Analysis of Momentum Budget of Zonal Mean Flow by using Isentropic Representation of EP-flux

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1 Introduction

Locations of zonal mean wind such as subtropical or polar front jets affect climate of Japan. Because they vary the basic states of the atmosphere and propagation of baroclinic instability and Rossby waves. Thus, it is important for climate diagnosis to analyze the changes of zonal wind. Especially in extratropics, the basic state of zonal wind does not only decide the directions of wave propagation but also is formed by eddy momentum transport.

Eliassen-Palm flux(EP-flux) can be a useful tool to understand the wave mean-flow interaction, since EP-flux represents group velocity vector of Rossby wave and its divergence shows a forcing term to zonal mean zonal wind. But conventional definition of EP flux has some problems in assumptions and treatments of lower boundary conditions for more quantitative analysis.

In this study, a new definition of EP-flux is applied. It is derived from primitive equations on isentropic surface. And a new monitoring tool of budget of zonal mean momentum equation have been developed to analyze changes of zonal flow more accurately. The tool is applied to diagnose monthly climate.

2 Analysis method

Formulations with less assumptions are more suitable for momentum budget analysis. In this study, a method suggested by Iwasaki (1989),Andrews (1983) is applied. Mass-weighted zonal mean on isentropic surface was useed in the method. The definition of EP-flux is derived from primitive equations, without any assumptions such as infinite small amplitude wave and quasi-geostrophic assumption. It also deals with problems about treatments of lower boundaries, and representing momentum transport more accurately. Following Iwasaki (1989), vertical coordinate is converted to zonal mean pressure on isentropic surfaces. The physical characteristics of this coordinate are equal to those of isentropic coordinate. In this method, zonal mean formulations are shown as follows:

$$\frac{\partial \overline{u^*}}{\partial t} + \frac{\overline{v^*}}{a}\left(\frac{\partial}{\partial \mu}\overline{u^*}\sqrt{1-\mu^2}\right)_{p_\dagger} + \overline{\omega_\dagger^*}\frac{\partial \overline{u^*}}{\partial p_\dagger} = \frac{1}{a\sqrt{1-\mu^2}}\nabla\cdot\boldsymbol{F} + f\overline{v^*} + \overline{X^*}\Gamma \tag{1}$$

$$\boldsymbol{F} = \left(F_\phi, F_{p_\dagger}\right) = \left[-a\sqrt{1-\mu^2}\ \ \overline{(u'v')^*}, -a\sqrt{1-\mu^2}\ \ \overline{(u'\omega_\dagger')^*} - \overline{\left(p\frac{\partial \Phi}{\partial \lambda}\right)}_{p_\dagger}\right] \tag{2}$$

$$a = radius\ of\ the\ earth,\ \mu = sin\phi,\ \overline{A} = zonal\ mean\ A\ on\ isentropic\ surface$$

$$A^* = \frac{\rho_\theta}{\overline{\rho_\theta}}A,\ p_\dagger = \frac{1}{2\pi}\int min\left(p(\lambda,\mu,\theta), p_{surf}(\lambda,\mu)\right)d\lambda$$

EP-flux is defined by (2). The meridional component of EP-flux shows momentum trasport of barotropic wave such as non-divergent Rossby wave and mature extratropical cyclones. The vertical component of it shows momentum transport of baroclinic wave such as divergent Rossby wave and growing extratropical cyclones. At the surface, vertical component of EP-flux is shown as follows:

$$F_{p_{surf}} = \overline{\left(p_{surf}\frac{\partial g z_{surf}}{\partial \lambda}\right)_{p_{surf}}} \tag{3}$$

It is equal to mountain drag and represents momentum exchange between the sufrace and the atmosphere accurately.

3 Data

All analysis in this study was done by using JRA-25 (Onogi, et, al., 2007). The results of the momentum budget analysis include some numerical errors as follows:

(a)Truncation errors in time due to calculations of momentum budget by instantaneous values.

(b)Numerical errors due to interpolation and differentiation especially in vertical.

The errors due to (a) are unavoidable because the JRA-25 is analyzed every 6-hour. To reduce the errors due to (b), The author used model grid data, with $\sigma - p$ hybrid coordinate in vertical and gaussian grid in horizontal. The resolution of the JRA-25 is T106L40 ($\sim$0.4hPa).

