Review of GFS Forecast Skills in 2014

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Acknowledgments : All NCEP EMC Global Climate and Weather Modeling Branch members are acknowledged for their contributions to the development and application of the Global Forecast Systems. **Disclaimer**: The review does not cover all aspects of the complex system, and is biased towards the presenter's personal experience.

Outline

1. Major GFS changes in recent years

2. Forecast skill scores
   - AC and RMSE
   - Precipitation
   - Surface 2-m temperature and 10-m wind
   - Verification Against Rawinsonde Observations
   - Hurricane Track and Intensity

3. Summary and Discussion

Change History of GFS Configurations

Mon/Year	Levels	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

Vertical layers double every ~11 yrs; change of horizontal resolution is rapid (~30 times in 35 years); sigma-Eulerian used for 27 yrs!

Source http://www.emc.ncep.noaa.gov/gmb/STATS/html/model_changes.html

Major GFS Changes

- 3/1999
  - **AMSU-A** and HIRS-3 data
- 2/2000
  - **Resolution change: T126L28 → T170L42 (100 km → 70 km)**
  - Next changes
    - 7/2000 (hurricane relocation)
    - 8/2000 (data cutoff for 06 and 18 UTC)
    - 10/2000 – package of minor changes
    - 2/2001 – radiance and moisture analysis changes
- 5/2001
  - **Major physics upgrade (prognostic cloud water, cumulus momentum transport)**
  - Improved QC for AMSU radiances
  - Next changes
    - 6/2001 – vegetation fraction
    - 7/2001 – SST satellite data
    - 8/200 – sea ice mask, gravity wave drag adjustment, random cloud tops, land surface evaporation, cloud microphysics…)
    - 10/ 2001 – snow depth from model background
    - 1/2002 – Quikscat included

Credit: Stephen Lord and Fanglin Yang

Major GFS Changes (cont'd)

- 11/2002
  - **Resolution change: T170L42 → T254L64 (70 km → 55 km)**
  - Recomputed background error
  - Divergence tendency constraint in tropics turned off
  - Next changes
    - 3/2003 – NOAA-17 radiances, NOAA-16 AMSU restored, Quikscat 0.5 degree data
    - 8/2003 – RRTM longwave and trace gases
    - 10/2003 – NOAA-17 AMSU-A turned off
    - 11/2003 – Minor analysis changes
    - 2/2004 – mountain blocking added
    - 5/2004 – NOAA-16 HIRS turned off
- 5/2005
  - **Resolution change: T254L64 → T382L64 (55 km → 38 km)**
  - **2-L OSU LSM → 4-L NOHA LSM**
  - Reduce background vertical diffusion
  - Retune mountain blocking
  - Next changes
    - 6/2005 – Increase vegetation canopy resistance
    - 7/2005 – Correct temperature error near top of model

Major GFS Changes (cont'd)

- 8/2006
  - Revised orography and land-sea mask
  - NRL ozone physics
  - Upgrade snow analysis
- 5/2007
  - **SSI (Spectral Statistical Interpolation) → GSI (Gridpoint Statistical Interpolation).**
  - **Vertical coordinate changed from sigma to hybrid sigma-pressure**
  - New observations (COSMIC, full resolution AIRS, METOP HIRS, AMSU-A and MHS)
- 12/2007
  - JMA high resolution winds and SBUV-8 ozone observations added
- 2/2009
  - **Flow-dependent weighting of background error variances**
  - **Variational Quality Control**
  - METOP IASI observations added
  - Updated Community Radiative Transfer Model coefficients
- 7/2010
  - **Resolution Change: T382L64 → T574L64 (38 km → 23 km)**
  - **Major radiation package upgrade (RRTM2 , aerosol, surface albedo etc)**
  - **New mass flux shallow convection scheme; revised deep convection and PBL scheme**
  - **Positive-definite tracer transport scheme to remove negative water vapor**

Major GFS Changes (cont'd)

- 05/09/2011
  - **GSI**: Improved OMI QC; Retune SBUV/2 ozone ob errors; Relax AMSU-A Channel 5 QC; New version of CRTM 2.0.2 ; Inclusion of GPS RO data from SAC-C, C/NOFS and TerraSAR-X satellites; Inclusion of uniform (higher resolution) thinning for satellite radiances ; Improved GSI code with optimization and additional options; Recomputed background errors; Inclusion of SBUV and MHS from NOAA-19 and removal of AMSU-A NOAA-15 .
  - **GFS:** New Thermal Roughness Length -- Reduced land surface skin temperature cold bias and low level summer warm bias over arid land areas; Reduce background diffusion in the Stratosphere .

- 5/22/2012
  - **GSI Hybrid EnKF-3DVAR** : A hybrid variational ensemble assimilation system is employed. The background error used to project the information in the observations into the analysis is created by a combination of a static background error (as in the prior system) and a new background error produced from a lower resolution (T254) Ensemble Kalman Filter.
  - **Other GSI Changes:** Use GPS RO bending angle rather than refractivity; Include compressibility factors for atmosphere ; Retune SBUV ob errors, fix bug at top ; Update radiance usage flags; Add NPP ATMS satellite data, GOES-13/15 radiance data, and SEVERI CSBT radiance product ; Include satellite monitoring statistics code in operations ; Add new satellite wind data and quality control.

- 09/05/2012
  - **GFS** : A look-up table used in the land surface scheme to control Minimum Canopy Resistance and Root Depth Number was updated to reduce excessive evaporation. This update was aimed to mitigate GFS cold and moist biases found in the late afternoon over the central United States when drought conditions existed in summer of 2012.

Major GFS Changes (cont'd)

- **07-08/2013**

  - GFS was moved from IBM CCS to WCOSS supercomputers. They two systems have different architectures.

  - GSI change on August 20: New satellite data, including METOP-B, SEVIRI data from Meteosat-10, and NPP CrIS data.

- **01/14/2015**
  - **Upgrade to T1534 Semi-Lagrangian (~13km)** : Use Lagrangian instead Hermite vertical interpolation; Use high resolution daily RGT SST and daily sea ice analysis; Extend high resolution forecast from 8 days to 10 days; Use McICA radiation approximation; Reduced drag coefficient at high wind speeds; Hybrid EDMF PBL scheme and TKE dissipative heating; Retuned ice and water cloud conversion rates, background diffusion of momentum and heat, orographic gravity-wave forcing and mountain block; Updated physics restart and sigio library; Consistent diagnosis of snow accumulation in post and model; Compute and output frozen precipitation fraction; Divergence damping in the stratosphere to reduce noise; Added a tracer fixer for maintaining global column ozone mass; Stationary convective gravity wave drag; New blended snow analysis to reduce reliance on AFWA snow; Changes to treatment of lake ice to remove unfrozen lake in winter; Modified initialization to reduce a sharp decrease in cloud water in the first model time step; Replace Bucket soil moisture climatology with CFS/GLDAS; Add vegetation dependence to the ratio of the thermal and momentum roughness.
  - **GSI Changes**: increase horizontal resolution of ensemble from T254 to T574; reduce number of second outer loop iterations from 150 to 100; upgrade to CRTM v2.1.3 ; move to enhanced radiance bias correction scheme; correct bug in AMSU-A cloud liquid water bias correction term; assimilate new radiances: F17 an F18 SSMIS, MetOp-B IASI ; increase ATMS observation errors; turn on cloud detection channels for monitored instruments: NOAA-17, -19 HIRS, GOES-13 and -14 sounders; changes in assimilation of atmospheric motion vectors (AMV): assimilate NESDIS GOES hourly AMVs, improve AMV quality control ; improve GPS RO quality control .

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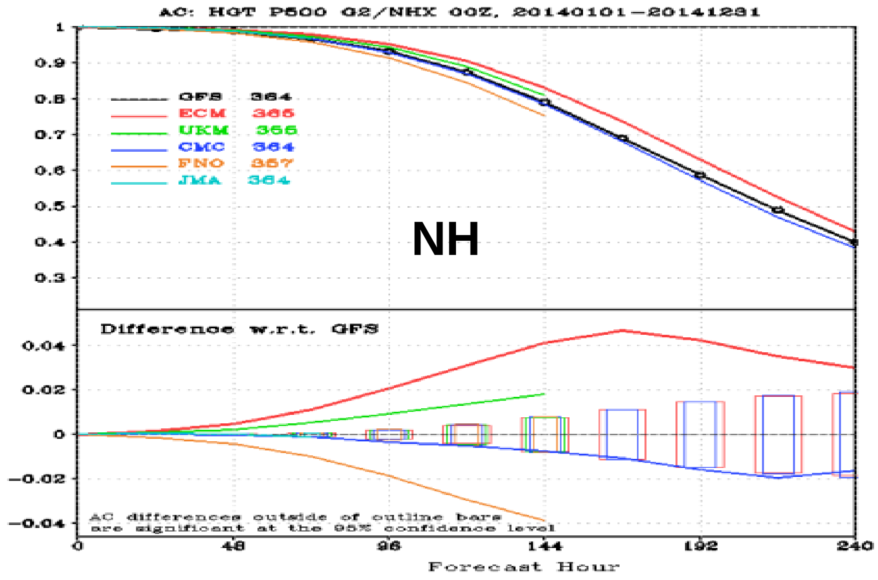
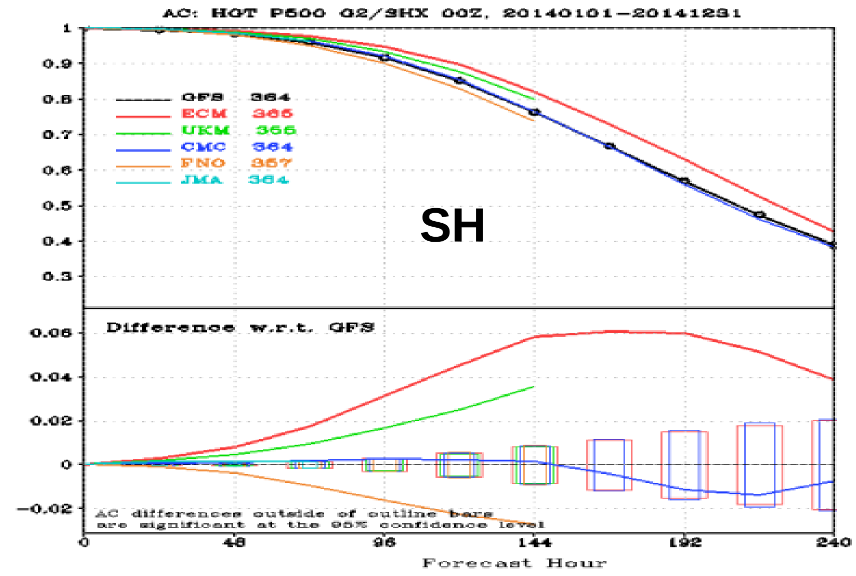
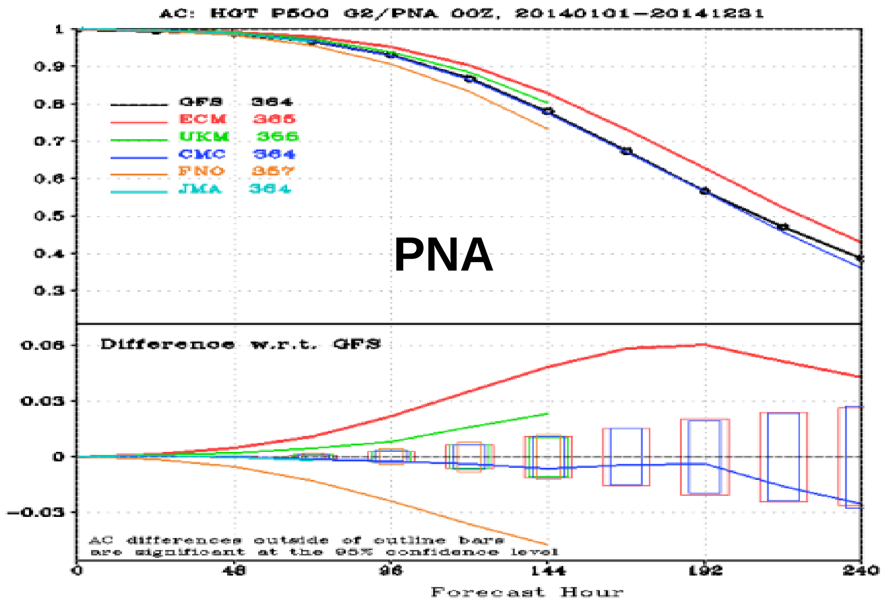
2014 Annual Mean 500-hPa AC

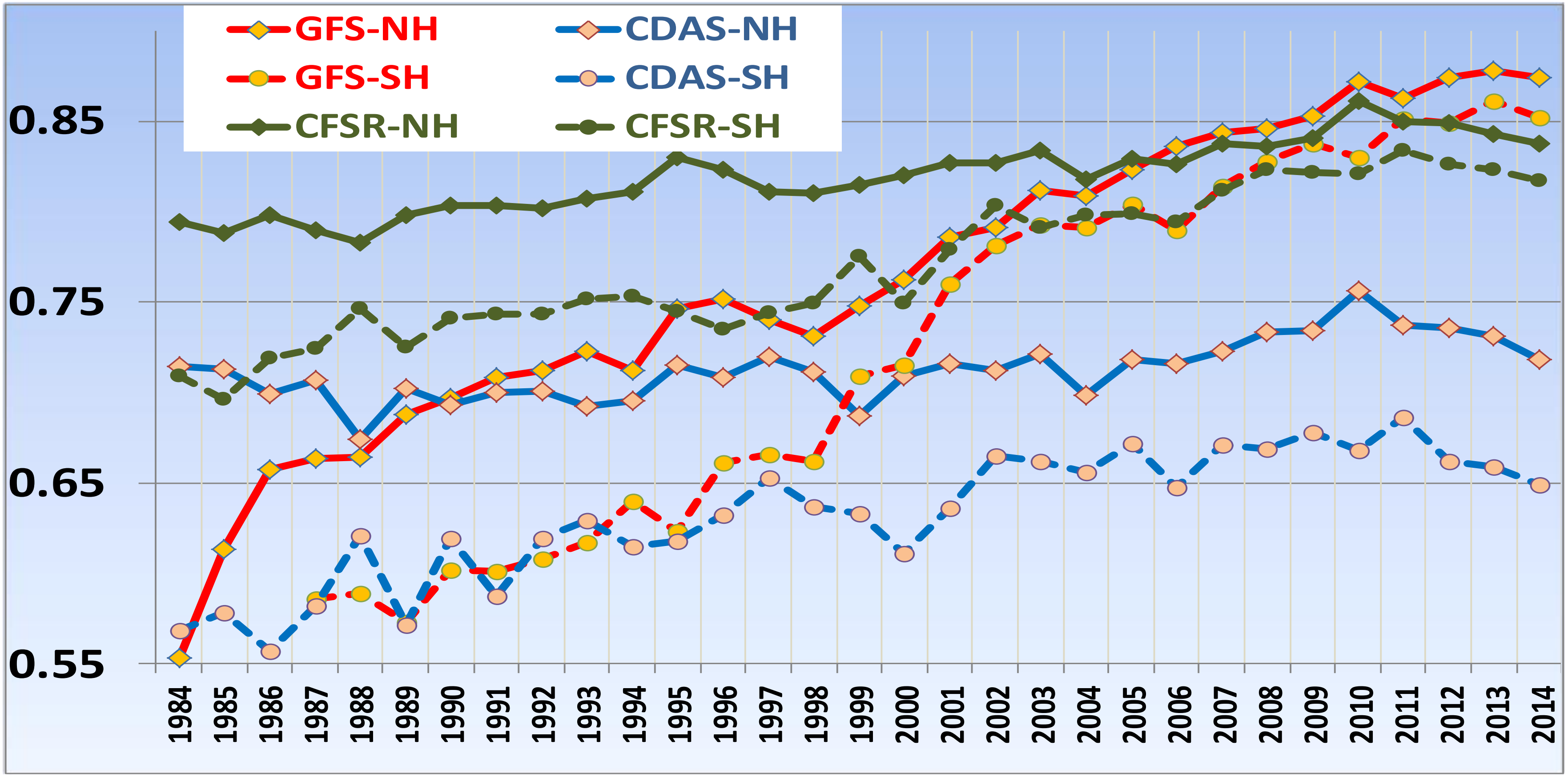






- GFS trails ECMWF and UKM in all regions and for all forecast length
- GFS is better than CMC in NH and PNA, but slightly worse in SH
- Useful forecast (AC=0.6) for NH: ECMWF 8.2 days, GFS 7.9 days

Annual Mean 500-hPa HGT Day-5 Anomaly Correlation



Increase is about 0.1 per decade

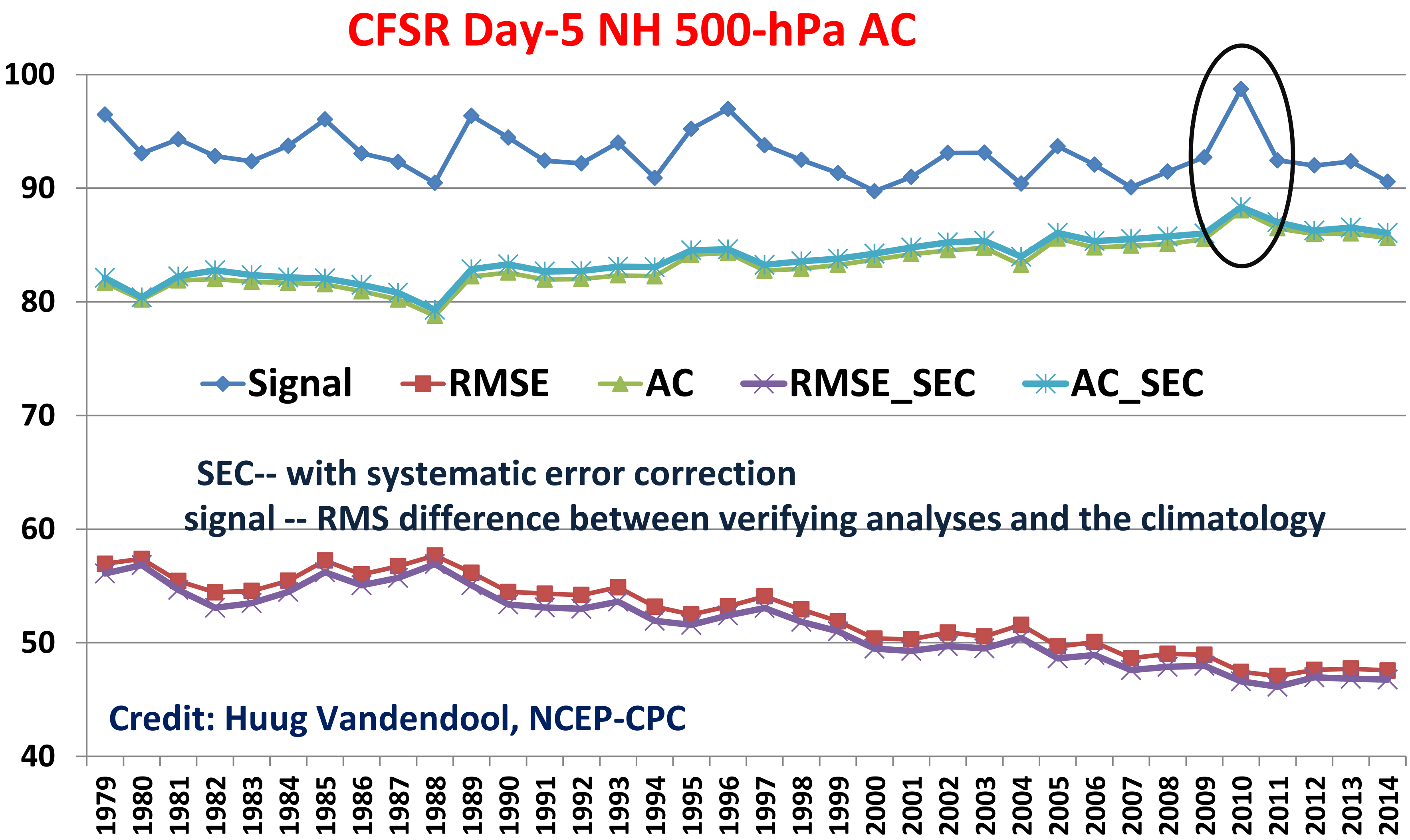
GFS scores for 2014 are slightly worse than for 2013.

After 2010 CDAS and CFSR scores have kept dropping !

-- Change of predictability or an indication of decay of the analysis systems?

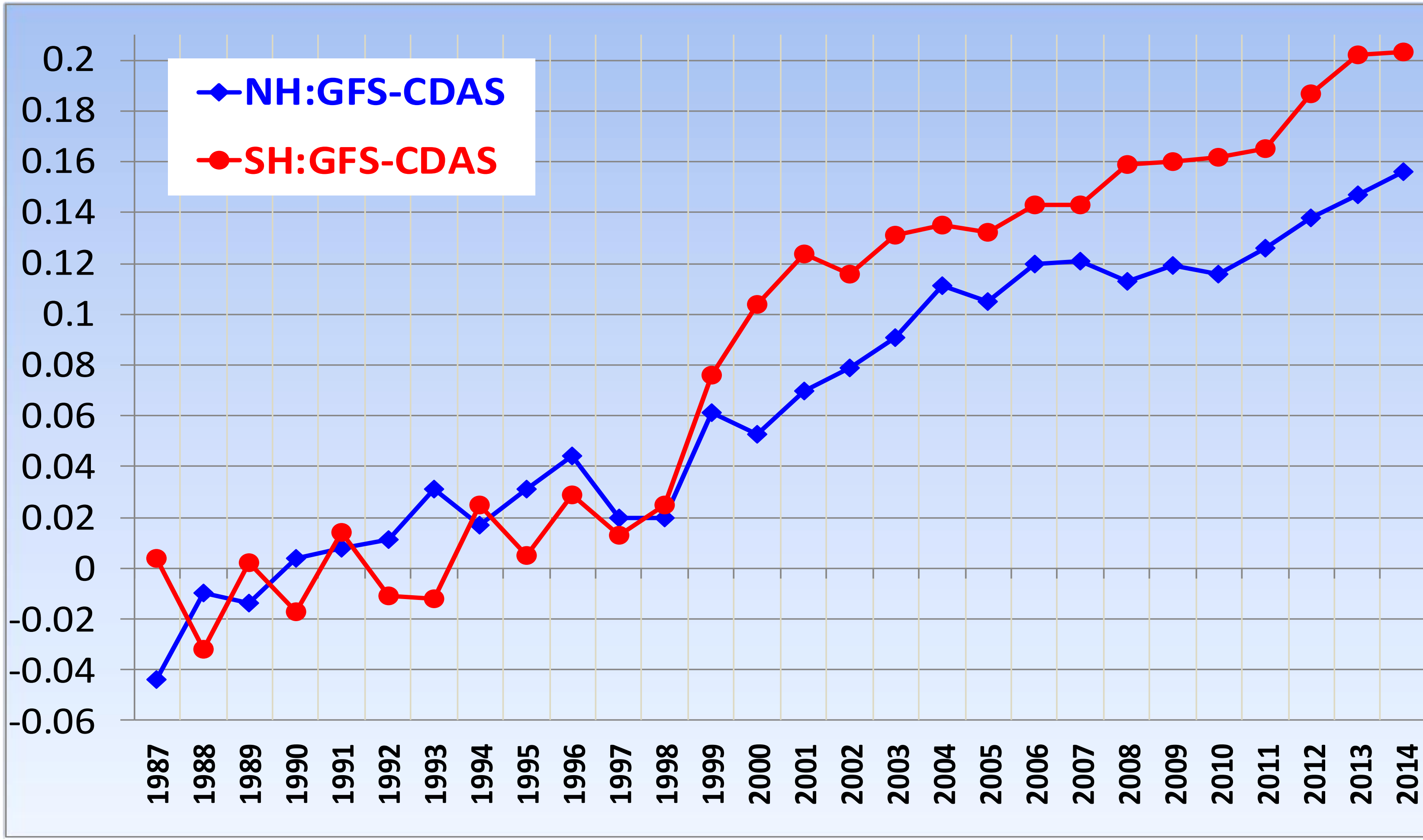
CDAS is a legacy GFS (T64) used for NCEP/NCAR Reanalysis circa 1995.

CFSR is the coupled GFS (T126) used for reanalysis circa 2006.



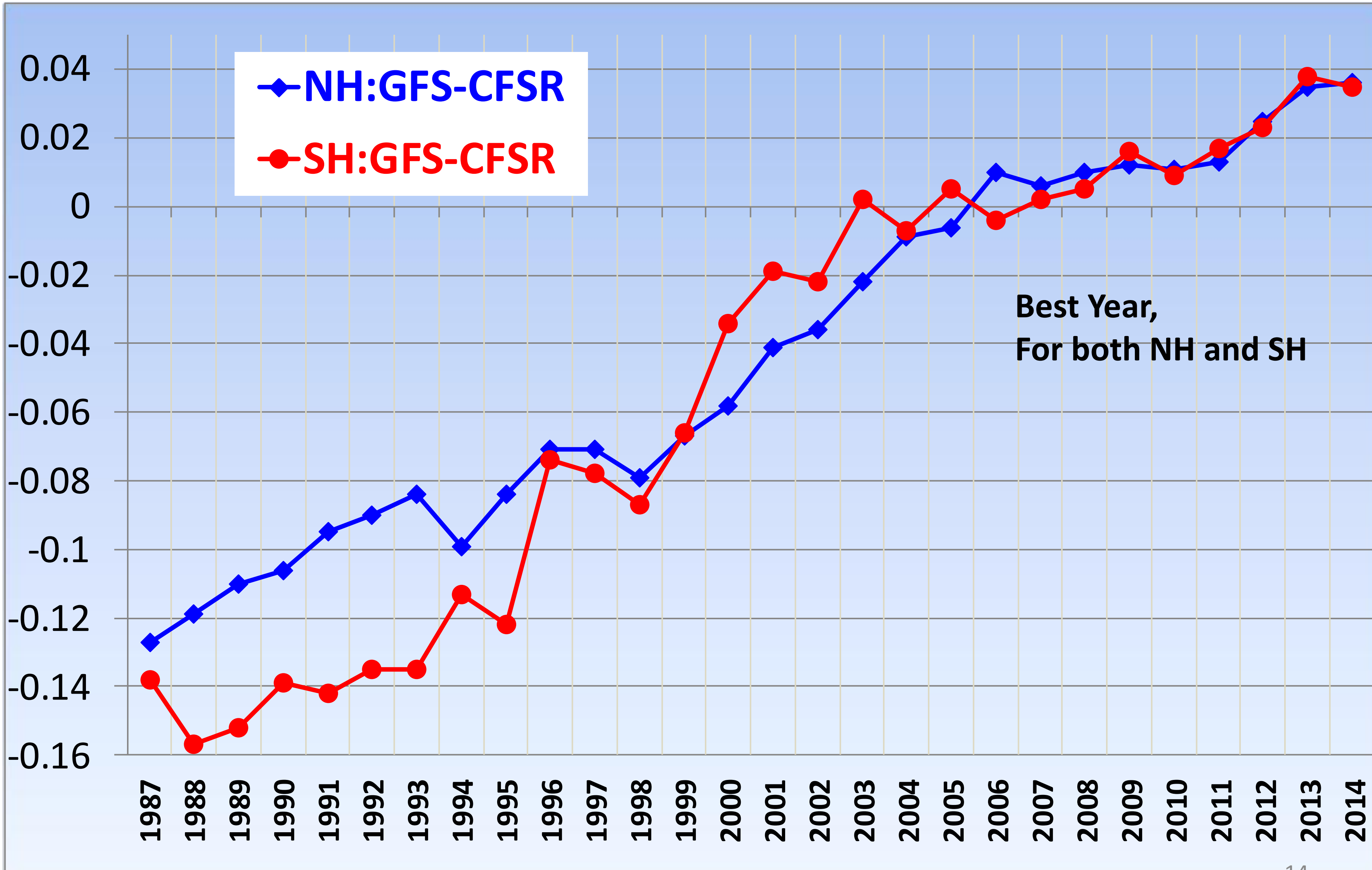
Huug: "An alternative explanation is that 2010 was really an exceptional year because of very large anomalies, strong negative NAO, very persistent. 2010 may be the record in forecast skill for the CFSR/CFSV2 system (and R1/CDAS) for a long time. 2011-14 are more normal years."

