The Use of Satellite Data in Regional NWP at the Environmental Modeling Center

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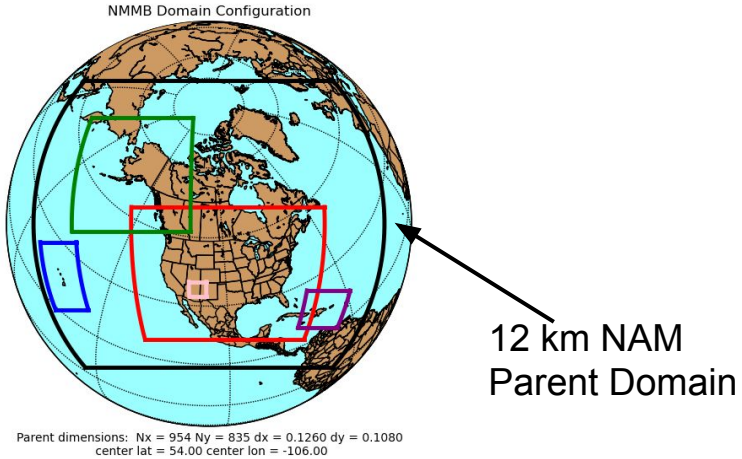
Andrew Collard, Geoff DiMego, Emily Liu, Shun Liu, Rahul Mahajan, Xiaoyan Zhang, and Yanqiu Zhu

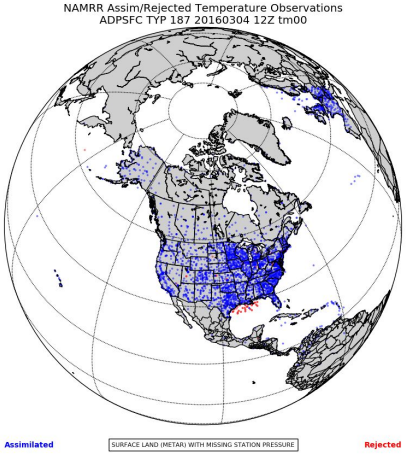
Satellite Data Use in Regional NWP: Outline

- Observation ingest and types of satellite observations
- Data Assimilation
  - How satellite data are treated in *regional* NWP and our wrinkles
- Practical Perspectives from the NAM and upcoming NAMv4 bundle
- Ongoing efforts at EMC
- What's next?
  - GOES-R + Lightning + radar
  - Cloudy radiances
  - Multiscale



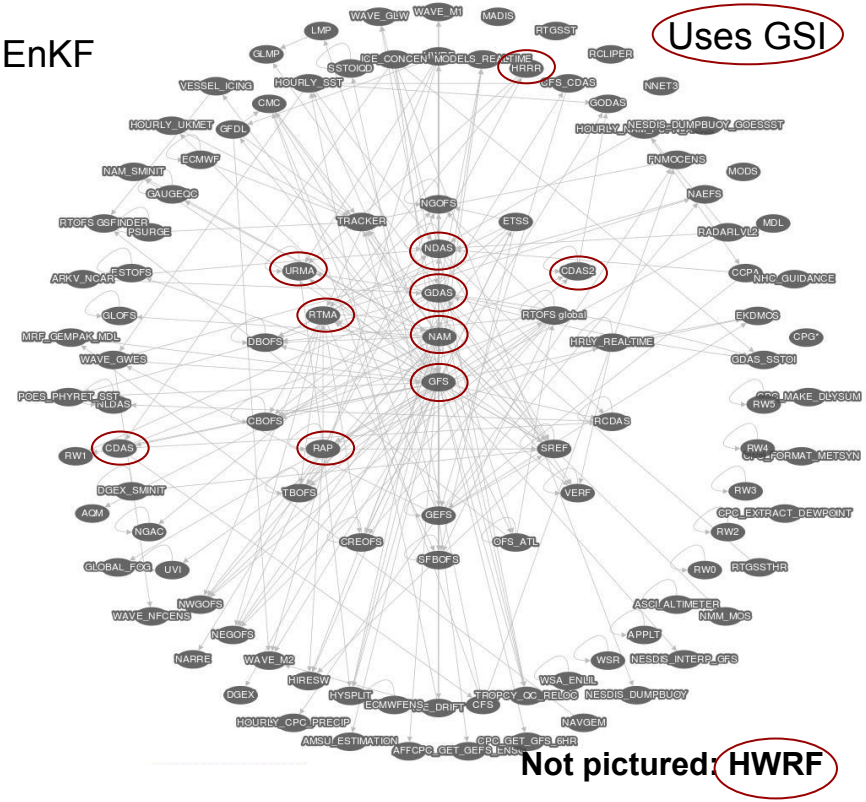
Observations Arriving at NCEP

- A global suite of environmental data assimilated input models
  - Observations are ingested continuously
    - 24x7x365
- Observations summary
  - Satellite sources - ~1.9 billion obs per day
    - Geostationary and polar orbiters
  - Non-satellite sources – ~470 thousand obs per day
    - Surface reports (e.g, land and marine)
    - Upper-air profiles (e.g., aircraft, soundings, profilers)
  - NEXRAD radial winds - ~763 million obs per day