Three-dimensional physical monitors are used for calculations of the friction terms and the diabatic component of EP-flux.

4th-order numerical diffusion is used to remove noises due to meridional derivatives of non linear terms such as the meridional component of EP-flux.

The isentropic coordinate is based on a precondition that potential temperature is static stable and a monotonic function of height. However, in the real atmosphere, there are some static instable regions such as boundary layers, tropics, and near tropopause. In this study, a dry convective adjustment is used to stabilize these instability.

4 Accuracy of the momentum budget analysis

Figure 1 and Figure 2 show the time series of momentum budget by a conventional method (pressure coordinate with quasi-geostrophic assumption) and an isentripic method at regions 30N-40N around 300hPa and 850hPa. In this regions circulations are tend to being influenced orography such as Himalaya. In addition, it is doubtful that quasi-geostropic assumption is appropriate. In the upper troposphere, though the sign of each term in the case of isentropic method coincide with that in conventional method qualitatively, the budgets are different. The isentropic method represents the budget more accurately than the conventional method. This difference seems to come from the quasi-geostrophic assumption. In the lower troposphere, in case of the pressure coordinate, artificial EP-fluxes emitted from the surface are converged and decreases westerly wind. On the other hand, in case of the isentropic coordinate, the emission of EP-fluxes from the surface are small. The EP-flux accelerates westerly in the lower troposphere, and decelerates in the upper troposphere. This di-pole structure of acceleration is consistent with the characteristics of baroclinic wave that weaken the vertical shear of zonal wind. In case of the isentropic coordinate, it represents momentum budget at both lower and upper troposphere. It suggests that EP-flux represents appropriate vertical and meridional eddy momentum transport quantitatively.

The numerical errors make the momentum budget less accurate as the terms of the momentum equation are integrated in longer time. In following sections, results of momentum budget are integrated 5days in the maximum.

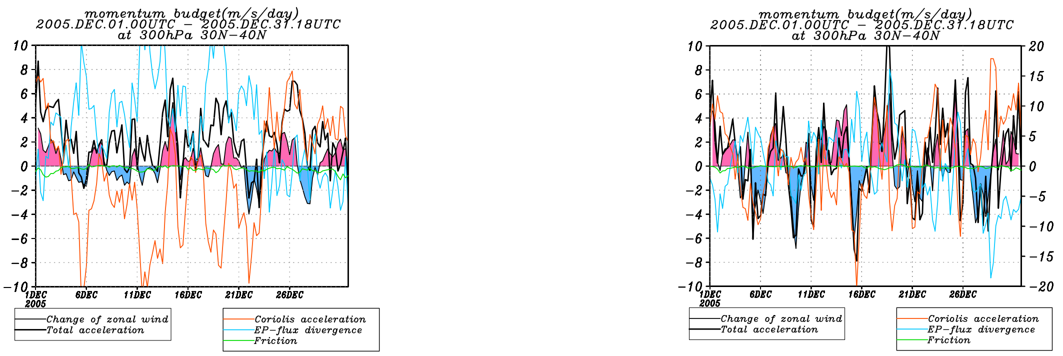

Figure 1: Time series of momentum buget at 30N-40N, 305.33hPa. Left and right panels show conventional method (quasi-geostrophic assumption on pressure coordinate) and isentropic method respectively. Thin black line: accelerating rate of zonal wind Thick black line: same as thick blak line but estimated from momentum budget, Blue line: acceleration by Coriolis forcing, Red line: acceleration by EP-flux(eddy forcing), Green line: acceleration by friction terms. pink and blue shaded show acceleration and decleration respectively.

