Preliminary Results of the JRA-55C, an Atmospheric Reanalysis Assimilating Conventional Observations Only

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Abstract

As a subset of the Japanese 55-year Reanalysis (JRA-55) project, the Meteorological Research Institute of the Japan Meteorological Agency is conducting a global atmospheric reanalysis that assimilates only conventional surface and upper air observations, with no use of satellite observations, using the same data assimilation system as the JRA-55. The project, named the JRA-55 Conventional (JRA-55C), aims to produce a more homogeneous dataset over a long period, unaffected by changes in historical satellite observing systems. The dataset is intended to be suitable for studies of climate change or multi-decadal variability. The climatological properties deduced from the early results of the JRA-55C are similar to those of the JRA-55 in the troposphere and lower stratosphere, except for high southern latitudes. On the basis of forecast skill, the quality of the JRA-55C is inferior to that of the JRA-55, but the JRA-55C has better temporal homogeneity than the JRA-55. The skill of the latter changes during the JRA-55 period. We have completed 85% of the entire JRA-55C calculation as of February 2014. We expect that the JRA-55C will contribute to a much better understanding of the impact of changes in observing systems on climate trends and variability estimated from the JRA-55.

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1. Introduction

To reproduce the past atmospheric states most realistically, major global atmospheric reanalysis datasets have been generated by using all available observational data. These multi-year reanalysis datasets are essential tools for climate research today. However, it is known that historical changes of observing systems cause inhomogeneities in these reanalyses that have discouraged use of the reanalyses to detect and examine climate variations and climate trends. Trenberth et al. (2008) have pointed out that, at the present time, variability on multi-year timescales (especially decadal) is not estimated very well in the reanalyses. Much effort such as quality control of the observations and/or observation data rescue has been made at reanalysis centers to improve the homogeneity of reanalysis products.

The second Japanese global atmospheric reanalysis, the production of which was recently completed by the Japan Meteorological Agency (JMA), has been named the Japanese 55-year Reanalysis (JRA-55; Ebita et al. 2011) and covers the period from 1958 to 2012. Early results from the JRA-55 indicate improvements in many respects relative to the first Japanese reanalysis, the Japanese 25-year Reanalysis (JRA-25; Onogi et al. 2007). The inhomogeneities in the JRA-25 product have been diminished in the JRA-55 by reduction of systematic model biases and use of advanced assimilation techniques. However, inhomogeneities are still a concern in JRA-55 because the JRA-55 reanalysis period includes both the post-1979 period of abundant satellite observations and the pre-satellite period before 1972.

To produce a more time-consistent reanalysis, the JMA Meteorological Research Institute (MRI) has started to produce a JRA-55 sub-product, the JRA-55 Conventional (JRA-55C). This sub-product uses the same data assimilation (DA) system and the same boundary conditions as the JRA-55 but assimilates only conventional observations. The JRA-55C is the first fixed observing system reanalysis to make use of conventional upper air observations; a pioneering reanalysis with a fixed observing system was undertaken by the Twentieth Century Reanalysis Project (20CR, Compo et al. 2011), which used surface-pressure observations only. The JRA-55C will be provided as an important component of the "JRA-55 family." Another sub-product, the JRA-55AMIP, assimilates no observational data and is also provided as a member of the JRA-55 family; it uses the numerical weather prediction (NWP) model used in the JRA-55 DA system and prescribes the same boundary conditions as do other members of the JRA-55 family. In this paper, we provide an overview of the JRA-55C project and early results from the JRA-55C.

2. Outline of the JRA-55C

The JRA-55C covers the period from November 1972, when the JRA-55 starts to use satellite data, to 2012. A 55-year reanalysis dataset that assimilates conventional observations only can be provided by using the JRA-55 products from the pre-satellite era (1958−1972) and the JRA-55C products from 1972−2012.

The observational data assimilated in JRA-55C are land and marine surface data (reported as SYNOP, SHIP, and BUOY defined by the World Meteorological Organization for observation exchanges), upper air data (observed by radiosondes, pilot balloons, and wind profilers) and tropical cyclone wind retrievals (TCR) (Fiorino 2002). The reason these observational data were adopted is that they existed throughout the period covered by the reanalysis. Australian manual surface pressure bogus data (PAOB) and aircraft data are not used in the JRA-55C, because they did not exist during the earlier part of the reanalysis period.

