NATIONAL WEATHER SERVICE

Status/Plan and Challenges in the Use of Sounder Data in NCEP Global Data Assimilation System

23rd international TOVS Study Conference

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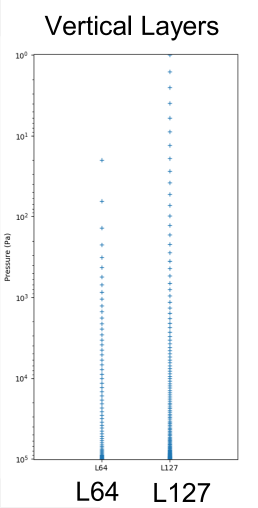
Recent Major Upgrades to GFS Data Assimilation

Operational in March 2021

- ❖ **Increased model layers from 64 to 127 and raising the model top from 55 km to 80 km**
- New background error as well as ensemble and balance related changes
- ❖ **Forecast Initialization & Balance : 4D Incremental Analysis Update (IAU) + TLNMC**
- Replace EnSRF with Modulated-ensemble LETKF, including model space localization and linearized observation operator
- Reduced humidity increments in the stratosphere
- Variational Quality Control (VarQC) redesign with Hilbert Curve (for conventional data)
- ❖ **AMSU-A channel 14 and ATMS Channel 15 without bias correction**
- ❖ **Correlated observation error for radiances from IR Hyperspectral sensors**
- ❖ **Geostationary radiances – ABI GOES-16, SEVIRI MeteoSat-8, and AHI Himawari-8**
- ❖ **AVHRR from MetOp-B and NOAA-19 for Near Sea Surface Temperature (NSST) analysis**
- Additional GPSRO from MetOp-C, GRAS, and more Cosmic-2)
- Commercial GPSRO
- High-density Aircraft Observations



❖ **Upgrades related to Radiance DA**

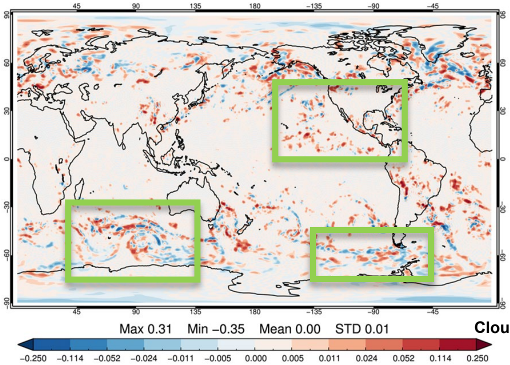
Status/Plan and Challenge: Use of Microwave Sounder Data in GFS

All-sky Approach – Observation Perspective

- Assimilate clear and non-precipitating cloud affected AMSU-A and ATMS radiances over ocean
- Non-precipitating Clouds: cloud liquid and ice are accounted for in the CRTM over the ocean to calculate the simulated radiances & Jacobians
- Observations contain precipitation are screened out
- Observation errors are modelled as function of symmetric cloud amount
- No cloud liquid water bias correction
- Assume cloudy scenes are overcast

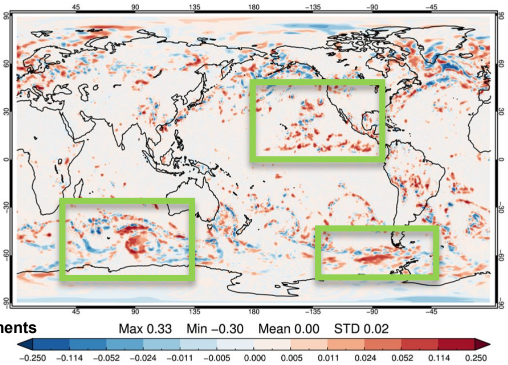
All-sky Approach - Analysis Perspective

- The total cloud condensate (q_{cw}) as control variable ($q_{cw} = q_{liq} + q_{ice}$)
- The splitting of q_{cw} into q_{liq} and q_{ice} is a function of air temperature
- Bias correction estimation uses data passed QC with consistent cloud information in the observation and forecast
- No cloud increments for forecast initialization
- **4D-Incremental Analysis Update (4D IAU)** - propagate increments in the assimilation window to reduce the spin down issue commonly observed in the initialization for hydrometers



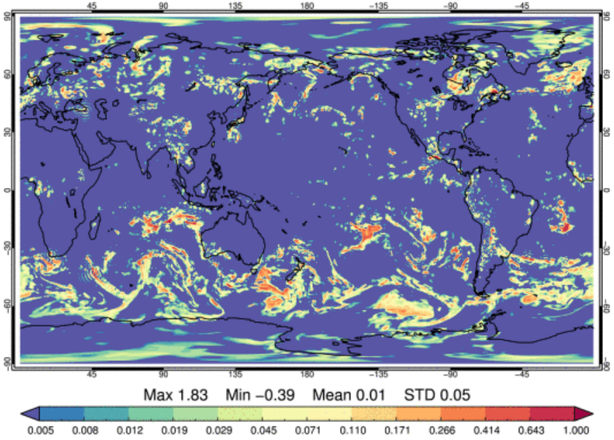
No cloudy observations – cloud increments come from correlations in the ensembles

850 mb Cloud Increments



Assimilate cloudy observations – cloud increments come from correlations in the ensembles and from cloudy MW observations

Cloud Water Mixing Ratio [g/kg] 850 hPa Initial Time



Status/Plan and Challenge: Balance and Forecast Initialization

Imbalances in the initial conditions can produce fast moving gravity waves in the forecast that can degrade skill.