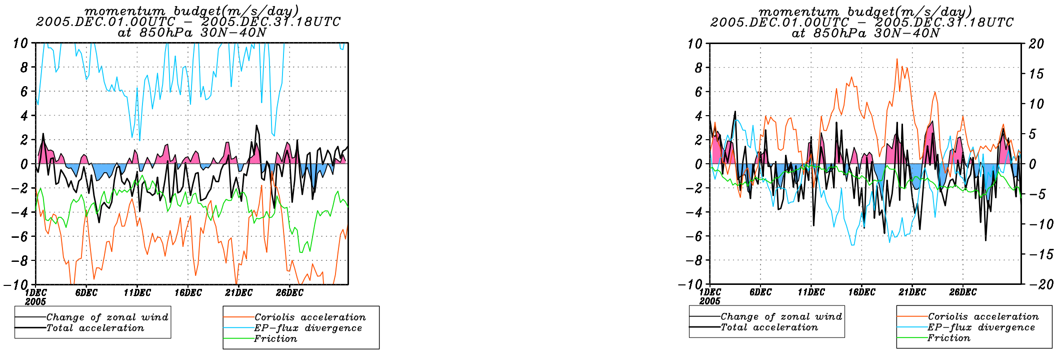

Figure 2: Same as 1. But at 845.43hPa.

5 Examples of diagnosis (mechanisms of anomalous zonal wind in 2005 and 2006 winter)

5.1 Anomalous jet in November-December,2005

In December 2005, both Siberian high and Aleutian low were strong. They enhanced East Asian monsoon and brought cold air in Japan.

Figure 3 shows latitude-time cross section of 5-day mean zonal wind around 300 hPa. In the middle of November 2005, westerly wind decelerated remarkably and easterly wind anomalies occurred. After that, the jet also decelerated over 50N-60N in the beginning of December 2005 and over 40-50N in the middle of the December. Easterly wind anomalies had been maintained by some remarkable deceleration events, not persistence of deceleration. In contrast with 40-50N, Strong westerly wind anomaly had persisted over 30-40N. Japan was located at the north of the jet core, and that influenced the persistence of cold temperature.

Figure 4 shows latitude-time cross section of each term of momentum equation around 300 hPa. Comparing the actual acceleration of zonal wind (Figure 4(a)) to that of estimated from mometum equation (Figure 4(b)), though the latter was tend to having larger amplitude, the former was corresponding to the sign and magnitude of the latter. That showed the momentum equation was almost closed. The momentum budget suggested that both Coriolis forcing by mean meridional flow (Figure 4(c),conversion planetary angular momentum to relative angular momentum) and the meridional convergence of the EP-flux (Figure 4(d)) contributed to the deceleration over 40-50N since the beginning of November 2005. In contrast, the meridional divergence of the EP-flux contributed to the acceleration of westerly wind over 30N-40N. 500 hPa weather chart (Figure 5) showed that a remarkable blocking high developed and wave activity propagated northward. That suggested that southward momentum transport by barotropic wave influenced the formation of zonal flow. In the beginning of December, the meridional convergence of the EP-flux contributed to the strong deceleration of westerly wind. To cancel the deceleration, the vertical divergence of the EP-flux and the Coriolis forcing accelerated westerly wind. It seemed that each deceleration event was corresponding to the strong deceleration by the meridional convergence of EP-flux. At 40N-50N, deceleration due to vertical convergence of EP-flux had persisted during December 2005. In the middle of the month, the budget changed to deceleration, and easterly wind anomalies were maintained again. In the lower troposphere, in the end of November vertical divergence of EP-flux accelerate westerly wind (not shown). The vertical structure of the acceleration anomalies were di-pole structure. It suggests that the vertical eddy momentum transport due to baroclinic waves was more active than normal over mid latitude.

Southward transport of the eddy momentum and coriolis forcing by mean meridional wind were triggers of the formation of westerly and easterly wind anomaly over 30N-40N and 40N-50N. The weaker northward transport of the transient eddy momentum and the stronger downward transport of stationary eddy momentum contributed to the maintenance of the structure of zonal mean flow.

5.2 November-December 2006

In contrast with December 2005, East Asian monsoon was weaker and it brought warmer temperature in Japan December 2006. Figure 6 shows latitude-time cross section of 5-day and zonal mean wind around 300hPa. There were easterly wind anomalies over 40N-50N. In the end of the November, westerly wind anomalies were formed and had persisted until the middle of December 2006. the westerly wind anomalies were maintained

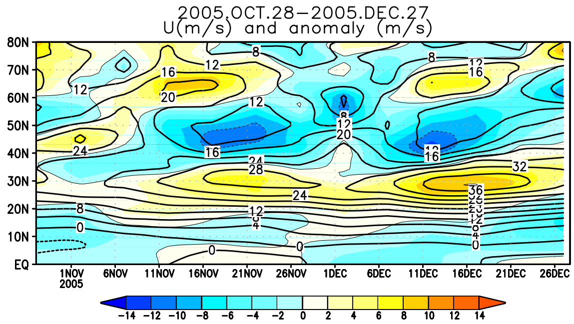

Figure 3: Latitude-time cross section of 5-day mean zonal mean zonalwind (contour) and its anomalies (shade) from the end of october to the end of december 2005 at 305.33 hPa.

