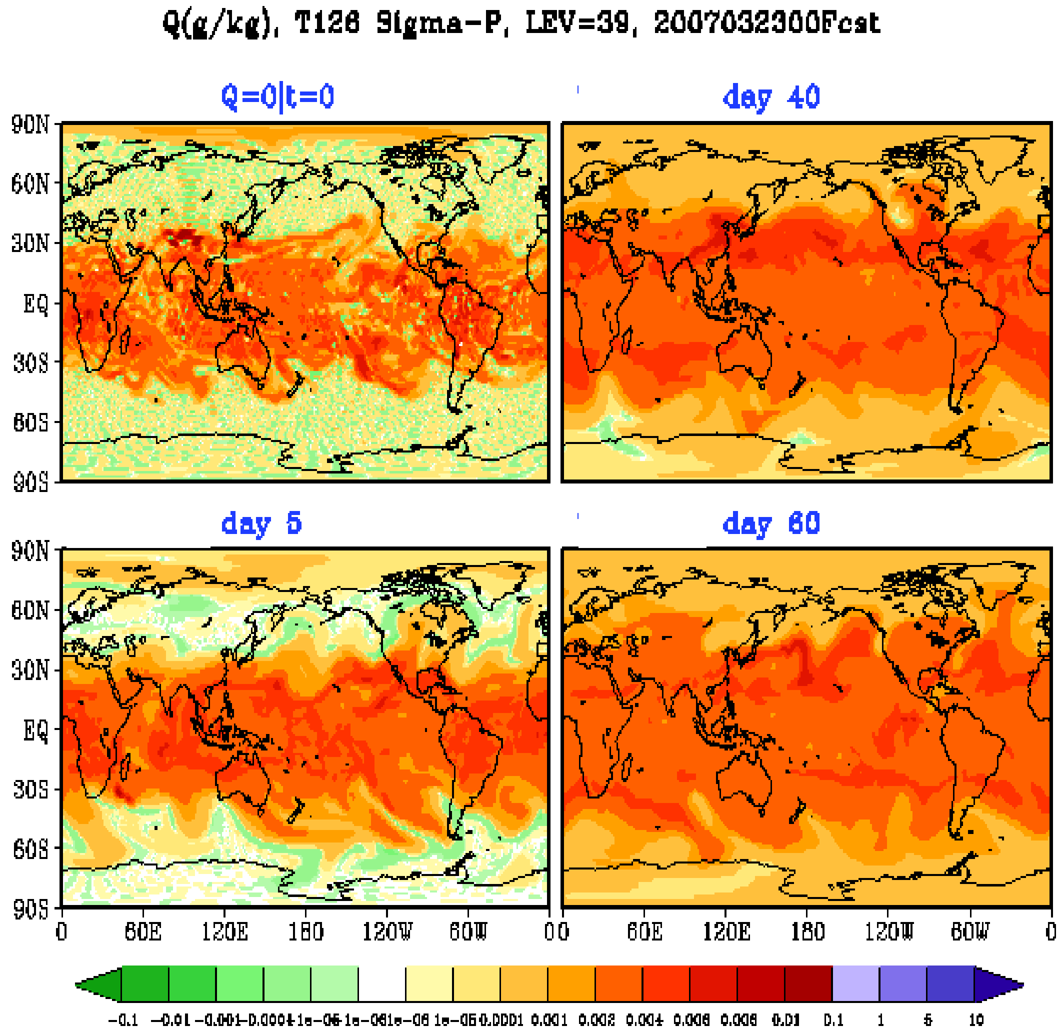


Flux-Limited Vertically-Filtered Scheme: flux-limited in space and central in time. The scheme is stable, and does not generate negative tracers.

Flux-Limited Horizontally-Filtered (Adams-Bashforth) Scheme: flux-limited in space and forward in time. Unstable for “climate” runs.

