Recent development of satellite data assimilation at JMA

Kozo Okamoto, Masahiro Kazumori, Takumu Egawa, Toshiyuki Ishibashi, Hiromi Owada, Akihiko Murata and Hidenori Nishihata

Japan Meteorological Agency (JMA), Tokyo, Japan

Abstract

Recent developments in satellite data assimilation at JMA since the last TOVS conference in May 2008 are presented. JMA introduced various satellite data in the global operational 4D-Var assimilation system: SSMIS of DMSP-F16 and -F17, NOAA19/AMSU-A and MHS, and Metop/ASCAT ocean surface wind and GRAS refractivity. Pre-processings of radiance assimilation was unified and improved for the better maintainability and extensibility and for increasing accuracy of analysis. Bias corrected radiances of SSMIS imaging and temperature sounding channels are comparable to corresponding channels of SSMI and AMSU-A in quality and show slightly positive impacts on forecasts. Assimilation of clear sky radiances of AIRS and IASI reduces warm biases in the upper troposphere in the low latitude but further development is needed for the operational implementation because there is degradation in the lower tropospheric temperature. The website is opened for real-time monitoring of radiances and AMVs: http://qc.kishou.go.jp/

1. Outline of JMA NWP system and satellite data (to be) assimilated

JMA operates two deterministic forecast models: the global spectral model (GSM) and mesoscale model (MSM, Japan Meteorological Agency 2007). GSM provides short-range (1 – 2 days) and one-week forecast and aeronautical forecast, and runs every six hours. The resolution is TL959L60 (roughly 20 km in horizontal resolution) with model top height of 0.1 hPa. MSM provides the disaster prevention information such as heavy rain prediction around Japan. It is a non-hydrostatic grid model with a horizontal resolution of 5 km and 50 vertical layers up to about 22 km (Saito et al. 2006). MSM runs every three hours and performs 15-h forecast at 00/06/12/18 UTC and 33-h forecast at 03/09/15/21 UTC.

The global data assimilation system is based on incremental 4D-Var with the resolution of TL959L60/T159L60 in the outer/inner loop. 6-hour assimilation window is divided into six time slots of about 1-hour. Data cut-off times are 2h25m for the early analysis, and 5h35m and 11h35m for the cycle analysis at 00/12 UTC and 06/18 UTC, respectively. Variational Bias Correction (VarBC, Sato 2007; Ishibashi 2009) is applied for all radiance data.

The assimilation system of MSM was significantly upgraded from a hydrostatic-base to a non-hydrostatic base in April 2010, where system components were fully investigated and renovated including control variables and penalty term suitable for a non-hydrostatic model (Honda et al. 2005). The new MSM 4D-Var, or JNoVA (JMA Non-hydrostatic model based Variational data Assimilation system), has the resolution of 5/15 km in the outer/inner loop. Assimilation window is three hours with three 1-hour time slots and data cut-off time is 50 minutes. While the global 4D-Var system assimilates radiances from various satellites, JNoVA still assimilates retrievals such as temperature profiles from ATOVS and total column water vapor (TCWV) from microwave imagers. The development of radiance assimilation in JNoVA is underway.

Satellite data operationally assimilated and to be assimilated in the global and meso-scale analysis systems are shown in Table 1 as of April 2010.

Table 1: Satellite data operationally assimilated in the global and meso-scale analysis systems as of April 2010. The table includes data under development of assimilation, depicted in parentheses.

