All-sky assimilation of temperature-sounding microwave data

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OUTLINE

- All-sky assimilation of temperature sounding microwave data at NCEP/EMC
  - Overview of the FV3GFS system
  - Status of all-sky radiance assimilation in the operational GFS
  - Ongoing and planned work
- All-sky assimilation of temperature sounding microwave data at ECMWF
- All-sky assimilation of temperature sounding microwave data at Met Office

FV3GFS hybrid 4DEnVar system became operational in June 2019 at NCEP

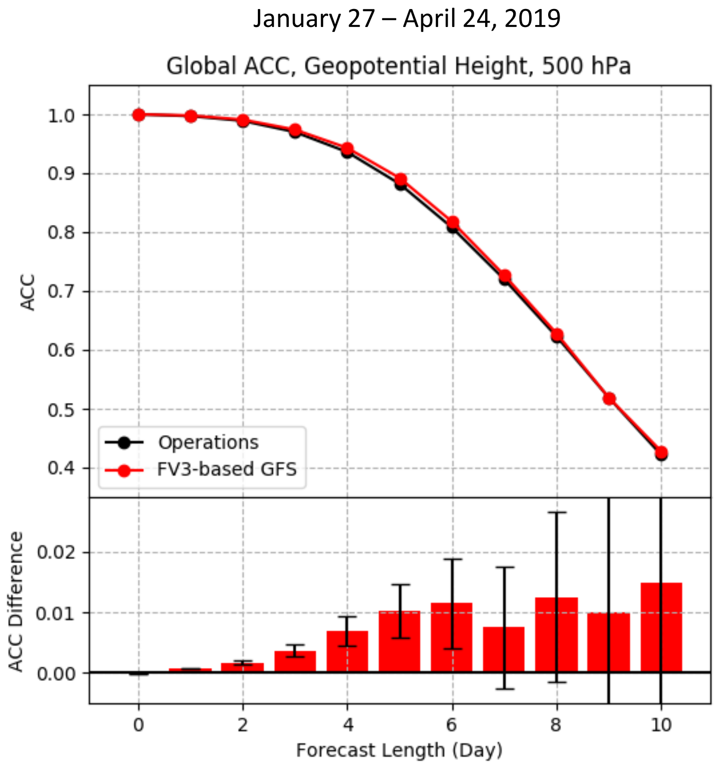
$$J(\mathbf{x}'_{\mathrm{c}},\mathbf{a}) = b_{\mathrm{c}}\frac{1}{2}(\mathbf{x}'_{\mathrm{c}})^{\mathrm{T}}\mathbf{B}_{\mathrm{c}}^{-1}(\mathbf{x}'_{\mathrm{c}}) + b_{\mathrm{e}}\frac{1}{2}\mathbf{a}^{\mathrm{T}}\mathbf{L}^{-1}\mathbf{a} + \frac{1}{2}\sum_{k=1}^{K}(\mathbf{H}_k\mathbf{x}'_{(\mathrm{t})k} - \mathbf{y}'_k)^{\mathrm{T}}\mathbf{R}_k^{-1}(\mathbf{H}_k\mathbf{x}'_{(\mathrm{t})k} - \mathbf{y}')$$

$$\mathbf{z} = \mathbf{B}^{-1}\mathbf{x}'_{\mathrm{c}} \qquad \mathbf{v} = \mathbf{L}^{-1}\mathbf{a}$$

Where the 4D increment is prescribed through linear combinations of the 4D ensemble perturbations plus static contribution.

$$\mathbf{x}'_k = \mathbf{C}_k\,[\mathbf{x}'_{\mathrm{c}} + \sum_{m=1}^{M}(\alpha^m \circ (\mathbf{x}_{\mathrm{e}})_k^m)]$$

- FV3 dynamic core, cubed-sphere grid, non-hydrostatic option
- Initial prototyping with (mostly) GFS physics (new: GFDL microphysics replaced Carr and Zhao scheme)
- Multiplicative inflation and stochastic physics (SPPT + SHUM only) for EnSRF perturbations
- C768 (~13km) L64 (55km top)
- Data assimilation: adaptation of original operational GSI hybrid 4DEnVar scheme with 80 ensemble members
- Ensemble and increment resolutions have been increased from ~39km to ~25 km


January 27 – April 24, 2019

Global ACC, Geopotential Height, 500 hPa

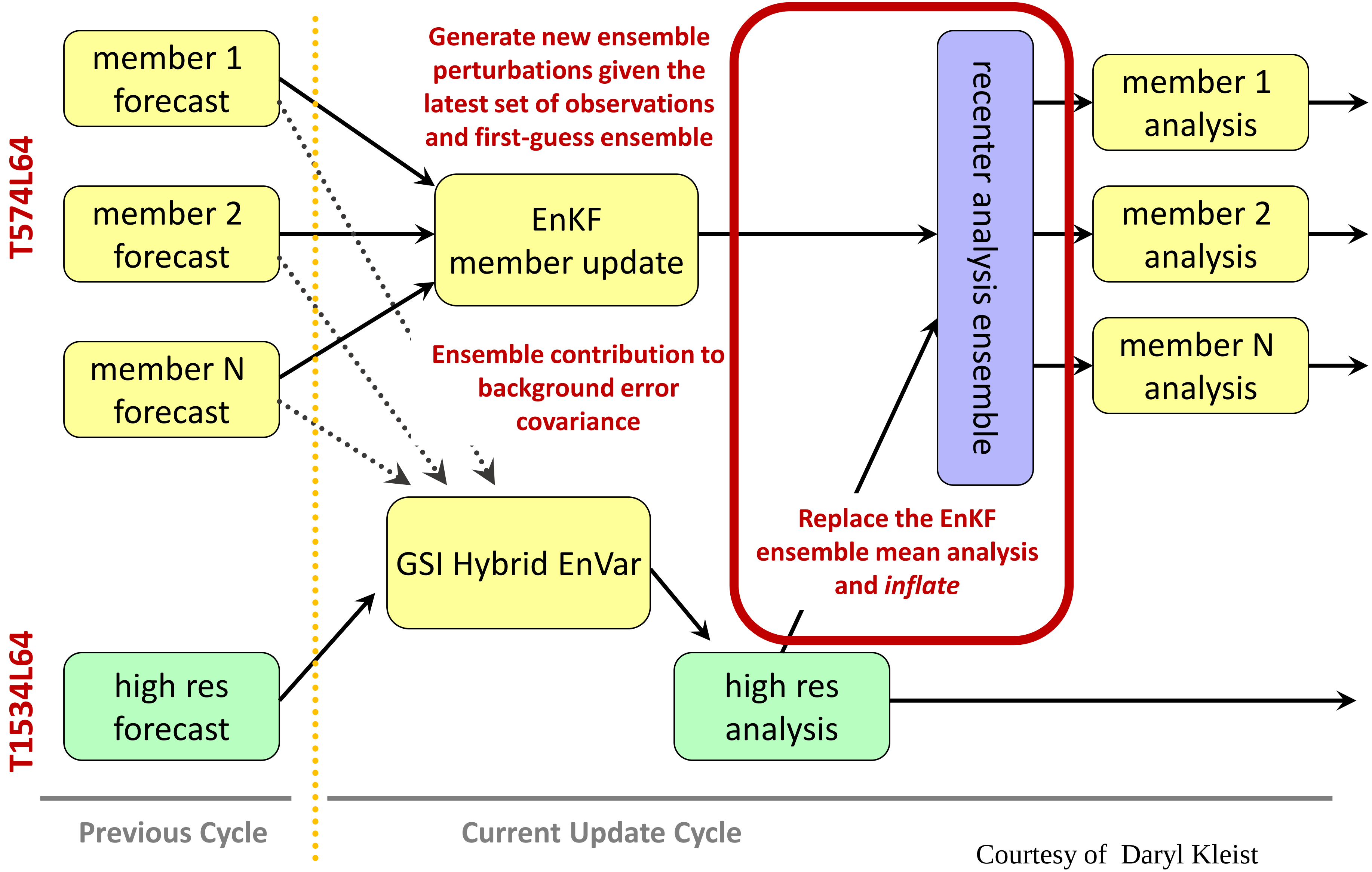
(Kleist and Thomas, 2019)

In En4DVar, ensemble perturbations are used to estimate $\mathbf{P}^{b}$ at the beginning of data assimilation window. The evolution of $\mathbf{P}^{b}$ in the window is through the tangent linear and adjoint of forecast model ($\mathbf{P}^{\mathbf{b}}(\mathrm{t}) = \mathbf{M}\mathbf{P}^{\boldsymbol{b}}\mathbf{M}^{\boldsymbol{T}}$).

In 4DEnVar,

- There is no need for tangent linear and adjoint of the forecast model.
- In addition to the static background error covariance, an ensemble of nonlinear model integrations over the data assimilation window provides the flow-dependent background error covariance implicitly.
- For analysis increment, the static part of solution $\boldsymbol{x}_c'$ and $\boldsymbol{\alpha}$ are time invariant in the data assimilation window, the time-evolving ensemble perturbations are the only 4D component. The 4D increment is not itself a model trajectory.
- Computationally efficient and better scalability, but with lots of costs in ensemble and much more IO.
- The ensemble is not updated in the FV3GFS at outer loop.

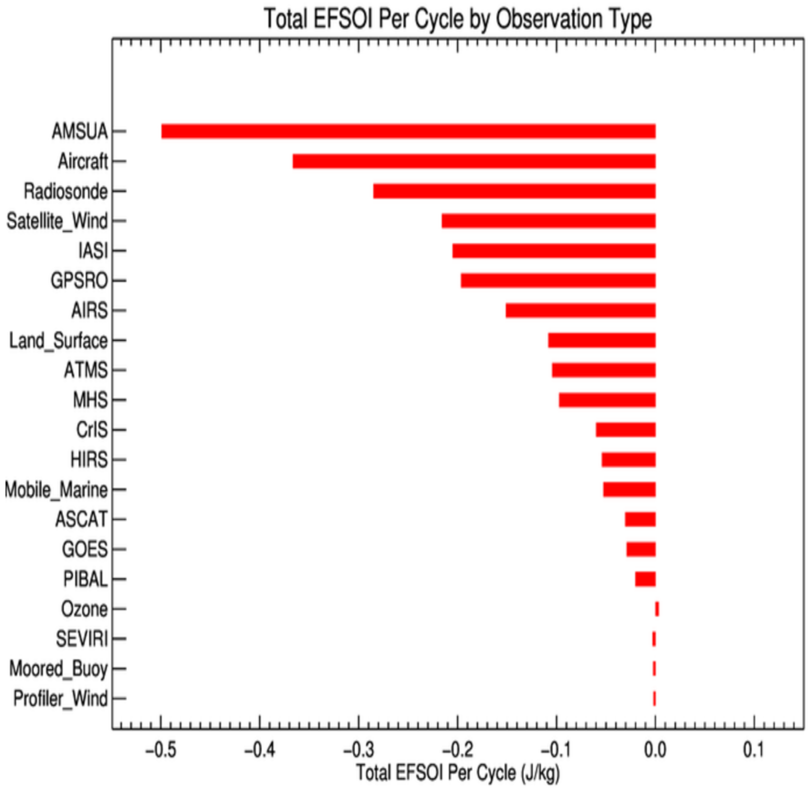
Dual-Res Coupled Hybrid Var/EnKF Cycling



Courtesy of Daryl Kleist

Status of radiance data assimilation in the FV3GFS

Ensemble Forecast Sensitivity to Observation Impact (EFSOI)



Total EFSOI impacts per cycle based on EnSRF products from a low resolution 4DEnVar configuration of the 2016 GSM GFS. (Courtesy of David Groff)

Microwave:

- AMSU-A: NOAA-15, 18, 19, MetOp-A, MetOp-B, Aqua
- ATMS: NPP, NOAA-20
- MHS: NOAA-18, 19, MetOp-A, MetOp-B
- SSMIS: DSMP-F17
- SAPHIRE: Megha-Tropique

Infrared:

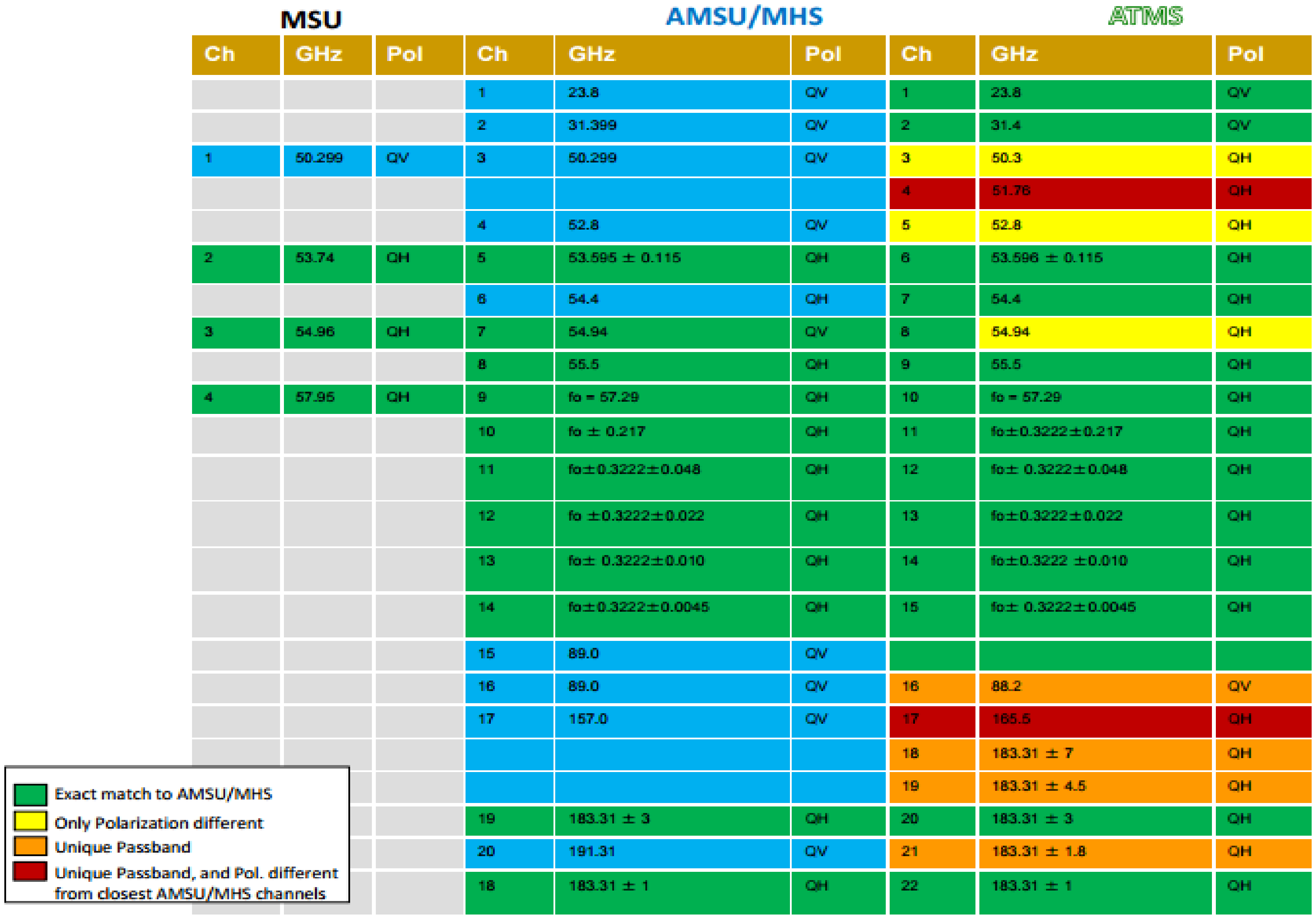
- AIRS: Aqua
- GOES-15 Sounder
- IASI: MetOp-A, MetOp-B
- CrIS: NPP, NOAA-20
- SEVIRI: MeteoSat-11
- AVHRR: MetOp-A, NOAA-18

❑ Microwave sounding data are an important data source. AMSU-A provides the largest impact as measured by EFSO and data denial experiments in the GFS data assimilation system among all radiance data.

❑ Over ocean, both clear-sky and cloudy radiances from AMSU-A and ATMS over ocean FOVs are assimilated in the all-sky approach (Zhu et al. 2016; Zhu et al. 2019), only clear-sky radiances are assimilated from other sensors

❑ Over land, only clear-sky radiances are assimilated for all the sensors

Cloudy Radiance Assimilation of AMUS-A and ATMS



MSU			AMSU/MHS			ATMS		
Ch	GHz	Pol	Ch	GHz	Pol	Ch	GHz	Pol
			1	23.8	QV	1	23.8	QV
			2	31.399	QV	2	31.4	QV
1	50.299	QV	3	50.299	QV	3	50.3	QH
						4	51.76	QH
			4	52.8	QV	5	52.8	QH
2	53.74	QH	5	53.595 ± 0.115	QH	6	53.596 ± 0.115	QH
			6	54.4	QH	7	54.4	QH
3	54.96	QH	7	54.94	QV	8	54.94	QH
			8	55.5	QH	9	55.5	QH
4	57.95	QH	9	fo = 57.29	QH	10	fo = 57.29	QH
			10	fo ± 0.217	QH	11	fo±0.3222±0.217	QH
			11	fo±0.3222±0.048	QH	12	fo± 0.3222±0.048	QH
			12	fo ±0.3222±0.022	QH	13	fo±0.3222±0.022	QH
			13	fo± 0.3222±0.010	QH	14	fo±0.3222 ±0.010	QH
			14	fo±0.3222±0.0045	QH	15	fo± 0.3222±0.0045	QH
			15	89.0	QV			
			16	89.0	QV	16	88.2	QV
			17	157.0	QV	17	165.5	QH
						18	183.31 ± 7	QH
						19	183.31 ± 4.5	QH
			19	183.31 ± 3	QH	20	183.31 ± 3	QH
			20	191.31	QV	21	183.31 ± 1.8	QH
			18	183.31 ± 1	QH	22	183.31 ± 1	QH

🟩 Exact match to AMSU/MHS
🟨 Only Polarization different
🟧 Unique Passband
🟥 Unique Passband, and Pol. different from closest AMSU/MHS channels

3

(Courtesy of Fuzhong Weng)

- Liquid water absorption is important in AMSU-A channels 1-5, and 15. Scattering becomes more important for channel 15.
- ATMS combines most of the channels from AMSU-A and MHS, providing measurements of atmospheric temperature and moisture profiles.

Configuration of all-sky radiance assimilation at NCEP (Zhu et al 2016, 2019)

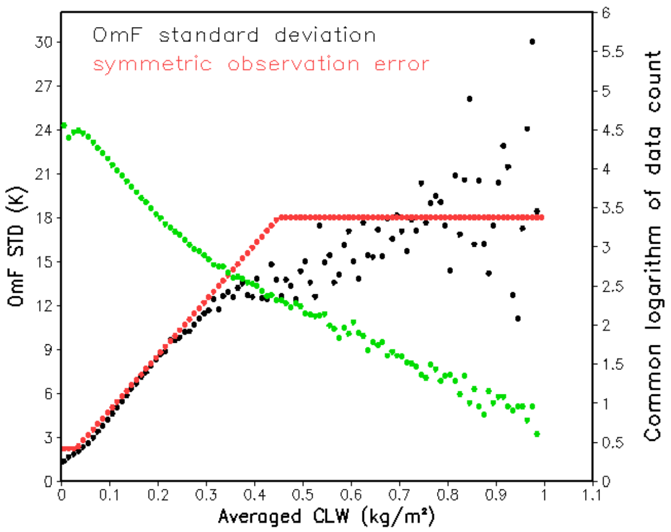
- AMSU-A channels 1-13 & 15, and ATMS channels 1-14 & 16-22 are assimilated in the all-sky approach in the operational GFS system. Radiances of clear-sky and those affected by non-precipitating clouds are used.
- In the previous clear-sky approach operational GFS, the clear-sky & radiances affected by thin clouds (with cloud effect removed) are used; In the all-sky approach operational GFS, quality control was modified to allow radiances affected by thick clouds to be assimilated, and cloud effect is considered.
- Observation error includes symmetric observation error as a function of CLW and situation-dependent observation error inflation
- Cloud control variable *cw*, the sum of cloud liquid water (*ql*) and cloud ice (*qi*).
  - Radiance data information is mapped onto not only T and q but also hydrometeor fields through Jacobians w.r.t hydrometeors
  - *cw* increment is partitioned to hydrometeor increments using a simple linear relation with T.

  Setting $x = 0.05 * (273.15 - T)$, we have $qi = f * cw$ and $ql = (1 - f) * cw$,

  $$\text{where } f = \begin{cases} 0 & (x < 0) \\ x & (0 \leq x \leq 1) \\ 1 & (x > 1) \end{cases}$$

- Background error covariance is composed of a static term and contribution from an ensemble. The background error cross covariances of cloud with other variables are provided by the ensemble part.
- Variational bias correction is applied to all-sky radiances with selected data sample.

Observation Error Assignment under All-sky Condition

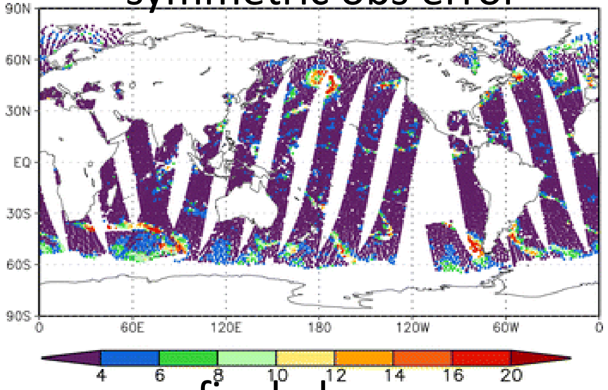


Symmetric Observation error

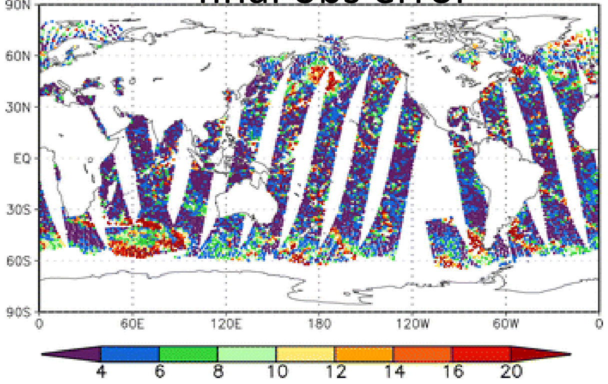
- Observation error is assigned as a function of the symmetric cloud amount (Geer et al. 2011)
- CLW retrieval formula (Grody and Wen 2006) is used for AMSU-A and ATMS

$$clw = \cos\vartheta \,\{ c_0 + c_1 \ln(285 - Tb_1) + c_2 \ln(285 - Tb_2)\}$$

- The symmetric observation error is specified as a function of $\overline{clw}$ in fitting to the OmF standard deviation



symmetric obs error

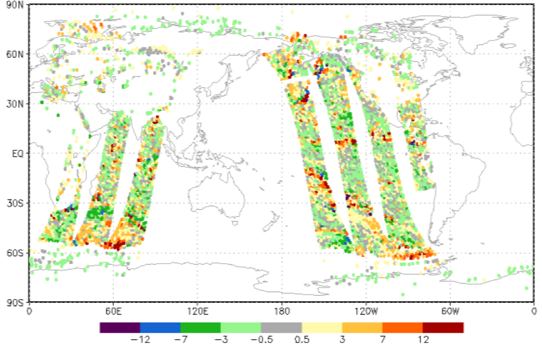


final obs error

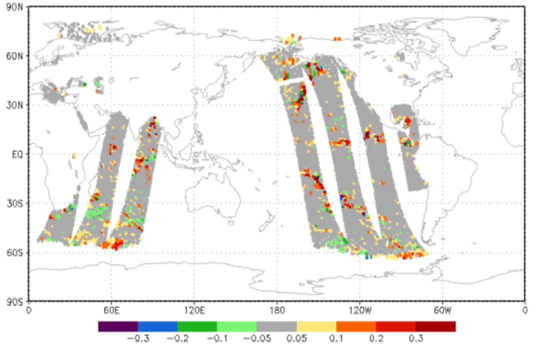
Situation-dependent Observation Error Inflation

Constructed empirically using the physically-based factors on which it is assumed the observation error (primarily through the Community Radiative Transfer Model (CRTM)) is dependent

- Cloud mismatch information between the observation and the first guess;
- Cloud water difference between the observation and the first guess;
- Large scattering index (Weng et al. 2003) value; Surface wind speed.