GFS Cntl: negative tracers

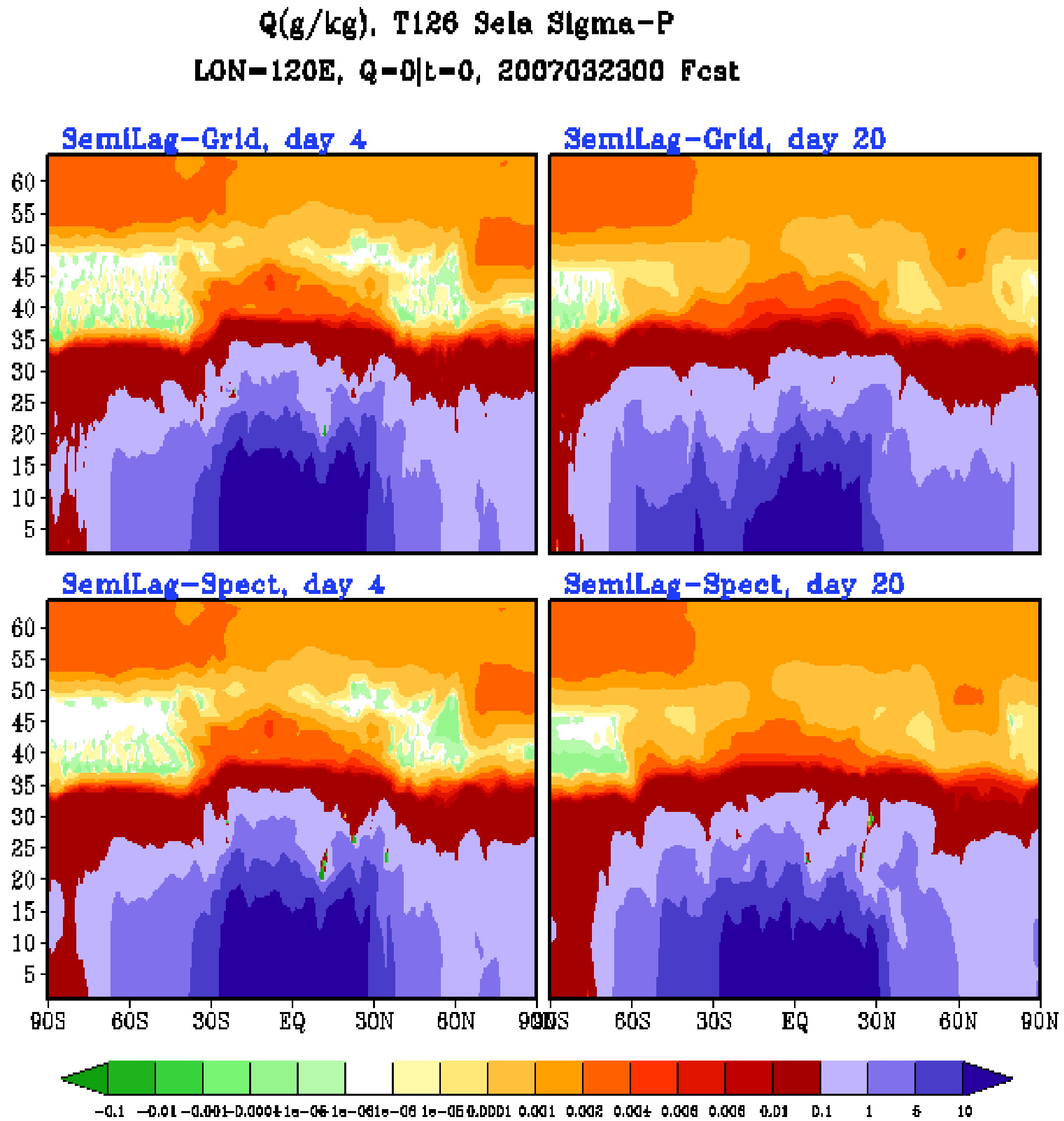
Flux-Limited Vertically-Filtered Scheme



After about 60 days of "climate" integration, all negative tracers disappeared.

For GFS 16-day NWP forecasts, most negative tracers will be eliminated after certain cycles of data assimilation and forecasts. The remaining negative tracers come from the Gibbs of spectral transform.

Joe-Sela Semi-Lagrangian Test



Joe-Sela's T126 experiments:

Semi-Lagrangian transport scheme does not produce negative tracers.

Spectral transform from Gibbs phenomenon still produces some negative tracers.

