Evaluation of synoptic eddy activities and their feedback onto the midlatitude jet in five atmospheric reanalyses with coarse versus fine model resolutions

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Abstract

Interaction between synoptic eddy and mean flow plays a crucial role in maintaining midlatitude westerly jet. In this study, climatologies of synoptic eddy activities and their feedback onto midlatitude jet for 1980–2016 are evaluated and compared through analyzing daily data from five atmospheric reanalyses with different resolutions including one coarse-resolution reanalysis (NCEP2) and four fine-resolution reanalyses (ERA-Interim, JRA-55, MERRA-2, and CFSR). Horizontal resolutions of the atmospheric models generating those reanalyses are approximately equivalent to 210, 79, 60, 50, and 38 km, respectively. Results show that the eddy activities and their feedback onto the midlatitude jet in those fine-resolution reanalyses are consistently and significantly stronger than those in the coarse-resolution reanalysis (NCEP2). The maximal relative increases that are found to occur primarily in the midlatitudes of the Southern Hemisphere are estimated to be up to 55% for the baroclinicity, 53% for the eddy energetics, 59% for the eddy forcing, and even 85% for the eddy feedback onto the mean flow. Those increases are reasonably conjectured to be related to increased model resolutions, since the synoptic eddy genesis is proportional to the low-level atmospheric meridional temperature gradient which is sensitive to the meridional resolution of atmospheric models. Although the coarse-resolution reanalysis resolves synoptic eddies insufficiently and thus underestimates their feedback onto the mean flow, the magnitudes of eddy-driven jets are almost the same among five reanalyses, implying a mismatch between the eddy feedback and the eddy-driven jet in the coarse-resolution reanalysis. Therefore, the results of this study imply the importance of using fine-resolution reanalyses in accurately understanding the midlatitude synoptic eddy–mean flow interaction.

Keywords Synoptic eddy · Eddy-driven jet · Baroclinicity · Synoptic eddy–mean flow interaction · Atmospheric reanalysis

1 Introduction

Interaction between synoptic eddy and mean flow is one of fundamental issues in theoretical and observational studies on the midlatitude atmospheric general circulation (Robinson 1994, 2006; Lorenz and Hartmann 2003; Held 2019). Linear baroclinic theories exhibit that the growth rate of synoptic eddies is determined by low-level atmospheric baroclinicity which is proportional to the meridional temperature gradient divided by static stability (Charney 1947;

Eady 1949; Chang et al. 2002). The baroclinicity-induced synoptic eddies propagate away from midlatitude baroclinic zones and converge with momentum in the midlatitudes, producing and maintaining the midlatitude westerly jet that is called the eddy-driven jet (Holopainen et al. 1982; Lorenz and Hartmann 2001; Vallis 2006).

Atmospheric reanalysis, as a kind of long-term, 3-dimensional, and homogenous observationally-constrained data, has been widely used for the midlatitude eddy–mean flow interaction studies. Since it is generated by a numerical weather prediction (NWP) model in which historical atmospheric observations are assimilated (Wikle 2005), atmospheric reanalysis dataset has large uncertainties resulting from the forecast model, the data assimilation, and the data source used. A variety of earlier comparative studies on the synoptic eddy statistics with different reanalyses were conducted in terms of the cyclone detection/tracking algorithm

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(Hodges et al. 2003, 2011; Trigo 2006; Wang et al. 2006; Bromwich et al. 2007; Raible et al. 2008) or the eddy variance/covariance statistics (Lau and Oort 1982; Chang and Yau 2016). They revealed a dependence of cyclone tracks on the resolution of forecast models that generate those reanalyses. Those comparative studies mostly utilized the old reanalysis datasets, such as the U.S. National Meteorological Center (NWC), the National Centers for Environmental Prediction (NCEP), the 25-year Japan Reanalysis (JRA-25), the 15-year European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA-15), and the 40-year ECMWF Reanalysis (ERA-40). Hodges et al. (2003) showed differences in both the frequency and the intensity of cyclones between ERA-15 and NCEP and related them to the differences in resolution of model integrations. Wang et al. (2006), Trigo (2006), and Raible et al. (2008) demonstrated a stronger cyclone activity in ERA-40 than in NCEP, which can be attributed to the higher resolution of the model integrated for ERA-40. By comparing four reanalyses, i.e., the ECMWF Interim Re-Analysis (ERA-Interim), JRA-25, the NCEP Climate Forecast System Reanalysis (CFSR), and the National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications (MERRA), Hodges et al. (2011) found that the numbers and intensities of extratropical cyclones are larger in the higher-resolution reanalyses than in the lower-resolution JRA-25 reanalysis, particularly over the Southern Hemisphere (SH). Tilinina et al. (2013) verified that the number of cyclones over the Northern Hemisphere (NH) increase with increase of the spatial resolutions of reanalyses for both winter and summer. Guo et al. (2009) found that the strengths of SH storm tracks are 25% and 5–10% weaker in NCEP and ERA-40, respectively, than in observation. Given the crucial role of synoptic eddies in the midlatitude atmospheric general circulation, a question raised here is whether the underestimated synoptic eddy activities in the lower-resolution reanalyses can affect their feedback onto the mean flow.

