The Role of Nonquasigeostrophic Forcing in Southern Hemisphere Blocking Onsets

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ABSTRACT

A generalized frictionless, adiabatic geostrophic zonal wind tendency equation is derived to diagnose the nonquasigeostrophic forcings to blocking onset in the Southern Hemisphere through case study and composite analysis. In general, the quasigeostrophic model is capable of representing the key physical processes associated with blocking onset in the troposphere reasonably well in most blocking cases. The consideration of nonquasigeostrophic forcings moderately improves the quasigeostrophic representation in a majority of the blocking events selected for this study, but not all events. This suggests that the nonquasigeostrophic terms could be important in a specific blocking event but not in a composite meaning. Furthermore, the nonquasigeostrophic forcing of geostrophic advection of ageostrophic relative vorticity term, \( F_{V^2} \), is extensively examined in this study. This forcing is found to be the leading nonquasigeostrophic forcing term among all nonquasigeostrophic forcings. In a composite sense, the forcing \( F_{V^2} \) appears to have an alternative contribution that is dependent upon the curvature of the geostrophic flow within the blocking structure. In general, the southwesterly flow is likely associated with the \( F_{V^2} \)-favoring effect to blocking onset whereas northwesterly flow is associated with the \( F_{V^2} \)-opposing effect. Therefore, it is important to use the geostrophic flow pattern prior to blocking onset to foresee this ageostrophic-related nonquasigeostrophic forcing to blocking onset. Finally, a pronounced overestimation of geostrophic zonal wind tendency by the quasigeostrophic model is commonly found for selected blocking events within the stratosphere, in comparison to the nonquasigeostrophic model. This overestimation is essentially caused by geostrophic wind approximation.

1. Introduction

The large-scale atmospheric circulation is commonly discussed in the quasigeostrophic (QG) framework (Bluestein 1992; Holton 2004) because of its ability to capture the essential processes of the large-scale circulation and a straightforward interpretation of these processes. It is well known that QG processes qualitatively account for the formation and maintenance of blocking flows (Shutts 1983; Illari 1984; Mullen 1987; Alberta et al. 1991; Lupo and Smith 1995). Specifically, the persistent advection of anticyclonic potential vorticity (PV) upstream of a developing block forces geopotential height rises and the establishment of an anticyclonic blocking circulation.

However, because of the exclusion of several nonquasigeostrophic (NQG) processes from the QG framework, such as diabatic heating, friction, and ageostrophic advection, some of the QG assumptions could become questionable when applied to the diagnosis of blocking cases. Bengtsson (1981) investigated the predictability of blocking using a series of numerical models and found that high-resolution primitive equation models successfully predicted a blocking event in great detail, while a QG model was inadequate for such predictions. Furthermore, there is also evidence (Alberta et al. 1991) for quantitative differences between the total QG and analyzed height tendencies during block evolution. This suggests that NQG processes could play an important role in blocking formation. The nature of these processes and the relative importance of each, however, are not fully known for individual blocking cases.

Krishnamurti (1968) proposed a diagnostic balance model that has provided much of the context for discussions of departures from QG vertical motions. Tsou and
Smith (1990) investigated the NQG processes during the development of a blocking anticyclone by using an extended height tendency equation that contains the static stability advection term and diabatic heating term. Raisanen (1997) presented a NQG height tendency equation derived from the vorticity and balance equations and the balanced omega equation. These diagnostic tools are useful since they can elucidate the role of processes not appearing in the QG height tendency equation. However, they do not distinguish geostrophic advection from ageostrophic advection processes. Lupo (2002) used an improved method of calculating the ageostrophic wind, rather than calculating it as a residual, to compute the total height tendency change associated with a blocking event, but this study did not quantify the specific contribution of the ageostrophic processes to blocking onset. Therefore, the importance of the ageostrophic processes relative to geostrophic processes is still not known for blocking onset.