OmF AMSUA METOPA Ch 2



Cloud water difference between FG and observation

Radiance Variational Bias Correction at NCEP

(Derber & Wu 1998; Zhu et al 2013, 2014)

$$\text{h} = h(x) + \sum_{i=1}^{N} \beta_i p_i(x)$$

where

$h(x)$ is radiative transfer model

β_i predictor coeff., augmented control variable,

p_i predictor, including

- Global offset
- Cloud liquid water (CLW)
- Integrated lapse rate
- Square of Integrated lapse rate
- Surface emissivity sensitivity to handle large land/sea difference
- Latitude dependent bias for SSMIS
- Fourth-order polynomial of scan angle

In the original clear-sky radiance assimilation for AMSU-A and ATMS

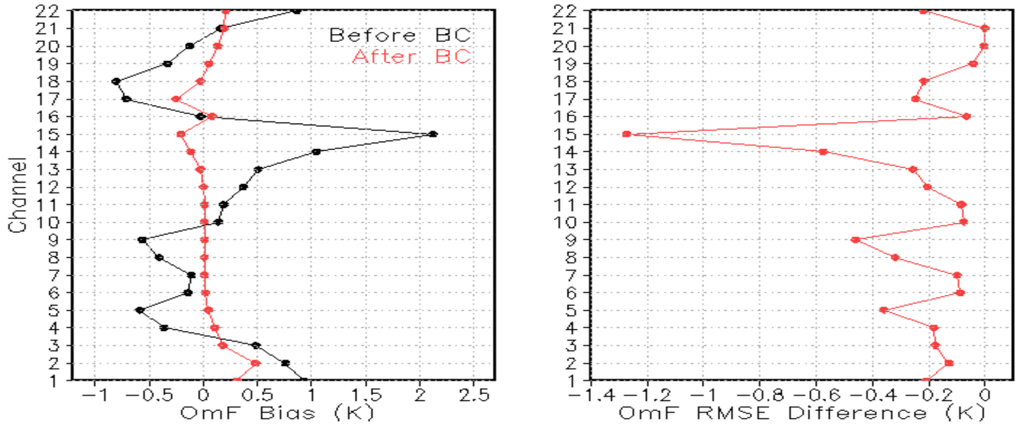
- Both clear-sky radiances and radiances affected by thin-clouds were assimilated, but the cloud effect was removed by the CLW bias correction term.
- Because of the angle-dependent feature of the CLW empirical formula, strong interaction between CLW and scan-angle bias correction terms was observed after a long data assimilation run

In the all-sky approach, the original CLW bias term was turned off; no other cloud related bias term is added so far

Radiance Variational Bias Correction at NCEP -- continued

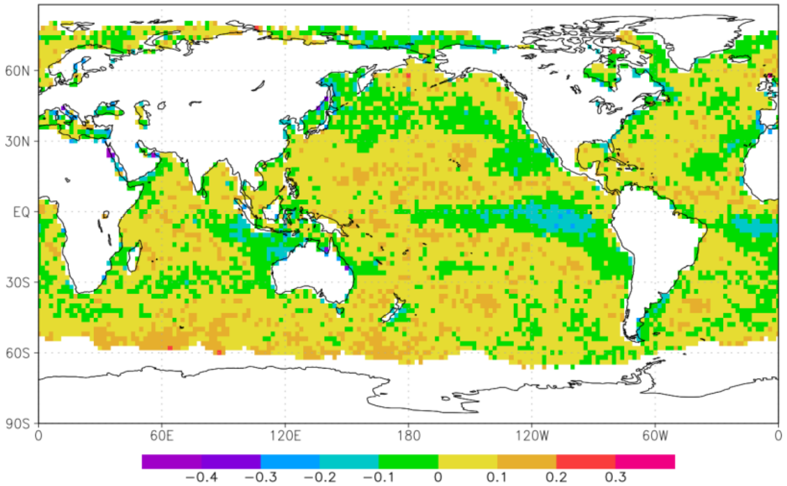
- Radiance bias correction is important. It can be larger than signal. Interaction between bias correction and quality control.
- Anchoring observations (such as radiosonde and GPS data) help to alleviate impact of forecast model bias on radiance data bias correction
- To minimize the impact of large state-dependent forecast model bias on all-sky bias correction, and to use all-sky radiances with large OmFs but not shocking the system,
  - Apply situation-dependent observation error inflation
  - Carefully select radiance data sample that are used in estimating radiance bias correction. Bias correction coefficients are obtained using only a selected data sample with consistent cloud liquid water between the first guess and the observation.

$$\tilde{h}(\mathbf{x},\Delta\beta) = \begin{cases} h(\mathbf{x}) + \sum_{k=1}^{N}\beta_{b,k}p_k(\mathbf{x}) & \text{(if with mismatched cloud, over ocean),} \\ h(\mathbf{x}) + \sum_{k=1}^{N}\beta_{b,k}p_k(\mathbf{x}) + \sum_{k=1}^{N}\Delta\beta_k p_k(\mathbf{x}) & \text{(otherwise),} \end{cases}$$



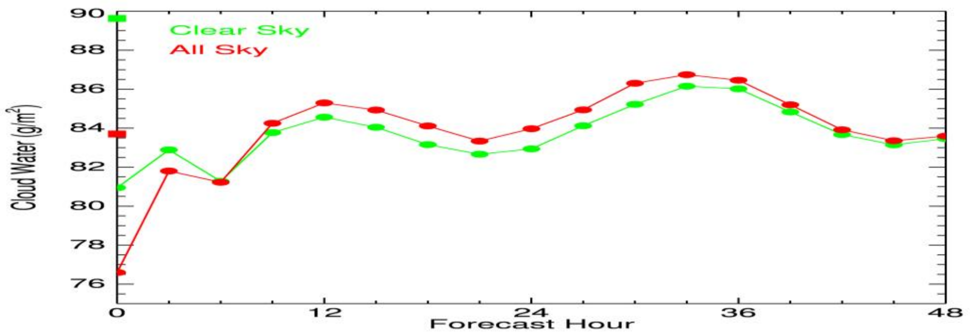
(left) The ATMS radiance OmF bias before (black line) and after (red line) bias correction and (right) the reduction of the OmF RMSE

ATMS NPP CH2 OmF/obserr over ocean Sept 2019

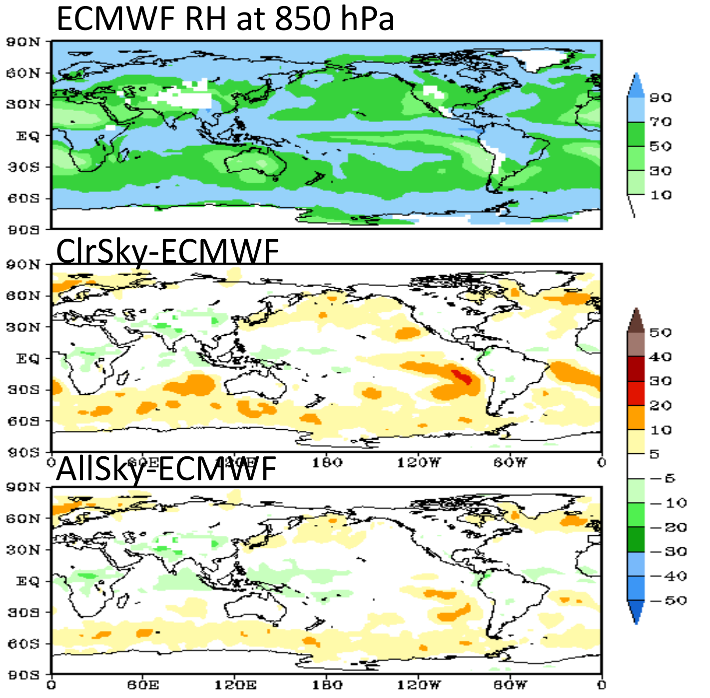


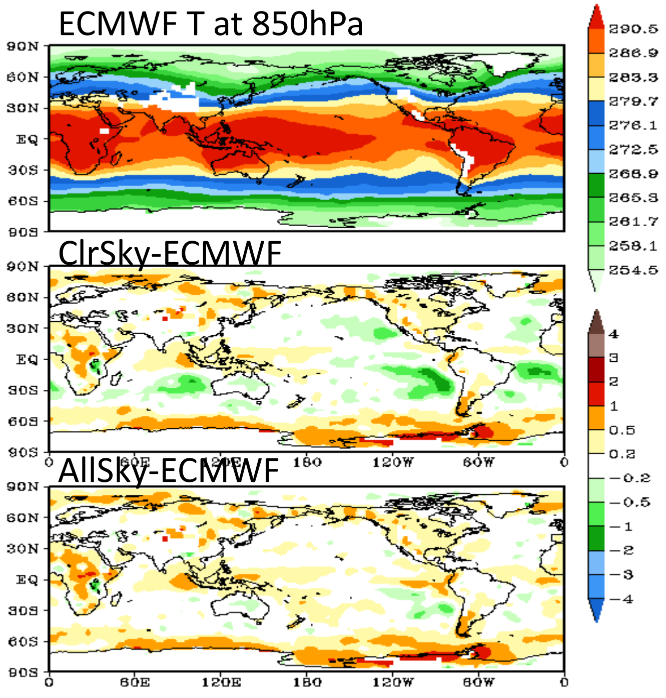
Impact of all-sky microwave radiance assimilation in the GFS (May 2016 implementation)

- About 10-12% increase in the use of AMSU-A channels 1-5 and 15, more realistic simulated brightness temperature
- Improved GFS temperature & relative humidity analyses & forecasts
- Reduced a known stratus bias off the west coasts
- The all-sky assimilation removed the excessive cloud analysis increments observed in the clear-sky operational system, but still experienced cloud loss at the 1st forecast step

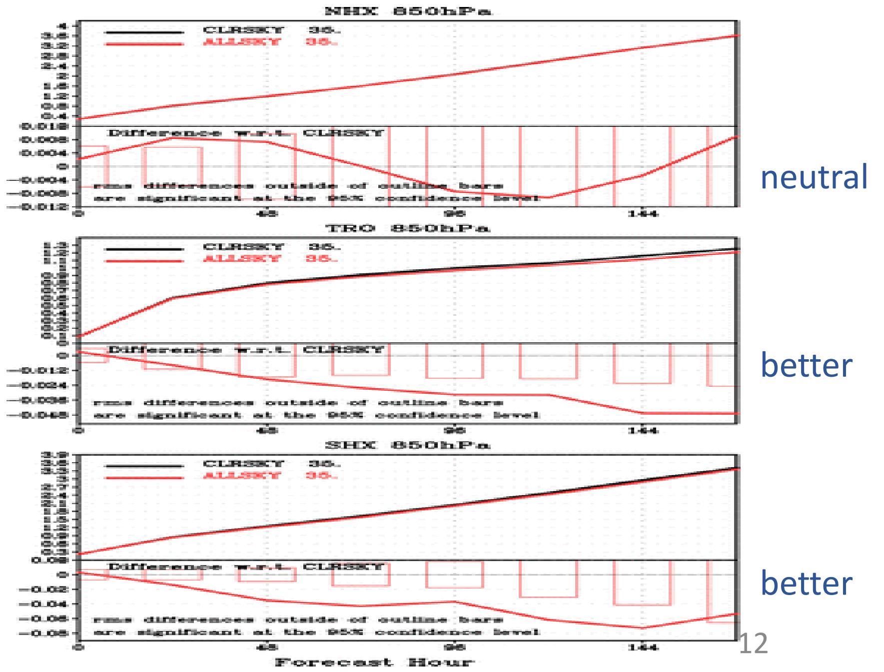


Evolutions of averaged global mean atmospheric column cloud water (g m^{-2}) during forecast issued from ClrSky (green line) and AllSky (red line) 0000 UTC analyses for the period from 27 Oct to 1 Dec 2013. The green and red closed squares at zero forecast hour represent the averaged global mean atmospheric column cloud water of the clear-sky and all-sky analyses, respectively.