Annual Mean 500-hPa HGT Day-5 Anomaly Correlation
GFS minus CDAS

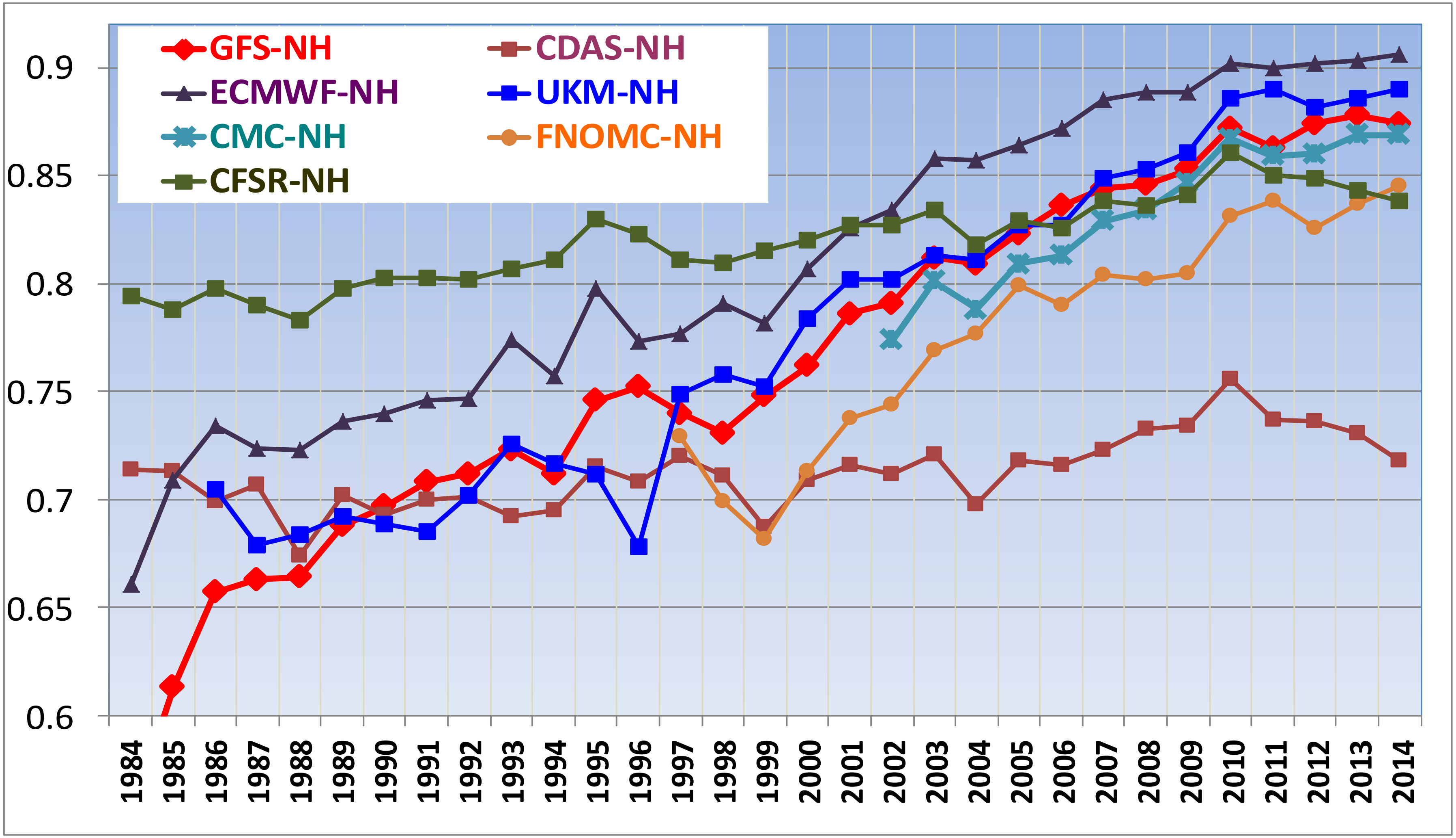


If CDAS truly reflects the predictability of the real atmosphere, GFS forecast skill was actually improved in 2014.

Annual Mean 500-hPa HGT Day-5 Anomaly Correlation
GFS minus CFSR

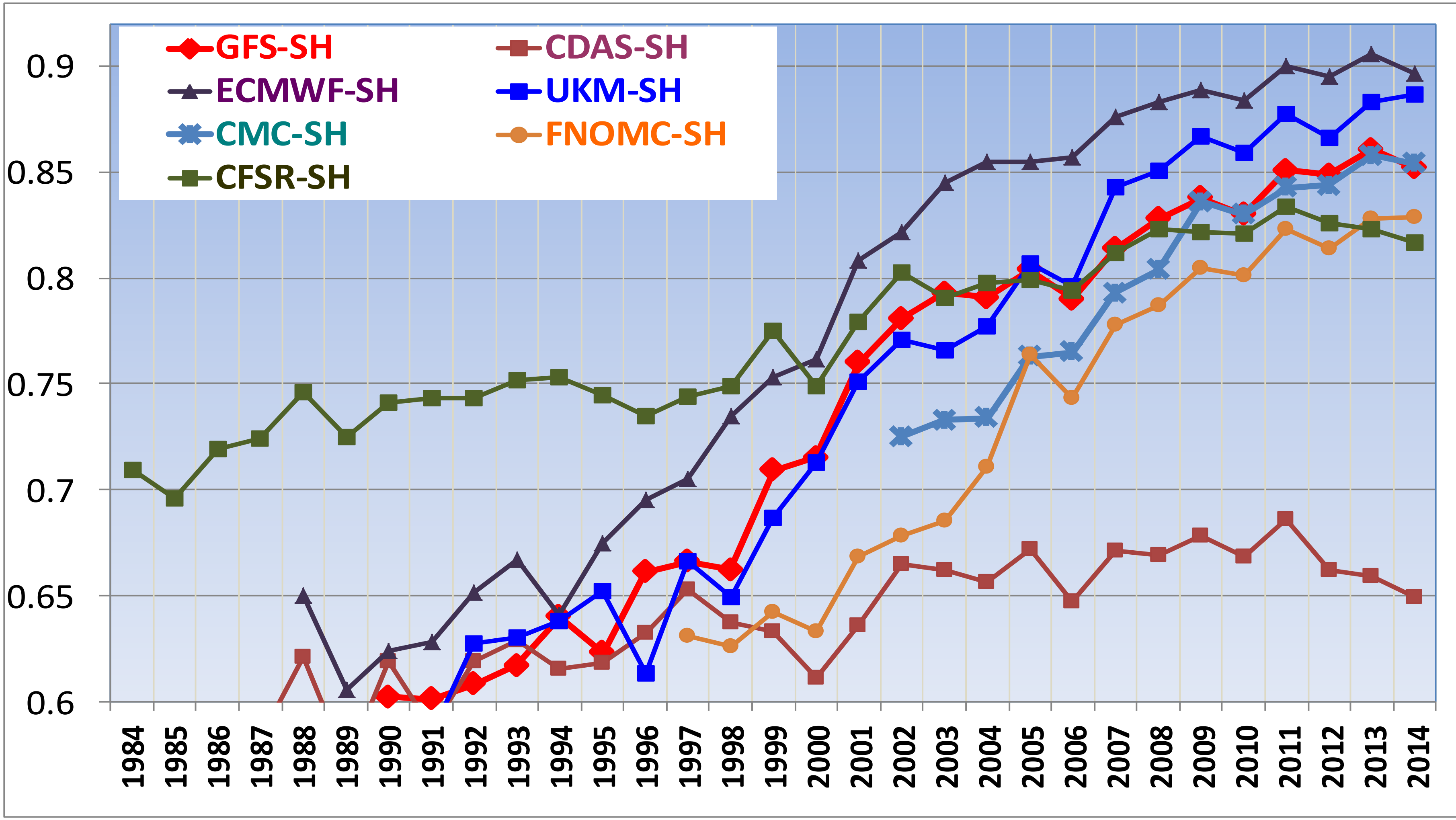


Annual Mean NH 500hPa HGT Day-5 AC



- **FNOMC made significant improvement in 2013 and 2014. Other models did not change much in 2014. CFSR and CDAS were worse.**

Annual Mean SH 500hPa HGT Day-5 AC

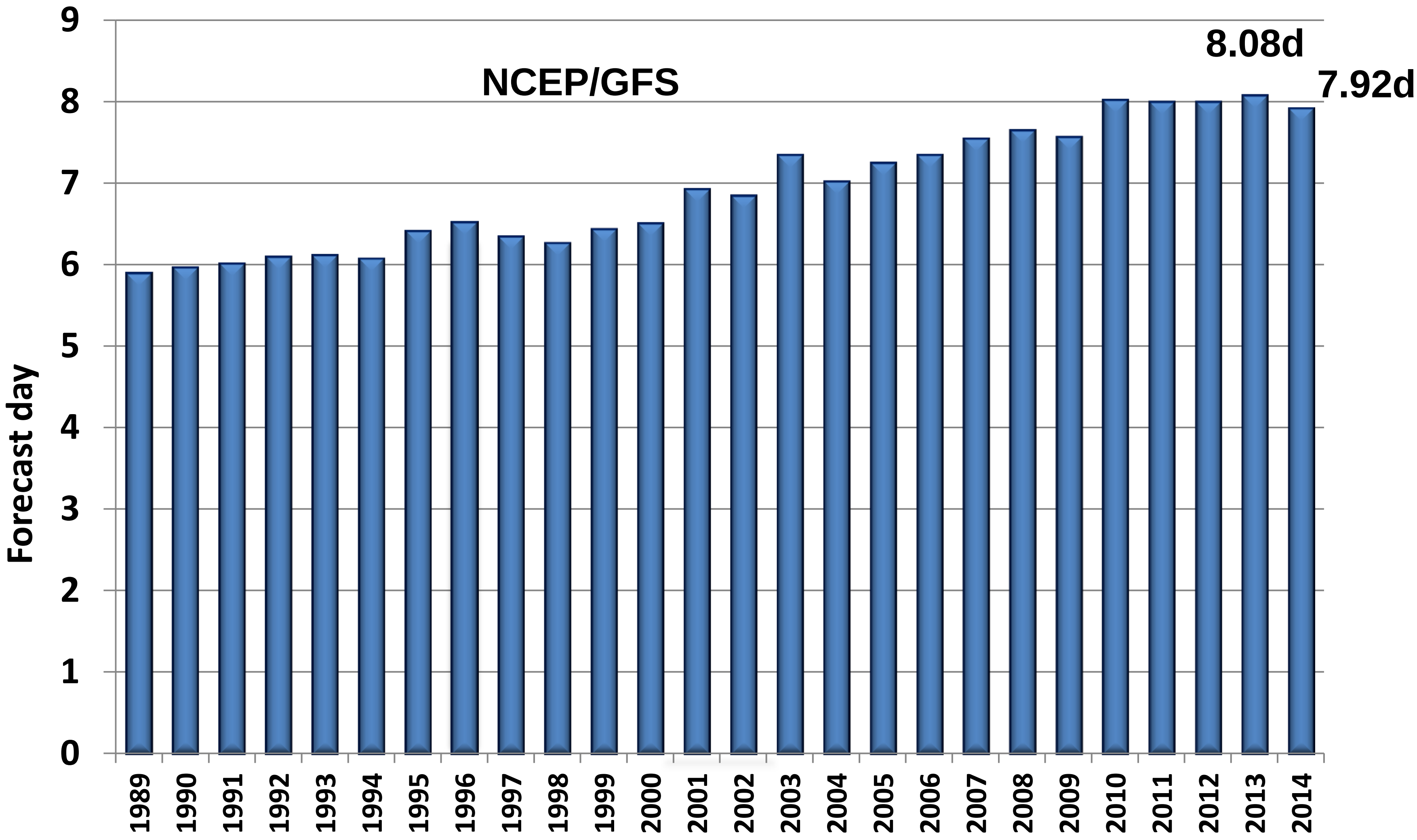


- **ECMWF, GFS and CMC were all worse in 2014 than in 2013. UKM and FNOMC were slightly improved. After 2009, CMC and GFS tied with each other.**

Reformatted Bob Kistler Diagram

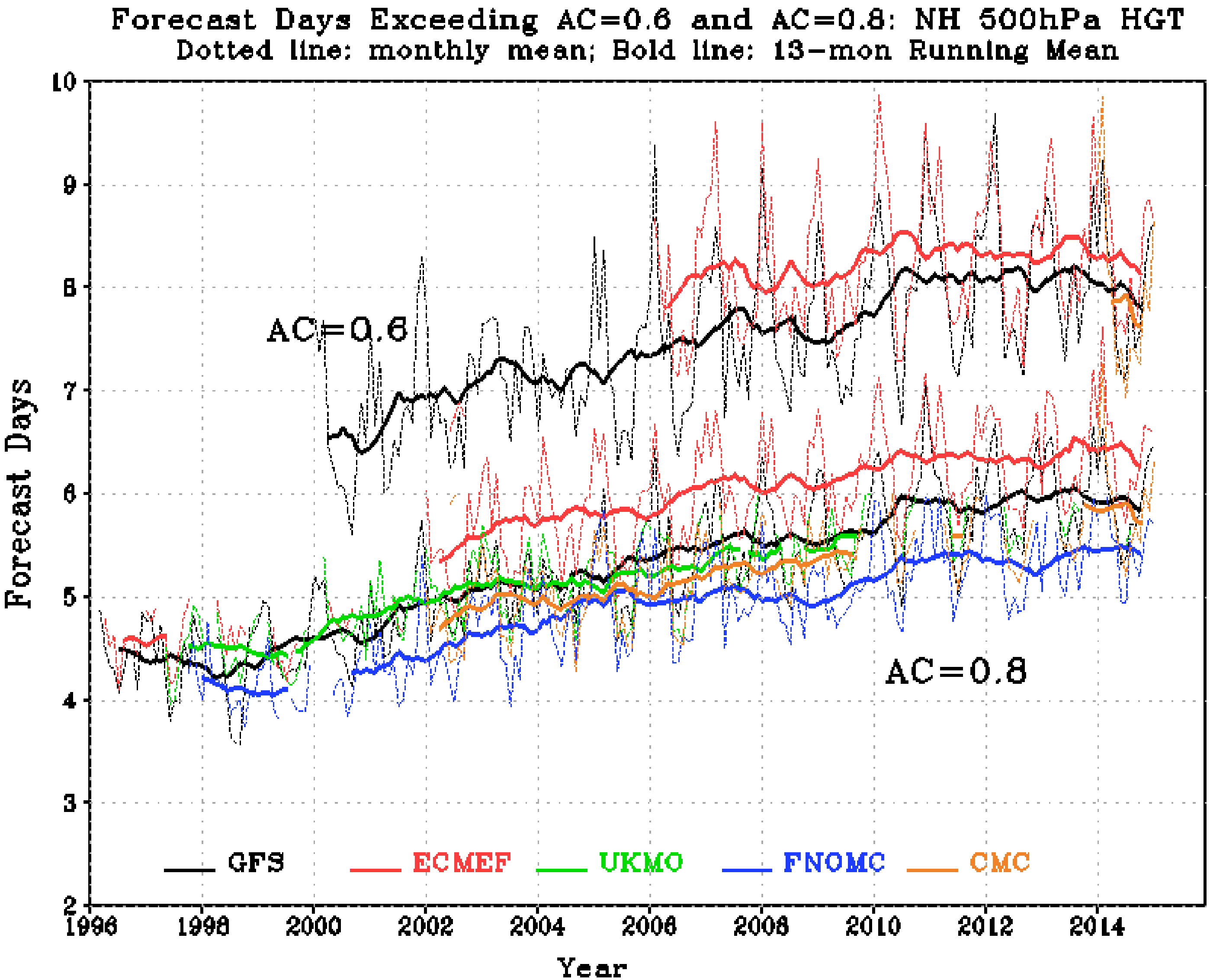
Day at which forecast loses useful skill (AC=0.6)

N. Hemisphere 500hPa height calendar year means



Increase is about one day per decade

Useful Forecast Days for Major NWP Models, NH

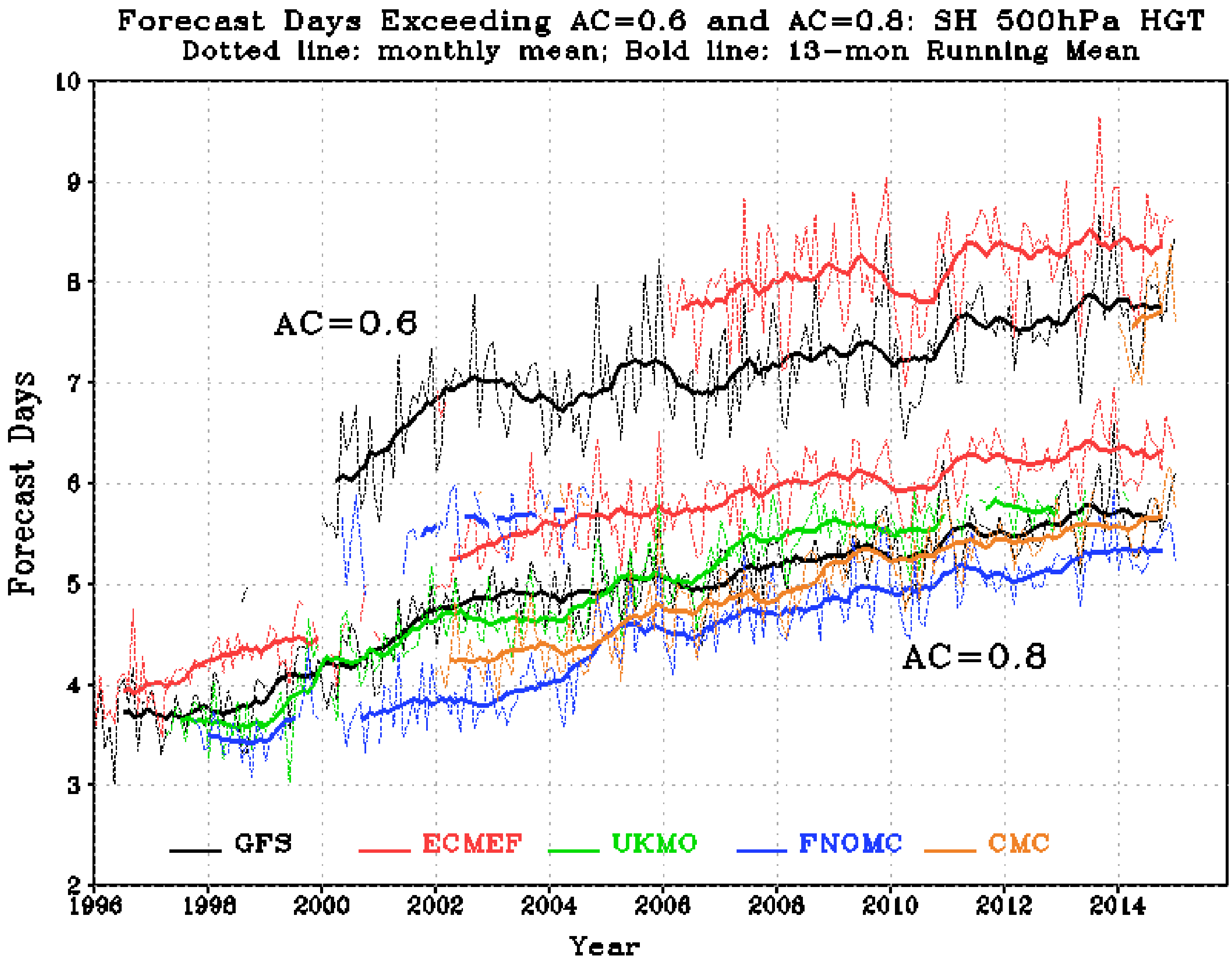


GFS lags ECM by ~0.3 day; CMC is slightly behind GFS

GFS lags ECM by ~0.4 day

http://www.emc.ncep.noaa.gov/gmb/STATS_vsdb/longterm/

Useful Forecast Days for Major NWP Models, SH



GFS lags ECM by ~0.6 day

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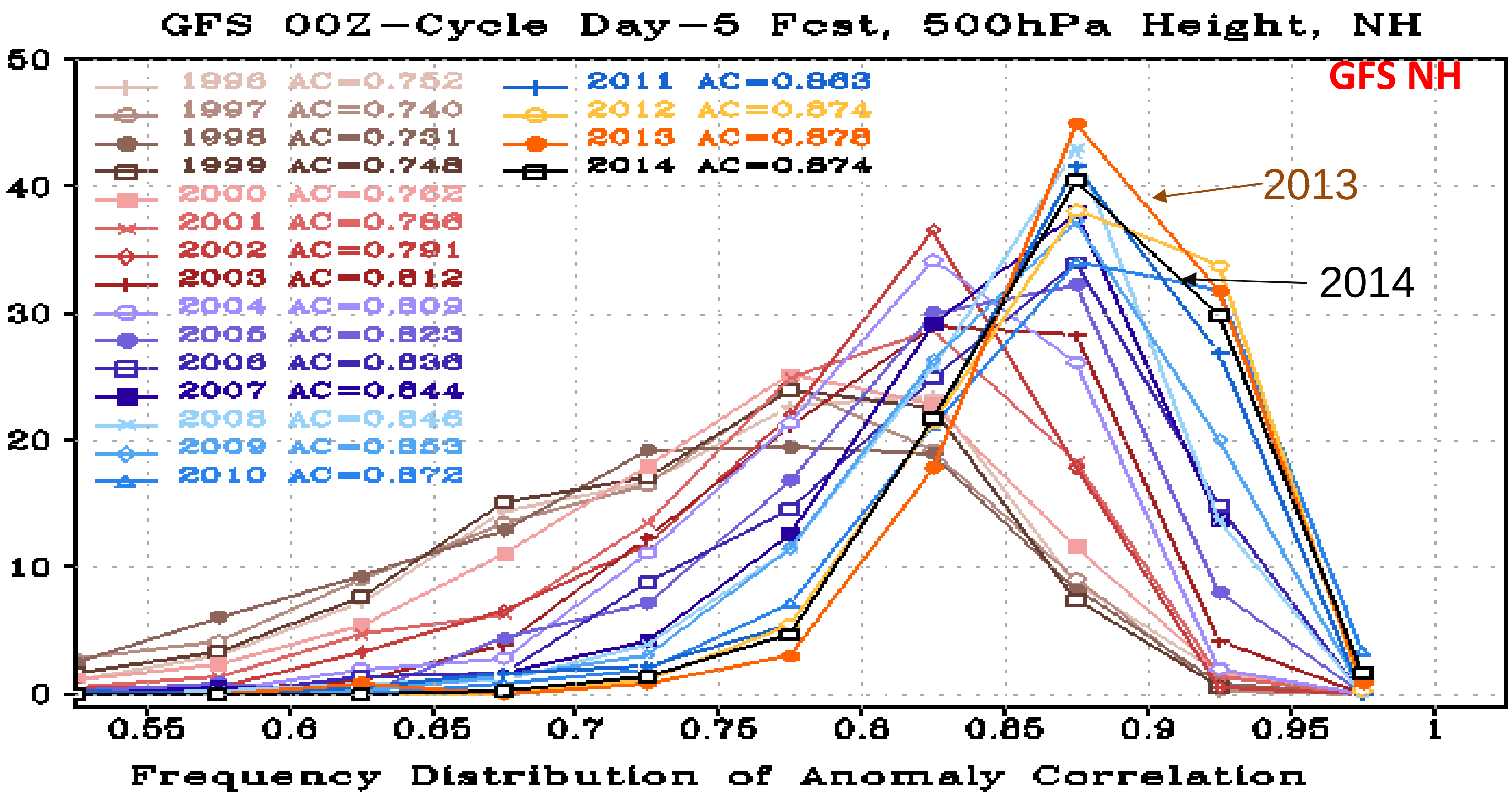
AC Frequency Distribution

Twenty bins were used to count for the frequency distribution, with the 1st bin centered at 0.025 and the last been centered at 0.975. The width of each bin is 0.05.



