AFWA DA FY08 2008
Weather Research and Forecasting Data Assimilation Improvement and Support

Final Report

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FY08 Tasks

4.1 Preparation of AFWA's operational data assimilation system for NPOESS

4.1a WRF-Var Core Development and Support

NCAR will:

i) Coordinate in-house collaboration between MMM and DATC activities along with coordination with AFWA, JCSDA and WRF community partners to ensure optimal efficiency in WRF-Var development and support

Held bi-weekly meetings and informal seminars.

Prepared the bi-monthly project reports.

Prepared the AFWA DA FY2009 SOW and the ACAPS SOW. Prepared the GSI parts of the DTC SOW.

Hans traveled to Washington, D.C. to attend the AFWA cloud analysis project planning meeting organized by John Eylander. The participants were John Eylander, John Zaptocny, Steve Lord, Michel Reinecher, Richardo Toldling, Bill Kuo, and Hans Huang.

Hans attended a GSI code management meeting with the DTC and GSD. The plan to have a Boulder code repository was discussed.

Hans attended the 2nd East Asia WRF Workshop and Tutorial (Seoul, Korea) at the invitation of the workshop organizers. He gave a presentation of the current WRFDA status and plans. He also gave two tutorial lectures.

Zhiquan and Hans attended the JCSDA 2008 Science Workshop and gave a presentation, "CRTM test and implementation in WRF-Var".

Zhiquan participated in the JCSDA CRTM working group meeting and the microwave working group meeting.

Zhiquan visited JCSDA April 28~30. He gave a seminar, "Radiance Data Assimilation for WRF Model: Overview and Results"[*]. He also attended the quarterly CRTM working group (CWG) meeting (as the core team member of CWG and the representative of AFWA/NCAR) and gave a 15min update on radiance assimilation status in WRF-Var.

Thomas Auligne participated in the JCSDA infrared sounder working group meeting.

Thomas visited JCSDA, EMC and GMAO to discuss radiance data assimilation related issues.

The WRF-Var team helped the CRTM core development team to test a pre-released CRTM version, which has improved computation efficiency.

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[*] http://www.jcsda.noaa.gov/documents/seminardocs/Liuz_RadianceAssim_20080429.pdf

The WRF-Var team had a coordination meeting with Andy Jones and Steve Fletcher to discuss the MMM-CIRA collaboration, in particular on the DA- and ACAPS-related tasks.

Hans, Yongsheng Chen, Thomas, and Xin Zhang participated in the WMO workshop on 4D-Var and ensemble Kalman filter inter-comparisons.

Hans presented WRF-Var and DATC to the NCAR new director.

Hans and Zhiquan participated in the AGU fall meeting and presented two studies:"A Case Study of Hurricane Initialization Using WRF 4D-Var", by Xin Zhang and Hans Huang, and "Impact of Assimilating Satellite Microwave Radiances on Hurricane Initialization and Prediction", by Zhiquan Liu, Dongliang Wang, Dale Barker, Xin Zhang, and Hans Huang

For preparing 2009 work, Dr. Jianjun Xu of JCSDA and NOAA/GSD personnel in Boulder were invited to visit NCAR for a week in December. During the visit, they shared their GSI/ARW experiences and a latest GSI version was installed on the NCAR IBM for future use.

Dr. Fuzhong Weng, senior scientist in the JCSDA visited NCAR and gave a seminar entitled "Advances in Community Radiative Transfer Model (CRTM) in Support of Satellite Data Assimilation"

ii) Provide WRF-Var Code Management

The following are the main highlights about this work.

- WRF-Var V3.0 was released to the community in April 2008. In addition, the WRF-Var trunk codes were merged with WRF repository.

- WRF-Var V3.0.1.1 was released to the community in August 2008. The build mechanism was redesigned, which dramatically reduced the compilation time (in half) with some compilers (e.g., IBM xlf, Linux intel).

- WRF-Var V3.1 will be released in Spring2009. In addition to bug fixes, the Var system highlights of V3.1 are radiance assimilation and 4D-Var capabilities and improved portabilities (all platforms and compilers which WRF can support). Some new capabilities which are not fully-tested are: global Var, the hybrid scheme, the NMM interface, the BE interpolation capability from band-wised BE files, Observation impact and sensitivity, a new (Lanczos) minimization algorithm, buddy check, and a MADIS observation data interface.

- A new regression test system designed for developers was developed, which is consistent with WRF regression test system and has the potential to merge with WRF regtest.

- An updated WRF-Var version was delivered to AFWA on May 21, with the modified CRTM, improved AIRS cloud detection and bias correction, and the 4D-Var capability.

- The CRTM version in WRF-Var was updated to the latest release 1.1 (2/29/2008 version), which improves the treatment of the low model top issue by supplying some climatology profiles above the model top. Recently, the CRTM version was upgraded to release 1.2.

- WRF-Var scripts were upgraded to accommodate higher time resolution related to the assimilation window and observation frequency, needed for RUC and 4D-Var.

- Hui-Chuan Lin tested a NCEP utility program, which can remove duplicated radiance data between adjacent satellite orbits. AFWA was advised to use this utility in their real-time radiance data processing.

iii) Provide scientific and technical support for WRF-Var (including, but not limited to, the ETKF algorithm) to AFWA operational and JME applications

The following are the main highlights of this work.

- Provided scientific and technical support to AFWA, JCSDA, JME, etc. Responded promptly to AFWA's help request and solved the problems in a timely manner.

- Prepared the codes, dataset, documentations, and lectures for the 1st WRF-Var tutorial of July 2008 and the 2d WRF-Var tutorial of February 2009. In total, nearly 100 students participated the tutorials.

- Responded to the help requests of community users via wrfhelp and the WRF forum with more than 260 e-mails and 240 posts.

- A new WRF data assimilation web page will be published with the WRF-Var 3.1 release.

- Dale Baker spent a week at NCAR working on the hybrid tasks. He also gave a short tutorial on the hybrid ETKF/Var. About 15 people attended the lectures and did the exercises.

iv) Add a switch in the OBSPROC namelist and provide the capability to do buddy checking on observations for quality control

Buddy check for "SOUND" & "SYNOP" observations have been implemented in WRF-Var in serial mode. Work is in progress to update it with an MPI option. Following "WRF/OBSGRID", the basic concept for implementing "*Buddy Check*" is to compare the innovation $(O\text{-}B)_b$ at (x_b, y_b) with the average innovation within a given distance. If the difference is more than certain tolerance limit (err_{max}), the observation is flagged as suspect. The tolerance limit depends on observation type, pressure level, and a user-defined weighting factor.

$$BD_b = | inv_b - \overline{inv_b} | \begin{cases} > err_{\max} & \textit{failed} \\ \le err_{\max} & \textit{passed} \end{cases}$$

$$inv_b = \left(O - B\right) \qquad \textit{At observation at location} \left(x_b, y_b\right)$$

$$\overline{inv_b} = 1 / N_B \sum_{i=1}^{N_B} inv_i \quad \textit{Averaged inv within a given distance} \left(\textit{Buddy}\right)$$

N_b is the number of "*Buddy*" points for observation at (x_b, y_b) .

It is implemented in WRF-Var as follows:

- Since the average innovation may contain contributions from bad observations, these need to be removed. This is achieved by doing multiple scans on *Buddy* observations (inv_i) by enforcing following criteria

$$|inv_i - \overline{inv_b}| \le err_{\max} \quad and \quad inv_i \le 1.25 * err_{\max}.$$

- Final average innovation ($\overline{inv_{b0}}$) calculated from the *good Buddy observations* is used to compute BD_{b0} for *Buddy Check* as follows:

$$BD_{b0} = |inv_b - \overline{inv_{b0}}| \begin{cases} > err_{\max} & failed \\ \le err_{\max} & passed \end{cases}$$

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- Number of observations within *Buddy* must be greater than or equal to 2.
- If number of observations within *Buddy* equals to 2 , $err_{\max} = 1.2 * err_{\max}$
- *Buddy Check* is done on pressure levels by sorting all observations in 13 pressure level bins with bin_width= 100 & 50 hPa below and above 300 hPa, respectively.
- Tolerances (err_{max}) varry with variable (wind, temperature, specific humidity, and pressure) and pressure levels. Default values of err_{max} for different variables are:

  max_buddy_t = 8.0 (degree)
  max_buddy_uv = 8.0 (m/s)
  max_buddy_rh = 40.0 (%) (used to convert err_{max} for q)
  max_buddy_p = 350.0 (Pa).

- Two new namelist variables "*check_buddy_print*" & "*check_buddy*" have been added.
- Currently *Buddy Check* is applied only for "SOUND" and "SYNOP" observations.
- Diagnostics for *Buddy Check* is written in a file named, "buddy_check" in RUN_DIR.

v) Provide the capability to output and display observation rejection information from WRF-Var in order to accumulate conventional blacklist/monitoring statistics. Also, increase length of obs identifier character string in obs_gts file to at least 20 characters.

WRF-Var has been modified to produce diagnostic files like, "qcstat_conv_01" and "rej_obs_conv_01". Here the last suffix "01" indicates the corresponding analysis "outer loop" number. Since WRF-Var default option for analysis "outer loop" number is 1, accordingly "01" file will be created with default option. The first file (qcstat_conv_01) holds (in Tabular form) the count (utilization/rejection level wise) of all conventional observations variable wise. The second file (rej_obs_conv_01) holds detailed info (variable & location etc.) about all the rejected observations with WRF-Var quality control procedure. A separate utility along with graphics (NCL based script) have been developed to read & display level-wise, locations of all the observations (observation type along with counts) written in "rej_obs_conv_01" file. Desired observations and level may be selected suitably at run time. A detailed report is already submitted with May-June, 2008 progress report. Revised version of this report is attached (FY08_DA_41a_v.pdf) with this final report.

For the second part of this task, the following updates have been made in "obsproc" and WRF-Var codes to increase the length of obs identifier as 40 character string.

- For *obsproc*, the format variable, *fmt_info,* in "var/obsproc/src/*module_write*" was modified. The station ID now has 40 characters in *obs_gts* file.

