A DIAGNOSTIC STUDY OF ATMOSPHERIC BLOCKING USING ANALOGY BETWEEN JET STREAM AND OPEN CHANNEL FLOW

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ABSTRACT

Atmospheric blockings due to persistent meandering of jet streams often cause meteorological extremes in mid-latitudes, such as long-term rainfalls, heat waves, draughts, and cold spells. Previous studies proposed various diagnosis methods of blockings, which are based on the detection of anomalous spatial distribution of pressure systems (Lejenäs and Okland, 1983; Tibaldi and Molteni, 1990; Pelly and Hoskins, 2003). This study introduces a new dynamical detection method based on energy conservation in the jet stream. This idea was first presented by Riffler (2005). In this method, we use sum of kinetic and potential energy flux in the jet stream, called *"specific energy"*, which is found to be analogous to flows studied in the open channel hydraulics. The latitudinal width of the jet stream has similarities of the depth of an open channel flow. Moreover, Rossby (1950) showed that a dynamically possible state characterized by blocking may exist which are compatible with the hydraulic jump in an open channel flow. This analogy suggests that specific energy controls a jet width expansion, which is observed near a blocking. To apply this theory to reanalysis, we derived a new specific energy equation considering changes of jet latitude and meridional profile of eastward wind speed. Utilizing this equation, Kitano and Yamada (2017) revealed minimum specific energy to form meandering jet stream (i.e. atmospheric blocking). In this extended abstract, we analyze a Pacific blocking episode using reanalysis and found energetic signals over Japan and its conservation and transport before occasion of atmospheric blocking.

Keywords: *Atmospheric blocking, open channel flow, specific energy, meteorological extremes*

1. INTRODUCTION

Atmospheric blockings due to persistent meandering of jet streams often cause meteorological extremes in mid-latitudes, such as long-term rainfalls, heat waves, draughts, and cold spells. Previous studies proposed various diagnosis methods of blockings, which are based on the detection of anomalous spatial distribution of pressure systems (Lejenäs and Okland, 1983; Tibaldi and Molteni, 1990; Pelly and Hoskins, 2003; Barriopedro et al., 2010).

Previous studies suggest that there are similarities between aspects of eastward-flowing zonal currents (i.e. jet stream) in mid- to high-latitude region and open channel flow hydraulics. The first suggestion of that similarity was by Rossby (1950, hereafter called "R1950", see Rex 1950). He pointed out that geostrophic zonal currents on a β-plane possess two dynamically possible states, like the open channel supercritical and subcritical flow, that are satisfied with continuity and momentum equations. The open channel flow (Chow 1959; Henderson 1966) is governed by a primary force balance between inertia force and pressure gradient force which are controlled by variation of the water depth. In contrast, R1950 suggested that zonal current in atmosphere is controlled by meridional jet width instead of the water depth. Considering the geostrophic equilibrium for horizontal pressure distribution, he derived an equation of conservation of momentum transport for meridionally uniform zonal current. This momentum transport becomes minimum when a non-dimensional number $U/a^2\beta$ becomes 1/3. Where, U is the characteristic eastward velocity, a characteristic jet width and β meridional gradient of the Coriolis parameter. Long (1955) and Ball (1959) focused on this parameter, called "*Rossby beta number*", in their theoretical and experimental studies. By the comparison of governing equations for quasi-geostrophic and two-dimensional stratified flow, they considered this as the counterpart of the Froude number for open channel or stratified flow. R1950 stated that atmospheric blocking is considered as moving hydraulic jump and he introduced the theoretical condition such that the jet width must increase to the double or more for occurrences of blocking. Riffler (2005) investigated the availability of jet width for a blocking diagnosis method utilizing a reanalysis dataset.

Armi (1974) and Armi (1988, hereafter called "A1988") simplified and sophisticated the above theory in his experimental documents. He derived a non-dimensional specific energy flux G'_0 for jet stream as follow.

$$G_0' = Ro_F^{\frac{2}{3}} + 2Ro_F^{-\frac{1}{3}} \quad (1)$$

$$Ro_F = \frac{U}{\alpha'\beta a^2} \quad (2)$$

Where, Ro_F is Froude/Rossby number, which means a ratio of kinetic and potential energy flux. α' is the velocity distribution coefficient, that is determined by meridional distribution of eastward velocity. Form of Eq. (1) is similar with the specific energy H'_0 in open channel hydraulics.

$$H_0' = (Fr^2)^{\frac{2}{3}} + 2(Fr^2)^{-\frac{1}{3}} \quad (3)$$

$$Fr^2 = \frac{\alpha'' U^2}{gh} \quad (4)$$

Where, Fr is Froude number. α'' is the coefficient for vertical distribution of streamwise velocity (Yen, 1973). Eq. (1) and (3) show that energy flux possesses a minimum value when Ro_F or Fr equals unity (i.e. critical jet width or water depth).