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- May 2001: prognostic cloud
- Oct 2002: T170L42 → T254L64
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- May 2007: SSI → GSI Analysis;
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- July 2010: T382L64 → T574L64; Major Physics Upgrade
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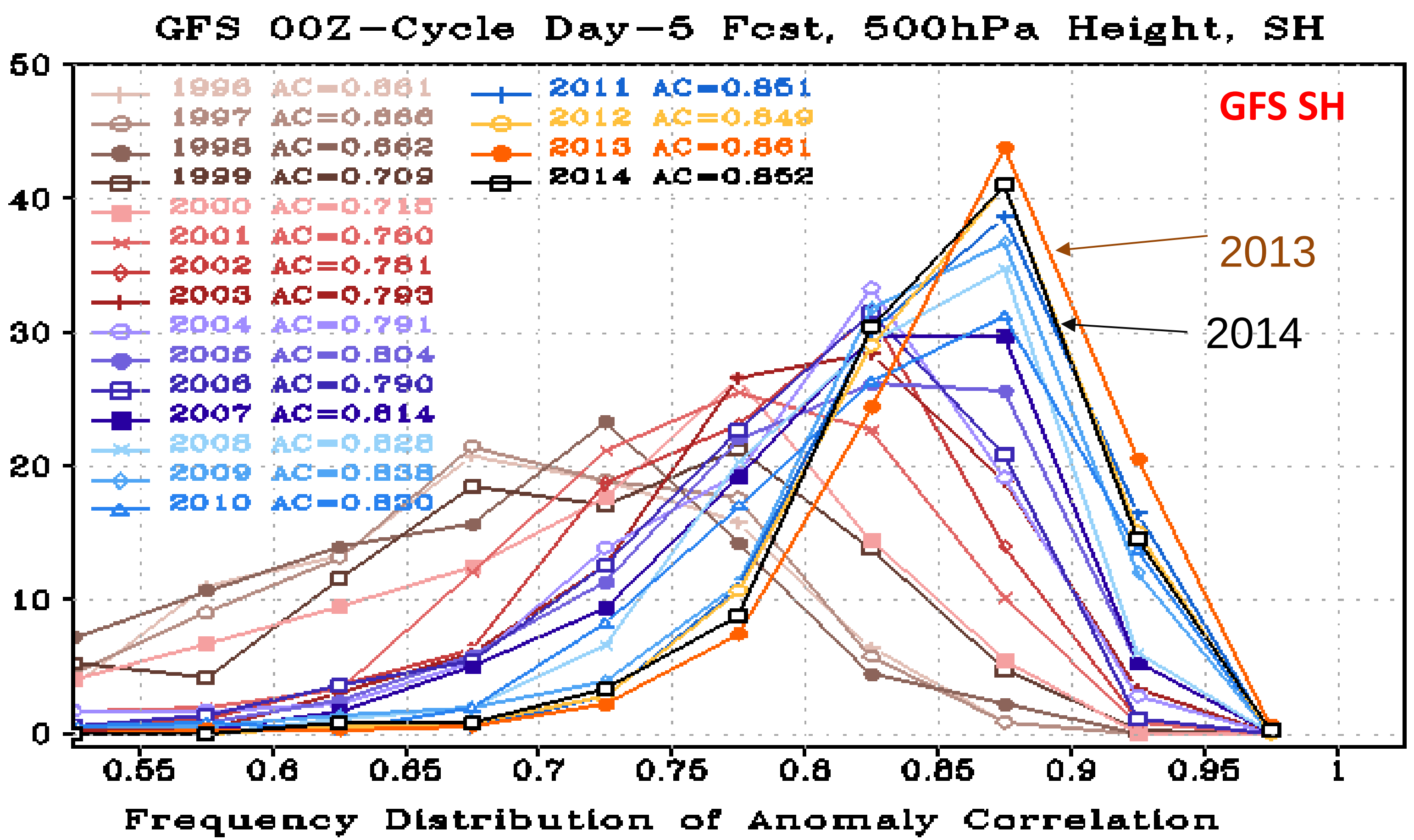

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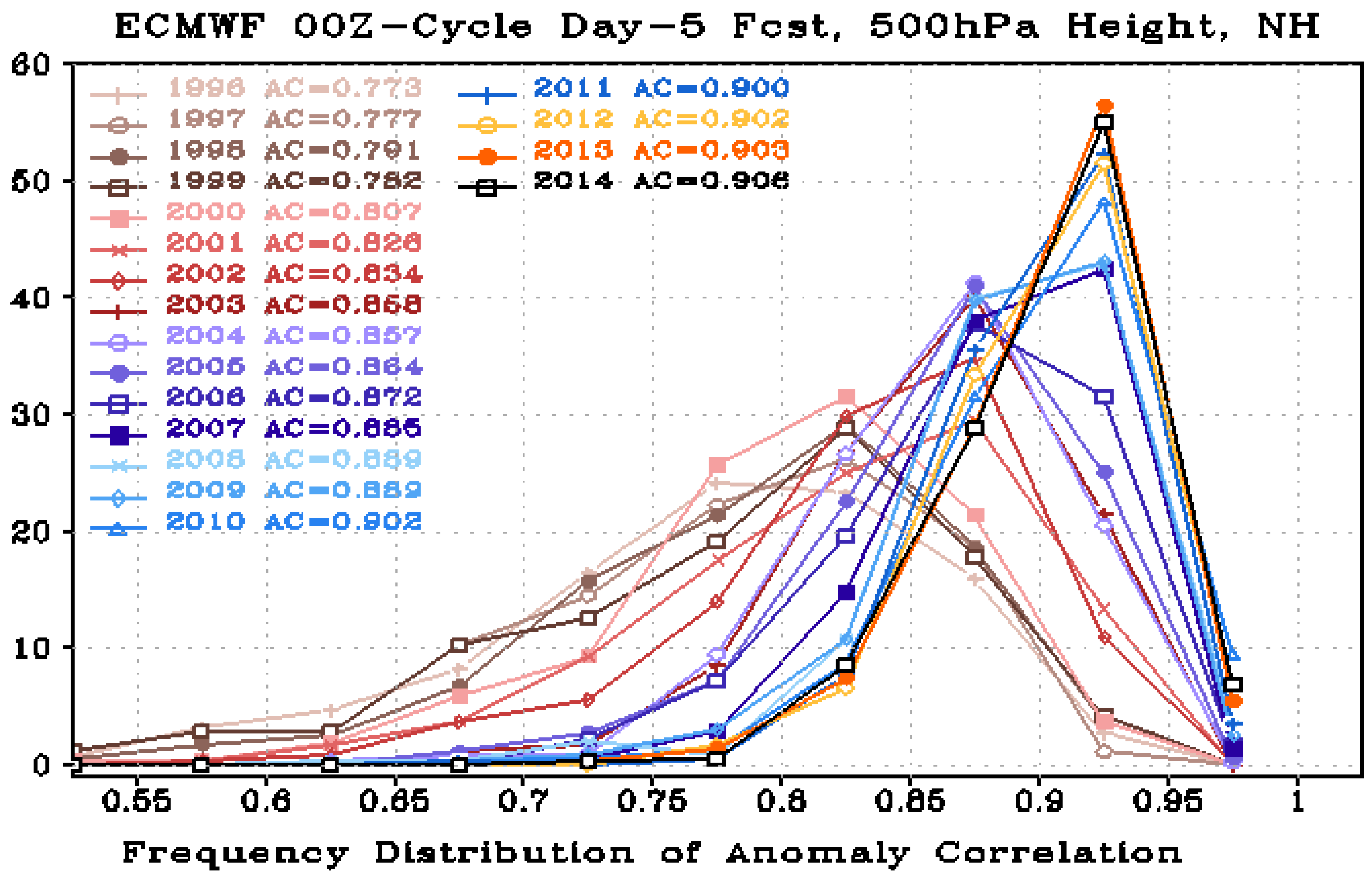
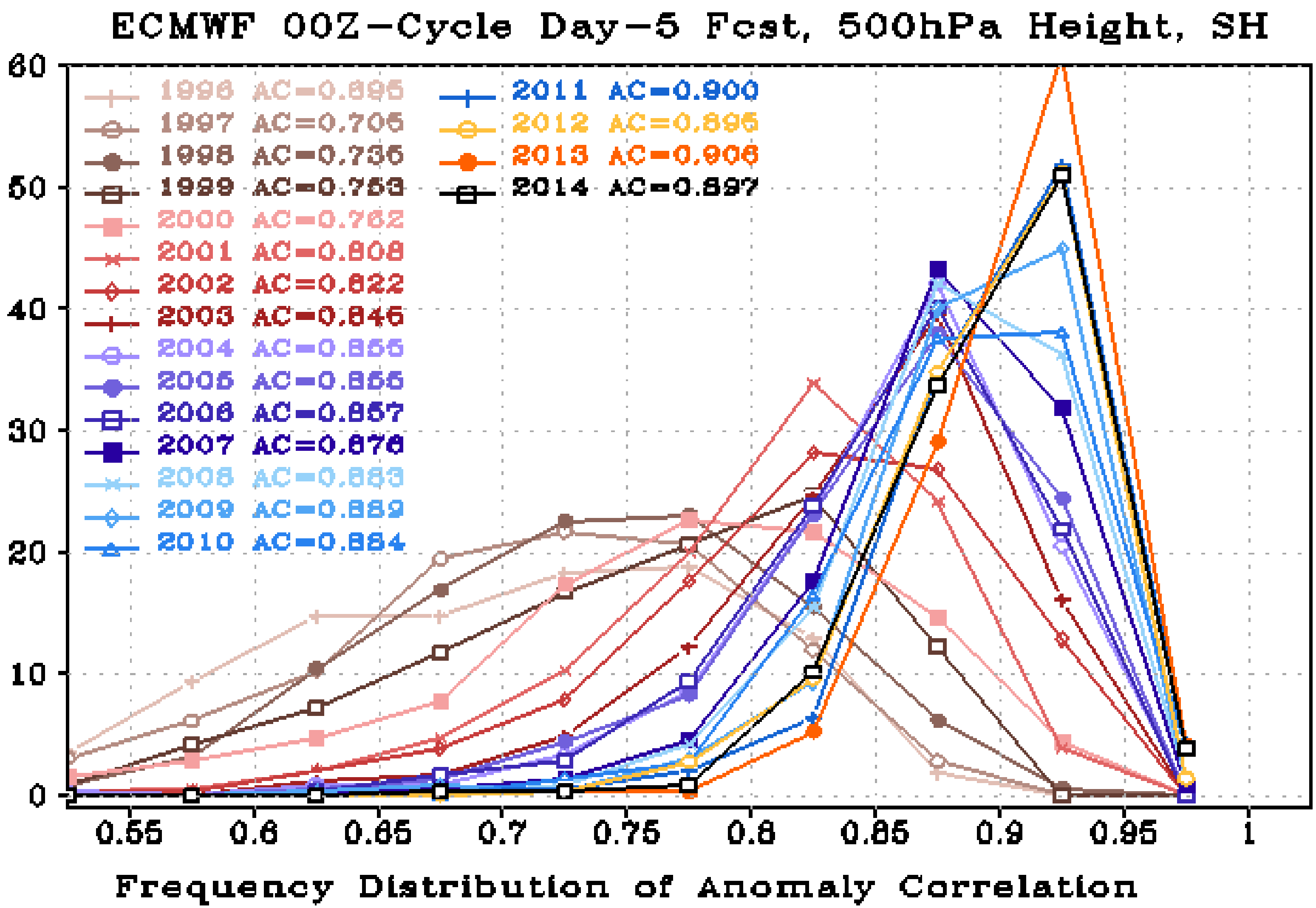
AC Frequency Distribution

ECMWF NH

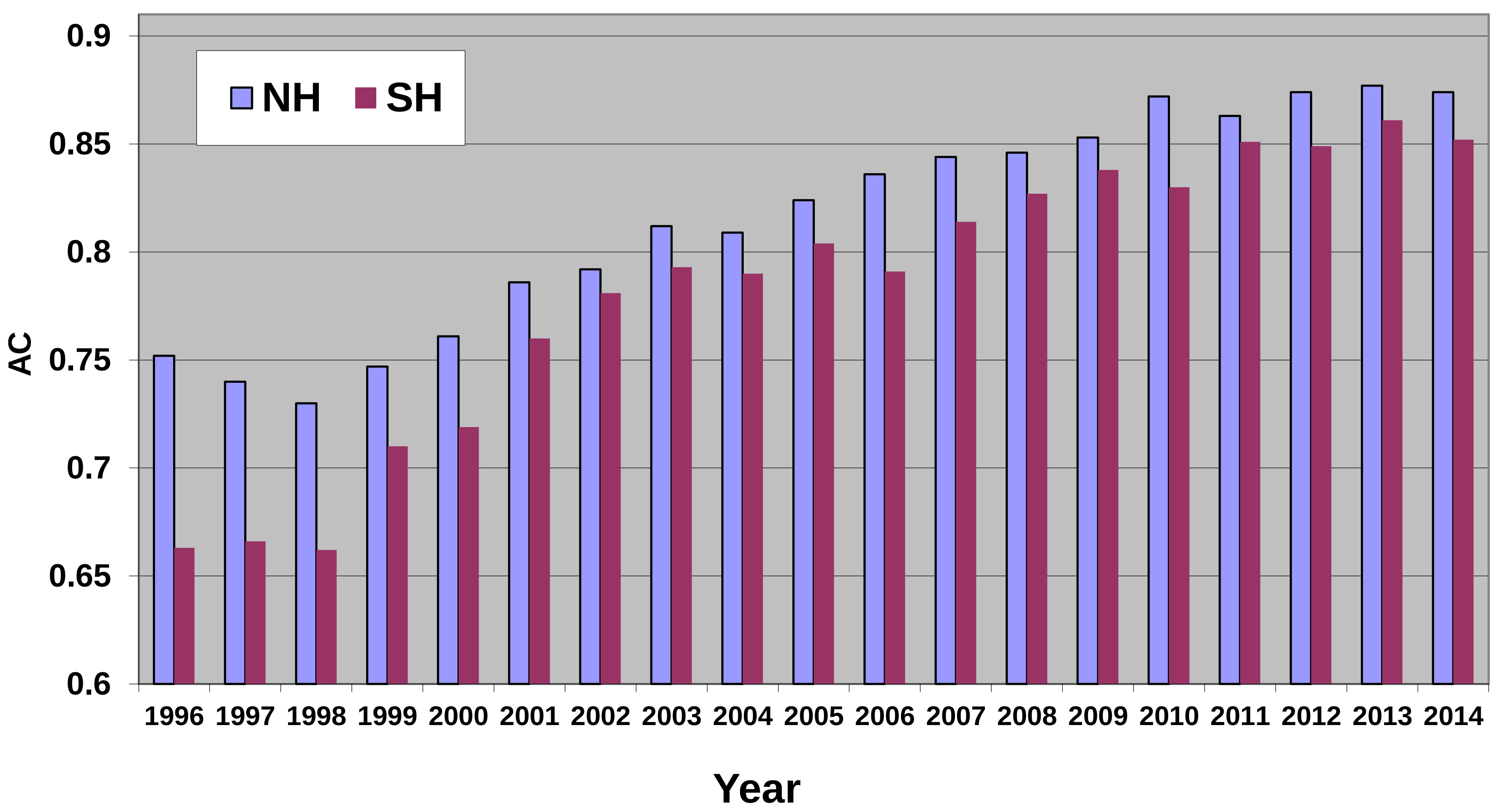


AC Frequency Distribution

ECMWF SH



GFS 00Z Cycle Day-5 500hPa Height Anomaly Correlation



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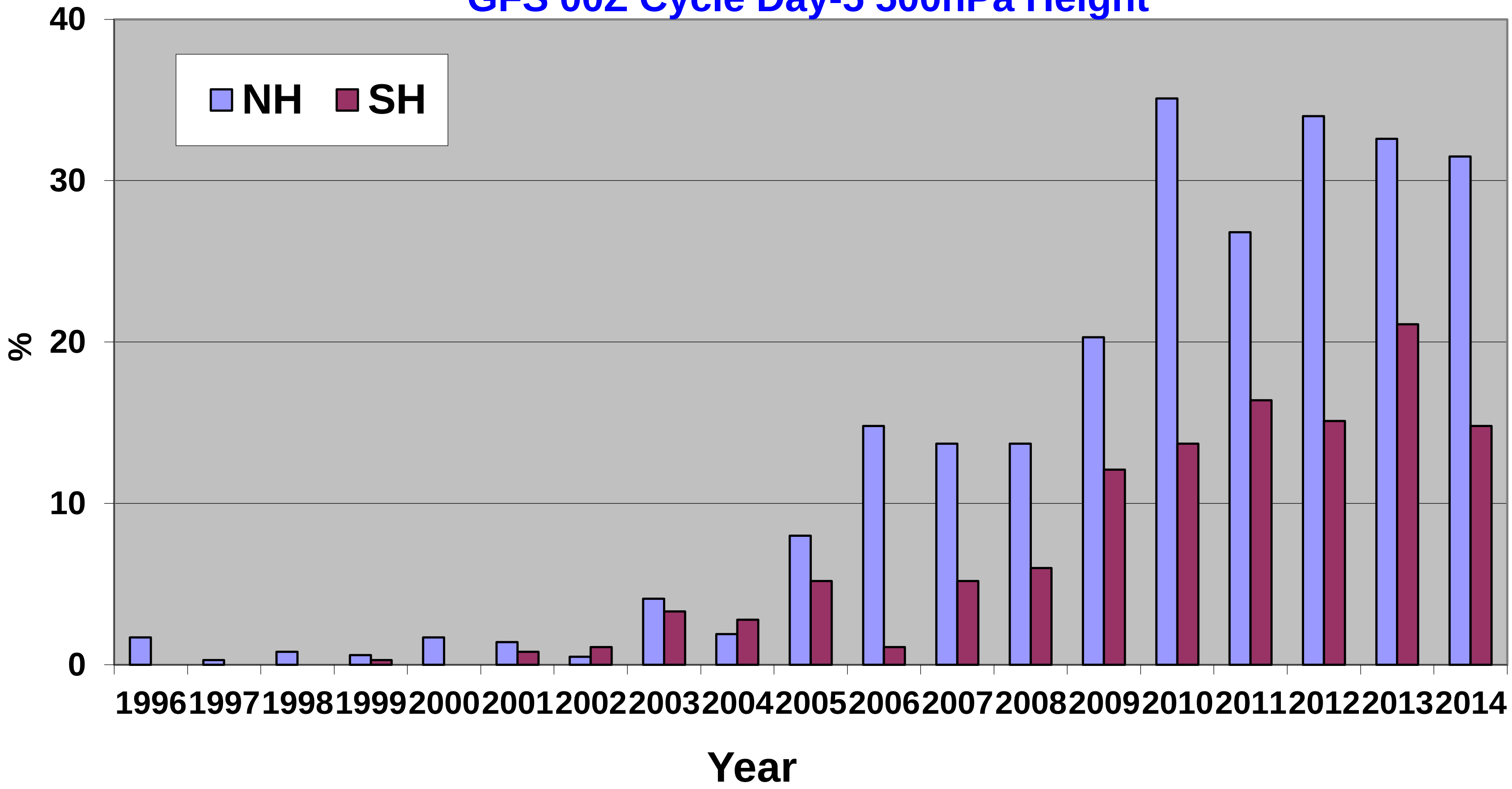
Percent Anomaly Correlations Greater Than 0.9
GFS 00Z Cycle Day-5 500hPa Height



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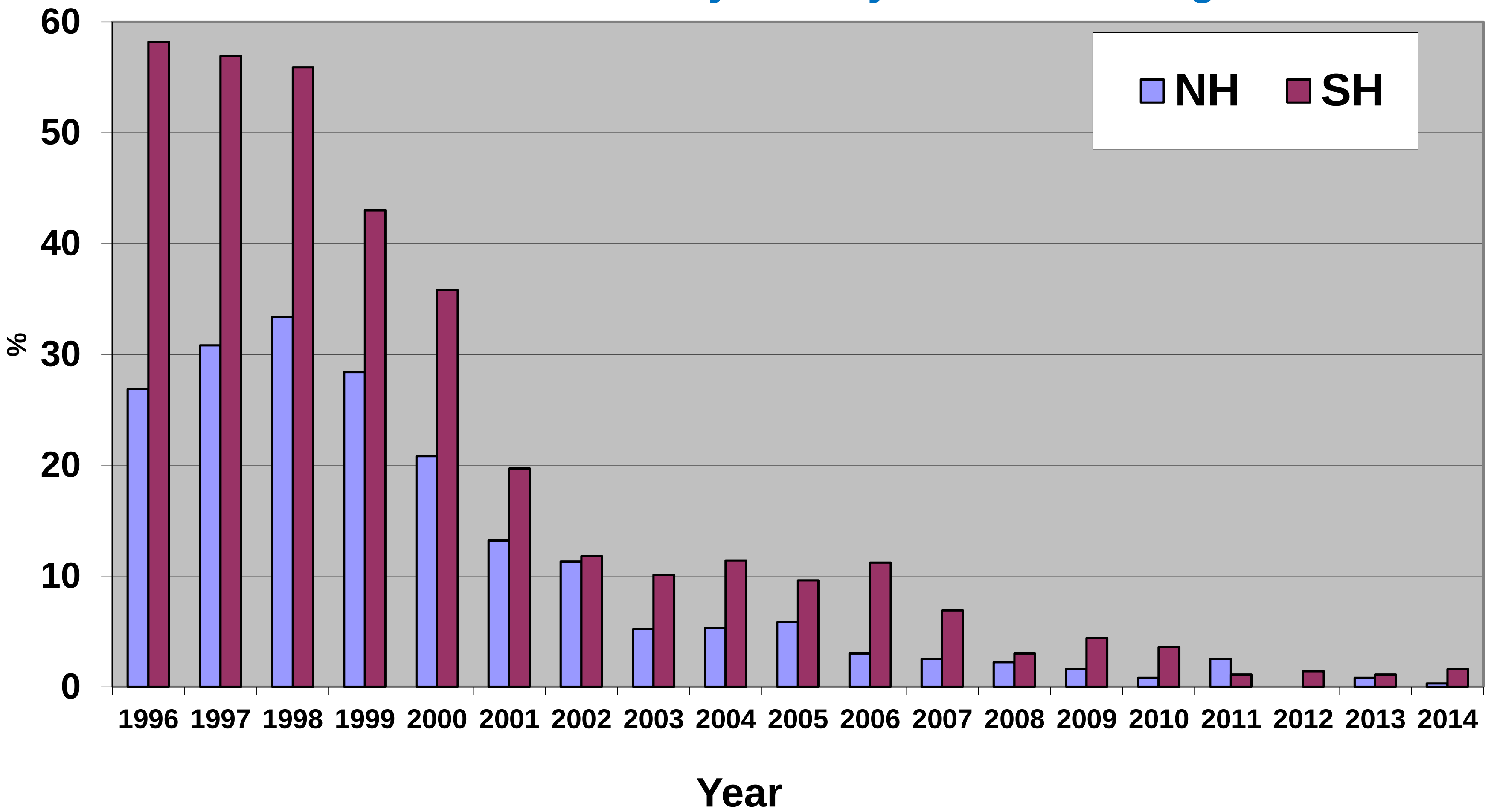
Percent Anomaly Correlations Smaller Than 0.7
GFS 00Z Cycle Day-5 500hPa Height



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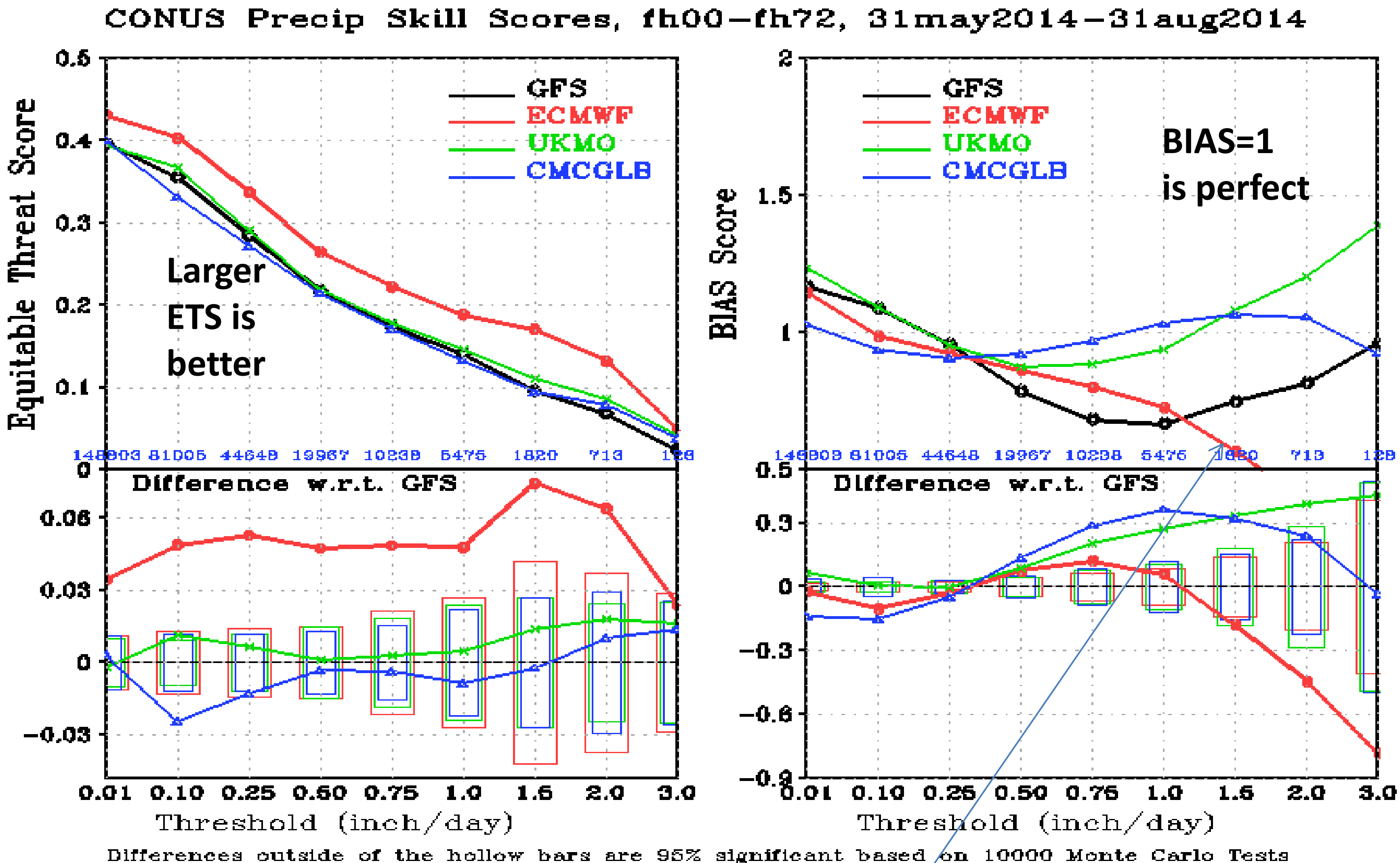
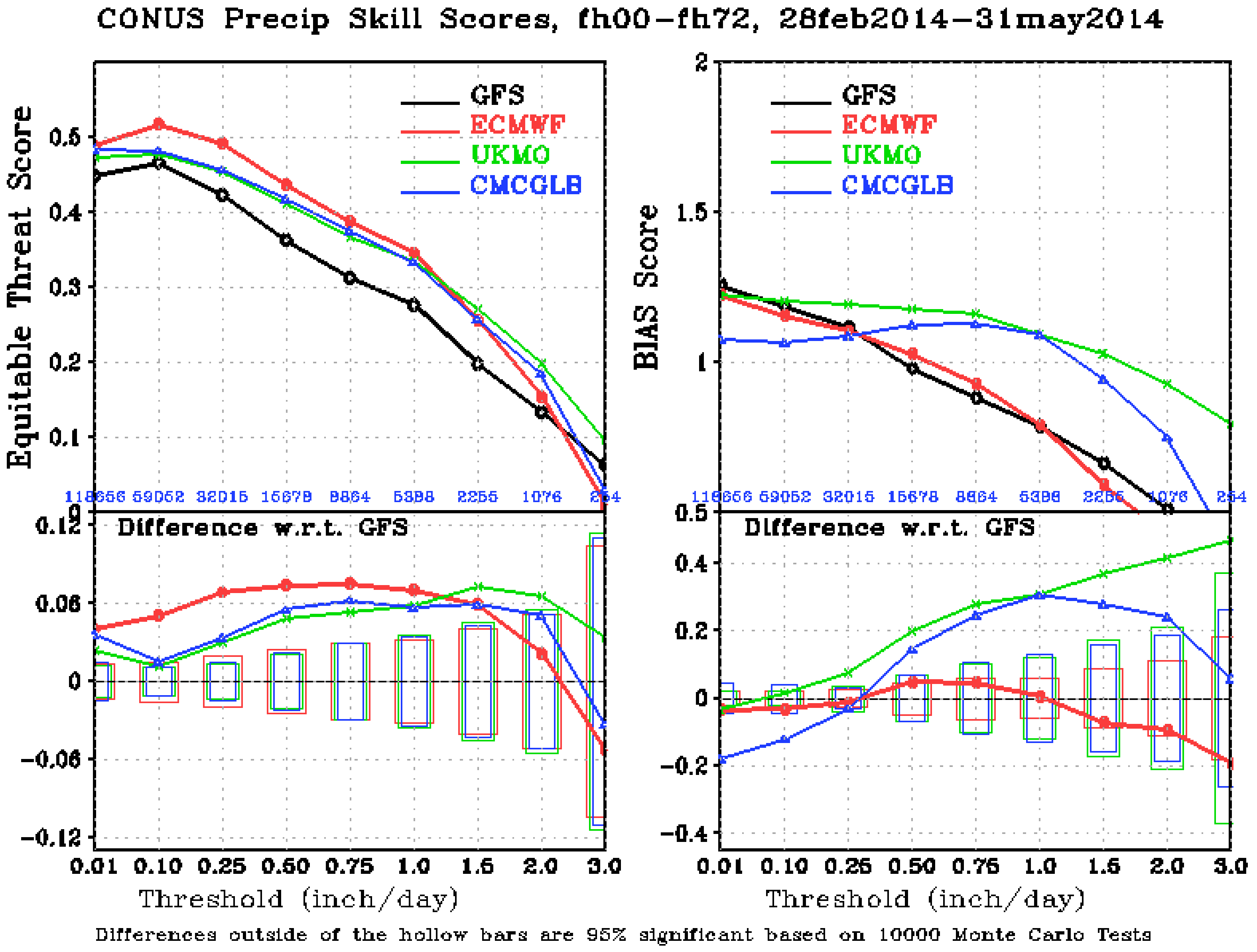
2014 JJA CONUS Precipitation Skill Scores, 0-72 hour Forecast

