On the Reduction of NCEP GFS Systematic Biases with FV3 Dycore and Advanced Microphysics

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Change History of GFS Configurations

Mon/Year	Lev	Truncations	Z-cor/dyncore	Major components upgrade
Aug 1980	12	R30 (375km)	Sigma Eulerian	first global spectral model, rhomboidal
Oct 1983	12	R40 (300km)	Sigma Eulerian	
Apr 1985	18	R40 (300km)	Sigma Eulerian	GFDL Physics
Aug 1987	18	T80 (150km)	Sigma Eulerian	First triangular truncation; diurnal cycle
Mar 1991	18	T126 (105km)	Sigma Eulerian	
Aug 1993	28	T126 (105km)	Sigma Eulerian	Arakawa-Schubert convection
Jun 1998	42	T170 (80km)	Sigma Eulerian	Prognostic ozone; SW from GFDL to NASA
Oct 1998	28	T170 (80km)	Sigma Eulerian	the restoration
Jan 2000	42	T170 (80km)	Sigma Eulerian	first on IBM
Oct 2002	64	T254 (55km)	Sigma Eulerian	RRTM LW;
May 2005	64	T382 (35km)	Sigma Eulerian	2L OSU to 4L NOAH LSM; high-res to 180hr
May 2007	64	T382 (35km)	Hybrid Eulerian	SSI to GSI
Jul 2010	64	T574 (23km)	Hybrid Eulerian	RRTM SW; New shallow cnvtion; TVD tracer
Jan 2015	64	T1534 (13km)	Hybrid Semi-Lag	SLG; Hybrid EDMF; McICA etc
May2016	64	T1534 (13km)	Hybrid Semi-Lag	4-D Hybrid En-Var DA
Jun2017	64	T1534 (13km)	Hybrid Semi-Lag	NEMS GSM, advanced physics
JAN 2019	64	FV3 (13km)	Finite-Volume	NGGPS FV3 dycore, GFDL MP

GSM has been in service for NWS operation for 38 years !

2

NOAA's Next Generation Global Prediction System
NGGPS v1

FV3GFS is being configured to replace spectral model (NEMS GSM) in operations in Q2FY19

Configuration:

- **FV3GFS C768 (~13km deterministic)**
- **GFS Physics + GFDL Microphysics**
- **FV3GDAS C384 (~25km, 80 member ensemble)**
- **64 layer, top at 0.2 hPa**
- **Uniform resolution for all 16 days of forecast**

Schedule:

- **3/7/18: code freeze of FV3GFS-V1 (GFS V15.0)**
- **3/30/18: Public release of FV3GFS-V1**
- **4/1 – 1/25/19: real-time EMC parallel**
- **5/25 – 9/10/18: retrospectives and case studies (May 2015 – September 2018; three summers and three winters)**
- **9/24/2018: Field evaluation due; EMC CCB**
- **10/01/2018: OD Brief, code hand-off to NCO**
- **12/20/2018-1/20/2019: NCO 30-day IT Test**
- **1/24/2019: Implementation**

Model: Infrastructure & Physics Upgrades

- Integrated FV3 dycore into NEMS
- Added IPD in NEMSfv3gfs
- Newly developed write grid component -- write out model history in native cubed sphere grid and Gaussian grid
- Replaced Zhao-Carr/Sundqvist microphysics with the more advanced GFDL microphysics
- Updated parameterization of ozone photochemistry with additional production and loss terms
- New parameterization of middle atmospheric water vapor photochemistry
- a revised bare soil evaporation scheme.
- Modify convection schemes to reduce excessive cloud top cooling
- Updated Stochastic physics
- Improved NSST in FV3
- Use GMTED2010 terrain to replace TOPO30 terrain

GFDL FV3 Dycore and Microphysics

GSM

Spectral
Gaussian
Hydrostatic
64-bit precision

↓

GFDL FV3

Finite-volume
Cubed-Sphere
non-hydrostatic
32-bit precision

Physics still runs at 64-bit precision

Zhao-Carr MP

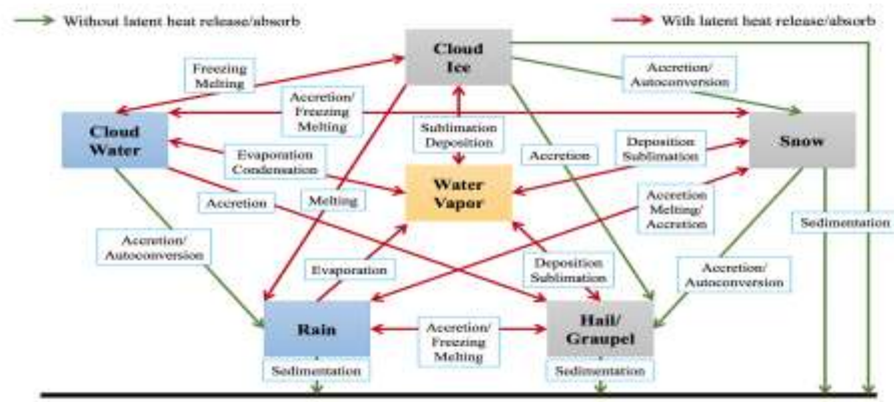
Prognostic could species: one total cloud water

↓

GFDL MP

Prognostics cloud species : five
Liquid, ice, snow, graupel, rain

more sophisticated cloud processes



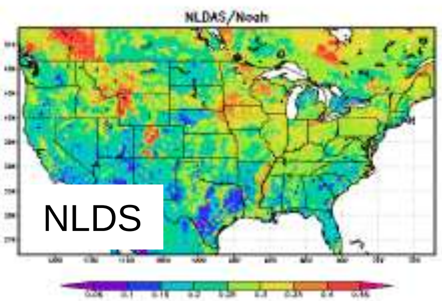
Revised Bare-Soil Evaporation For Reducing Dry and Warm Biases

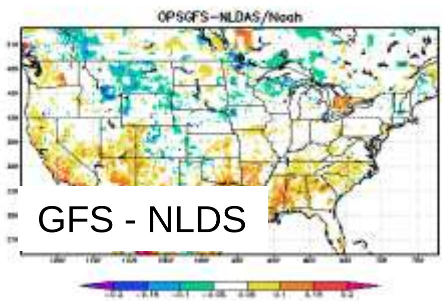
$$FX = (\Theta_1 - \Theta_{dry})/(\Theta_{sat} - \Theta_{dry})$$

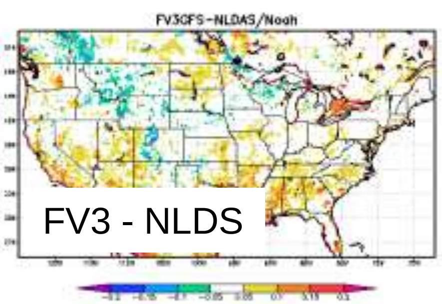
$$E_{dir} = (1 - \sigma_f)(FX)^{fx} E_p$$

where FX is the fraction of soil moisture saturation in the upper soil layer, Θ_1, Θ_{dry}, and Θ_{sat} are the soil moisture in the upper soil layer, air dry (minimum), and the saturation (porosity) values, respectively, and fx is an empirical coefficient. Nominally, $fx = 1$ yielding a linear function

In the current model, θ_{dry} is set to the same as wilting point θ_{ref}. In reality, θ_{dry} is usually lower than θ_{ref}







4th-layer Soil Moisture

Reduced dry bias

The latent heat flux now contributed more from the bare soil evaporation which is directly dependent on the first layer soil moisture. Thus we have strong and fast coupling between precip and soil moisture.

The goal is to keep or increase the latent heat flux while keeping the deep soil moisture intact

From: Helin Wei

Updated Ozone Physics in FV3GFS

Funded by NOAA Climate Program Office

Naval Research Laboratory CHEM2D Ozone Photochemistry Parameterization (CHEM2D-OPP, *McCormack et al.* (2006))

$$\frac{\partial \chi}{\partial t}(P-L) = (P-L)_0 + \left.\frac{\partial (P-L)}{\partial \chi_{O3}}\right|_0 \left(\chi_{O3} - \overline{\chi}_{O3}\right) + \left.\frac{\partial (P-L)}{\partial T}\right|_0 \left(T - \overline{T}\right) + \left.\frac{\partial (P-L)}{\partial c_{O3}}\right|_0 \left(c_{O3} - \overline{c}_{O3}\right)$$

NEMS GSM
Includes reference tendency and dependence on O3 mixing ratio

FV3GFS
Additional dependences on temperature and column total ozone

Reference tendency $(P\text{-}L)_0$ and all partial derivatives are computed from odd oxygen ($Ox \equiv O_3+O$) reaction rates in the CHEM2D photochemical transport model.
CHEM2D is a global model extending from the surface to ~120 km that solves 280 chemical reactions for 100 different species within a transformed Eulerian mean framework with fully interactive radiative heating and dynamics.

χ_{O3} prognostic Ozone mixing ratio
T Temperature
c_{O3} column ozone above

From: Shrivinas Moorthi

Water Vapor Sources and Sinks in the Stratosphere/Mesosphere

- This new scheme is based on "*Parameterization of middle atmospheric water vapor photochemistry for high-altitude NWP and data assimilation*" by McCormack et al. (2008), from NRL

- Accounts for the altitude, latitude, and seasonal variations in the photochemical sources and sinks of water vapor over the pressure region from 100–0.001hPa (~16–90km altitude)

- Monthly and zonal mean H_2O production and loss rates are provided by NRL based on the CHEM2D zonally averaged photochemical-transport model of the middle atmosphere

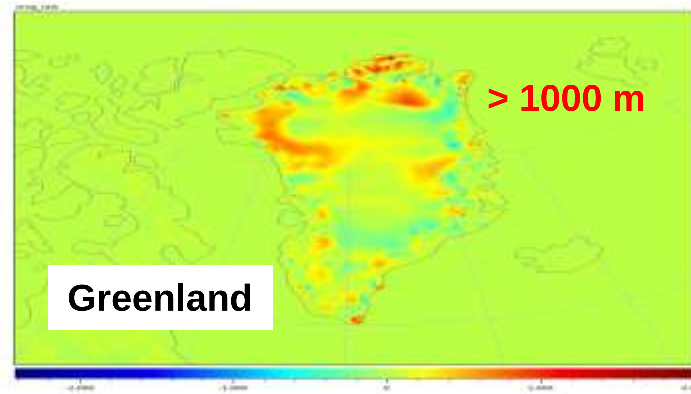
- The scheme mirrors that of ozone, with only production and loss terms.