Satellite/Instrument		Global Analysis	Meso-scale Analysis
Sounder	NOAA15,16,18,19/AMSU-A	Radiance	Temperature , (→Radiance)
	NOAA15,17,18,19/AMSU-B,MHS	Radiance	Temperature , (→Radiance)
	Aqua/AMSU-A	Radiance	(Radiance)
	Metop/AMSU-A,MHS	Radiance	Temperature , (→Radiance)
	DMSP16/SSMIS	Radiance	(Radiance)
	(Aqua/AIRS, Metop/IASI)	(Radiance)	(Radiance)
MW Imager	TRMM/TMI	Radiance	TCWV(→Radiance) , Rain Rate
	Aqua/AMSR-E	Radiance	TCWV(→Radiance), Rain Rate
	DMSP16,17/SSMIS	Radiance	(TCWV(→Radiance), Rain Rate)
VIS/IR Imager	MTSAT-1R, Meteosat-7,9, GOES-11,12	Radiance	(Radiance)
		AMV	AMV
	Aqua,Terra/MODIS	AMV	X
Scatterometer	Metop/ASCAT	Ocean surface wind	(Ocean surface wind)
GPS-RO	GRACE	Refractivity	(Under development)
	Metop/GRAS	Refractivity	(Under development)
Ground-based GPS		(Zenith Total Delay)	TCWV (→Zenith Total Delay)

2.1 Unify and improve pre-processings of radiance assimilation

JMA's operational data assimilation system consists of decoding, short-range forecast to create first-guess, observation pre-processings, main analysis and post-processings. The observation pre-processings include QC, thinning, adjusting of observation errors and bias correction, and run separately depending on data type. Radiance pre-processings had been developed separately for sounders, clear sky radiances (CSRs) of geostationary satellite imagers and MW imagers despite using several same processing packages including RTTOV. Since this separate development had harmed the maintainability of source codes and extensibility to the new instruments, the unified pre-processings of radiance assimilation were created. In addition, improvements of pre-processing were made (Kazumori 2009a): First, cloud screening QC was made stricter for MW imagers by changing rejection criterion of total column cloud liquid water (TCCLW) from 0.18 kg/m^2 to 0.1 kg/m^2. In order to remove residual cloud effect on radiance, TCCLW was added as a VarBC predictor. Second, using ATOVS pixels at both edge scan positions was resumed because their O-B statistics were not profoundly different from those at inner positions. Finally RTTOV-8.7 was introduced in both pre-processing and main analysis instead of RTTOV-7. The improved pre-processings resulted in making fewer but more reliable MW imager data available, increasing ATOVS data and more accurate estimation of MW ocean surface emissivity. Cycle experiments including the new radiance assimilation pre-processings and using RTTOV-8.7 in the main analysis showed a clear improvement of tropospheric humidity analysis by reducing model dry bias. Forecast of tropospheric temperature and geopotential height, especially over the ocean in the Tropics and S.H., were improved. The new radiance pre-processings and the introduction of RTTOV-8.7 became operational in October 2008.

Furthermore, the latest version of RTTOV (version 9.3, Saunders et al. 2008) was introduced in the operational global data assimilation system in March 2009 (Kazumori 2009b). In our cycle experiment to asses impacts of using RTTOV9.3 relative to using RTTOV8.7, stratospheric temperature forecasts were significantly improved verified against their own analyses (left panel of Fig. 1) and GPS-radio occultation (RO) retrievals (right panel of Fig. 1). This improvement is caused by better Jacobian mapping from a newly introduced vertical interpolation algorithm (Rochon et. al. 2007) and by discontinuing invalid Zeeman effect (Kobayashi et.al. 2009).