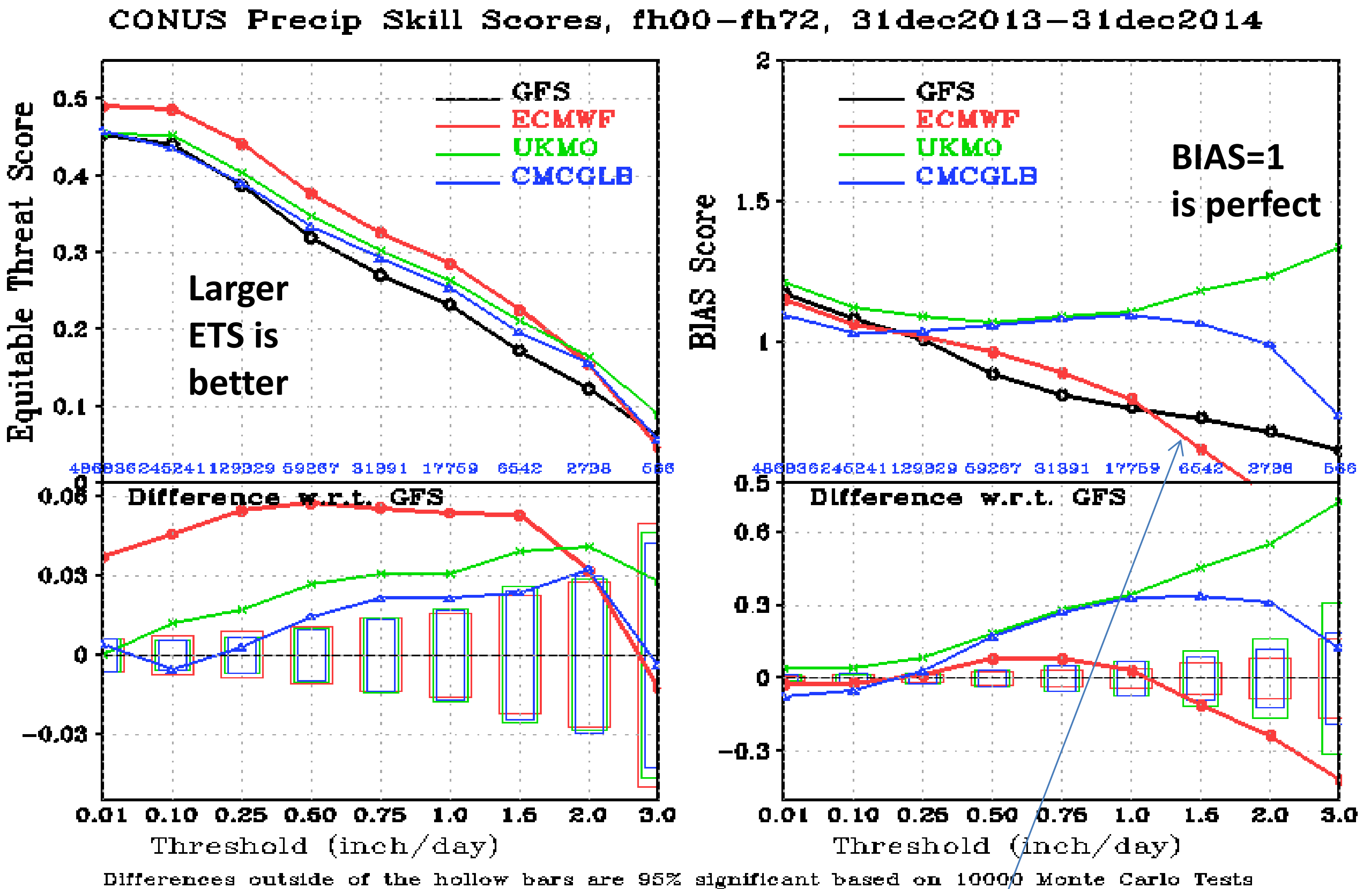


- **ECMWF had the best ETS score. GFS, UKM and CMC were close to each other.**
- **ECMWF underestimated heavy rainfall events. GFS was dry for moderate rainfall events..**

2014 Spring CONUS Precipitation Skill Scores, 0-72 hour Forecast

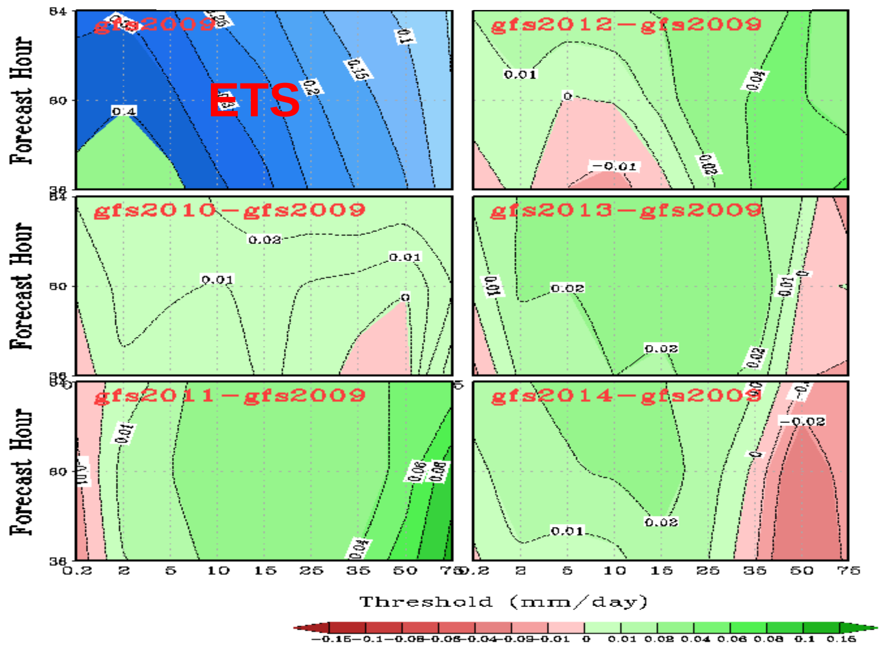


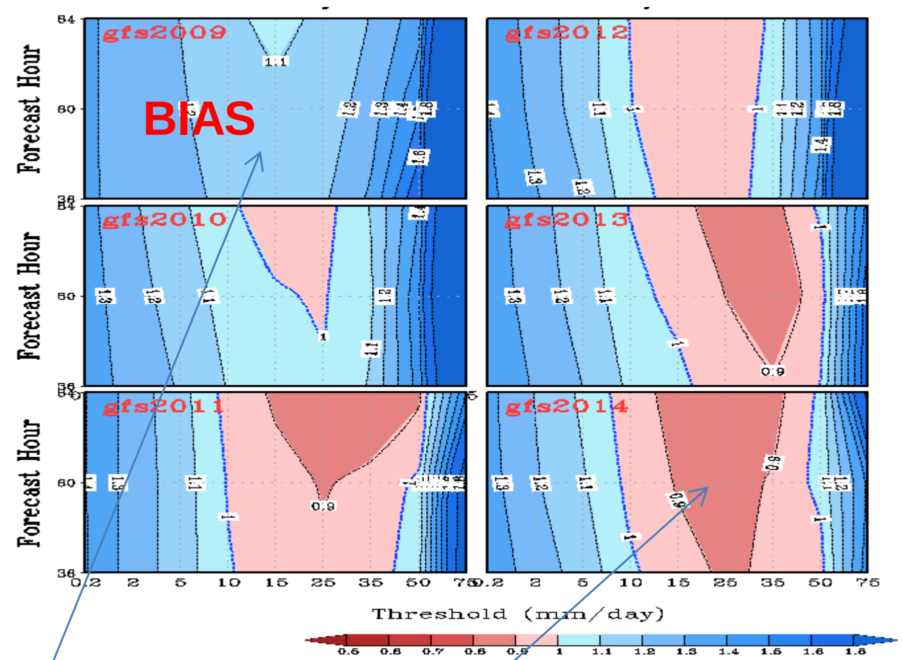
2014 Annual Mean CONUS Precipitation Skill Scores, 0-72 hour Forecast



- ECMWF has the best ETS score.
- Both GFS and ECMWF underestimated moderate and heavy rainfall events.

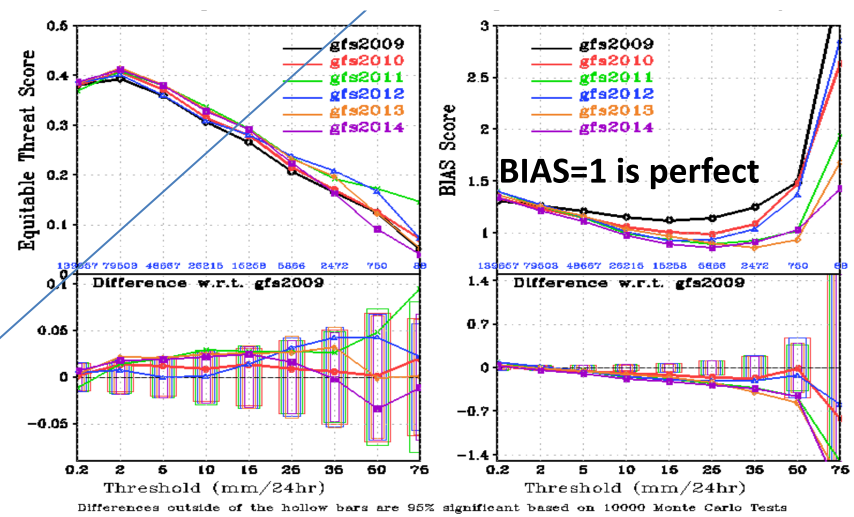
GFS Precipitation ETS and Bias Scores over CONUS, Annual Mean, 2009 ~ 2014





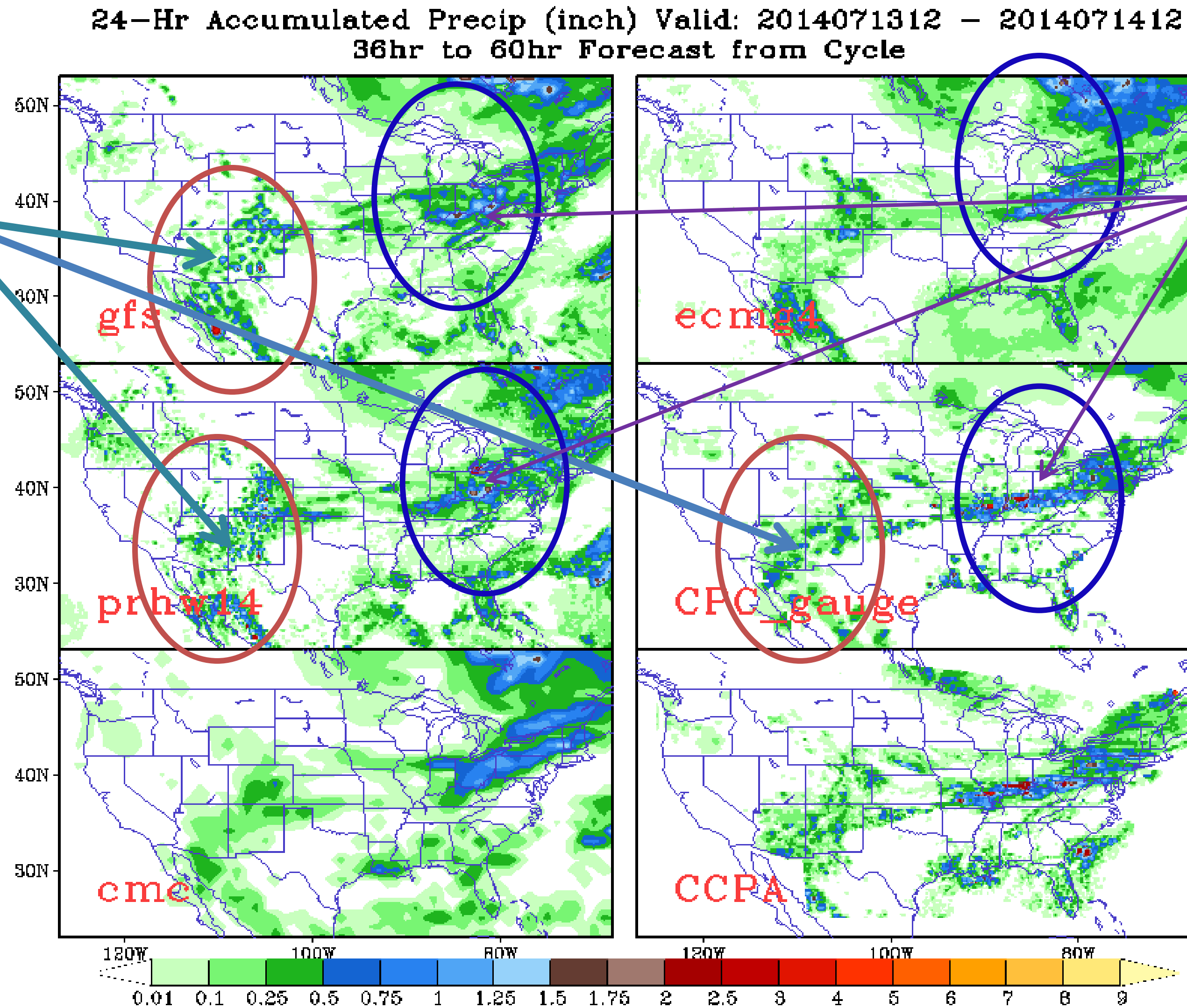
- Compared to 2009, GFS precipitation ETS score was improved after July-2010 T574 GFS upgrade for all but light rain events
- ETS scores from 2012 to 2014 did not exceed 2011.
- 2009 had wet bias for moderate rainfall events; Dry bias was developed in subsequent years and has been getting drier and drier in recent years.

FH 36-60



Typical high bias in the west?

Too much rainfall at high elevation?



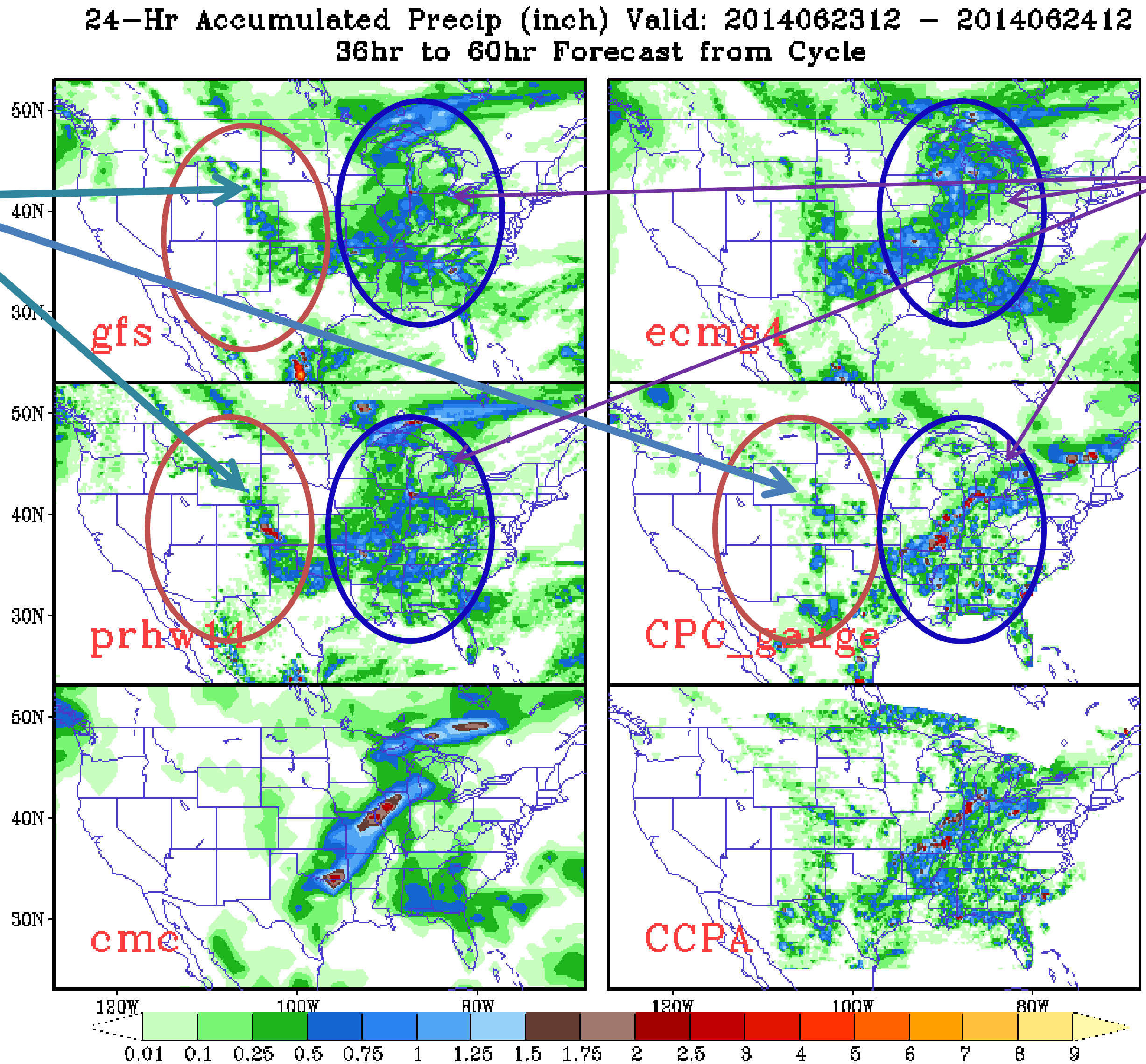
Low bias in the central to east?

Need more and detailed verification over sub-regions.

Another case

Typical high bias in the west?

Too much rainfall at high elevation?



Low bias in the central to east?

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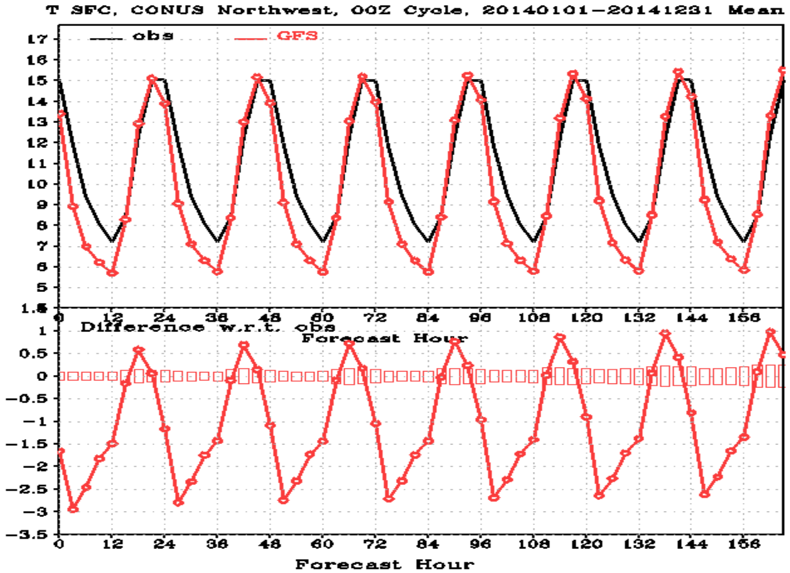
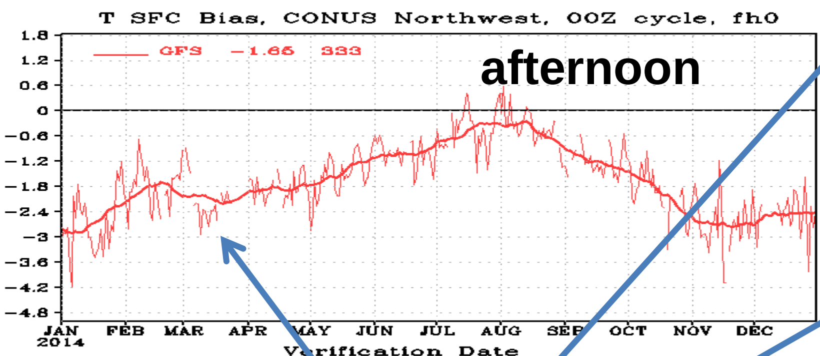
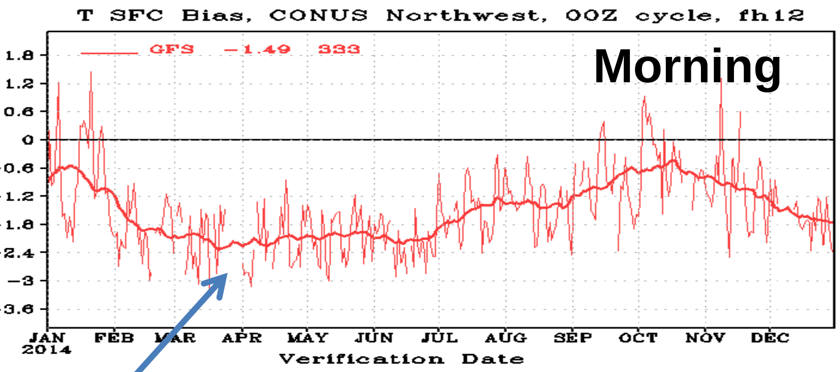
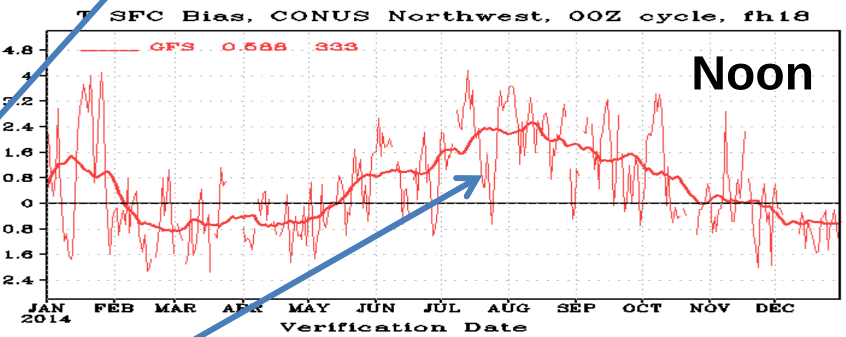
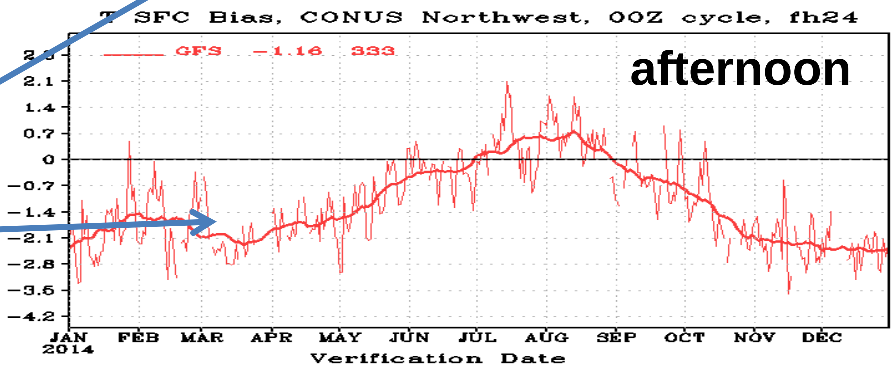
2014 CONUS Northwest GFS T2m Verified against Obs







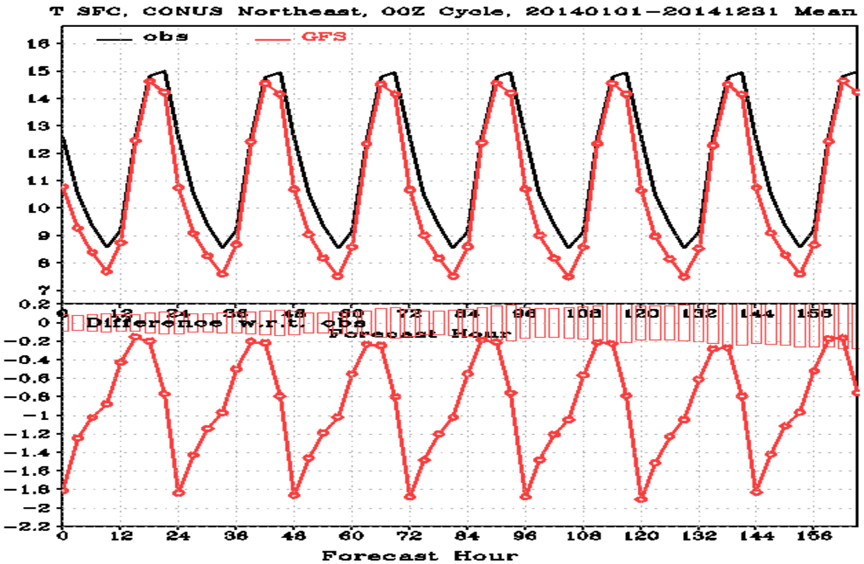


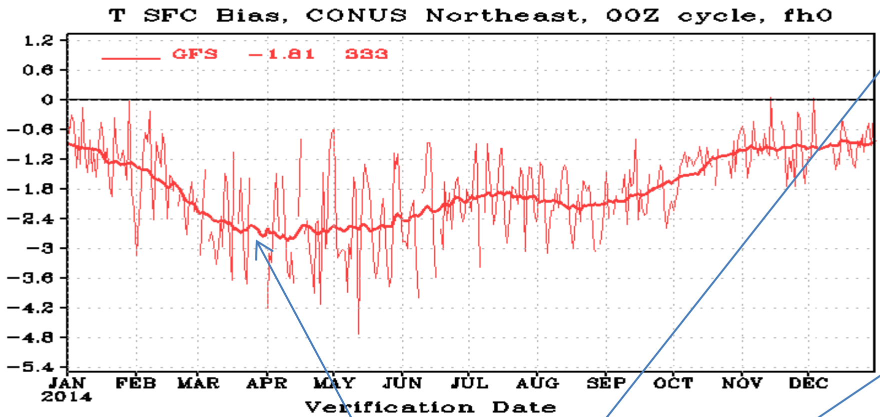


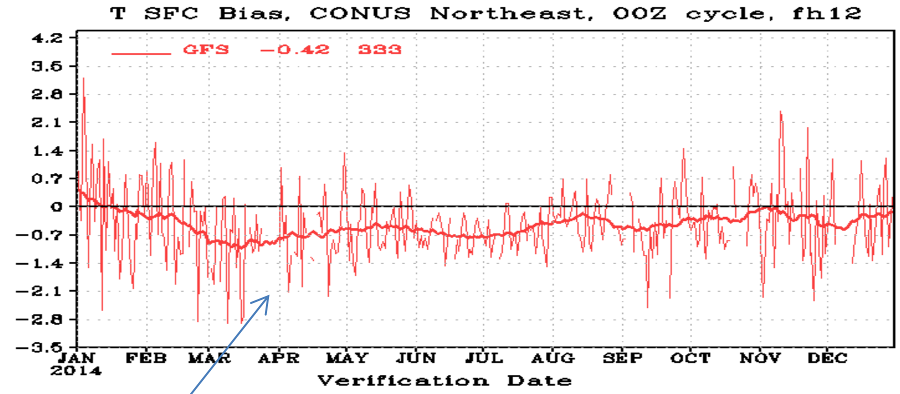
- **cold bias in the afternoon for all seasons except in summer**
- **Cold bias in the morning for all seasons**
- **warm bias at noontime in summer**
- **T2m is not assimilated. Large biases found in fh0**

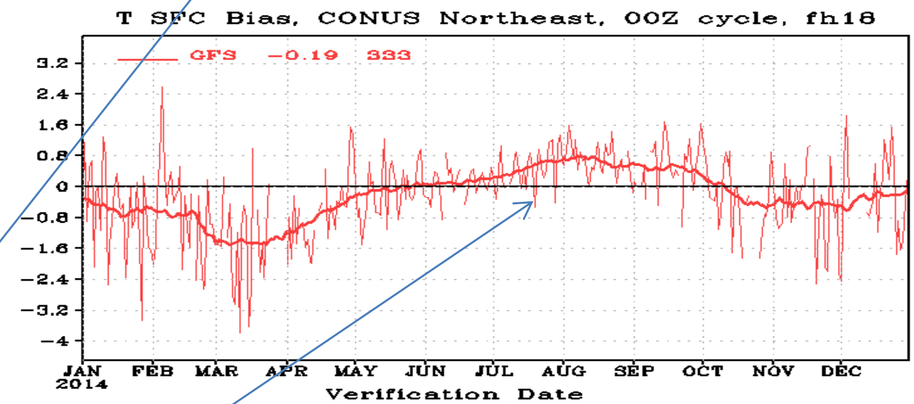
http://www.emc.ncep.noaa.gov/gmb/STATS_vsdb/annual/g2o_2014/g2o/