GDAS use the following two methods to produce more balanced initial conditions for forecast

- Tangent Linear Normal Mode Constraint (TLNMC) --- initialization within data assimilation minimization
  - Time tendencies of the increment are calculated using a simplified tangent-linear version of the forecast model (dry adiabatic).
  - Time tendencies are then projected onto the fast gravity wave modes to provide a correction for the analysis.

  Ref: Daryl Kleist and co-authors, Monthly Weather Review, 2009 (DOI: 10.1175/2008MWR2623.1)

- 4D Incremental Analysis Update (IAU) --- propagate increments in the assimilation window
  - It reduces imbalances introduced by discontinuous analysis step, localization, and imperfect background error covariances, ….etc.
  - It helps spin up non-updated state variables (such as clouds).

  Ref: Lili Lei and Jeffrey Whitaker, Monthly Weather Review, 2016 (DOI: 10.1175/MWR-D-15-0246.1)

The LNMC in operational GDAS, the tendency model is dry adiabatic

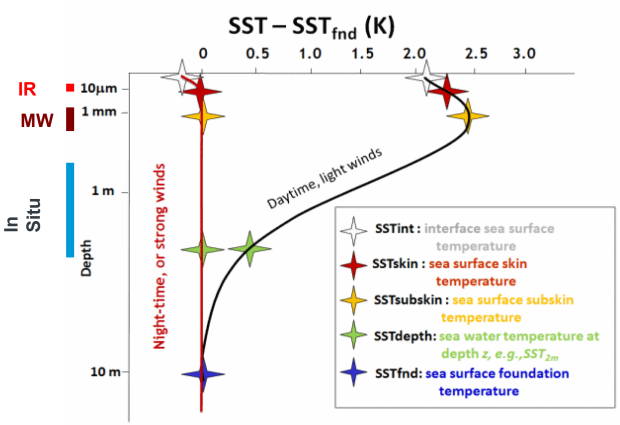
- Experiments adding moisture physics and boundary layer turbulence to the time tendency model had been conducted
- Forecast skill slightly improves in temperature, moisture and winds
- However, computational cost is high (~10% more)

Status/Plan & Challenge: Assimilation of Radiances for NSST Analysis

NSST Profile

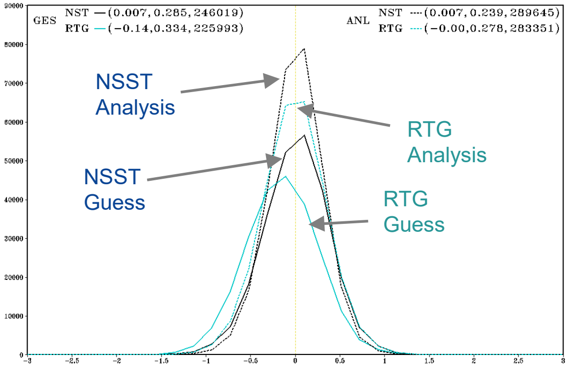
High wind speed conditions or during the **night** (red)

Low wind speed during the **day** (black)



- Foundation Temperature is the analysis variable.
- Diurnal warming and sub-layer cooling T-Profile are simulated by NSST Model in the cycling of GFS.
- NSST T-Profile for atmospheric model and CRTM
- The input surface temperature to CRTM depends on instrument type
  - IR – temperature at 0.015 mm
  - MW – temperature at 1.0 mm
- Satellite radiances: AVHRR, AIRS, CrIS IASI, AMSU-A and ATMS are used in NSST along with in-situ observations to constrain the foundation temperature.
- The use of radiances in NSST analysis leads to better NSST profiles and this, in turn, improves the radiance assimilation.

IASI Window Channel (data passed QC)



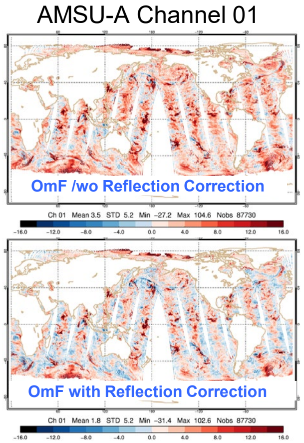
Using the NSST at 0.015 mm for IASI in CRTM leads to more data passed quality control and better residual statistics.

Status/Plan and Challenge: Planned Upgrades related to Radiance DA

- NPP OMPS-LP (UV and VIS blended)
- NOAA-20 OMPS-TC (OMPS-NP retrievals not consistent with those from NPP in tropics) Use top 5 layers retrieved ozone due to extended model layers and top
- ❖ **Assimilate antenna-corrected AMSU-A, MHS, and ATMS brightness temperature (SDR)**
- ❖ **Precipitation-sensitive AMSU-A & ATMS radiances**
- ❖ **All-sky assimilation of GMI**
- ❖ **GOES-17 ABI CSR**
- ❖ **Revised correlated observation errors for IASI over land/sea and CrIS over sea**
- ❖ **VIIRS and AVHRR for near sea surface temperature (NSST) analysis with revised thinning**
- Stereo AMVs (GOES/GOES, GOES/Himawari)
- Leo-Geo AMVs
- GOES-17 mitigated AMVs
- Updated utilization of ASCAT winds

❖ **Upgrades related to Radiance DA**

Status/Plan and Challenge: Precipitation-Affected AMSU-A, ATMS, & GMI for Next Implementation



