Usage of Atmospheric Reanalysis Data for Dynamical Diagnoses of the Atmospheric Circulation and Climate Variability

Hisashi Nakamura[1,2], Y. Kosaka[1], D. Hotta[3], K. Nishii[1], T. Miyasaka[1] and K. Takaya[2]
[1]Department of Earth and Planetary Science, University of Tokyo, Japan
[2]Frontier Research Center for Global Change, JAMSTEC, Japan
[3]Forecast Department, Japan Meteorological Agency, Japan
Correspondence: hisashi@eps.s.u-tokyo.ac.jp

INTRODUCTION

The release of the first global atmospheric reanalysis project by the U.S. National Centers for Environmental Prediction (NCEP) and U.S. National Center for Atmospheric Research (NCAR) (Kalnay et al. 1996) has exerted an epoch-making impact on our data analysis study of the large-scale atmospheric circulation and its variability. Since then, several global atmospheric reanalysis datasets have been released, including the NCEP-Department of Energy (DOE) reanalysis (Kanamitsu et al. 2002), European Centre 40-year Reanalysis (ERA40; Uppala et al. 2005) and Japanese 25-year Reanalysis (JRA-25; Onogi et al. 2005, 2007). Compared to conventional operational analyses of the atmosphere, those reanalysis datasets have several advantages with which our understanding of the large-scale atmospheric circulation and its variability has been deepened. The advantages include (i) availability of 6-hourly global analysis of the global atmospheric state over decades with relatively high, uniform quality, (ii) availability of variables at more vertical levels than in conventional analysis, and (iii) inclusion of various model-diagnosed variables that were not available widely to the community in conventional analysis. In this paper, examples are presented where our diagnoses were benefited from those advantages of the reanalysis datasets in application of modern diagnostic methods.

EXAMPLE 1: SUMMERTIME TELECONNECTION ASSOCIATED WITH ANOMAOUS CONVECTIVE ACTIVITY OVER THE NORTHWESTERN PACIFIC (P-J PATTERN)

A fixed configuration of a forecast model used for a reanalysis and assimilation of satellite-measured wind and thermal fields throughout the period since the 1980s provide the global atmospheric circulation fields over a quarter of the century. It is particularly beneficial in study of climatic phenomena and monthly or seasonal anomalies in the Tropics and Southern Hemisphere. The following is an example where analysis of reanalysis data has revealed essential dynamics of an atmospheric teleconnection pattern associated with tropical convective anomalies. Analyzing six years of monthly operational analysis data with resolution of 10° both in latitude and in longitude and only four pressure levels, Nitta (1987) found a Pacific-Japan (PJ) teleconnection pattern characterized by a pressure seesaw between the tropical northwestern Pacific and Japan and accompanied by anomalous convection near the Philippines. His claim that the pattern exhibits an equivalent barotropic structure around Japan and the first baroclinic structure in the Tropics has been believed in the community until Kosaka and Nakamura (2006) analyzed its three-dimensional structure based on monthly reanalysis data for a 25-year period. They showed that, unlike what Nitta (1987) claimed, its structure is characterized by vorticity anomalies with their axes tilting poleward tilting with height, which could not have been revealed without the usage of long-term reanalysis data with sufficiently high spatial resolution. Kosaka and Nakamura (2008) have confirmed that the characteristic vertical structure of the PJ pattern can be recognized in each of the four reanalysis datasets (NCEP-NCAR, NCEP-DOE, ERA-40, JRA-25) and that dry energetics, i.e., conversions of kinetic energy (KE) and available potential energy (APE) from the three-dimensional climatological mean state into the PJ-associated anomalies, is quite consistent among the four datasets. At the same time, they have shown substantial discrepancies in APE generation due to anomalous convection among three out of the four datasets available for them, which arose not only from uncertainties in convective diabatic heating evaluated in forecast models but also from discrepancies in spatial correlation between anomalies in diabatic heating and temperature within the deep tropics. This is a typical example that shows strong model dependency of diabatic heating fields. Using the NCEP-DOE reanalysis, Kosaka and Nakamura (2006) showed the primary importance of dry energy conversion for the maintenance of the PJ pattern, to reveal its characteristics as a dry dynamical mode. Results of Kosaka and Nakamura (2008) suggest that the APE generation by anomalous convection and the energy conversion from the mean state can be equally important in the maintenance of the monthly PJ pattern, which is thus likely to possess characteristics of both dry and moist dynamical modes. Nevertheless, a quantitative assessment of the relative importance between the dry and moist processes requires further improvement in evaluation of diabatic heating in reanalysis. Refer to Kosaka's paper (2008) in this abstract volume for more specifics.