From: Shrivinas Moorthi

Terrain: GMTED2010 vs GTOPO30

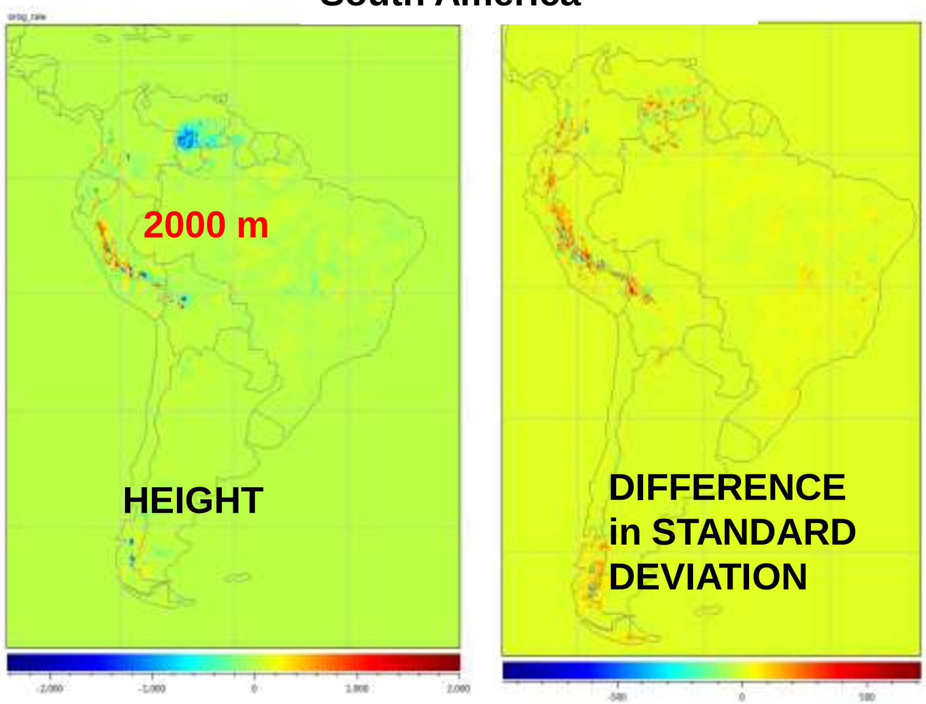
GMTED2010:
A **more accurate** replacement for GTOPO30 data, created by USGS in 2010. Primarily derived from NASA Shuttle Radar Topography Mission (SRTM) data.

GMTED minus GTOPO30

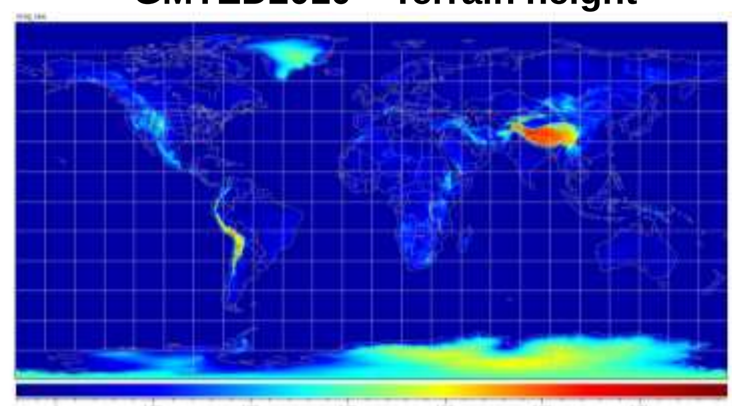


DIFFERENCES IN GREENLAND ARE LARGE IN MAGNITUDE AND AREAL EXTENT.

South America



GMTED2010 – Terrain height



From: George Gayno & Fanglin Yang

DA: Infrastructure Changes

- Improved GSI code efficiency
- The GSI does not currently have the capability to operate on a non-rectangular grid. Forecasts are therefore provided via the FV3 write-grid component on the Gaussian grid required by the GSI. **Increments are interpolated back on the cube-sphere grid** within the FV3 model itself.
- Both the analysis and EnKF components are now performed at **one-half of the deterministic forecast resolution** (increased from one-third in current operations) and is now C384 (~26km) instead of 35km. This reduced issues when interpolating between ensemble and control resolutions.
- **Tropical cyclone relocation** is **omitted** from the implementation, as is the full field **digital filter**.
- The current operational GDAS/GFS system uses a total (non-precipitating) cloud condensate, whereas the FV3-GFS has **five separate hydrometeor** variables.

From: DA Team

DA Infrastructure Changes – cont'd

- The initial FV3 data assimilation scheme retains the total cloud condensate control variable by **combining liquid water and ice amounts** from the model, but avoids issues with how to split the analysis increments into the component species by **not feeding the increment back** at all.
  - This approach (treating the cloud as a "sink variable") will **still update the other model fields to be consistent with the cloud increment** through the multivariate error correlation in the background error specification while also **mitigating "spin-down" issues** seen in current operations.

- **Only** the **SHUM** (Stochastically Perturbed Boundary Layer Specific Humidity) and **SPPT** (Stochastically Perturbed Physics Tendencies) are included as stochastic physics in the EnKF. The **SKEB** (Stochastic Energy Backscatter) **was not** available to be **used** at the time the code was frozen, and amplitude parameters for SHUM and SPPT were modified to compensate.

From: DA Team

Retrospective and Real-Time Parallels

Three and an half years of retrospective runs

http://www.emc.ncep.noaa.gov/gmb/emc.glopara/vsdb/prfv3rt1	**real-time parallel**
http://www.emc.ncep.noaa.gov/gmb/emc.glopara/vsdb/fv3q2fy19retro1c	hord=5, Dec2017 ~ Aug2018
http://www.emc.ncep.noaa.gov/gmb/emc.glopara/vsdb/fv3q2fy19retro2c	hord=5, Jun2017 ~ Nov2018
http://www.emc.ncep.noaa.gov/gmb/emc.glopara/vsdb/fv3q2fy19retro4c	hord=5, Jun2016 ~ Nov2016
http://www.emc.ncep.noaa.gov/gmb/emc.glopara/vsdb/fv3q2fy19retro6c	hord=5, Jun2015 ~ Nov2015

In total
11 streams,
2000 days,
8000 cycles

Aggregated STATS

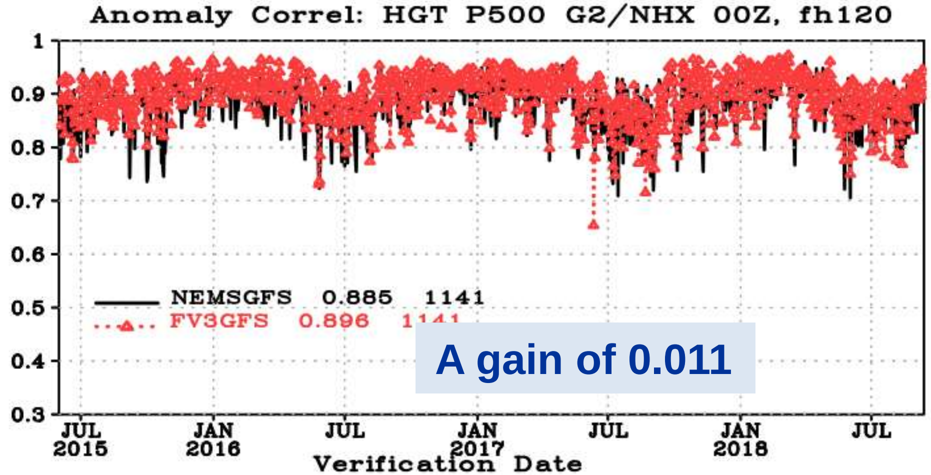
http://www.emc.ncep.noaa.gov/gmb/emc.glopara/vsdb/gfs2019b

Comparing NEMS GFS with FV3GFS, including all cases from hord5 runs, and 2015 and 2016 winter/spring streams with hord6.

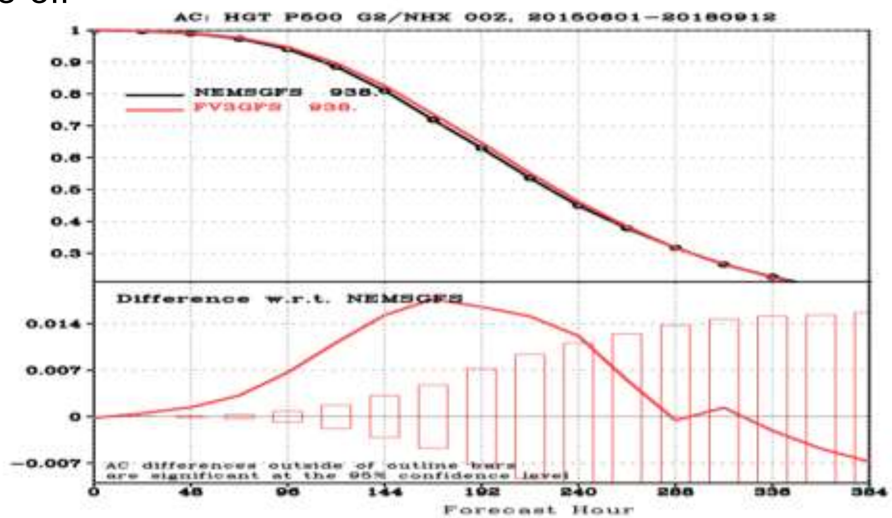
http://www.emc.ncep.noaa.gov/users/Alicia.Bentley/fv3gfs/ MEG evaluation page
http://www.emc.ncep.noaa.gov/gmb/STATS_vsdb/ International models

NH 500-hPa HGT Anomaly Correlation
(20150601 ~ 20180912)