RTM accuracy under scattering conditions

- Current Status: Advance Delta Addington (ADA) with parameterized surface reflection correction
- A proper surface emissivity model to work with multiple scattering algorithm is necessary
- The bi-directional reflectance distribution function (BRDF) for MW is under development by CRTM team

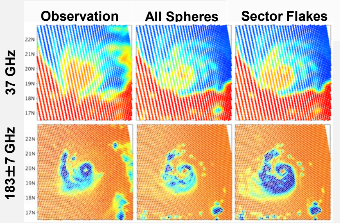
$$L_\nu(\mu, 0) = \varepsilon_{\nu,sfc} \cdot B_\nu(T_{sfc}) + \rho_{\nu,sfc} \cdot R^{\downarrow}_{\nu,sfc} + \rho_{\circledast,\nu,sfc} \cdot R^{\downarrow}_{\circledast,\nu,sfc}$$

Fractional Cloud Coverage

- Two-column radiance calculation
- Four types of cloud overlapping schemes (hydrometer-weighted average cloud cover for MW)
- Significant impact for small-scale cloud and precipitation in convective region
- How to represent cloud fraction at each FOV?
  - Interpolate from surrounding grid points?
  - Calculate cloud fraction profile based on PDF scheme (same as the one in GFDL)

Use cloud optical table consistent with model particle size distribution and non-spherical snow

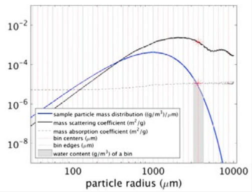
Using scattering table for spherical particle leads to systematic errors



- Too much scattering at low frequencies
- Too little scattering at high frequencies

- New LUTs generated by integrating scattering properties over PSD (Exponential PSD for GFDL cloud physics)
- Use scattering properties of sector snowflakes in Liu (2008) scattering database
- Replace spherical snow particles in model with sector snowflakes

  One sphere snow is replaced by multiple sector snowflakes of the same size to preserve total mass of particles within each size bin



Credit: Figures and information from Yinghui Lu, Penn State

Status/Plan and Challenge: Impact of Precipitation-Affected AMSU-A/ATMS

- Augment analysis control variable to include precipitating hydrometers
- Relax precipitation screening by remove 54.5 GHz precipitation check to allows precipitation affected radiances.
- Screen observations affected by strong convective situations by:
  - Cloud effect ΔBT check using 53.6 GHz

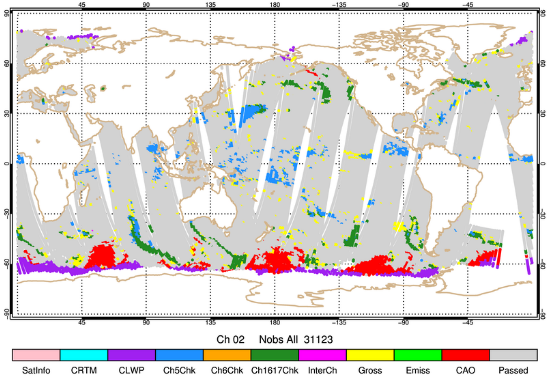
    $\Delta BT = BT - BT^{clr}_{sim}$ using 53.6 GHz $\quad \Delta BT_{obs} < -0.5\,K$ or $\Delta BT_{sim} < -0.5\,K$

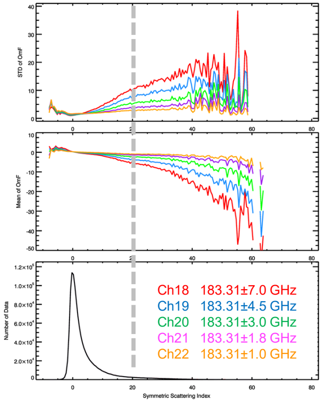
  - Symmetric scattering index derived from 90 and 150 GHz

    $$SI = (BT_{90} - BT_{150}) - (BT^{clr}_{90,\,sim} - BT^{clr}_{150,sim})$$

    $$SI_{sym} = 0.5\,(SI_{obs} + SI_{sim}) > 20\ \mathrm{K}$$

- CAO (Cold Air Outbreak) – screen out the CAO area where the forecast model tend to produce too much ice cloud.

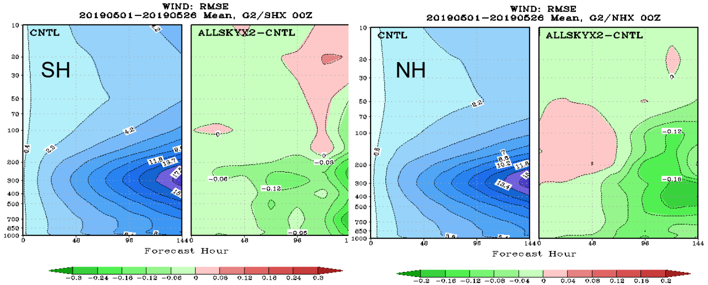




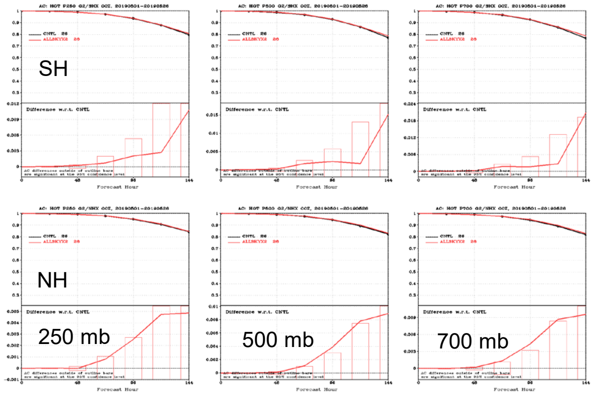
Impact on Forecast

- Positive impact on NWP key variables for both hemispheres
- Experiment used CRTM default cloud optical table
- Experiment using the cloud table that is consistent with model physics is underway