Atmospheric Data Assimilation at EMC

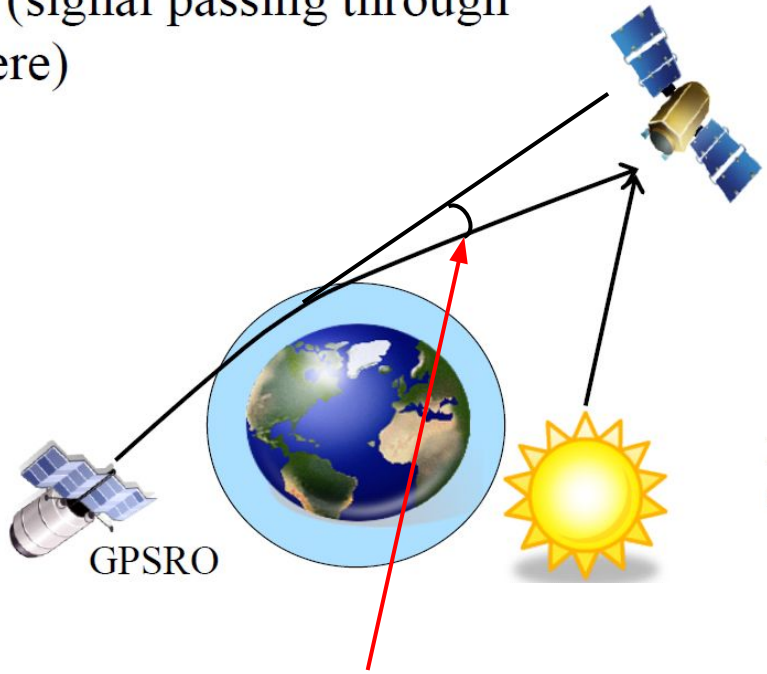
- Variational Gridpoint Statistical Interpolation (GSI) + EnKF
- GSI Underpins the vast majority of the production suite
  - 2DVar - Hourly analyses
    - RTMA/URMA
  - Global - Weather, Climate, Reanalysis
    - GFS, CFS, CFSR (Global Spectral Model)
  - Regional - Weather, Aviation
    - NAM (uses Nonhydrostatic Multiscale Model on the B-grid; NMMB)
  - Short term - Hourly, Aviation, Near-term hazards
    - RAP, HRRR (WRF-ARW)
  - Tropical Storms
    - Hurricane WRF (WRF-NMM)
- Nearly every system that *<u>does not</u>* use GSI has an upstream dependency on a system that *<u>does</u>* use GSI



Types of Satellite Data

Occultation (signal passing through the atmosphere)

E.g., COSMIC



Limb sounding: Viewing the Earth's atmosphere **tangentially**

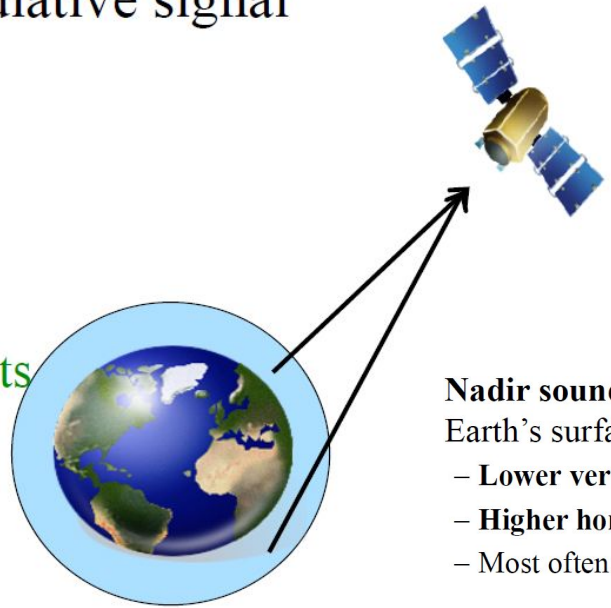
- **Higher vertical** resolution
- **Lower horizontal** resolution

What we assimilate: **Bending angle**

Types of Satellite Data

Passive (receiving radiative signal from source)

- Visible Instruments
- IR Instruments
- Microwave Instruments



Active (transmit and receive) satellite instruments are less commonly used in NWP.

exception Scatterometer winds

Nadir sounding: Viewing **towards** the Earth's surface

- **Lower vertical** resolution
- **Higher horizontal** resolution
- Most often used in NWP

What we assimilate: **Radiances, retrieved atmospheric motion vectors, and some retrievals in non-variational capacity**

How are Satellite Data Used in Regional NWP?

- Radiance assimilation
- Satellite Winds
- GPS RO
- Non-variational cloud analysis

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How are Sat. *Radiances* Used in Regional NWP?

- Radiance assimilation
  - Variational DA → Minimize a cost function
  - Prefer to use the observation in its rawest form, when possible
  - Requires developing an observed equivalent, i.e. model simulated satellite observation (where the CRTM comes in)

$$J = J_b + J_o + J_c$$

$$J = \frac{1}{2}\left[x - x_{\mathbf{b}}\right]^T B^{-1}\left[x - x_{\mathbf{b}}\right] + \frac{1}{2}\left[H(x) - y\right]^T R^{-1}\left[H(x) - y\right] + J_c$$

The difference between the observations and the background transformed into model space, the first guess departure.