Day-5

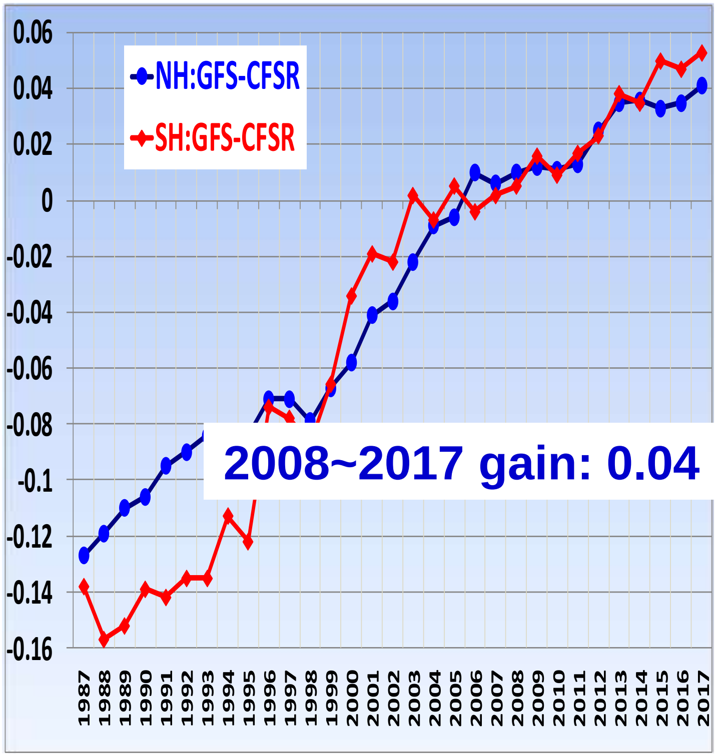


Die-off



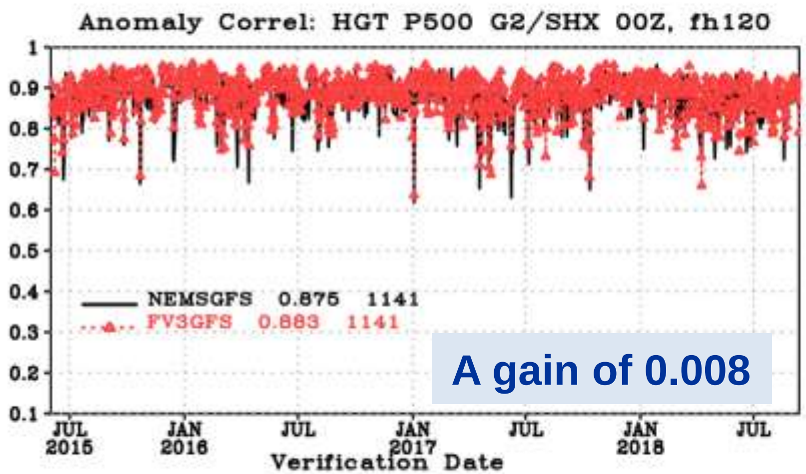
Increase is significant up to day 10

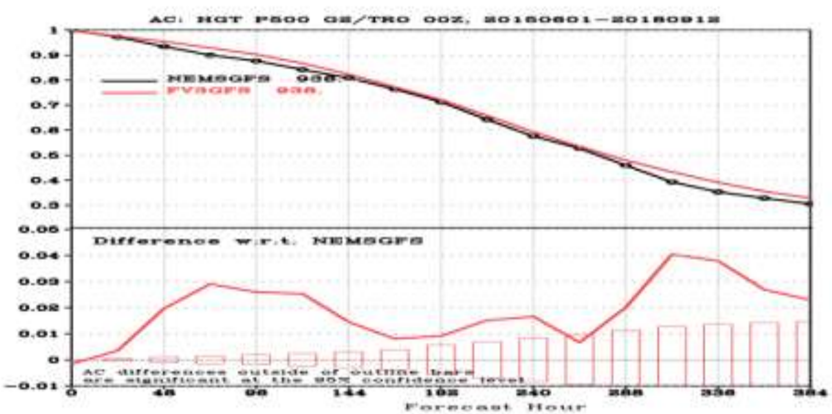
Annual Mean day-5 ACC, GFS - CFSR



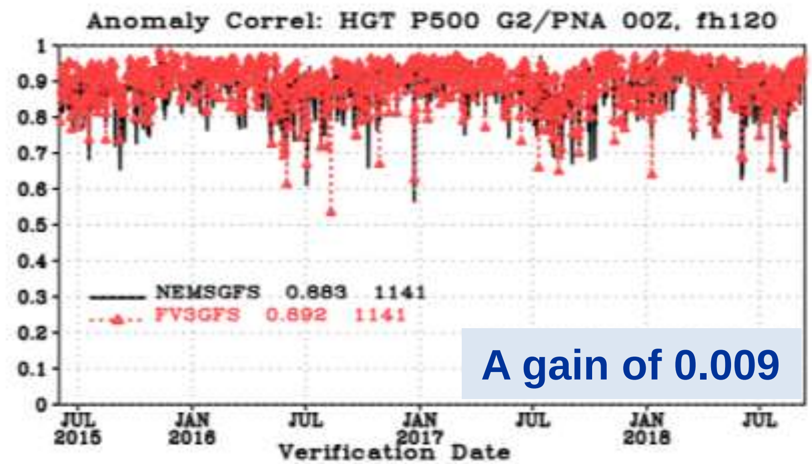
SH and N. America 500-hPa HGT ACC
(20150601 ~ 20180912)

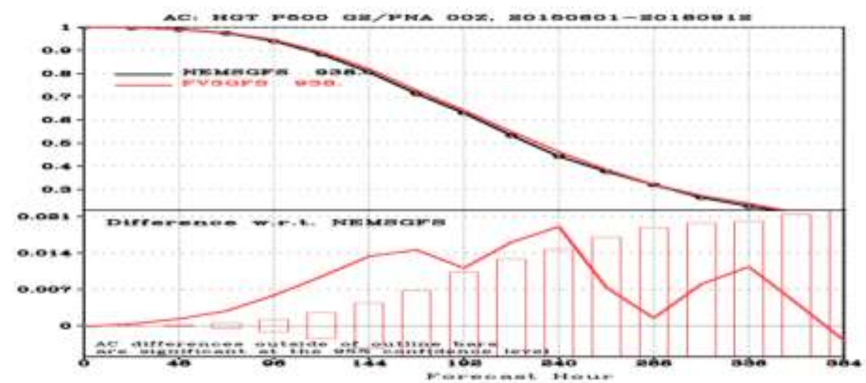
SH





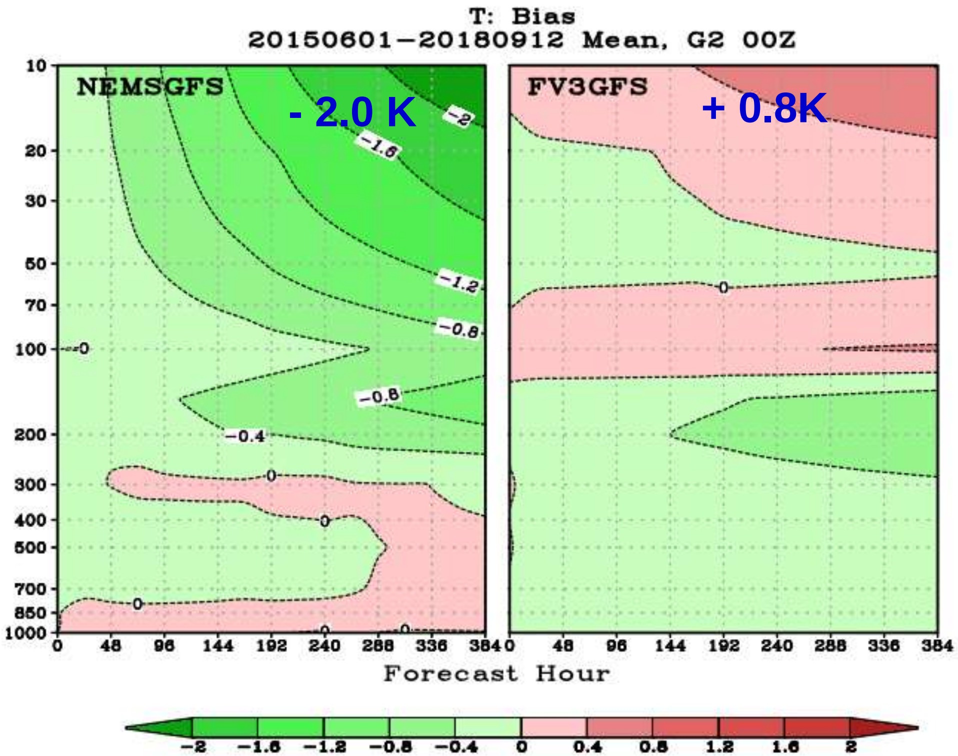
Pacific North America



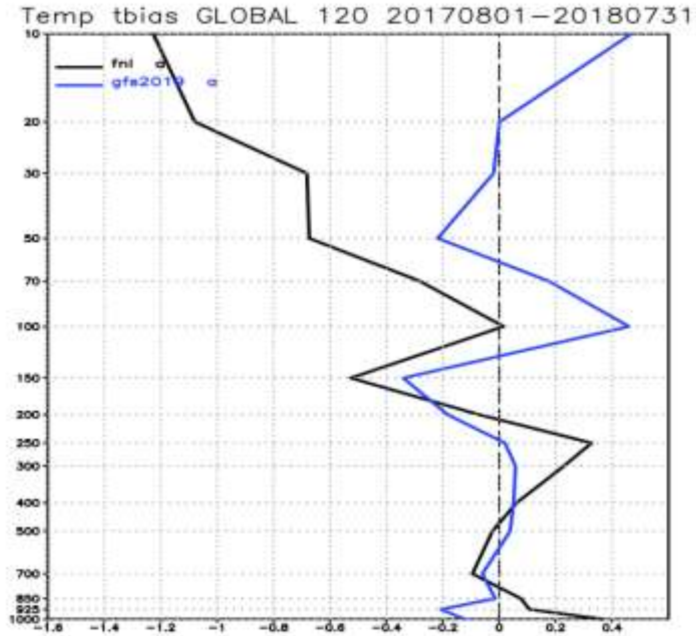


Temperature Biases

Global Mean, verified against analysis



Global Mean, against RAOBS

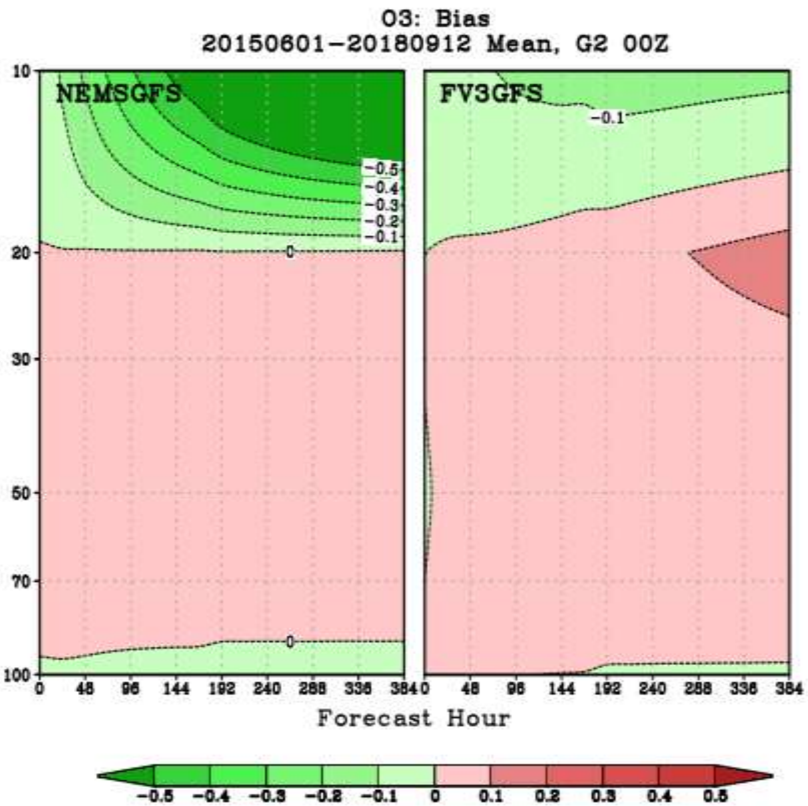


GSM has strong cold bias in the middle to upper stratosphere (- 2K).
FV3GFS warm bias (+0.8K) is caused by a radiation bug (fixed).

