Reanalyses as predictability tools

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Abstract

Reanalysis data have been used for research actively in meteorology, climatology and environmental studies. They are currently used in the operational climate monitoring and seasonal forecasting systems as well. Major advantage of reanalysis data is its homogeneity in time. Hindcast experiments based on homogeneous analyses give a measure of forecast predictability and predictable signals. In JMA, its own reanalysis (JRA-25) data have been widely used in works related to climate services as the fundamental data. Growing use of reanalysis data both in research and operational communities would enforce the feedbacks between them. JMA as an operational weather center will continue the reanalysis activity to support the climate and weather services. Recently JMA just has started the new project of reanalysis, JRA-55. The preliminary analysis of JRA-55 shows steady improvement in a field such as typhoon analysis. The better reanalysis product would be applied to assess the past weather disaster and used for disaster prevention in the future.

1. Introduction

Reanalysis is to produce analysis data for the past long period by applying the fixed analysis procedures to maximally available observation data. Reanalysis is different from real-time operational analysis in operational weather forecast systems especially in data use and its quality control. Observational data used in reanalysis are composed of mainly three types: conventional data used for operational numerical weather prediction (NWP), delayed data which were not used operationally and data recovered or digitalized later. In reanalysis, enhanced quality control for these observational data improves its quality. More accurate data for boundary conditions like sea surface temperature, and forcing data for radiative processes like the solar insolation and the variability of radiatively active gas concentration are taken into considered in recent reanalyses. Such better treatments of the observational data would result in totally better quality of reanalysis and homogeneity for a long period.

By now, more than ten reanalysis projects by operational weather centers and research institutes are finished, ongoing and planned (Table 1). In general, the target period has come to be longer, the resolution higher, and more sophisticated assimilation schemes have been applied from the optimum interpolation in the past to the 4D-Var or EnKF at the present.

Considering the homogeneity in quality, we could say that reanalysis is a very useful ‘tool’ to measure the predictability of weather and climate forecasts. The predictability means that how much skill forecast systems have, or how certain phenomena can be predicted. To evaluate a forecast skill objectively is important to further improve forecast systems. Reanalysis data can be used as the truth or the best estimate in such predictability measurement together with observational data. In addition to the evaluation of actual predictability of forecast systems, there is another aspect of reanalysis data as a predictability tool. The potential predictability of weather and climate systems under the assumption of a perfect model can be investigated by conducting long-term forecast experiments based on homogenous initial conditions from reanalysis data. In this sense, reanalysis data are essential products for operational weather centers. In this paper, we demonstrate some of practical examples for these applications.

Table 1: List of reanalysis projects (as of September 2010)

Reanalysis	Producer	Period	Resolution	Assimilation
NASA/DAO	NASA/DAO	1980-1995	2x2.5L20	3D-OI+IAU
ERA-15	ECMWF	1979-1993	T106L31	3D-OI
NCEP-NCAR	NCEP-NCAR	1948-present	T62L28	3D-Var SSI
NCEP-DOE	NCEP-DOE	1079-present	T62L28	3D-Vat SSI
ERA-40	ECMWF	1957.9-2002.8	TL159L60	3D-Var
JRA-25/JCDAS	JMA-CRIEPI	1979-present	T106L40	3D-Var
ERA-Interim	ECMWF	1989-present	TL255L60	4D-Var
CFSR	NCEP	1979-2010	T382L64	3D-Var GSI
MERRA	NASA	1979-2010	1/2x1/2deg	3D-Var GSI
20th Century reanalysis	NOAA-CIRES	1871-2008	T62L28	EnKF
JRA-55 (ongoing)	JMA	1957.12-2012	TL319L60	4D-Var
ERA-20C (planning)	ECMWF		TL511	Weak constraint 4D-Var

2. Overview of JRA-25reanalysis

In this section, we give a short description of JMA reanalysis, JRA-25 (Onogi et al., 2007) because it will be referred in the later sections. Following preceding reanalysis by NCEP and ECMWF, JMA also launched their own reanalysis project, JRA-25 under the collaborative study with the Central Research Institute of Electric Power Industry (CRIEPI) in April 2000 and completed it in March 2006. Since April 2006 this analysis has been continued in the near-real time (2-day behind) as JCDAS (the Japanese Climate Data Assimilation System) based on the same system as JRA-25.

JRA-25/JCDAS data are freely available for research purposes (see the following web page for details, http://jra.kishou.go.jp/JRA-25/index_en.html). JRA-25 data are also available from the NCAR data archive (http://dss.ucar.edu/datasets/ds625.0/). The JRA-25 has become to be widely used, and more than 1,700 researchers in the world have been registered as JRA-25 users as of August 2010. Furthermore JMA has started the new project for the next version of reanalysis, JRA-55, which will be introduced in the section 4.

The basic specification of JRA-25 data is briefly summarized as follows.

Assimilation system : JMA operational one as of April 2004

Global model resolution: T106L40, nearly 120 km resolution and with model top of 0.4 hPa

Assimilation scheme : three-dimensional variational data assimilation scheme

The SSM/I precipitable water retrievals and TOVS/ATOVS radiance data are assimilated. The daily COBE-SST and sea ice data (Ishii et al. 2005) and daily three-dimension ozone profile data are used as JMA original boundary data.

