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A study on the maintenance of the winter subtropical jet streams in the northern hemisphere

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ABSTRACT

Two mechanisms were previously proposed to explain the maintenance of the winter subtropical jet streams in the northern hemisphere. First, based upon the total kinetic energy budget analysis, the winter subtropical jet streams can be locally maintained by the balance between the kinetic energy generated by ageostrophic flow and the divergence of kinetic energy flux. Second, these jet streams can be maintained by the interhemispherical interaction between the atmospheric, rotational and divergent circulations. It is shown in this study that the kinetic energy budget analyses of the rotational and divergent components of the atmospheric circulation can be used to illustrate, respectively, the two aforementioned mechanisms maintaining subtropical jet streams, and also the inter-relationship between these two mechanisms.

1. Introduction

Since the importance of the jet streams was recognized by Rossby and his collaborators (1947) at the University of Chicago some 40 years ago, numerous efforts have been made to explore the mechanism that maintains jet streams. Based upon Namias and Clapp's (1949) confluence theory, Blackmon et al. (1977) illustrated the maintenance of subtropical jet streams with the ageostrophic circulations driven by cyclone waves. Holopainen (1978) also suggested this ageostrophic circulation mechanism in terms of the kinetic energy budget analysis. He argued that subtropical jet streams are maintained by the balance between the kinetic energy generation by ageostrophic circulation and divergence of kinetic energy flux.

As portrayed by Krishnamurti (1961) and Blackmon et al. (1977), the winter subtropical jet streams in the northern hemisphere exhibit a three-wave structure. Palmén and Newton (1969) pointed out that subtropical jet streams are located at the northern end of the Hadley circulation. Based upon his studies for the planetary-scale divergent circulation (Krishnamurti, 1971; Krishnamurti et al., 1973), Krishnamurti (1979) used a schematic diagram (Fig. 1) to suggest that the formation of the 3 subtropical jet streams is related to the rainfall over 3 tropical continents through the planetary-scale divergent circulations. From these studies, we can infer that the planetary-scale divergent circulations contribute in some way to the maintenance of the subtropical jet streams.

Although Krishnamurti does not provide any diagnostic analysis to substantiate his suggestion, it is obvious in his scheme that the inter-hemispheric interaction between the rotational and divergent circulation is an important factor in maintaining the subtropical jet streams. In contrast, the ageostrophic circulation mechanism proposed by Holopainen is relatively a regional effect. In spite of this difference between the two mechanisms maintaining subtropical jet streams, ageostrophic circulation plainly contains divergent circulation. Moreover, both Holopainen and Krishnamurti's mechanisms explain the maintenance of same subtropical jet streams. There-

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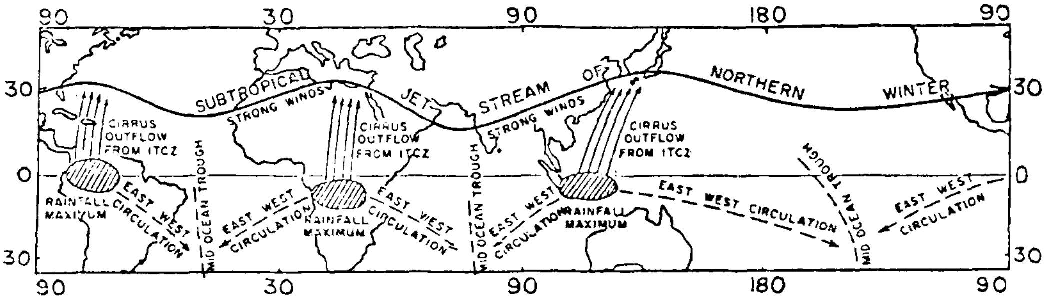

Fig. 1. A schematic illustration of the subtropical jet streams and some associated features during northern winters; from Krishnamurti, 1979).

fore, some consistency must exist between the two mechanisms.

The atmospheric divergent flow is generally at least an order of magnitude smaller than the rotational flow. Also, the subtropical jet streams are essentially depicted by the rotational flow. Chen and Wiin-Nielsen (1976) showed that the atmospheric divergent flow acts as a catalyst to release the available potential energy to support the rotational flow. Our intent in this study is to use the same energetics scheme to show the consistency between Krishnamurti's divergent circulation mechanism and Holopainen's ageostrophic circulation mechanism for the maintenance of the subtropical jet streams.