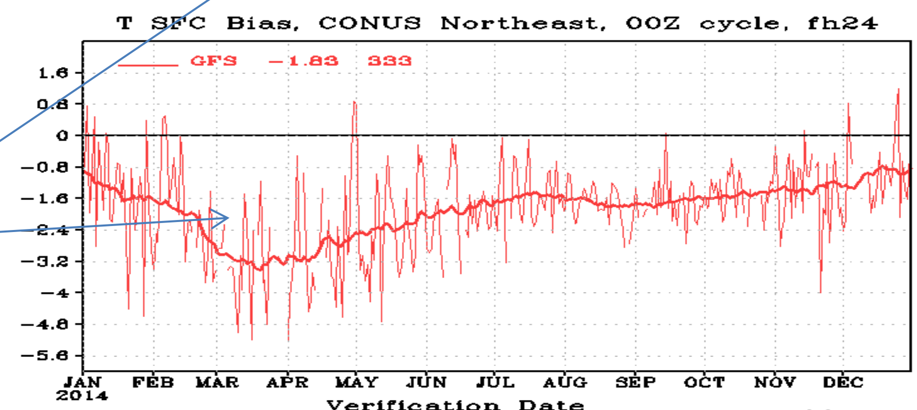
2014 CONUS Northeast GFS T2m Verified against Obs









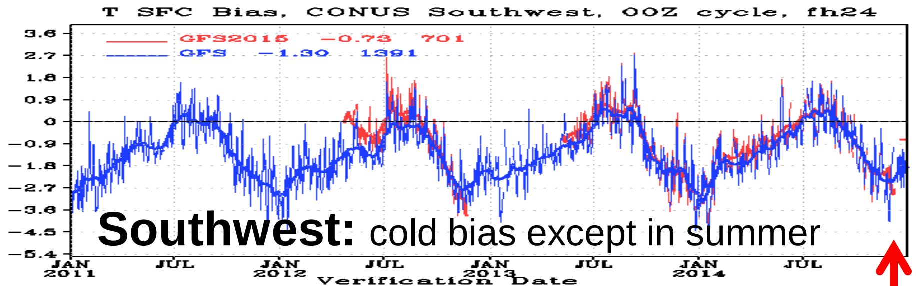


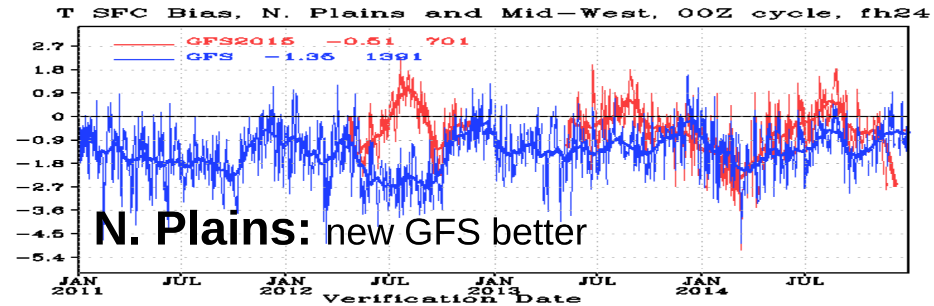
- **Large cold bias in the afternoon for all seasons**
- **Minor cold bias in the morning for all seasons**
- **noontime biases are small.**

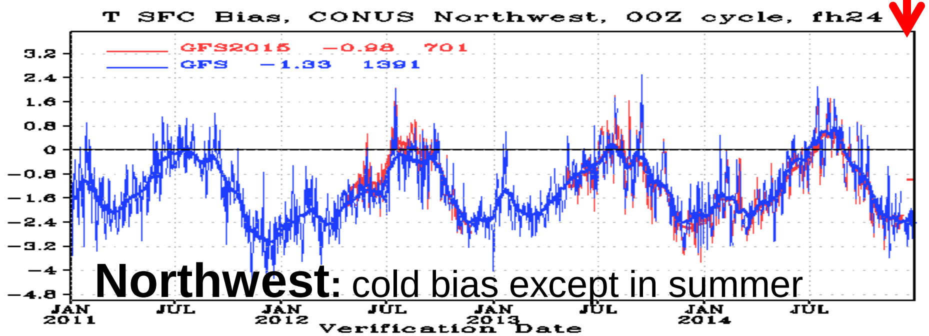
http://www.emc.ncep.noaa.gov/gmb/STATS_vsdb/annual/g2o_2014/g2o/

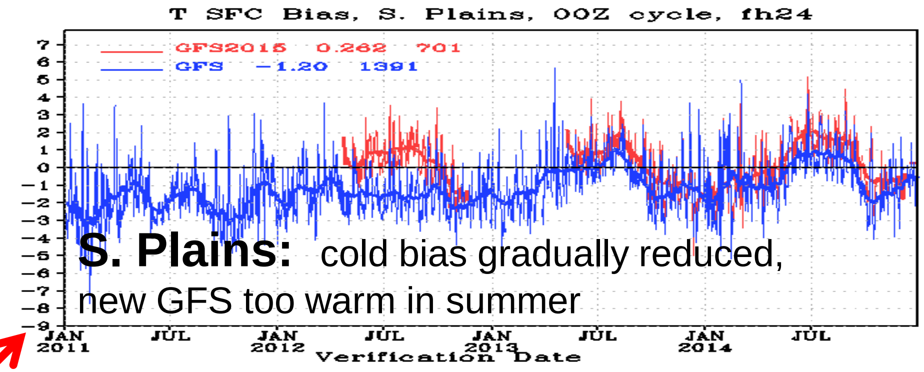
Afternoon (00Z) T2m Bias, 2011 ~ 2014

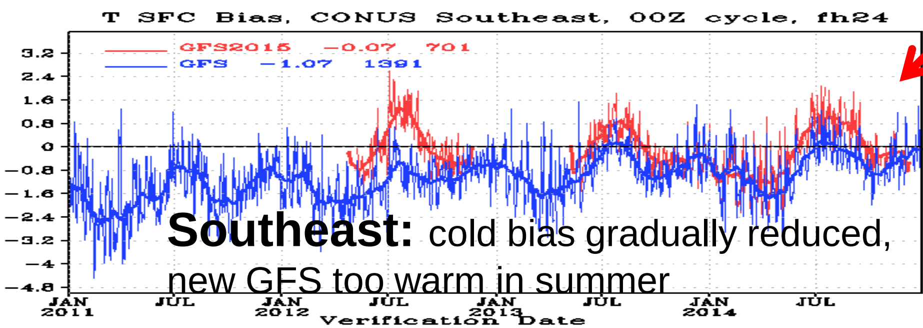
Red: T1534 GFS retro runs
Blue: T574 ops GFS

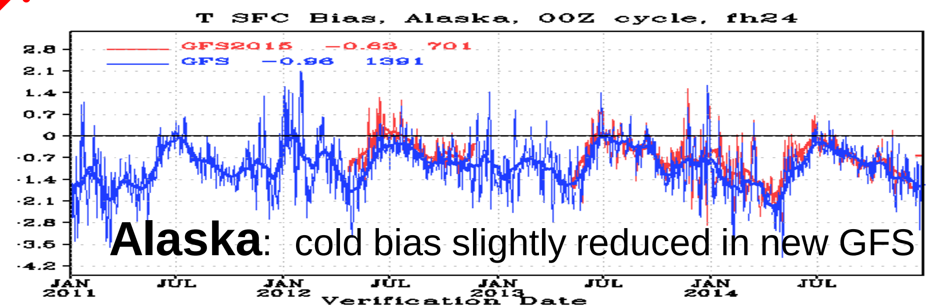


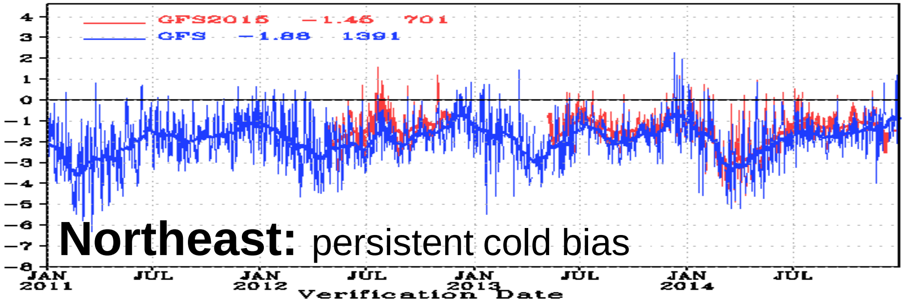










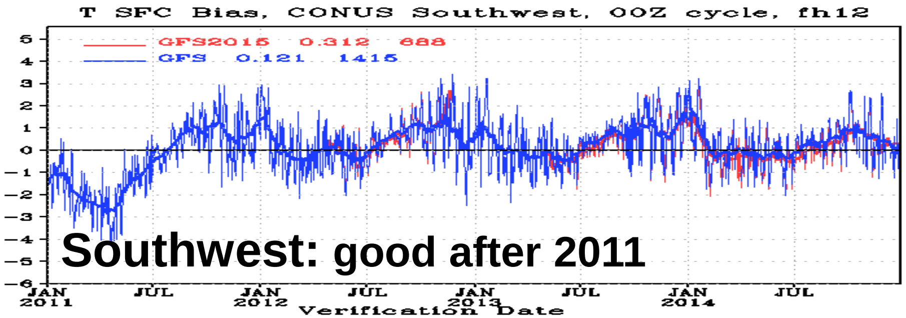


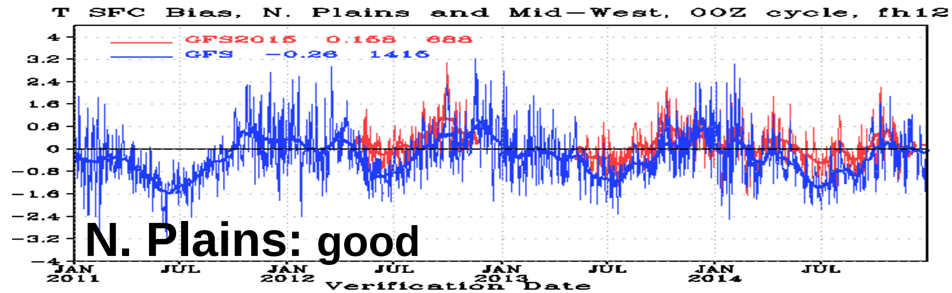
- **Biases change with season**
- **Cold biases in all regions and all season except summer**
- **T1534 is generally warmer**

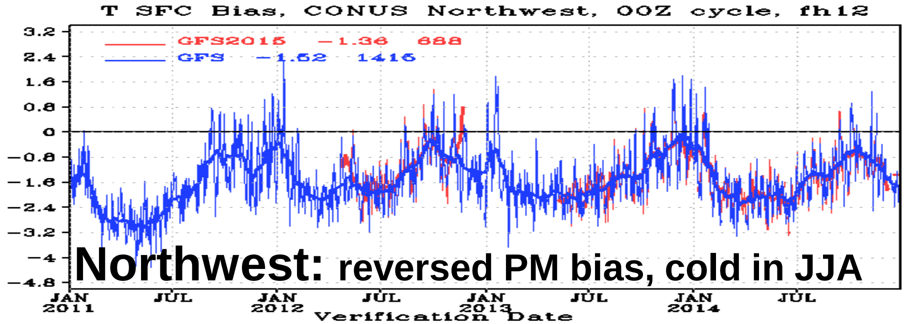
http://www.emc.ncep.noaa.gov/gmb/STATS_vsdb/annual/g2o_20112014/g2o/

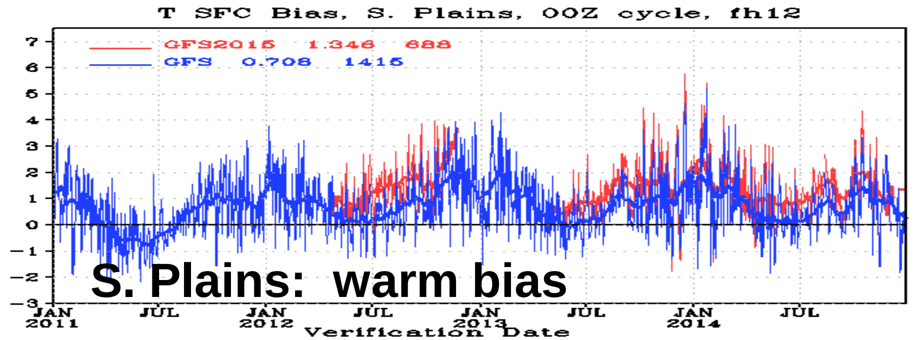
Morning (12Z) T2m Bias, 2011 ~ 2014

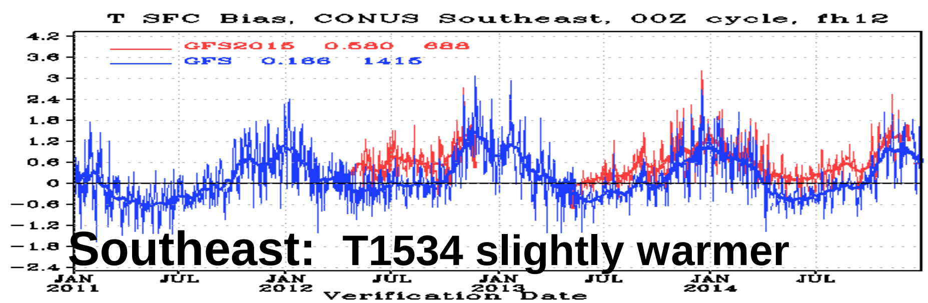
Red: T1534 GFS retro runs
Blue: T574 ops GFS

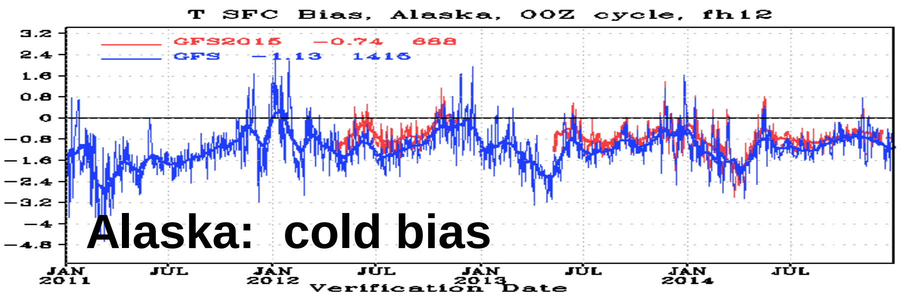


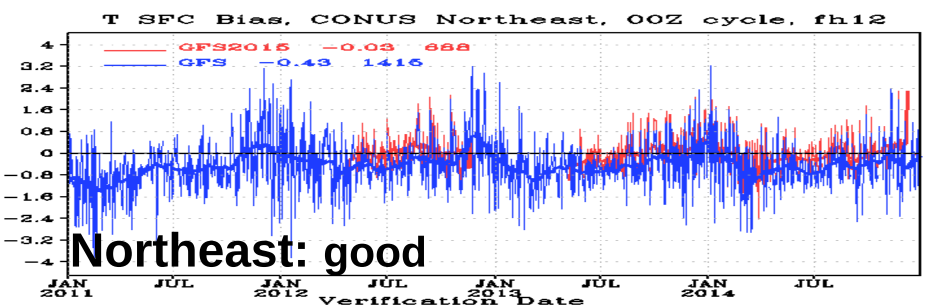






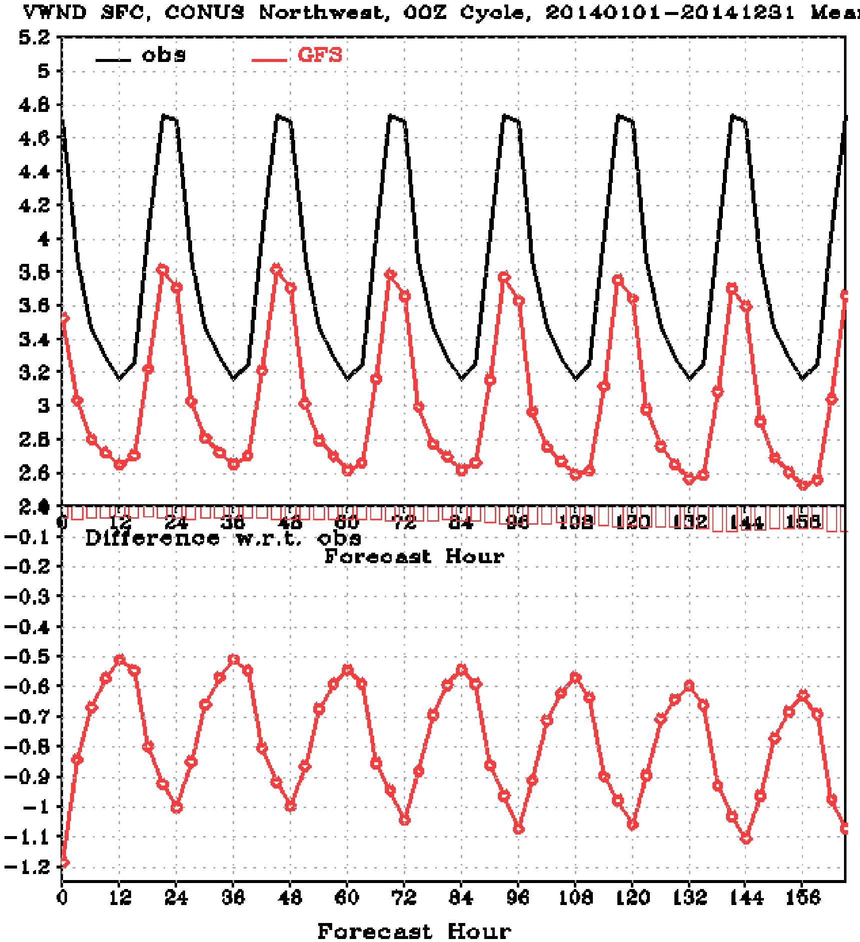


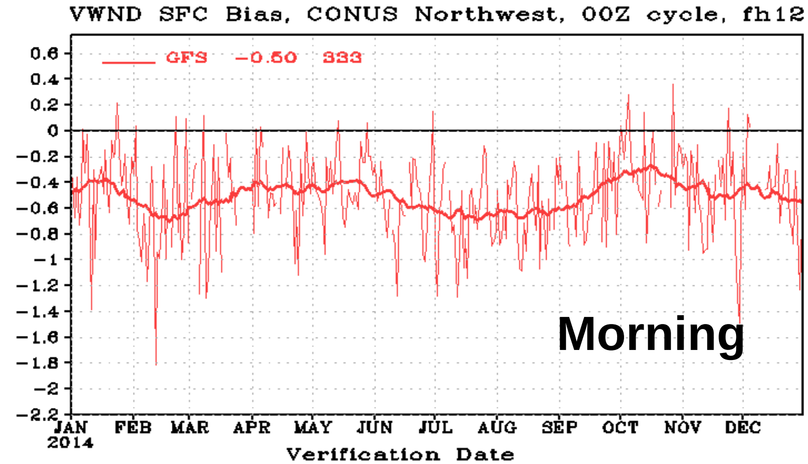


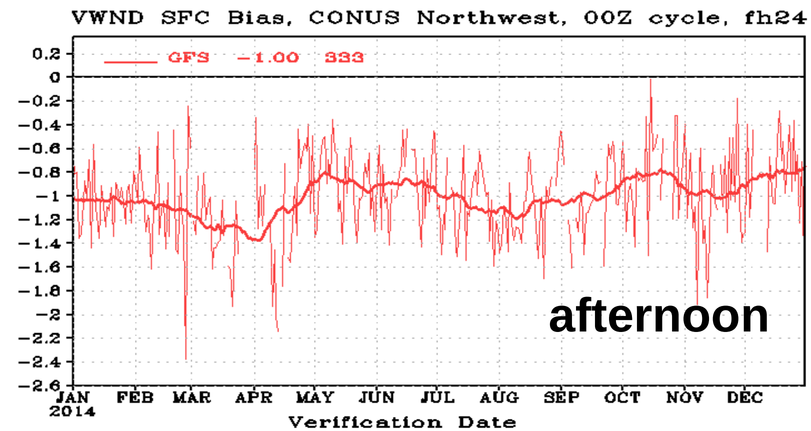


- Biases change with season
- 2011 had the largest bias
- Mixed warm and cold biases in different regions
- T1534 is generally warmer

2014 CONUS Northwest GFS 10-m Wind





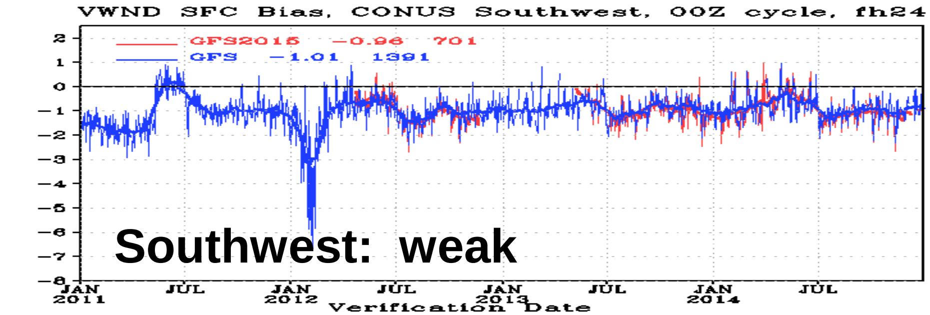


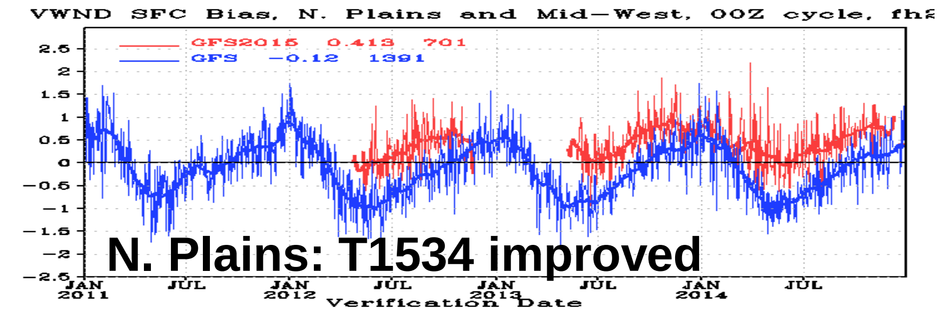
- **GFS has the right diurnal cycle, but wind is ~ 20% weaker than observed.**
- **The biases are found in all forecast hours and all seasons.**

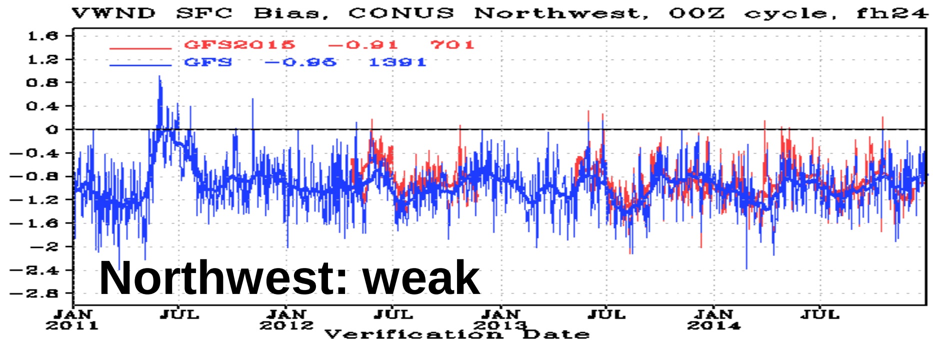
http://www.emc.ncep.noaa.gov/gmb/STATS_vsdb/annual/g2o_2014/g2o/

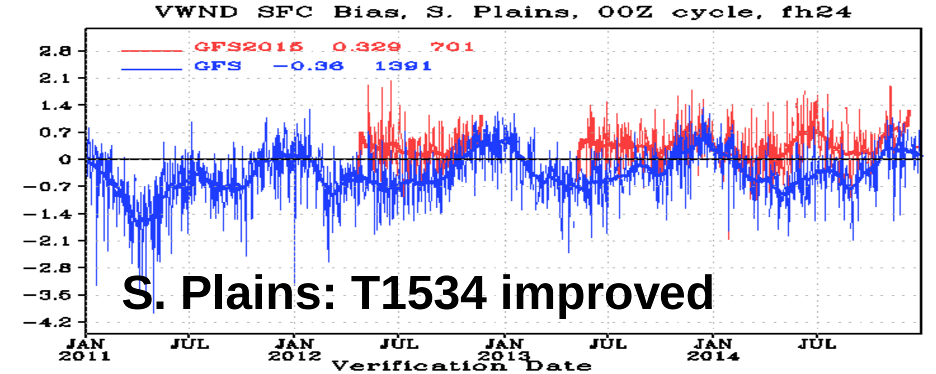
Afternoon (00Z) 10-m Wind Bias, 2011 ~ 2014

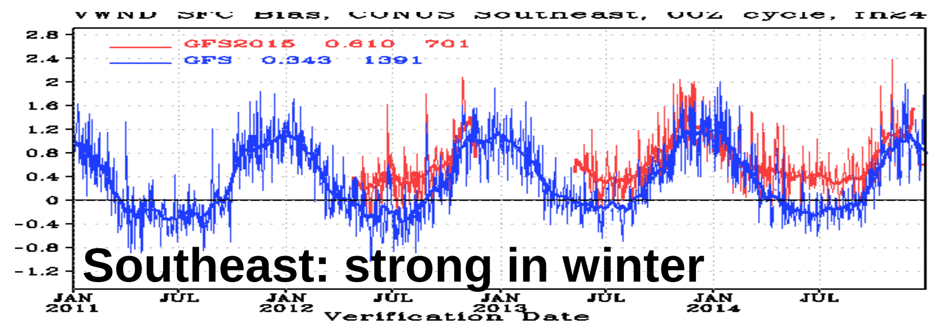
Red: T1534 GFS retro runs
Blue: T574 ops GFS