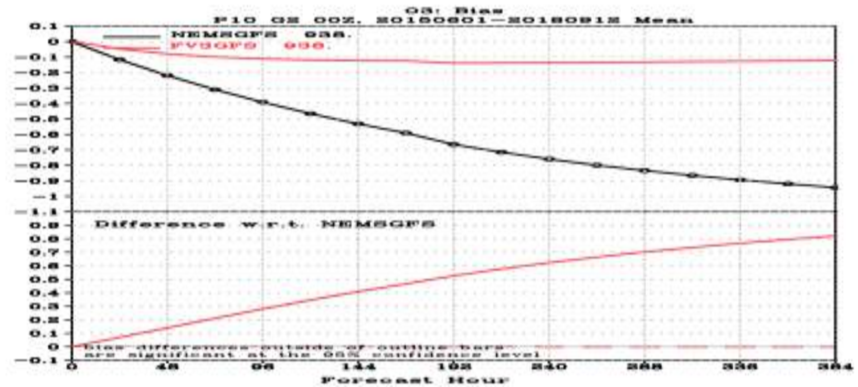
Sensitivity studies showed that the reduction of the cold bias is primarily attributed to the new FV3 dycore, and in a certain degree to the improvement in Ozone physics

Ozone Bias

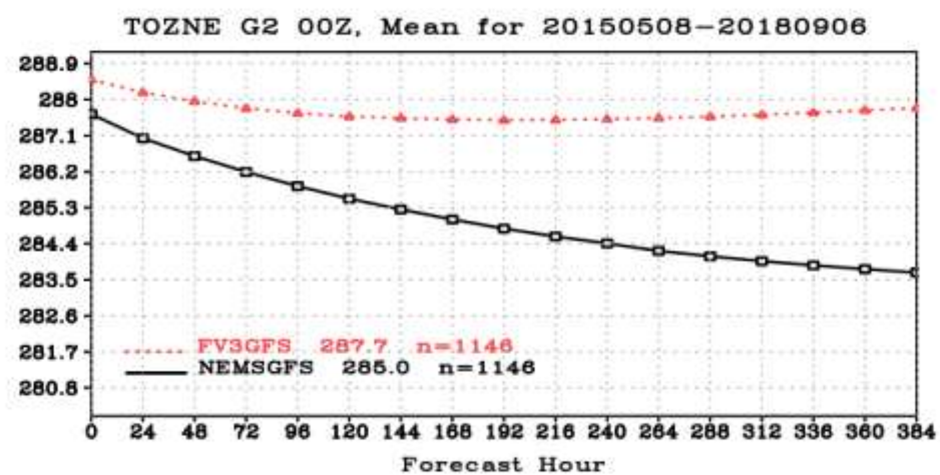
Verified against analyses



O3 at 10 hPa

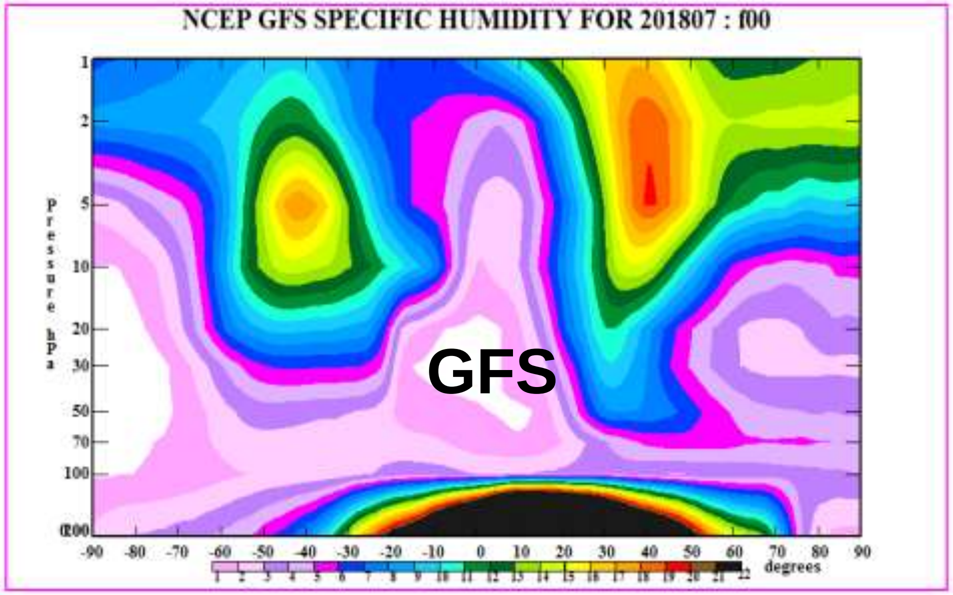


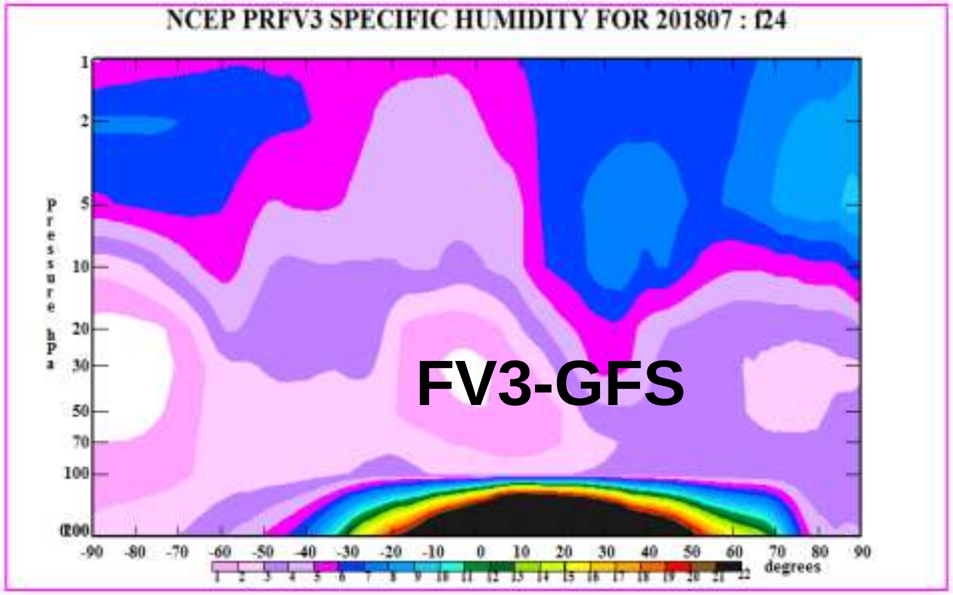
Column Total Ozone



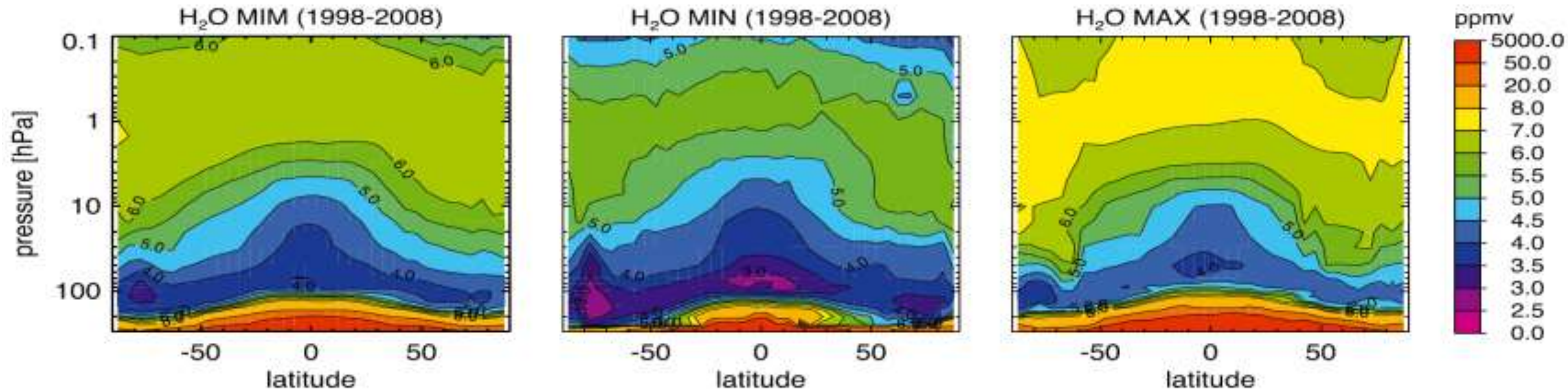
GSM loses ozone in forecast.
FV3GFS conserves better.