2. Comparison between mechanisms of Holopainen and Krishnamurti

2.1. *Kinetic energy equations*

The kinetic energy equations of rotational and divergent flows proposed by Chen and Wiin-Nielsen (1976) are formulated for a closed domain. In order to consider the local maintenance of these two flow components, we need to include the divergence of kinetic energy flux as shown by Chen et al. (1978). Therefore, we write the kinetic energy equation as:

$$\frac{\partial k_D}{\partial t} \sim \underbrace{-\nabla\cdot(\mathbb{V}_D k)}_{FD(k)} \underbrace{-(f+\zeta_R)(u_D v_R - u_R v_D)}_{-C(k_D,k_R)} \underbrace{-\mathbb{V}_D\cdot\nabla\phi}_{G(k_D)}, \tag{1}$$

$$\frac{\partial k_R}{\partial t} \sim \underbrace{-\nabla\cdot(\mathbb{V}_R k)}_{FR(k)} + \underbrace{(f+\zeta_R)(u_D v_R - u_R v_D)}_{C(k_D,k_R)} \underbrace{-\mathbb{V}_R\cdot\nabla\phi}_{G(k_R)}. \tag{2}$$

The notation used in eqs. (1) and (2) is conventional. Subscripts R and D represent rotational and divergent components, respectively. Because this study will not completely analyze the kinetic energy budget of the rotational and divergent flow, only terms that are important to the maintenance of k_D and k_R are retained in eqs. (1) and (2).

2.2. *Comparison between two mechanisms*

We have briefly reviewed the comparison between the mechanisms proposed by Holopainen (1978) and Krishnamurti (1979) for the maintenance of the subtropical jet streams. However, the main aim of this study is to explore a possible consistency between the two mechanisms. To accomplish this, we have to reexamine how these two mechanisms were developed.

Analyzing the kinetic energy budget, Holopainen (1978) suggested that the subtropical jet streams are maintained mainly by the physical processes delineated by the kinetic energy equation

$$\frac{\partial k}{\partial t} \simeq -\nabla\cdot(\mathbb{V}k) - \mathbb{V}'\cdot\nabla\phi \tag{3}$$

That is, the counterbalance between the divergence of horizontal kinetic-energy flux, $-\nabla\cdot(\mathbb{V}k)$, and the generation of kinetic energy by ageostrophic flow, $-\mathbb{V}'\cdot\nabla\phi$. The kinetic energy is generated on the upstream side of jet streams and is transferred to the downstream side where the kinetic energy is destroyed.

Based upon the cross-jet circulation (v_a) inferred by the sensible-heat and momentum transports by cyclone waves, Blackmon et al.

(1977) illustrated the maintenance of subtropical jet streams in terms of the zonal momentum budget analysis

$$\frac{\mathrm{d}u}{\mathrm{d}t} = fv_a, \tag{4}$$

where $v_a (= v - v_g)$ is ageostrophic meridional wind and v_g is geostrophic meridional wind. According to eq. (4), the zonal flow associated with the subtropical jet stream is accelerated by Coriolis force on the upstream side of jets where v_a flows poleward in the upper level, i.e., thermally direct secondary circulation. The opposite situation occurs on the down-stream side of jets. Multiplying eq. (4) by u, one finds that the total time variation of zonal kinetic energy is caused by the work done by Coriolis force (fuv_a), which is equal to the work done by the cross-contour flow along the x-direction, i.e., $-u\partial\phi/\partial x$. This simple argument shows that Holopainen's suggestion is consistent with Blackmon et al.'s (1987) energetics illustration.

From the viewpoint of divergent circulation effects, Chen and Wiin-Nielsen (1976) showed that the rotational flow of a closed domain is supported by the interaction between this flow component and divergent circulation $[C(k_D,k_R)]$. This interaction is energetically supplied by the generation of divergent kinetic energy $[G(k_D)]$. For a closed domain, one finds:

$$C(k_D,k_R) \simeq G(k_D). \tag{5}$$

Since k_D is always small, one may assume that the relationship depicted by eq. (5) is also locally true, provided $-\nabla\cdot(\mathbf{V}_D k)$ is insignificant. Krishnamurti (1979) suggested that the planetary-scale divergent circulations correlate the atmospheric circulation between the tropics and midlatitudes and contribute in some way to the maintenance of the subtropical jet streams. Krishnamurti's mechanism can be energetically illustrated by eq. (1) or (5).