In addition, sensitivities of the midlatitude eddy–mean flow interaction to the model resolution were explored in previous studies with focus on the transient eddy activities (Boville 1991; Williamson et al. 1995; Blender and Schubert 2000) and on the mean state (Boyle 1993; Williamson 1999; Roeckner et al. 2006). As pointed out by Boville (1991) and Williamson et al. (1995), the eddy kinetic energy tends to have a monotonic increase as the model horizontal resolution increases from T21 to T106. Using cyclone-tracking diagnostics, Blender and Schubert (2000) and Jung et al. (2006) quantified the sensitivity of extratropical cyclone characteristics to horizontal resolution and found that the number of cyclones increases with increase of resolution. However, the increase of model resolution led to more mixed results in zonal wind (Boyle 1993; Williamson et al. 1995).

A consistent improvement in midlatitude westerly jet was not found with increased resolution from T21 to T106. This might come somewhat as a bit of a surprise since stronger eddy activities could contribute to a stronger midlatitude jet via eddy-to-mean flow feedback.

Given the importance of model resolution in simulating synoptic eddy activity and the availability of new reanalyses with higher horizontal resolutions, it is essential to continue assessing the modern reanalyses to understand their uncertainties and reliabilities in the midlatitude eddy–mean flow interaction. By comparing five modern atmospheric reanalyses with different resolutions including one coarse-resolution reanalysis (NCEP2) and four fine-resolution reanalyses (ERA-Interim, JRA-55, MERRA-2, and CFSR), this study aims to evaluate climatologies of synoptic eddy activities and their feedbacks onto midlatitude jets for the modern satellite period of 1980–2016 and clarify whether the resolutions of models generating the reanalyses matter in the midlatitude eddy–mean flow interaction. The paper continues in Sect. 2 with a brief description of five atmospheric reanalysis datasets used. The comparisons of the genesis and energetics of synoptic eddies are presented in Sect. 3. The eddy feedback onto mean flow and the eddy-driven jets are compared in Sects. 4 and 5, respectively. Final section is devoted to conclusions and discussion.

2 Description of datasets

Five atmospheric reanalyses with different model resolutions are used in this study. One coarse-resolution reanalysis is NCEP-DOE Reanalysis 2 (NCEP2) (Kanamitsu et al. 2002). Four fine-resolutions reanalyses are ERA-Interim (Dee et al. 2011), JRA-55 (Kobayashi et al. 2015), MERRA-2 (Gelaro et al. 2017), and CFSR (Saha et al. 2010). Table 1 summarizes detailed information of the five reanalyses. NCEP2, ERA-Interim, JRA-55, and CFSR use spectral models with horizontal resolutions of T62 (210 km), T255 (79 km), T319 (60 km), and T382 (38 km), respectively. MERRA-2 is generated with a finite volume model that uses a cubed-sphere horizontal discretization at a resolution of $2/3^\circ$ longitude by 0.5° latitude (approximately 50 km). In the process of data assimilation, NCEP2, MERRA-2, and CFSR employ three-dimensional variational (3D-VAR) data assimilation, while ERA-Interim and JRA-55 use the most advanced four-dimensional variational (4D-VAR) data assimilation system. In addition, compared with the satellite retrievals implemented in NCEP2, the four fine-resolution reanalyses use variational bias correction to raw satellite radiances. In particular, the 55-year Japanese Reanalysis Project (JRA-55) is a new reanalysis that improves the representations of phenomena on a wide range of space-time scales compared

Table 1 Detailed information of five atmospheric reanalyses used in this study

Reanalysis name	Organization	Products resolution	Date range	Horizontal resolution of forecast model	Data assimilation	Satellite data
NCEP2	NCEP/DOE	$2.5^\circ \times 2.5^\circ$	1979–2017	T62 ~210 km	3D-VAR	Retrievals
ERA-Interim	ECMWF	$1.5^\circ \times 1.5^\circ$	1979–2017	T255 ~79 km	4D-VAR	Raw satellite radiances
JRA-55	JMA	$1.25^\circ \times 1.25^\circ$	1958–2017	T319 ~60 km	4D-VAR	Raw satellite radiances
MERRA-2	NASA GMAO	$0.625^\circ \times 0.5^\circ$	1980–2017	$(2/3)^\circ \times 0.5^\circ$ ~50 km	3D-VAR	Raw satellite radiances
CFSR	NCEP	$0.5^\circ \times 0.5^\circ$	1979–2017	T382 ~38 km	3D-VAR	Raw satellite radiances

with JRA-25 (Harada et al. 2016). Besides, NASA Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), assimilates observations that are not available to its predecessor, MERRA, and provides improvements in the extensive qualities (Gelaro et al. 2017).

In this study, we use daily pressure-level products of zonal and meridional components of wind, vertical velocity, geopotential height, and air temperature. Horizontal resolutions of the products are 2.5° by 2.5° (longitude/latitude) for NCEP2, 1.5° by 1.5° for ERA-Interim, 1.25° by 1.25° for JRA-55, 0.625° by 0.5° for MERRA-2, and 0.5° by 0.5° for CFSR. Note that it is the resolution of model that determines the eddy resolving, but not the resolution of product. For comparison, a difference of each variable between each of the four fine-resolution reanalyses and the coarse-resolution NCEP2 is calculated, in which a field of NCEP2 is interpolated into grids of each fine-resolution reanalysis with using spherical harmonics, and then a relative change (increase or decrease) is defined with a ratio (%) of the difference relative to NCEP2. Based on the shared time spanning of five reanalysis datasets (Table 1), this study focuses on the June–July–August (JJA) and December–January–February (DJF) climatologies of synoptic eddy activities and their feedbacks onto midlatitude jets for 1980–2016. Here DJF of 1980 refers to December of 1980 and January and February of 1981, and so on. Synoptic eddies are extracted by lanczos filter with a 2–8 day band-pass filtering via 31 weights.