The DA system used in the JRA-55C is a four-dimensional variational data assimilation (4D-Var) system, exactly the same system used in the JRA-55. The model used in the DA system has a horizontal resolution of TL319 (= 60 km), with 60 layers in the sigma-pressure hybrid vertical coordinate. The top of the atmosphere is 0.1 hPa. For DA, the scaling factor for the background error covariance matrix (B-matrix) is 1.8 times the scaling factor used in the JRA-55 satellite era through the period covered by the JRA-55C. This larger scaling factor is also used during the pre-satellite era of the JRA-55. The quality of analysis is acknowledged to be largely dependent on the background error covariance matrix when the number of observational data is small (Whitaker et al. 2009). The scaling factor was determined from assimilation experiments prior to JRA-55 production. The JRA-55C and JRA-55 boundary conditions, such as historical sea surface temperatures (SSTs) and distributions of the concentrations of ozone, other greenhouse gases, and aerosols, are exactly the same. The

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three dimensional daily mean ozone produced by a DA system of chemistry climate model was used for radiation scheme of NWP model of JRA-55 for the period after 1979 to take into account the historical change of ozone concentration. The daily ozone distributions before 1978 are time-interpolated three dimensional climatological monthly means over 1980 to 1984. The historical change of greenhouse gas concentration is also taken into account. The aerosols used for JRA-55 are monthly climatology.

The production is executed with three separate streams. Stream A covers the period from November 1972 to August 1980 and is identical to the period associated with stream A in JRA-55. Stream B covers the period from September 1980 to the middle of 2005 (undecided). Stream C covers recent years, beginning in the middle of 2005. Stream A has been completed and Streams B and C are being calculated. The computations for 36 years were completed as of February 2014.

For reference, we show the number of radiosonde temperature observations in Fig. 1 by five latitude bands. The number of the observations in the mid-latitude of the northern hemisphere is larger than the other areas. The number peaked in the 1970s and 1980s, and decreased in 1990s. The numbers of observations in the stratosphere are increase as time advances. The time variation of the numbers may affect the quality of the JRA-55C reanalysis. Still, the variation is smaller than that in JRA-55, which assimilates various types of satellite observations. Details will be presented in the JRA-55 description paper which we are preparing.

3. Preliminary results of the JRA-55C

3.1 Evaluation of synoptic variability

a. Difference of 6-hourly snapshots

The differences between the JRA-55 and JRA-55C 6-hourly fields are illustrated by the differences of geopotential heights at 500 hPa at 12 UTC on 25 August 1993 (Fig. 2a). The difference indicates the impact of satellite observations on the reanalysis field. The height differences are smaller than 15 m in the extra-tropics in the Northern Hemisphere (NH), except for a part of Arctic Ocean and a part of the eastern North Pacific Ocean (in the vicinity of the Gulf of Alaska) where observations are relatively sparse. In contrast, large differences are apparent throughout most of the extra-tropics in the Southern Hemisphere (SH). The difference between the JRA-55 and the ERA-Interim (Dee et al. 2011), which is a reanalysis dataset produced by European Centre for Medium-Range Weather Forecasts, is smaller than the difference between the JRA-55 and JRA-55C (Figs. 2a, b). Since the satellite observations are assimilated in both the JRA-55 and ERA-Interim, we can therefore say that the impact of satellite observations on the analysis field is greater than the impact of differences in the data assimilation system in the SH.

Local anomaly correlations of 6-hourly geopotential height at 500 hPa between reanalyses are illustrated in Figs. 2c, d. The area of high correlation between JRA-55C and JRA-55 covers most of the earth, except for high latitude areas of the SH (60°S−90°S) and the eastern part of the South Pacific Ocean, where conventional observations are sparse. The area of high correlation between JRA-55 and ERA-Interim covers most of the earth. Similar correlation pattern can be found at most of the levels in the troposphere (not shown).

b. 2-day forecast score

The quality of reanalysis data can be assessed from the accuracy of forecasts made using the reanalysis data as the initial conditions, because the skill of a NWP forecast is sensitive to the initial conditions. As was the case with the JRA-55, 9-day forecasts were projected on a daily basis using reanalysis data at 12 UTC as the initial conditions using the NWP model in the DA system. Figure 3 shows the root-mean-square error (RMSE) of the 500 hPa geopotential height forecasts at day 2 verified against the corresponding geopotential heights from the analyses of the JRA-55C, JRA-55, JRA-25, and the historical JMA Operational systems.