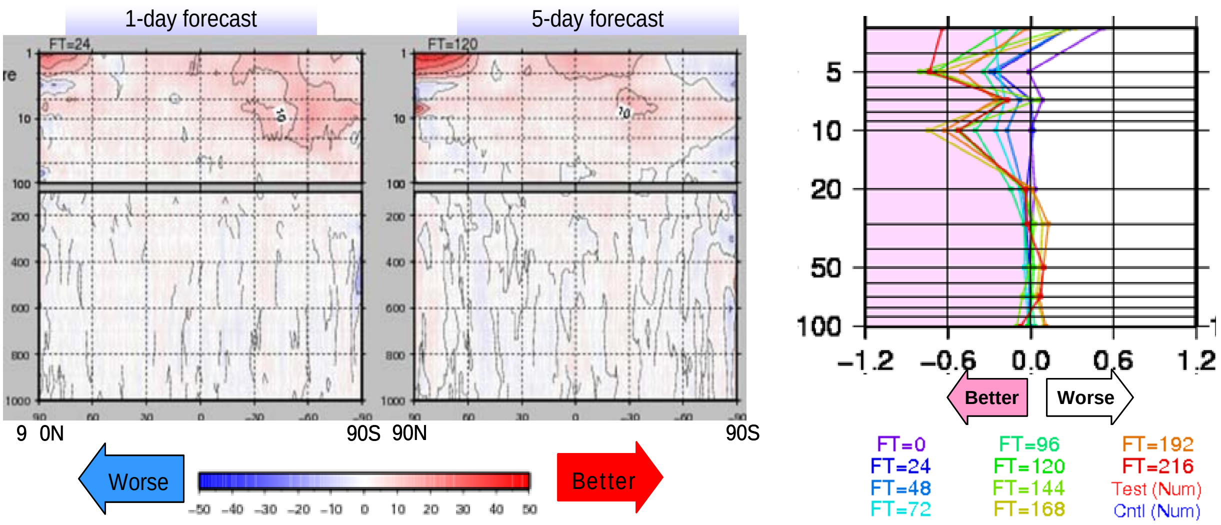

Figure 1: (left) Monthly zonal mean of forecast improvement rate for temperature in September 2008. The improvement rate is defined as normalized root mean square of forecast error difference and positive values indicate smaller forecast errors. (right) Difference of standard deviation for temperature forecast in the N.H. verified against GPS-RO

2.2 SSMIS radiance assimilation

JMA has been assimilating clear radiances of MW imagers in the global data assimilation since May 2005 (Okamoto et al. 2008). We have been receiving SSMIS SDR of DMSP-F16 and -F17 from NESDIS and UKMO via ftp. Although SSMIS suffers calibration anomaly of unexpectedly large emissivity of reflector and warm load contamination by sunlight, these organizations have been developed correction algorithms and providing corrected data. It was found that the quality of most channels of SSMIS are comparable to that of corresponding channels of SSMI and AMSU-A after QC and bias correction (Fig. 2). Thus, we assimilate clear radiances of SSMIS imaging and temperature sounding channels in a similar way to SSMI and AMSU-A, respectively.

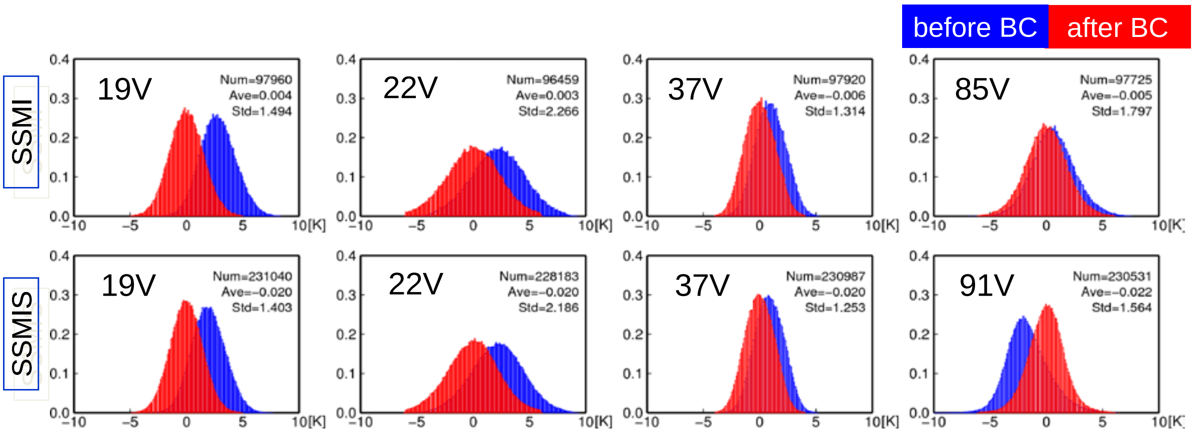

Figure 2: Frequency distribution and statistics for the O-B of brightness temperature before/after bias correction.