3 Genesis and energetics of synoptic eddies

Since it indicates genesis of midlatitude synoptic eddies, atmospheric baroclinicity is firstly examined for five atmospheric reanalyses, in terms of the maximum Eady growth

rate (Lindzen and Farrell 1980; Hoskins and Valdes 1990) which is defined as

$$\sigma_{BI} = 0.31 \frac{f}{N} \left| \frac{\partial \bar{V}}{\partial z} \right|, \quad (1)$$

where N denotes the Brunt-Väisälä frequency ($N = |(g/\theta)(\partial\theta/\partial z)|^{1/2}$), g is the gravity acceleration, z the vertical coordinate, θ the potential temperature, $\bar{V}$ the horizontal wind, and f the Coriolis parameter. Note that the Eady growth rate is calculated with daily data and then averaged over seasons (Simmonds and Lim 2009).

Figure 1 shows zonally-averaged latitude-altitude sections of differences (shaded) in climatological maximum Eady growth rate between each of the four fine-resolution reanalyses and NCEP2, in which the climatology of NCEP2 is contoured. The maximum baroclinicity is located in the lower and middle troposphere in the mid-latitudes during both JJA and DJF (contours in Fig. 1), and generally undergoes an enhancement from warm season to cold season. Overall, all the fine-resolution reanalyses (ERA-Interim, JRA-55, MERRA-2, and CFSR) exhibit larger baroclinicity than NCEP2, with the largest increase in the near-surface and the upper troposphere at mid-latitudes. The differences in baroclinicity between four fine-resolution reanalyses and NCEP2 show comparable magnitudes and are more remarkable in SH than NH for both JJA and DJF. To be more concrete, the percentage changes relative to NCEP2 in the midlatitude low-level baroclinicity averaged over the green boxes labeled in Fig. 1a and e are illustrated in Fig. 13 for each fine-resolution reanalysis. The midlatitude low-level baroclinicity are consistently larger in four fine-resolution reanalyses than in NCEP2, with a relative increase of up to 55% over SH and 46% over NH. CFSR demonstrates the largest magnitude over SH, while ERA-Interim gives the largest magnitude over NH. Furthermore, spatial distributions of those differences

Fig. 1 Latitude-altitude sections of differences (shading; day^{-1}) in climatological zonally-averaged maximum Eady growth rate between four fine-resolution reanalyses (ERA-Interim, JRA-55, MERRA-2, and CFSR) and one coarse-resolution reanalysis (NCEP2) for JJA (left

panels) and DJF (right panels). The climatologies of zonally-averaged maximum Eady growth rate for NCEP2 are contoured (interval: 0.1 day^{-1}). The green boxes in **a** and **e** indicate the target regions for area average used in Fig. 13

vertically-averaged over 1000–850 hPa in eddy genesis are presented in Fig. 2. The largest increases in low-level baroclinicity are over the SH midlatitudes, western North Pacific, and from North America to North Atlantic, where the climatological baroclinic zones are located.

The larger midlatitude low-level baroclinicity in fine-resolution reanalyses implies the stronger synoptic eddy genesis and thus tends to result in an overall strengthening of storm tracks. Synoptic eddy activities are compared by calculating their energetics together with their generation and conversion

Fig. 2 Horizontal distributions of differences (shading; day^{-1}) in climatological maximum Eady growth rate vertically-averaged over 1000–850 hPa between four fine-resolution reanalyses (ERA-Interim,

JRA-55, MERRA-2, and CFSR) and one coarse-resolution reanalysis (NCEP2) for JJA (left panels) and DJF (right panels). The climatologies of the maximum Eady growth rate for NCEP2 are contoured (interval: 0.2 day^{-1})

terms. Figure 3 presents vertical structures of differences in eddy available potential energy (EAPE), which is defined as

$$\text{EAPE} = \frac{C_p \tau}{2} (\overline{T'}^2), \quad (2)$$

where $\tau = -R/(pC_p)(p_0/p)^{R/C_p}(\partial\theta/\partial p)^{-1}$ is an inverse measure of the background stratification (Lorenz 1955), T is the temperature, θ the potential temperature, R ($=287 \text{ JK}^{-1}\text{kg}^{-1}$) the gas constant for dry air, C_p ($=1004 \text{ JK}^{-1}\text{kg}^{-1}$) the specific heat capacity of dry air at the constant pressure, and p_0 ($=1000 \text{ hPa}$) the mean sea level pressure. The overbar denotes the climatological mean and

Fig. 3 As in Fig. 1, but for EAPE (shading; m^2s^{-2}) in which the contours indicate the climatologies of EAPE for NCEP2 (interval: $10 \text{ m}^2\text{s}^{-2}$)

the prime denotes 2–8 day band-pass filtered components. The zonally-averaged EAPE maximizes in the middle troposphere in the midlatitudes (contours in Fig. 3). In SH, EAPE is stronger in fine-resolution reanalyses than in NCEP2, with the largest increases in the middle and upper troposphere. In NH, the differences between four fine-resolution and NCEP2 are small for both seasons. More precisely, the percentage changes of each fine-resolution reanalysis relative to