The present study is the continuing work of Dong and Colucci (2005), which is a diagnostic study of the weakening in the geostrophic westerlies associated with Southern Hemisphere (SH) blocking onsets using a QG tendency equation for the geostrophic zonal wind (hereafter QG wind tendency equation). In the present study, a NQG tendency equation for the geostrophic zonal wind (hereafter NQG wind tendency equation) is derived from an alternative NQG height equation that is similar to Bluestein’s Eq. (2.18,9) of Bluestein (1992), by combining the frictionless, isobaric vorticity equation with the adiabatic, isobaric thermodynamic equation. This NQG wind tendency equation is then applied to a number of selected SH blocking events through case study and composite analysis so as to extensively evaluate the NQG forcings to SH blocking onsets.

The remainder of this study is organized as follows. A detailed explanation of the NQG wind tendency equation is presented in section 2. The datasets and criteria for blocking onset detection are described in section 3. The role of geostrophic advection of ageostrophic relative vorticity in block onset is discussed in section 4 for selected blocking events, and section 5 for composite blocking events. Finally, discussion and conclusions are given in sections 6 and 7, respectively.

2. Diagnostic model

A QG diagnostic equation for the geopotential height (z) tendency field can be written as follows using Bluestein (1992):

\[
\nabla^2 \varphi_p - \left[ \frac{f_0}{g} \frac{\partial}{\partial \varphi} \left( \frac{1}{\sigma_p} \frac{\partial}{\partial \varphi} \right) \right] \left( \frac{\partial \varphi}{\partial t} \right) = \left( \frac{f_0}{g} \right) \mathbf{V}_g \cdot \mathbf{V}_p \left( \zeta_g + f \right) - f_0 \frac{\partial}{\partial \varphi} \left[ \left( \frac{1}{\sigma_p} \right) \mathbf{V}_g \cdot \mathbf{V}_p \left( \frac{\partial \varphi}{\partial \varphi} \right) \right].
\]

(1)

Here \( \mathbf{V}_g \) is the geostrophic wind, \( \mathbf{V}_p \) is the gradient operator in spherical coordinates on a constant pressure \( p \) surface, \( f_0 \) is the Coriolis parameter, \( g \) is gravity, and \( \sigma_p \) is the static stability written as

\[
\sigma_p = - \left( \frac{\alpha}{\theta} \right) \frac{\partial \theta}{\partial \varphi}.
\]

(2)

which is assumed to vary with pressure only.

The above height tendency equation in Eq. (1) can also be written in terms of QGPV as follows:

\[
\nabla^2 \varphi_p - \left[ \frac{f_0}{g} \frac{\partial}{\partial \varphi} \left( \frac{1}{\sigma_p} \frac{\partial}{\partial \varphi} \right) \right] \left( \frac{\partial \varphi}{\partial t} \right) = \left( \frac{f_0}{g} \right) \mathbf{V}_g \cdot \mathbf{V}_p q,
\]

(3)

where QGPV is expressed as

\[
q = \left( \frac{g}{f_0} \right) \nabla^2 \varphi + f + f_0 g \frac{\partial}{\partial \varphi} \left[ \frac{1}{\sigma_p} \left( \frac{\partial \varphi}{\partial \varphi} \right) \right].
\]

(4)

By multiplying both sides of Eq. (3) by \( -(g/f_0) \) and differentiating with respect to \( y \), recognizing that \( \sigma_p \) is isobarically constant in the QG framework, one obtains the geostrophic zonal wind tendency equation as follows:

\[
\nabla^2 u_g - \left[ \frac{f_0}{g} \frac{\partial}{\partial \varphi} \left( \frac{1}{\sigma_p} \frac{\partial}{\partial \varphi} \right) \right] \left( \frac{\partial u_g}{\partial t} \right) = \frac{\partial [ \mathbf{V}_g \cdot \mathbf{V}_p q ]}{\partial y},
\]

(5)

where \( u_g = -(g/f_0)(\partial \varphi/\partial y) \) is the \( u \) component of the geostrophic wind.