For typical open channels, the coefficient α'' is often assumed to be constant in each open channel (Jaeger, 1956) and effects of its variation can be ignored. Theoretical and experimental studies for geostrophic current (R1950 and A1989) also consider α' as constant along the current. In realistic atmosphere, however, velocity distribution dynamically changes especially near the atmospheric blocking. Kitano and Yamada (2017, in Japanese, hereafter called "KY2017") focused on the effects of the velocity distribution coefficient for geostrophic wind and they derived a non-dimensional specific energy flux equation for the variable velocity distribution which is based on β-plane approximation. Utilizing this equation, they revealed that formation of meandering jet stream (i.e. atmospheric blocking) needs high specific energy. They also confirmed that this feature can be observed qualitatively in a reanalysis. However, specific energy flux is not conserved quantitatively at jet-width expansion area because β-plane approximation is not satisfied.

The purpose of this study is to investigate behavior of the specific energy flux of jet stream in which Coriolis parameter approximation is not considered and reveal the usability of specific energy flux for blocking diagnosis method. This extended abstract begins in section 2 with derivation of the specific energy flux equation for geostrophic currents. In section 3, we show and discuss detail analyses of a blocking event utilizing this theory.

2. DERIVATION OF THE SPECIFIC ENERGY FLUX EQUATION

In this section, we briefly explain the energetic equation for jet stream. Energy of jet stream is given by flux of kinetic and potential energy,

$$G = \int_{-a}^{a} u\left(\frac{u^2 + v^2}{2} + \frac{p}{\rho}\right) dy. \quad (5)$$

Where, u is eastward wind velocity, v equatorward wind velocity, p pressure, ρ density of atmosphere, y equatorward direction, and a half width of jet stream (see Figure 1). Considering the geostrophic equilibrium, pressure distribution is given by

$$p(y) = p_{-a} + \rho \int_{-a}^{y} f\, u\, dY. \quad (6)$$

Where, f is Coriolis parameter, Y equatorward direction. Unit depth volume transport V over north-south cross-section is defined by

$$V = \int_{-a}^{a} u\, dy = Const. \quad (7)$$

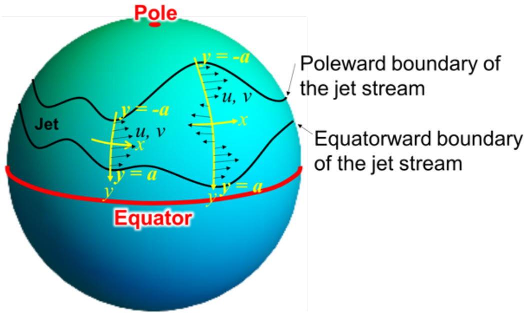

Figure 1. Schematic diagram of coordinates and parameters.

Substituting Eqs. (6) and (7) into (5), the energy equation is rewritten as follow.

$$G = \int_{-a}^{a} u\frac{u^2+v^2}{2}dy + \int_{-a}^{a} u \int_{-a}^{Y} f\,u\,dY\,dy + \frac{p_{-a}V}{\rho}. \tag{8}$$

Where, third term is constant. First and second terms are defined by specific energy of jet stream G_0.

$$G_0 = \int_{-a}^{a} u\frac{u^2+v^2}{2}dy + \int_{-a}^{a} u \int_{-a}^{Y} f\,u\,dY\,dy. \tag{9}$$

Previous studies (A1989 and KY2017) considered β-plane approximation to Eq. (9) and ignored equatorward wind velocity v. KY2017 introduced non-dimensional specific energy equations as follow.

$$G_0' = \frac{G_0}{\frac{1}{2}V^{\frac{7}{3}}\Omega^{\frac{2}{3}}L^{-\frac{2}{3}}} = \alpha_1' Ro^{\frac{2}{3}} + 2\frac{L}{\Omega}\alpha_2'\,\beta Ro^{-\frac{1}{3}} + \frac{L^{2/3}}{V^{1/3}\Omega^{2/3}}f_0. \tag{10}$$

$$Ro = VL/\Omega a^3,\quad \alpha_1' = \int_{-1}^{1} u'^3\,dy',\quad \alpha_2' = \int_{-1}^{1} u' \int_{-1}^{1} u'Y'dY'\,dy',\quad u' = u/(V/a),\quad y' = \frac{y}{a},\ Y' = \frac{Y}{a}.$$

Where, Ω is rotation speed of the earth, L distance between pole and equator, Ro Rossby number, β meridional gradient of Coriolis parameter, f_0 Coriolis parameter at jet center ($y=0$), u' non-dimensional eastward velocity, y' (Y') poleward direction. α_1', α_2' velocity distribution coefficients. They revealed that zonal currents in blocking situation, which is characterized by α_1' and α_2', need high specific energy.