NCEP2 in area-averaged EAPE over the green boxes labeled in Fig. 3a and e are illustrated in Fig. 13. Consistent with those in baroclinicity, the relative increases in EAPE for four fine-resolution reanalyses are up to 53% in SH and 12% in NH. CFSR gives the largest increase since its forecast model has the highest resolution among five reanalyses. The spatial distributions of differences averaged over 1000–250 hPa in EAPE between four fine-resolution reanalyses and NCEP2

are displayed in Fig. 4. All fine-resolution reanalyses present similar spatial patterns but with different magnitude. In JJA (left panels of Fig. 4), remarkably stronger EAPE in four fine-resolution reanalyses are identified over the midlatitudes of SH. In DJF (right panels of Fig. 4), large values of increased EAPE occur over the North Pacific, the North Atlantic, and the South Indian Ocean, where are known as storm tracks.

The eddy kinetic energy (EKE) is further calculated and compared, which is defined as

$$\text{EKE} = \frac{1}{2} \left(\overline{u'^2} + \overline{v'^2} \right), \quad (3)$$

where u' and v' are the synoptic-scale (2–8 day) fluctuations of zonal and meridional wind, respectively. Results for EKE are similar to EAPE. More intense EKE are identified in fine-resolution reanalyses, especially in the upper troposphere between 400 and 200 hPa in SH, as shown in Fig. 5. Relative increases of upper-level EKE over the midlatitudes are comparable in the fine-resolution reanalyses and reach up to 43% in SH and 10% in NH (as summarized in Fig. 13). The spatial structures of differences in vertically-averaged EKE from 400 hPa to 200 hPa between four fine-resolution reanalyses and NCEP2 (Fig. 6) are similar to those seen in EAPE (Fig. 4), with the largest increase in the midlatitudes over SH.

The increases in EAPE and EKE should be related to the energy conversion between eddies and mean flow (Chang et al. 2002). The differences in eddy–mean flow interaction between four fine-resolution reanalyses and NCEP2 are investigated by analyzing barotropic and baroclinic energy conversions. The baroclinic energy conversion includes energy conversions from the mean available potential energy to the EAPE (BCEC1) and from the EAPE to the EKE (BCEC2). The analysis of baroclinic energy conversion is based on the following formulas (Cai et al. 2007; Lee et al. 2012),

$$\text{BCEC1} = \left(\frac{p_0}{p} \right) \left(\frac{R}{g} \right) \left(-\frac{d\theta}{dp} \right)^{-1} \left(\overline{u'T'} \frac{\partial \bar{T}}{\partial x} + \overline{v'T'} \frac{\partial \bar{T}}{\partial y} \right), \text{ and} \quad (4)$$

$$\text{BCEC2} = - \left(\frac{p_0}{p} \right)^{C_v/C_p} \left(\frac{R}{g} \right) \left(\overline{\omega'T'} \right), \quad (5)$$

where C_p and C_v are the specific heat capacity of dry air at the constant pressure and volume, respectively. BCEC1 is related to the horizontal eddy heat flux and the mean temperature gradient, while BCEC2 is determined by vertical eddy heat flux. The percentage changes of each fine-resolution reanalysis relative to NCEP2 in vertically-averaged BCEC1 and BCEC2 from 1000 to 250 hPa at midlatitudes are displayed in Fig. 7. Here the energy

conversions in SH are only analyzed, since the largest differences in eddy energetics are over there. Overall, the magnitudes of BCEC1 and BCEC2 are significantly larger in four fine-resolution reanalyses than NCEP2, with a relative increase of up to 37% for BCEC1 and 47% for BCEC2, respectively, indicating larger baroclinic eddy genesis in fine-resolution reanalyses. In general, MERRA-2 and CFSR show larger magnitudes of eddy energetics and eddy conversion than JRA-55 and ERA-Interim owing to their relatively higher resolution. It can also be seen in Fig. 7 that the significantly larger EAPE and EKE in fine-resolution reanalyses are consistent with the increases in baroclinic energy conversion.

The barotropic energy conversion (BTEC) from the EKE to the mean kinetic energy is also analyzed with the following formula (Simmons et al. 1983; Cai et al. 2007),

$$\text{BTEC} = -\frac{p_0}{g} \left[\frac{1}{2} \left(\overline{v'^2} - \overline{u'^2} \right) \left(\frac{\partial \bar{u}}{\partial x} - \frac{\partial \bar{v}}{\partial y} \right) + \left(-\overline{u'v'} \right) \left(\frac{\partial \bar{v}}{\partial x} + \frac{\partial \bar{u}}{\partial y} \right) \right], \quad (6)$$

which indicates the energetic process in feedback of synoptic eddies onto the mean flow. Synoptic eddies give energy back to the mean flow equatorward of the jet cores and over the exit regions of the jet stream. The changes of each fine-resolution reanalysis relative to NCEP2 in zonally-averaged BTEC at 250 hPa over 30°–50° S are also shown in Fig. 7. The barotropic energy conversions from eddies to mean flow are also stronger in the fine-resolution reanalyses over SH, suggesting a stronger eddy feedback onto the mean flow.