Furthermore, the following data are introduced into reanalysis in JRA-25 for the first time at the time of the reanalysis.

- Wind profile retrievals surrounding tropical cyclones
- SSM/I snow coverage
- Digitized Chinese snow depth station data
- Reprocessed GMS-AMV data

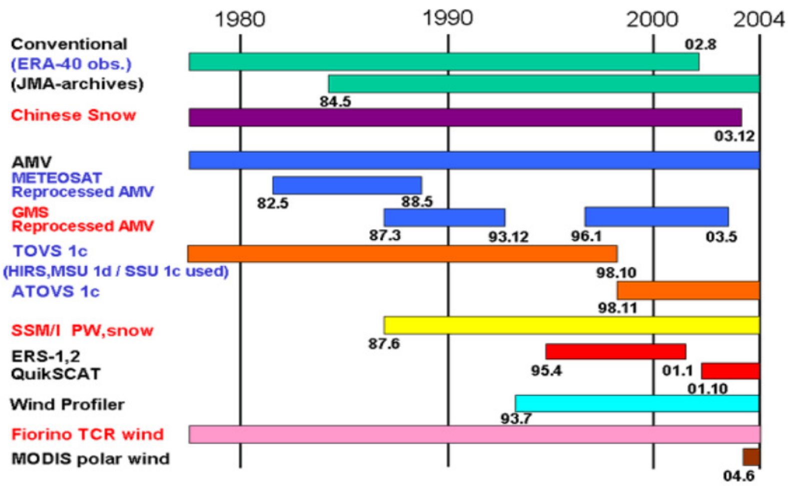

Figure 1: Major observational data sources used for JRA-25. The data written with red color are used in reanalysis for the first time.

The first data among four is a kind of bogus data, which is useful in reproducing tropical cyclones well. This is one of unique features in JRA-25/JCDAS data. Observational data for JRA-25 are summarized in Figure 1. As you see, available data varies year to year in reanalysis. Due to the changes of data, the data quality might be affected. However, to produce analysis with homogenous quality by reducing such affections is one of major efforts to reanalysis.

3. Applications using reanalysis data and its benefit

3.1. Monthly forecasting

In operational weather forecasts, especially long-range forecast, re-forecast (hindcast) over a long period (more than about 15 years) is an important procedure in order to assess the performance of forecast systems and to extract forecasted signals effectively. For these purposes, a high-quality long-term data with the homogeneity in space and time, are required. In this sense, reanalysis data are essential for the operational long-range forecast. In this section, we will introduce some practical use of reanalysis data for the JMA's operational long-range forecast related to the predictability. The Climate Prediction Division (CPD) in JMA is in charge of operational forecasts from one-month to seasonal time scales. The forecasts are based on the following two models: the atmosphere model for the one-month prediction and the atmosphere-ocean coupled model for the three-month, seasonal and El-Nino outlooks. Their specifications are summarized in Table 2.

For the weather forecast, reanalysis data are used for several purposes. Firstly, reanalysis data are used for forecast verification as the truth atmospheric states. Reanalysis data are used to assess impacts by including some physical processes as well.

Table 2: Specification of GCM at CPD/JMA (as of September 2010)

Forecast systems	Periods	Descriptions
One-month ensemble forecast	34 days	JMA-GSM (AGCM): TL159L60, BGM+LAF (50 members/week), Prescribed SST anomaly, Land surface analysis
Three-month, seasonal ensemble forecast	Max.210 days	JMA/MRI-CGCM AGCM: TL95L40, OGCM: 0.3-1 deg x 1 deg, 51 vertical levels, Initial perturbations: Lagged averaging Forecast Method + Bred Vector in tropics and extratropics and perturbed Ocean analysis (51 members/month)
ENSO outlook	7 months	

An example is a work reported by Koster et al. (2010). They conducted an experiment with initials of NCEP reanalysis to assess the influence of land surface conditions on the predictability in the long-range forecast, and showed the possible impact to potential predictability. In this experiment two cases with/without land surface initialization are examined from the viewpoint of predictability of precipitation and surface air temperature. They showed that the realistic initialization of land conditions is beneficial for forecasts at a monthly time scale. In relation to the topic regarding the land surface scheme, the homogeneous quality of the atmospheric analysis is also beneficial for other analysis such as ocean analysis or land analysis. We give an example of an off-line experiment of JMA land surface analysis with forcing of operational forecast and JRA-25 (Figure 2). The JRA-25 system is based on the JMA operational assimilation system of April 2004. So after 2004 the soil wetness in the operational case had increased gradually and finally got close to almost the same level as in the case of JRA-25, which is relatively stable in time. This result indicates that the homogeneity of the atmospheric reanalysis is important for the quality of analyses of other components of climate systems as well.