In Eq. (10), β-plane approximation is assumed. It could explain the idealized atmospheric situation but in realistic atmosphere there are situations in which this approximation is not satisfied. In next section, we use Eq. (9) and analyze a Pacific blocking episode utilizing ERA-Interim reanalysis dataset (Dee et al., 2011).

3. RESULTS AND DISCUSSION

Figure 2 shows the specific energy flux derived by Eq. (9) between 21 February to 3 March 1989. Vertically averaged data between 2500-12000 m, which is set to exclude influence of terrain and stratosphere, is used. Poleward boundary of the jet stream ($y = -a$) is defined by a constant pressure line (p = 395 hPa). Equatorward boundary of the jet stream ($y = a$) is defined to let V becomes constant ($V = 8.7\mathrm{x}10^7\ \mathrm{m^2/s}$) by Eq. (7). High specific energy flux ET1, ET2 in Figure 2 may represent energy transports from west to east. Figure 3 shows the horizontal wind velocity and specific energy flux in each time step written by blue dashed lines in Figure 2. On February 22 and 26 (Figure 3 (a) and (c)), high specific energy flux characterized by higher kinetic energy exists near Japan and its surroundings. After that (Figure 3 (b), (c) and (d), (e)), area of high specific energy flux is replaced eastward and Ω-type blockings are formed over central North Pacific region.

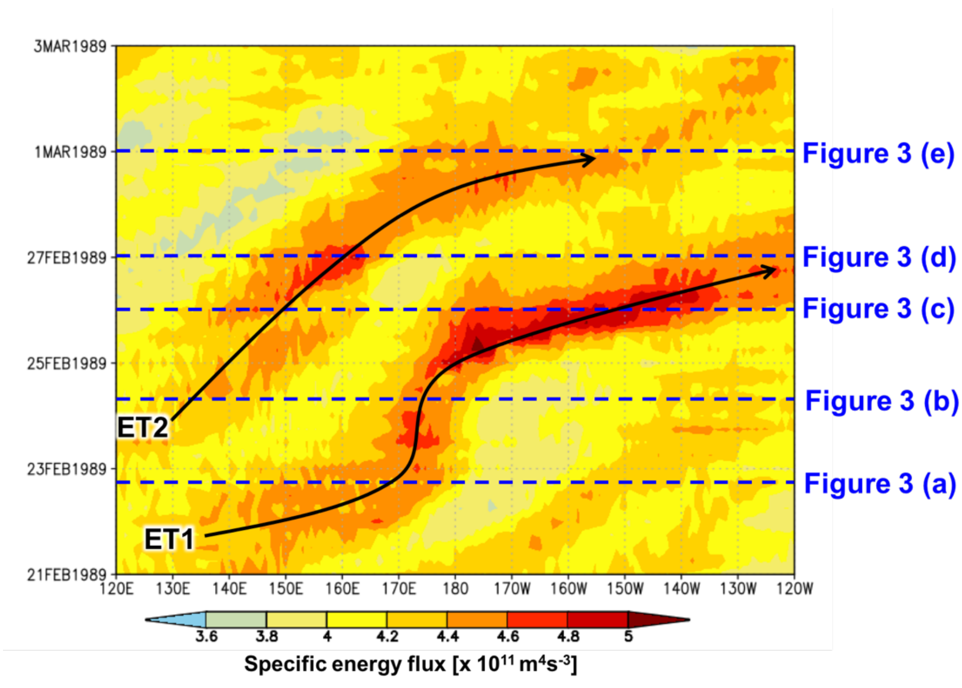

Figure 2. Hovmöller diagram of the specific energy flux over North Pacific region from February 21 to March 3, 1989. Vertically averaged data between 2500 to 12000-m height is used. Poleward boundary of the jet stream ($y = -a$) is defined by a constant pressure line (p = 395 hPa). Equatorward boundary of the jet stream ($y = a$) is defined to let V becomes constant ($V = 8.7\mathrm{x}10^7\ \mathrm{m^2/s}$) by Eq. (7).