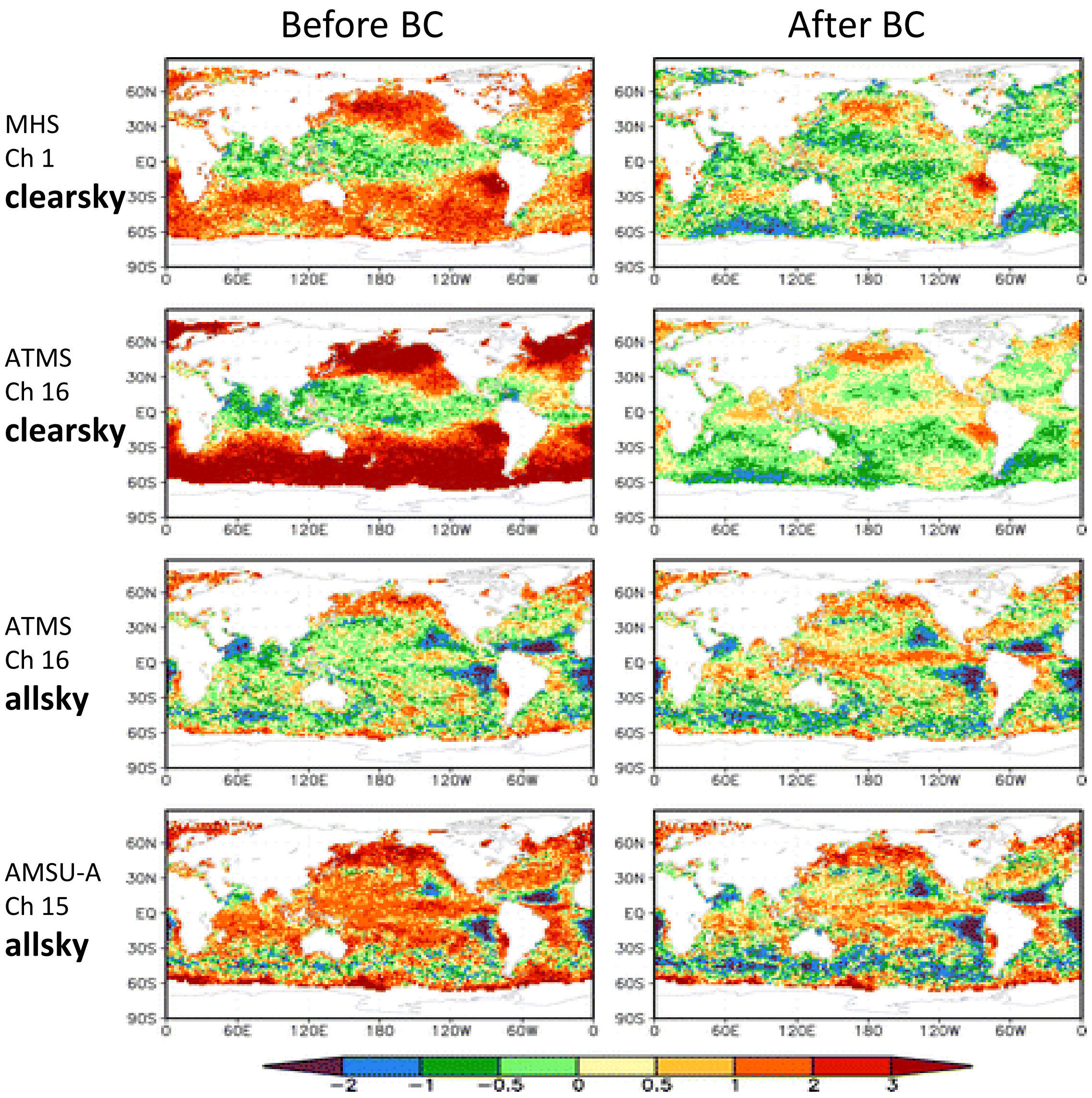




Temperature forecast RMSE & RMSE difference against own analysis



Improved Data Consistency among Different Instruments



One-month averaged OmF over water of June 2015

- Conflicting observational information will degrade the analysis quality and system performance
- Prior to 2019 GFS upgrade, radiance data from microwave sensors (AMSU-A, ATMS and MHS) were assimilated differently.
- ATMS & MHS were assimilated in clear-sky approach:
  - MHS: only clear-sky radiance data are assimilated in the GFS;
  - ATMS: Both clear-sky radiances and those affected by thin clouds were assimilated with cloud effect being removed by the CLW bias predictor term.
- Expansion of the all-sky approach to ATMS radiances
  - Introduced WV channels into the all-sky framework;
  - Made ATMS radiance OmFs more consistent with AMSU-A;
  - Improved specific humidity field;
  - Provided indications of the deficiencies in quality control procedures of the original ATMS and MHS clear-sky radiance assimilation.

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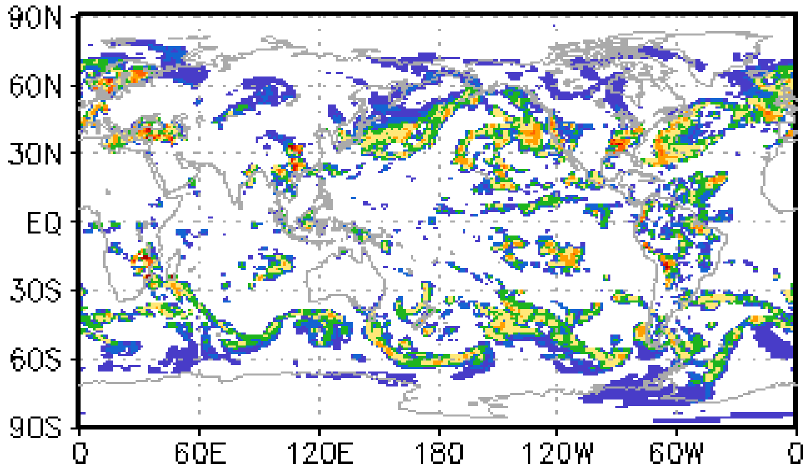
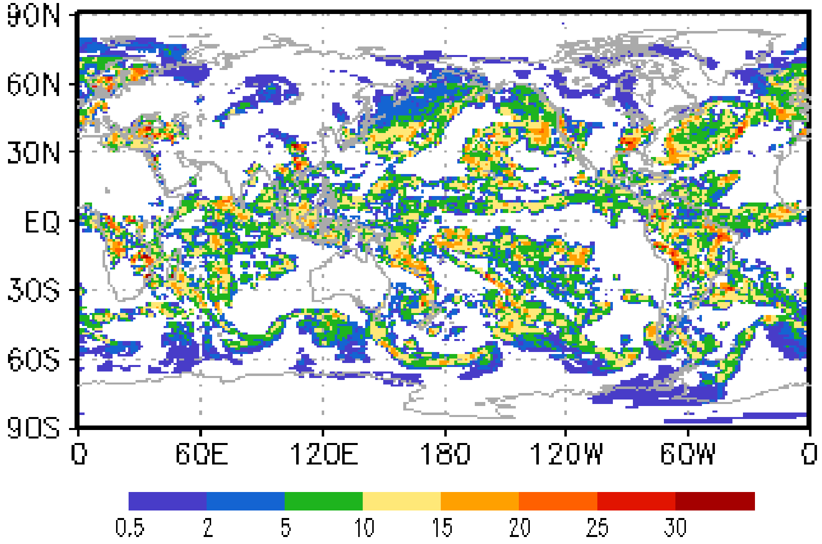
Background Error Covariance

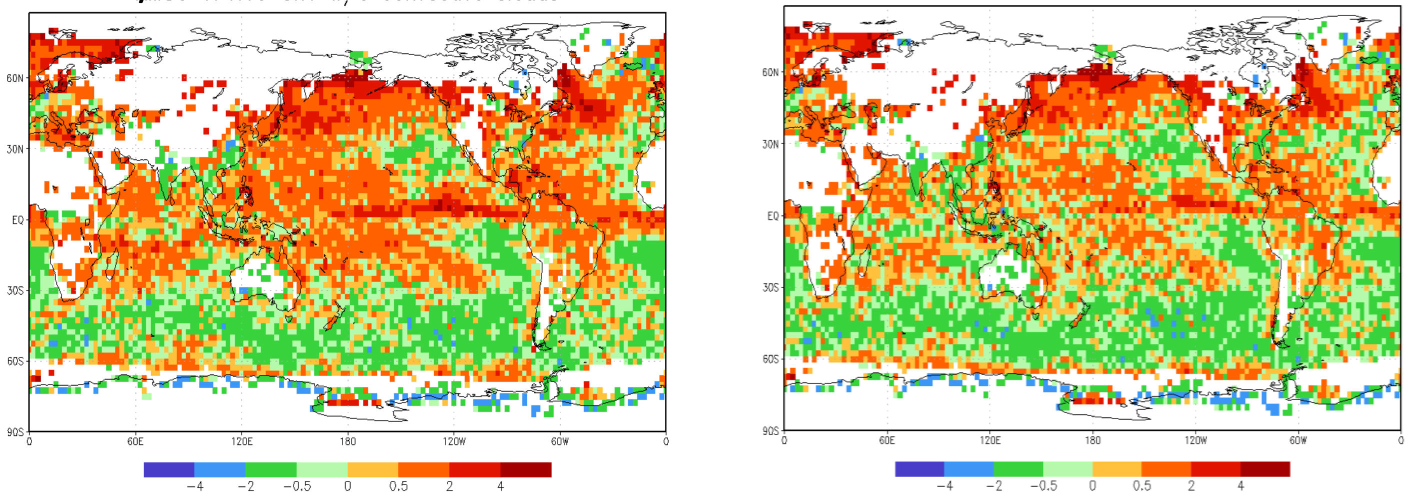
- Adding convective clouds improves ensemble spread and OmF
- Different characteristics were observed for grid-scale and convective clouds
  - In the tropics, the contribution from convective clouds is dominant (z14-25)
  - The contribution from convective clouds corresponds clearly with the ITCS and SPCZ
- Covariance between cloud water and other variables is not specified in the static term
- Ensemble provides flow-dependent covariance information

Ensemble spread: grid-scale (~800 hPa)



Combined ensemble spread (~800 hPa)





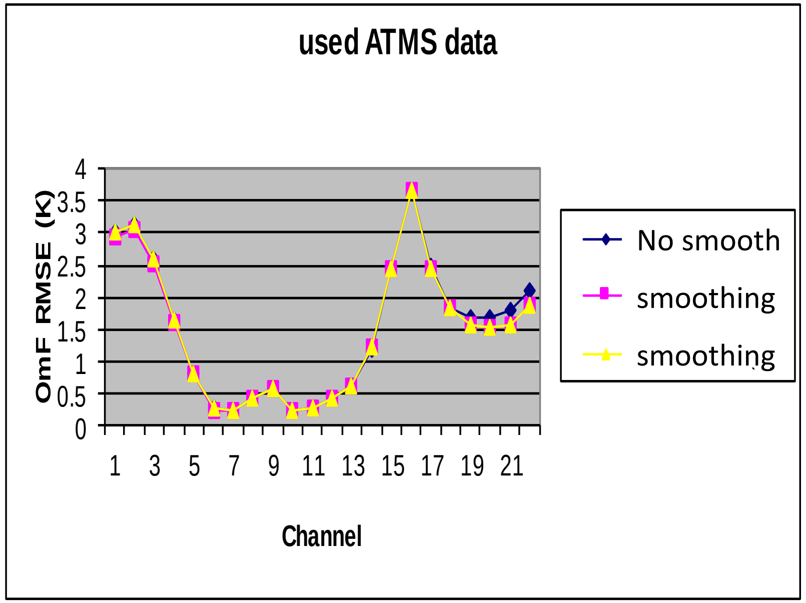
w/o convective clouds

with convective clouds

AMSU-A N19 Ch 1

Evaluation of ATMS BUFR with co-located VIIRS cloud products

- ATMS varied beam widths: 5.2^o ch 1-2, 2.2^o ch 3-16, 1.1^o ch 17-22
- In FV3GFS, AAPP spatial mapping/averaging is applied to all channels to 3.3^o ; Surface properties based on the FOV size & shape. Due to model's predictability of cloud, smoothing observations reduces OmF RMSE of water vapour channels.
- A NCEP/NESDIS STAR joint effort: to evaluate the usefulness of co-located VIIRS cloud products in the all-sky microwave ATMS radiance assimilation (Y. Zhu, Q. Zhao, H. Sun, S. Nadiga, L. Soulliard, T. King, J. Jung, S. Melchior, H. Andrew, W. Wolf)
- Preliminary results from a sample data file showed positive impact of the application of VIIRS cloud top height standard deviation, super cooled cloud water and mixed phase cloud amounts in the FOV -- further reducing OmF RMSE of the cloud-sensitive channels.
- The preparation for one-month real-time test data files is underway for further evaluation.