- To accommodate 40 character station ID in WRF-Var, following files are modified,

var/da/da_control/da_control.f90
var/da/da_define_structures/da_define_structrues.f90
var/da/da_obs_io/da_scan_obs_ascii.inc
var/da/da_obs_io/da_read_obs_ascii.inc
var/da/da_obs_io/da_obs_io.f90
var/da/da_setup_structures/da_setup_obs_structures.inc
var/da/da_setup_structures/da_setup_structures.f90

- Entire procedure has been tested with CWB 2007081300 case. For this case SATEM, SATOB, and AIREP data had station ID > 5 characters. With updated code, corresponding station ID's have now been stored with 40 characters.
- The updated "*filtered_obs*" file now, has exactly same format as "*ob.ascii",* i.e. 40 characters for station ID.

vi) Create a default global set (non-optimal) of bias correction coefficients and background error covariances for use on short notice in any part of the world.

Global background error (BE) statistics have been generated in six 30-degrees latitudinal domains thus covering the entire globe. Desired code have been developed and extensively tested for interpolating the background error (BE) statistics for any regional domain from globally generated BE statistics in six 30-degrees bands. Performance of interpolated BE statistics is examined for four typically selected regional domains with the corresponding actual BE generated using one months forecasts. Results suggest that the interpolated BE statistics is performing reasonably well in the sense that WRF-Var analysis produced with interpolated BE statistics is not differing much with the corresponding WRF-Var analysis produced with actual BE statistics. In all four regional test domains considered here, both temperature and winds absolute analysis differences are mainly confined within ± 1.0. The analysis minimization procedure needed more iterations to minimize the initial cost function for achieving the same convergence criteria with interpolated BE statistics as compared with the original BE statistics. A full report, (FY08_DA_41a_vi.pdf), on this part of the task is attached to this final report.

Global set (non-optional) of bias correction coefficients have been created which may be used for any regional domain. Various steps in accomplishing this task are summarized as follows.

- WRF-Var code was updated with "global WRF-ARW" options. Thus WRF-Var now can run with global WRF-ARW model as its first guess. These changes have been merged with WRF-Var Version3.1
- Global WRF-ARW was configured with appropriate namelist options at 257 x 129 x 41 grid resolution. This is equivalent to approximately 156 Km. horizontal resolution.
- With above configurations, WPS & REAL was run in a six hourly cycle for the period 00 UTC 15th August, 2007 to 18 UTC 14 September, 2007 generating initial conditions (wrfinput_d01) for running WRF-ARW and to serve as "first guess" for running WRF-Var in cold starting mode.
- 12 & 24 hour forecasts are generated in a 12 hourly cycle for the entire period mentioned above for the purpose of generating global background errors (BE).
- "gen_be" utility have been updated to generate global background errors at any desired resolution.
- Six hourly global radiance data (AMSUA, AMSUB, MHS, SSMIS, AIRS and EOS_AMSUA) was collected for the entire period.

- Six hourly WRF-Var cycling (in cold start mode) was run by suitably switching off all the main analysis control variables except for variational bias correction (VARBC).
- The procedure started with a suitable initial first guess for bias correction (VARBC.in) as an input at the starting cycle time (2007081500). After running WRF-Var, initial first guess for bias correction (VARBC.in) gets modified as "VARBC.out". Subsequently, the updated first guess for bias correction (VARBC.out) from the previous cycle was used as the first guess for the next cycle. Thus towards the end of 124 cycles corresponding to one month six-hourly cycling from 2007081500 to 2007091418, final "VARBC.out" was produced. This will serve as standard global bias correction for any regional domain.

The global bias correction produced (VARBC.out) was successfully tried to run WRF-Var in T8 domain with radiance for 2007081512 UTC. Attached Table (Table_item_4.1.a.vi.pdf) summarises the observation minus background (omb) & observation minus analsysis (oma) statistics produced using old VARBC and the global VARBC corresponding for all types of radiance data used in this case.

vii) Upgrade/optimize digital filter algorithm for application with latest version of WRF.

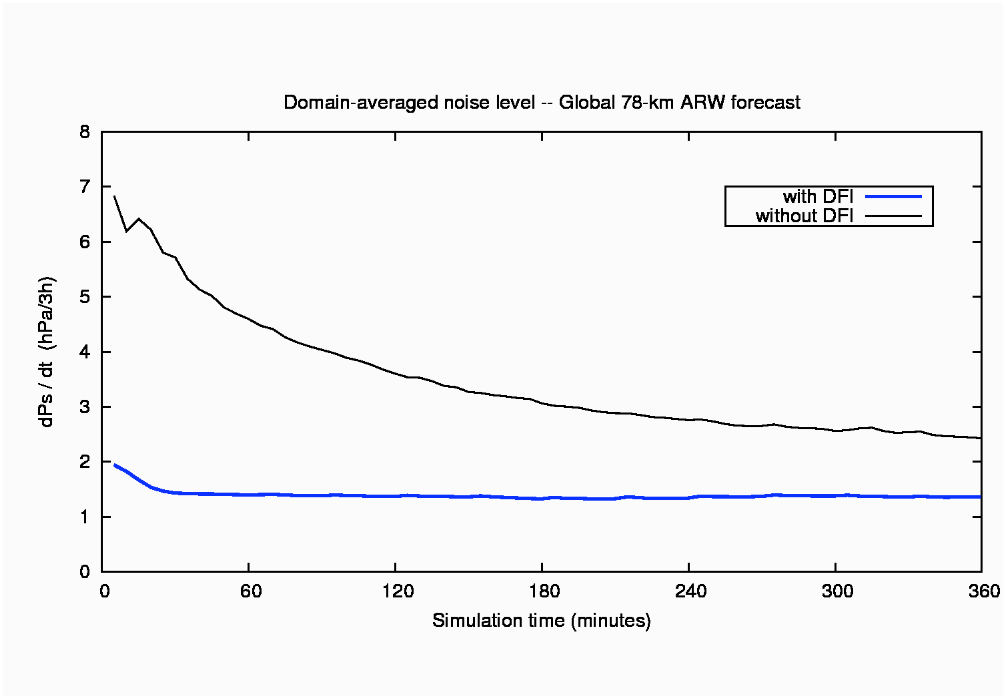
The implementation of a digital filtering initialization (DFI) for WRF has been completed and made available in the Version 3.0 release. The WRF DFI implementation is based on two existing codes – one from NOAA's Global Systems Division and another from Hans Huang and Min Chen – with the best aspects of both systems being used: the implementation supports eight different digital filters and three DFI schemes, and is cleanly integrated into the WRF software framework to provide a single-executable system (i.e., initialization and the model integration all proceed from a single run of the WRF executable). DFI is activated through run-time options in WRF's namelist, where various other DFI-related options may also be set. A technical description of the WRF DFI is given in the WRF Version 3 technical note, and user-level documentation is provided in the ARW Version 3 Modeling System Users' Guide.

Although three filtering schemes and eight filters are available in WRF DFI, the recommended configuration uses the Twice DFI scheme with a Dolph filter and a filter cutoff period of 3600 seconds. More concisely, the following settings of namelist variables in the "dfi_control" namelist are recommended:

dfi_opt	3 (Twice DFI)
dfi_nfilter	7 (Dolph filter)
dfi_cutoff_seconds	3600

Using the Dolph filter with a 3600-second cutoff period, a backward integration of 60 minutes followed by a forward integration of 120 minutes in the Twice DFI scheme should be sufficient for the removal of most noise in a model initial state.

The effectiveness of WRF DFI in removing noise from the model initial state is evident in the reduction in absolute surface pressure change, which is used as a proxy for noise, during the first few hours of a model forecast. In the figure below, the domain-averaged absolute surface pressure change (hPa / 3 hr) is plotted for a global 78-km ARW domain for an uninitialized model run (black curve) and a model run initialized with WRF DFI (blue curve) using the options recommended above.



viii) Maintain and perform regression testing of 4D-Var component of WRF-Var.

The following are the main highlights about work, which is continuously in progress.

- Fixed a serious bug in 4D-Var, which misused the non-conventional observations such as GPS PW, radar reflectivity. Re-run T8 domain cold cycling run from 2007081421 to 2007082021. Furthermore, the hurricane IKE case was carried out to demonstrate the performance of 4D-Var. The experiments show that the 4D-Var outperformed 3D-Var on both hurricane track and intensity analysis and forecasts. The results was reported in 2008 Fall AGU meeting.

- A new regression test system has been established, which is consistent with the current WRF regression system.

- The WRF 4D-Var paper was published on Mon. Wea. Rev. recently.

- The WRFDA group started a project with AirDat. One of the tasks is to optimize WRF 4D-Var for a possible operational implementation of WRF 4D-Var at AirDat.

- Work for improving computational performance of WRF adjoint is almost done. The updated 4DVar code performance has improved around 30%. (None AFWA task) These changes will be included in the WRF-Var 2009 Spring release.

- Support 4D-Var codes usage outside NCAR.

ix) Develop adjoint of WRF-Var's minimization algorithm, additional I/O, and couple with 4D-Var's adjoint of the ARW forecast model, to create a diagnostic tool for evaluating observation/analysis impact on forecast accuracy

The adjoint method is used to calculate the sensitivity of short-range (24-h) forecast errors to the initial conditions and ultimately to the observations used in the observations at initial time. The work has been divided into independent tasks, which were studied in parallel and then combined to produce a diagnostic chain.

1. Forecast accuracy

The forecast error is defined as the dry energy norm, and its gradient with respect to the initial conditions interprets the analysis error that contributes to the model forecast errors. The dry energy norm has been redefined to be more consistent with WRF variables, e.g. potential temperature and pressure. The external utility program has been revised for the calculation of the new dry energy norm and its gradients with respect to the model state variables. It has been tested on a case over AFWA T8 domain on September 5th 2007 and produced reasonable results. These gradients are used as inputs for the initial forcing of the WRF-ARW adjoint model.

The WRF-ARW adjoint modeling system has been modified to be consistent with the new definition of the dry energy norm (that has pressure). With this modification, the output of the WRF-ARW adjoint modeling system contains the gradient of the error norm with respect to pressure.