The changes relative to NCEP2 in eddy energetics are similar among four fine-resolution reanalyses and are significantly stronger than those in NCEP2, which coincides with the larger eddy genesis. The eddy genesis measured by the Eady growth rate is proportional to the meridional temperature gradient, which is sensitive to the meridional resolution of model. Thus, the increase in the horizontal resolution of model generating a reanalysis is likely one of key factors determining the large differences in eddy genesis as well as eddy activities between fine-resolution and coarse-resolution reanalyses. However, it is noted that, although the eddy activities have a large enhancement when the horizontal resolution of model increases from 210 km (NCEP2) to 79 km (JRA-55), they do not continue increasing monotonically when the horizontal resolution increases from 79 to 38 km among fine-resolution reanalyses. This implies that there presumably exists a critical horizontal resolution for which the model can sufficiently resolve the synoptic eddies. In addition to the horizontal resolution of model, other factors such as observations, assimilation system, and model physical parameterizations can also affect the transient eddy statistics (Held 1978; Stephenson 1994; Guo and Chang 2008).

Fig. 4 As in Fig. 2, but for EAPE (shading; m^2s^{-2}) vertically-averaged over 1000–250 hPa in which the contours indicate the climatologies of EAPE for NCEP2 (interval: $10 \text{ m}^2\text{s}^{-2}$)

The largest differences in the eddy activities found in SH for both JJA and DJF are likely due to the sparse observations there (Hodges et al. 2011). There are much less ground-based observations available to constrain the reanalysis in SH than NH. In SH, available observations

that are assimilated into forecast models are dominated by satellite observations. Thus, atmospheric reanalyses in SH are more susceptible to model errors than in NH, although modern assimilation techniques and improved models have mitigated this deficiency to some degree.

Fig. 5 As in Fig. 1, but for EKE (shading; m^2s^{-2}) in which the contours indicate the climatologies of EKE for NCEP2 (interval: $10 \text{ m}^2\text{s}^{-2}$)

4 Feedback of synoptic eddies onto mean flow

Synoptic eddies can exert forcing on the mean flow via redistributing momentum and heat through eddy momentum flux ($\overline{u'v'}$) and eddy heat flux ($\overline{v'T'}$). According to the Eulerian

mean zonal wind equation, we can write the zonally-averaged zonal wind tendency as,

$$\frac{\partial [\bar{u}]}{\partial t} \propto -\frac{\partial}{\partial y} \left(\left[\bar{u'v'} \right] \right). \quad (7)$$

Fig. 6 As in Fig. 2, but for EKE (shading; m^2s^{-2}) vertically-averaged over 400–200 hPa in which the contours indicate the climatologies of EKE for NCEP2 (interval: $20 \text{ m}^2\text{s}^{-2}$)

A convergence (divergence) of the eddy momentum flux indicates a tendency of westerly acceleration (deceleration) (Hoskins et al. 1983). The negative (positive) eddy momentum fluxes north (south) of the midlatitude jet acts to generate the convergence of eddy momentum at midlatitudes, forming a mean westerly forcing on the jet, as shown in

Fig. 8a and b. Figure 8c and d present the differences in the convergence of eddy momentum flux at 250 hPa between four fine-resolution reanalyses and NCEP2. The convergences of eddy momentum fluxes are consistently larger in fine-resolution reanalyses than in NCEP2, with the largest differences in the midlatitudes of SH. As Fig. 8d is compared with Fig. 8b, it can be seen that the convergence of

momentum flux over the SH midlatitudes in DJF increases by 50% in each of four fine-resolution reanalyses relative to NCEP2. Therefore, corresponding to the weakening of eddy activities in NCEP2, the eddy momentum forcing on mean flow is also attenuated.

Synoptic eddies can redistribute heat and drive the mean temperature and meridional circulation through eddy heat flux, as shown in Fig. 9. In both seasons, the eddy heat flux is directed poleward, which plays an important role in transporting the heat from low to high latitudes and decreasing the baroclinicity (Fig. 9a, b). The maxima in eddy heat flux are located in the middle and lower troposphere in the midlatitudes. Similar to the convergence of eddy momentum flux, the absolute values of midlatitude low-level eddy heat fluxes are consistently larger in four fine-resolution reanalyses than in NCEP2 (Fig. 9c, d). The strengthened eddy heat flux could be related to the increased mean meridional temperature gradient according to the baroclinic adjustment theory (Held 1978).

To measure the complete feedback of synoptic eddies onto the mean flow, the geopotential height tendency induced by each of the forcing terms is further diagnosed with the quasi-geostrophic potential vorticity (QGPV) equation employed by Fang and Yang (2016),

$$\left[\frac{1}{f} \nabla^2 + f \frac{\partial}{\partial p} \left(\frac{1}{\sigma_1} \frac{\partial}{\partial p} \right) \right] \left(\frac{\partial \bar{\Phi}}{\partial t} \right) \propto -f \frac{\partial}{\partial p} \left(\frac{\alpha}{\sigma_1} \frac{\bar{Q}_d}{\bar{T}} \right) - f \frac{\partial}{\partial p} \left(\frac{\alpha}{\sigma_1} \frac{\bar{Q}_{eddy}}{\bar{T}} \right) + \bar{F}_{eddy}, \quad (8)$$