The RMSE scores of the JRA-55C were larger than those of the JRA-55 but smaller than those of the JRA-25 in the NH before 1998. The difference of the scores between the JRA-55 and JRA-55C is likely due to the impact of satellite observations. Because the impact of satellite observations increased from year to year, the skill of the JRA-55 gradually improved. In contrast, the scores of the JRA-55C were comparable to those of the JRA-55 in the late 1970s.

It is inevitable that the quality of the JRA-55C, which assimilates conventional observations only, will be inferior to that of the JRA-55, which assimilates all available observational data, including satellite observations. The quality of the JRA-55C were comparable level to the JRA-55 in the late 1970s, as stated above. In terms of consistency, however, the quality of the JRA-55C was more homogeneous than that of the JRA-55 during the reanalysis period.

In the SH, the RMSE scores of the JRA-55C were larger than those of the JRA-25 from the early 1980s. This result suggests that assimilation of satellite observations was more effective than the improvement of the assimilation system from the JRA-25 to JRA-55. Because the quality of the JRA-55 and JRA-25 over the SH depends largely on satellite observations, the skills of the JRA-55 and JRA-25 improved gradually during the reanalysis period. In contrast, the scores of the JRA-55C showed no large improvement during the reanalysis period. The quality of the JRA-55C was rather homogeneous compared to the quality of the JRA-55 and JRA-25 during this period. The RMSE scores of the JRA-55C were smaller during the 1970s than after 1980, despite the fact that the number of surface pressure observations increased over the SH, particularly in higher latitudes. The fact that the RMSE scores did not decrease with increasing numbers of observations is contrary to expectations. One possible explanation is that obser-

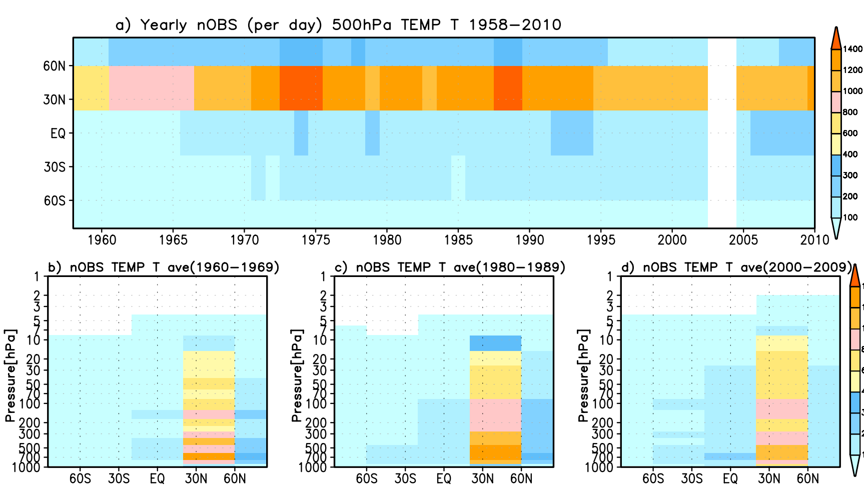

Fig. 1. The number of radiosonde temperature observations used in JRA-55C in five latitude bands. a) Time series of data counts at levels near 500 hPa, and latitude-pressure cross sections of data counts for b) the 1960s, c) the 1980s and d) the 2000s (excluding the year 2003 and 2004). Units are day^{-1}. Color bar boundaries are 0, 100, 200, 300, 400, 600, 800, 1000, 1200 and 1400 day^{-1}. The numbers before 1972 are provided by JRA-55. The five latitude bands are 90°N−60°N, 60°N−20°N, 20°N−20°S, 20°S−60°S and 60°S−90°S.