2. Evaluation of the forecast model tangent-linear

Linearity test indicates that the WRF tangent linear model is a good approximation of the WRF nonlinear model for at least 24 hours under the adiabatic assumption. With the WRF adjoint modeling system, adjoint-based sensitivity is studied using the AFWA T8 case on 5 January 2007. Various order approximations of the forecast error reduction due to the improved analysis by WRF 3DVAR is evaluated compared with the NCEP GFS analysis over the whole model domain. It is shown that higher-than-first-order accuracy is required for a comprehensive evaluation of the analysis that contributes to an improved (impaired) forecast.

3. Analysis sensitivity

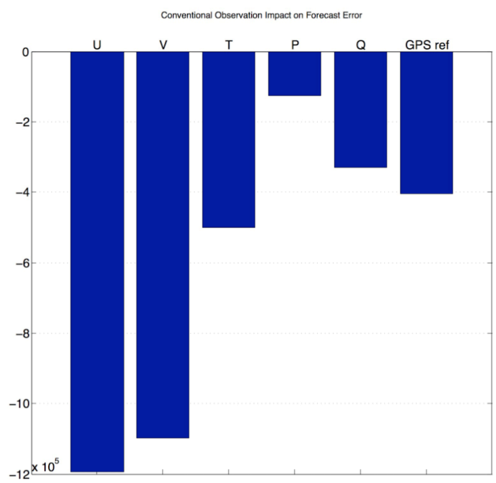
A “line-by-line” approach was initially chosen to calculate the adjoint of the assimilation system. Unlike approximate methods used in other NWP centers, this approach could extend to calculate the sensitivity to observation error or bias correction. Initial work has been performed to calculate the line-by-line tangent-linear of the analysis but various technical issues, such as the need to maintain a separate adjoint code, have led to the decision to use a different approach.

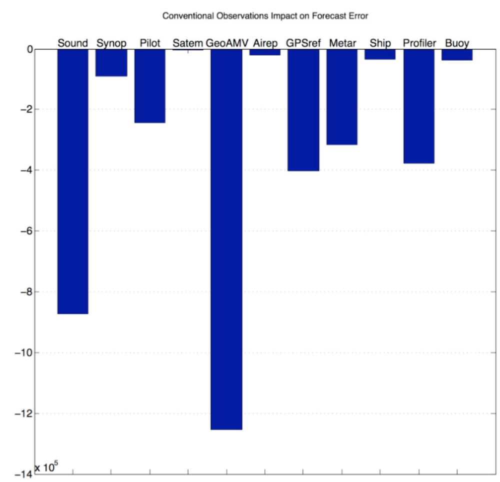
A new minimization scheme based on the Lanczos algorithm has been developed and validated in WRF-Var. It produces results that are exactly similar to the ones from the current Conjugate Gradient scheme, but also computes the estimated Hessian (i.e. the inverse of the analysis-error covariance matrix). This product is then used to calculate the exact adjoint of the WRF-Var assimilation. The calculation has been successfully validated with an adjoint test up to machine precision.

Experiments have been conducted for a test case over AFWA T8 domain with various inputs, which provided sensitivity (and corresponding observation impact) of analysis increments to every observation used in the WRF-Var system and also the Degree of Freedom for Signal (DFS) of every observation. These diagnostics are very informative on the use of various observations and the behavior of the analysis.

The adjoint of the analysis using the Lanczos algorithm has been coupled with the adjoint of WRF-ARW model. This part completed the full chain to obtain the observation impact on forecast accuracy. Diagnostics can be plotted individually or aggregated by observation type. The figures below show the impact of conventional observations on the accuracy of a 24-hour forecast for 2008090500 over AFWA

T8 domain (Tropical Atlantic). Results are aggregated either by meteorological quantity (i.e. U, V components of the wind, Temperature, Pressure, Humidity Q, GPS refractivity) or by instrument (i.e. Radiosonde, SYNOP, Pilot, SATEM, Geostationary Atmospheric Motion Vectors, Aircraft, GPS refractivity, METAR, Ship, wind Profiler, Buoy). Wind is the information from observations, which has the most impact on forecast accuracy. Geostationary Atmospheric Motion Vectors and Radiosondes are the two main sources of information.





4.1.b Radiance Assimilation Development for WRF-Var

NCAR will:

i) Perform preliminary QC, bias correction and monitoring studies for METOP/AMSU (Note: NCAR may have to obtain this data on its own as AFWA may not yet have a data feed.)

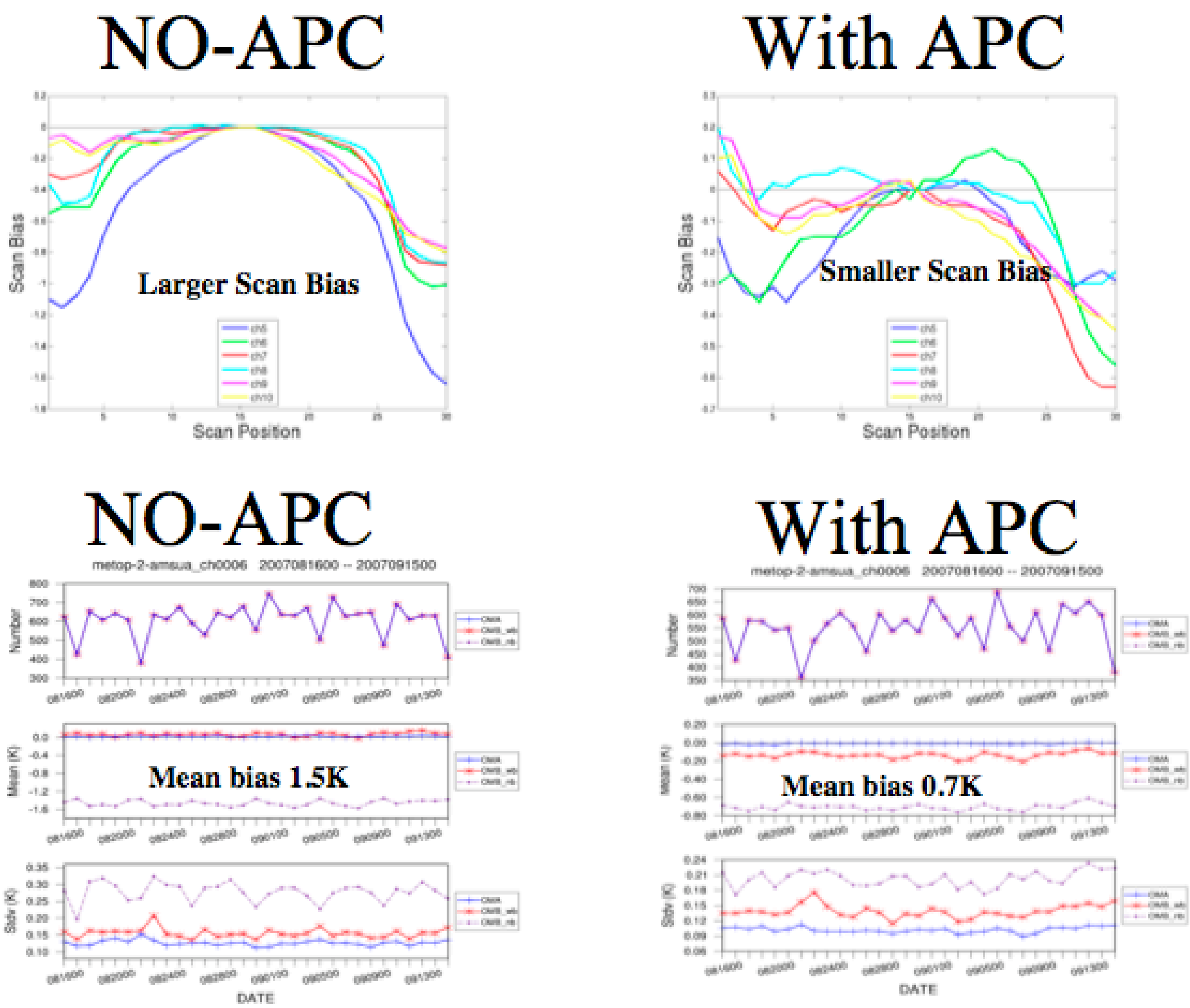
The month-long (August to September 2007) METOP AMSU-A/MHS radiance data (in NCEP BUFR format) are downloaded from NCEP public ftp server. New developments include:

(1) The observation interface and basic quality control in WRF-Var are extended to include METOP AMSU-A and MHS radiances.

(2) Harris&Kelly bias correction code is modified to include METOP AMSU-A and MHS radiances. The initial bias correction coefficients were generated over T8 domain.

(3) WRF-Var is modified to incorporate the Antenna Pattern Correction (APC) capability of CRTM. It is be more appropriate to apply CRTM APC to Antenna Temperatures (Ta) and improve the fit between the observations and background.

From the monitoring statistics of one-month data, it was found that the bias of METOP AMSU-A radiance is larger than those from other AMSU-A instruments (e.g., noaa-15 and noaa-16). After communicating with JCSDA persons, we realize that METOP AMSU-A radiances used in NCEP BUFR files are “Antenna Temperatures (Ta)” rather than usual Brightness Temperatures. Figure below compares the scan bias statistics and time series of bias/rms of innovation for METOP AMSU-A channels with and without APC. Both the scan bias and total bias are reduced after applying APC.



ii) Further develop QC and bias-correction algorithms for SSMIS and perform case studies.

The development work includes:

(1) Process AFWA provided (orbital) SSMIS data into 6h time-window.

(2) Based on the code for AMSU from http://www.nco.ncep.noaa.gov/pmb/codes/nwprod/sorc/bufr_dupsat.fd/, developed a new code to remove the duplicated SSMIS data in BUFR files within 6h time-window.

(3) Add and test an additional precipitation check over different surface type (Ferraro, 1997, JGR). This has small impact for SSMIS sounding channels.

(4) SSMIS radiances have coverage only at 00 UTC and 1200 UTC over T8 domain. It was found that SSMIS biases exhibit substantial diurnal cycle, i.e., biases at 00 UTC and 1200 UTC have significantly different values (Figure 4.1b.ii-1). It is probably due to UPP calibration difference for ascending and descending orbits according to NRL SSMIS expert (Steve Swadley). When applying bias correction (both Harris&Kelly bias correction and variational bias correction) in usual way (i.e, unified treatment for all times), the oscillation can not be removed. If we apply the bias correction separately for 00UTC and 12UTC, the oscillation is well removed (Figure 4.1b.ii-2). This method is used in the DATC extended tests.