Having studied the development of the two mechanisms, we can now address the question of how Holopainen's ageostrophic circulation mechanism and Krishnamurti's divergent circulation mechanisms are related. Suppose eq. (5) is regionally true, the ageostrophic effect of eq. (3) can be expressed as:

$$-\mathbf{V}\cdot\nabla\phi = -\mathbf{V}_R\cdot\nabla\phi - \mathbf{V}_D\cdot\nabla\phi \simeq -\mathbf{V}_R\cdot\nabla\phi + C(k_D,k_R). \tag{6}$$

Based upon assumptions stated above and eq. (6), Holopainen's mechanism delineated by eq. (3) is equivalent to eq. (2). On the other hand, Krishnamurti's mechanism can be illustrated by eqs. (1) or (5). Of course, the discussion above is theoretical and should be substantiated by diagnostic analysis.

3. Energetics analysis

3.1. Data

The content of divergent-wind component in the wind data is important to the present study. Contrasting the GFDL and ECMWF FGGE III-b analyses, Julian (1984) concluded that the wind data generated by the European Center for Medium Range Weather Forecasts (ECMWF) contain a reasonable planetary-scale divergent circulation. Therefore, the ECMWF FGGE III-b 200-mb wind fields of the 1978/79 winter (December-February) are used in this study. The rotational- and divergent-wind components over the entire globe are generated from the horizontal gradients of streamfunction and velocity potential, respectively. The streamfunction and velocity potential are obtained by solving the Poisson equation with the HWSSSP subroutine documented in the software library of the CRAY-1 computer at the National Center for Atmospheric Research. The computations of every term in eqs. (1) and (2) are carried out twice for each day. This study presents the seasonal average of the daily results.

3.2. Rotational and divergent circulations

The 200-mb rotational and divergent circulations of the 1978/1979 northern winter are shown in Fig. 2. Three subtropical jet streams exist over the east coasts of Asia and North America, and north Africa. As illustrated by Namias and Clapp (1947), these jet streams are associated with confluence and diffluence on the upstream and downstream sides, respectively. Also, three mid-ocean troughs are observed over three southern oceans. Regardless of other detailed structures of the rotational circulation shown in Fig. 2a, these features mentioned above are consistent with Krishnamurti's schematic diagram of the 200-mb circulation during northern winter (Fig. 1).