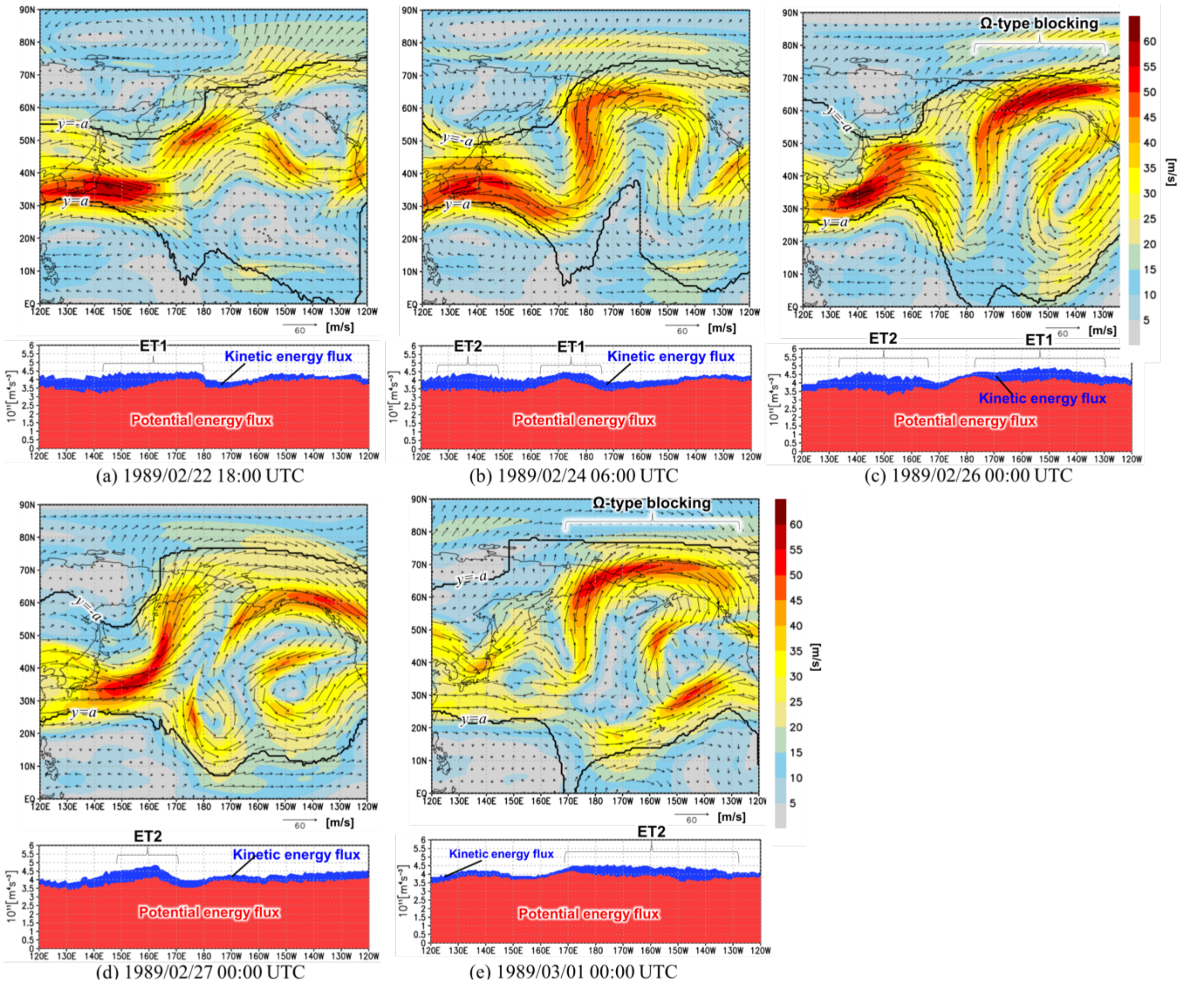

Figure 3. Wind velocity (above) and specific energy flux (below).

4. SUMMARY

KY2017 stated that eastward flow in situation of atmospheric blocking characterized by wide width of jet ($2a$) and meridional profile of u theoretically needs high specific energy flux. In Figures 2 and 3, this feature is confirmed by simultaneous generation of atmospheric blocking and high specific energy flux. These results imply that high specific energy flux could be treated as a blocking diagnosis method. Furthermore, before the occasion of atmospheric blocking, high specific energy flux is generated over upstream region. This generation could be a trigger of the Pacific blocking episodes.

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