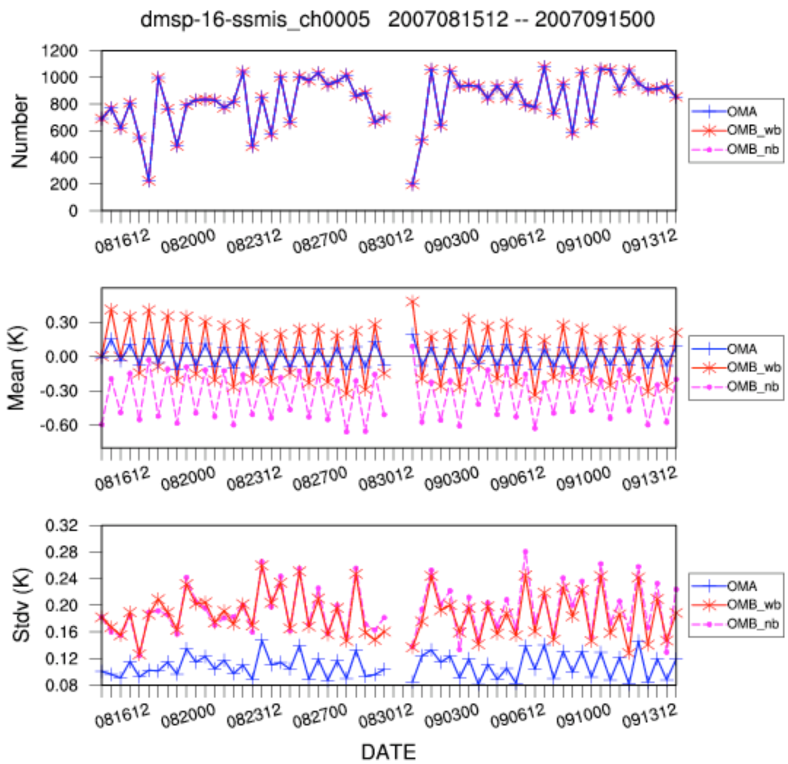


Figure 4.1b.ii-1. Time serial of the mean and standard deviation of OMB/OMA. OMB plots include the values with and without the bias correction (unified treatment for all times).

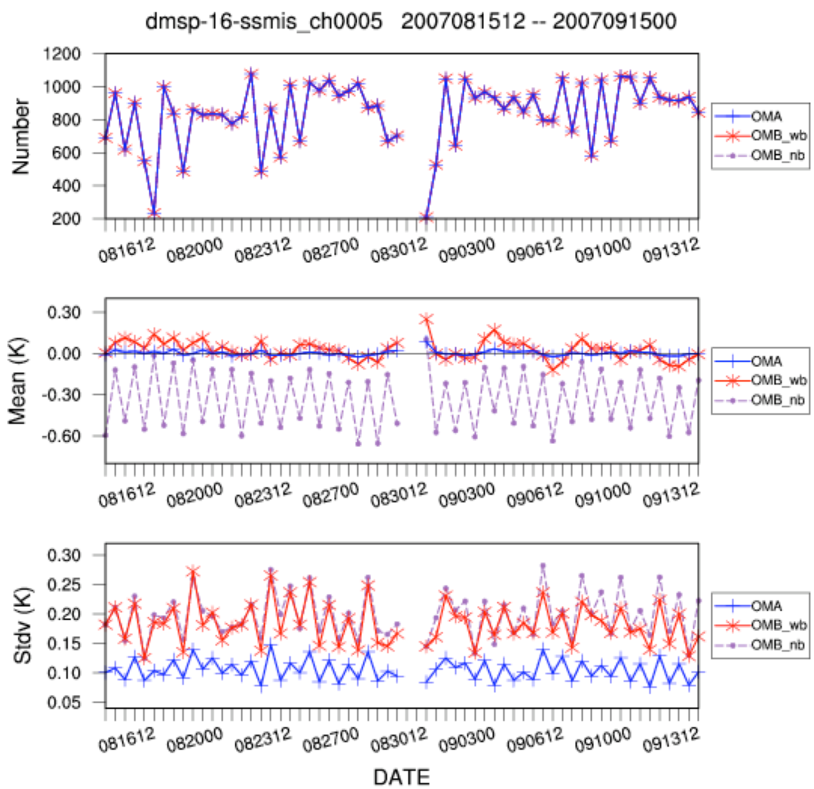


Figure 4.1b.ii-2. Same as Figure 4.1b.ii-1, but apply bias correction separately for 00UTC and 12UTC.

Case study: convective case at 00UTC 5/13/2008

A convective case (2008051300) over US continent is investigated to evaluate the impact of radiance assimilation on the convective precipitation forecast in a relatively high resolution (9km for assimilation), SSMIS radiance data for this case is collected from NCEP. WRF-Var analysis (in a 9km resolution) was used for initializing WRF model at 00 UTC May 13, 2008 and then followed by a WRF 36h forecast with a 9km/3km nested domain. WRF-Var assimilation started at 1200 UTC May 12 with a 'cold-start' from GFS, and followed by 3h cycling assimilation till 00 UTC May 13.

3 experiments are conducted:

(1) GTS: Only conventional data is assimilated.
(2) GTS+SSMIS: same as GTS, but plus SSMIS radiances.
(3) GTS+SSMIS2: same as GTS+SSMIS, but with the increased observation weight.

SSMIS data have coverage at 1500UTC May 12th and 0000UTC May 13th (see Figure 4.1b.3).

Figures 4.1b.ii-4,5,6 shown below are of radar reflectivity from the 3 assimilation experiments and radar observation, respectively for the initial analysis, 3h and 6h forecast. At initial time GTS experiment generates some spurious precipitation in the southwest of Texas comparing to radar observations. Adding SSMIS radiances apparently makes spurious precipitation weaker both at initial time and short-term forecast. However, if we increase the background error (i.e., give observations more weight), the spurious precipitation is even enhanced in short-term forecast.

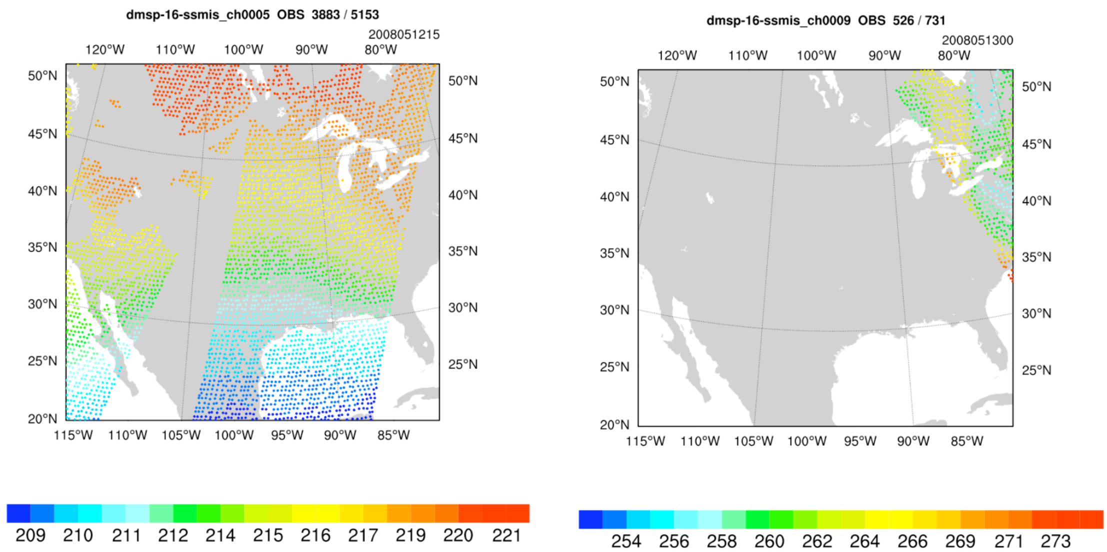


Figure 4.1b.ii-3: SSMIS coverage at 1500UTC May 12th and at 0000UTC May 13th.

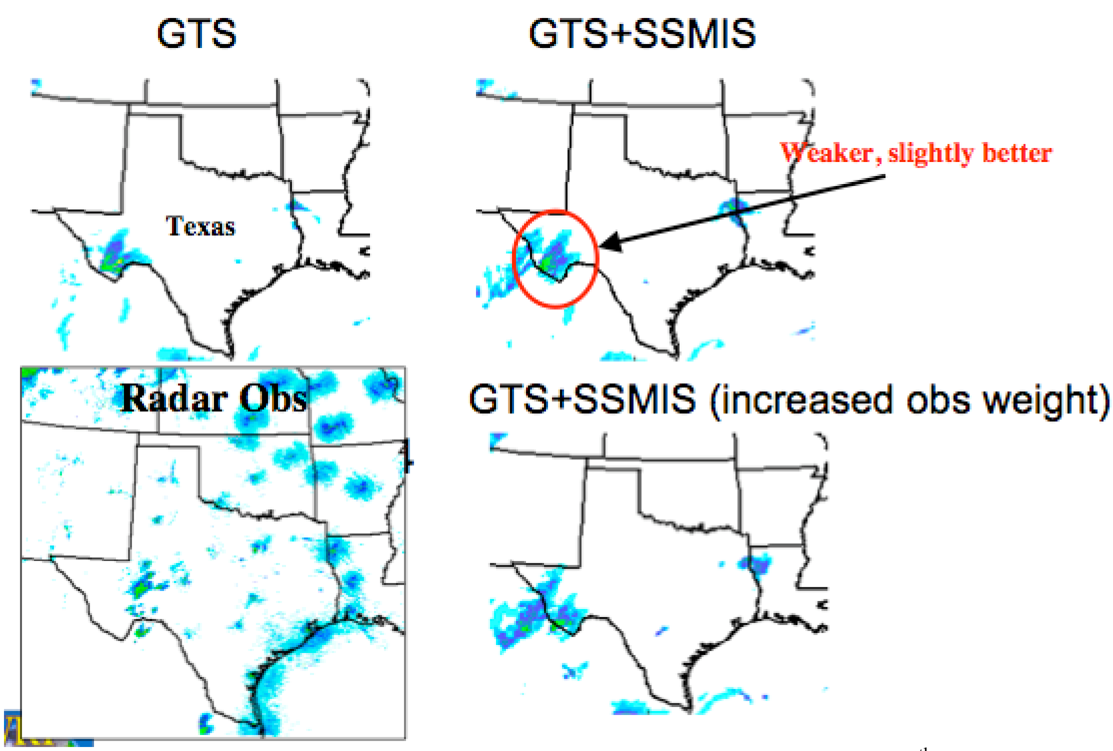


Figure 4.1b.ii-4: Radar reflectivity at the initial time 00UTC, May 13th.