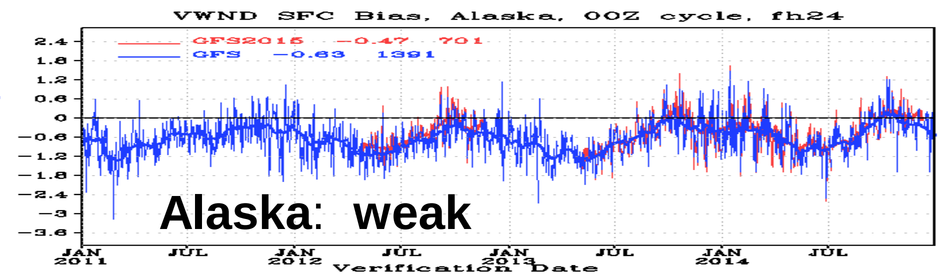


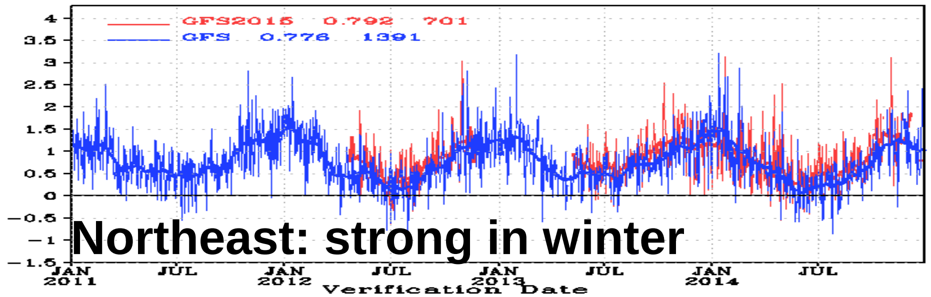








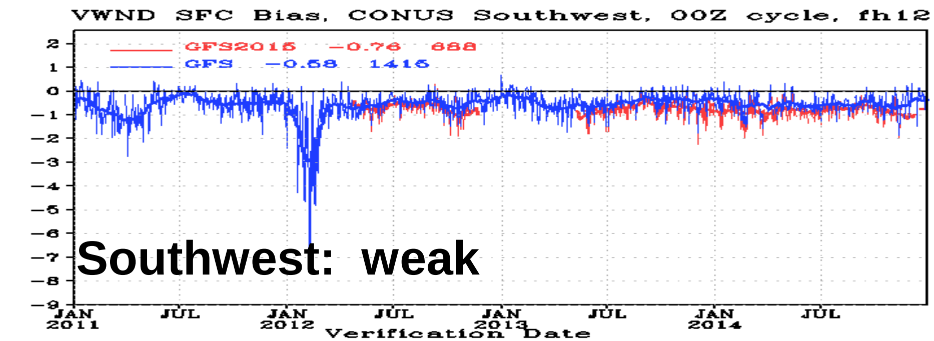


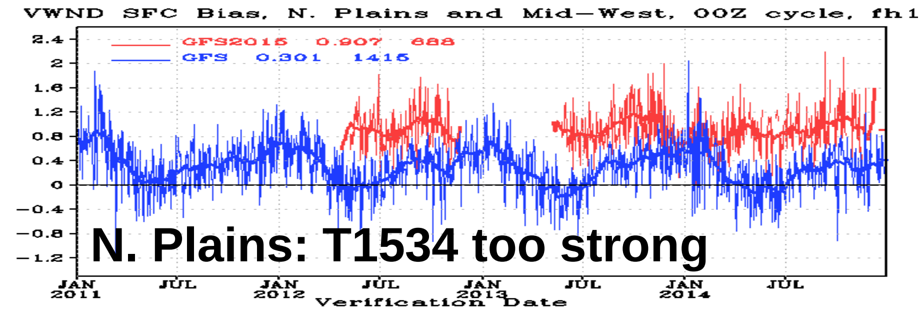


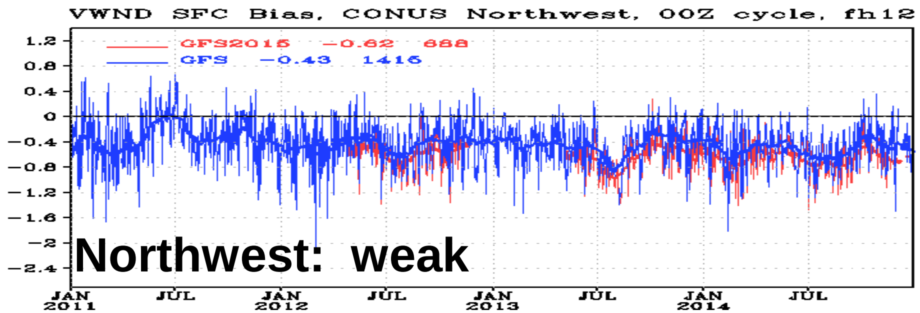
- **GFS sfc wind is too weak in the west, and too strong in the east (especially in winter)**
- **The biases did not change in the past four years; T1534 is improved in the Plains.**

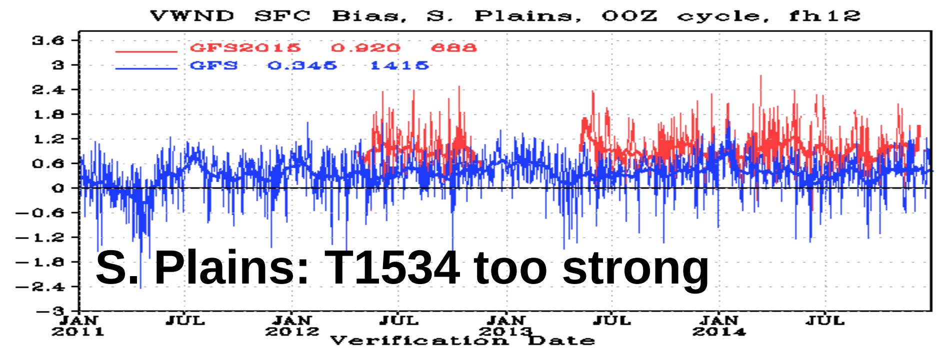
Morning (12Z) 10m-Wind Bias, 2011 ~ 2014

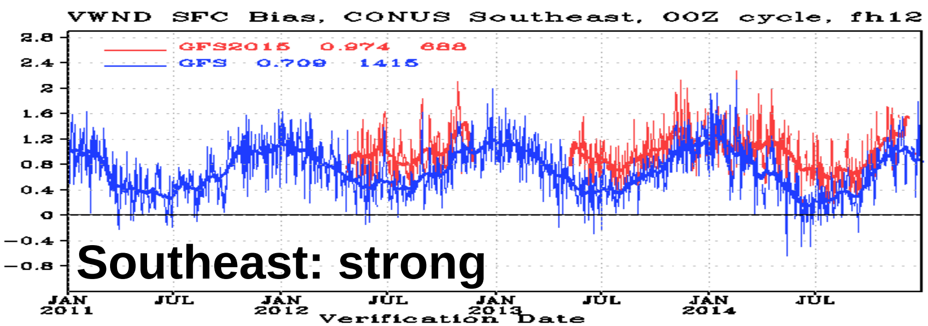
Red: T1534 GFS retro runs
Blue: T574 ops GFS

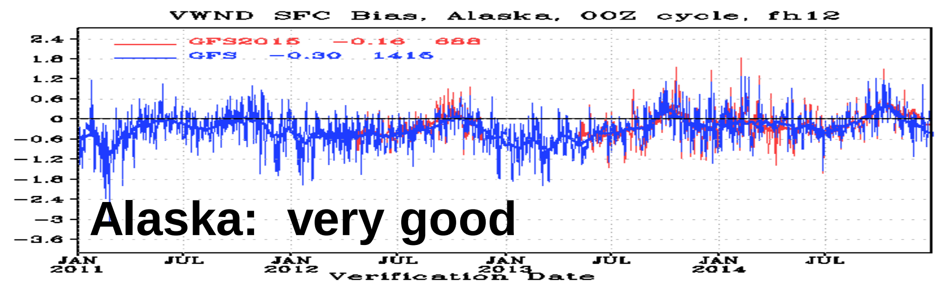


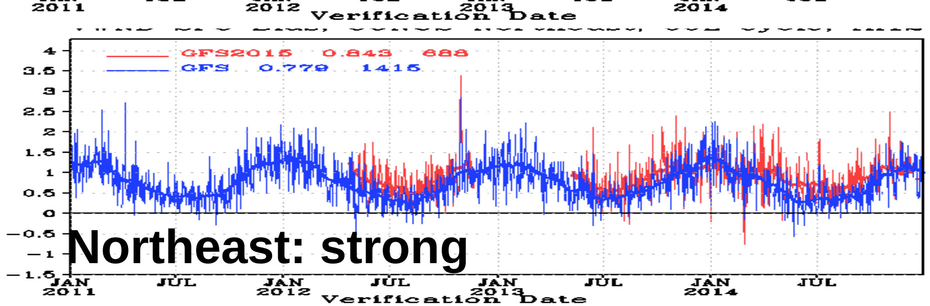








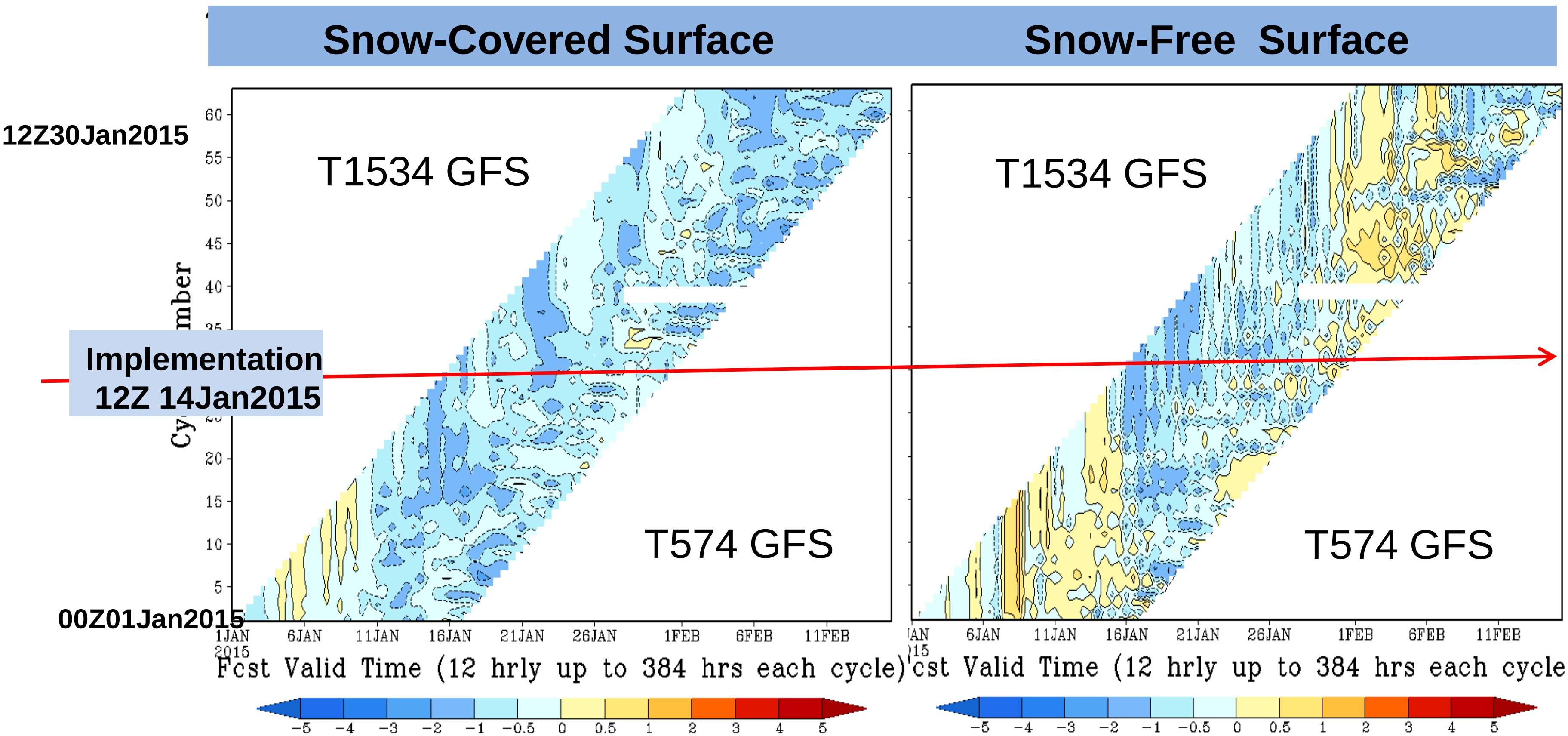




- GFS sfc wind is too weak in the west, and too strong in the east (especially in winter)
- T1534 winds a bit too strong in the N an S Great Plains

Jan-Feb 2015 GFS Cold Bias, A New Model Problem?

T2m – T_sig0.995 over East CONUS [30N-50N, 70W-100W]



- T2m is colder than T_sig0.995 over snow-covered surface
- T2m can be either colder or warmer than T_sig0.995 over snow-free surface
- T2m – Tsig0.995 over snow is not necessarily colder after T1534 implementation.
- Need more stability and regime dependent analysis.

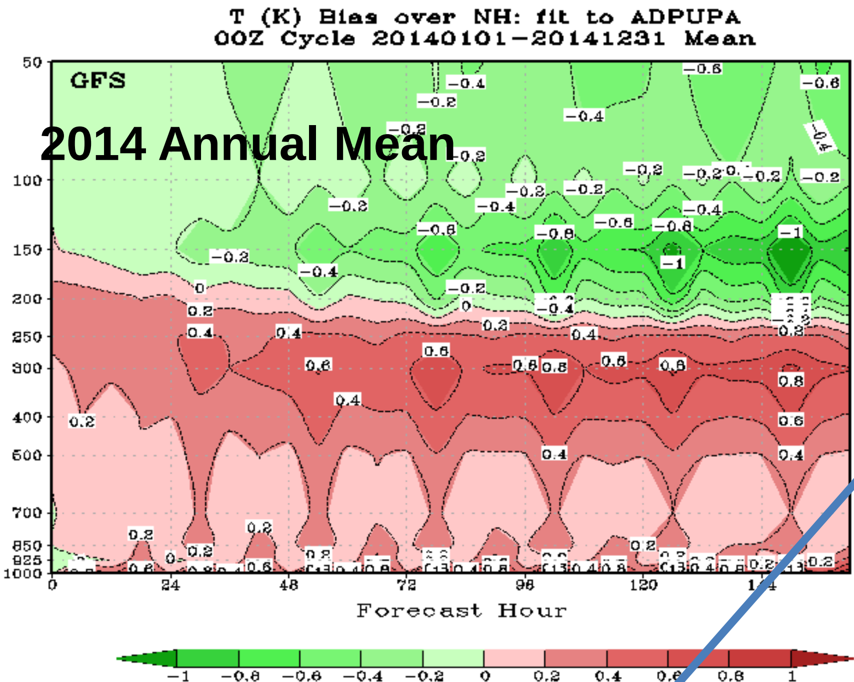
Outline

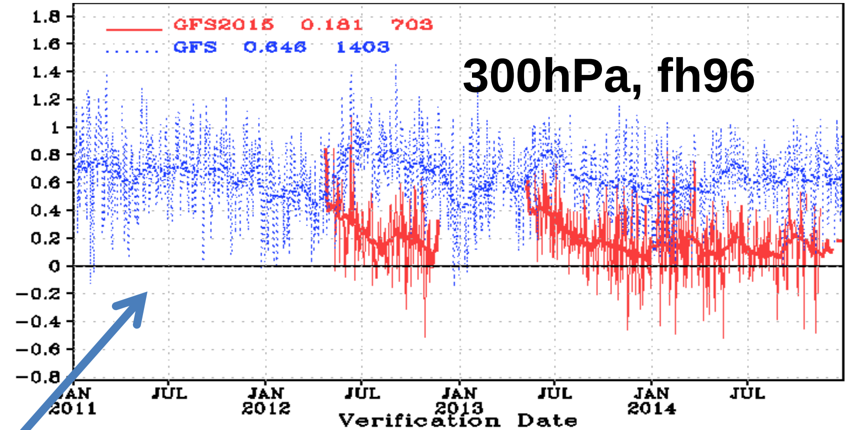
1. Major GFS changes in recent years

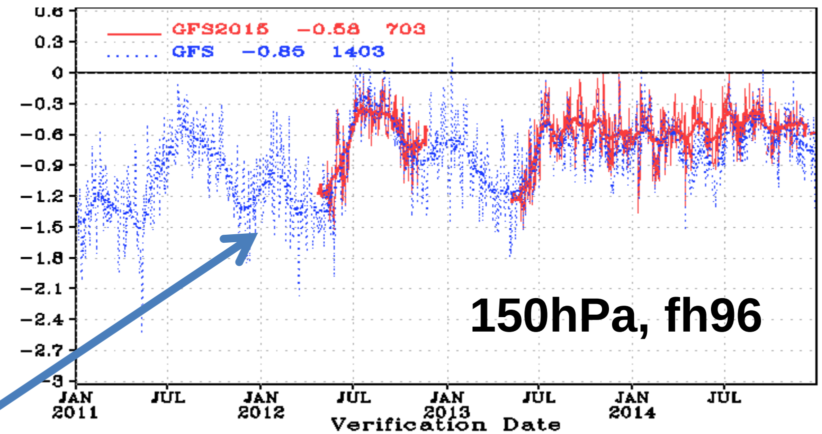
2. Forecast skill scores
   - AC and RMSE
   - Precipitation
   - Surface 2-m temperature and 10-m wind
   - **Verification Against Rawinsonde Observations**
   - Hurricane Track and Intensity

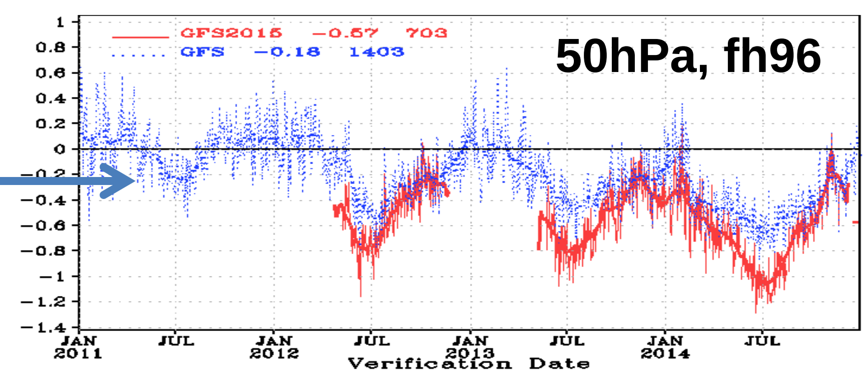
3. Summary and Discussion

NH Temperature Bias, Verified against Rawinsonde Observations



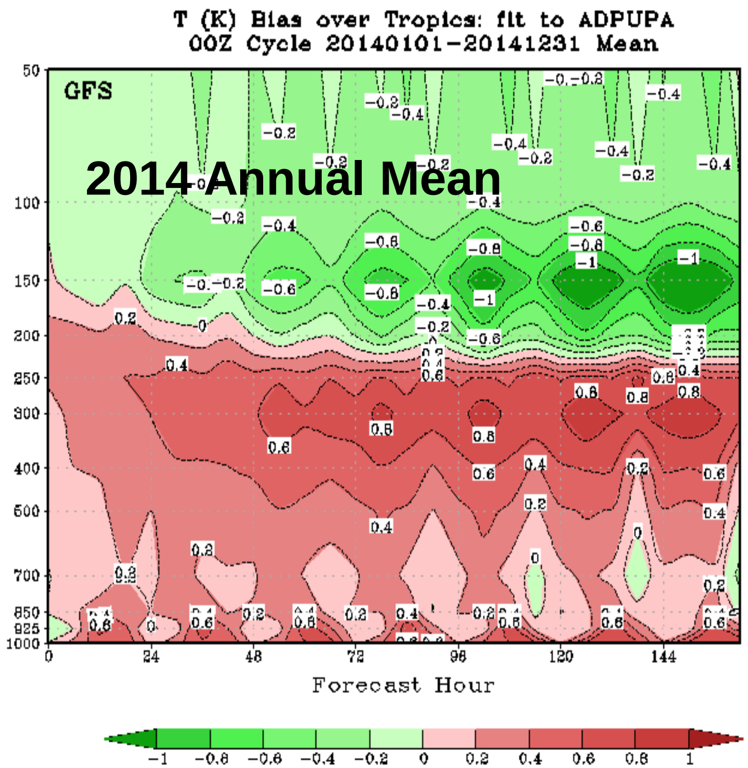


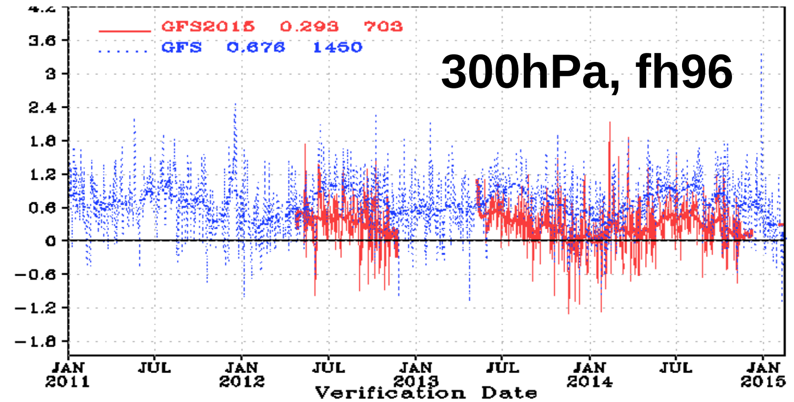


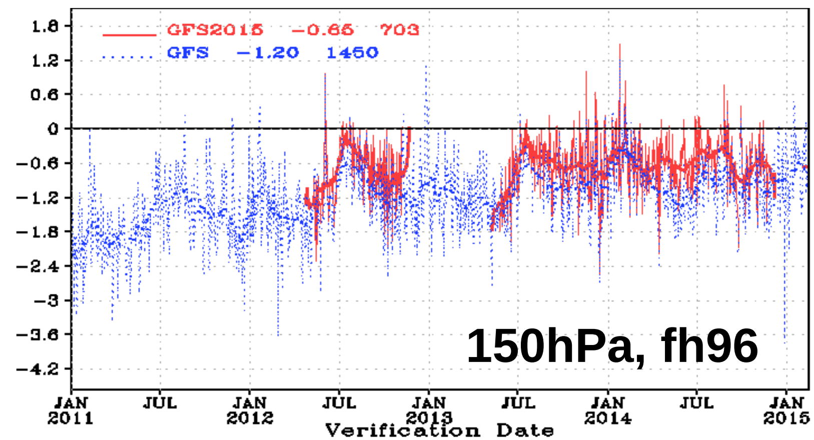


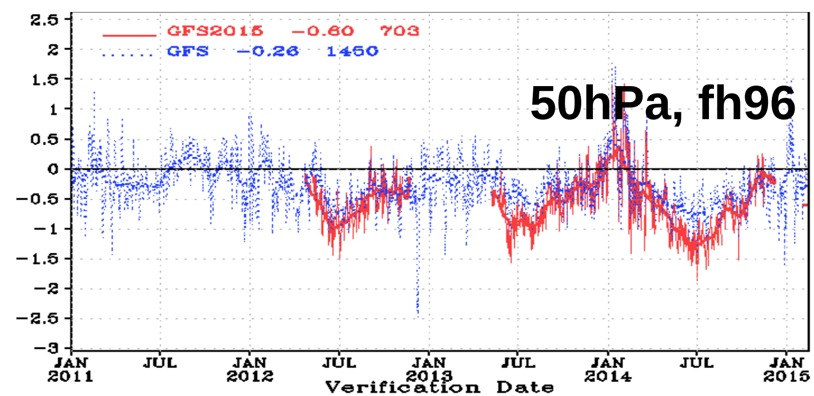
- Warm biases in the troposphere in all four years; warm bias reduced in T1534 GFS.
- Cold bias near tropopause did not changed much from year to year
- Changed from warm bias to cold bias in the middle stratosphere. T1534 is even colder.