Vector Wind RMSE



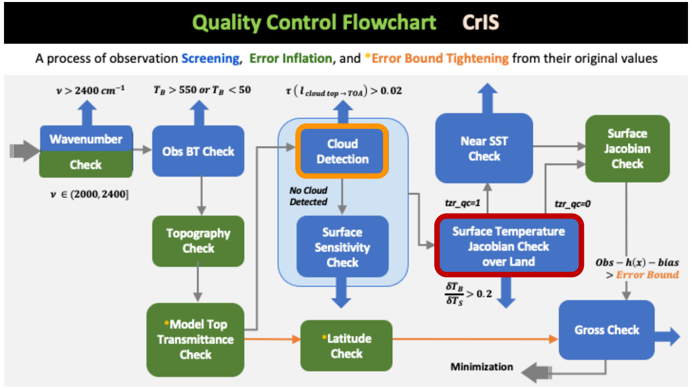
Anomaly Correlation



Status/Plan and Challenge: Hyperspectral Infrared Sounders in GFS

Instrument	Satellite	Status	Channel Usage
IASI 616 Subset	MetOp-A	Assimilating	174 channels assimilated: LW: 160 channels MW: 14 channels
	MetOp-B	Assimilating	
	MetOp-C	Monitoring to replace MetOp-A	
CrIS 431 Subset	NPP	Monitoring due to lost of LW	100 channels assimilated: LW: 92 channels MW: 8 channels
	NOAA-20	Assimilating	
AIRS 281 Subset	AQUA	No Data Flow	117 channels assimilated

- Clear-sky assimilation
- Correlated observation error
- Hyperspectral IR sensors go through the same QC procedures except for CrIS
- CrIS has additional surface sensitivity check over non-sea areas due to adverse interaction between the quality control and bias correction


Quality Control Flowchart CrIS

A process of observation Screening, Error Inflation, and *Error Bound Tightening from their original values

Cloud Detection

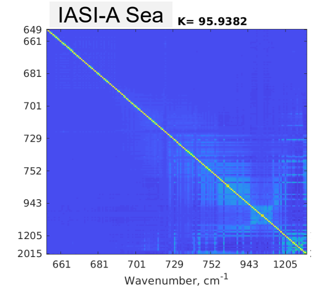
- Minimizes a one-dimensional cost function to retrieve cloud height and fraction from a selected channels from 15 μm CO_2 *band*
- A cloud is detected if

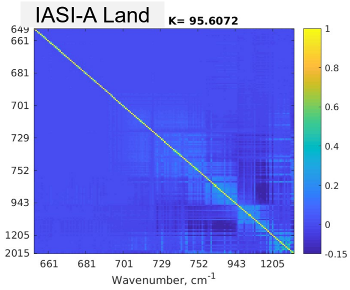
$$\sum_{i=1}^{N}\frac{\left(I_{i,obs}-I_{i,cld}\right)^2}{\sigma_i^2} < D\sum_{i=1}^{N}\frac{\left(I_{i,obs}-I_{i,clr}\right)^2}{\sigma_i^2} \quad where\ D = 0.75$$

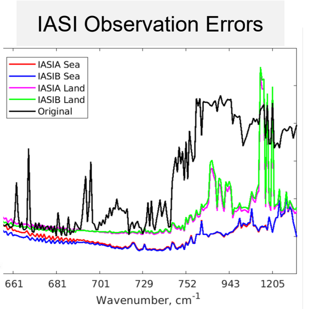
$I_{i,clr}$: simulated clear-sky brightness temperature (BT) for channel *i*
$I_{i,cld}$: simulated cloud-impact BT from an opaque cloud for channel *i*
σ_i : diagonal observation error

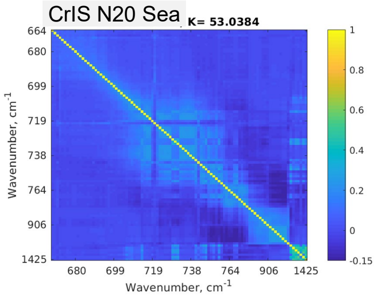
A channel j is rejected if the cloud to space transmittance is greater than 0.02

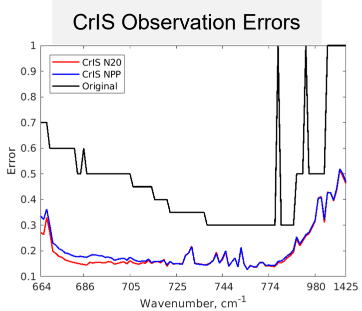
Status/Plan and Challenge: Correlated Observation Error