Penalty = Fit to background + Fit to observations + Constraints

x = Analysis ; x_b = Background

$\delta x = x - x_b$ = Analysis increment

B = Background Error Covariance

H = (Nonlinear) Forward Model ; H = Linearized about x_b

y = Observations ; $d = y - Hx_b$ = Observation Innovation

$R = E + F$ = Instrument Error + Representativeness Error = Observation Error

J_c = Constraint terms

How are Sat. *Radiances* Used in Regional NWP?

Bias Correction

- The differences between simulated and observed observations can show significant biases.
- The source of the bias can come from:
  - Inadequacies in the characterization of the instruments.
  - Deficiencies in the forward models.
  - Errors in processing data.
  - Biases in the background.
- Except when the bias is due to the background, we would like to remove these biases.

How are Sat. *Radiances* Used in Regional NWP?

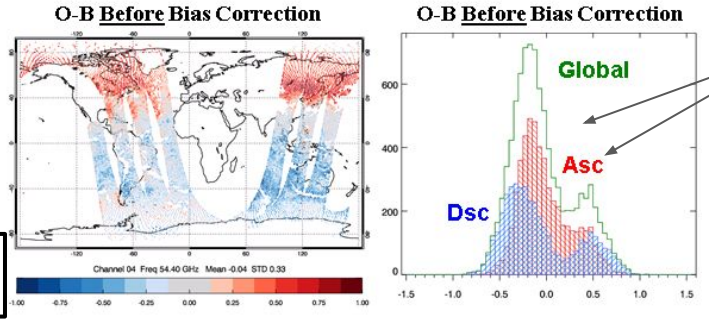
Bias Correction

- The differences between simulated and observed observations can show significant biases
  - For radiances, biases can be much larger than signal
  - Essential to bias correct the data
  - NCEP uses a variational bias correction scheme (other centers are similar) using atmospheric air mass and scan angle predictors
    - Biases in the background.
- Except when the bias is due to the background, we would like to remove these biases.

How are Sat. *Radiances* Used in Regional NWP?

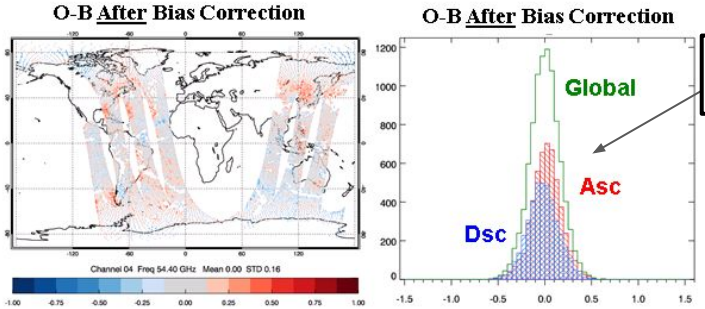
- Radiance assimilation
  - But there are biases! Correcting them works pretty well for global models

SSMIS: An extreme example on an instrument with complicated biases!



Bimodal, non-Gaussian

Before bias correction

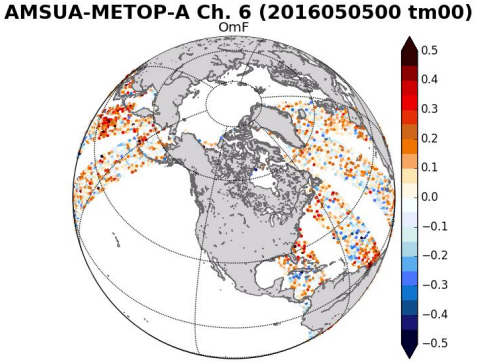


Much more Gaussian

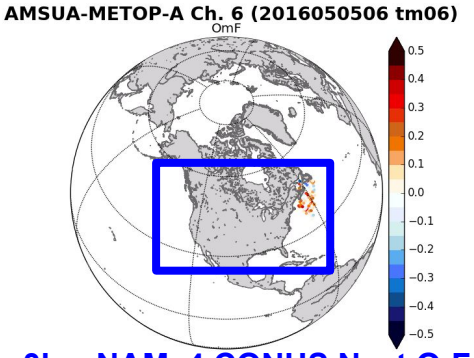
After bias correction

Regional Radiance Wrinkles

- Limited, regional domains are ***not*** generally sufficient for capturing the radiance bias
  - E.g. polar orbiting satellite data is non-uniform in the limited area and highly variable
- Adaptively estimated bias correction estimates from regional data tend to not be as robust as they are from global estimates
  - The bias correction predictors are computed as a *global* statistic and are not well formulated for the regional problem (limited domains and times)
- In the NAM we still estimate the bias corrections for the very large parent domain, and use those terms in our nest domains
  - E.g., NAMv4 upgrade where AK and CONUS have their own DA cycle
  - Other centers may use the bias correction terms from their global model