Tropical Temperature Bias, Verified against Rawinsonde Observations



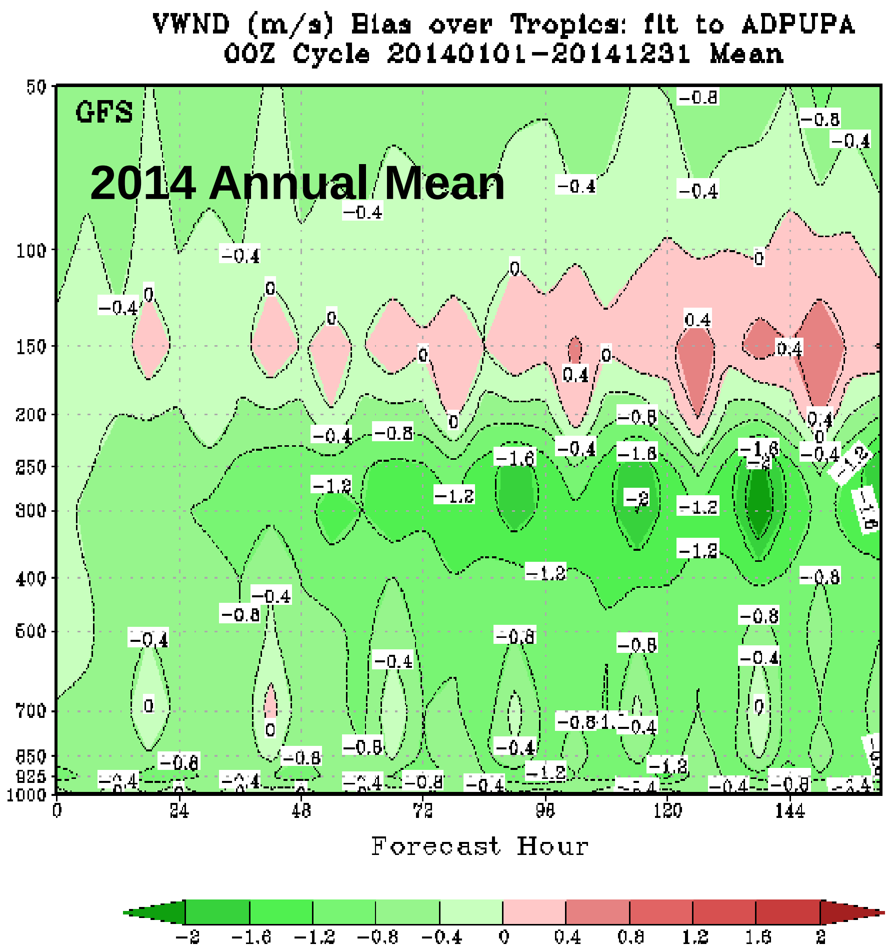


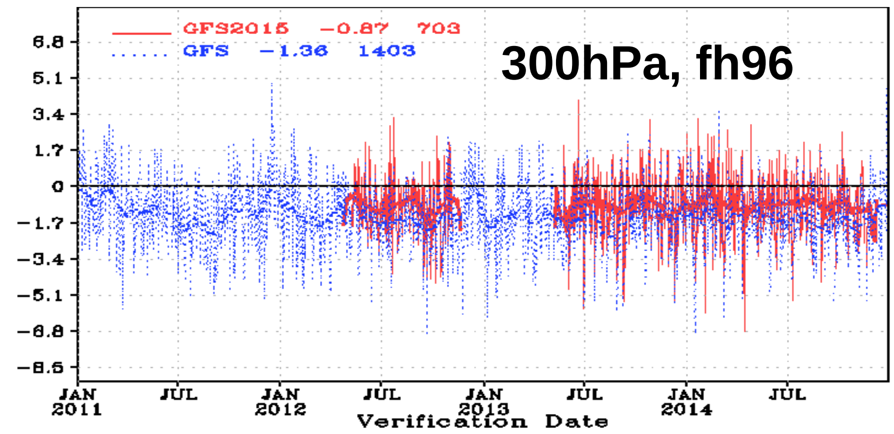


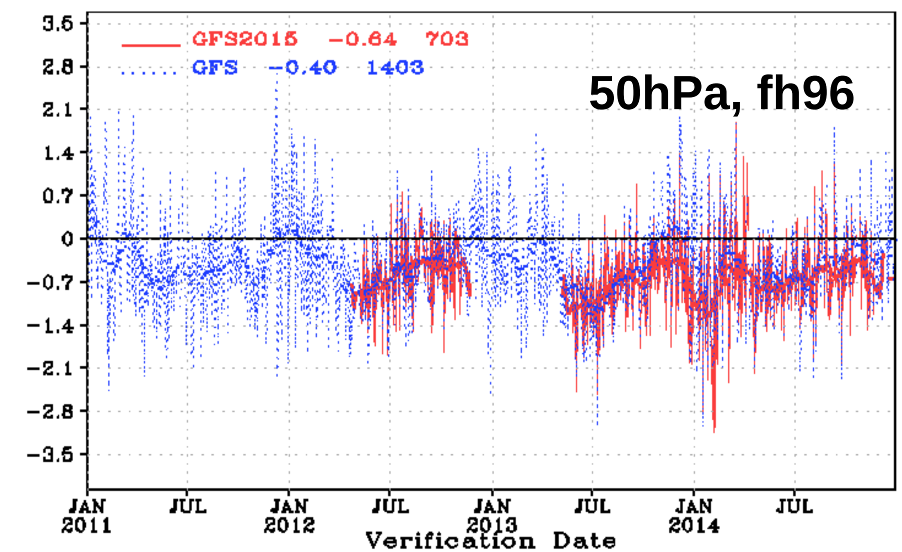


- **Same feature as in the NH**

Tropical Wind Bias,   Verified against Rawinsonde Observations

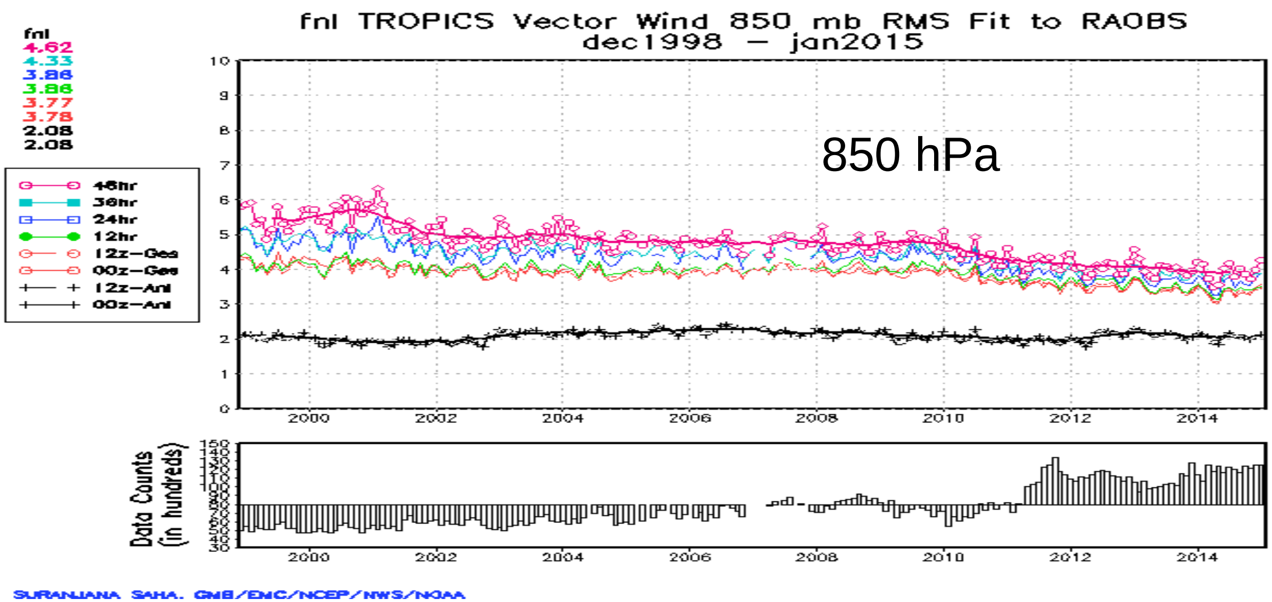


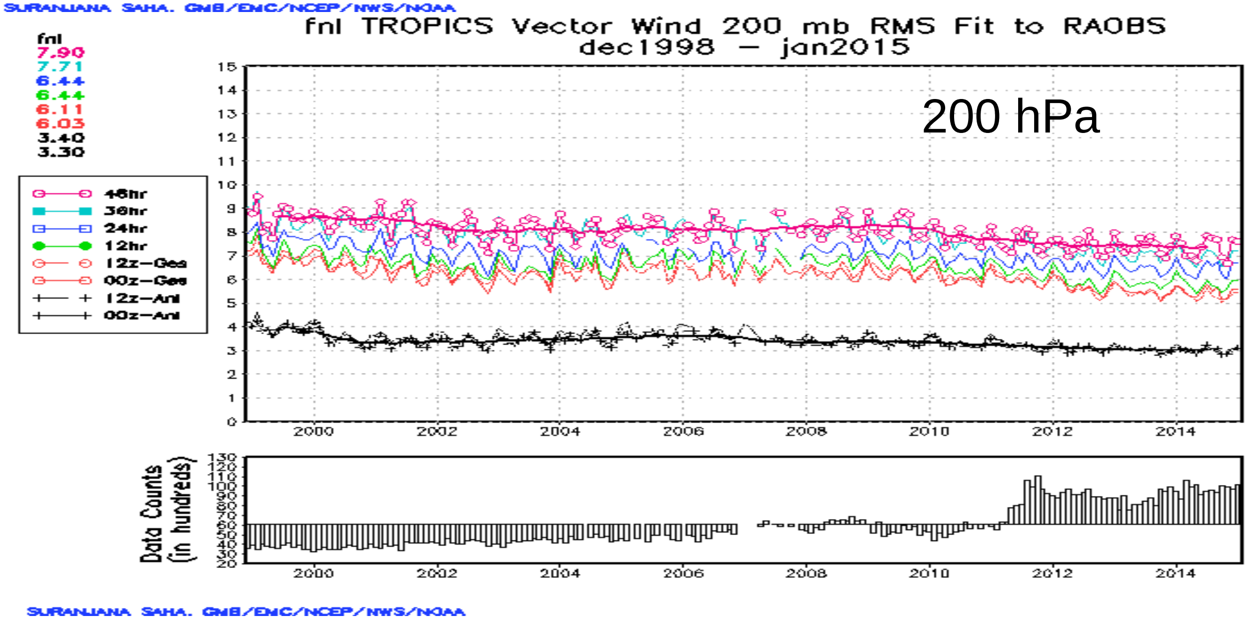




- Weak wind biases at all layers except above tropopause
- Biases reduced in the troposphere in T1534 GFS
- Weak wind biases slightly increased in the stratosphere in T1534 GFS

Long-Term Fit-to-Obs : Tropical Wind, 1998-2014
Credit: Suru Saha





- **RMSE of predicted tropical wind has been gradually reduced from year to year.**
- **The improvement after 2010 T574 implementation was the largest.**
- **RMSE of analyses was reduced by 1.0 m/s from 1998 to 2014 at 200 hPa, but showed little change at 850hPa.**

Outline

1. Major GFS changes in recent years

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   - Surface 2-m temperature and 10-m wind
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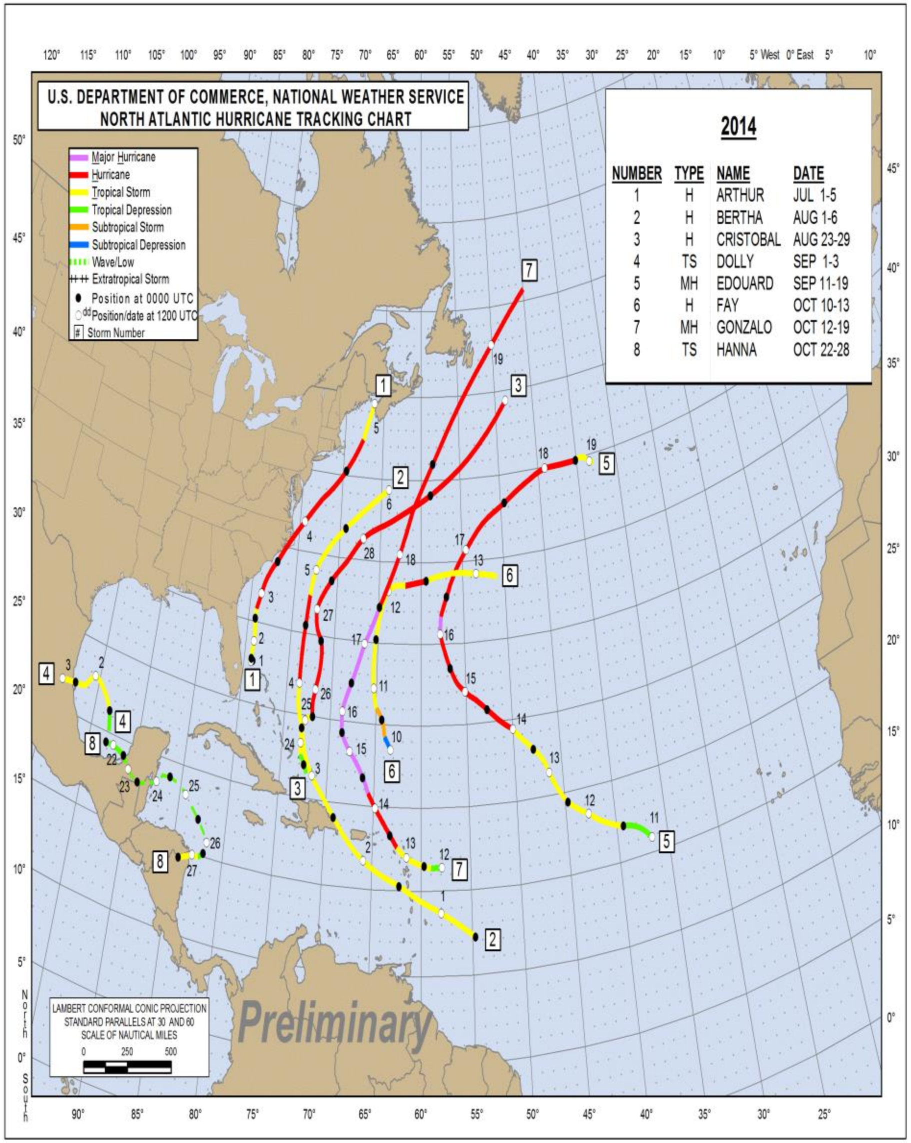
   - **Hurricane Track and Intensity**

3. Summary and Discussion

2014 Atlantic Hurricanes



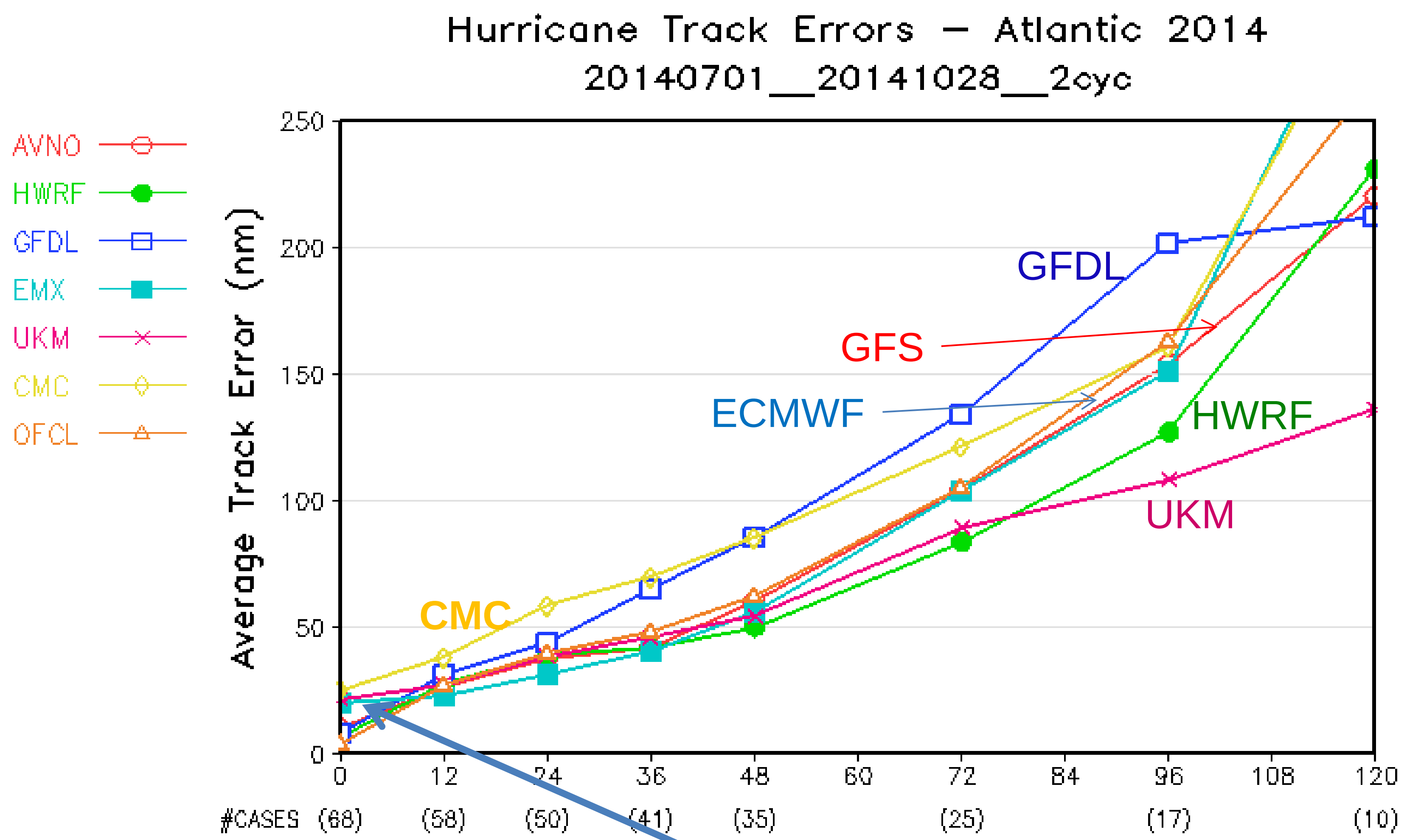
www.nhc.noaa.gov

First system formed	**July 1, 2014**
Last system dissipated	**October 28, 2014**
Strongest storm	**Gonzalo – 940 hPa , 145 mph**
Total depressions	**9**
Total storms	**8**
Hurricanes	**6**
Major hurricanes (Cat. 3+)	**2**
Total fatalities	**19 total**
Total damage	**~ $262 million**

http://www.wikipedia.org

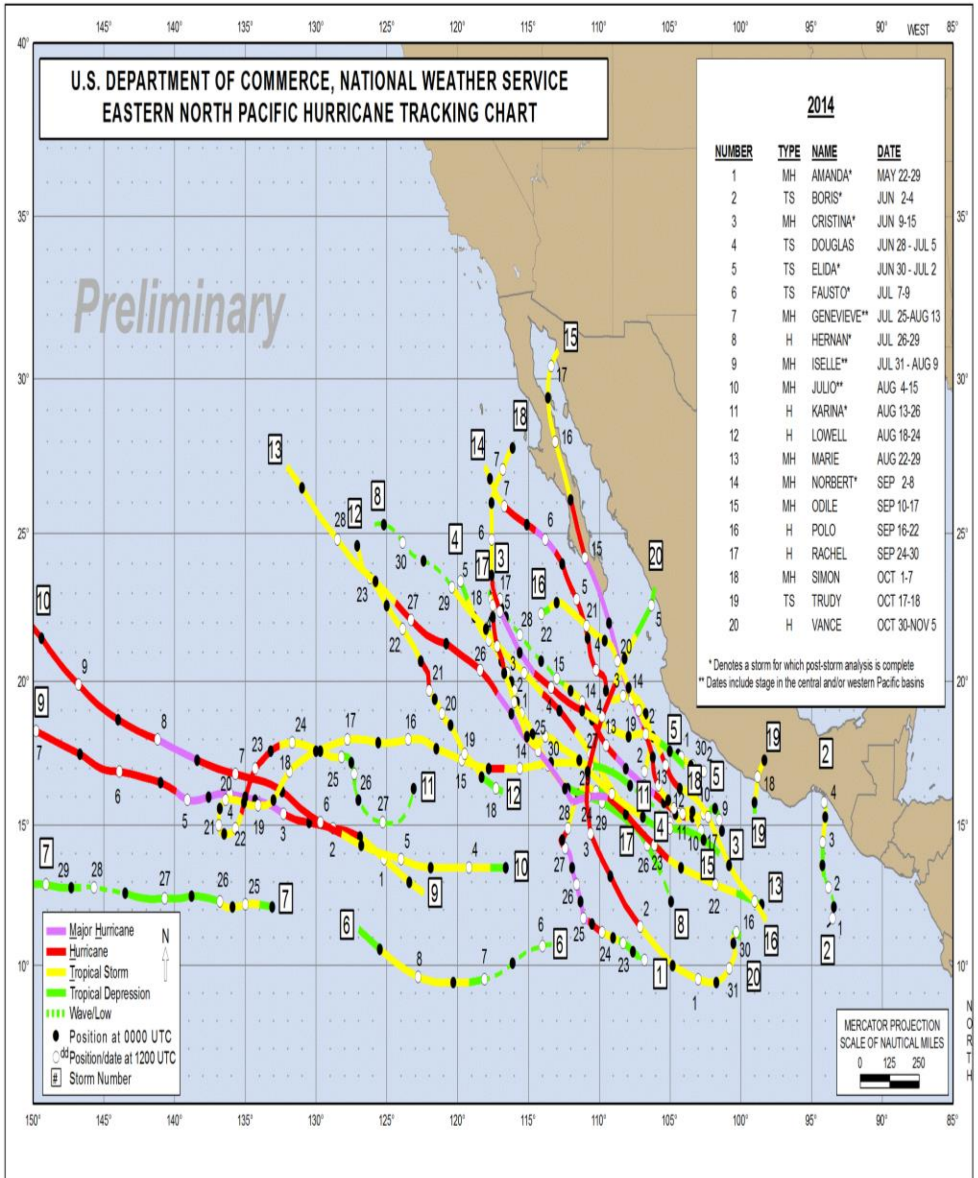
A quiet year. One landfall storm over US

NOAA's Atlantic Hurricane Season Outlook (08/07/2014): 7-12 named storms, 3-6 hurricanes, 0-2 major hurricanes



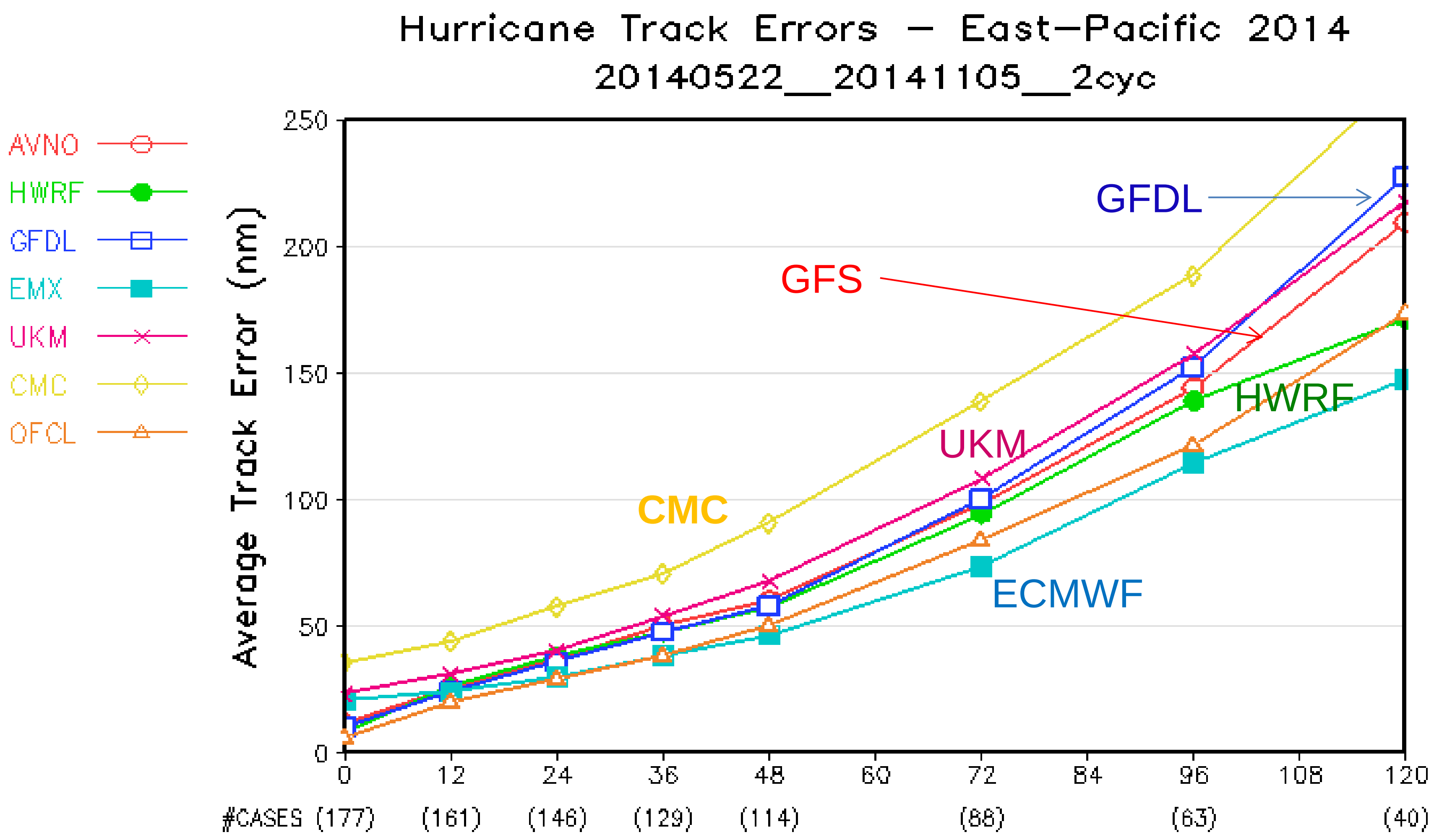
- **HWRF and UKM had better track forecasts. ECMWF had smaller errors than GFS for day1-2 forecasts, and larger error for day-5 forecast.**
- **Among all global NWP models, GFS had the smallest initial track error (because of the use of hurricane relocation ?)**
- **Note: OFCL are based on guidance of “early” models**

2014 Eastern Pacific Hurricanes



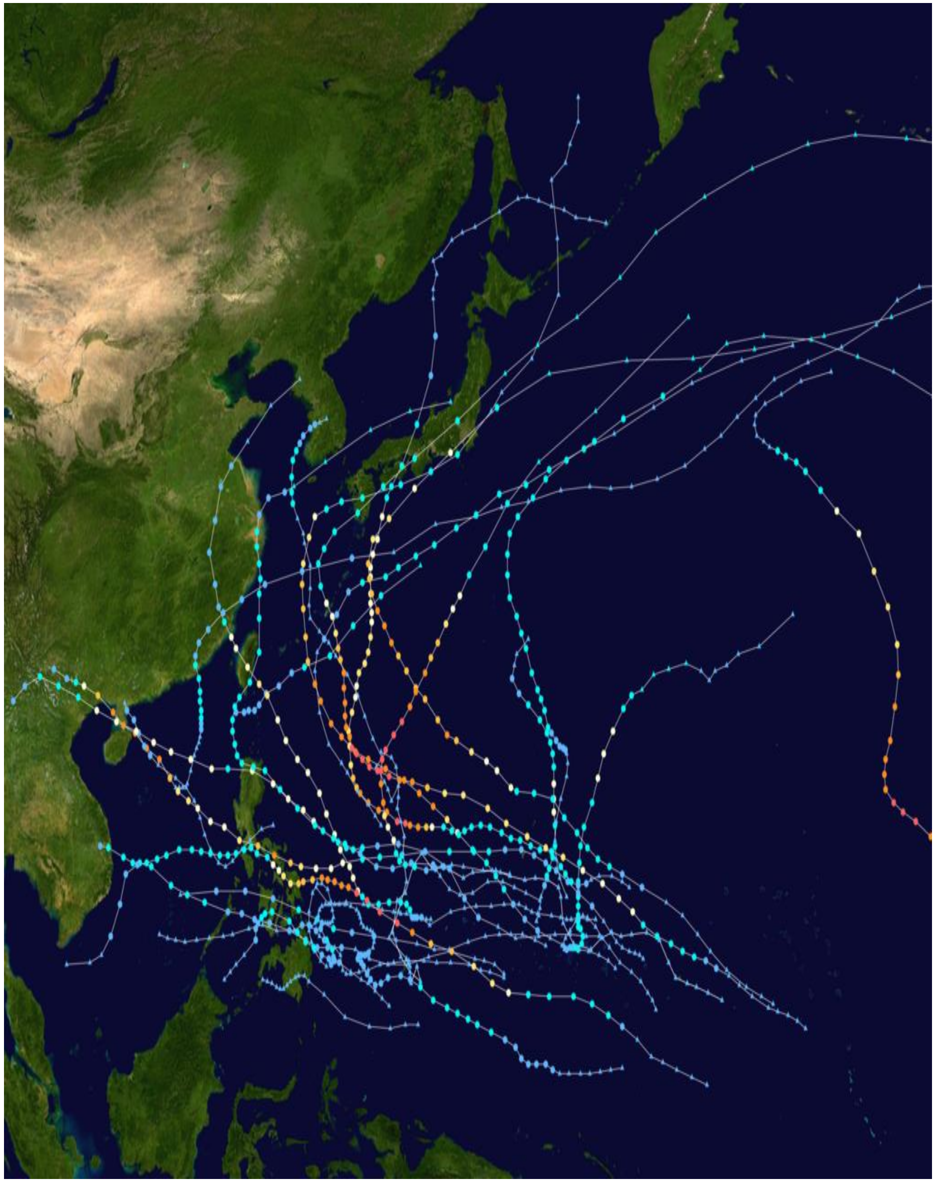
www.nhc.noaa.gov/

First system formed	May 22, 2014
Last system dissipated	November 5, 2014
Strongest storm	Marie – 918 hPa, 160 mph
Total depressions	23
Total storms	22
Hurricanes	16 (record high, tied with 1990 and 1992)
Major hurricanes (Cat. 3+)	9
Total fatalities	42
Total damage	$1.24 billion



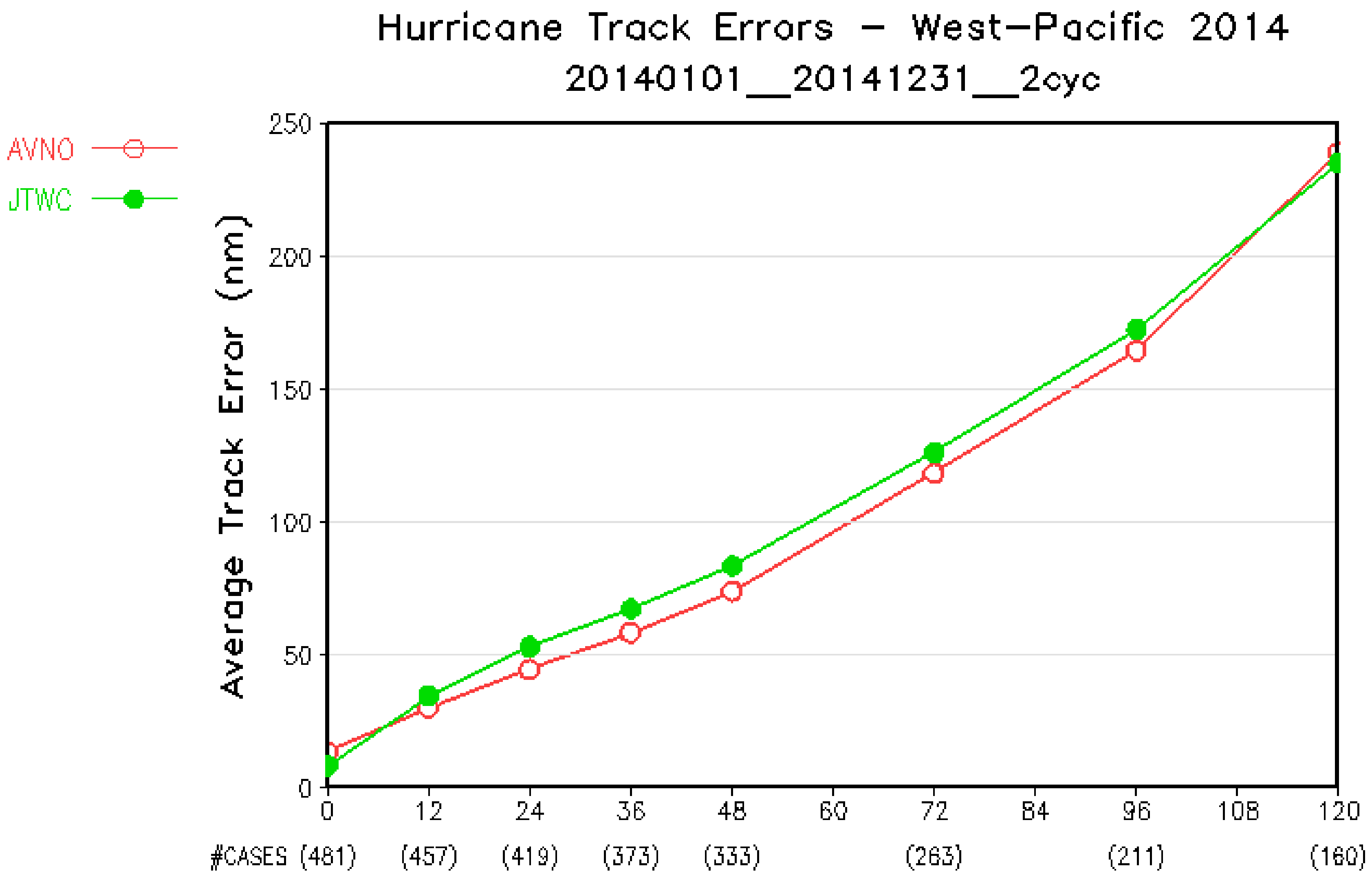
- **ECMWF had the smallest track errors.**
- **GFS was slightly worse than HWRF, but better than GFDL and UKM.**
- **CMC had the largest track error.**