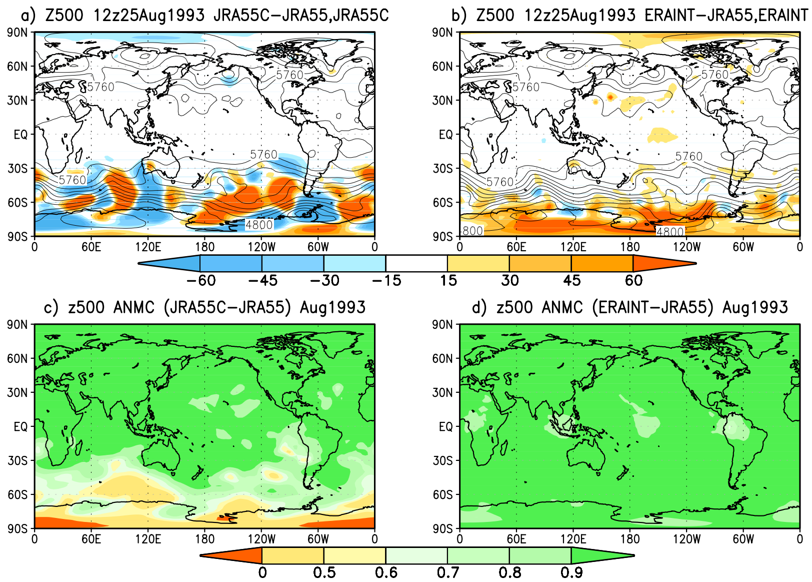

Fig. 2. Geopotential heights at 500 hPa at 12 UTC on 25 August 1993 from reanalyses (upper panels) and local anomaly correlation coefficient of 6-hourly geopotential height at 500 hPa between reanalyses in August 1993 (lower panels). a) The 500 hPa geopotential heights of JRA-55C (contours) and height differences between the JRA-55C and JRA-55 (shadings). b) Same as a) but for ERA-interim (contours) and height differences between the ERA-interim and JRA-55 (shadings). Units are geopotential meters (gpm). The contour interval is 120 gpm. c) Local anomaly correlation coefficient between JRA-55C and JRA-55. d) Same as c) but between JRA-55 and ERA-interim.

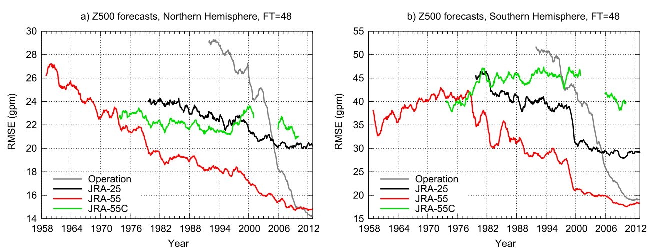

Fig. 3. Time series of the RMSE of 2-day forecasts of geopotential height at 500 hPa verified against the corresponding analysis for (a) the NH (20°N−90°N) and (b) SH (20°S−90°S). Units are geopotential meters (gpm). A 12-month running mean was applied for smoothing. "Operation" indicates the JMA operational forecast started from the JMA operational analysis at the indicated time. Each forecast is started from the data produced by the corresponding reanalysis. Note that green lines are drawn only for years during which the JRA-55C forecast process has been completed.

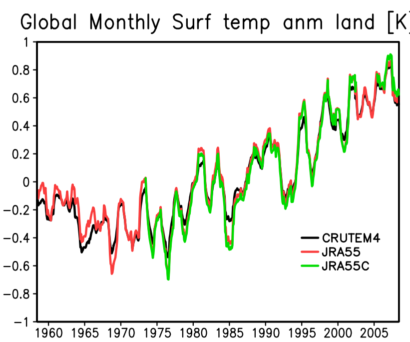

Fig. 4. Time series of globally averaged land surface temperature anomalies (K). The anomalies are departures from the monthly climatology averaged from 1971 to 2000. The globally averaged values have been calculated from the land grids of the DA system where CRUTEM4 data exist. A 13-month running mean has been applied for smoothing.

vational coverage was too sparse to correctly represent synoptic weather patterns during this period.