For imaging channels of SSMIS, channels 13, 14, 16 and 17 (19V, 22V, 37V and 92V) are assimilated over the ocean. The same pre-processings as other MW imagers (Okamoto et al. 2008) are applied for SSMIS: (1) removing cloud affected pixels using cloud indices and TCCLW criteria (see the Section 2.1), (2) gross error QCs for O-B with respect to brightness temperatures and TCWV retrievals, (3) thinning to one pixel in a 200 km box, (4) inflating observation errors (four times larger than predefined error values estimated from O-B standard deviation), and (5) correcting biases using a linear regression approach whose coefficients are given by the previous analysis with VarBC. Impacts of the addition of SSMIS imaging channel radiances on the analysis and forecast were small and neutral. Assimilating TCWV and rain rate retrievals in JNoVA, as is done for other MW imagers, is under development.

For temperature sounding channels of SSMIS, tropospheric channels 2, 3, 4 and 5 are assimilated. Channels 6, 7 and 24 are removed due to large bias inconsistency on ascending/descending orbits. Channels 21, 22 and 23 are not used because they are sensitive to temperature above the model top. A scan line QC, which removes data whose scan lines are erroneously located, is added to AMSU-A QC procedures such as cloud and gross-error QCs (Okamoto et al. 2006). Larger observation error (1.0 K) and smaller thinning distance (160 km) than AMSU-A (0.4 K and 250 km, respectively) are assigned. Two 50-days cycle experiments in September 2008 and January 2009 showed the addition of those temperature sounding channels of DMSP-F16/SSMIS slightly improved data coverage and yielded positive impact on short-range forecasts of Z500 in the S.H. More details about assimilating the imaging and sounding channels of SSMIS can be found in Egawa (2010) and Kazumori (2009c), respectively.

2.3 AIRS & IASI clear radiance assimilation

The assimilation of clear radiances of the hyperspectral infrared sounders of AIRS and IASI has been developed. We have been receiving AIRS 324 channel data at warmest FOVs from NASA and IASI 616 channel data at all FOVs from NESDIS via ftp. The current target of assimilation is radiances sensitive to the stratospheric and tropospheric temperature in the CO_2 15 µm and 4.3 µm bands. Channels affected by ozone or minor gases, the surface and the atmosphere above the model top are rejected. Shortwave infrared channels of IASI are removed because of large instrumental errors. As the first step of assimilation development, humidity sensitive channels are not included because of relatively difficult usage in that their high nonlinearity and humidity biases of our forecast model may deteriorate analysis. Among remaining channels, channels with higher priority are selected using a measure of an entropy reduction (ER, Rogers 2000; Rabier et all 2002). Because it is found that both ER and reduction of analysis error based on a MAP analysis does not differ so much by adding channels over 100 channels, 82 channels of AIRS and 74 channel of IASI are used. We are planning, as a next step of development, that additional channels will be used in order to extract the humidity and lower tropospheric information.

Channels affected by clouds are identified and removed using cloud top height (CTH) determined by a