2014 Western Pacific Typhoons



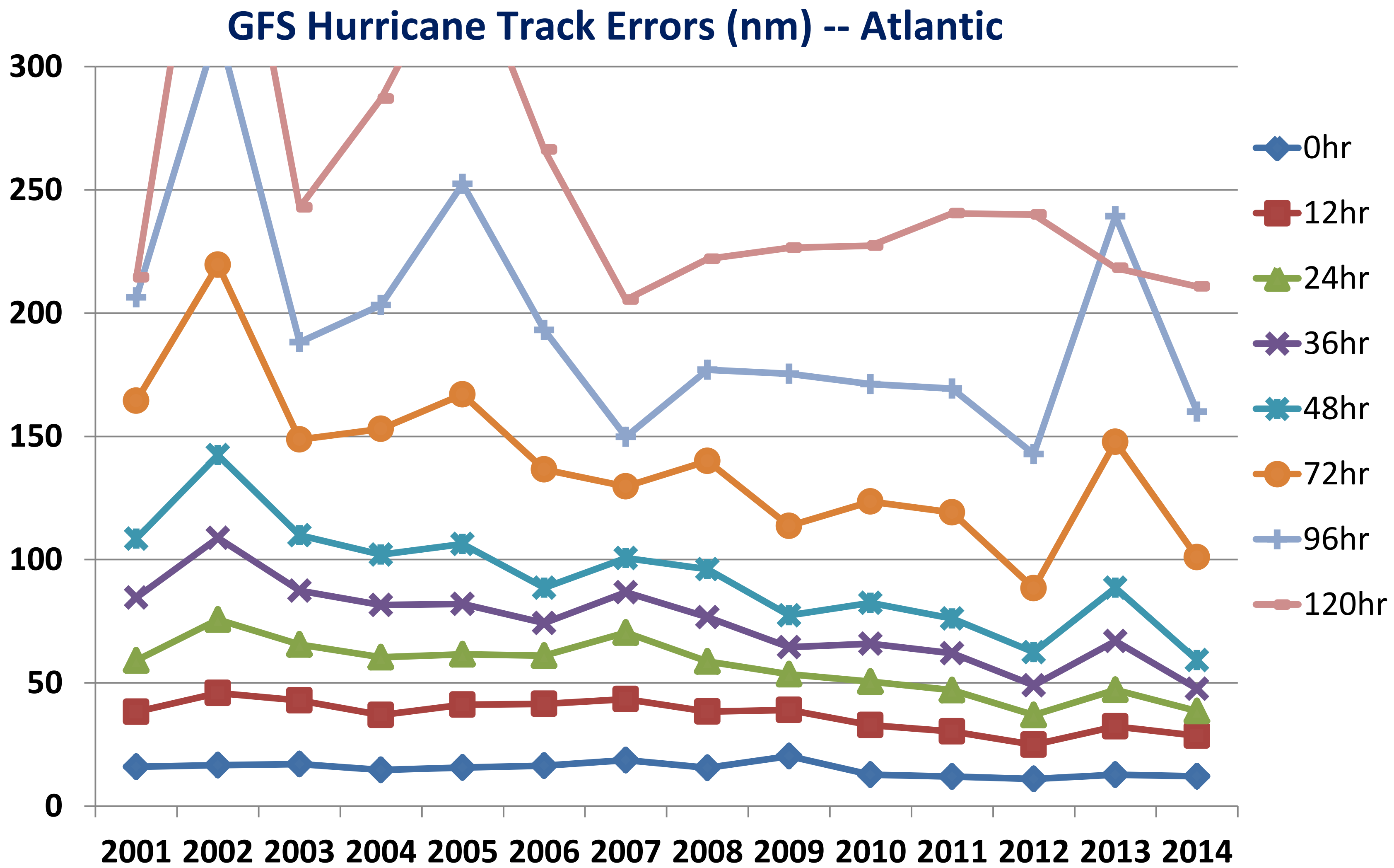
First system formed	January 10, 2014
Last system dissipated	January 1, 2015
Strongest storm	Vongfong: 900 hPa, 130 mph
Total depressions	30
Total storms	23
Typhoons	11
Supper Typhoons	8
Total fatalities	538
Total damage	$8.4 billion

http://www.wikipedia.org



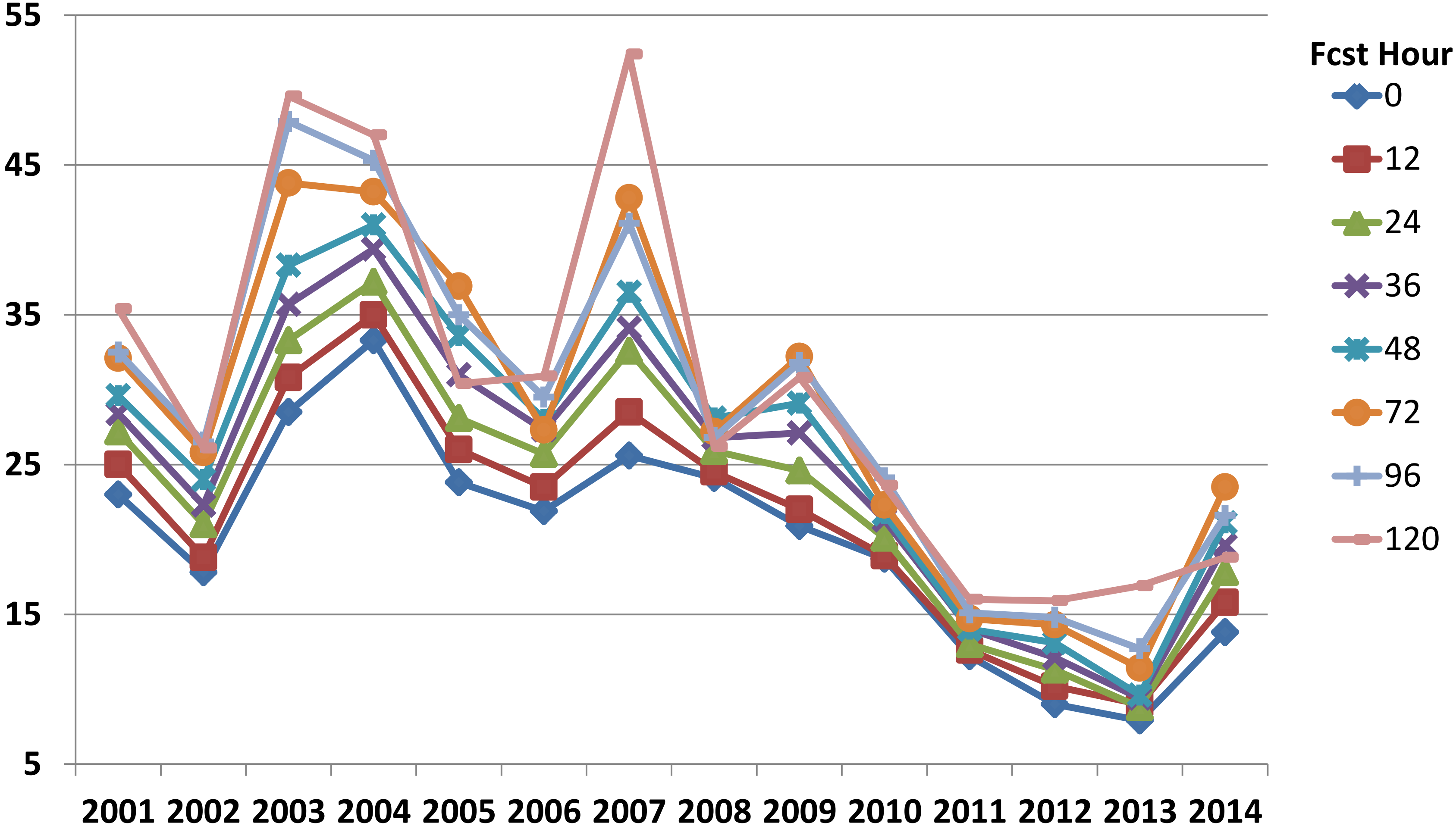
JTWC are based on guidance of early models

Hurricane Track and Intensity Forecast Errors
NCEP GFS : 2001 ~ 2014



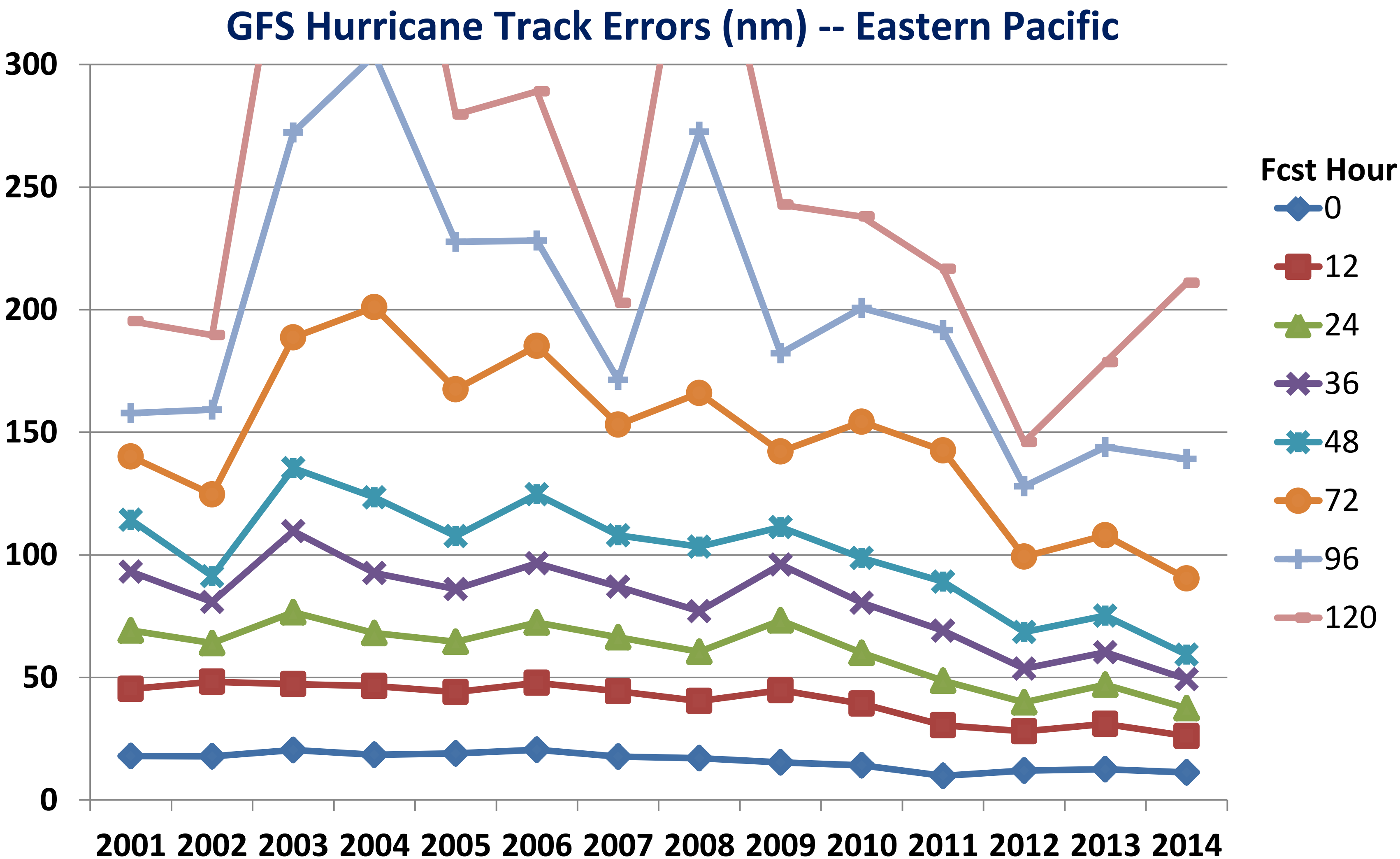
- **2014 is better than 2013**
- **Tracks for all forecast lengths have been improved in the past 14 years; 72-hr track error reduced from 200nm to 100nm**

GFS Hurricane Intensity Errors (kts)-- Atlantic

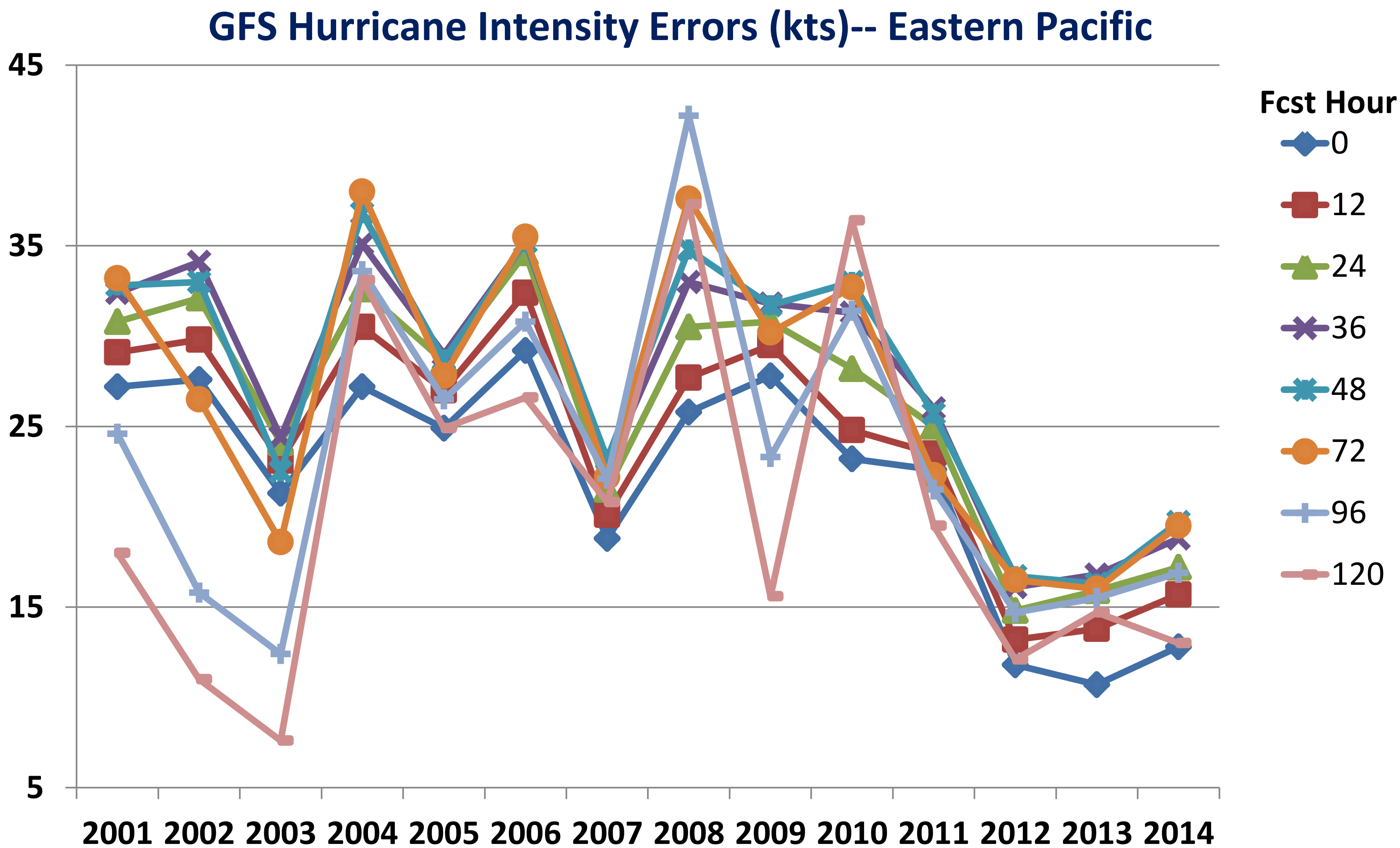


2014 intensity error increased, larger than 2013 and 2012 ! Why ??

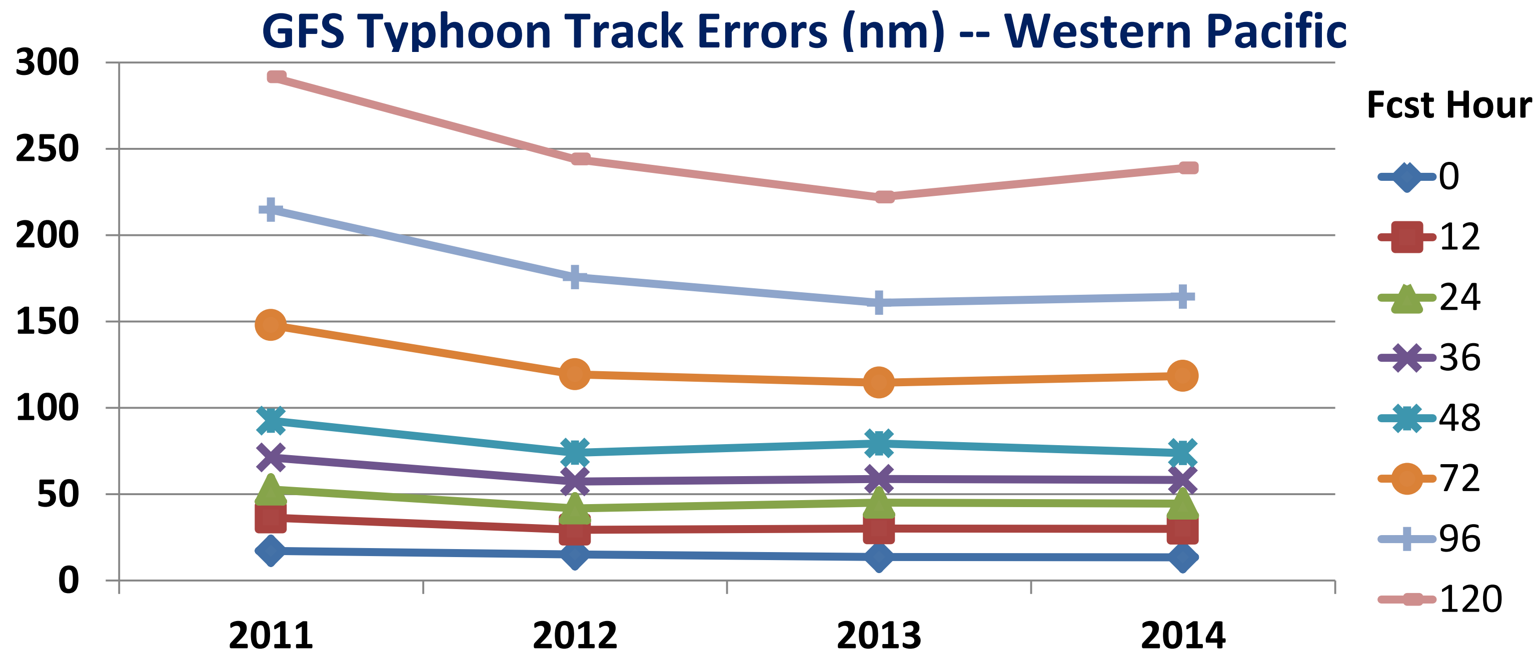
Intensity improved in 2010 and 2011 due to GFS resolution increase from 35km to 23km; and in 2012 and 2013 due to ENKF-3DVAR GSI Implementation in May 2012

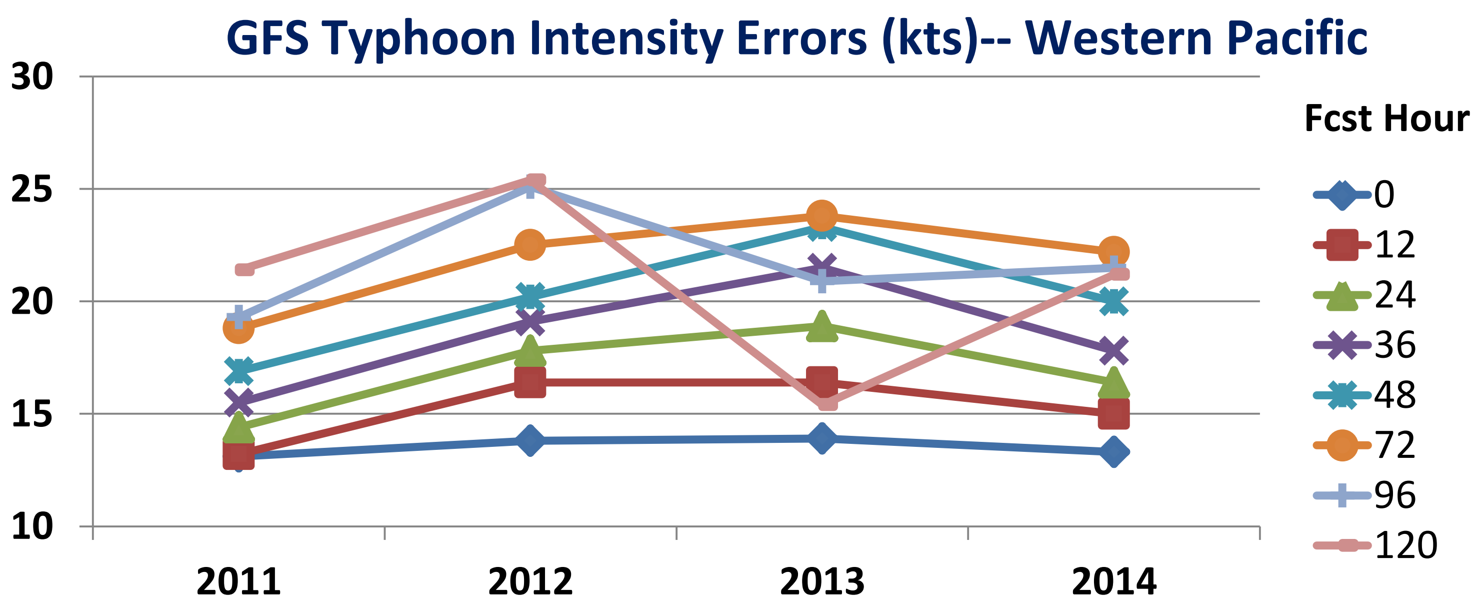


- **2014 had the smallest track errors.**
- **Significant track error reduction in the past 14 years. 36-hr track error reduced from 100nm to 50nm; 72-hr track reduced from 200 to 100 from 2004 to 2014 !**



intensity error for 2014 is slightly larger than that for 2013


GFS Typhoon Track Errors (nm) -- Western Pacific
300
250
200
150
100
50
0
2011
2012
2013
2014
Fcst Hour
0
12
24
36
48
72
96
120


GFS Typhoon Intensity Errors (kts)-- Western Pacific
30
25
20
15
10
2011
2012
2013
2014
Fcst Hour
0
12
24
36
48
72
96
120

Outline

1. Major GFS changes in recent years

2. Forecast skill scores
   - AC and RMSE
   - Precipitation
   - Surface 2-m temperature and 10-m wind
   - Verification Against Rawinsonde Observations
   - Hurricane Track and Intensity

3. **Summary and Discussion**

Configuration of Major Global High-Res NWP Models (2014)

System	Analysis	Forecast Model	Forecast Length and Cycles	upcoming
NCEP GFS	**Hybrid 3DVAR** (T382) + **EnkF** (T254)	**Semi-implicit Spectral T574L64** (23km, 0.03 hPa)	4 cycles 16 days	**semi-lag T1534 (01/14/2015 operation)**
ECMWF IFS	**4DVAR** T1279L91 (T255 inner loops)	**Semi-Lag Spectral T1279L137** (16km, 0.01 hPa)	2 cycles 10 days	
UKMO Unified Model	**Hybrid 4DVAR** with MOGREPS Ensemble	SISL Gridded, **ENDGame dycore**, **70L, 85km**; **N768, 17km**	4 cycles 6 days	
CMC GDPS v4.0.0	**4D-EnVAR; 4D-IAU**	**Semi-lag Gridded 74L, 2hPa** (25km)	2 cycles 16 days	
JMA GSM	**4DVAR**	**Semi-lag spectral TL959 L100** (0.1875 deg; **0.01 hPa**)	4 cycles 12Z- 264 hr	
FNMOC NAVGEM	**4DVAR Ens Hybrid**	**NAVGEM T425L60 semi-lag** (31km; 0.04hPa)	2 cycles 7.5 days	

Red indicates changes made in 2014

Summary and Discussion

- There was no major GFS upgrades in 2014.

- 2014 was a difficult year to forecast for most global NWP models. GFS useful forecast (AC>0.6) in NH reduced form 8.08 days in 2013 to 7.92 days in 2014, trailing behind ECMWF by ~0.3 days.

- In the past 14 years, GFS hurricane track and intensity forecast had been gradually improved in both the Atlantic and Pacific basins. Track errors reduced by half for 72-hour forecasts in both basins from 2001 to 2014.

- GFS CONUS precipitation forecast was improved after the 2010 T574 implementation, and did not vary much in the past 4 years. For moderate rainfall events, GFS changed from wet bias in 2009 to dry bias in recent years.

- It seems GFS tends to overestimate light rainfall in Western US, and to underestimate heavy rainfall events over Eastern US.

- GFS has T2m cold biases for all seasons and in all regions over the CONUS, except that in summer over the Great Plains and Southeast GFS has warm bias.

Summary and Discussion

- The characteristics of GFS 2-m temperature biases have not changed much in the past few years. The new T1534 GFS is slightly warmer than previous versions of GFS.

- Surface temperature biases change with the time of the day and season. More regime dependent analysis is needed to understand the causes.

- It seems GFS is locked into a cold surface state. Cold bias exists in first guess and initial conditions, and only amplifies slightly with forecast time. Will assimilating more surface data reverse the model cold state?

- GFS 10-m wind is in general too weak in the west, and too strong in the east (especially in winter). The biases did not change much in the past four years; T1534 is improved in the Great Plains.

- T574 GFS had warm bias in the upper troposphere and cold bias in the lower stratosphere. These biases have been in general reduced in the new T1534 GFS.

- T574 GFS also had weak wind bias in both the troposphere and stratosphere. Bias in the troposphere is reduced in the new T1534 GFS.