IASI-A Sea


IASI-A Land


IASI Observation Errors


CrIS N20 Sea

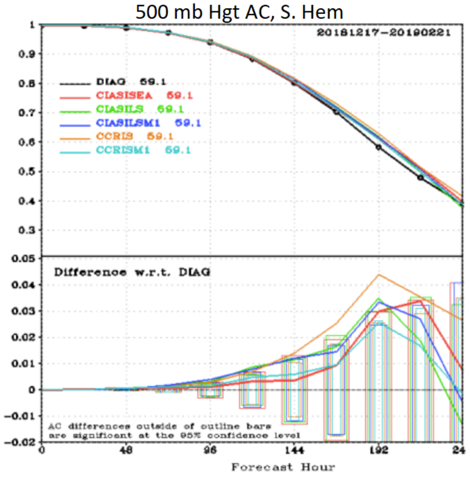

CrIS Observation Errors

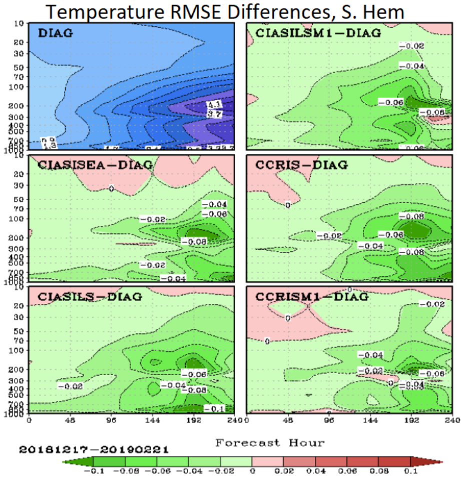
- Errors over land are larger than those over sea
- Significant broader correlation structures for CrIS

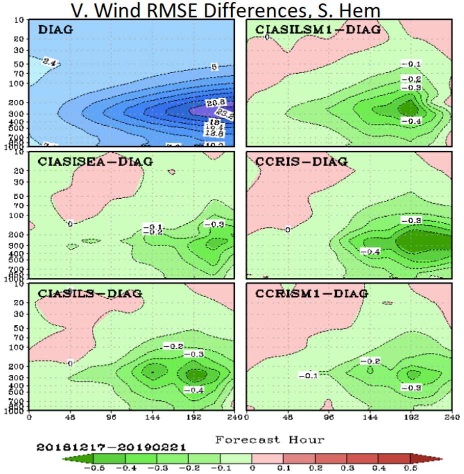
- Spectrally correlated observation error matrices for IASI and CrIS are estimated with the Desrosiers diagnostics.
- Correlated observation errors are important in the water vapor, ozone and surface sensitive bands
- Infrared observations have different error characteristics over land, therefore, errors over land and ocean are estimated separately.
- The estimated R matrices are reconditioned by raising the smallest eigenvalues to a threshold and then empirically tuned inflation factors are applied to the diagonals.
- The correlated observation error estimation leads to reduced errors in the diagonals. This error reduction results in tighter cloud detection and thus prevents the sub-optimal analysis caused by the assimilation of potentially cloud-contaminated radiances.

Kristen Bathmann & Andrew Collard DOI: 10.1002/qj.3925

Status/Plan and Challenge: Impact of Correlation Observation Error


500 mb Hgt AC, S. Hem


Temperature RMSE Differences, S. Hem


V. Wind RMSE Differences, S. Hem

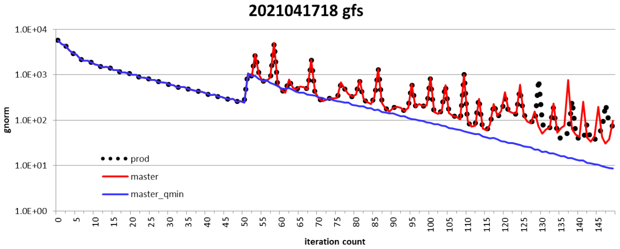
Verified against
ECMWF analysis

- IASI is assimilated with correlated error over land and sea, with separate matrices over these surfaces. CrIS is assimilated with correlated observation error over sea only.
- Correlated error has a positive forecast impact, especially in the southern hemisphere.
- Accounting for correlated error over land improved the NWP impact as well as IASI residual statistics.
- Significant improvements were found in the temperature forecast biases at 1000 hPa, likely a result of improved cloud detection (i.e., stricter cloud detection)

Kristen Bathmann & Andrew Collard DOI: 10.1002/qj.3925

Status/Plan and Challenge: Issues with QC and Minimization

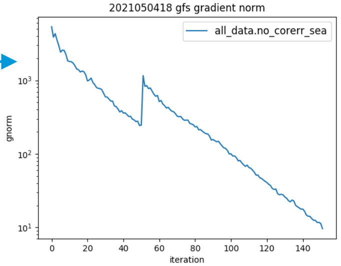
- Cloud detection algorithm (minimum residual method) is not robust enough to prevent the sub-optimal analysis caused by the assimilation of potentially cloud-contaminated radiances
- Exclude observation from sea ice, snow and mixed surface types improves the analysis and subsequent forecast
- It is not hard to find saw tooth or spiky minimization in operational run
    - In some cases, the minimization issues are related to correlated observation error and some CrIS moisture channels (non-linearity?)
    - Leaky cloud detection may be the source of the problem --- under investigation


2021041718 gfs

The source of the convergence difficulty comes from observations in polar region where the humidity is relatively low.