Following the derivation in Bluestein (1992) of the generalized height tendency equation from the full vorticity and thermodynamic equations, a similar NQG height tendency equation could be derived as follows:

\[
\nabla^2 \varphi_p + f_0 \frac{\partial}{\partial \varphi} \left( \frac{1}{\sigma_p} \frac{\partial}{\partial \varphi} \right) \left( \frac{\partial \varphi}{\partial t} \right) = - \left( \frac{f_0}{g} \right) \mathbf{V}_h \cdot \mathbf{V}_p (\zeta + f) - f_0 \frac{\partial}{\partial \varphi} \left[ \left( \frac{1}{\sigma_p} \right) \mathbf{V}_h \cdot \mathbf{V}_p \left( \frac{\partial \varphi}{\partial \varphi} \right) \right] - \left( \frac{f_0}{g} \right) \frac{\partial \zeta}{\partial t} - \left( \frac{f_0}{g} \right) \omega \frac{\partial \zeta}{\partial \varphi} - \left( \frac{f_0}{g} \right) (\zeta + f - f_0) \mathbf{V}_p \cdot \mathbf{V}_h - \left( \frac{f_0}{g} \right) \mathbf{k} \cdot \left( \mathbf{V}_p \omega \times \frac{\partial \mathbf{V}_h}{\partial \varphi} \right).
\]

(6)
where all above variables have the standard meanings as explained in Bluestein (1992). Note that the static stability parameter $\sigma$ is now a three-dimensionally varying variable.

\[
\nabla^2 + f_0^2 \frac{\partial}{\partial p} \left( \frac{1}{\sigma} \frac{\partial}{\partial p} \right) \left( \frac{\partial z}{\partial t} \right) = -\left( \frac{f_0}{g} \right) \mathbf{V}_g \cdot \nabla \rho (\zeta_g + f) - \left( \frac{f_0}{g} \right) \mathbf{V}_a \cdot \nabla \rho (\zeta + f) - f_0^2 \frac{\partial}{\partial p} \left[ \left( \frac{1}{\sigma} \right) \mathbf{V}_g \cdot \nabla \rho \left( \frac{\partial z}{\partial p} \right) \right] - f_0^2 \frac{\partial}{\partial p} \left[ \left( \frac{1}{\sigma} \right) \mathbf{V}_a \cdot \nabla \rho \left( \frac{\partial z}{\partial p} \right) \right] - \left( \frac{f_0}{g} \right) \frac{\partial \zeta_a}{\partial t} - f_0 \frac{\partial}{\partial p} \left[ \mathbf{V}_p \cdot \nabla \rho \left( \mathbf{V}_h \right) - \left( \frac{f_0}{g} \right) \mathbf{k} \cdot \left( \mathbf{V}_p \times \nabla \mathbf{V}_h \right) \right].
\]

By separating the horizontal wind vector into geostrophic and ageostrophic components in the vorticity advection and thermal advection terms [first and second terms on the right-hand side (rhs) of Eq. (6)], the NQG height tendency equation in Eq. (6) can also be written as

\[
\left[ \nabla^2 + f_0^2 \frac{\partial}{\partial p} \left( \frac{1}{\sigma} \frac{\partial}{\partial p} \right) \right] \left( \frac{\partial z}{\partial t} \right) = -\left( \frac{f_0}{g} \right) \mathbf{V}_g \cdot \mathbf{V}_p (\zeta_g + f) - \left( \frac{f_0}{g} \right) \mathbf{V}_a \cdot \mathbf{V}_p (\zeta + f) - f_0^2 \frac{\partial}{\partial p} \left[ \left( \frac{1}{\sigma} \right) \mathbf{V}_g \cdot \mathbf{V}_p \left( \frac{\partial z}{\partial p} \right) \right] - f_0^2 \frac{\partial}{\partial p} \left[ \left( \frac{1}{\sigma} \right) \mathbf{V}_a \cdot \mathbf{V}_p \left( \frac{\partial z}{\partial p} \right) \right] - \left( \frac{f_0}{g} \right) \frac{\partial \zeta_a}{\partial t} - f_0 \frac{\partial}{\partial p} \left[ (\xi + f - f_0) \mathbf{V}_p \cdot \mathbf{V}_h \right] - f_0 \frac{\partial}{\partial p} \left[ \left( \frac{1}{\sigma} \right) \mathbf{V}_p \cdot \nabla \mathbf{V}_h \right].
\]