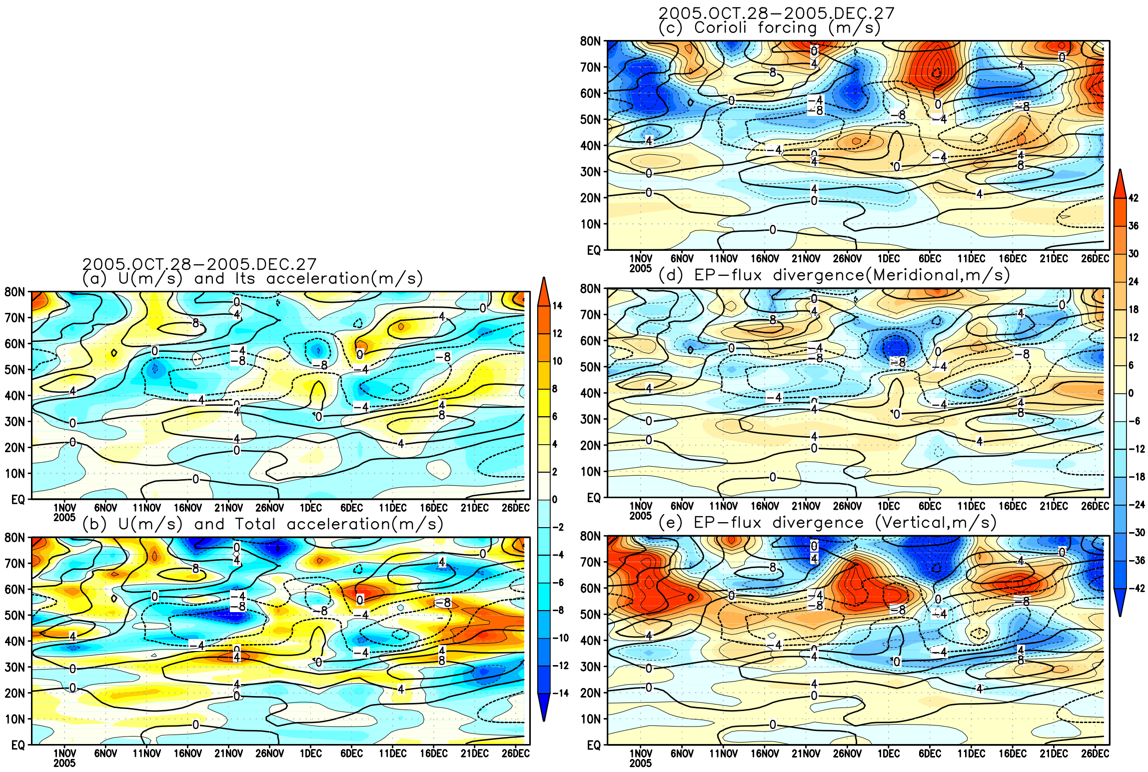

Figure 4: Latitude-time cross section of 5-day mean zonal mean zonal wind anomalies (contour) and each term anomalies of the zonal mean momentum equation (shade) from the end of october to the end of december 2005 at 305.33 hPa.

over 30N-50N. Japan was located at the south of the westerly wind, and that influenced the persistence of warm temperature.

Figure 7 shows latitude-time cross section of 5-day mean zonal mean zonal wind around 300 hPa. The meridional divergence anomalies of the EP-flux had persisted from the end of November to the middle of December over 40N-50N (Figure 7(d)). That contributed to the maintenance of the acceleration of the westerly wind anomalies. At that time, 500 hPa weather chart showed (Figure 8) positive height anomalies were extended in zonal from Eurasia continent to the Pacific Ocean. The wave activity propagated equatorward. That suggested that eddies transported more momentum poleward than its normal and it is consistent with the results of momentum budget. On the other hand, vertical component of the EP-flux and Coriolis forcing worked to cancel each other ((Figure 7 (c), (e)).