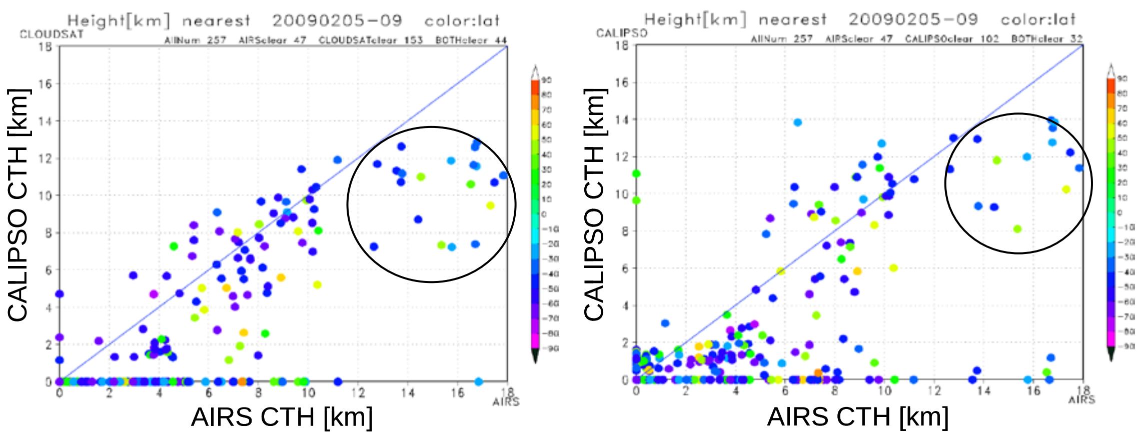

Figure 3: Comparison of AIRS cloud top height (CTH) with those from CloudSat (left) and CALIPSO (right) from 5 through 9 February 2009. CloudSat and CALIPSO CTHs are taken from 2B-GEOPROF and 2B-GEOPROF-LIDAR data set, respectively, and matchup criteria are 5 km from the center of AIRS FOV and 20 minutes.

CO2 slicing method. The method often fails to identify CTH for small clouds or positive O-B of reference channels. In these cases, clear detection algorithms are applied based on cloud flag derived from the VIS/NIR imager of AIRS and AVHRR cloud analysis collocated with IASI FOV, and comparison of JMA's SST analysis with SST retrieval from AIRS or IASI observation. Please note that the clear detection uses no atmospheric background information while the CO2-slicing method uses it, indicating the latter can be affected by model biases and dependent on the performance of the current O-B based bias correction procedure. If CO2-slicing fails but the clear detection algorithm declare clear, the pixel is flagged as clear. If both CO2-slicing and clear detection fail, it is assumed that clouds are located at the tropopause. This assumption may cause wrong assignment of excessively high CTH to some clouds and remove some channels that would be used if correct CTH is given. This feature is somewhat confirmed from comparisons with CloudSat and CALIPSO (circles of Fig. 3). This is, however, safer than vice versa because it prevents cloud-contaminated channels from wrongly used. Figure 3 shows that CTH from AIRS agrees with CloudSat and CALIPSO within 1-2 km but AIRS overestimates CTH for high clouds, described above, and identifies clouds where CloudSat and CALIPSO do not, probably because of different FOV sizes.

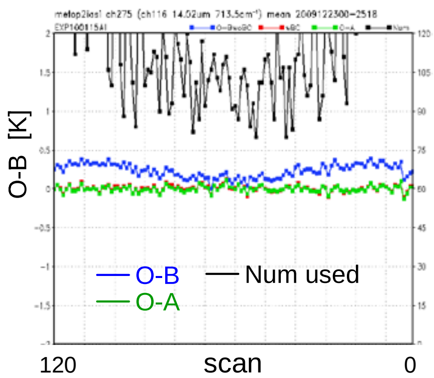

Figure 4: O-B mean vs. scan position for IASI channel 275 from 23 through 25 December 2008. Mean observation-minus-analysis (O-A) and number used also plotted in green and black line.