where Φ is the geopotential height, α the reciprocal of density, and σ_1 the static stability parameter. $\bar{Q}_d$ is the climatological mean diabatic heating, $\bar{Q}_{eddy}$ the synoptic eddy heat forcing, and $\bar{F}_{eddy}$ the synoptic eddy vorticity forcing, which are defined, respectively, as

$$\bar{Q}_{eddy} = -\nabla \cdot \overline{V_h T'} - \frac{\partial (\overline{\omega' T'})}{\partial p} + \frac{R}{C_p p} (\overline{\omega' T'}), \quad \text{and} \quad (9)$$

$$\bar{F}_{eddy} = -\nabla \cdot \overline{V_h \zeta'}. \quad (10)$$

Numerical solutions of geopotential height tendency in Eq. (8) can be obtained by successive over-relaxation method. According to the quasi-geostrophic relationship, the zonal wind tendency can be further derived as,

$$\frac{\partial \bar{u}}{\partial t} = -\frac{1}{f} \frac{\partial}{\partial y} \left(\frac{\partial \bar{\Phi}}{\partial t} \right), \quad (11)$$

which is denoted as $\bar{u}_t$. Figure 10 only shows the differences in transient eddy vorticity forcing since it determines the equivalent barotropic structure of eddy-driven jets (Fang and Yang 2016). In climatology, zonally-averaged eddy vorticity forcing is negative south of the eddy-driven jet core (around 50°) and positive north of the jet core and reaches the maximum in the upper troposphere, as seen from contours in Fig. 10. The eddy vorticity forcing with such a meridional dipole distribution acts to accelerate the westerly in the midlatitudes, as the eddy momentum flux does in Fig. 8. In general, the differences of the eddy vorticity forcing between

Fig. 7 Changes in percentage (%) relative to NCEP2 of climatological zonally-averaged BCEC1 (averaged over 30°–60° S and 1000–250 hPa), EAPE (averaged over 30°–70° S and 1000–250 hPa), BCEC2 (averaged over 30°–60° S and 1000–250 hPa), EKE (aver-

aged over 30°–70° S and 400–200 hPa), and BTEC (at 250 hPa averaged over 30°–50° S) over SH in **a** JJA and **b** DJF for each of the four fine-resolution reanalyses

fine-resolution reanalyses and NCEP2 are in phase with the climatology, characterized by increases in positive forcing and decreases in negative forcing, indicating the stronger eddy vorticity forcing in fine-resolution reanalyses. The differences also demonstrate an equivalent barotropic vertical structure with the maximum in the upper troposphere in the SH midlatitudes and are relatively small over NH. The eddy vorticity forcing is averaged over the poleward flank of jet and between 500 hPa and 150 hPa, as shown in green boxes labeled in Fig. 10, and their relative changes are calculated for four fine-resolution reanalyses, as given in Fig. 13. It can be seen that the eddy vorticity forcing of ERA-Interim, JRA-55, MERRA-2, and CFSR are notably larger than that of NCEP2, with maximal relative increases of up to 59% in SH and 21% in NH. Accordingly, the differences in derived westerly tendencies induced by eddy vorticity forcing (i.e., the eddy dynamical feedback) at 250 hPa over SH are shown Fig. 11. In general, the effect of eddy vorticity forcing on mean flow is to accelerate the westerly in the midlatitudes, as seen from contours in Fig. 11 for NCEP2. Relative to NCEP2, there are considerable increases in westerly tendencies over SH, especially over the South Indian Ocean, in four fine-resolution reanalyses. MERRA-2 and CFSR present the largest increase. The percentage changes in midlatitude ($40^{\circ} - 60^{\circ}$ N or $40^{\circ} - 60^{\circ}$ S) zonally-averaged westerly

tendencies shown in Fig. 13 denote an overall increase of even up to 85% relative to NCEP2 in fine-resolution reanalyses. Thus, the eddy vorticity forcing and eddy dynamical feedback increase greatly in fine-resolution reanalyses, as compared with NCEP2. The percentage increases in eddy forcing and eddy feedback are larger than those in eddy energetics (up to 53%). This may indicate that twice horizontal derivations of wind field make the eddy vorticity forcing and eddy feedback more sensitive to the horizontal resolution of model that generates reanalysis. The results confirm the importance of using high-resolution reanalysis in the studies of the midlatitude eddy–mean flow interaction.

5 Eddy-driven jets

Since the eddy forcing and eddy feedback onto the mean flow are notably larger in fine-resolution reanalyses than those in NCEP2, it is expected that the eddy-driven jets (also referred to as the midlatitude jets) are strengthened in high-resolution reanalyses. Figure 12 illustrates the latitude–altitude sections of the differences in zonally-averaged zonal wind between four fine-resolution reanalyses and NCEP2. In JJA, two well-separated jets are observed in SH with the subtropical jet located at 30° S and the eddy-driven jet

Fig. 8 Latitude–altitude sections of climatological zonally-averaged eddy momentum flux (shading; units: m^2s^{-2}) and its convergence (black contours; intervals: $4 \times 10^{-6} \text{ ms}^{-2}$) in **a** JJA and **b** DJF for NCEP2 (upper panels). Differences in the convergence of zonally-

averaged eddy momentum flux (10^{-6} ms^{-2}) at 250 hPa between four fine-resolution reanalyses and NCEP2 are shown in lower panels for **c** JJA and **d** DJF