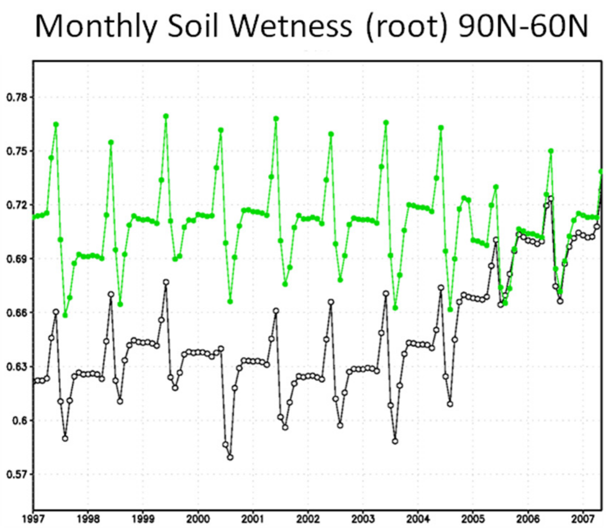

Figure 2: Monthly soil wetness variation averaged over the 90N-60N for 1997-2007. Green line indicates the results with JRA-25 forcing. Black line is forced with the JMA operational forecasts.

To investigate the year-to-year variability of the inherent predictability of models is also a useful application of reanalysis data. Figure 3 shows root mean square errors (RMSEs) of 500 hPa height over the northern and southern hemispheres at day 5 forecasts in JRA-25 forecast experiment and JMA operational global forecast. During the overlapped period, JRA-25 results have smaller RMSE than the JMA operational ones. Because JRA-25 is based on the assimilation system in 2004, the difference indicates its better performance than the operational system at that time. As you see, after 1998 the RMSEs have been reduced gradually. It resulted from the introduction of ATOVS in 1998, 3D-Var in 2001 and 4D-Var in 2005. Before 2005 year-to year variations in the results of JRA-25 can be seen although they look roughly stable compared with the recent decrease tendency in the operational results. These are considered to be associated with the interannual variation of the inherent predictability.

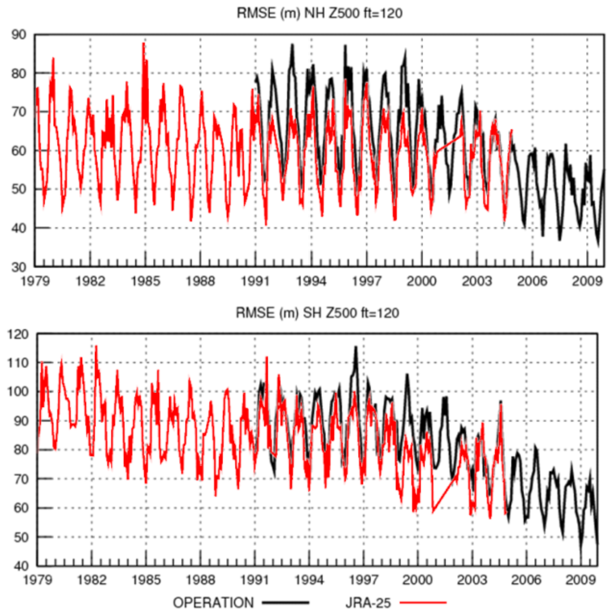

Figure 3: RMSE of height at 500hPa at day 5 forecast by JMA-AGCM. Red line is the result in JRA-25 forecast experiment. Black line shows the results of JMA operational forecast.

3.2. Seasonal forecasting

We have discussed the cases within a month time scale in the previous section. Here we introduce results related to a seasonal time scale. The diagram of the JMA three-month forecast system is shown in Figure 4. JRA-25/JCDAS analysis is used as initial conditions for hindcast experiments and real-time operational forecasts. These results are verified with the reanalysis data. Reanalysis data provide us with the consistent hindcast/forecast environment, and would contribute to the improvement of the forecast performance.

Reanalysis data can be used in the monitoring of climate conditions. In particular monitoring, the El-Nino/La-Nina condition is the most crucial because it is one of the largest signals and predictable in seasonal forecast.

Ocean monitoring is based on the ocean assimilation system. The current ocean assimilation system at JMA is the Multivariate Ocean Variational Estimation system/Meteorological Research Institute Community Ocean Model (MOVE/MRI.COM), which became operational in February 2008 after development by MRI (Usui, N. et al. 2006). Figure 5 shows a diagram of the MOVE/MRI.COM system. The assimilation system is based on three-dimensional variational technique, together with an incremental analysis update.

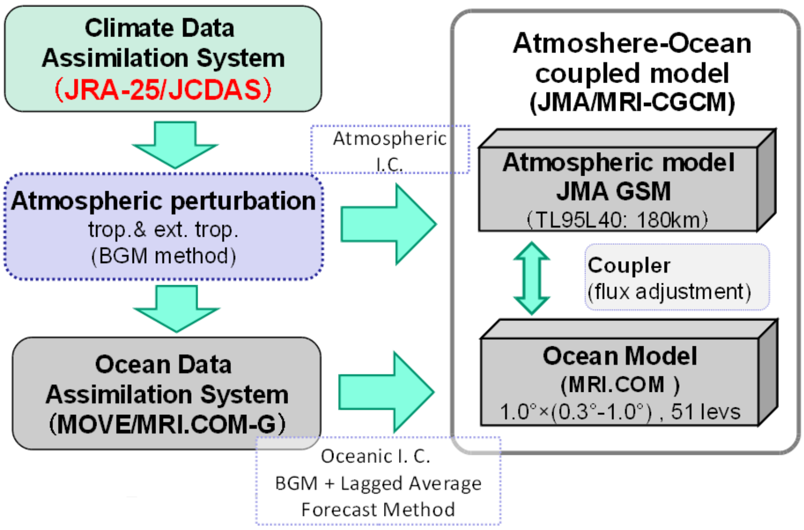

Figure 4: Diagram of JMA three-month forecast system, which is used for seasonal and El-Nino outlooks.