Zonal Mean SPFH and SPARC Climatologies

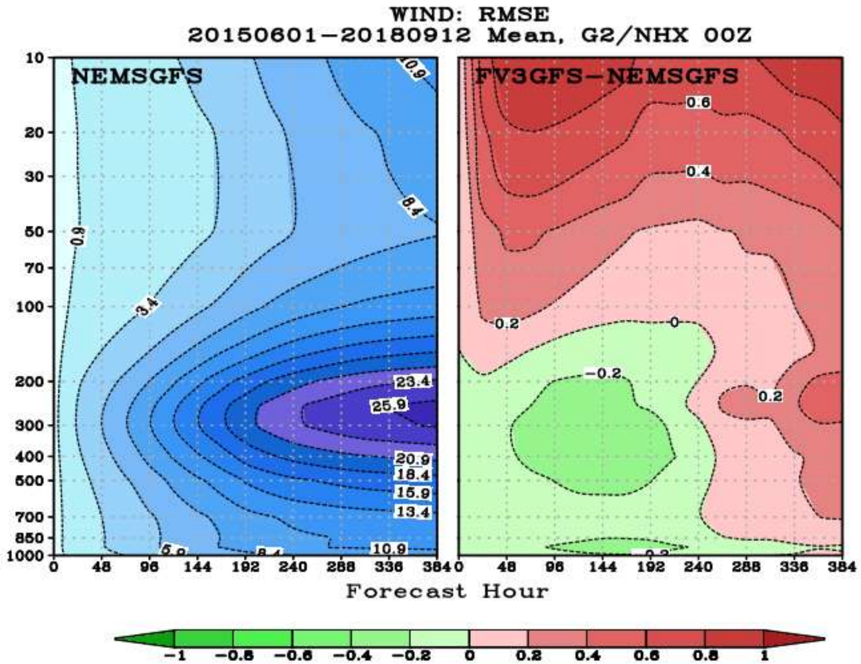




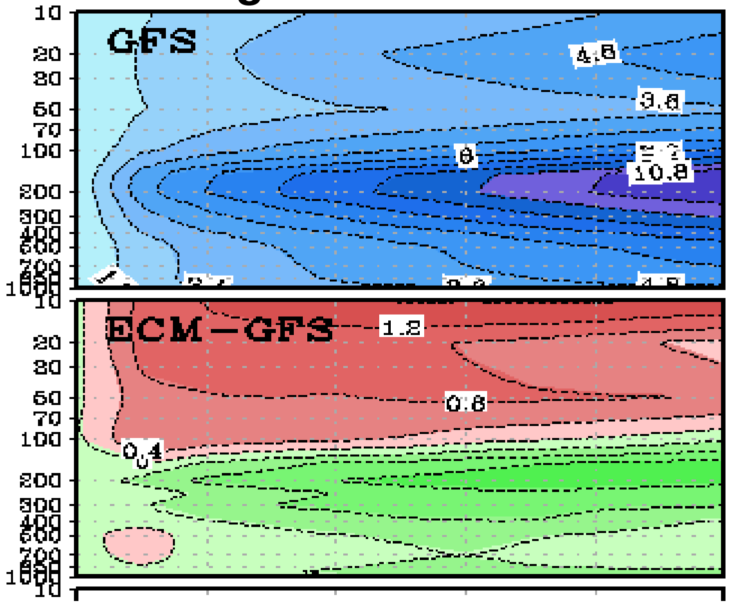
HEGGLIN ET AL.: SPARC DATA INITIATIVE WATER VAPOR COMPARISONS



NH WIND RMSE
Verified against analyses



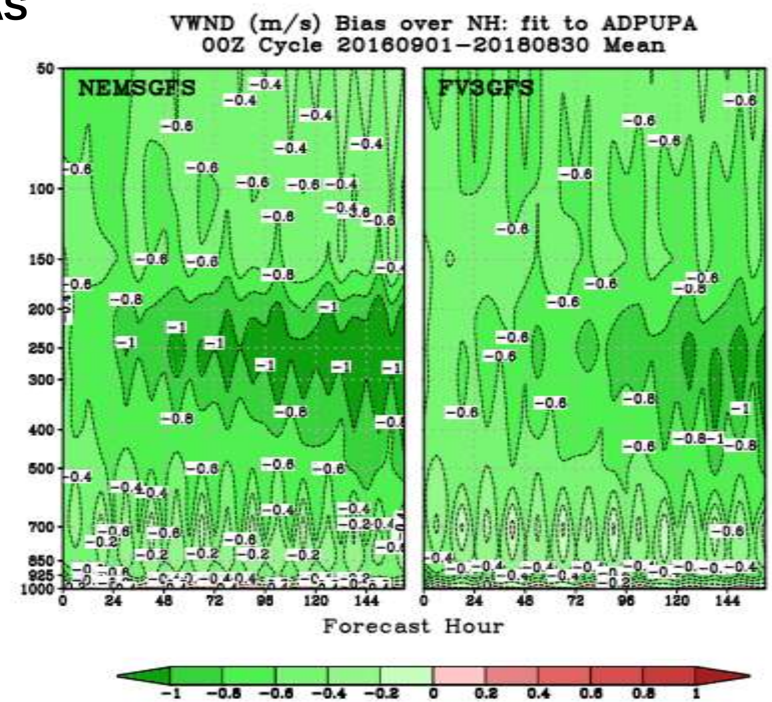
August 2018



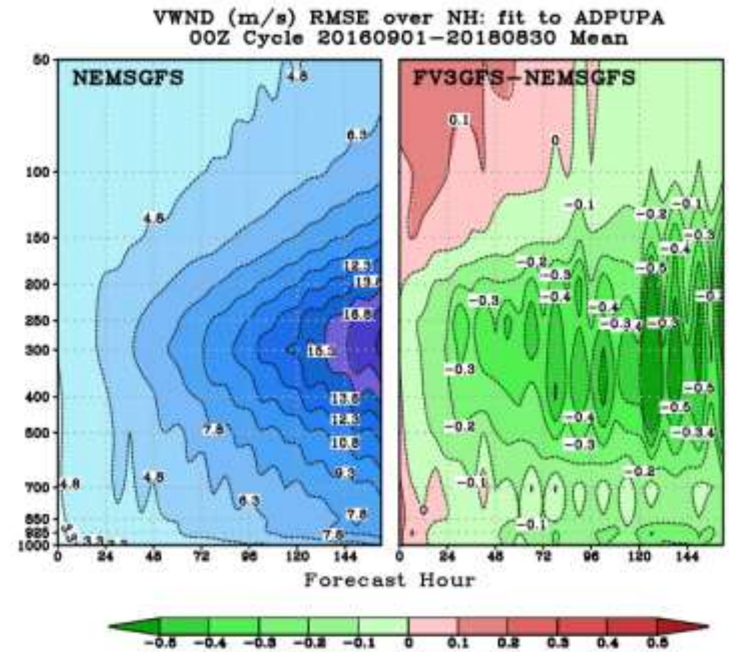
- **FV3GFS has larger RMSE than GSM in the stratosphere**
- **FV3GFS RMSE is similar to ECMWF RMSE**
- **GSM winds in the stratosphere is too smooth due to strong damping.**
- **Weaker and smoother winds usually (falsely) make RMSE smaller. Extra caution is required in evaluation of vector wind field.**

NH WIND BIAS and RMSE
Verified against ROBS, 20160901 ~ 20180831

BIAS



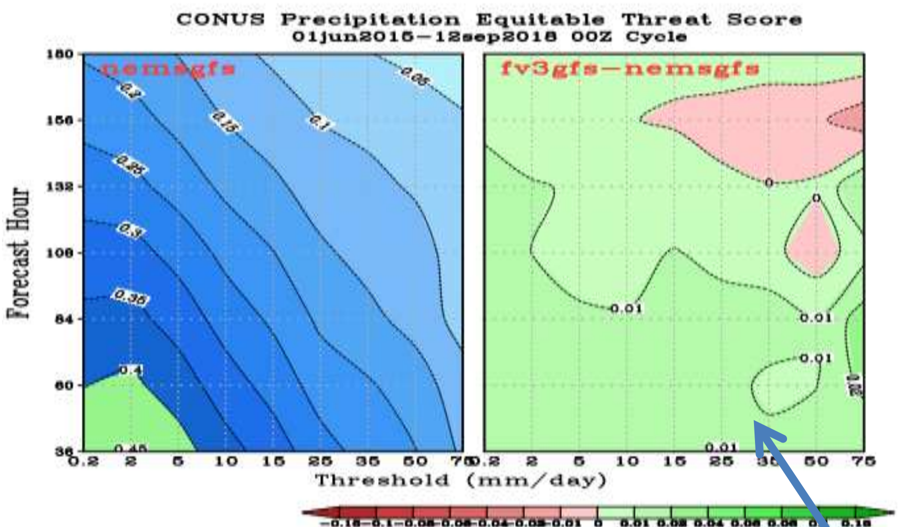
RMSE

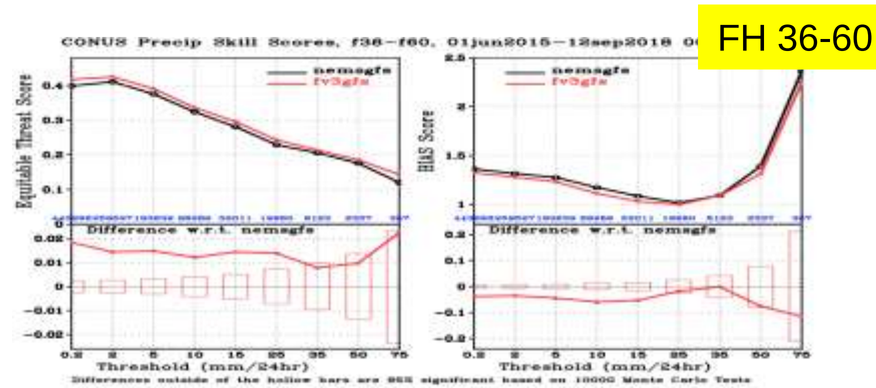


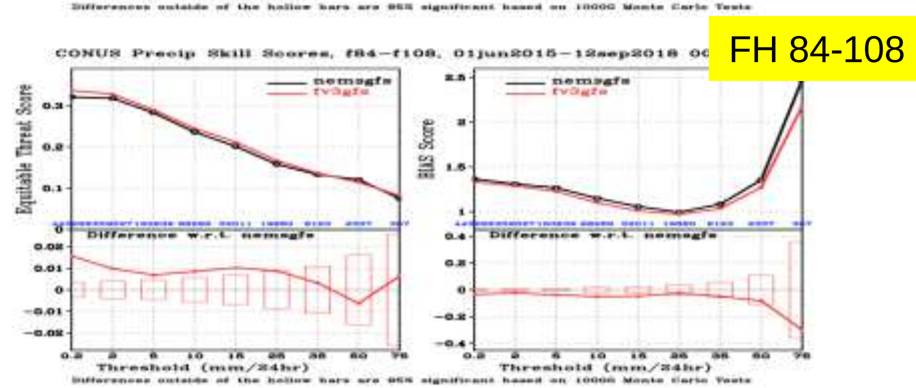
- Winds in both GSM and FV3GFS are weaker than observed, but **FV3GFS is closer to the observation**.
- FV3GFS has stronger winds at the jet level, **reduced RMSE in the troposphere**, but worse in the stratosphere