Fig. 9 Latitude-altitude sections of climatological zonally-averaged eddy heat flux (shading; units: K ms^{-1}) in **a** JJA and **b** DJF for NCEP2 (upper panels). Differences in the climatological zonally-

averaged eddy heat flux (Kms^{-1}) at 850 hPa between four fine-resolution reanalyses and NCEP2 are shown in lower panels for **c** JJA and **d** DJF

located at 50° S (contours in left panels of Fig. 12). The subtropical jet is baroclinic without corresponding near-surface westerly below its maximum, while the eddy-driven jet is barotropic with surface westerlies. There is a single merged jet in NH, with the maxima located at 40° N in the upper troposphere. In DJF, there exists a merged westerly jet over both hemispheres (contours in right panels of Fig. 12). The midlatitude upper-level westerlies in four fine-resolution reanalyses are stronger than those in NCEP2, with maxima in the subtropical jet core. However, the midlatitude surface westerlies in fine-resolution reanalyses are comparable with those in NCEP2. The low-latitude easterlies are remarkably stronger in ERA-Interim, JRA-55, and MERRA-2 than those in NCEP2 and are weaker in CFSR than in NCEP2.

The percentage changes of four fine-resolution reanalyses relative to NCEP2 in midlatitude (40°–60° N or 40°–60° S) zonally-averaged westerly wind at 850 hPa are shown in Fig. 13. The low-level wind is usually used to indicate the eddy-driven jet, which differs from the subtropical jet that is confined to the upper-troposphere (Woollings et al. 2018). In SH, the eddy-driven jets in four fine-resolution reanalyses are slightly larger than that in NCEP2, with a relative increase of 1–2% for both seasons. In NH, JRA-55 and MERRA-2 have a 4% increase in eddy-driven jet, while ERA-Interim and CFSR even have a decrease of 1.5 and 0.5%, respectively. Given the significant increases of up to 59% for eddy vorticity forcing and 85% for the eddy

feedback onto the mean flow, as shown in Fig. 13, it is surprising that the eddy-driven jets do not increase as large as eddy forcing and eddy feedback. The jets seem to be less sensitive to the resolutions of models that generate the reanalyses than synoptic eddies, which is likely due to the data assimilation. The assimilation of observations modifies the biases of model-generated eddy-driven jet and constrains the eddy-driven jet of reanalysis. Thus, eddy-driven jets are less susceptible to model resolution by assimilating observations.

6 Conclusions and discussion

In order to evaluate the capability of reanalysis datasets with different forecast model resolutions in representing midlatitude eddy–mean flow interaction, we perform comparisons among five reanalyses, one coarse-resolution reanalysis (NCEP2) and four fine-resolution reanalyses (ERA-Interim, JRA-55, MERRA-2, and CFSR). Horizontal resolutions of the atmospheric models generating those reanalyses are approximately equivalent to 210, 79, 60, 50, and 38 km, respectively.

We found that the eddy genesis, eddy energetics, eddy forcing, and eddy feedbacks onto the mean flow in four fine-resolution reanalyses are consistently and significantly stronger than those in the coarse-resolution reanalysis (NCEP2). The percentage changes of four fine-resolution

Fig. 10 As in Fig. 1, but for the eddy vorticity forcing (shading; 10^{-11} s^{-2}) in which the contours indicate the climatologies of the eddy vorticity forcing for NCEP2 (interval: $5 \times 10^{-12} \text{ s}^{-2}$) with zero lines omitted

reanalyses relative to NCEP2 are shown in Fig. 13, and the maximal relative changes are listed in Table 2. The eddy genesis measured by the Eady growth rate increases by up to 55% in fine-resolution reanalyses relative to NCEP2, which gives rise to an overall strengthening of storm tracks. The synoptic eddy energetics represented by EAPE and EKE show significant increases in fine-resolution reanalyses with

the largest percentage change of up to 53%, corresponding to the significant increase in the baroclinic energy conversion. The barotropic energy conversion from EKE to the mean kinetic energy also increases by 59% in fine-resolution reanalyses, indicating the stronger eddy barotropic momentum feedback onto mean flow in fine-resolution reanalyses. The eddy vorticity forcing and the eddy feedback diagnosed

Fig. 11 Horizontal distributions of differences in climatological zonal wind tendencies ($\bar{u}_t$; shading: 10^{-5} ms^{-2}) at 250 hPa over SH induced by eddy vorticity forcing between four fine-resolution reanalyses (ERA-Interim, JRA-55, MERRA-2, and CFSR) and NCEP2 for JJA (left panels) and DJF (right panels). The climatologies of $\bar{u}_t$ for NCEP2 are contoured (interval: $5 \times 10^{-6} \text{ ms}^{-2}$)

Fig. 12 As in Fig. 1, but for the zonal wind speed (shading; m s^{-1}) in which the contours indicate the climatologies of zonally-averaged zonal wind speed for NCEP2 (interval: 6 m s^{-1})

by QGPV equation are consistently stronger in four fine-resolution than in NCEP2, with the relative increases of up to 59 and 85%, respectively. Those large increases occur more considerably in SH than in NH, which is likely due to the sparse observations in SH, as discussed in Hodges et al. (2011). The stronger eddy activities in fine-resolution reanalyses are consistent with those pointed out in previous studies using cyclone tracking algorithm (Hodges et al. 2011;