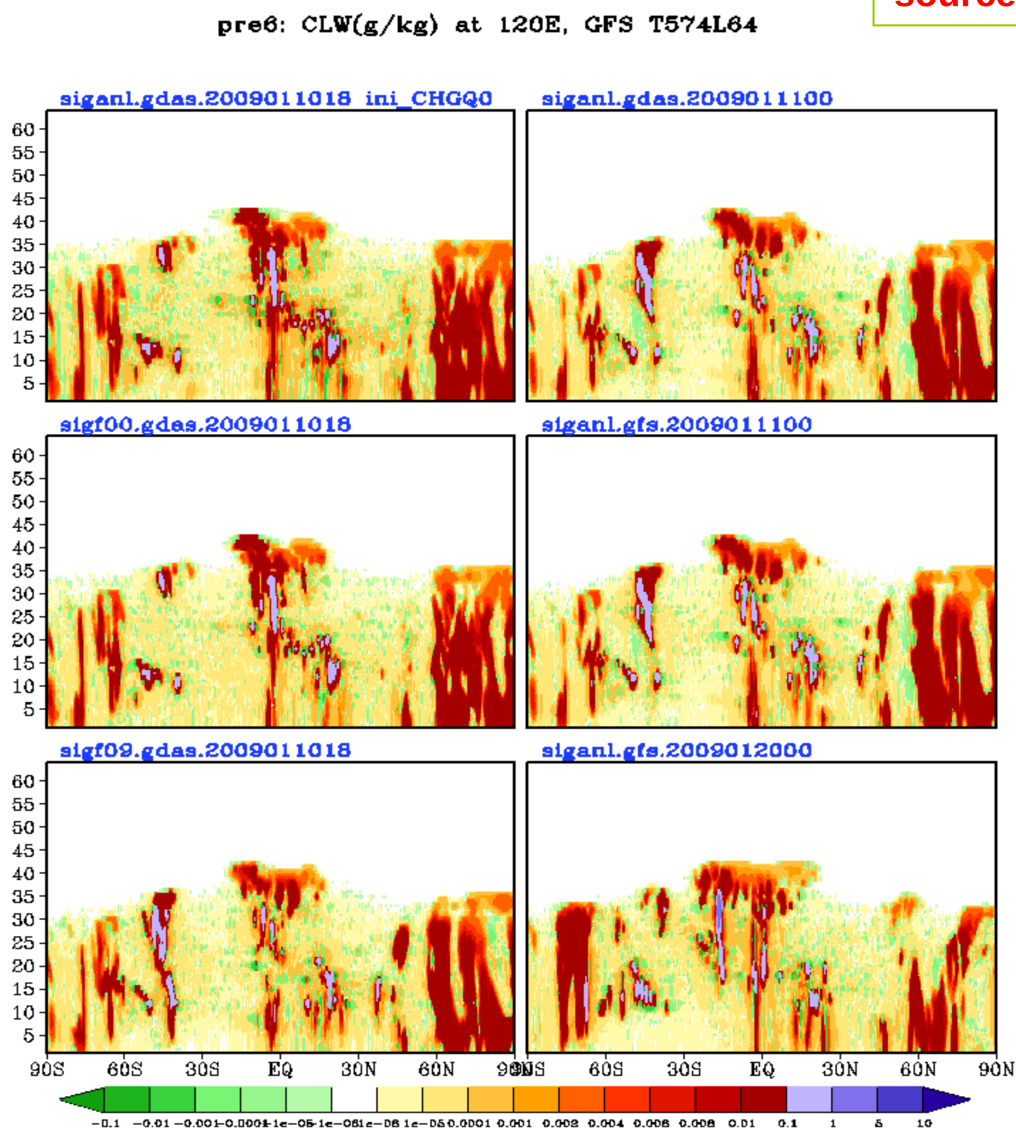
GFS T574L64 Test with Data Assimilation

Spectral transform is the major source of negative cloud water

Initial condition
2009011018 cycle

Run CHGRES, remove negative CLW

9 hours of GDAS fcst, with TVD and modified precpd.f



Next GDAS cycle
After **GSI anal** step

Next GFS cycle
After **GSI anal** step

After 10 days of cycling