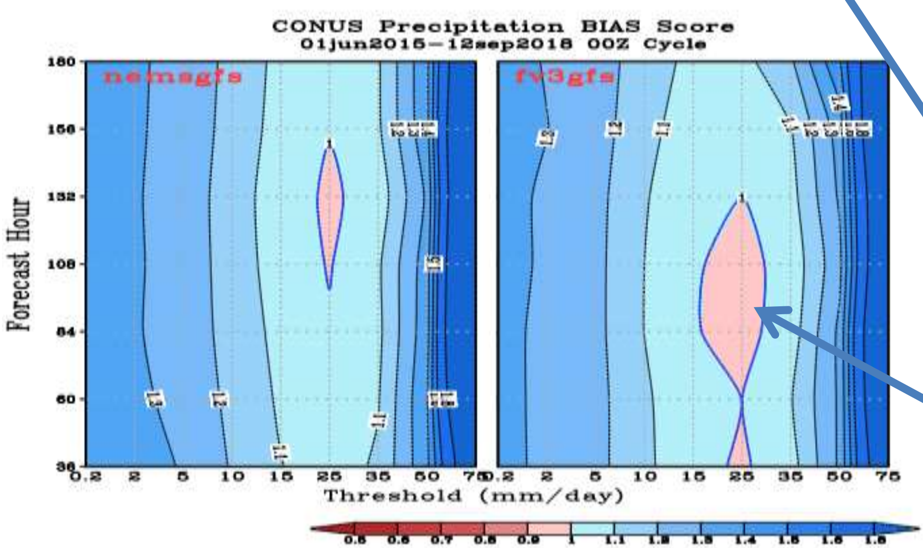
CONUS Precip ETS and BIAS SCORES

00Z Cycle, verified against gauge data, 20150601~ 20180912





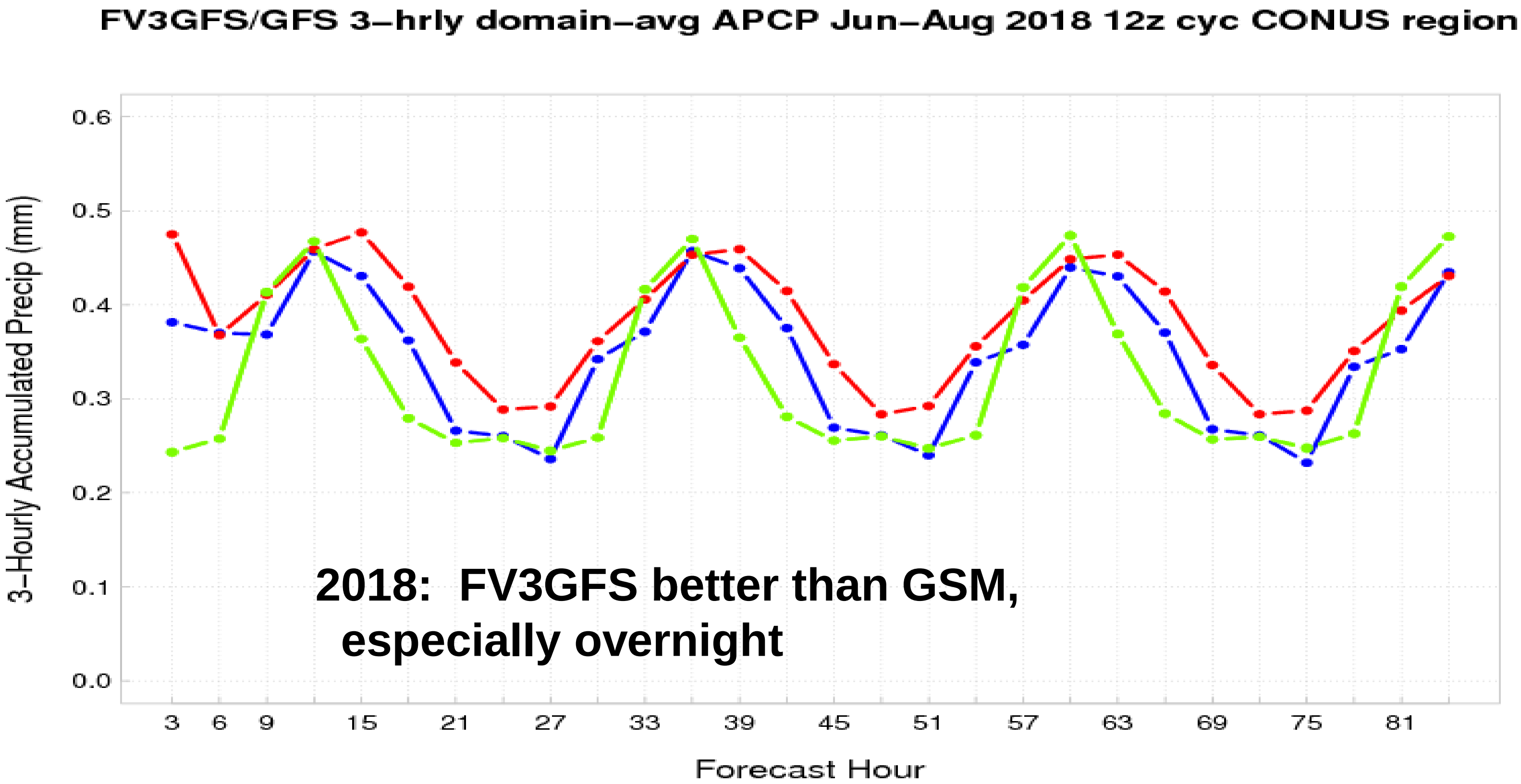




- Improved ETS scores for almost all thresholds and at all forecast length
- **Reduced wet bias for light rains**
- Slightly worsened dry bias for moderate rain categories

Improved Precipitation Diurnal Cycle

SUMMER 2018 CONUS DOMAIN-AVG PCP



FV3GFS **ops GFS** **OBS**

From: Ying Lin

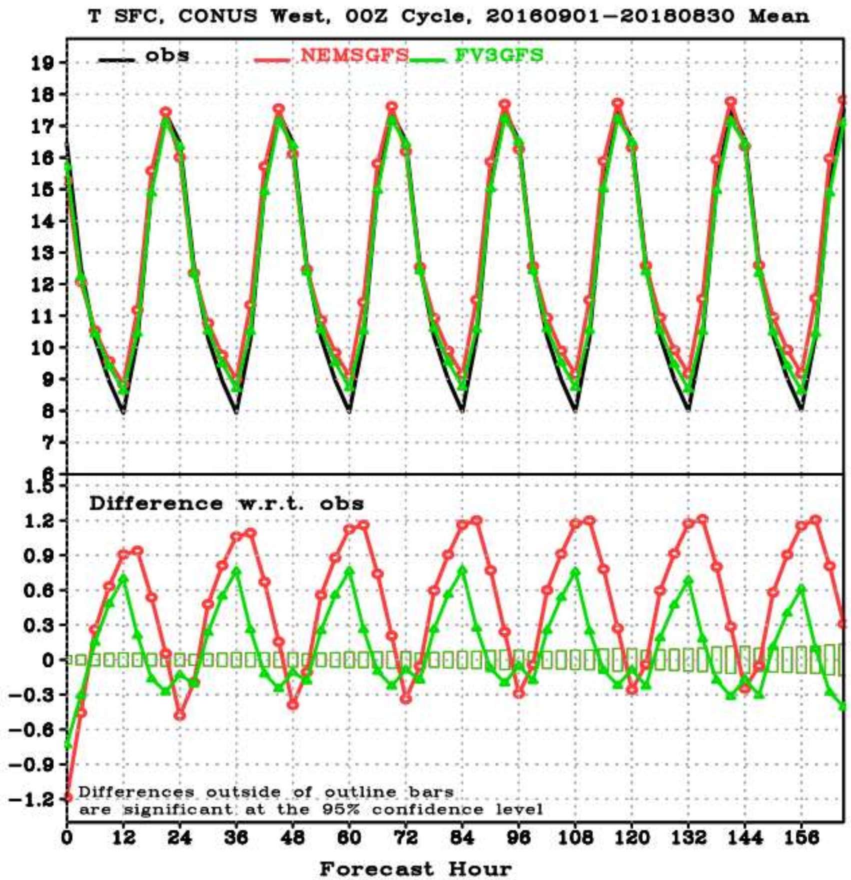
CONUS 2-m Temperature

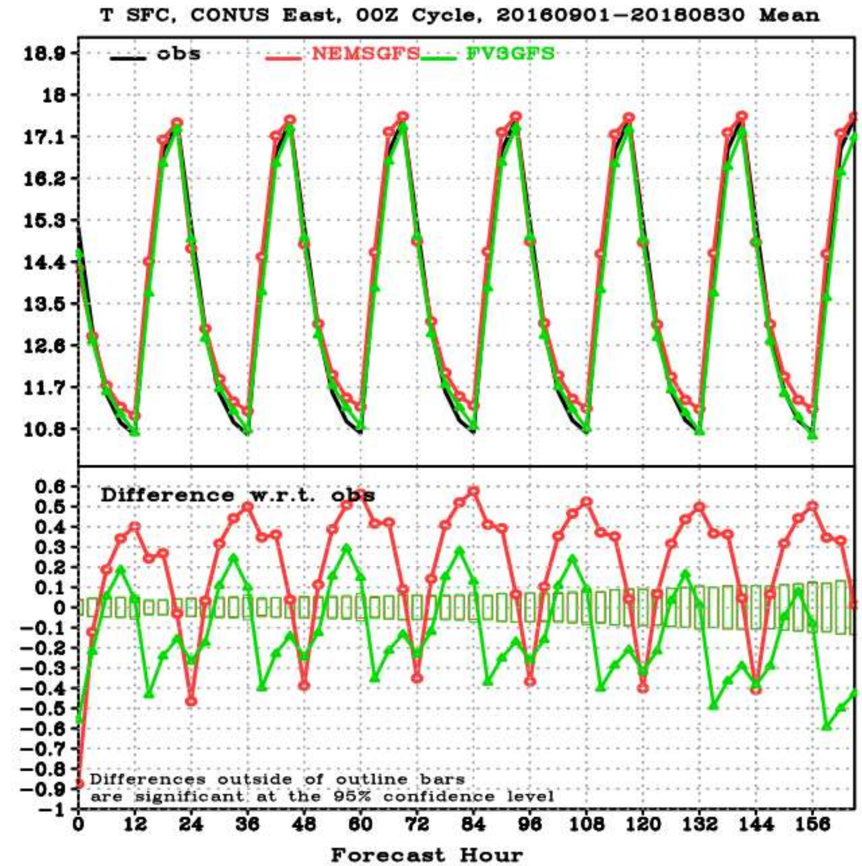
Verified against Station Observations, 3-year mean

WEST

OBS GFS FV3GFS

EAST





Slight FV3GFS improvement in both the min and the max

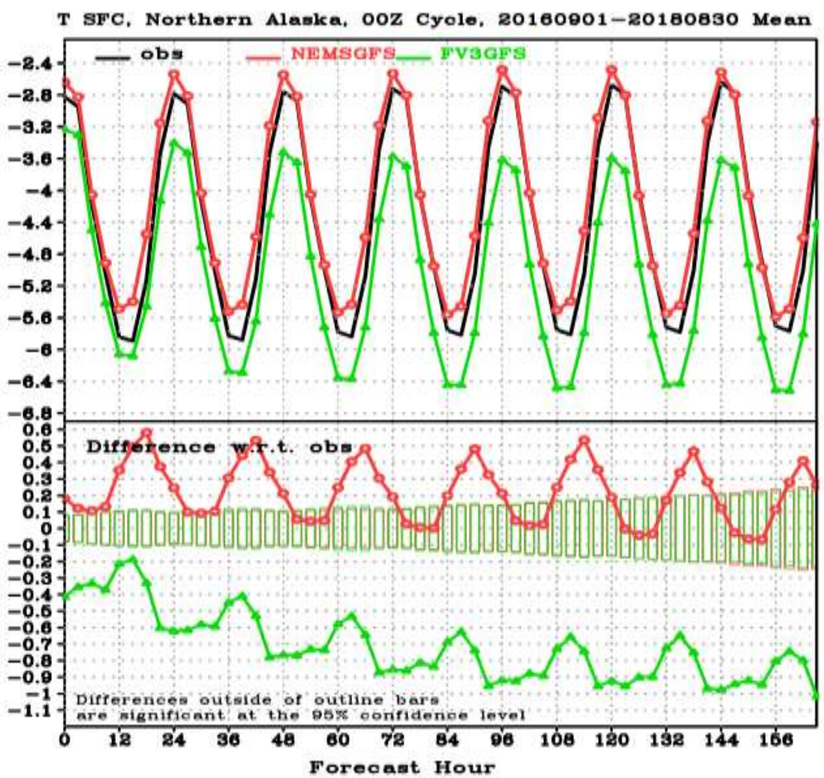
2-m Temperature over Alaska

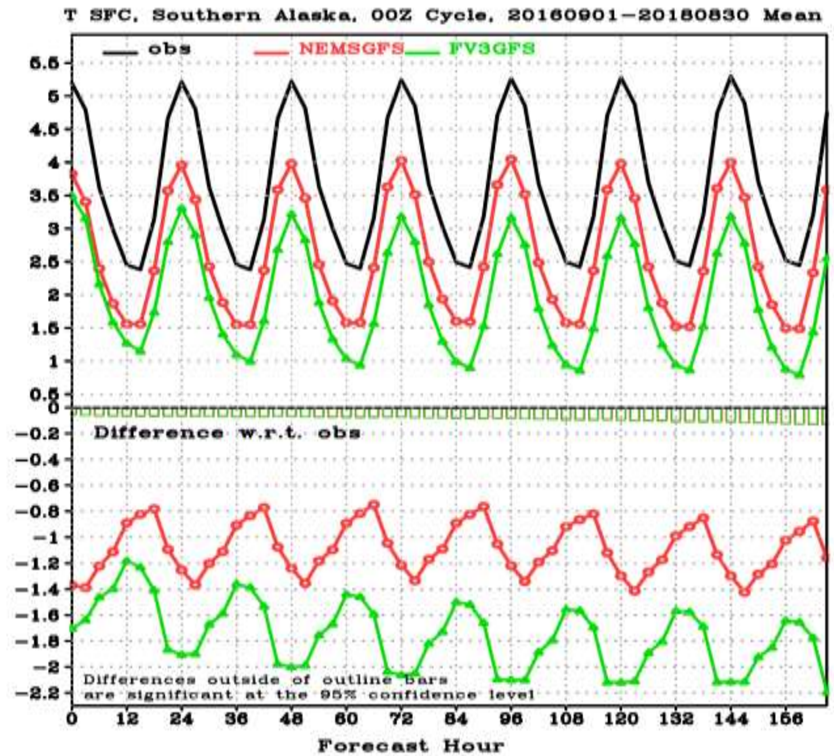
Verified against Station Observations, 3-year mean

NORTH ALASKA

OBS GFS FV3GFS

SOUTH ALASKA





FV3GFS has large cold bias !