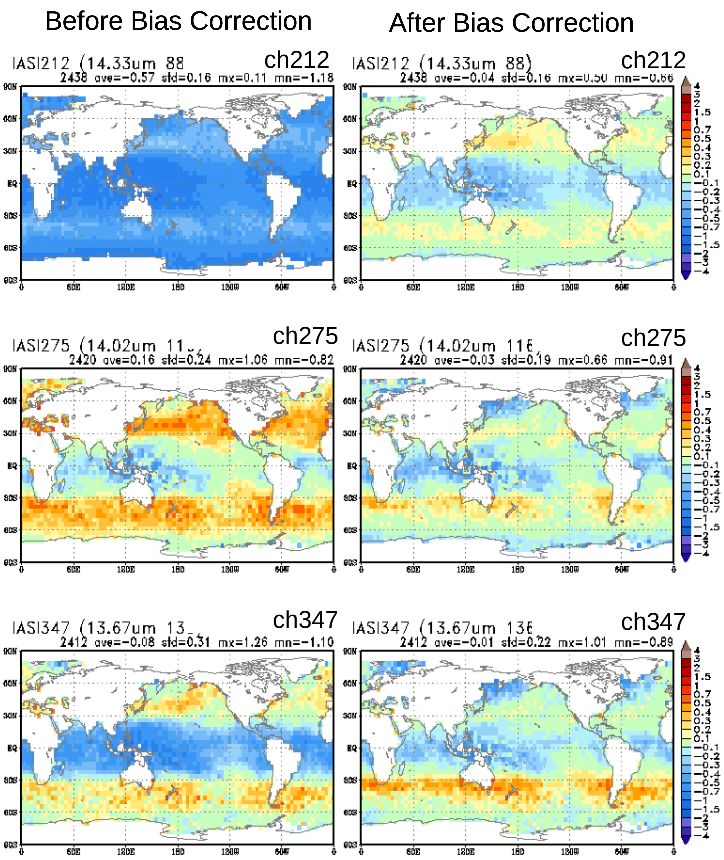

Figure 5: Monthly averaged O-B of IASI channels 212, 275 and 347 before (left column) and after (right column) bias correction. The average is taken from 1 through 31 January 2009.

Removing biases of brightness temperature is crucial not only because variational assimilation assumes there are no biases in observations used but also because bias corrected O-B is used in QC and cloud detection of CO2 slicing method. VarBC is applied for both AIRS and IASI with the predictors of normalized brightness temperature calculated from first-guess, nadir view angle raised to one, two, three and four, and constant. Adding the fourth-order term, unlike Collard and McNally (2009), is based on the variation of O-B of channels sensitive to lower tropospheric temperature with nadir view angle (blue line in Fig. 4). Figure 5 shows monthly averaged O-B before and after the bias correction for channels 212, 275 and 347 of IASI, sensitive to the stratospheric temperature, upper tropospheric temperature and mid-tropospheric temperature, respectively. The biases for these channels are reduced after the bias correction but still remains in the low latitudes for all of these channels (negative biases) and the latitude band of 30-50S for the tropospheric channels (positive biases). We suppose that most of these remaining biases results from model biases, shown in Fig. 6, but cannot deny the possibility of deficiencies of cloud detection and bias correction procedures. The validation of these procedures is still underway.

Cycle experiments to assess IASI and AIRS assimilation has been conducted for 20 December 2008 through 9 February 2009 ("Jan2009" experiment) and 20 July through 9 September 2009 ("Aug2009" experiment) using a low-resolution suite of the operational global data assimilation system. Monthly average of zonal mean temperature difference in the right panel of Fig. 6 shows the IASI and AIRS assimilation cools the upper troposphere around 200 hPa in the low latitude and warms mid-troposphere in the 30-60 degrees in the S.H., reflecting Fig. 5. Compared with the 3-day forecast temperature error shown in the left panel of Fig. 6, this analysis difference demonstrates that the AIRS and IASI assimilation successfully reduces model biases. This favorable impact is also found in much better fitting to radiosonde temperature at 200 hPa and is kept until 2-day forecast. However, the cooling of lower troposphere in the mid-latitude in the summer hemisphere seems to be excessive and does not agree with ECMWF analysis (not shown). We have found from sensitivity tests that the cooling does not result from observation themselves nor background error covariance. Thus, we