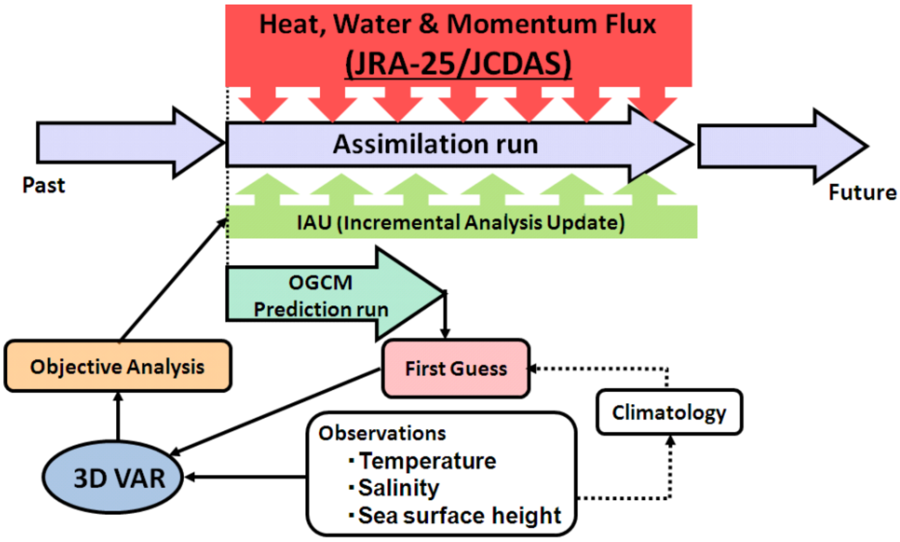

Figure 5: Diagram of ocean assimilation system

In the ocean analysis, the analysis is carried out with the forcing of JRA-25/JCDAS data. Here we show that the merit of the ocean analysis by using atmospheric reanalysis data. Heat content of ocean subsurface is one of the most important factors in the ocean monitoring. JMA have been monitoring the heat content since the operational start of the ocean assimilation system in February 1996. By comparing the past operational results and JRA-25 data, we can evaluate the performance of the assimilation system. Figure 6 shows comparison of JRA-25 and the operational results of zonal wind stress anomalies (left) and net heat flux anomalies (right). Anomaly is a deviation from the temporal average of 1995-2005. Horizontal dashed lines indicate the major changes of the operational assimilation system. As you see, the difference has been reduced gradually along the upgrade of the system.

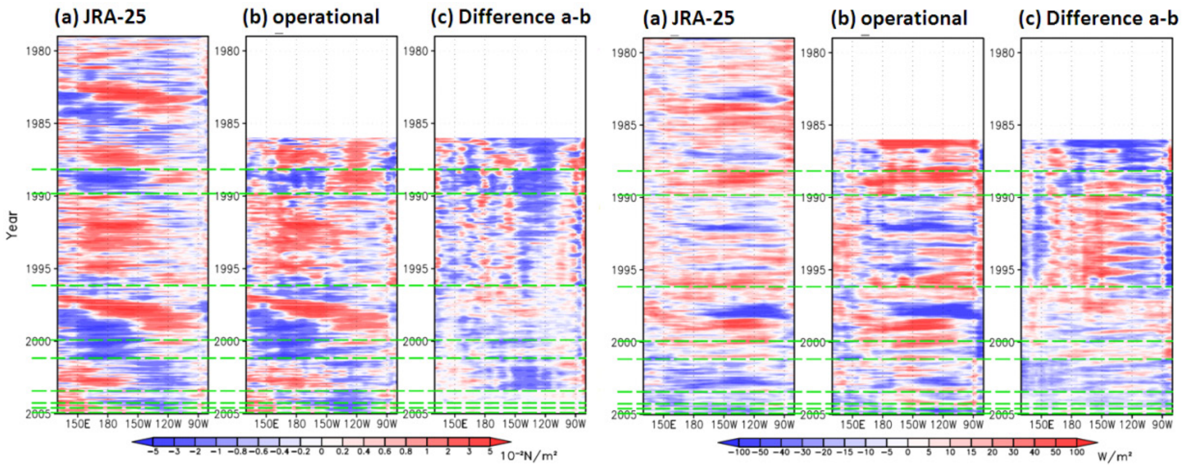

Figure 6: Zonal wind stress anomalies (left) and net heat flux anomalies (right).