3.2 Representation of climatology and variability

a. Globally averaged annual-mean surface temperature on land

Globally averaged annual-mean surface air temperature (SAT) is frequently monitored as an index of global warming in climate studies. Figure 4 presents time series of the globally averaged SAT anomalies at a height of 2 m over land estimated by the JRA-55, JRA-55C, and Climatic Research Unit temperature dataset version 4 (CRUTEM4, Jones et al. 2012), which is a gridded dataset of global historical near-surface air temperature anomalies over land produced by the Met Office Hadley Centre and the Climatic Research Unit at the University of East Anglia. The globally averaged temperatures in Fig. 4 were calculated from the land grids of the DA system where CRUTEM4 data existed. The time series of JRA-55 and JRA-55C are generally consistent with the CRUTEM4 time series. The correlation coefficient between the JRA-55C and CRUTEM4 anomalies was 0.96 for the period 1973−2002.

b. Precipitation over East Asia

The precipitation products of the JRA-55 and JRA-55C are based on 6-hour forecasts from each analysis. Although precipitation is not a directly assimilated variable, precipitation provides an integrated evaluation of the performances of the DA system. Figures 5a, b, c, d illustrate the distributions of seasonally averaged precipitation for June, July, and August (JJA) over the East Asia region estimated from the Global Precipitation Climatology Project (GPCP) version 2.1 (Huffman et al. 2009), JRA-55, JRA-55C, and JRA-25, respectively. A Taylor diagram (Taylor 2001) of the spatial patterns of the precipitation is also shown in Fig. 5e. The precipitation band associated with the Baiu front is similar in the JRA-55 and JRA-55C and is more realistically reproduced by the latter than by the JRA-25. The JRA-55 and JRA-55C precipitation patterns within the dashed rectangle were better correlated with the GPCP than the JRA-25 and ERA-Interim precipitation patterns, as shown in the Taylor diagram (Fig. 5e). The normalized standard deviations of the JRA-55 and JRA-55C indicate greater consistency with the GPCP than those of the JRA-25 and ERA-Interim. These results indicate that the upgraded DA system used in the JRA-55 improves the climatological precipitation pattern over the East Asia region during JJA, although areas with relatively sparse observations, such as high latitudes of the SH, indicate lower correlations (not shown).

c. Zonal mean temperature and zonal wind

Figure 6 depicts the climatological zonally averaged temperature and zonal wind speed for JJA (1980−2000 mean). The difference in climatological temperatures reproduced from the JRA-55 and JRA-55C was smaller than 0.2K in the troposphere over the tropics and in the NH, whereas the differences between the JRA-55 and ERA-Interim were slightly larger than those between the JRA-55 and JRA-55C. Similarly, the differences of

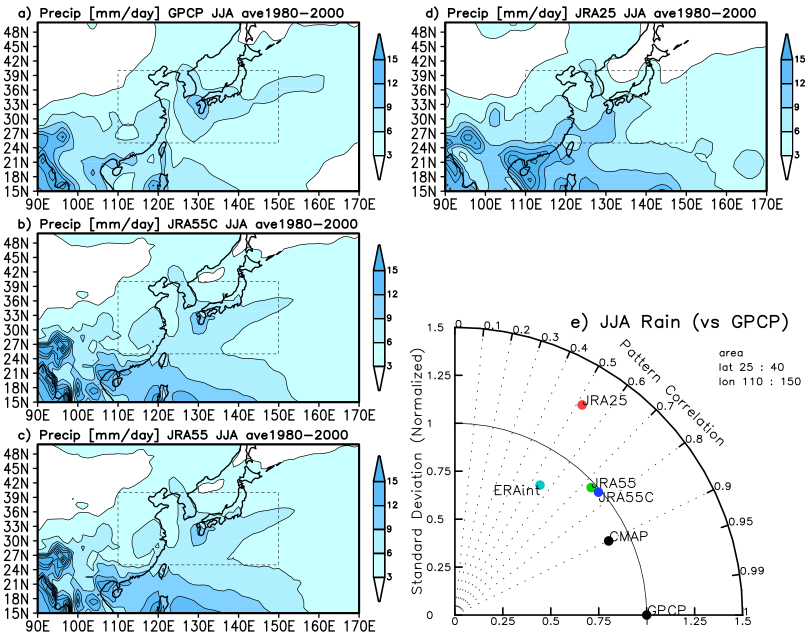

Fig. 5. JJA mean climatological precipitation (mm day^{-1}) of a) GPCP Ver 2.1, b) JRA-55C, c) JRA-55, and d) JRA-25. e) Taylor diagram of the correlation coefficients and standard deviations of the differences of precipitation determined from reanalyses and observations in the dashed rectangle. The period for the statistics is 1980−2000.