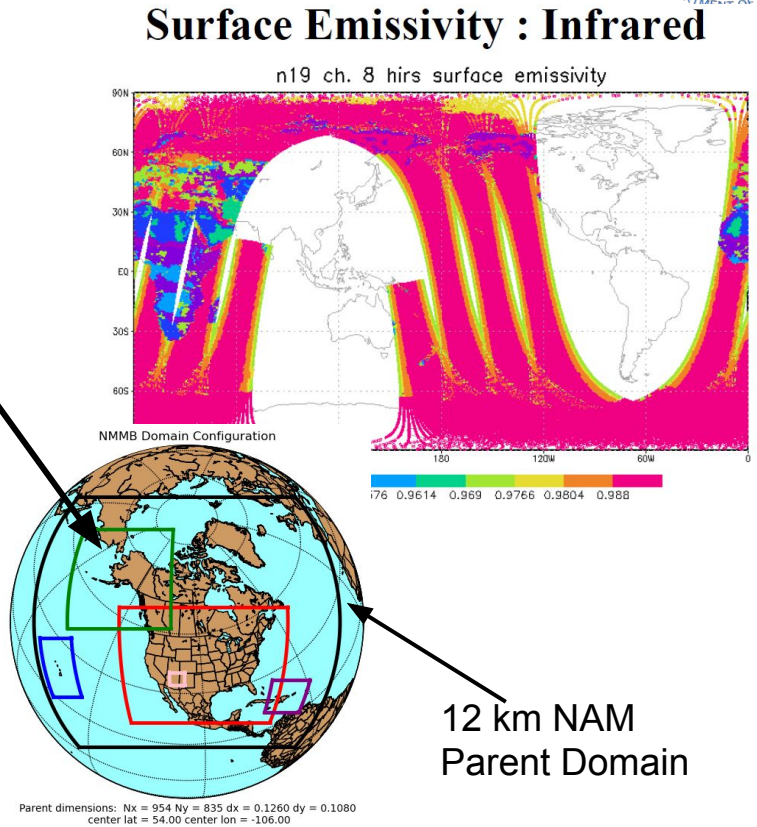
GDAS (GFS DA system) O-Fs



3km NAMv4 CONUS Nest O-Fs

Regional Radiance Wrinkles

- We assimilate far fewer radiances over land (typically) - *which is where our regional domains are focused*
  - Poor knowledge of surface emissivity and temperature
  - characteristics for land / snow / ice.
    - Also makes detection of clouds / precipitation more difficult over these surfaces.
- For observations that are used over land:
  - Usually receive lower weights if sensitive to the surface



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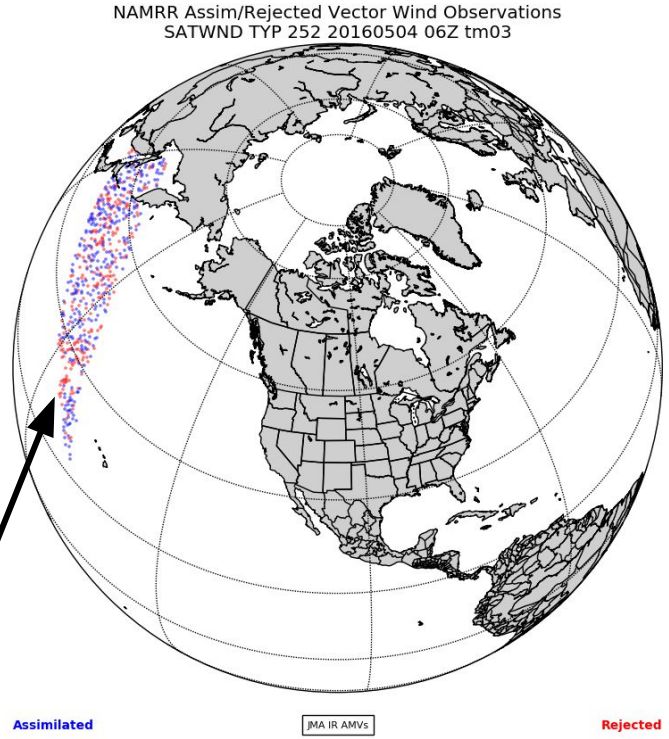
How are Sat. *Winds* Used in Regional NWP?

- Satellite winds are a retrieved product and are fairly straightforward to use
- No need for a complex observation operator
- No major differences between use in global and regional systems
- Largest challenge is dealing with uncertainties in the height assignment of the AMVs



Satellite winds from JMA Himawari-8 (IR) assimilated in developmental NAMv4

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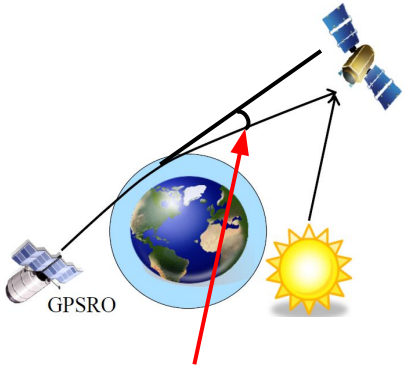
How are *GPS RO* data Used in Regional NWP?