3.3. Climate system monitoring

JRA-25 is being continued as JCDAS up to the near-real-time, operated just two days behind. So they are good products for monitoring climate systems (see, web page of Tokyo Climate Center, http://ds.data.jma.go.jp/tcc/tcc/). Especially reanalysis provides us various physical quantities which cannot be observed directly. Figure 7 is an example of monitoring of global warming with the reanalysis (Onogi et al., 2007; Simmons et al., 2004). The reanalysis gives a global view of surface temperature, which plays a complemented role to fill the special coverage of conventional (in-situ) observational data. The reanalysis data helps us to monitor various aspects of climate systems, to diagnose model predictions and to understand mechanisms.

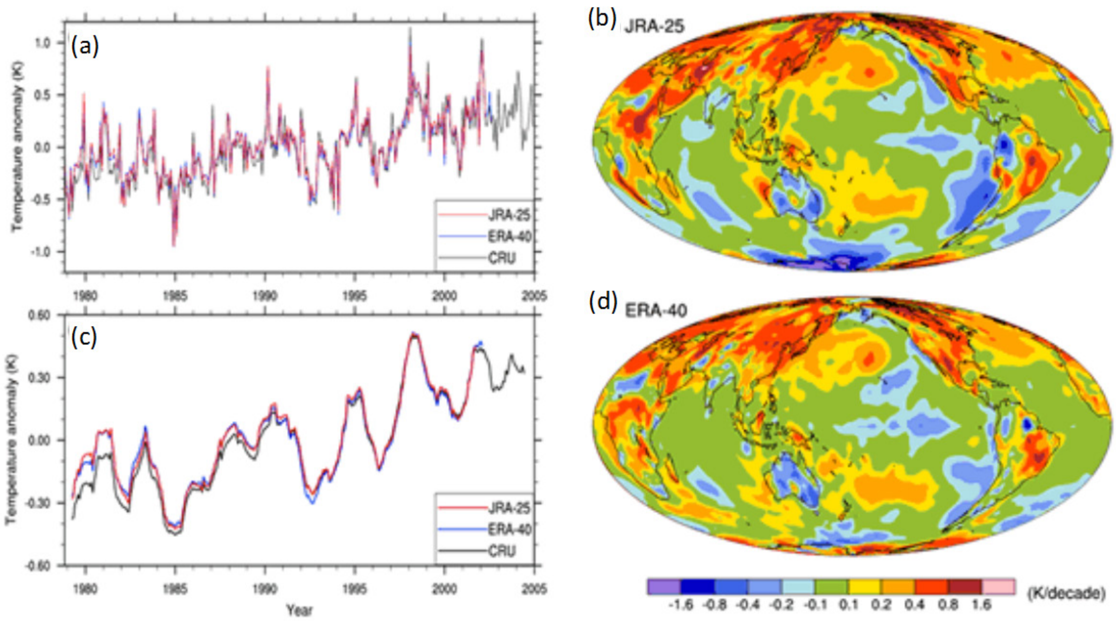

Figure 7: Monitoring of the global mean surface air temperature. (a) time-series of monthly temperature, Red line (JRA-25), Blue (ERA-40) and Black (CRU). (b) Horizontal distribution of surface temperature trends by JRA-25. (c) Same as (a) but for the 12-month running mean (d) the same as (b) but for ERA-40.

Reanalysis using Kalman filter techniqueRecently some new assimilation schemes based on the Kalman filter technique have been developed and used in some operational systems. JMA also has started the development toward the operational use. In the development, a collaborative research project, AFES-LETKF (local ensemble transform Kalman filter) experimental ensemble reanalysis (ALERA) had been conducted among JMA, Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Chiba Institute of Science University (Enomoto et al. 2010). Figure 8 shows schematics for the AFES-LETKF system and some results of the system. EnKF is a technique to utilize the ensemble spread as background error estimation at the analysis (Figure 8a). EnKF can take the flow-dependent background error into consideration. Examples of ALERA analysis field and spread distribution are shown in Figures 8b and 8c. This result suggests that this method can provide us with analysis and uncertainty simultaneously. In other words, we can obtain the information on time-dependent accuracy of analysis fields. Figure 8d is a case of a tropical cyclone. Around the tropical cyclone ensemble spreads are large. It suggests that EnKF technique indicate uncertainty of the analysis (predictability in ensemble forecasts) for particular events.