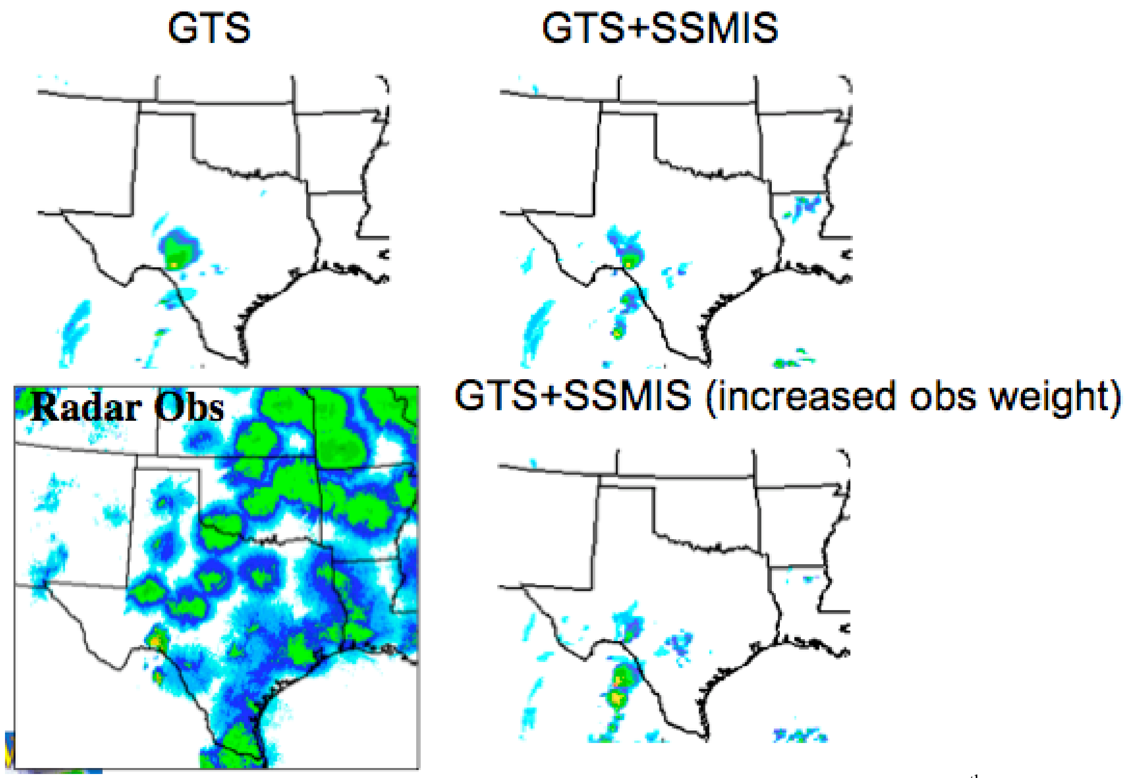


Figure 4.1b.ii-5: Radar reflectivity of 3h forecast, valid at 0300UTC, May 13th.

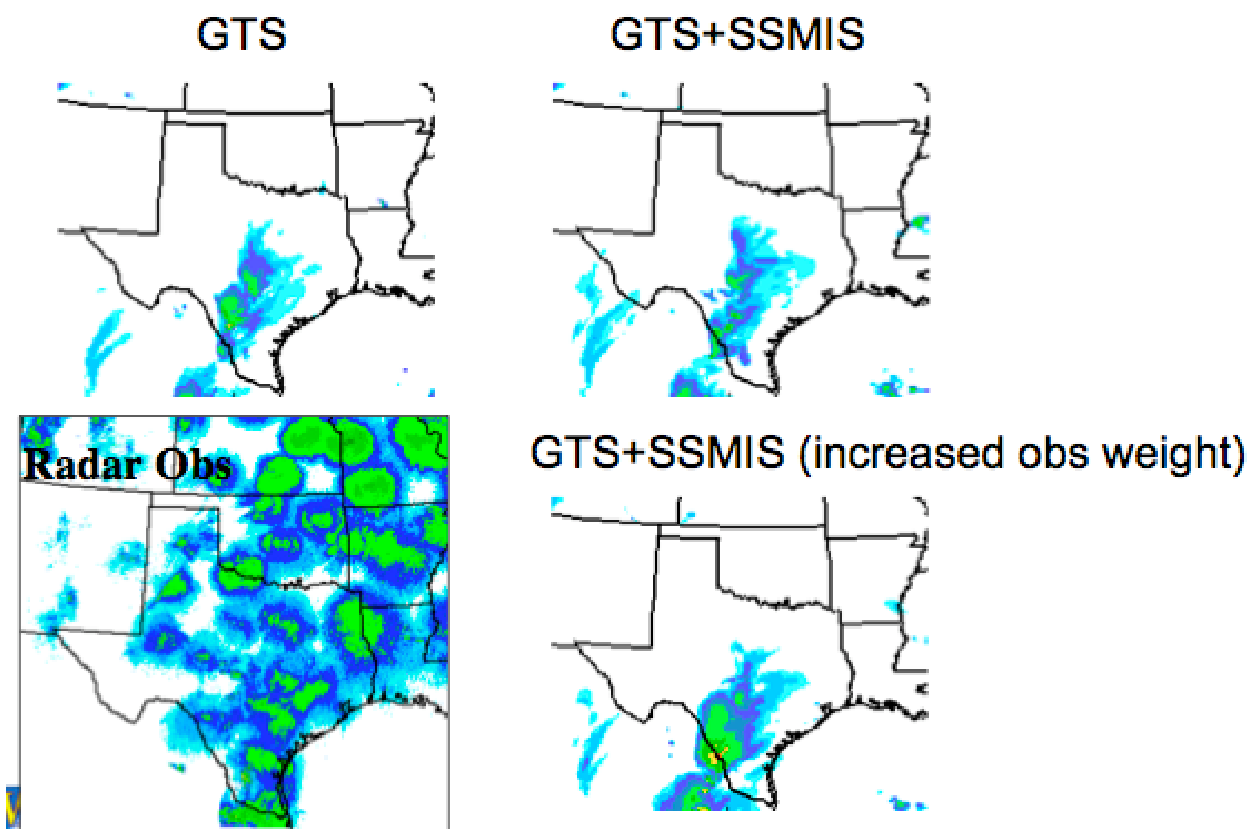


Figure 4.1b.ii-6: Radar reflectivity of 6h forecast, valid at 0600UTC, May 13th.

iii) Further investigate use of CRTM in cloudy radiance mode for microwave instruments including initial development of QC and observation error characteristics under cloudy conditions and summarize results in a report with recommendations to AFWA on further study to achieve accurate cloudy radiance assimilation.

We follow two paths to investigate cloudy radiance assimilation. On the one hand, we developed a 1DVAR research tool in order to better understand the 'physics' of cloudy radiances. On the other hand, the total water control variable Qt scheme for cloudy radiance assimilation in WRF-Var was tested. Currently, studies basically focus on the simulated cloudy radiances both in the framework of 1DVAR and WRF-Var. A more detailed report on the task is attached (FY08_DA_41biii.pdf).

iv) Perform initial evaluation of CRTM cloudy radiance simulation for infrared (AIRS) instrument and summarize results in a report with recommendations to AFWA on further study to achieve accurate cloudy radiance assimilation.

This work represents an initial investigation of problems associated with the simulation of AIRS cloudy radiances. It required to develop additional capabilities inside the CRTM code to compute overcast radiances efficiently. During this study, a new tool has also been developed within WRF system to calculate simulated radiances at each model grid point using CRTM for any satellite instrument. A more detailed report on the task is attached (FY08_DA_41biv.pdf)

4.2 Development Of Unified Variational/Ensemble Radiance Data Assimilation Capability

NCAR will:

i) Further develop the WRF-Var/ETKF hybrid variational/ensemble scheme: Vertical localization, variable-dependent covariance localization, and flow-dependent hydrometeor covariances.

The implementation of the basic hybrid in WRF-Var proceeds as described in Lorenc (2003) and Wang et al. (2008a,b). The hybrid system has been extended to include a) vertical localization and b) flow-dependent hydrometeor covariances. The details can be found in the attached report FY08_DA_42.pdf.

ii) Add capability to make use of ensemble information (spread) with WRF-Var's observation minus background QC check.

The current standard quality control (QC) option in WRF-Var is to reject observations with innovations larger than a threshold, i.e.,

$| \mathbf{Hx} - \mathbf{y} | < C\,\sigma_o$

Where **H** is the observation operator, **x** is the model state, y is the observation, and σ_o is the static observation error. The constant factor C (default is 5) is an empirical number used in WRF-Var. When an ensemble forecast system co-exists with the varational system, the ensemble background error estimates can be used in the QC:

$| \mathbf{Hx} - \mathbf{y} | < C\,[\sigma_o^2+\mathbf{HP}^f\mathbf{H}^T]^{1/2}$

The "QC-OBS" option in WRF-Var is activated to generate modified *filtered_obs* for each ensemble member. The modified *filtered_obs* has grid-wind *u,v,* and vapor mixing ratio *q* for most conventional observations. The ensemble background error variances are computed and added to the observation error by a stand-alone program "***ens_obs_var***" which creates a new *filtered_obs* to be assimilated by WRF-Var.

Results from a 6-day experiment can be found in the detailed report. The ensemble QC is also tested extensively in the one-month hybrid experiment shown in Task 4.3.g. In general, the ensemble QC allows more observations been assimilated, but the impact on the forecast is insignificant.

iii) Code and perform initial tests for an EnKF capability within WRF-Var that leverages the existing QC, bias correction, observation operator and parallelism for all observations.