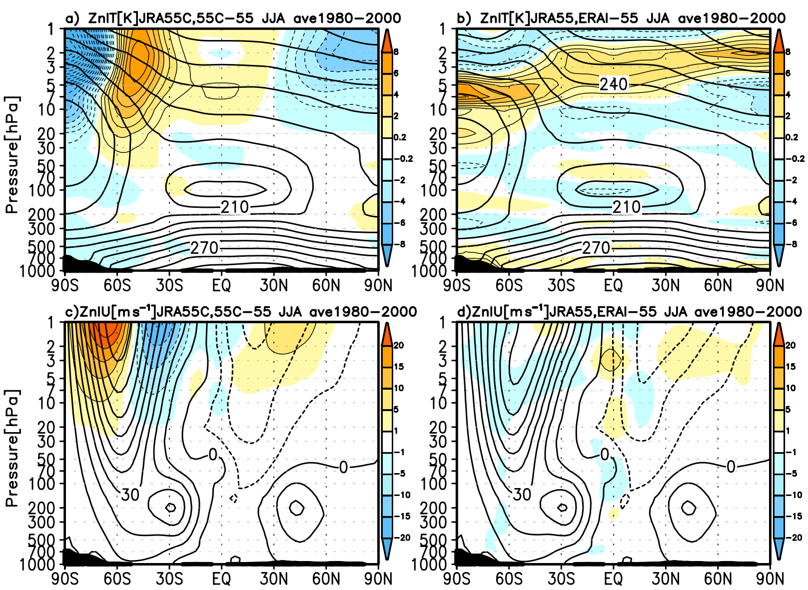

Fig. 6. Latitude-pressure cross section of zonally averaged (a, b) temperature (K) and (c, d) zonal wind speed (m s^{-1}) for JJA (1980−2000 mean). Contours denote temperature and zonal wind speed for (a, c) JRA-55C and (b, d) JRA-55. Shading indicates the difference (a, c) between JRA-55C and JRA-55 and (b, d) between ERA-interim and JRA-55. Contour interval is 1 K for temperature and 5 m s^{-1} for zonal wind speed. Each climatology corresponds to the 1980−2000 average.

climatological zonal wind speeds reproduced from the JRA-55 and JRA-55C were small in the troposphere compared with the corresponding differences between the JRA-55 and ERA-Interim. However the zonal wind difference between the JRA-55 and JRA-55C was large in the upper stratosphere (1 hPa to 10 hPa), especially in the winter hemisphere. The temperature difference between the JRA-55 and JRA-55C (Fig. 6a) also showed large difference in the upper stratosphere corresponding to the zonal wind difference. The climatological zonal wind and temperature of the JRA-55AMIP displayed a similar difference pattern with the JRA-55 in the upper stratosphere during the winter hemisphere (not shown), which is warm bias in mid-latitude and cold bias in the high-latitude in the winter hemisphere. We hypothesize that the difference between the JRA-55 and JRA55C was caused by the paucity of conventional data and systematic NWP model bias in the upper stratosphere. While the climatological temperature difference between the JRA-55 and ERA-Interim have a layered structure in the upper stratosphere, this would be related to the difference of data processing of the brightness temperature from the highest-peaking channels of satellites between these DA systems.

d. Quasi-Biennial Oscillation

Figure 7 displays a time-height cross section of mean zonal wind speeds averaged between 10°S and 10°N, for JRA-55, JRA-55C, JRA-55AMIP, and 20CR (Compo et al. 2011). The Quasi-Biennial Oscillation (QBO) in the middle-to-lower stratosphere is apparent in the JRA-55 and JRA-55C but not in the JRA-55AMIP. The QBO is also absent from the 20CR, which uses the NCEP Global Forecast System to assimilate only surface pressure observations. These results suggest that radiosonde observations play an important role in reproducing the QBO in reanalyses. One reason why the JRA-55AMIP does not represent the QBO could be that the NWP model has not yet adopted a non-stationary gravity wave parameterization. According to Kawatani and Hamilton (2013), only four of the models that were a part of the Coupled Model Intercomparison Project Phase 5 (which included parameterization of non-stationary gravity waves) realistically simulated the QBO spontaneously. The JMA is presently studying adaptation of this parameterization to an operational NWP model.