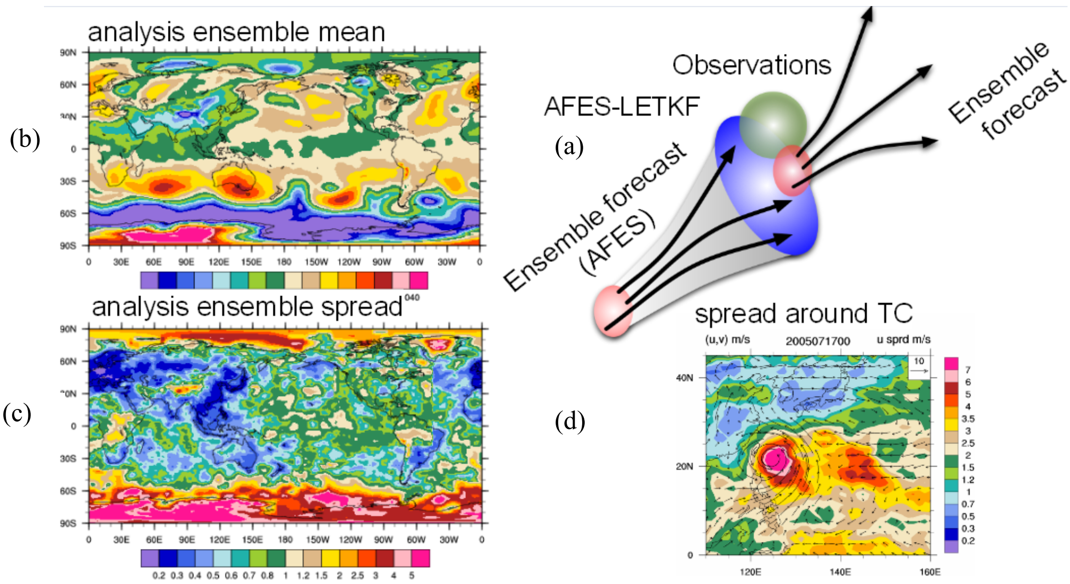

Figure 8: (a) Schematics for ALERA system (upper right), (b) an example of ensemble mean (upper left), (c) ensemble spread (lower left) and (d) horizontal distribution of ensemble spread around a tropical cyclone (lower right) for surface pressure.

Figure 9 shows two examples of relationship between an occurrence of some phenomena and the ensemble spread increase in the LETKF. Figure 9a suggests that just before stratospheric sudden warming (SSW) the ensemble spread had been enhanced. It might be beneficial to prediction of the SSW. Similar enhancement of the ensemble spread can be seen for the monsoon onset over the Vietnam as shown in Figure 9b. The analysis based on the EnKF base assimilation scheme would be a product that is suitable for investigating predictability for such phenomena.

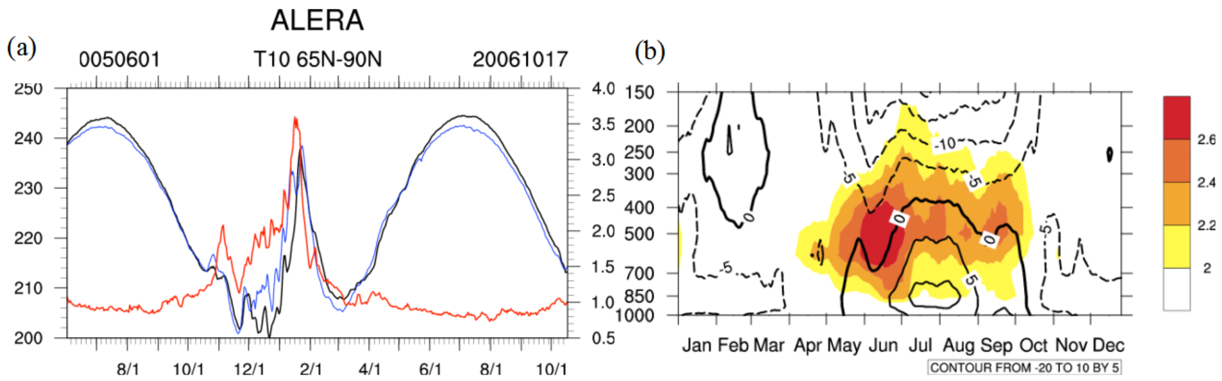

Figure 9: (a) Zonal temperature variation averaged for 65N-90N at 10hPa. NCEP CDAS (blue line), ALERA mean (black) and ALERA spread (red) at Stratospheric Sudden Warming in the arctic stratosphere. (b) Time-pressure section of 30day running mean zonal wind at 850hPa (contour line) and ensemble spread (shaded) over the southern part of Vietnam in the ALERA.

4. Status of JRA-55

As mentioned in the introduction, JMA just has already started the second global reanalysis project, JRA-55. The changes of fundamental specification are summarized in Table 3.

Table 3: Comparison of specification between JRA-25 and JRA-55

	JRA-25 (1979-2004)	JRA-55 (1958-2012)
Resolution	T106L40 (~120km) *(top layer at 0.4 hPa)*	TL319L60 (~60km) *(top layer at 0.1 hPa)*
Time integration	Eularian	Semi-Lagrangian
Assimilation scheme	3D-Var	4D-Var *(with T106 inner model)*
B matrix	Constant	Different **B** matrices for pre-satellite and satellite eras
Bias correction (radiosonde)	Radiation bias only (Andrae *et al.*, 2004)	RAOBCORE v1.4 (Haimberger, 2007, *J. Climate*)
Bias correction (radiances) For satellite	Offline	Variational Bias Correction
Long-wave radiation	*Line absorption* Statistical band model *Water vapor continuum* e-type	*Line absorption* Table lookup + K-distribution *Water vapor continuum* e-type + p-type

Major changes of JRA-55 from the previous version JRA-25 are as follows.