Tilina et al. 2013). The large increases in eddy activities and eddy forcing in fine- versus coarse-resolution reanalyses may be mainly related to the increases in the horizontal resolutions of models generating those reanalyses which tend to enhance the meridional temperature gradient that determines the eddy genesis. As horizontal resolutions increase from 79 to 38 km, the magnitudes of the variables shown in Fig. 13 among fine-resolution reanalyses do not continue

Fig. 13 Changes in percentage (%) relative to NCEP2 of climatological area-averaged Eady growth rate (σ_{BI}), EAPE, EKE, eddy vorticity forcing (F_{eddy}), zonal wind tendencies (u_t) at 250 hPa induced by F_{eddy} , and zonal wind speed at 850 hPa over SH (upper panels) and NH (lower panels) for JJA (left panels) and DJF (right panels)

for each of the four fine-resolution reanalyses. Note that σ_{BI} , EAPE, EKE, and F_{eddy} are averaged over the green boxes labeled in Figs. 1, 3, 5 and 10, respectively; u_t at 250 hPa and zonal wind at 850 hPa are averaged over 40°–60°S in SH and 40°–60°N in NH

Table 2 The maximal increases in percentage (%) of fine-resolution reanalyses relative to NCEP2 and the corresponding hemisphere for area-averaged Eady growth rate (σ_{BI}), baroclinic energy conversion 1 (BCEC1), eddy available potential energy (EAPE), baroclinic energy

conversion 2 (BCEC2), eddy kinetic energy (EKE), barotropic energy conversion (BTEC), eddy vorticity forcing (F_{eddy}), 250 hPa zonal wind tendencies (u_t) induced by F_{eddy} , and 850 hPa zonal wind speed of each fine-resolution reanalysis relative to those of NCEP2

Variable	σ_{BI}	BCEC1	EAPE	BCEC2	EKE	BTEC	F_{eddy}	u_t	850 hPa u
Maximal increase (%)	55	37	53	47	43	59	59	85	4
Hemisphere	SH	SH	SH	SH	SH	SH	SH	SH	NH

increasing monotonically. Within this range of the resolution the models may be able to sufficiently resolve the synoptic eddies. In addition to the model horizontal resolution, the eddy activities and their feedback onto the mean flow may also be affected by observations, assimilation system (Guo and Chang 2008), and model physical parameterizations (Stephenson 1994).

It is surprising that, although the eddy activities and their feedback onto mean flow are so different, the eddy-driven jets indicated by the midlatitude 850 hPa westerly wind are comparable in amplitudes among five reanalyses. The amplitudes of eddy-driven jets in four fine-resolution reanalyses exhibit to be only 1–4% larger than those in NCEP2, with the largest increase of 4% over NH (Table 2). Thus, the eddy-driven jets are less susceptible to model resolution through

assimilating observations. The coarse-resolution reanalysis tends to lead to an underestimation of midlatitude synoptic eddy activities and their feedback onto mean flow and a mismatch between the eddy feedback and the eddy-driven jet. Thus, the results of this study imply the importance of using fine-resolution reanalyses in the studies of midlatitude eddy–mean flow interaction.

Our findings also have implications for model simulations. It is suggested that fine-resolution atmospheric circulation models are needed to investigate midlatitude eddy–zonal mean flow interaction. Williamson et al. (1995) and Jung et al. (2012) found that mean atmospheric circulation errors in the extratropics are rather small, even at relatively low horizontal resolution. However, it is worth noting that atmospheric models with low resolution that are tuned to be particularly skillful in simulating midlatitude atmospheric circulation through adjusting physical process parameterizations may have defects in properly characterizing the interaction between synoptic eddy and mean flow.

We note that further evaluations with diverse reanalyses could be expanded. In this study, in terms of the dynamical framework of QGPV equation, we only focus on the dynamical (vorticity) forcing of synoptic eddies. While in the framework of QGPV dynamics, the transient eddy heat forcing and the diabatic heating also have effects on the mean flow, although they may not be dominant. The heat forcing of synoptic eddies tends to lead to eastward acceleration (deceleration) of the mean flow in the lower (upper) troposphere, which is similar (opposite) to the role of eddy vorticity forcing (Lau and Holopainen 1984; Fang and Yang 2016). Moreover, this study only examines the sensitivity to the horizontal resolution of the model generating the reanalysis. It would be of interest to investigate the sensitivity to its vertical resolution, since increased vertical resolution might be conducive to more accurately representing variables related to vertical shear that also can affect the transient eddy activities through the baroclinicity. Besides, comparisons with out-of-sample observations that are not assimilated into reanalyses to validate the real strength of eddy activities and mean flow need to be conducted in the future study. A candidate for such observations might be station records that are not routinely fed into numerical model. Also, further model sensitivity experiments are needed to foster a better understanding of resolution dependence of midlatitude eddy–mean flow interaction.

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at <https://www.esrl.noaa.gov/psd/>. The ERA-Interim data was produced by ECMWF and is available at <https://apps.ecmwf.int/datasets/>. The JRA-55 data was developed by the Japan Meteorological Agency (JMA) and is available at https://jra.kishou.go.jp/JRA-55/index_en.html. MERRA-2 is available at https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access/. The CFSR data was provided by Research Data Archive at the National Center for Atmospheric Research and is available at <https://doi.org/10.5065/D69K487J>.

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