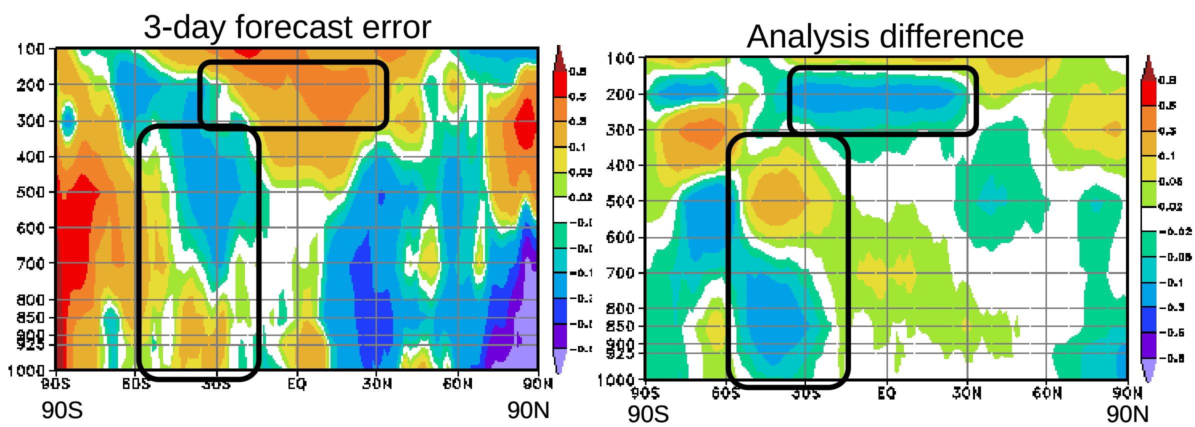

Figure 6: Monthly averaged zonal mean temperature in January 2008. (Left) 3-day forecast error against initial state. (Right) analysis difference by assimilating the AIRS and IASI radiance.

suppose that it is related to some model processes. The IASI and AIRS assimilation slightly increases moisture in the analysis, being in better agreement with AMSR-E retrievals. Forecast scores show seasonal and field dependency: MSLP improved in both Jan2009 and Aug2009 experiments but T850 and wind speed at 250hPa degraded in Jan2009 experiment. We are investigating the cause of these degradations, including the effect of cloud missed, remaining biases, interaction among cloud detection, QC and bias correction, and model response to the analysis field modified by AIRS and IASI.

3. Plans

JMA has been steadily introducing new satellites and improving processings in the operational data assimilation systems. However, there are significant developments needed including radiance assimilation of hyperspectral sounders in the global analysis. Also, replacing retrieval assimilation with radiance assimilation is important issue. Preliminary results that assimilating radiances instead of temperature retrievals from AMSU-A are encouraging (Kazumori 2010) while there are issues peculior to regional assimilation systems: implementing VarBC where data available are highly variable in each analysis and limited channels used due to low model top.

Other developments with radiance assimilation in the global analysis are assimilating cloudy/rainy radiances and utilizing more data over land by introducing better land emissivity estimate. Moreover, optimizing observation error covariance matrices and building an observation impact estimation scheme are underway (Ishibashi 2010).

References

Collard, A. D. and A. P. McNally, 2009: The assimilation of Infrared Atmospheric Sounding Interferometer radiances at ECMWF. *Quat. J. Roy. Meteorol. Soc.* **135**, 1044-1058

Egawa, T., 2010: Assimilation of SSMIS Imager Channels in the JMA's Global 4D-Var Data Assimilation System. CAS/JSC WGNE Research Activities in Atmospheric and Oceanic Modelling. (in press).

Honda, Y., M. Nishijima, K. Koizumi, Y. Ohta, K. Tamiya, T. Kawabata, T. Tsuyuki, 2005: A pre-operational variational data assimilation system for a non-hydrostatic model at the Japan Meteorological Agency: formulation and preliminary results. *Quat. J. Roy. Meteorol. Soc.* **131**, 3465-3475

Ishibashi, T, 2010: Optimization of Error Covariance Matrices and Estimation of Observation Data Impact in JMA global 4D-Var. CAS/JSC Research Activities in Atmospheric and Oceanic Modelling, 40, (in press).

Ishibashi, T., 2009: Implementation of a New Background Error Covariance Matrix in the Variational Bias Correction Scheme for the JMA Global 4D-Var System. CAS/JAC WGNE Research Activities in Atmospheric and Oceanic Modelling. 39, 15-16.