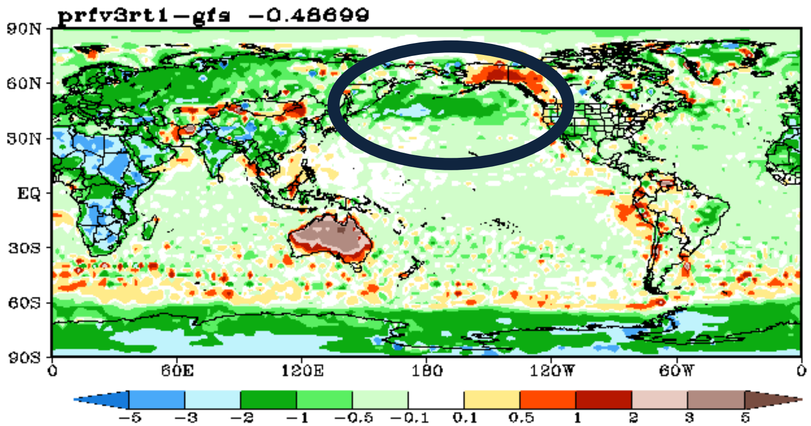
Likely caused by a cold NSST and an overestimate (underestimate) of cloud in summer (winter)

Diagnosing and Fixing an NSST Issue

- In response to feedback on how well gulf stream was resolved, the background error correlation lengths were revised to be more consistent with those used in other operational SST analyses (50km).
- After a number of months of pre-operational testing an SST anomaly of ~3K was noted in the northern Pacific. This was a symptom of a lack of observations in the area and the reduced influence of distant observations because of the reduction in length scales.
- At the same time anomalies in lake temperatures were noted by the MEG team which was also traced to a lack of observations being assimilated.

Both of these are solved by switching on a climatological update of the tref to the background SST field. This option is currently being tested along with an increase in background error length scales to 100km.

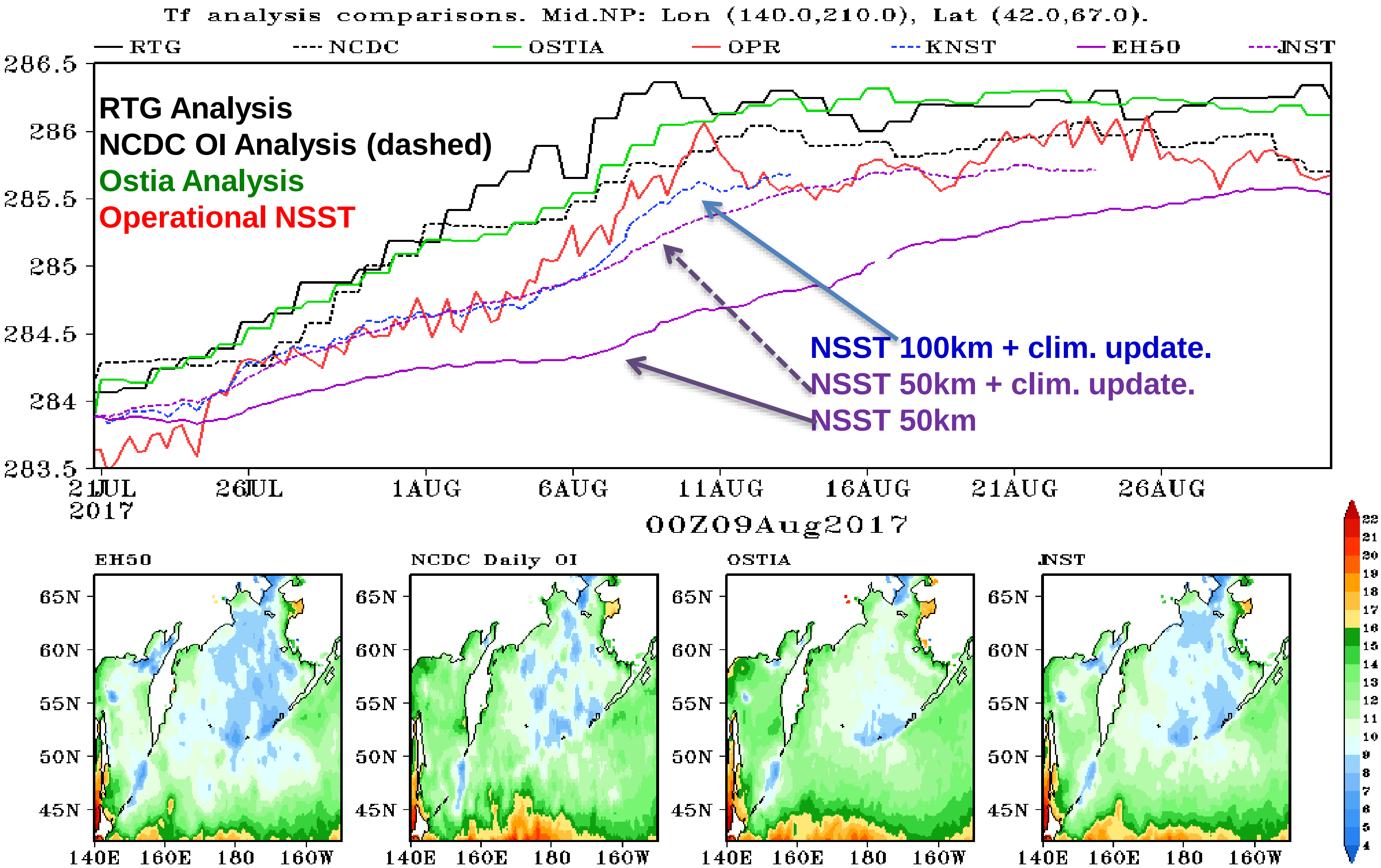
Tref, 26 May – 18 September 2018



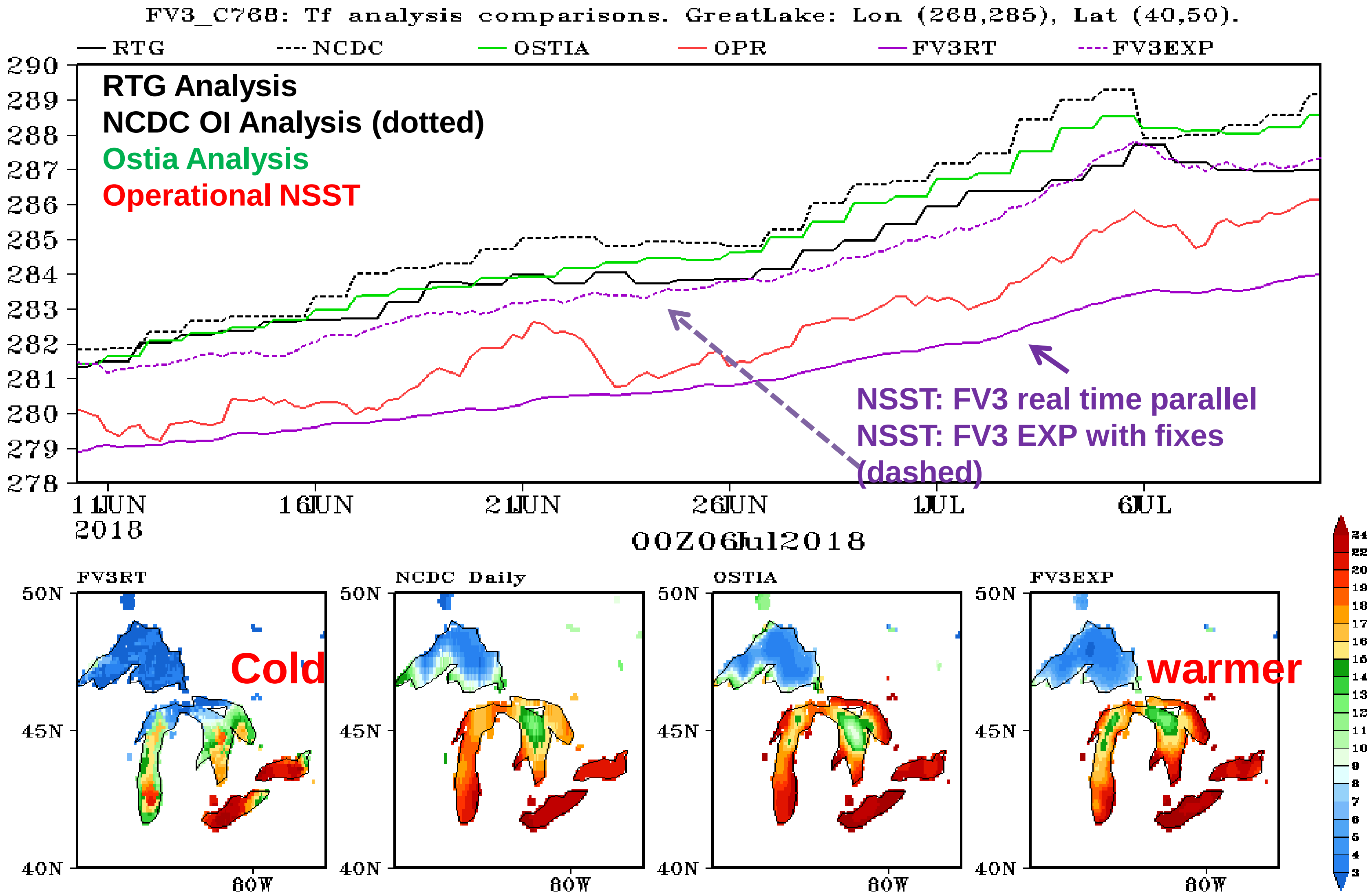
gcycle is now called hourly in GDAS forecast step