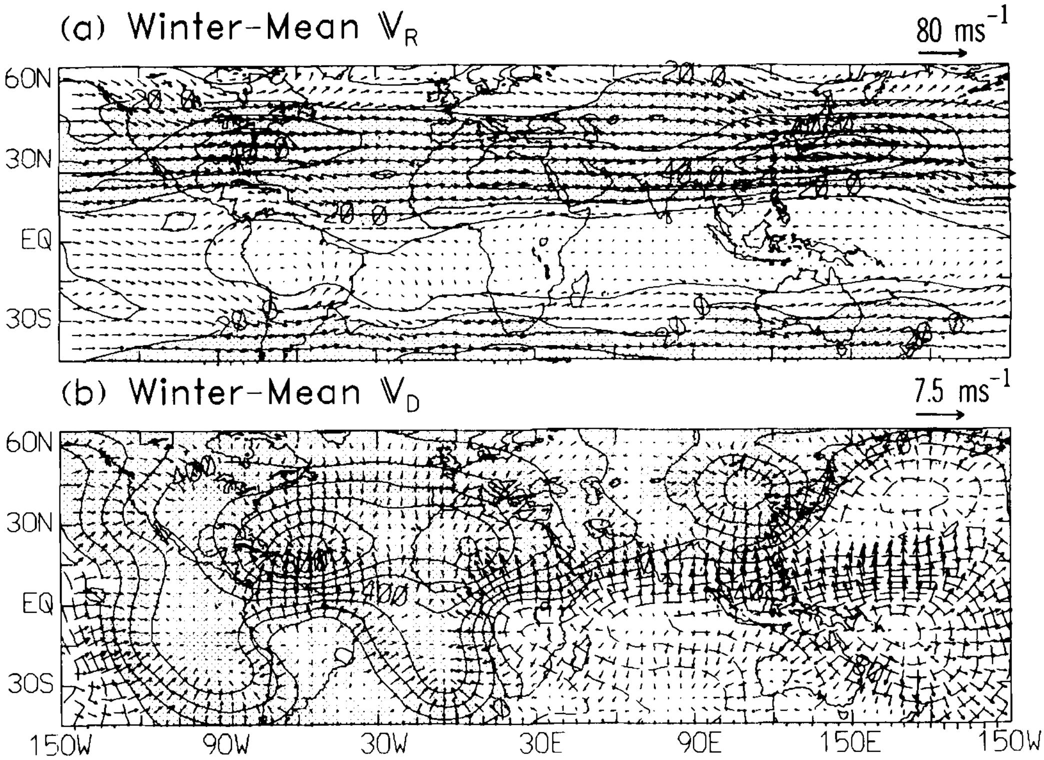

Fig. 2. The seasonal-mean 200-mb (a) rotational ($\mathbb{V}_R$) and (b) divergent ($\mathbb{V}_D$) circulation during northern winter (December '78-February '79). Thin solid lines of (a) are isotachs and contour intervals are 10 ms^{-1}. The contours of (b) are velocity potential (χ) whose positive values are shaded. The contour intervals of χ are 2×10^6 m^2s^{-1}.

As far as the 200-mb divergent circulation (Fig. 2b) is concerned, three convergence centers in the northern hemisphere are connected with the three subtropical jet streams as Krishnamurti expected. However, three divergence centers in the southern hemisphere are located southeast of Krishnamurti's tropical rainfall centers, especially the divergence center east of New Guinea. This divergence center is maintained by the warm sea surface water accumulated over the western Pacific.

3.3. *Diagnostic result and discussion*

The planetary-scale rotational and divergent atmospheric circulations are depicted well in Fig. 2. To avoid redundance in the depiction of atmospheric circulations, the distribution of atmospheric kinetic energy is not shown. In this section, we shall focus on the investigation of the physical processes involved in the maintenance of subtropical jet streams in terms of energetics analysis.

The subtropical jet streams are mainly described by the rotational flow (Fig. 2a). Therefore, eq. (2) is used to illustrate how these jet streams are maintained. As revealed by the comparison between the rotational circulations $\mathbb{V}_R$ and $G(k_R)$ (Fig. 3a), the rotational kinetic energy is generated on the upstream side of jet streams by the downgradient cross-contour flow and is destroyed on the downstream side by the upgradient cross-contour flow. On the other hand, the FR(k) (Fig. 3b) distribution shows that the generated rotational kinetic energy on the upstream side of the jet streams is transported to the downstream side. The counterbalance between $G(k_R)$ and FR(k) shown in Fig. 3 seems to provide the major maintenance of the sub-