- GPS Radio Occultation tends to be one of the most impactful observation in the *global* (top 5 or 6)
  - It is used similarly in the regional
  - These data are not bias corrected
- Assimilate the bending angle
  - High vertical resolution (~100m)
  - Lower along track resolution (~200 km)



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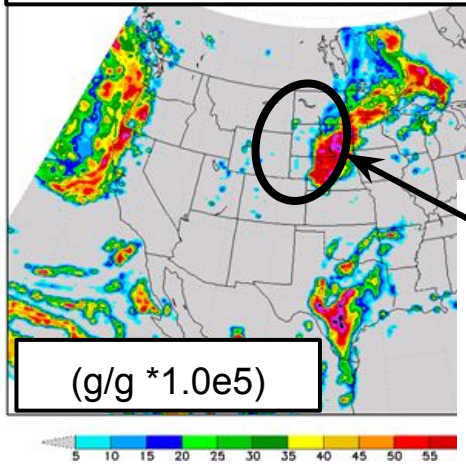
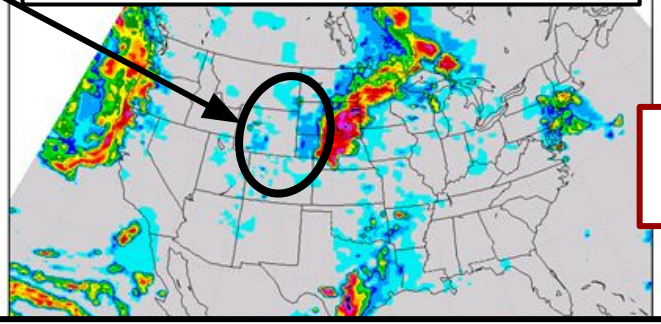
Applications of GSD's Cloud Analysis Package for the NAM

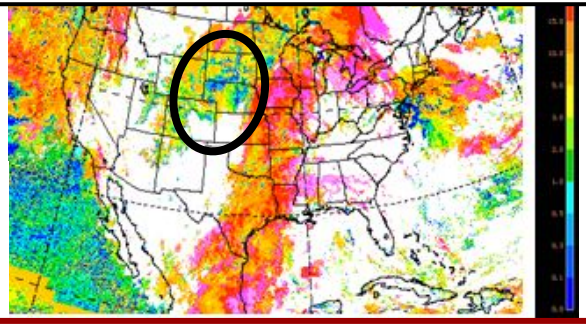
Total column cloud water before cloud analysis



Total column cloud water after cloud analysis



NASA Langley cloud base height



Added cloud water corresponds to low cloud bases

- Includes DDFI with radar derived temperature tendencies
- Cloud and hydrometeor modifications based upon satellite (e.g. NASA Langley data), surface observations, and radar observations

Where Does this fit in a Regional Operational NWP Model?

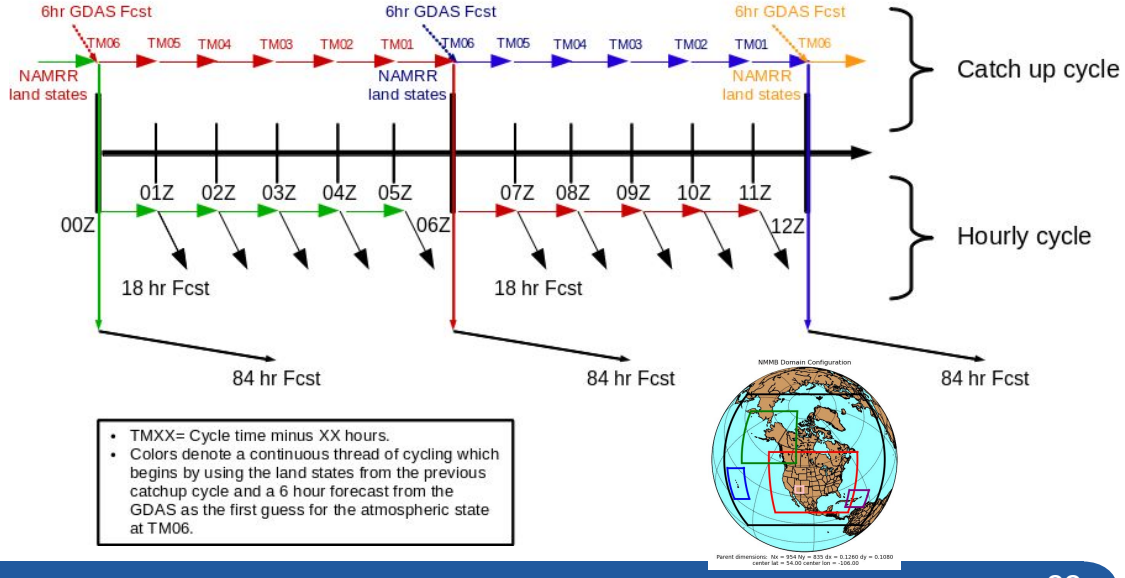
Perspectives from the NAM and developmental NAMv4

Where Does this fit in a Regional Operational NWP Model?