- longer period (1958-2012),
- higher resolution (T106L40 → TL319L60),
- adoption of 4D-Var as an assimilation scheme,
- incorporation of trends of GHG concentration,
- improvement of radiation scheme,
- background error tuning during the pre-satellite period.

Background error tuning is under consideration on how it should be taken in the actual assimilation procedure. Simple examination had been carried out by multiplying the background error matrix by 1.8. The results are shown in Figure 10. In this experiment, supposing that no-tuning cases with satellite data are the truth (control case), both of no tuning and tuning cases without satellite data are evaluated by subtracting from control case are examined. Compared with no-tuning cases, the tuning cases seem to have reduced anomalies. It suggests the improvement of analysis field by the background error tuning over the no satellite period.

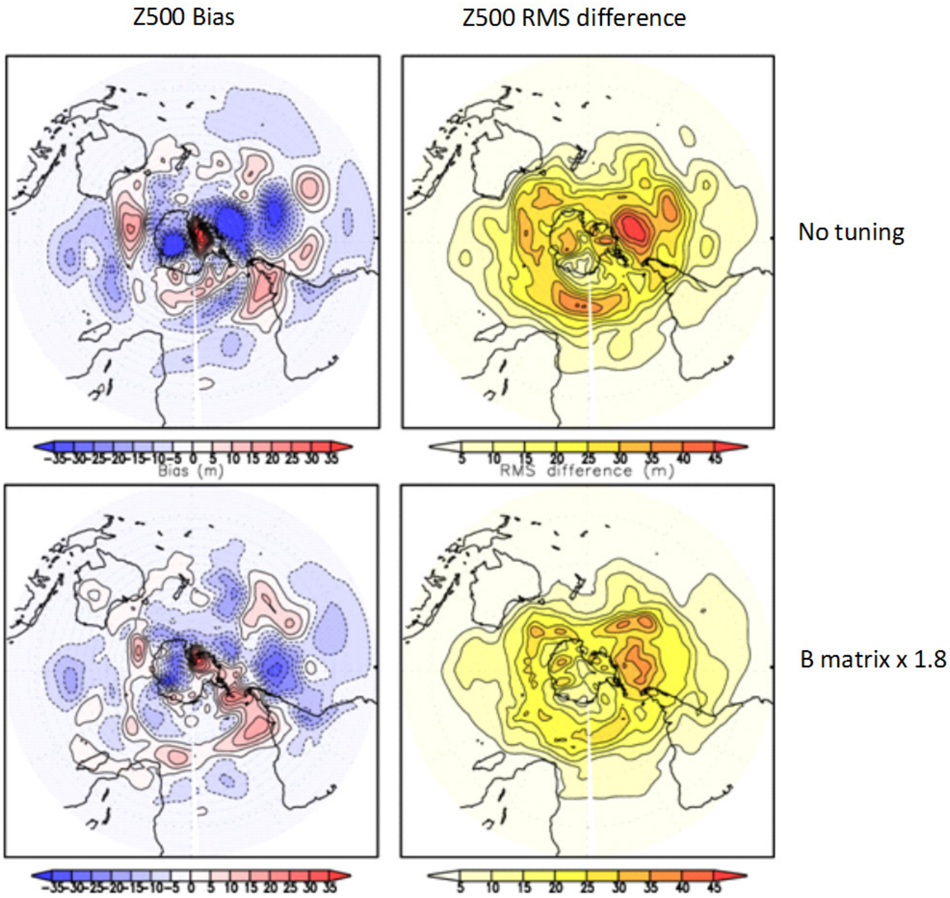

Figure 10: Tuning of background error covariance matrix.

In addition to those improvements, other uniqueness in JRA-55 is to introduce more enhanced quality control procedure for the conventional data. Owing to this enhanced QC, many station data might be recovered. It would contribute improvement of analysis data depending on the type of data.

These improvements would make JRA-55 product more useful in wider application fields. An important role of reanalysis data as a predictability tool is to pursue the limit of predictability based on homogenous characteristic of reanalysis. One of such trials is to downscale reanalysis product with a regional model. Figure 11 shows the forecast experiment results for one of most devastating typhoon, Isewan typhoon (Typhoon Vera) in 1959 based on ERA-40 and a test analysis of the JRA-55 system. As you can see, stronger winds around typhoon center are analyzed in the JRA-55 test analysis. This derives from difference of model resolution. Figure 12 shows comparison of the one-day total rainfall on September 26, 1959 between observation and forecast with the JMA non-hydrostatic regional model (NHM) from the JRA-55 test analysis. JMA NHM shows its excellent reproducibility. These results suggest the possibility of dynamical down-scaling as a kind of predictability tool.