Solution: qsat = max(qmin,qsat) & qmin=10^{-7}

Turn off correlated obs error over ocean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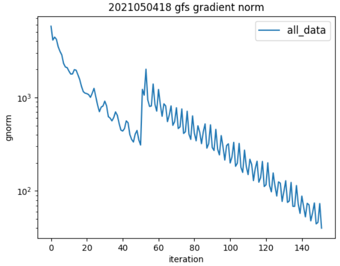
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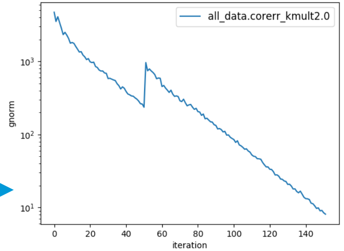
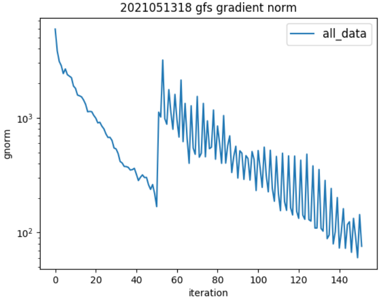
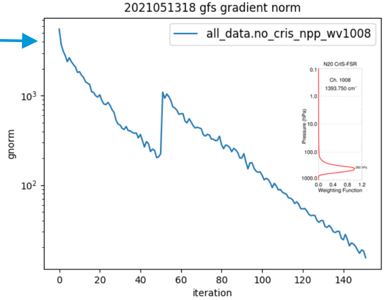
Inflate the entire R matrix



Turn off CrIS NPP water vapor channel 1008


2021051318 gfs gradient norm

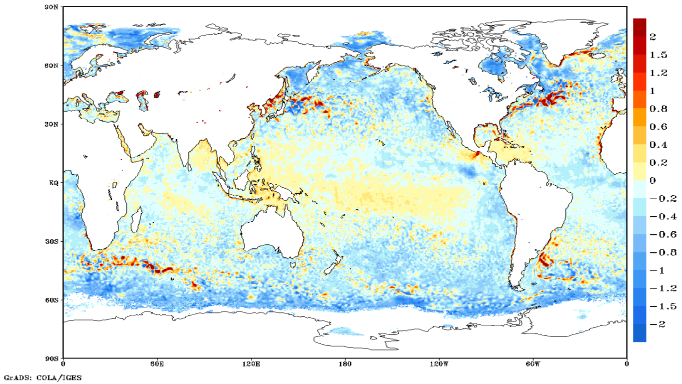

2021051318 gfs gradient norm

Credit: Russ Treadon, John Derber, and Kristen Bathmann

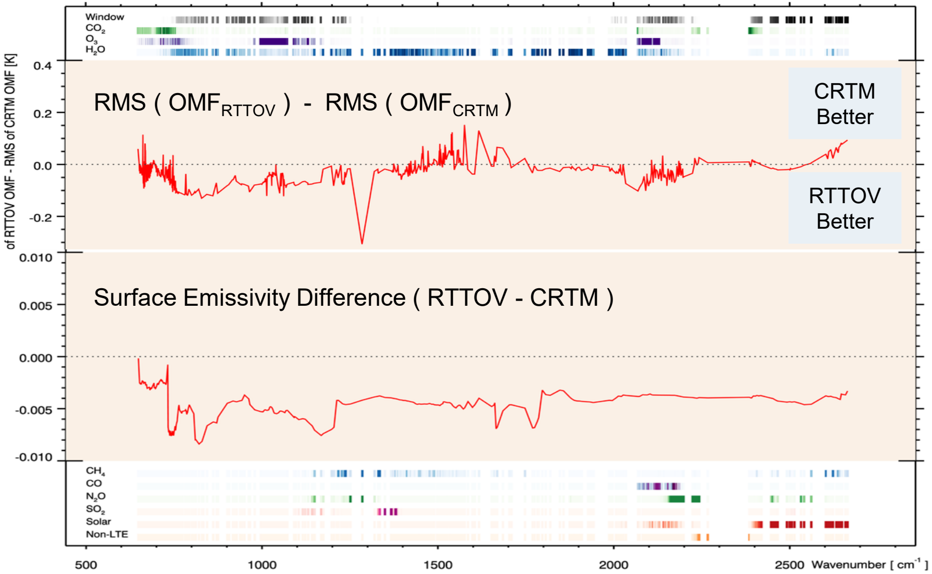
Status/Plan and Challenge: Issues with IR Ocean Emissivity Model and NSST

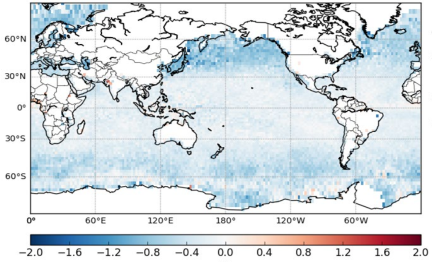
- In window channels the RTTOV simulated brightness temperatures systematically fit observations better than CRTM
- CRTM overestimates the surface emissivity over the ocean
- The CRTM IRSSE model does not have sea surface temperature dependency --- revised IRSSE is under evaluation
- There is a known problem in the operational NSST foundation temperature analysis: too cold in higher latitudes
- The cold bias in NSST is likely related to the bias in the surface emissivity
- Test is underway to investigate whether the revised IRSSE could improve the NSST foundation temperature analysis