Perspectives from the NAM and developmental NAMv4

- Use all that we can in regional domain (allowing for lower model top)
- Data-cutoff times
  - Fewer observations arrive at NCEP/NCO in time for the analysis
    - Especially true for rapidly updated systems
  - Global: Update every 6 hours using long(er) time window, uses more data per analysis
  - Regional: Update hourly (or 3 hourly) with narrow(er) time window, uses less data per analysis
- Catchup/Partial cycling to get these missed data

NAMv4 DA Cycling Diagram (with Optional Hourly Updates Turned on)



How Many Satellite Observations are Used in a NAM Analysis?

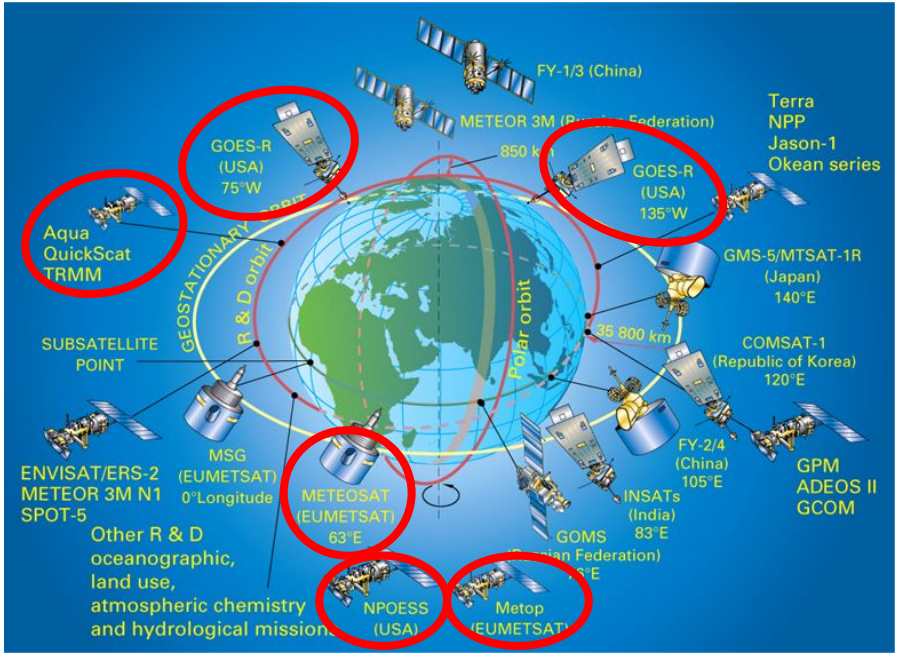
After thinning and QC – satellite radiances make up about 40% of all observations used in a single NDAS/NAM analysis.

Sample usage from a 00Z NAM analysis on Feb. 20th, 2015.

Type	Nobs	% of Total
Surface Pressure	54 296	5.2%
Temperature	172 676	16.6%
Wind (*includes sat winds*)	284 938	27.3%
Moisture	79 866	7.7%
NEXRAD Radial Wind	9 978	0.96%
Precipitable Water	362	0.03%
GPS	9 436	0.91%
Radiance	**430 491**	**41.3%**
Total Obs	1 042 043	100.0%

Satellite Data Used in the Operational NAM

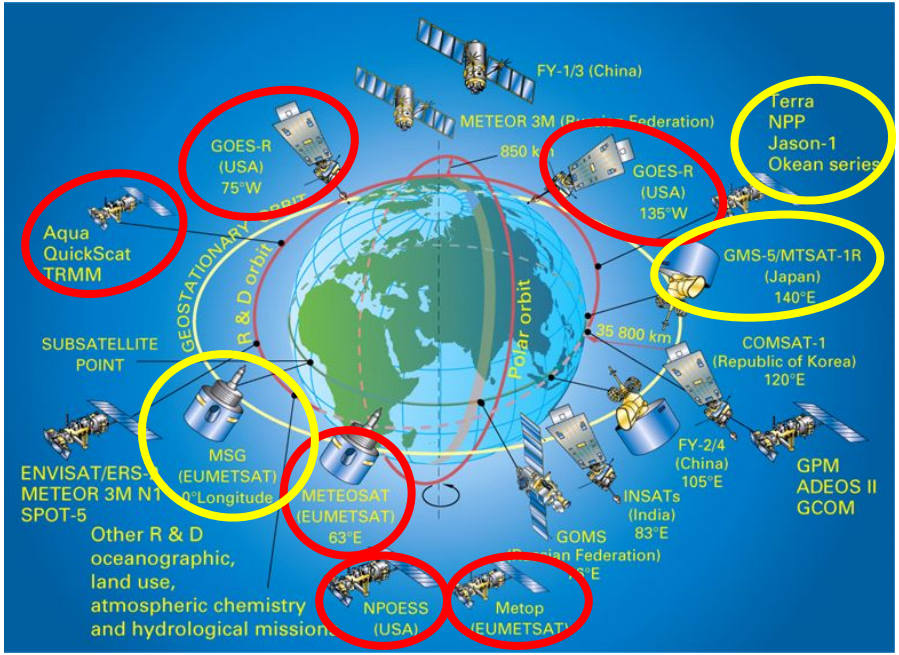
- Radiances
  - NOAA15: AMSUA
  - NOAA18: AMSUA, MHS
  - NOAA19: AMSUA, MHS
  - METOP-A: HIRS4, AMSUA, MHS, IASI
  - GOES15: SNDR1-4
  - AQUA: AIRS, AMSUA
- Satellite Winds
  - GOES-13, GOES-15
  - METEOSAT-7,METEOSAT-10
  - METOP-A, METOP-B
  - NOAA-18, NOAA-19