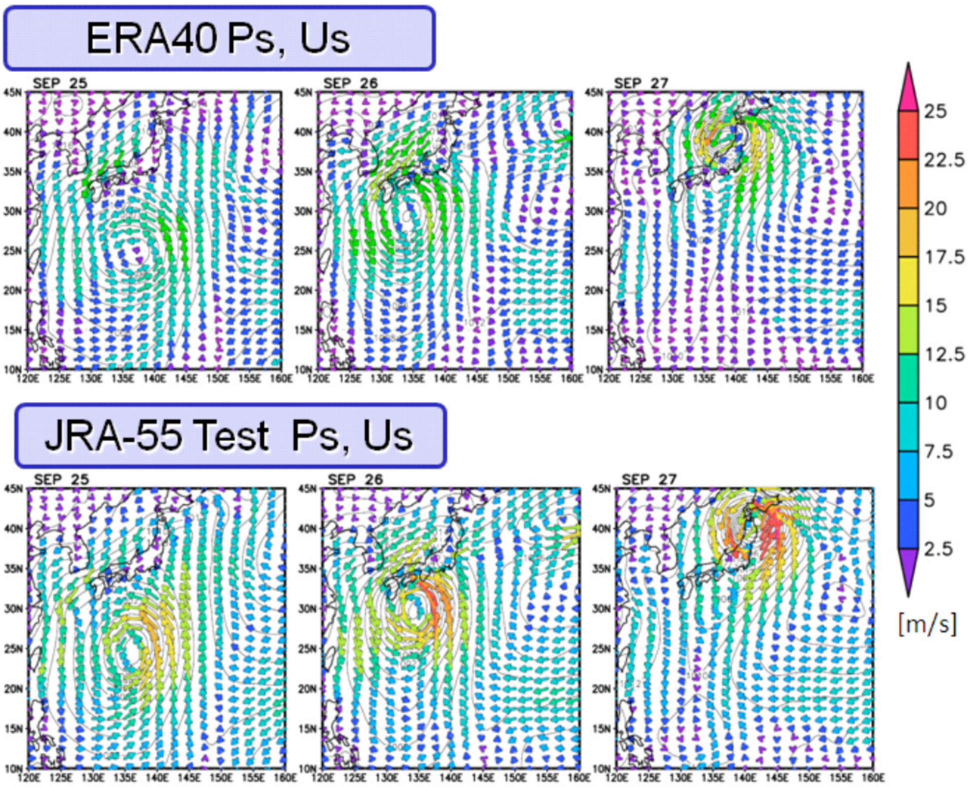

Figure 11: Typhoon Vera surface wind and sea-level pressure distribution. Upper panel is depicted with ERA40 1.25degree data. Lower is JRA-55 test version.

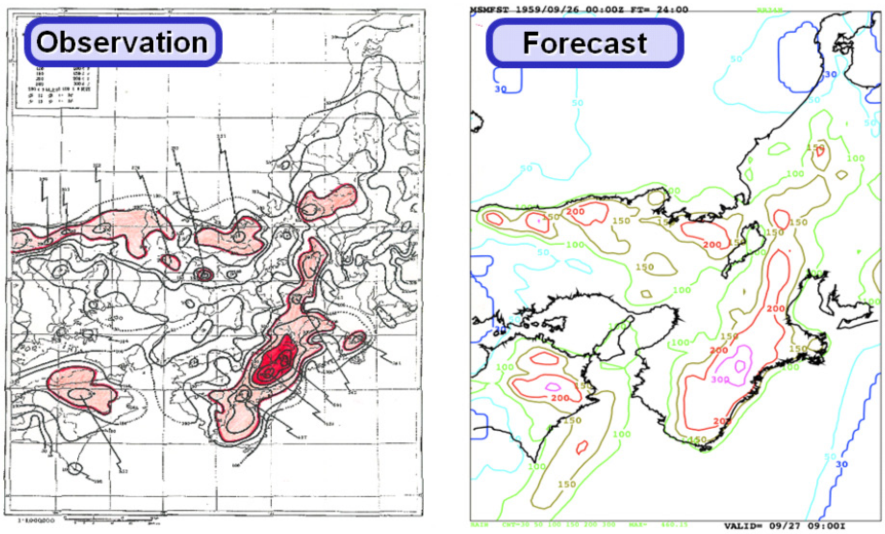

Figure 12: Total rainfall on September 29, 1959. (a) observation (b) forecast with JMA non-hydrostatic regional model.

5. Summary

Reanalysis data have been used actively for research purposes. Besides such active use of reanalysis data for research fields, it is being used as essential data for operational work related to climate services in operational centers, e.g. as initial conditions for hindcast experiments and operational seasonal forecasts. Based on the homogeneity in time of reanalysis data, it enables us to investigate predictability of forecast systems by means of verifications of past events.

Through the active use of reanalysis data in both aspects, the connection between research community and operational one would be tightened if the cyclic feedback relationship (Figure 13) is activated. Reanalysis data will have such functions.

Figure 13: Diagram for function of reanalysis

Considering the wide usefulness of reanalysis data, JMA will continue to make an effort for reanalysis activity. In 2006 JMA completed their own reanalysis, JRA-25, and still now the analysis is being continued as JCDAS. Furthermore, recently the new reanalysis data have been requested strongly since the importance of reanalysis data has been increased in both operational and research activities. As the evolution of forecast models, reanalysis data also have to be developed to play its essential role in the operational forecast. In this sense, reanalysis data should be upgraded in several years time with the latest assimilation and forecast systems to improve the forecast systems.

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