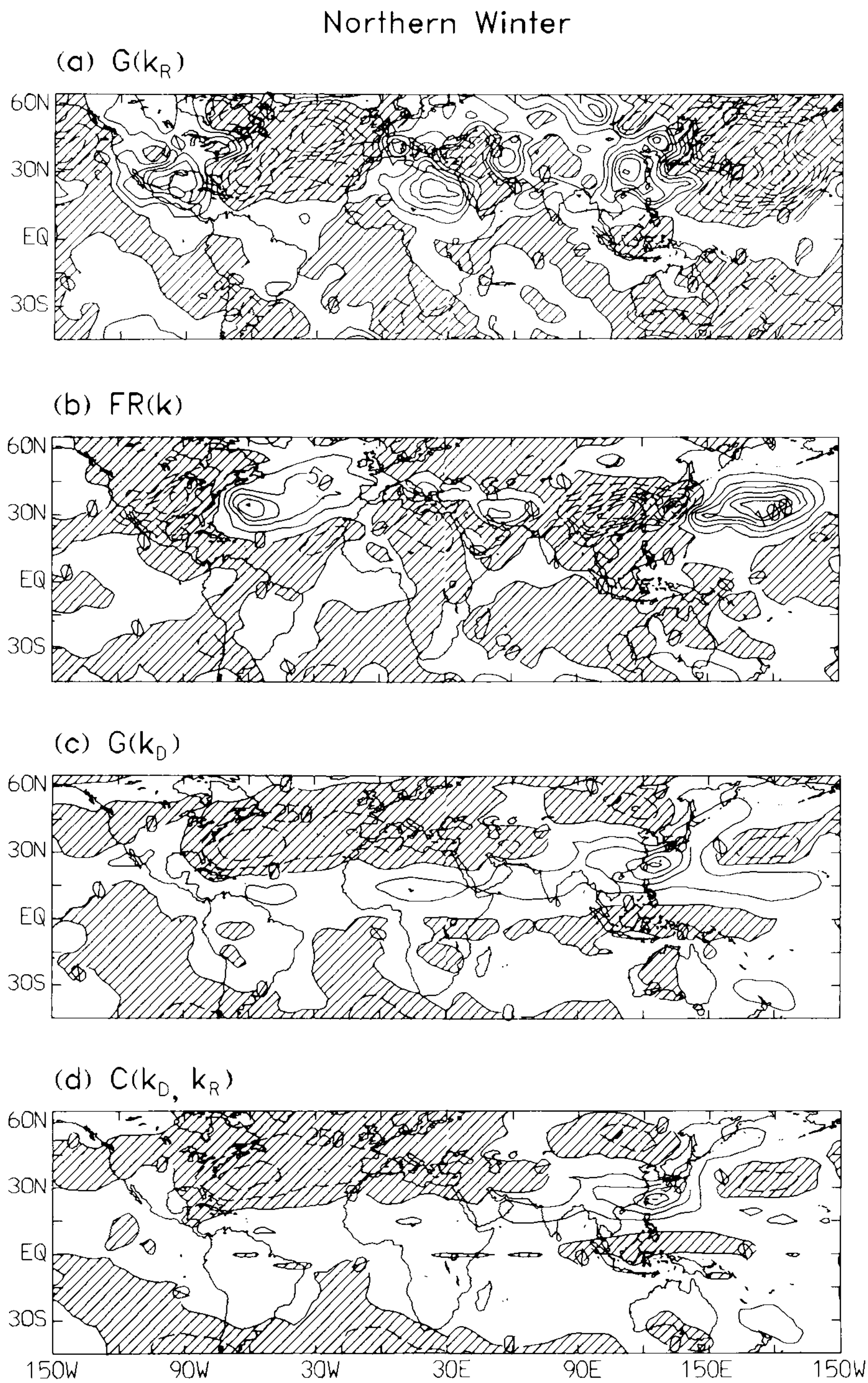

Fig. 3. Various energy conversions averaged over the entire northern winter: (a) $G(k_R)$, (b) $FR(k)$, (c) $G(k_D)$ and (d) $C(k_D, k_R)$. Contour intervals are $2.5 \times 10^{-3} m^2 s^{-3}$.

tropical jet streams as suggested by Holopainen (1978) in eq. (3). According to eq. (6), the kinetic energy generation by ageostrophic effect should also include $G(k_D)$ (Fig. 3c). Futhermore, the discussion in Subsection 2.2 indicated that the interaction between the rotational and divergent flows, $C(k_D,k_R)$ (Fig. 4d), is approximately equivalent to $G(k_D)$. This matter will be discussed in further detail later. At any rate, both $G(k_D)$ and $C(k_D,k_R)$ have a similar distribution, and also are positive along the equatorward side of jet streams. In other words, either $G(k_D)$ or $C(k_D,k_R)$ maintains subtropical jet streams there. Note that the divergence of kinetic-energy flux by divergent flow is relatively insignificant compared to other energetic processes expressed in eq. (2). Apparently, the energetics analysis of the rotational flow presented above demonstrated that Holopainen's ageostrophic circulation mechanism maintaining the subtropical jet streams can be illustrated by eq. (2).

Next, we shall discuss the effect of divergent circulation on the maintenance of subtropical jet streams following Krishnamurti's suggestion. The comparison between $G(k_D)$ (his Fig. 4c) and the planetary-scale divergent circulation (his Fig. 2b) seems to indicate that the divergent kinetic energy is generated by the downgradient divergent flow between the equator and the northern subtropical jet streams. The most significant positive $G(k_D)$ is associated with subtropical jet streams. Furthermore, the local values of $G(k_D)$ and $C(k_D,k_R)$ are comparable in magnitude. Also, the patterns of their distribution are similar. As inferred from the small magnitude of divergent circulation ($\mathbb{V}_D$) compared to rotational circulation ($\mathbb{V}_R$), the divergent kinetic energy is small. It manifests from these facts that the generated divergent kinetic energy is mostly converted to support the rotational flow, especially three subtropical jet streams through the interaction between divergent and rotational flows. In view of the result discussed here, eq. (5) is true in the local energetics of divergent flow. It becomes obvious that Krishnamurti's divergent circulation mechanism maintaining the subtropical jet streams can be revealed through eq. (5).

As far as the maintenance of the subtropical jet streams is concerned, we may conclude that both Holopainen and Krishnamurti mechanisms are related through eqs. (5) and (6).

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