Satellite Data in the NAMv4 Upgrade

Upcoming NAMv4 bundle (Q1FY17) will have the following new data

- New Radiances:
  - METOP-B: HIRS4 (monitored) AMSUA, MHS, IASI
  - NOAA NPP: ATMS, CRIS
  - METEOSAT-10: SEVIRI
  - DMSP-F17: SSMIS
- New Satellite Winds:
  - Himawari-8
  - METEOSAT-7,-10: Imager WV AMVs
  - NOAA-15, 18, 19: AVHRR IR AMVs
  - METOP-A,-B: AVHRR IR AMVs
- New GPS
  - METOP-B (subtype 3)



Longer Term and Other Ongoing Efforts at EMC

Not Exhaustive!

Longer Term and Other Ongoing Efforts at EMC

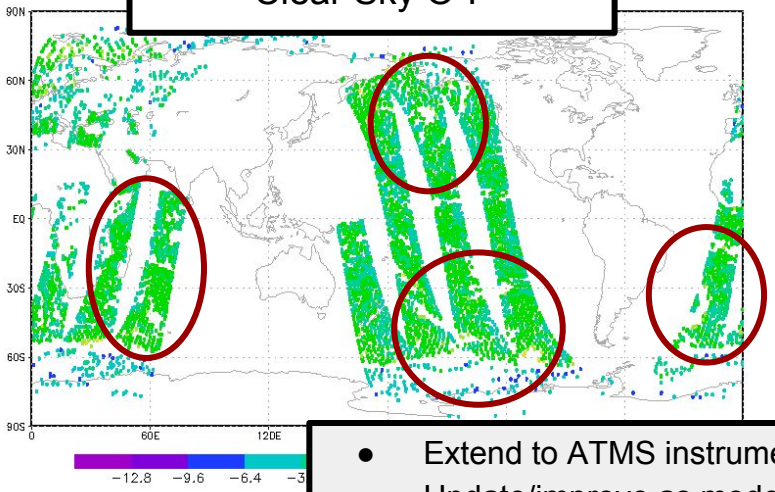
Assimilation of All Sky Radiances

(operational as of this week's GFS upgrade!)
Zhu et al. (2016, *MWR*, In review)

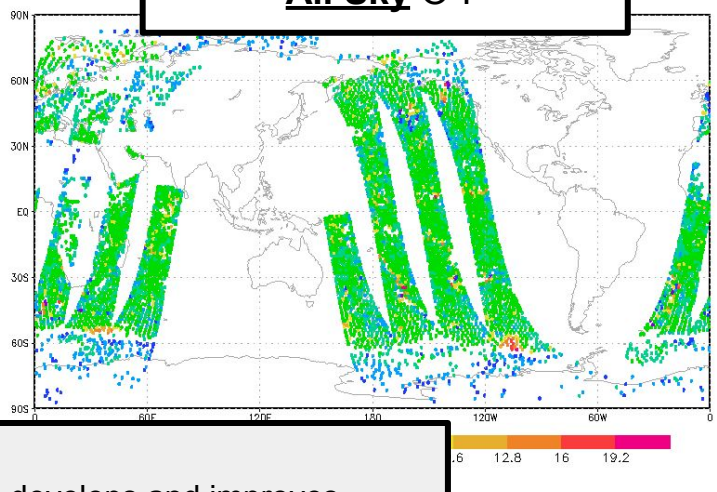
Precipitating clouds are still excluded in all sky

- Beginning with AMSU-A microwave radiances
  - 10% more observations used from channels 1-5 and 12% more from channel 15 in GFS

Clear Sky O-F



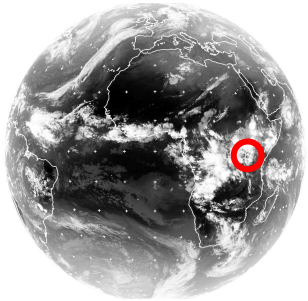
All Sky O-F

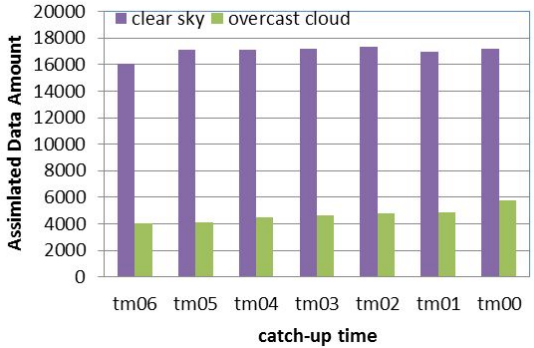


- Extend to ATMS instrument
- Update/improve as model physics develops and improves
  - e.g., updated microphysics