EXAMPLE 2: DIAGNOSES OF THERMAL FORCINGS ON SUMMERTIME SUBTROPICAL ANTICYCLONES AND LOW-LEVEL BAROCLINICITY ALONG STORM TRACKS

Another advantage of the reanalysis datasets lies in the inclusion of separate contributions to diabatic heating from various physical processes due to cumulus convection, large-scale condensation, radiation, surface fluxes among others. Of course, their model dependency and uncertainties have to be realized, and the usage of those variables therefore requires a certain level of caution. Nevertheless, the reanalysis data provide us with a unique opportunity to make a *qualitative* assessment on which diabatic heating contribution is the primary thermal forcing on a given atmospheric phenomenon. An evaluation of the total diabatic heating distribution has been possible based on conventional operational analysis through thermodynamic equation. Though may be more accurate than its counterpart provided in (re)analysis, the diabatic heating thus evaluated indirectly cannot be decomposed into the individual contributions.

As an example of such an assessment as above, Wu and Liu (2003) examined longitudinal dependency of vertical profiles of various diabatic-heating contributions within the summertime subtropics for each of the hemispheres based on the NCEP/NCAR reanalysis. They found that subtropical anticyclones are associated locally with shallow low-level radiative cooling over the ocean and with upward sensible heat flux from the heated continents to their east. Miyasaka and Nakamura (2005) incorporated the zonally symmetric component of diabatic heating and the zonal-mean flow, both based on the July climatology of the NCEP-DOE reanalysis, into a nonlinear atmospheric planetary wave model (Rodwell and Hoskins, 2001). They have shown that each of the surface subtropical anticyclones, whose center is situated in the eastern portion of a particular ocean basin, is forced primarily with a local low-level heating/cooling couplet that consists of near-surface heating over the western portion of the continent and low-level maritime cooling off the coast. Inspection of diabatic heating contributions has revealed that this couplet, which reflects a pronounced zonal land-sea thermal contrast across the west coast of a subtropical continent, is a manifestation of heating due mainly to sensible heat flux over the dry, heated continent and cloud radiative cooling off the coast. This result is consistent with Wu and Liu (2003), but inconsistent with Rodwell and Hoskins (2001), who emphasized the primary role of monsoonal deep heating to the east of an anticyclone. Miyasaka (2008; in this abstract volume) has confirmed the conclusion of Miyasaka nd Nakamura (2005), by incorporating the corresponding diabatic heating fields based on the JRA-25 data to the same planetary wave model. At the same time, the surface anticyclonic response to the JRA-25 heating/cooling tends to be slightly weaker than that to the NCEP-DOE heating/cooling, which appears to be due to stronger vertical diffusion counteracting on radiative cooling with low-level maritime clouds in the JRA-25 data.