The poleward shift of the jet was formed and maintained by poleward momentum transport due to the stationary eddy activity.

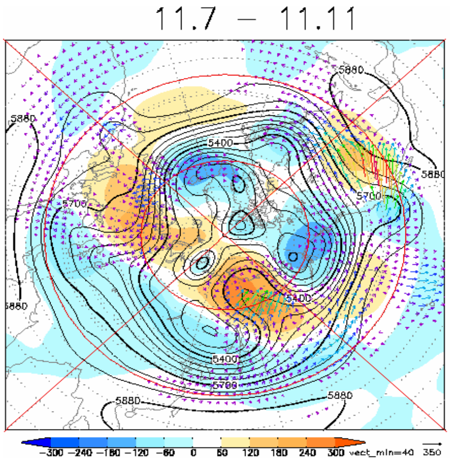

Figure 5: 5-day mean 500 hPa height (contour), its anomalies (shaded) and 250 hPa wave-activity flux (vectors) from 7 to 11 Nobember 2005.

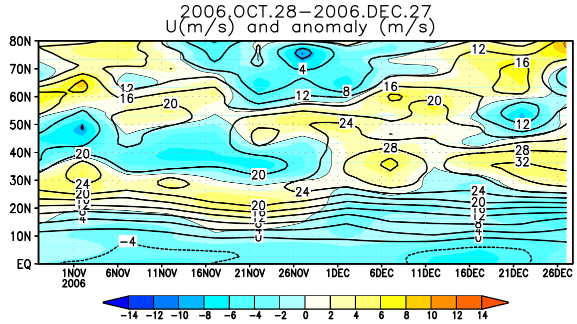

Figure 6: Same as figure 3 but from the end of October to the end of December 2006.

5.3 Discussions

In a point view of AO, the AO Index showed that there were negative(cold in Japan) phase in 2005 winter and positive(warm in Japan) phase in 2006 winter (Hasegawa, et, al., 2008). The pattern of eddy momentum transport that stationary eddy contributed to was similar to the AO as the dynamical mode discussed by Kimoto, et al.(2001). However, in December 2005, the transient eddy momentum transport in meridional and stationary eddy momentum transport in vertical also contributed. That suggested the meridional structure of zonal mean flow was symmetric between 2005 and 2006, but the mechanism of the formation and maintenance of the anomalous jet was asymmetric.