The zonal wind difference between the JRA-55 and JRA-55C was large in the upper stratosphere compared to that in the lower stratosphere. Both the JRA-55 and JRA-55C indicated the

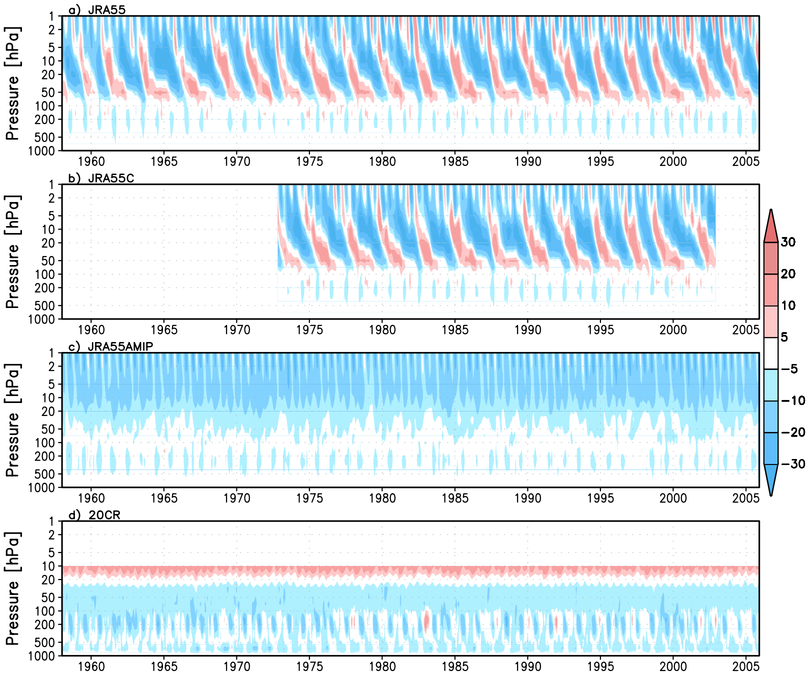

Fig. 7. Time-height cross section of equatorial (5°S−5°N) zonal mean U wind component from 1958 to 2005 shown in a) JRA-55, b) JRA-55C, c) JRA-55AMIP, and d) 20CR. Units are m s^{-1}.

semi-annual oscillation (SAO) like variation in the upper stratosphere, although the amplitude of the variation of the JRA-55C was smaller than that of the JRA-55. The amplitude of the JRA-55AMIP was smaller than that of the JRA-55C.

4. Summary

To create a more temporally homogeneous reanalysis product, the MRI/JMA has started a sub-project, the JRA-55C, which assimilates conventional observations only, but uses the same DA system and the same boundary conditions as the JRA-55. The climatological properties inferred from the early results of the JRA-55C are similar to the climatological properties of the JRA-55 in the troposphere and lower stratosphere, except for high latitudes of the SH. On the basis of forecast skill of 500 hPa heights, however, the quality of the JRA-55C as initial conditions was inferior to that of the JRA-55. The scores of the JRA-55C during 1980−1998 were comparable to those of the JRA-55 in the 1970s in the extra-tropics of the NH, the implication being that the JRA-55C is more homogeneous than the JRA-55. It is expected that the quality of the analysis will be consistent throughout the reanalysis period.

The entire JRA-55C production will be completed in the middle of 2014. Thereafter, the product will be provided to the meteorological community together with the products of the JRA-55 and JRA-55AMIP. As a member of this “JRA-55 family” the JRA-55C provides a unique reanalysis dataset and contributes to understanding the impacts of observing system changes on the estimation of climate trends and variability.

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