Longer Term and Other Ongoing Efforts at EMC

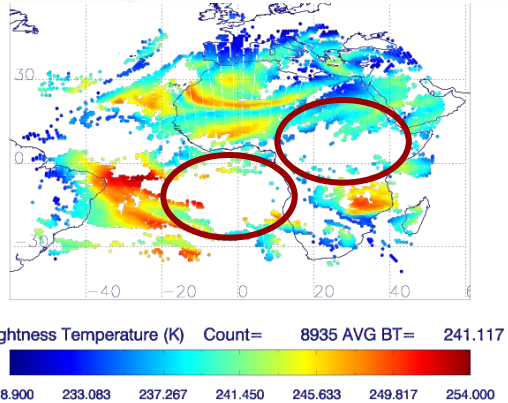
Assimilation of Seviri All Sky Radiances as GOES-R Proxy in NAMv4-Africa



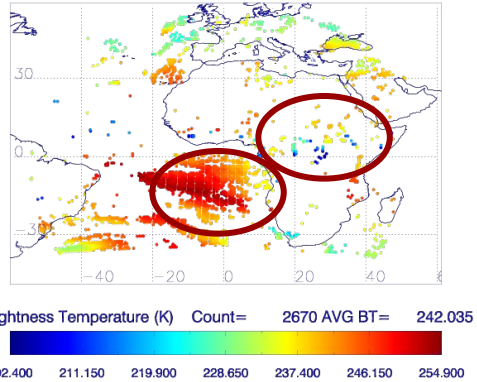


Water Vapor Band

Clear-sky Brightness Temperature



Overcast cloudy Brightness Temperature

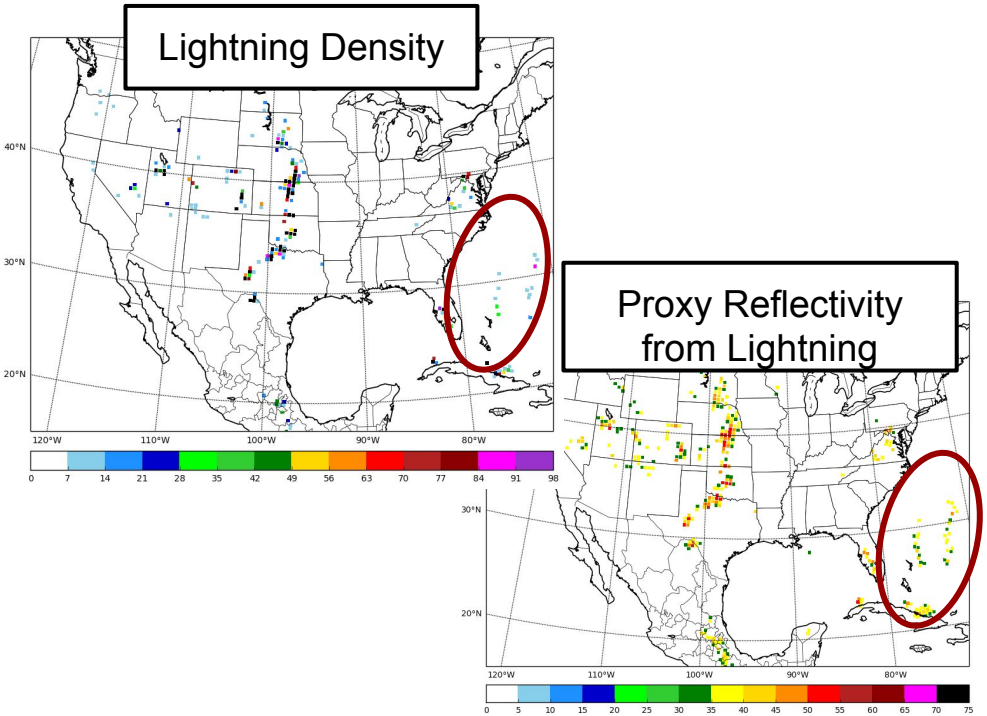


20% more water vapor channel data assimilated after overcast cloud-affected pixels are selected.

Longer Term and Other Ongoing Efforts at EMC

Assimilation of Lightning Observations

- Clear indication of convective storm(s)
  - Can provide data where radar coverage is poor or non-existent
  - Current obs from NLDN and ENI networks
- Current approach: Convert lightning observations to reflectivity
  - Use reflectivity in cloud analysis
  - Discussion ongoing with colleagues for other methods
- Initial implementation will be with NAMv4 Bundle
- Future: GOES-R GLM



Closing

- Satellite data plays a significant part in regional NWP
- Substantial testing/development required for each new instrument/platform
- Looking forward
  - Lightning DA
  - Cloudy/All Sky
  - Improved assimilation of radiances over land
  - Multiscale analysis using satellite, radar, etc.
    - Retain fine structure in high-res obs (e.g. radar/sat) while spreading information from sparse observations appropriately (e.g. upper air), Li et al (2015, *MWR*)

Thank you! Questions?