To build the EnKF capability efficiently, the Data Assimilation Research Testbed (DART), developed at NCAR, is modified and combined with WRF-Var. DART provides not only parallelized EnKF engine, but also many other special treatments in EnKF (horizontal/vertical localization, adaptive inflation, covariance averaging, etc.). An interface between WRF-Var and DART is implemented to convert observations and their ensemble prior estimates computed in WRF-Var to a DART readable observation file. Although the current interface only supports conventional observations in WRF-Var, it can be easily generalized to include other type of observations (radiance, radar, etc.), or to use other data assimilation system (e.g. GSI).

Detailed comparisons of using standard DART (with its own observation operators) and using WRF-Var computed prior estimates can be found in the extended report. Here we only show the vertical structures of the analysis increments of water vapor mixing ratio by assimilating one temperature observation at 500 hPa at 12UTC 2007/08/15 on a 16-member ensemble.

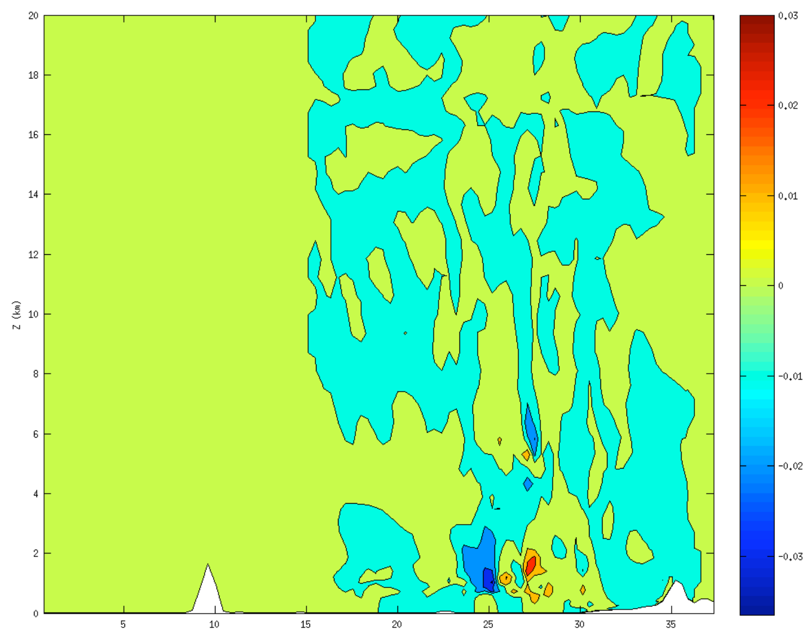


Figure: The north-south vertical structure of the ensemble mean analysis increments of water vapor mixing ratio due to assimilate a temperature observation at 500 hPa at 12UTC August 15, 2007. The ensemble observation prior estimates are computed by WRF-Var.

4.3 Comprehensive Test-Rig for WRF Data Assimilation Developments

NCAR will test the impact of the following capabilities through extended period testing in AFWA-defined theaters. A final report detailing the DATC testing performed will be delivered. The report

will include an impact assessment in terms of a) scientific verification and validation, b) computational performance and, c) Potential technical changes required to implement upgrades at AFWA.

All the sub-tasks under 4.3 have been undertaken using the DATC T8 testbed, which was re-created using the latest WRF and WRF-Var at the beginning of the project (March 2008). A more detailed report is attached (FY08_DA_43.pdf)

a) Variational (Desroziers and Ivanov 2001) retuning of default (obserr.txt) observation errors.

Some minor bug fixes in WRF-Var and tuning utilities have been committed in the DATC branch.

One set of observation error tuning factors (listed in the table below) was calculated using statistics for one-month (15 August - September15, 2007) over the T8-45km domain with both conventional data and SSMIS radiance data assimilated. From these tuning factors, we can see that the default observation errors for surface specific humidity (q) are obviously overestimated. It should be mentioned that the error for moisture observations in the default observation error file, obserr.txt, is in relative humidity (rh) units (%) and WRF-Var internally converts rh error into q error (g/kg). SOUND and PILOT observations have error tuning factors close to 1, indicating that the original error specifications for these observation types are appropriate. The default errors for all other observation types need to be tuned.

Another set of experiments was performed to assess the impacts of implementation of the tuned observation errors in data assimilation after the tuning factors were calculated. With the tuned error factors implemented, WRF-Var converged somewhat faster and the ratio of cost function to observation number was closer to the expected value of 0.5. Though, the impact on forecasts of using the tuned observation errors into data assimilation is minor, the impact on analyses is significant (not shown).

observation errors (as specified in obsproc obserr.txt)

	u	v	t	p	rh
synop	1.10	1.10	2.00	100.00	10%
metar	1.10	1.10	2.00	100.00	10%
ship	1.10	1.10	2.00	160.00	10%
geoamv	4.5/2.5	4.5/2.5			
airep	3.60	3.60	1.00		
pilot	2.20-3.20	2.20-3.20			
buoy	1.40	1.40	2.00	100.00	10%
sonde_sfc	1.10	1.10	1.00	100.00	10%
sound	1.10-3.30	1.10-3.30	1.00		10%

tuning factors (calculated from one-month T8 45km statistics using Desroziers and Ivanov 2001 meth

	u	v	t	p	q
synop	1.53178	1.42053	0.71714	1.01492	0.36295
metar	1.35625	1.37874	0.77263	0.55409	0.41035
ship	1.83227	1.75137	0.55884	1.02982	0.34033
geoamv	0.63814	0.63368			
airep	0.85161	0.89761	0.83873		
pilot	0.94792	1.00316			
buoy	1.32761	1.27819	0.64789	0.62578	0.31459
sonde_sfc	1.34267	1.26656	1.26856	0.97855	0.36821
sound	1.13093	1.12852	1.08534		0.90609

b) Investigate impact on observation rejection algorithm due to multiple "outer-loops".

The necessary code development work has been done to activate analysis "outer loop" and generate statistics for data utilization/rejection for each outer loop. The modified code was tested in both the CONUS and AFWA T8 domain.

A month-long WRF-Var run with multiple outer-loops was conducted in the T8 domain for the testing period of 15 August – 15 September 2007. The following table shows an example of the observation rejection statistics when WRF-Var was run with multiple (two) outer-loops. The statistics suggests that WRF-Var assimilates more data with multiple outer-loops (fewer rejections).

Details and figures are given in the attachment for 4.3b).

			ptop	1000	900	800	600	400	300	250	200	150	100	50	0
obs	type	var	pbot	1200	999	899	799	599	399	299	249	199	149	99	2000
outerloop=1															
sound	U	used		23	86	110	146	262	144	179	193	168	170	166	1647
		rej		1	4	9	4	1	0	2	0	0	1	0	22
outerloop=2															
sound	U	used		24	90	119	149	263	144	181	193	168	171	166	1668
		rej		0	0	0	1	0	0	0	0	0	0	0	1

c) Better fit to observations via the "First Guess At Appropriate Time" (FGAT) technique.
This section of the report to be provided by July 2008.

Configuration for FGAT mode was extended to allow minute-level time window set up in both OBSPROC and WRF-Var. The updated OBSPROC and WRF-VAR codes were tested and the DATC suite scripts were also modified to accommodate FGAT mode related changes.

Two sets of month-long experiments in WRF-Var regular and FGAT mode were conducted in the T8 domain for the testing period of 15 August – 15 September, 2007. The results from these experiments indicate the FGAT technique provides a inceased number of asynoptic observations (GEOAMV, AIREP, PILOT, QSCAT and etc.) for the data assimilation in WRF-Var. Some marginal improvements are noted for the wind, although the overall impact on forecasts is neutral. Details and figures are given in the attachment for 4.3c).

d) the impact of AIRS radiances (final tuning of NCEP 281-channel subset).

AIRS thinning algorithm was improved to pick the warmest pixel within the thinning box, which has a greater chance of being a clear pixel. Cloud detection algorithm, which can retain AIRS channels above the cloud top, was improved to be more computationally efficient by modifying related CRTM subroutines.

Two sets of month-long experiments with and without AIRS data assimilation were conducted at both 45km and 15km resolution grids in the T8 domain for the testing period of 15 August – 15 September, 2007. The WRF-Var system with AIRS data assimilation capability proves to be robust and the configuration for AIRS radiance data assimilation is suitable. The monthly runs show assimilation of AIRS radiance data reduced the biases of moisture forecasts and imposed positive impacts to reduce the RMSEs of the forecasts of wind, temperature and moisture fields throughout the entire forecast range. Details and figures are given in the attachment for 4.3d).

e) the impact of SSMIS radiances (final tuning of AMSU-like channel subset).

AFWA provides two months SSMIS BUFR data. We process the orbital files into the 6-h time window and remove the duplicated pixels between the orbital files. The SSMIS data over T8 domain have the coverage only at 00UTC and 12UTC. Test domain is over Atlantic ocean and also cover partly US continental. The period of the experiments is from 00UTC August 15th to 18 UTC September 15 in 2007. The tests are firstly performed in a 45km resolution, which is served as the "quick look" tests and is helpful to find the problem with a lower computational cost. Then the tests are conducted in a 15km resolution. The experiments documented here are listed as follows.

(1) Experiments in 45km resolution

a. **GTS_CYCL**: assimilate only conventional observations (GTS), full cycling WRF/WRF-Var
b. **SSMIS_CYCL**: assimilate GTS plus SSMIS radiances, full cycling WRF/WRF-Var
c. **GTS_COLD**: same as the experiment a, but the background fields for each WRF-Var assimilation are from a WRF 6h forecast initialized from global GFS analysis. This is a no-cycling run and each assimilation is independent from each other.
d. **SSMIS_COLD**: same as the experiment c, but plus SSMIS radiances.

(2) Experiments in 15km resolution (cycling mode)

e. **GTS**: cycling run, this is the benchmark for evaluating radiance impact.
f. **GTS+SSMIS**: plus SSMIS radiances
g. **GTS+SSMIS+AIRS**: further plus AIRS radiances in addition to SSMIS radiances

Major conclutions include:

Assimilating SSMIS radiances produces a positive impact on upper air atmosphere both in the analysis and forecast scores when verifying the ECMWF analysis, which contains a great deal of radiance information in their 4DVAR assimilation. The impact on moisture is apparently bigger than other for U, V and T. When adding AIRS radiances in addition to SSMIS radiances, further improvement on the analysis and the forecast can be observed, particularly for the wind fields. The SSMIS radiance impact on the surface variables is neutral or slightly negative. However, the AIRS data produces a slightly positive impact. Details and figures are given in the attachment for 4.3e).

f) Evaluate an AFWA Rapid Update Cycle (RUC) using the hybrid variational/ensemble data assimilation algorithm and digital filter.