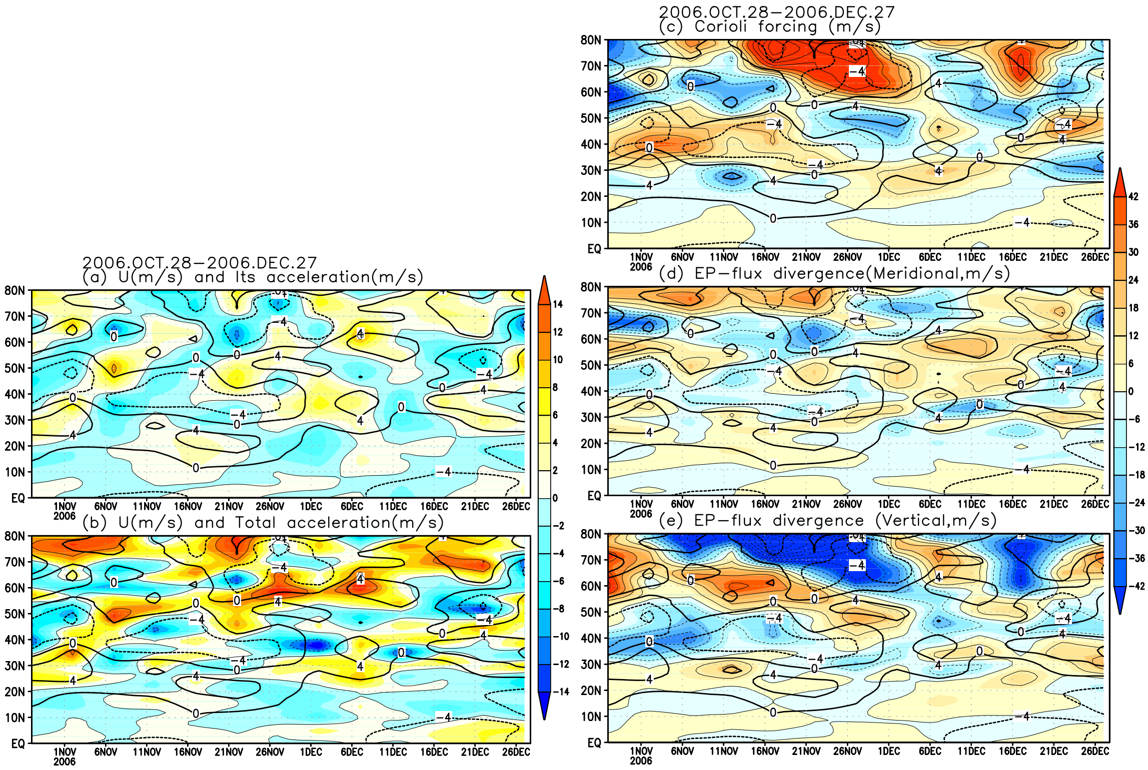

Figure 7: Same as Figure 4 but from 7 to 11 December 2006.

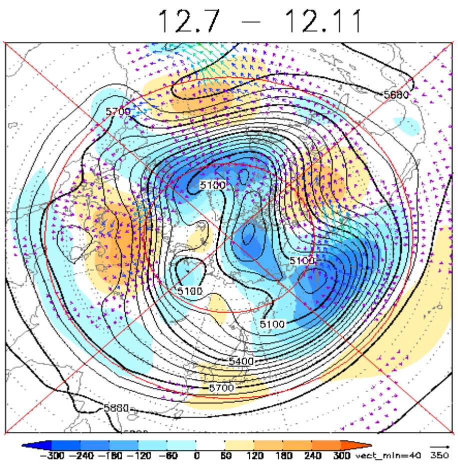

Figure 8: Same as Figure 5 but from 7 to 11 December 2006.

6 Summary and Conclusions

To understand zonal mean zonal wind variations and roles of eddies in detail, a new monitoring tool of momentum budget has been developed. The new definition of the EP-flux based on an isentropic coordinate represented the vertical and meridional momentum transport more accurately at both upper and lower troposphere. By using this tools, the author diagnosed the formation the anomalous jets in 2005 and 2006 winter. The results of the analysis showed momentum transport by transient eddy in meridional and stationary in vertical contributed to the formation and maintenance of the easterly wind anomaly over 40N-50N in winter 2005. On the other hand, momentum transport by stationary eddy in meridional contributed in winter 2006. That suggested the mechanism of the formation of the jets were asymmetric though the structure of the jets were symmetric.

The momentum budget can show how much eddy momentum transport contribute to the anomalous basic state, but not show what is the cause of the anomalous wave activity. Thus, to understand the mechanism of anomalous basic state, boundary conditions or distributions of forcing should be also considered. In this study, the author discussed about the roles of eddies for the formation of basic state. Feedbacks between the basic state and the wave propagation should be considerd in the future work.

References

Andrews, D.G., 1983: A finite-amplitude Eliassen-Palm theorem in isentropic coordinates. *J. Atmos. Sci.*,**40**, 1877-1883.

Hasegawa, H., Y. Harada, H. Nakamigawa and A. Goto , 2008: The Feature of Atmospheric Circulation in the Extremely Warm Winter 2006/2007. ,Extended abstracts of this conference, P2-12

Kimoto,M.,F.-F. Jin, M. Watanabe and N. Yasutomi, 2001: Zonal-eddy coupling and a neutral mode theory for the Arctic Oscillation, *Geophys. Res. Lett.*,**28**, 737-740.

Iwasaki,T. 1989: A diagnostic formulation for wave-mean flow interactions and Lagrangian-mean circulation with a hybrid vertical coordinate of pressure and isentropes. *J. Meteor. Soc. Japan.*,**67**, 293-312.

Onogi, K. and co-authors, 2007: The JRA-25 reanalysis. *J. Meteor. Soc. Japan.*,**85**, 369-432.

Tanaka,D., T. Iwasaki, S. Uno, M. Ujiie and K. Miyazaki, 2004: Eliassen-Palm flux diagnosis based on isentropic representation. *J. Atmos. Sci.*,**61**, 2370-2383.