Foundation Temperature Difference

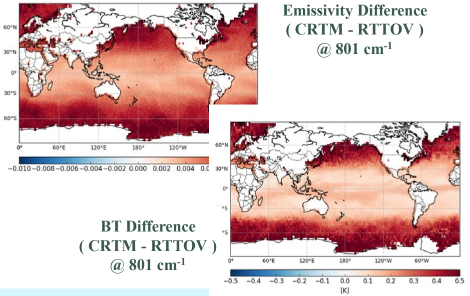


Monthly Mean
OPR - OST





OMF @ 801 cm^{-1}



Emissivity Difference
(CRTM - RTTOV)
@ 801 cm^{-1}

BT Difference
(CRTM - RTTOV)
@ 801 cm^{-1}

Status/Plan and Challenge: Summary

- Need BRDF type surface reflection/emissivity models to couple with multi-stream scattering solvers.
- Modelling:
  - Move towards microphysical consistency across the components (cloud physics/microphysics and radiative transfer for heating/cooling rates) in the forecast model and observation operators (mid-term goal).
  - Use the same cloud optical data base for radiative transfer calculation in the model and observation operators (long-term goal).
  - Construct cloud optical table with cloud parameters that are consistent with forecast model (short-term goal; underway for MW).
- Sub-grid variability
  - Revisit the inclusion of sub-grid convective cloud and fraction in the observation operator for MW.
  - Explore the use of collocated cluster information from imager (IASI with AVHRR, ATMS with VIIRS…etc) for better handling the cloud sub-grid heterogeneity and overlap in a field of view.
- Test the revised CRTM IRSSE model for:
  - IR clear-sky radiance assimilation
  - NSST analysis --- check if the improved surface emissivity estimation reduce the cold bias in foundation temperature
- Test clear-sky IR radiance assimilation with difference cloud detection scheme?
- Continue to investigate the minimization issue induced by correlated observation errors and moisture channels from hyperspectral IR sensors
- Explore the use of channels from SWIR band.
- Work towards the all-sky assimilation for IR radiances
  - While a two-column radiance calculation is sufficient for all-sky MW radiance assimilation, the IR may need up to around 100 sub-columns to produce acceptable accuracy due to strong sensitivity to variations in cloud fraction and overlap as a function of altitude (Alan Geer and co-authors, Tech Memo 815).
  - Need to investigate how to handle cloud fraction and cloud overlap with computational efficiency while obtaining acceptable RTM result.

Status/Plan and Challenge: Summary

Preparation for the second generation of the EUMETSAT Polar System (EPS-SG)

- Test the use of IASI reconstructed radiance for assimilation --- to prepare for IASI-NG
- Work with CRTM team to evaluate
  - MW sounder - MWS (23 – 229 GHz)
  - MW Imager - MWI (18 - 183 GHz)
  - Ice Cloud Imager - ICI (183 - 664 GHz)
- CRTM 3.0 will add support for full Stokes polarization simulation capability across all wavelengths

Backup Slides

Hybrid 4D Ensemble-Variational System

$$J(\boldsymbol{\delta x}_c,\boldsymbol{\alpha}) = \beta_c(\boldsymbol{\delta x_c})^T\boldsymbol{B}^{-1}(\delta\boldsymbol{x_c}) + \beta_e\frac{1}{2}\sum_{m=1}^{M}\boldsymbol{\alpha}_m^T\boldsymbol{L}^{-1}\boldsymbol{\alpha}_m + \boxed{\frac{1}{2}\sum_{k=1}^{K}(\boldsymbol{H}_k\boldsymbol{\delta x}_k-\boldsymbol{d}_k)^T\boldsymbol{R}_k^{-1}(\boldsymbol{H}_k\boldsymbol{\delta x}_k-\boldsymbol{d}_k) + J_c}$$

Adding time dimension in 4DEnVar

J_o term divided into observation bins as in 4DVar

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

$$\boldsymbol{\delta x}_k = \boldsymbol{\delta x}_c + \boxed{\sum_{m=1}^{M}\left(\boldsymbol{\alpha}_m\circ\left(\boldsymbol{\delta x}_{e,m}\right)_k\right)}$$

Increment associated with
static background covariance
+
Increment associated with
flow-dependent ensemble covariance

Solution – the Minimizer

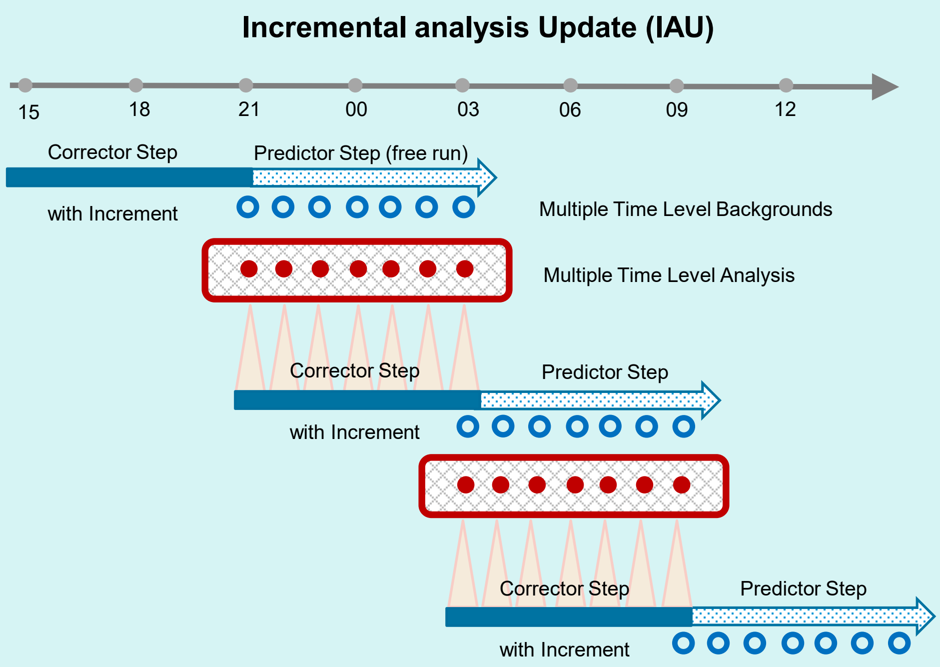
- J is a quadratic function. At minimum, $\nabla J = 0$
- Iterative minimization algorithm is used to solve $\nabla J = 0$ for δx_c and α
- Conjugate gradient method is used in NCEP hybrid analysis