Another example can be found in our latest assessment of the maintenance mechanism of near-surface baroclinicity observed along mid-latitude storm tracks. Though indicated theoretically as the necessary condition for baroclinic instability in a realistic circumstance, the critical importance of the near-surface baroclinicity for the successive development of baroclinic disturbances along the storm tracks has not been pointed out observationally until the availability of thermal data at the 925-hPa level in the reanalysis data (Nakamura and Shimpo, 2004). Hoskins and Valdes (1990) was the first to make this kind of assessment, by incorporating the zonally asymmetric component of diabatic heating into a planetary wave model. In their assessment the heating had been obtained as the residual of thermodynamic equation. They showed that latent heat release associated with individual cyclones is organized along a storm rack over a particular ocean basin to act as a thermal forcing of planetary waves. They showed that the resultant planetary wave response act to maintain near-surface baroclinicity, suggestive of a self-maintaining nature of a storm track with a moisture supply into cyclones from a warm ocean current south of the baroclinic zone. To verify the conclusion of Hoskins and Valdes (1990), we have recently performed a similar diagnosis with a planetary wave model in which contributions to the zonally asymmetric diabatic heating from individual processes are assigned separately as a thermal forcing. Our assessment indicates that the near-surface baroclinicity, which is strongest across a midlatitude oceanic frontal zone, can be maintained much more effectively by surface sensible heat flux than by latent heat release associated with storms. This result is inconsistent with the assessment by Hoskins and Valdes (1990) but consistent with a hypothesis by Nakamura et al. (2004), who emphasized the primary importance of differential heat supply from the ocean across an oceanic frontal zone for the maintenance of the near-surface baroclinicity along a storm track.

EXAMPLE 3: PROPAGATION OF ROSSBY WAVE PACKETS THROUGH LOCALIZED VERTICAL WAVEGUIDES: A NEW ASPECT OF TROPOSPHERE-STRATOSPHERE DYNAMICAL LINKAGE

Increased vertical resolution of the reanalysis data relative to conventional operational analyses is beneficial also in study of troposphere-stratosphere dynamical linkage through quasi-stationary Rossby wave packets. Confined zonally, their propagation should be sensitive to both latitudinal and longitudinal structure of westerly jets and associated static stability around the tropopause level. Through their analysis of the NCEP/NCAR reanalysis, Nishii and Nakamura (2004) have found that intra-seasonal height fluctuations along the lower-stratospheric polar night jet (PNJ) in the southern hemisphere during late winter and early spring of 1997 were mainly associated with Rossby wave packets that had propagated from localized tropospheric anomalies. Their upward propagation was through localized waveguides ("chimneys"). Using the same data, Nishii and Nakamura (2005) have presented pieces of observational evidence that part of wave activity associated with a wave packet along the PNJ can propagate *downward* through a "chimney" to force a tropospheric circulation anomaly locally, yielding zonal teleconnection from a tropospheric anomaly in a given region to another tropospheric anomaly in a distant region via the stratospheric PNJ. Nishii (2008; in this abstract volume) has conformed the downward propagation of Rossby wave packets. However, he has also found some subtle differences in the three dimensional structure of "chimneys" as revealed among the reanalysis data sets. The differences may result from those in stratospheric temperature fields that arise from model biases used in the reanalyses. The model biases become apparent in the analyses when satellite measurements for the stratosphere are missing.

EXAMPLE 4: FORMATION OF COLD SURFACE ANTICYCLONES ASSOCIATED WITH EXTERNAL ROSSBY WAVE TRAINS

Increased vertical resolution in the troposphere in the reanalysis datasets (and forecast models used) is also beneficial in application of such a modern dynamical diagnosis as potential vorticity inversion (Hoskins et al. 1985) or a wave-activity flux for stationary Rossby waves (Takaya and Nakamura, 2001) that requires second vertical derivative of streamfunction anomalies. Combining those two diagnostic tools, Nakamura and Fukamachi (2004) examined how a cool surface anticyclone develops in summer over the Sea of Okhotsk in the presence of a blocking anticyclone aloft. They showed that the accumulation of the surface cold anomaly results from cold-air advection by anomalous easterlies induced by the tropopause-level anticyclonic PV anomaly associated with the blocking ridge that has developed to the north of the Sea. The advection occurs across the strong zonal thermal gradient between the warm Asian Continent and the cool sea surface of the Okhotsk. Essentially the same mechanism is found operative in the extreme intra-seasonal amplification of the Siberian High (Takaya and Nakamura, 2005). An upper-level pressure ridge and a trough to the east develop as components of a quasi-stationary Rossby wavetrain, inducing anomalous northeasterlies at the surface. Acting on tight thermal gradient to the north of the Tibetan Plateau, they advect extremely cold air from Northeastern Siberia to amplify the cold surface anticyclone. The development of both the Siberian and Okhotsk Highs can thus be interpreted as interaction of an external Rossby wavetrain with surface baroclinicity, through the incipient equivalent barotropic anomalies turn into more baroclinic structure and thus they can extract available potential energy from the baroclinic background state. One of the major differences between the developments of those highs can be found in the strength of their upward influence. The surface cold anomaly associated with the Siberian High is substantially stronger than its counterpart associate with the Okhotsk High, reflecting the corresponding difference in background baroclinicity that is much stronger in winter. Acting as an anticyclonic anomaly, the stronger cold surface anomaly in winter can induce stronger circulation aloft. Acting on tight vorticity gradient associated with the intensified westerly jetstream, the induced northerlies over the Far East yield anomalous cyclonic vorticity advection, reinforcing the cyclonic anomaly associated with the wavetrain (Takaya and Nakamura, 2005). In contrast, under much weaker upper-level vorticity gradient, the cool surface anomaly associated with the Okhotsk High cannot exert significant influence in the upper troposphere.