Add additional quality control using VIIRS cloud products

	Original GSI OmF		Optically thin cloud ice hoc_stdv>12000m		Super cooled cloud water & mixed phase cldmnt>50%	
ch	count	RMSE	count	RMSE	count	RMSE
1	979.0	3.0955	721.0	2.8800	651.0	2.8515
2	955.0	3.1897	715.0	3.1807	645.0	3.0209
3	972.0	2.8461	717.0	2.7262	647.0	2.6907
4	995.0	2.1986	727.0	2.0291	657.0	2.0484
16	874.0	4.2861	640.0	4.2685	582.0	4.1727
17	933.0	2.6082	684.0	2.5708	623.0	2.3520
18	938.0	1.9201	688.0	1.6351	624.0	1.6266
19	970.0	1.8441	714.0	1.5886	646.0	1.5946
20	970.0	1.9576	714.0	1.7091	646.0	1.7306
21	968.0	2.0682	714.0	1.8271	646.0	1.8661
22	963.0	2.2220	714.0	1.9845	646.0	2.0305

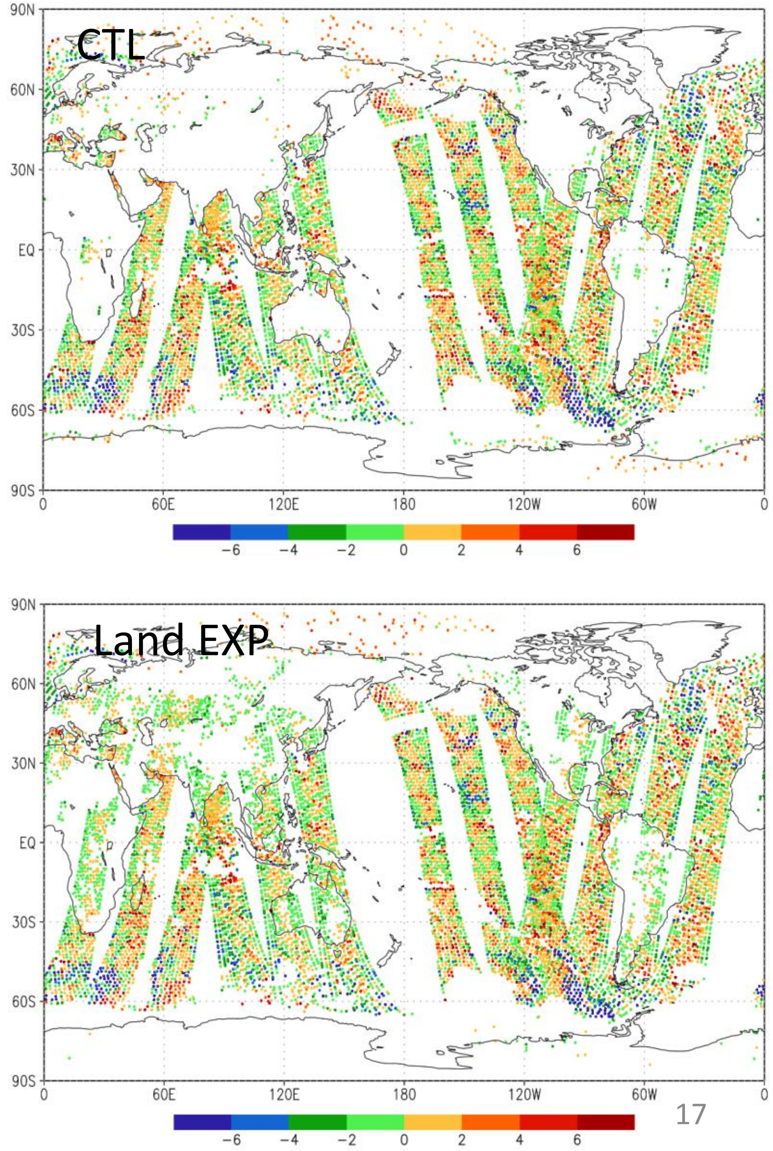
Radiance assimilation over Land

- Far fewer radiances are used over land than over ocean in the operational GFS system
- Uncertainties of NESDIS microwave land physical emissivity model in the CRTM; Uncertainties of land surface state properties, e.g. land surface skin temperature (LST) and soil moisture
- Surface emissivity is retrieved in the GFS system based on

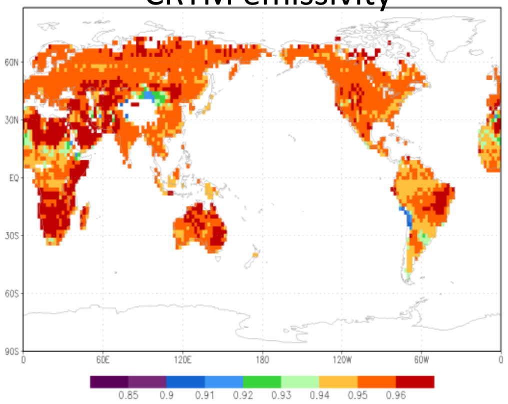
  $$BT_{obs} = \varepsilon T_s \Gamma + BT_{up} + \Gamma (1 - \varepsilon) BT_{down}$$

  and is used in the assimilation of sounding channels
- Emissivity sensitivity calculated in the CRTM is problematic when user-supplied emissivity is used. Radiance bias correction and quality control workaround.
- Impact experiment & testing with CSEM are under way (Y. Zhu, M. Chen)

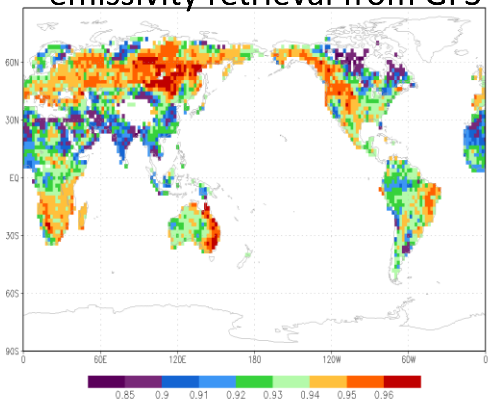
ATMS NPP + AMSU-A N18 ch3
06Z April 23, 2019



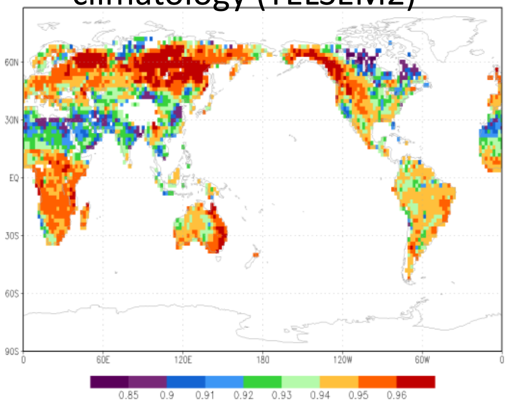
CRTM emissivity



emissivity retrieval from GFS



climatology (TELSEM2)



All-sky radiance assimilation over ocean

- Prior to FV3, the GFS forecast model used Zhao and Carr (1997) microphysics with cw prognostic variable. Cloud analysis was fed back to the model.
- The FV3GFS system uses GFDL microphysics with hydrometeor prognostic variables. Cloud analysis increment is not fed back to the model for now.
- Test hydrometeors as control variables in the GSI (Kim et al. 2019; Liu et al. 2019; Tong et al. 2019), no partitioning is needed
- Test IAU and/or other cloud control variable(s) to improve balance among T, q, and hydrometeors and cloud loss issue (when cloud increments are fed back to model)
- Test correlated observation error on MW data (Bathmann et al. 2019)
- Previous testing using variational quality control, which considers non-Gaussian distribution, didn’t seem beneficial. More tests are necessary
- Expand the all-sky approach to other sensors, i.e., GMI, AMSR2, MHS, in the GFS

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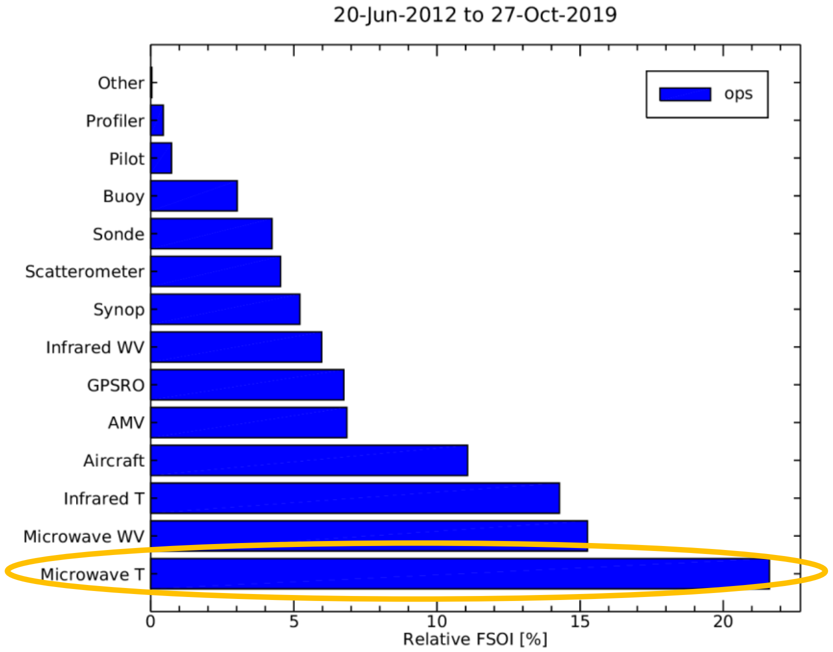
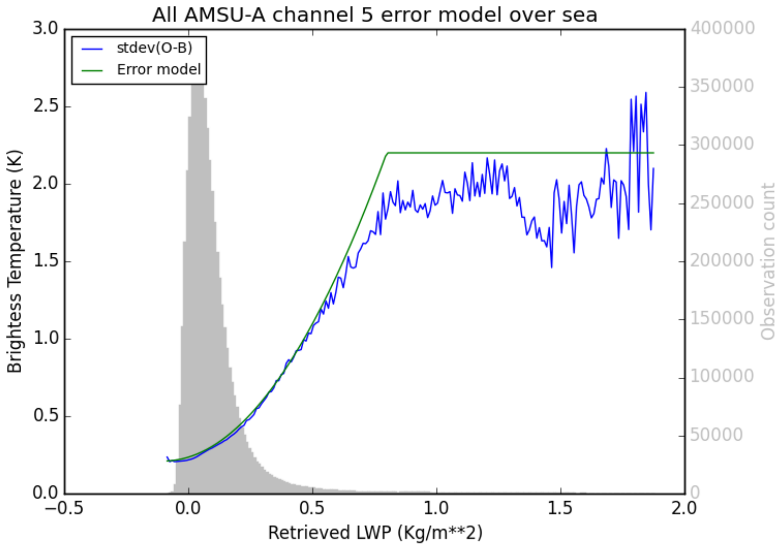
AMSU-A all-sky at ECMWF – Pete Weston