The digital filter capability was first tested and was integrated into the DATC suite scripts. A complete suite of scripts for the DATC end-to-end hybrid variational/ensemble data assimilation and forecast was built, which supplemented the development work for this system. The AFWA released ETKF code was modified for additional tests.

Three sets of month-long experiments were conducted in the T8 domain for the testing period of 15 August – 15 September , 2007. The experimental descriptions are as the following:

- **Cycling-1 (CYC1):** Cycling with the existing "*da_solve_etkf.f90*" code.
- **Cycling-2 (MDCYC1):** An updated version of *da_solve_etkf.f90* (by Dr Chris Snyder) was implemented for additional tests.
- **Cycling-3 (3DVAR):** This run has covered usual 3D-VAR runs with deterministic forecast, no ensembles. We wanted to compare its results with above listed "hybrid" runs.

With the analyses generated from these three experiments respectively, WRF was run through the whole time period and produced deterministic forecasts up to 48 hours.

The CYC1 run was performed using a slightly modified version of ETKF ("*solve_etkf*") code. Modest inflation factors were generated and no run failures have been noted. The MDCYC1 is similar to the CYC1 run, except that a new version of "*solve_etkf*" code was used. It produced two-three times higher inflation factors compared to those of CYC1 run. There were a few CFL issues. It has been noted in other studies that lack of localization in ETKF causes such problems when there is a tropical cyclone or hurricane present (personal communication with Drs Chris Snyder and Josh Hacker). Verification results of these three cycling runs have indicated that "hybrid" based runs provide improved RMSE scores compared to 3DVAR run. Details and figures are given in the attachment for 4.3f) and 4.3g).

g) Test Ensemble-based QC (from task 4.2.ii) applied in the above RUC application.

The code was developed for the task **4.2.ii**. Some new scripts to incorporate the ensemble-based QC into the end-to-end hybrid WRF-Var/ETKF and WRF system were added.

Two sets of month-long experiments with and without the ensemble-based QC features were conducted in the T8 domain for the testing period of 15 August – 15 September , 2007. The diagnostic studies show the former experiment (with ensemble-based QC feature) contains many more observations compared to the latter. We've also verified results with observations. The overall results indicate that "QC_ENS" with "hybrid" runs provides encouraging results compared to 3DVAR based standard runs. Details and figures are given in the attachment for 4.3f) and 4.3g).

h) Access, decode, and perform extensive sensitivity study of the utility of assimilating ground processed QSCAT & WINDSAT EDRs.

This section of the report to be provided by July 2008.

Two sets of month-long experiments with and without QSCAT observations were conducted in the T8 domain for the testing period of 15 August – 15 September , 2007. QSCAT observations were thinned before being ingested into the data assimilation system. Cycling experiments with QSCAT data have shown that assimilation of QSCAT data imposes positive impacts on the surface wind analyses and forecasts up to 24 hours and marginal impacts beyond the boundary layer. Details and figures are given in the attachment for 4.3g).

Due to lack of WINDSAT data in "little_r" format, the extensive test of impacts of WINDSAT EDRs is suspended.FY07 carryover tasks

FY07 Carryover Tasks

FY07 4.1c iii) Modify WRF-Var to match the Arakawa-C grid and variables of WRF.

WRF-Var has been updated to perform analysis on Arakawa-C grid. Updated code has been extensively tested in several possible ways both in single and MPI environment. Stability of the updated code has also been tested in cycling mode. WRF-ARW forecasts produced with analysis on Arakawa-C grid is very stable and compares well with the forecasts produced by WRF-Var on Arakawa-A grid. Scores like RMSE, suggests that the quality of WRF-Var analysis produced on Arakawa-C grid is slightly better than the on A-grid. As expected, the updated WRF-Var code should reduce the computational cost for 4DVar. Updated code was tested for 4D-Var computational efficiency in a small domain consisting of 31x25x17 grid points. Results show, a gain of 12% computational efficiency. A more detailed report is attached (FY07_DA_41c_iii.pdf).

FY07 4.1c.iv) Lateral Boundary Condition control in WRF-4DVAR data assimilation system

Background

It is well known that lateral boundary conditions (lbcs) have significant influence on forecast results with regional models because of advection of information from boundary region into model interior domain from all inflow directions within 3-dimensional model domain. Damaging impact of uncertainties in lbcs on the forecast has been demonstrated in many research studies as well as through standard operational forecast practice. Since weather data analysis by means of data assimilation relies heavily on model forecast it is desirable to account for and to reduce impact of uncertainties in the lbcs when correcting the forecast by observations. In four-dimensional variational (4DVAR) data assimilation approach the impact of lbc uncertainties could be reduced by including lbc quantities in a control vector when minimizing 4D cost function.

Approach to control of lbc in WRF-4DVAR

To include the lbc control in the 4DVAR system with WRF it is necessary to start from formulation of the lbcs in the WRF model. Several different formulations of the lbcs are available in the WRF model (WRF technical document, Skamarock, et al, 2007, 2008). The specific formulation of interest to the data assimilation is referred to as “specified lbcs”. The specified lbcs (slbcs) are used in all model simulations/forecasts which include real world, as opposed to idealized, cases. The slbcs formulation is obviously the only option for the operational forecast applications.

The slbcs formulation is detailed in the WRF modeling system technical documents (Skamarock et al., 2007, 2008). The formulation is based on updating a rate of change of a prognostic variable in the following way, after Davies and Turner (1977),

$$\frac{\partial \psi_n}{\partial \tau} = f_1(\psi_{LS} - \psi) - f_2\Delta^2(\psi_{LS} - \psi) \qquad (1)$$

where, ψ_n is a prognostic variable at a grid point within so called boundary zone (Figure 6.1 in Skamarock et al., 2007), ψ_{LS} is value of the prognostic variable from an external data source such as global model simulation (so called large scale data) and f_1 and f_2 are coefficients, referred to as “weighting function coefficients”. The operator Δ^2 is a 5-point horizontal smoother . The expression (1) is the same as the expression (6.1) in (Skamarock et al., 2007). The weighting coefficients are directly proportional to distance in grid point index space of the point within the zone from the perimeter and inversely proportional to model time step (thus update of the time rate of change).

From the expression (1) it is evident that the influence of uncertainties in lbcs, pertinent to the data used and not numerics, on the model solution results from uncertainties contained in ψ_{LS} . This implies, as expected, that the uncertainties in a global model solution or other source of large scale data in the regional forecast is the source of slbc errors.

To reduce these errors in the lbcs by the 4DVAR data assimilation approach, the new control variable vector must include quantities which define ψ_{LS}. These are large scale grided fields of horizontal wind components, potential temperature, perturbation pressure and humidity. These quantities are typically available on coarser grid and only every several hours in time (typically every 6 hours). Consequently, for the WRF model forecast the quantities in ψ_{LS} are spatially and temporally interpolated values of the original large scale quantities (Skamarock et al., 2008).

There are two possible choices for defining the slbcs control vector. One is to use already interpolated, in space and time, quantities and other is to use the original large scale quantities. Because the latter approach would involve including a data preprocessing algorithm (WPS) in the data assimilation it would be more complex to implement. Thus, we would opt for defining the slbc control variables using already interpolated fields. An additional desired property of this approach results from the fact that the lbc quantities on the forecast model grid are time dependent which is similar to many additional sources of model uncertainties that may be considered in future versions of WRF-4DVAR. This implies that introducing of the slbc control in 4DVAR could serve as template for treating other time dependent model errors which would be by design also represented on the forecast model spatial grid.

In summary, the slbc control in the WRF-4DVAR would include the following: wind, potential temperature, pressure and humidity fields on the forecast model grid within the specified relaxation zone at several time instances within data assimilation interval. g Because the time interpolation operator that is applied to the slbc data fields is implemented within the forecast, and not in the preprocessing, the time instances (or points) which would characterize time dimension of the slbc control vector are specified by frequency of large scale data.

The introducing of the slbc control variable in 4DVAR requires that the cost function is augmented to include a background term for this control. This is expressed

$$J_d = \frac{1}{2}\left[\psi_{LS}(n,\tau_{lbc}) - \psi_{LS}^b(n,\tau_{lbc})\right]^T B_{lbc}^{-1}\left[\psi_{LS}(n,\tau_{lbc}) - \psi_{LS}^b(n,\tau_{lbc})\right]$$

where the superscript b indicates background (or first guess) values and B_{lbc}^{-1} is inverse of background error covariance for the slbc control. This error covariance could be assumed diagonal using only estimates of error variance or could be (eventually) obtained from an estimate of large scale error covariance for the quantities in ψ_{LS}. The former approach would be used.

Code development

Introducing of the slbc control in WRF-4DVAR included following code development:

a) Tangent linear (tl) and Adjoint (ad) modules of lbc updates in the forecast model (the expression (1))
b) Computing of new background component of the cost function

c) Introducing new control variable in minimization

The **tl** and **ad** slbc operators , consisting of several functions or routines in the WRF **tl** and **ad** models were written already in 2006-07 period. In the period of the current task (2008) the existing tl and ad codes were only evaluated to ensure consistency between the nonlinear, tl and ad computations. The existing tl and ad slbc code is consistent with WRF-V2 model code.

New background cost function was introduced in the optimization portion of the WRF-4DVAR code system (referred to as **var** component of the system)

Programming on introducing of the new control variables in **var** was started but not completed by the data of this report

Numerical results

The only numerical result accomplished were **tl** and **ad** consistency tests. Due to incomplete code in **var** with new slbc control variables the 4DVAR with the slbc control has not been tested.

Future work

The current task will continue by Vukicevic without additional cost. Vukicevic is PI on another ongoing project involving new developments in WRF-4DVAR (Improving forecast of precipitation by . This project is entitled "Improving prediction of precipitation by objective estimation of bulk effects of cloud and precipitation microphysical processes"; Sponsored by NSF - ATM 0754998; Funding period May 1 2008-April 30 2011.