From: DA Team

Fixing the N. Pacific Cold Bias



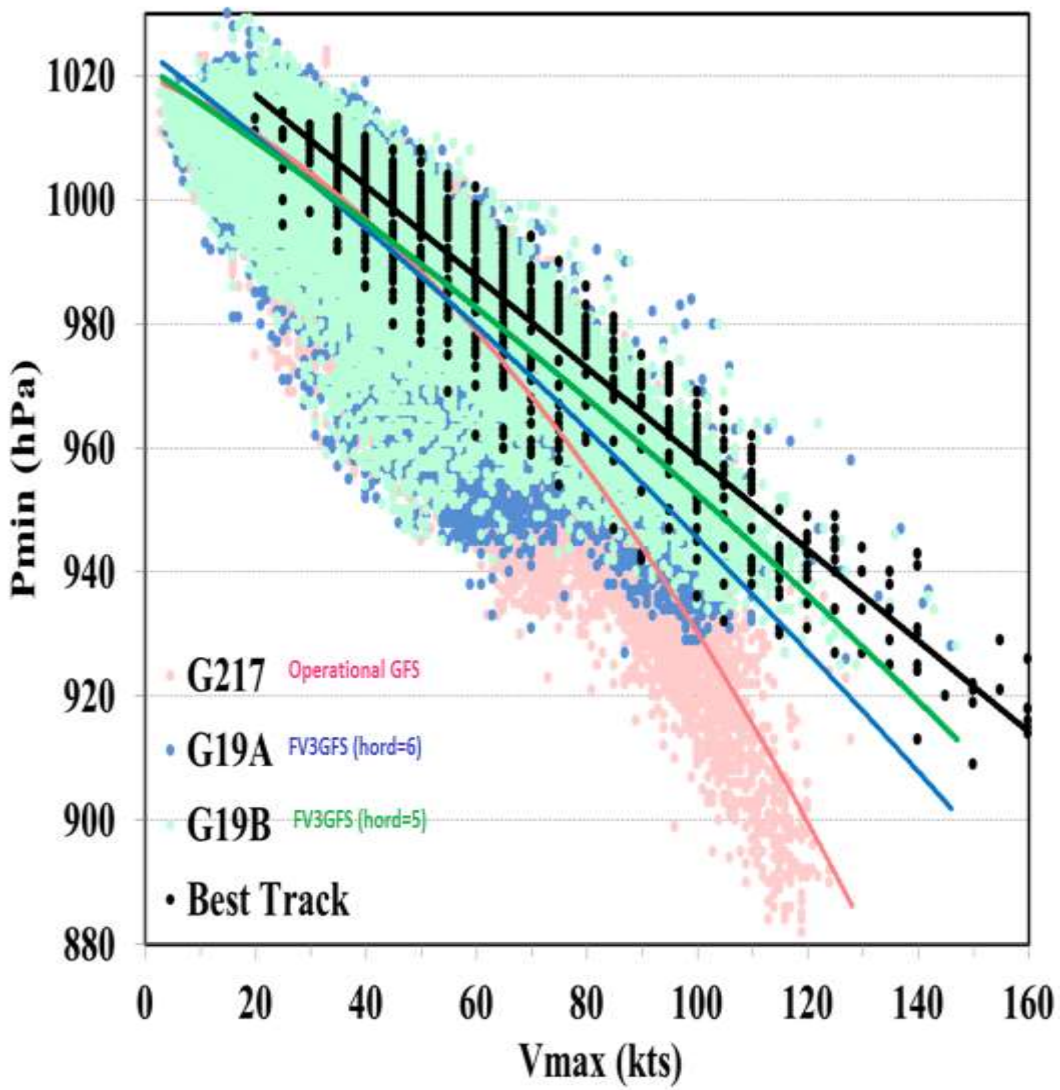
Fixing the Great Lakes Cold Bias



Improved Wind-Pressure Relationship

FV3GFS shows a much better W-P relation than ops GFS for strong storms

For FV3GFS, W-P relation with hord=5 is better than hord=6



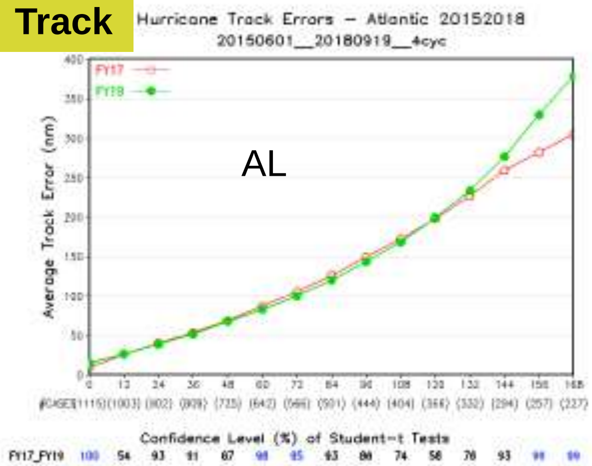
Graph made by HWRF group

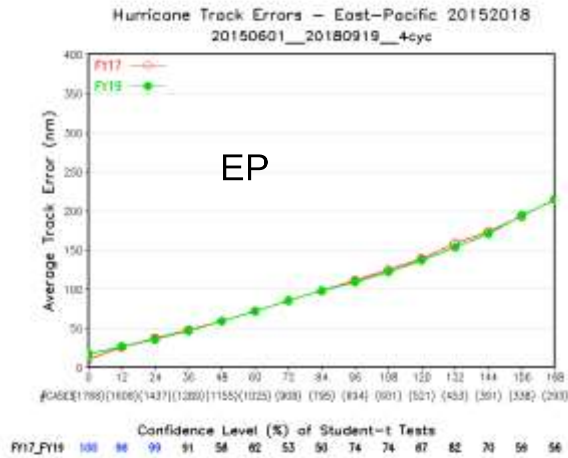
Hurricane Track and Intensity

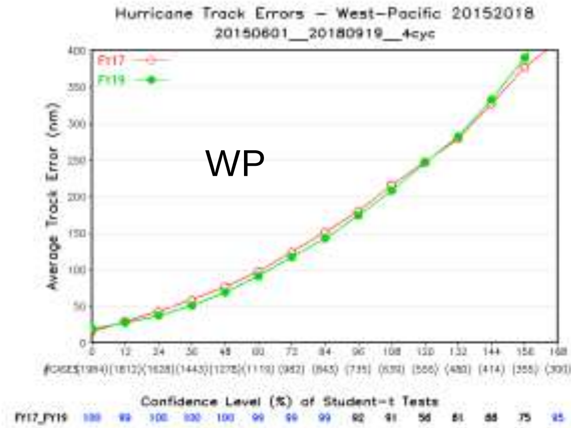
20150601 ~ 20180919

Red: NEMS GFS; Green FV3GFS

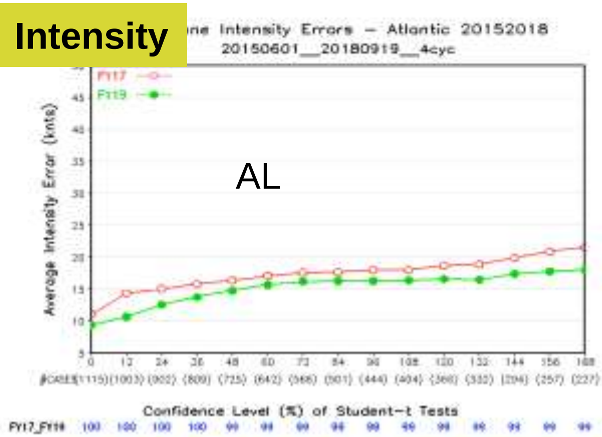
Track

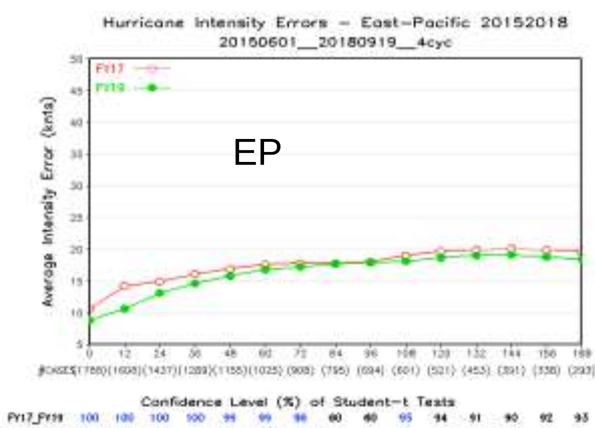


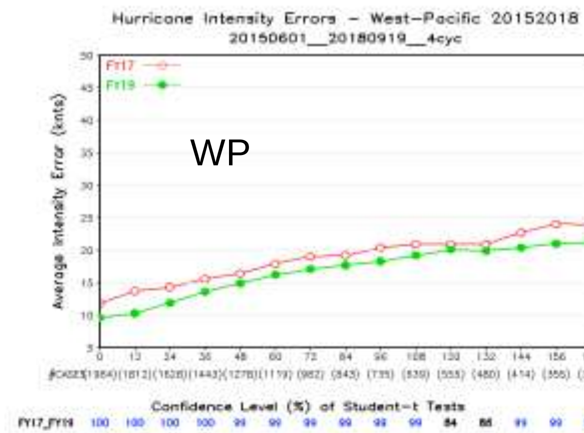




Intensity





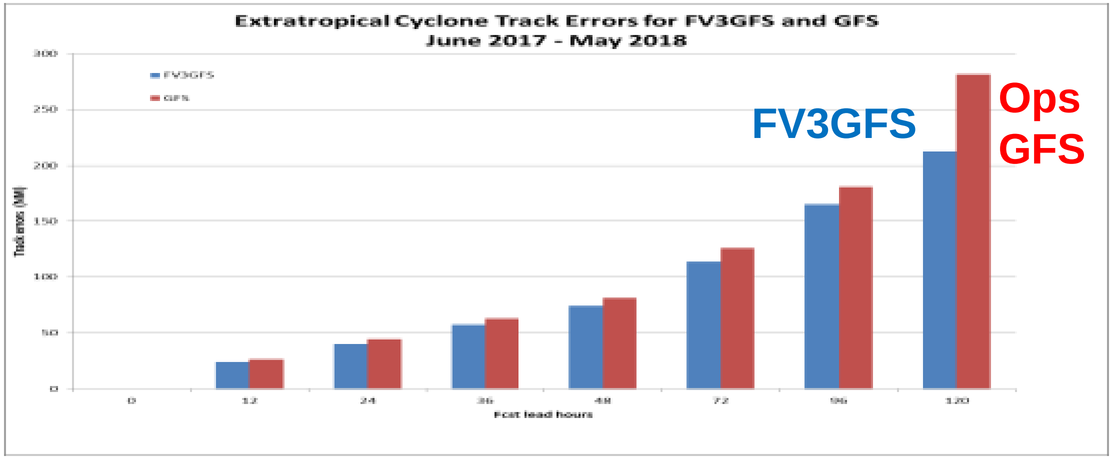


- **Intensity is improved over all basins**
- **Tracks in AL and WP are improved for the first 5 days except at FH00, and degraded in day 6 and day 7. Track in EP is neutral**

Extratropical Cyclone Track

Jun 2017 ~ May 2018

FV3GFS track errors are consistently smaller than that of GFS. Error at 120 hour is substantially smaller. (Unit: NM)



Track errors

FCST hr	0	12	24	26	48	72	96	120
FV3GFS	0.0	24.09	40.38	57.04	73.91	113.66	165.22	212.75
GFS	0.0	26.59	44.17	62.87	81.08	125.89	180.85	281.57
diff	0.0	-2.50	-3.79	-5.83	-7.17	-12.23	-15.63	-68.82

Number of cases

FCST hr	0	12	24	26	48	72	96	120
FV3GFS	15490	14895	13904	10069	6231	2285	799	239
GFS	16672	16156	15031	10906	6776	2563	925	281
diff	-1182	-1261	-1127	-837	-545	-278	-126	-42

FV3GFS captures slightly smaller number of cases.

From: Guang-Ping Luo

Summary -- Benefits

- (significantly) Improved 500-hpa anomaly correlation
- Intense tropical cyclone deepening in GFS not observed in FV3GFS
- FV3GFS tropical cyclone track forecasts improved (within 5 days)
- Warm season diurnal cycle of precipitation improved
- General improvement in HWRF and HMON runs
- Some indication that fv3gfs can generate modest surface cold pools from significant convection
- FV3GFS with advanced GFDL MP provides better initial and boundary conditions for driving standard alone FV3, and for running downstream models that use advanced MP.
- Improved ozone and water vapor physics and products
- Improved extratropical cyclone tracks
- Improved precipitation ETS score (hit/miss/false alarm)
- Overall reduced T2m biases over CONUS

Summary -- Concerns

- **FV3GFS can be too progressive with synoptic pattern**
- **Precipitation dry bias for moderate rainfall**
- **SST issues – North Pacific and lakes are too cold in the transition season**
- **T2m over Alaska is too cold, likely caused by cold NSST and/or cloud microphysics issue in the Arctic region.**
- ***Both GFS and FV3GFS struggle with inversions***

Thank you