- We get strong positive impact from clear-sky assimilation of MW temperature sounders, hard to beat with all-sky assimilation
- Most of the work to optimise AMSU-A all-sky has involved adopting aspects of the clear-sky configuration resulting in surprisingly large changes to forecast accuracy, e.g.:
    - Thinning
    - Non-cloud related quality control
    - Interpolation
    - Dynamic emissivity retrieval
- The traditional all-sky ingredients are also important:
    - RTTOV-SCATT
    - Variable observation error model based on retrieved cloud liquid water path over sea and scattering index over land
- The long-term aim is to assimilate all microwave instruments through the all-sky system at ECMWF

FSOI by observation category



AMSU-A observation error model

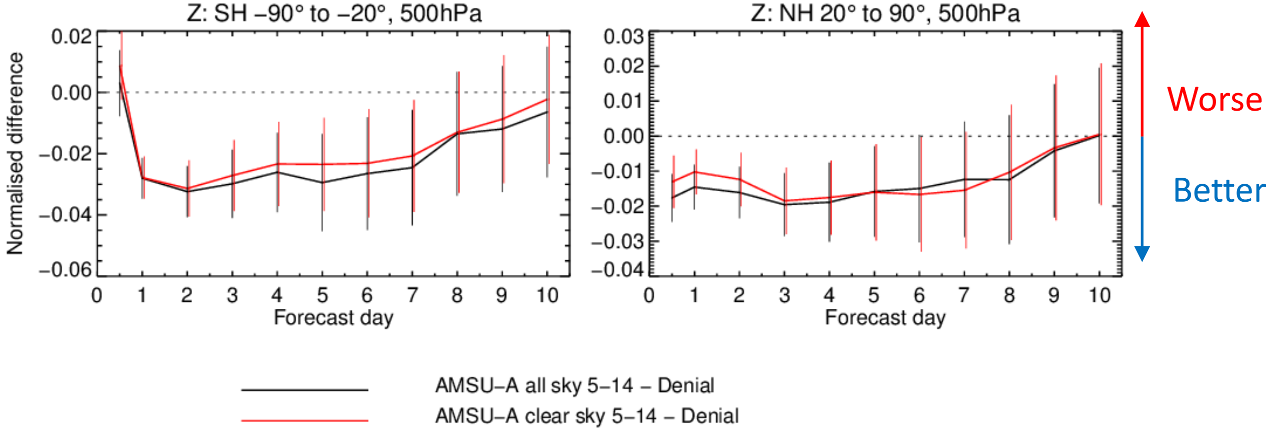


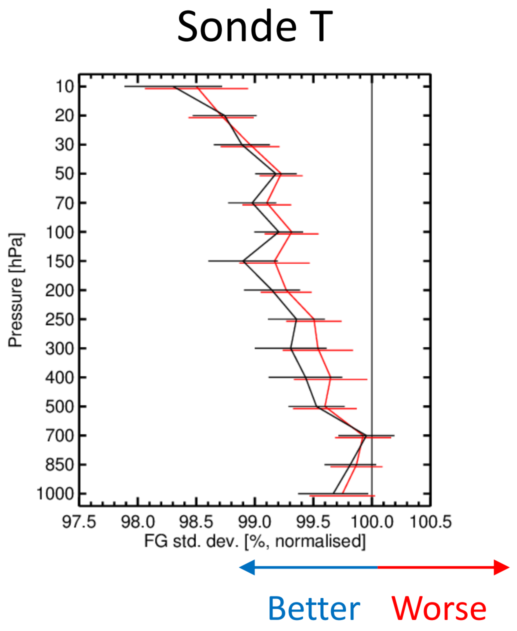
Results – extra-tropics

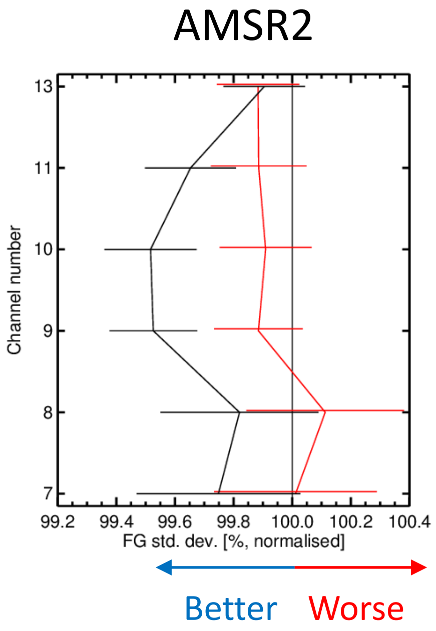
- In the extra-tropics all-sky and clear-sky AMSU-A now **perform similarly** against an AMSU-A denial
- This can be seen in:
    - Forecast scores, e.g. Z500
    - First guess fits to independent observations

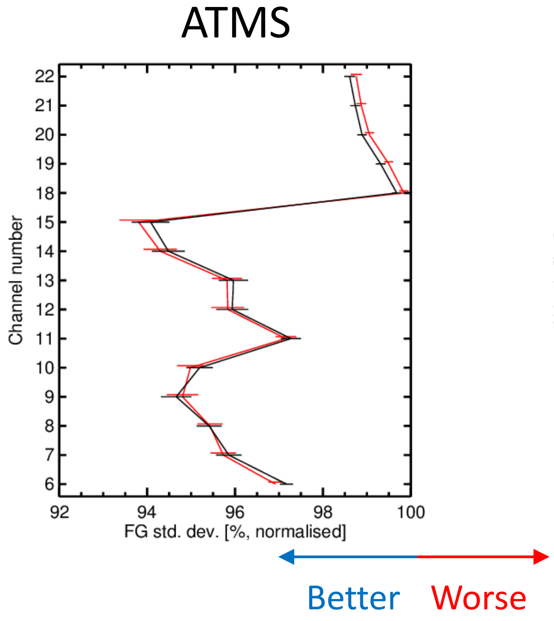
1–Jun–2017 to 28–Feb–2018 from 324 to 362 samples. Verified against own–analysis.

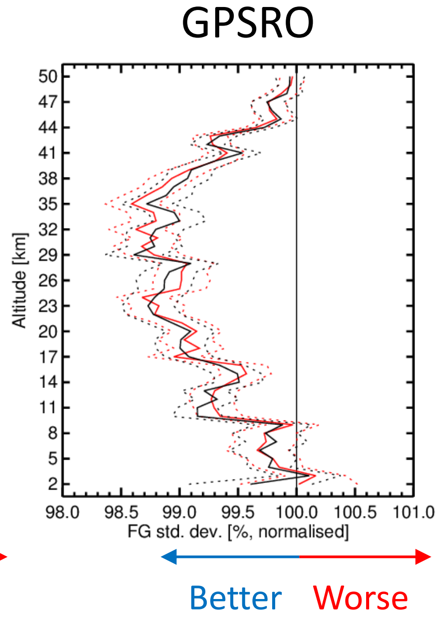
Confidence range 95% with AR(2) inflation and Sidak correction for 8 independent tests.





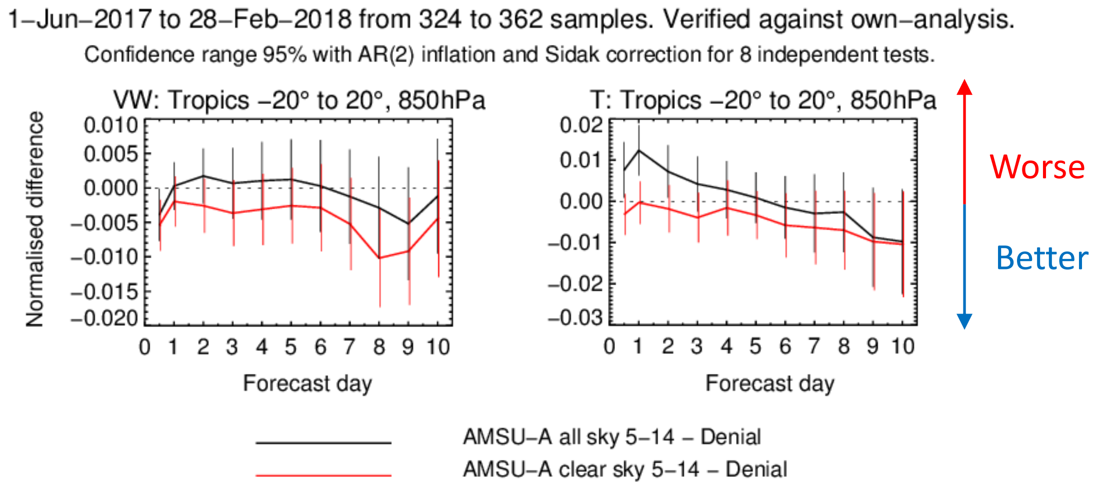






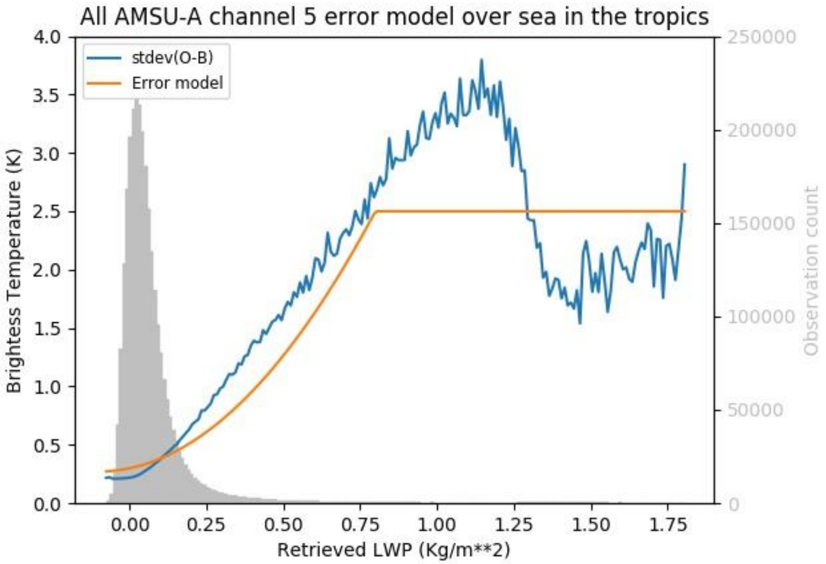
Issues and future improvements

- However, all-sky performance in the tropics results in **degradations** compared to clear-sky
  - Forecast scores, e.g. T850, VW850

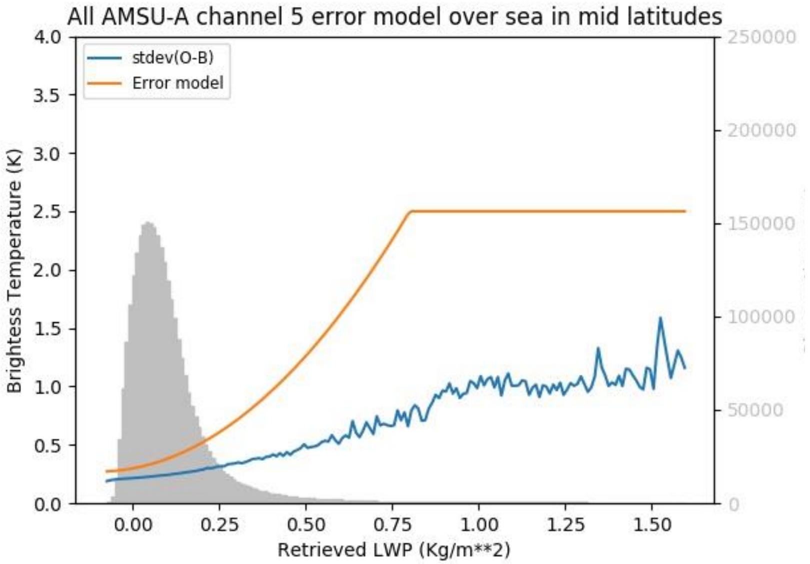


- Future work to improve results which will hopefully lead to operational switch of AMSU-A from clear-sky to all-sky :
  - Eradicate remaining thinning differences
  - Observation errors varying between convection and frontal cloud