SUMMARY

In this paper we have presented several examples where the usage of reanalysis datasets has contributed to our deeper understanding of the atmospheric circulation and its anomalies with combination of modern dynamical diagnostic tools. At the same time, those examples have revealed uncertainties in quality of the reanalysis data, especially in diabatic heating fields that are strongly dependent of model representation/parameterization of cumulus convection, cloud formation and radiation. A more quantitative assessment of the uncertainties in diabatic heating requires a carefully designed diagnosis, including evaluation of vertical motion based, for example, on nonlinear balance equation before performing heat budget analysis, although another uncertainty may arise from that evaluation. We also found that stratospheric thermal fields that are sensitive to model bias in the absence of satellite-derived thermal fields can cause subtle differences in localized vertical waveguide structures diagnosed in the reanalysis data. Therefore, we have to exercise our caution when interpreting our diagnosis if based on any of those model-dependent variables.

Despite those shortcomings, our community has been benefited from the reanalysis datasets. Hopefully, the next generation reanalysis data will become available near future, where we expect more than just providing longer series of data fields. Our expectation includes (i) higher quality in the model-dependent variables through improvement in forecast models and data assimilation procedures, (ii) reanalysis based on coupled ocean-atmosphere models for more consistent representation of ocean-atmosphere interaction, and (iii) the inclusion of ensemble forecast fields for better assessment of predictability of extreme events and thereby deeper understanding of the dynamics behind.

REFERENCES

Hoskins, B.J., P.J. Valdes, 1990: On the existence of storm tracks. J. Atmos. Sci., **47**, 1854–1864.

Hoskins, B.J., M.E. McIntyre, A.W. Robertson, 1985: On the use and significance of isentropic potential vorticity maps. Quart. J. Roy. Meteor. Soc., **111,** 877–946.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, D. Joseph, 1996: The NCEP/NCAR 40-year reanalysis project. Bull. Amer. Meteor. Soc. **77**, 437–471.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S. K. Yang, J. J. Hnilo, M. Fiorino, G.L. Potter, 2002: NCEP-DOE AMIP-II reanalysis (R-2). Bull. Amer. Meteor. Soc. **83**, 1631–1643.

Kosaka, Y., and H. Nakamura, 2006: Structure and dynamics of the summertime Pacific-Japan teleconnection pattern. Quart. J. Roy. Meteor. Soc., **132**, 2009–2030.

Kosaka, Y., H. Nakamura, 2008: A comparative study on the dynamics of the Pacific-Japan (PJ) teleconnection pattern based on reanalysis datasets, SOLA, **4**, 9–12.

Miyasaka H. Nakamura, 2005: Summertime subtropical highs and tropospheric planetary waves in the Northern Hemisphere. J. Climate, **18**, 5046–5065.

Nakamura, H., T. Fukamachi, 2004: Evolution and dynamics of summertime blocking over the Far East and the associated surface Okhotsk high. Quart. J. Roy. Meteor. Soc., **130**, 1213–1233.