Japan Meteorological Agency, 2007: Outline of the operational numerical weather prediction at the Japan Meteorological Agency. Appendix to WMO numerical weather prediction progress report, available on http://www.jma.go.jp/jma/jma-eng/jma-center/nwp/outline-nwp/index.htm

Kazumori, M., 2010: Initial Results of a Direct Radiance Assimilation Experiment in the JMA Mesoscale 4D-Var data assimilation system. CAS/JSC WGNE Research Activities in Atmospheric and Oceanic Modelling. (in press).

Kazumori, M., 2009a: The impacts of an Improved Quality Control and Ocean Emissivity Model for Microwave Radiance Assimilation in the JMA Global 4D-Var Data Assimilation System. CAS/JSC WGNE Research Activities in Atmospheric and Oceanic Modelling. 39, 1.19 - 1.20.

Kazumori, M., 2009b: Impact Study of the RTTOV-9 Fast Radiative Transfer Model in the JMA Global 4D-Var Data Assimilation System. CAS/JSC WGNE Research Activities in Atmospheric and Oceanic Modelling. 39, 1.21 - 1.22.

Kazumori, M., 2009c: Assimilation Experiments on Pre-processed DMSP-F16 SSMIS Radiance Data in the JMA. Global 4D-Var Data Assimilation System. CAS/JSC WGNE Research Activities in Atmospheric and Oceanic Modelling. 39, 1.23 - 1.24.

Kobayashi, S., M. Matricardi, D. Dee, S. Uppala, 2009: Toward a consistent reanalysis of the upper stratosphere based on radiance measurements from SSU and AMSU-A. *Quat. J. Roy. Meteorol. Soc*. **135,** 2086-2099

Okamoto, K., H. Owada, T. Egawa and T. Ishibashi, 2008: Assimilation of radiance data at JMA: recent developments and prospective plans. *Proceedings of the 16the international TOVS study conference, Angra dos Reis, Brazil, 7-13 May 2008.*

Okamoto, K., H. Owada, Y. Sato, and T. Ishibashi, 2006: Use of satellite radiances in the global assimilation system at JMA. *Proceedings of the 15th International TOVS Study Conference, Maratea, Italy, 4-10 October 2006.*

Rabier, F., N. Fourrie, D. Chafai, and P. Prunet, 2002: Channel selection methods for infrared atmospheric sounding interferometer radiances. *Quart. J. Roy. Meteor. Soc.*, **128**, 1011-1027.

Rochon, Y. J., L. Garand, D. S. Turner, and S. Polavarapu, 2007: Jacobian mapping between vertical coordinate systems in data assimilation. *Quat. J. Roy. Meteorol. Soc*. **133,** 1547-1558.

Rodgers, C. D., 2000: Inverse methods for atmospheric sounding: Theory and Practice, World Scientific, 238pp.

Saito, K., J. Ishida, K. Aranami, T. Hara, T. Segawa, M. Narita, and Y. Honda, 2007: Nonhydrostatic atmospheric models and operational development at JMA. *J. Meteor. Soc. Japan*, **85B**, 271-304.

Sato, Y., 2007: Introduction of variational bias correction technique into the JMA global data assimilation system. CAS/JAC WGNE Research Activities in Atmospheric and Oceanic Modelling. 36, 1-19.

Saunders, R., M. Matricardi, A. Geer, P. Rayer, O. Embury and C. Merchant,2008: RTTOV-9 science and validation report. available on EUMETSAT SAF website http://research.metoffice.gov.uk/research/interproj/nwpsaf/rtm/rttov9_files/rttov9_svr.pdf

International TOVS Study Conference, 17th, ITSC-17, Monterey, CA, 14-20 April 2010. Madison, WI, University of Wisconsin-Madison, Space Science and Engineering Center, Cooperative Institute for Meteorological Satellite Studies, 2011.