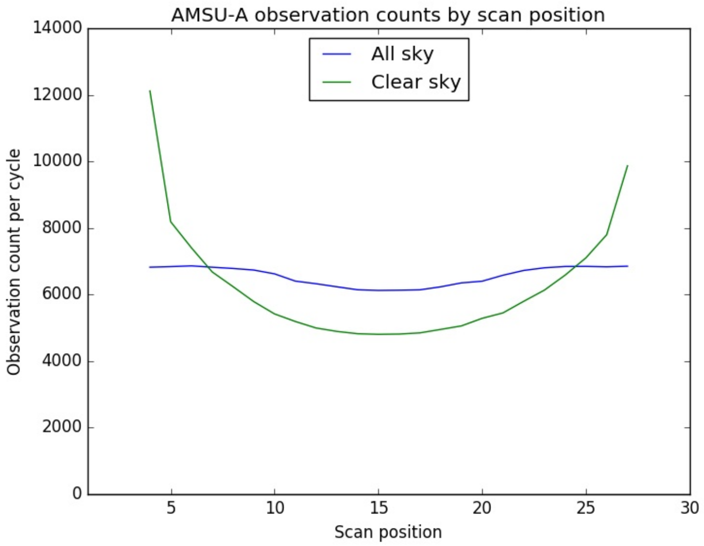
Tropics



Mid latitudes



Obs distribution across scan



OUTLINE

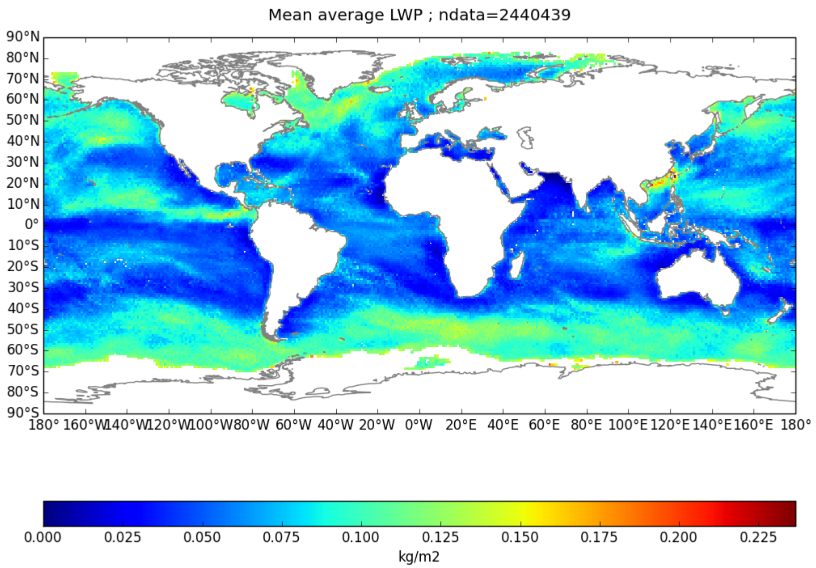
- All-sky assimilation of temperature sounding microwave data at NCEP/EMC
  - Overview of the FV3GFS system
  - Status of all-sky radiance assimilation in the operational GFS
  - Ongoing and planned work
- All-sky assimilation of temperature sounding microwave data at ECMWF
- All-sky assimilation of temperature sounding microwave data at Met Office

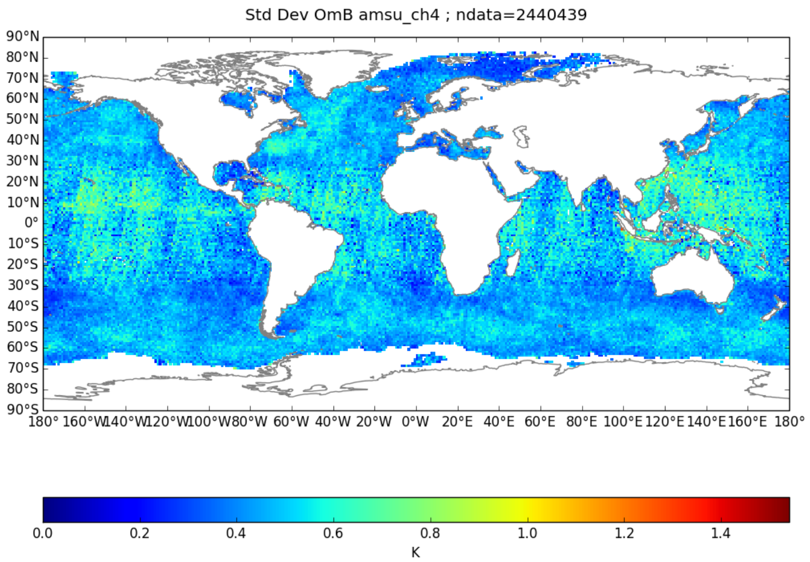
Overview of All sky method

- Coupling of cloud liquid water to 4DVar – including partitioning of increments – 4DVar works in total moisture
- Improved radiative transfer (switch to model levels from 43 fixed set)
- Variable observation error – account for complexities in modelling cloud
- Assess impact via a three month trial
- Changes applied to five satellites containing AMSUA (NOAA15,18,19,Met-A,B)
- Initially retain rain check for AMSUA (ignoring scattering effects)

Uncertainties in the presence of cloud

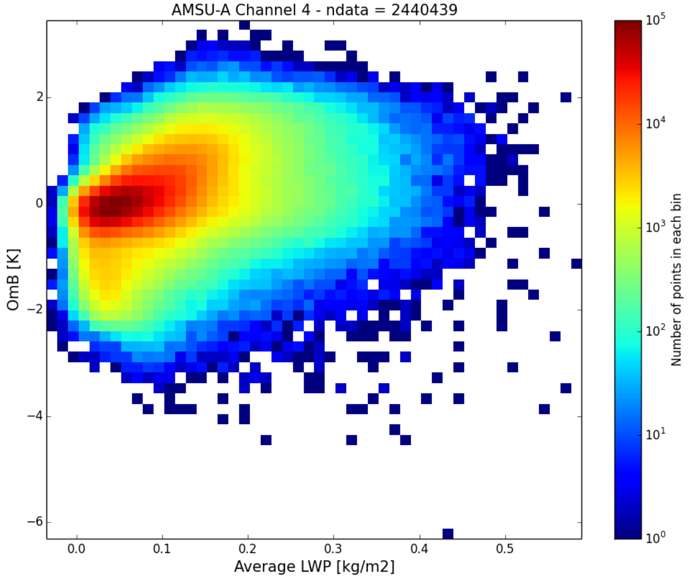
- A monitoring experiment was set up to evaluate errors for AMSU-A Ch 4 and Ch 5 observations affected by cloud. To this end, the data assimilation system was modified to perform radiance calculations on model rather than on standard levels.
- LWP retrieved from both real and simulated AMSU-A Ch1 and Ch2 observations (Weng et al., 2003)

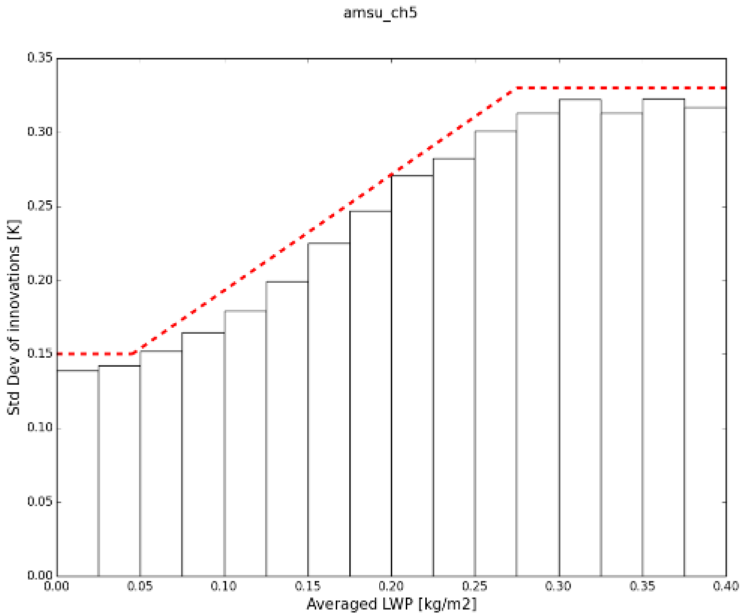

Mean average LWP ; ndata=2440439

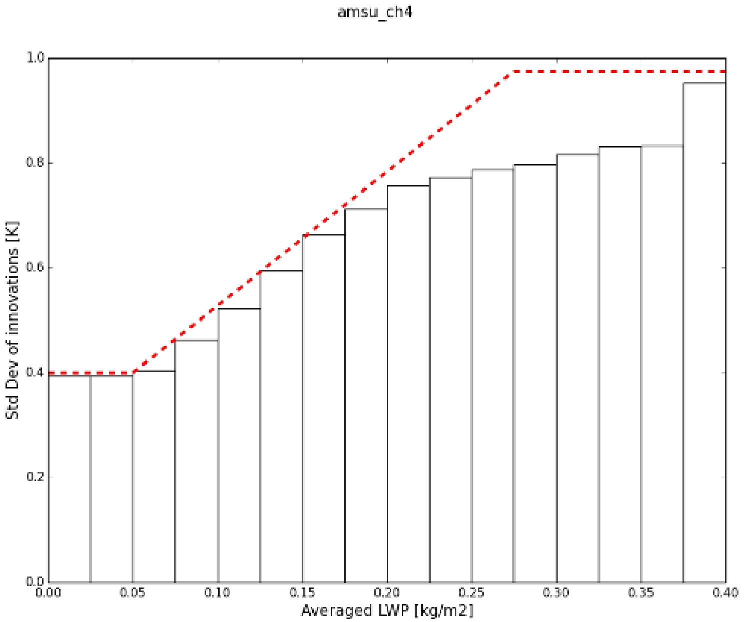

Std Dev OmB amsu_ch4 ; ndata=2440439

Cloud-dependent errors

- Evidence of non-linear dependence of the innovation distributions on average LWP
- Also significant biases esp. at low LWP values (but no VarBC corrections on data)
- Stddev of innovations are still well approximated by piece-wise linear relationship in avg LWP







Single-ob experiment

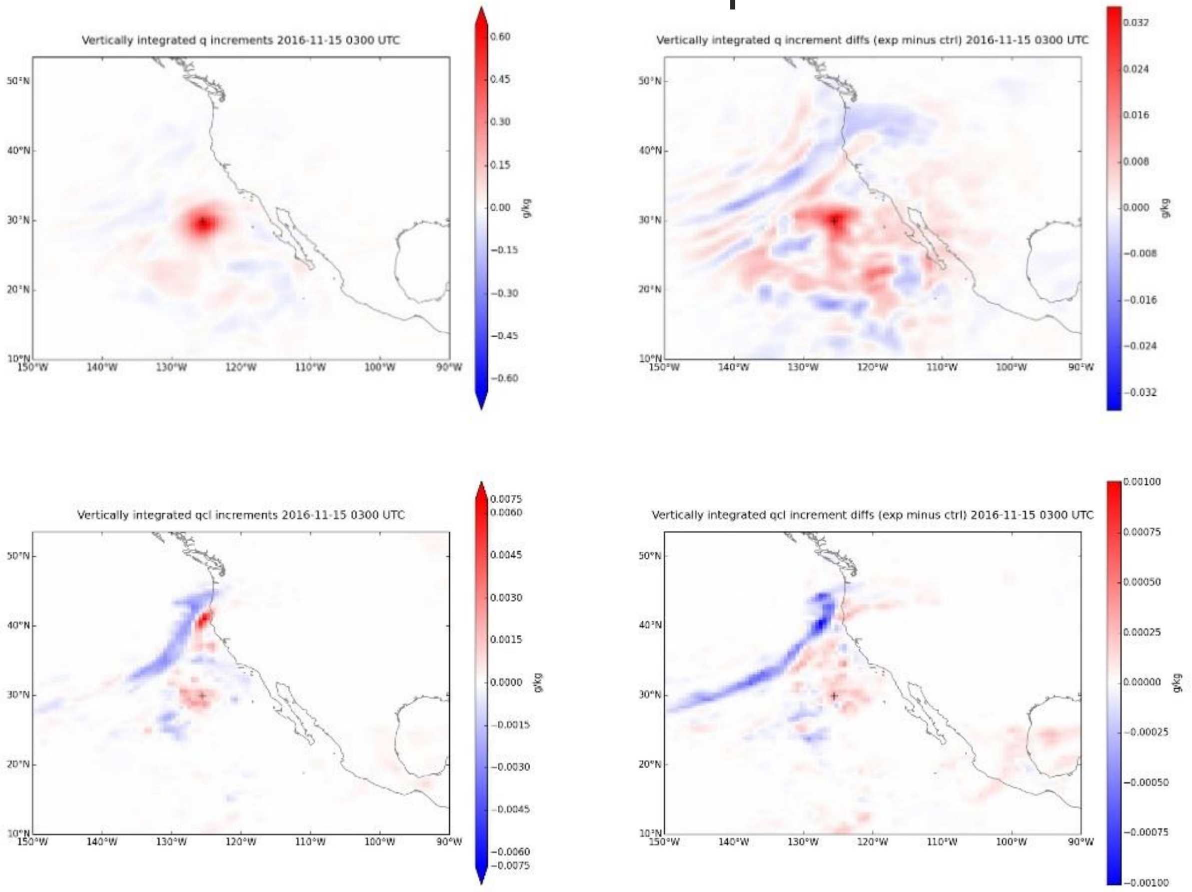
- Analysis increments from assimilation of a single cloudy scene
- Radiances from MHS Ch3 and Ch4, AMSU-A Ch6 and Ch8 to Ch14 on Metop-B (CTRL) compared to those obtained when AMSU-A Ch4 and Ch5 radiances (normally discarded in the presence of cloud) were also assimilated (Exp)