Nakamura, H., A. Shimpo, 2004: Seasonal variations in the Southern Hemisphere storm tracks and jet streams as revealed in a reanalysis data set. J. Climate, **17**, 1828–1842

Nakamura, H., T. Sampe, Y. Tanimoto, A. Shimpo, 2004: Observed associations among storm tracks, jet streams and midlatitude oceanic fronts. Earth's Climate: The Ocean-Atmosphere Interaction, C. Wang, S.-P. Xie, and J. A. Carton (Eds.), Geophysical Monograph, **147**, American Geophysical Union, 329–345.

Nishii, K., H. Nakamura, 2004: Lower-stratospheric Rossby wave trains in the Southern Hemisphere: A case study for late winter of 1997. Quart. J. Roy. Meteor. Soc., **130**, 325–345.

Nishii, K., H. Nakamura, 2005: Upward and downward injection of Rossby wave activity across the tropopause: A new aspect of the troposphere-stratosphere linkage. Quart. J. Roy. Meteor. Soc., **131**, 545–564.

Onogi, K, H. Koide, M. Sakamoto, S. Kobayashi, J. Tsutsui, H. Hatsushika, T. Matsumoto, N. Yamazaki, Kamahori, K. Takahashi, K. Kato, R. Oyama, T. Ose, S. Kadokura, K. Wada, 2005: JRA-25: Japanese 25-year reanalysis project—progress and status. Quart. J. Roy. Meteor. Soc., **131**, 3259–3268.

Onogi, K., J. Tsutsui, H. Koide, M. Sakamoto, S. Kobayashi, H. Hatsushika, T. Matsumoto, N. Yamazaki, H. Kamahori, K. Takahashi, S. Kadokura, K. Wada, K. Kato, R. Oyama, T. Ose, N. Mannoji, R. Taira, 2007: The JRA-25 Reanalysis. J. Meteor. Soc. Japan, **85**, 369–432.

Nishii, K., H. Nakamura, 2005: Upward and downward injection of Rossby wave activity across the tropopause: A new aspect of the troposphere-stratosphere linkage. Quart. J. Roy. Meteor. Soc., **131**, 545–564.

Nitta, T., 1987: Convective activities in the tropical western Pacific and their impact on the northern hemisphere summer circulation. J. Meteor. Soc. Japan, **65**, 373–390.

Rodwell, M.J. and B.J. Hoskins, 2001: Subtropical anticyclones and summer monsoons. J. Climate, **14,** 3192–3211.

Takaya, K, H. Nakamura, 2001: A formulation of a phase-independent wave-activity flux for stationary and migratory quasi-geostrophic eddies on a zonally varying basic flow. J. Atmos. Sci.**,** **58**, 608–627.

Takaya, K, H. Nakamura, 2005: Mechanisms of intraseasonal amplification of the cold Siberian High. J. Atmos. Sci., **62**, 4423–4440.

Uppala, S.M., P.W. K°allberg, A.J. Simmons, U. Andrae, V. da C. Bechtold, M. Fiorino, J.K. Gibson, J. Haseler, A. Hernandez, G.A. Kelly, X. Li, K. Onogi, S. Saarinen, N. Sokka, R.P. Allan, E. Andersson, K. Arpe, M.A. Balmaseda, A.C.M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, S. Caires, F. Chevallier, A. Dethof, M.

Dragosavac, M. Fisher, M. Fuentes, S. Hagemann, E. H´olm, B.J. Hoskins, L. Isaksen, P.A.E.M. Janssen, R. Jenne, A.P. McNally, J.-F. Mahfouf, J.-J. Morcrette, N.A. Rayner, R.W. Saunders, P. Simon, A. Sterl, K.E. Trenberth, A. Untch, D. Vasiljevic, P. Viterbo, J. Woollen, 2005: The ERA-40 re-analysis. Qurart. J. Roy. Meteor. Soc., **131**, 2961–3012.

Wu, G.X., Y. Liu, 2003: Summertime quadruplet heating pattern in the subtropics and the associated atmospheric circulation. *Geophys. Res. Lett.,* **30,** 1201, doi:10.1029/2002GL016209.