FY07 4.2b ii) Perform study of the multivariate nature of tropical and mesoscale ensemble-based forecast error covariances, and their potential application within WRF-Var

An initial effort has been made to incorporate cross-correlation between moisture and other analysis control variables using temperature and moisture (relative humidity) correlations. With this simple approach, results are very encouraging in producing a good multivariate moisture analysis. In the sense that with new formulations of moisture analysis control variables, moisture data do have influence on wind and temperature analysis and vise-versa. The new formulation has been tried out on three different domains (T8, CONUS and TROPICAL) with different horizontal and vertical resolutions. A detailed report is attached (FY07_DA_42b_ii.pdf).

FY07 4.3d Set up, and test performance of WRF grid-nudging capability in a high-resolution AFWA domain

The T8-15 km domain and a period of seven days in August 2007 (August 15 – 21) are selected for this task. A pair of experiments were conducted for the fourteen initial times at 0000 and 1200 UTC in the week. The first was the control run using GFS analysis and forecast as initial and boundary conditions. The model configuration is identical to those used for other development and tests utilizing this domain, except for the upper w-Rayleigh damping option that has become available in WRF Version 3. The second experiment started the model at t-12 h and used gridded analysis nudging as a way to dynamically initialize the model. The nudging was ramped down at the end of the 12 h pre-forecast period to minimize the shock when the nudging term was switched off. The nudging coefficients for wind, temperature and mixing ratio were chosen to be 0.005, 0.003 and 0.001, respectively. The 1x1 degree GFS analyses at 6 hourly interval were used during this 12 hour period. A 48 hour forecast was followed.

Verification using conventional observations (from radiosondes and surface stations) via MET (Model Evaluation Tools) shows that there are very small differences in the RMSE statistics between the two runs. An example of the temperature verification is shown in Fig. 4.3.1. Since a large portion of the domain is over water, caution should be taken to interpret the verification results.

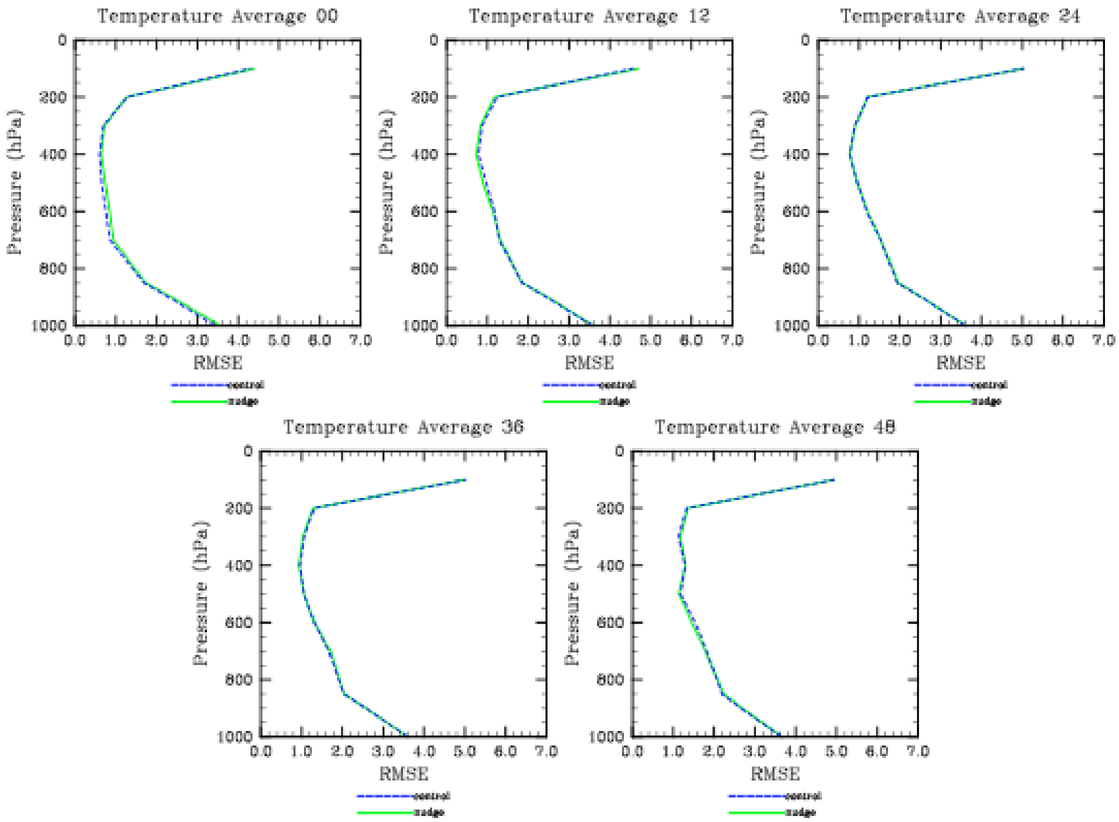


Figure 4.3.1 RMSE plots of temperature for the forecast hours of 0, 12, 24,36 and 48 hours. The blue dashed lines are for the control runs and green solid lines are for the nudging runs.

In the last bi-monthly report, an analysis of tropical storm Erin forecast from 0000 UTC August 15 was presented, and it indicated some benefit of using a pre-forecast period with nudging in the model simulated tropical storm structure (e.g. warm core at 800 – 650 mb layer).

The week of August 15 – 21 was the week when tropical storm Dean evolved to a category 5 hurricane when it made landfall at Yucatan. Track and mean intensity errors (as measured by the mean sea-level pressure) for the 48 hour forecast periods at 6 hourly interval were computed against best track data and averaged, and the figures are shown in Fig. 4.3.2. The model storm position is estimated using RIP4, a supported post-processing program. Since the 1x1 degree GFS analyses were used to initialize the model and as the target analyses for nudging, the intensity of the storm was not represented well at the initial times. This is illustrated clearly in the intensity error plots. As the model progressed, the intensity errors were decreased. The runs with the 12-h pre-forecasting period show somewhat better performance in the first-day forecasts.

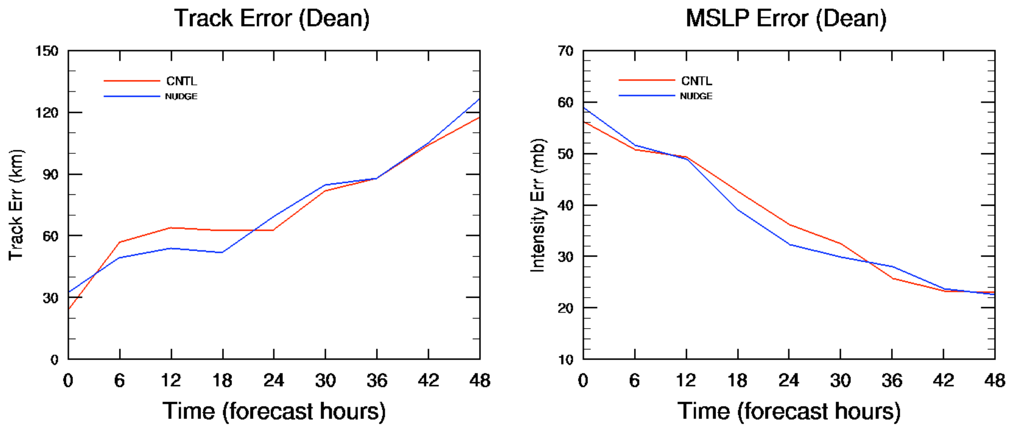


Figure 4.3.2 Track errors (left, in kilometers) for Hurricane Dean (August 2007), and intensity error as measured by mean-sea-level pressure (right, in mb). The red line is the error from the control runs, and blue line is for the runs with 12-h pre-forecasting period.

Like the analysis with Erin, the benefit of having a pre-forecasting period can be seen in some of the forecasts where the storm can reach the hurricane intensity sooner. An example of the forecast is shown in Fig. 4.3.2. In the run with the 12-h pre-forecast, the storm reached hurricane intensity about 12 hours earlier than the run without. The mean sea-level pressure at 24 hour forecast time are 994 mb in the control run versus 981 mb in the run with the pre-forecast.

These experiments demonstrated some benefit of using a pre-forecasting period with nudging toward a global analysis. If the analysis comes from higher resolution dataset, it might be possible for the mesoscale model to benefit more.

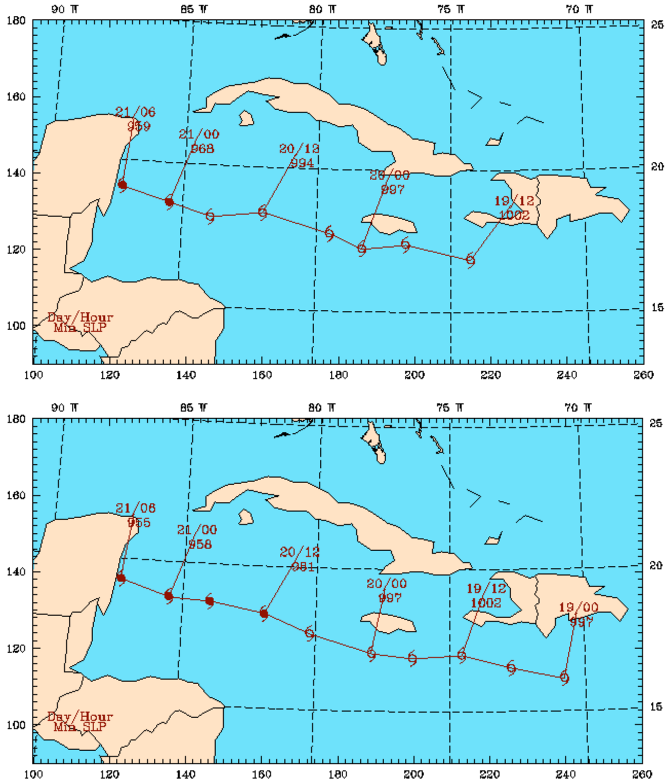


Figure 4.3.3 Six-hourly track positions from runs starting at 1200 UTC August 19. The top one is from the control run, and bottom from the nudging run. The solid hurricane symbols indicate the storm intensity has reached hurricane intensity (< 981 mb).