CTRL

Exp minus CTRL

$\sum_i q'(z_i)$

$\sum_i q_{cl}'(z_i)$



N320 global experiment

Model horizontal resolution at 60 km. Data Assimilation method: hybrid 4D-Var

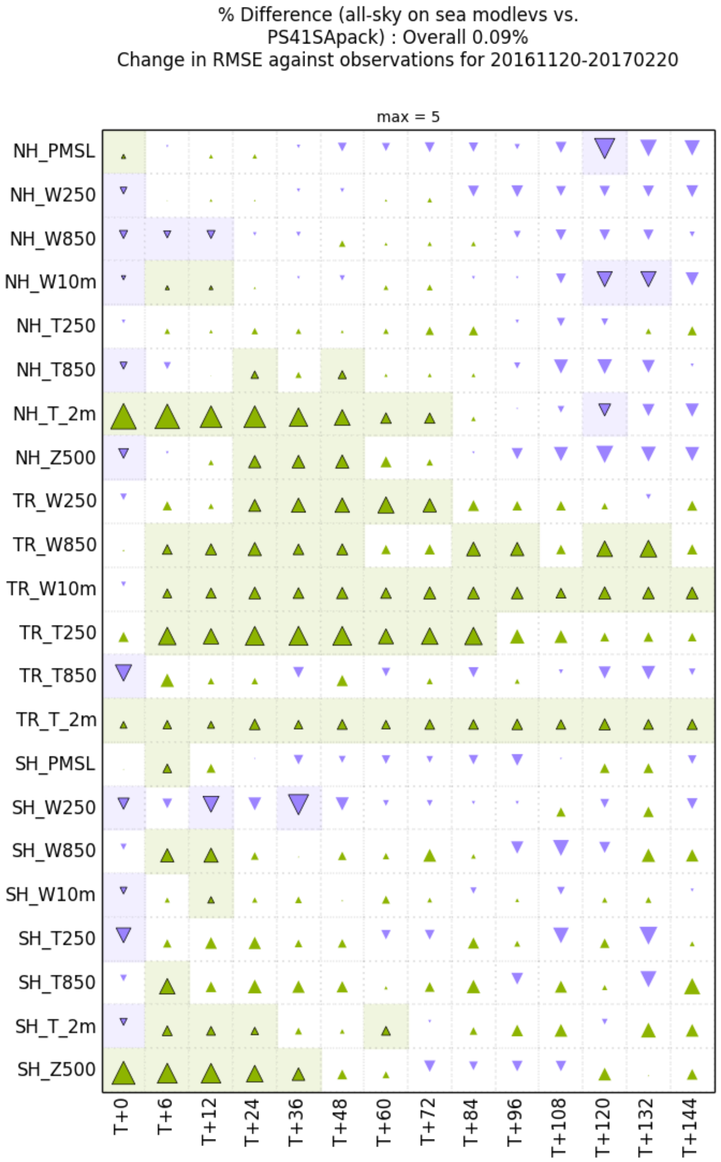
Following results are for an

- *Experiment:* new moisture incrementing operator; non-zero jacobian wrt clw for ATOVS; all-sky (nonprecipitating) AMSU-A Ch4 and Ch5. Other channels are handled as control. Control mimics operational settings as closely as possible.

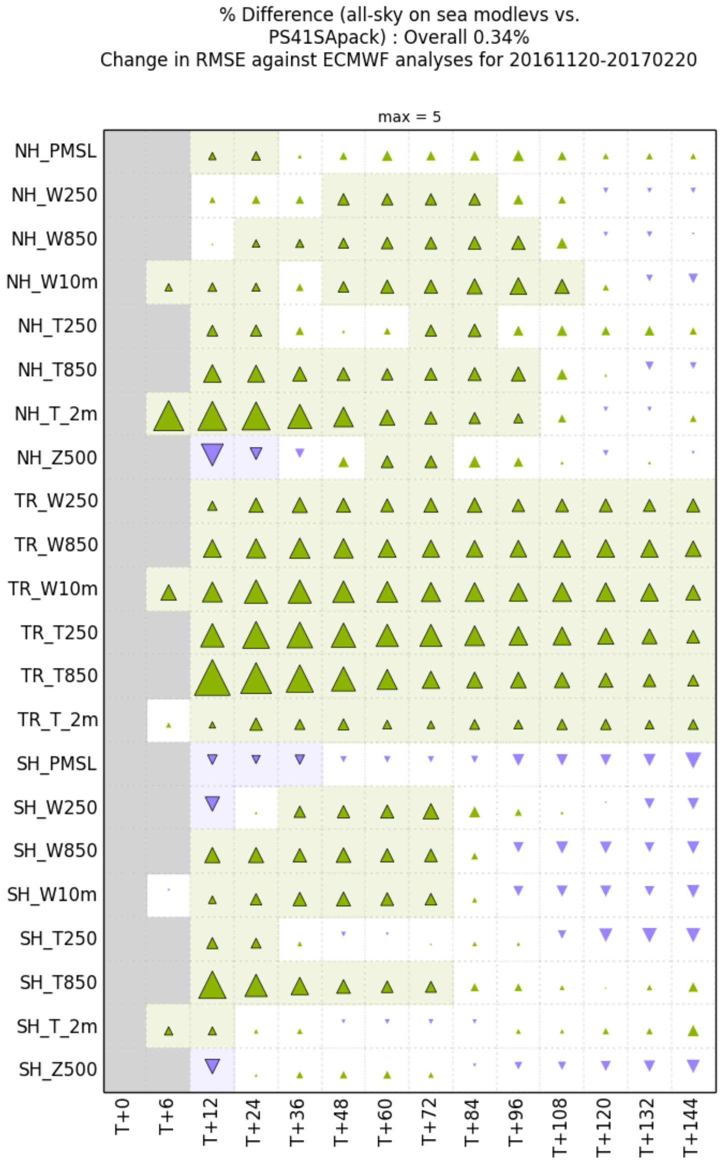
- Period is 15 November 2016 0600 UTC to 20 February 2017

Score cards

- Change in RMSE (green: smaller than control) against EC analyses (right) and against obs (left)
- Max RMSE diff = max triangle area: 5%
- Shading when diff significant at 0.05 level



% Difference (all-sky on sea modlevs vs. PS41SApack) : Overall 0.09%
Change in RMSE against observations for 20161120-20170220

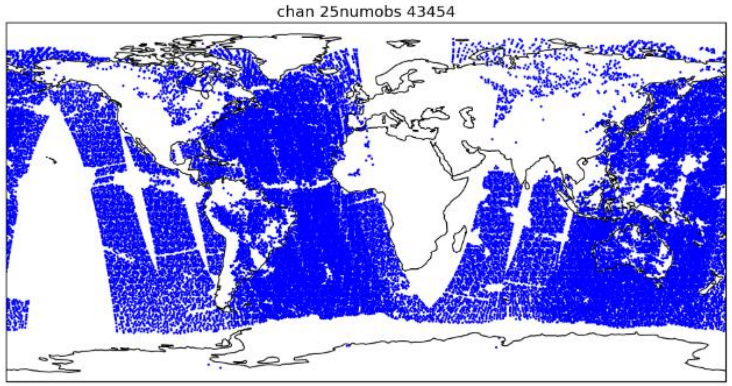


% Difference (all-sky on sea modlevs vs. PS41SApack) : Overall 0.34%
Change in RMSE against ECMWF analyses for 20161120-20170220

Current Operational Status

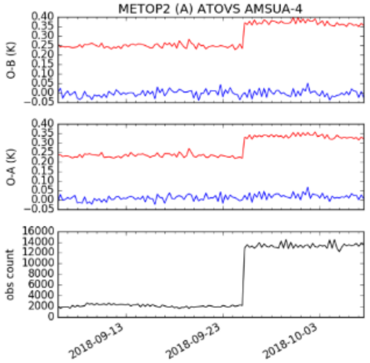
FSOI by AMSU channel

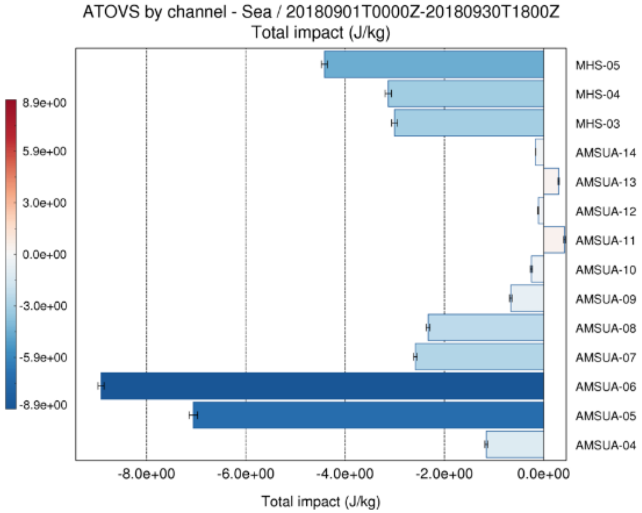
AMSUA all sky – Operational in autumn 2018



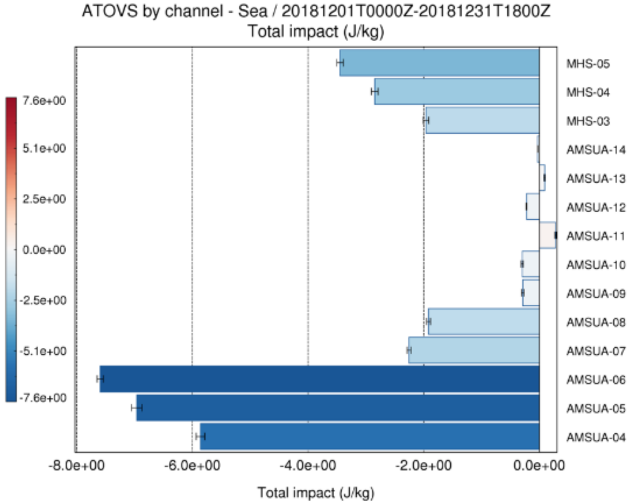
Over sea all conditions except precipitation

Over land more extensive cloud screening





Before all sky update



After

Refs:

S Migliorini, A Lorenc & W Bell, 2018: A moisture incrementing operator for the assimilation of humidity- and cloud-sensitive observations, Q.J.R.M.S., doi:10.1002/qj.3216

S Migliorini & B Candy, 2019: All-sky satellite data assimilation of microwave temperature sounding channels at the Met Office, Q.J.R.M.S., doi: 10.1002/qj.3470