J	Penalty = fit to bkg J_b + fit to ensemble J_e + fit to obs J_o + Constraints J_c	L	Correlation matrix for ensemble covariance localization (effectively the localization of ensemble perturbations)
β_c β_e	Weighting factor for statistic and ensemble bkg error covariances ($\beta_s+\beta_e = 1$)	B	Static bkg error covariance (time invariant)
δx_c	Increment from variational analysis	d_k	Observation innovation $(y_{o,k} - h(x_k) - Bias)$
$(\delta x_{e,m})_k$	The m-th ensemble perturbations at time k	$y_{o,k}$	Observation at time k
δx_k	Hybrid increment at time k	h	Forward observation operator
α_m	Extended control variable: weight to each ensemble member (varies in space which determines the ensemble covariance localization scale)	H	Linearized observation operator $H = \left(\frac{\partial h}{\partial x}\right)$
R_k	Observation error covariance	K, M	K number of time bins, M number of ensemble members

4D Incremental Analysis Update (IAU)

Data Assimilation

- Accommodations for the extended vertical resolution and model top (under testing at NOAA)
    - Examples: re-estimate static background error covariance, retuning ensemble spread, parameters for normal model constraint, …etc
- 4D-Incremental Analysis Update (under testing at NOAA)
    - Propagation of increments in the assimilation window
    - Reduces imbalances introduced by discontinuous analysis step, localization, imperfect background error covariance, … etc
    - Potentially significant for fast-moving weather systems
    - May help spin up non-updated state variables
    - May help the spin down issue commonly observed in the initialization for hydrometeors
- Use linearized observation operator to calculate ensemble perturbation in observation space - sacrifice the accuracy for computing efficiency (under testing at NOAA)



$$h\left(x_{e,m}^{f}\right) - h\left(\overline{x_e}^{f}\right) = \boldsymbol{H}\,\delta x_{e,m} \quad \text{where} \quad \boldsymbol{H} = \left.\frac{\partial h}{\partial x}\right|_{\overline{x_e}^{f}}$$

Status/Plan and Challenge: Balance and Forecast Initialization

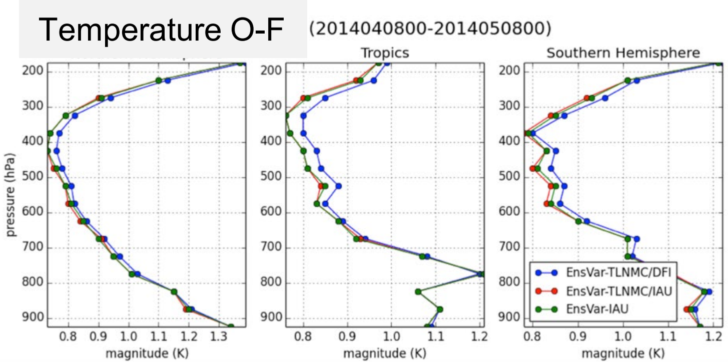
Low resolution trials of two forecast initialization methods with/without Tangent Linear Normal Mode Constraint (TLNMC)

- Digital Filter Initialization (DFI)
- 4D Incremental Analysis Update (IAU)

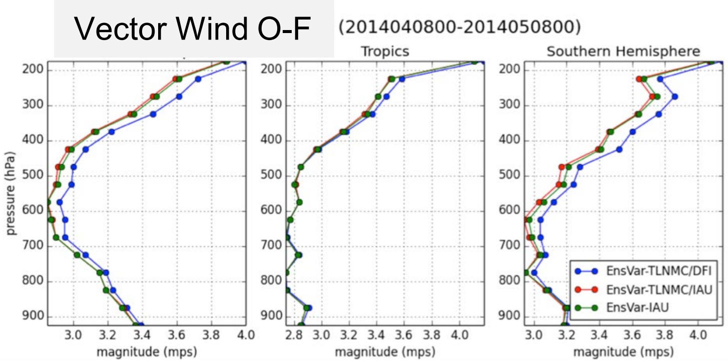
- Digital Filter Initialization (DFI) with TLNMC is the worst performing.
- **TLNMC + IAU** is the best performing.

4D IAU has several benefits:

- It reduces imbalances introduced by discontinuous analysis step, localization, and imperfect background error covariances, ….etc.
- **It helps spin up non-updated state variables (such as clouds)**.



Temperature O-F (2014040800-2014050800)



Vector Wind O-F (2014040800-2014050800)

Fit to Rawinsonde

Lili Lei and Jeffrey Whitaker (MWR, 2016)
DOI: 10.1175/MWR-D-15-0246.1