In a similar fashion to deriving the QG geostrophic zonal wind tendency equation [Eq. (5)] as done by Dong and Colucci (2005), that is, by multiplying both sides of Eq. (7) by $-\left( \frac{g}{f_0} \right)$ and differentiating with respect to $y$, recognizing that $\sigma$ now is a three-dimensionally varying variable, one obtains the NQG geostrophic zonal wind tendency equation as follows:

\[
\left[ \nabla^2 + f_0^2 \frac{\partial}{\partial p} \left( \frac{1}{\sigma} \frac{\partial}{\partial p} \right) \right] \left( \frac{\partial u}{\partial t} \right) = \frac{\partial}{\partial y} \left[ \mathbf{V}_g \cdot \mathbf{V}_p (\zeta_g + f) \right] + \frac{\partial}{\partial y} \left[ \mathbf{V}_a \cdot \mathbf{V}_p (\zeta + f) \right] + \frac{\partial}{\partial y} \left[ \mathbf{V}_m \cdot \mathbf{V}_p (f_0 \mathbf{V}_h) \right] + \frac{\partial}{\partial y} \left[ \mathbf{V}_e \cdot \mathbf{V}_p (f_0 \mathbf{V}_h) \right] + \frac{\partial}{\partial y} \left[ \mathbf{V}_v \cdot \mathbf{V}_p (f_0 \mathbf{V}_h) \right] + \frac{\partial}{\partial y} \left[ \mathbf{V}_c \cdot \mathbf{V}_p (f_0 \mathbf{V}_h) \right] + \frac{\partial}{\partial y} \left[ \mathbf{V}_s \cdot \mathbf{V}_p (g \mathbf{k} \cdot (\mathbf{V}_p \times \nabla \mathbf{V}_h)) \right] + \frac{\partial}{\partial y} \left[ \mathbf{V}_t \cdot \mathbf{V}_p (g \mathbf{k} \cdot (\mathbf{V}_h \times \nabla \mathbf{V}_h)) \right] + \frac{\partial}{\partial y} \left[ \mathbf{V}_u \cdot \mathbf{V}_p (g \mathbf{k} \cdot (\mathbf{V}_h \times \nabla \mathbf{V}_h)) \right].
\]

The individual forcings on the rhs of the above NQG geostrophic zonal wind tendency equation [Eq. (8)] are elucidated below.

- $F_{V1}$: Equivalent to QG vorticity advection forcing,
- $F_{V2}$: Advection of ageostrophic relative vorticity by the geostrophic wind,
- $F_{V3}$: Advection of absolute vorticity by the ageostrophic wind,
- $F_{T1}$: Equivalent to QG thermal advection forcing,
- $F_{T2}$: Thermal advection by the ageostrophic wind,
- $F_{ageo}$: Tendency of the ageostrophic vorticity,
- $F_{vert}$: Vertical advection of relative vorticity,
- $F_{div}$: Horizontal divergence forcing,
- $F_{lifting}$: Tilting forcing, and
- $F_{extr}$: Extra forcing.

Specifically, $F_{V1} + F_{T1}$ is equivalent to the total QG forcing, except that the static stability $\sigma$ is a constant on the isobaric surfaces in the QG framework. All NQG forcings in Eq. (8) are straightforward and have the equivalent meanings as in the full vorticity equation. The NQG forcing $F_{extr}$ is resulted from the three-dimensionally varying static stability $\sigma$ in the left-hand side of Eq. (8).

### 3. Data

The forcings and other quantities were calculated from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis of 6-hourly SH temperatures and geopotential heights at 17 vertical pressure levels ($P = 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 hPa$) on a $2.5^\circ \times 2.5^\circ$ grid (Kalnay et al. 1996). Calculations of $u$-component wind tendencies were performed at 6-h intervals during the selected periods of interest (usually a period of 5 days prior to block onset). The instantaneously calculated wind tendencies were integrated over consecutive time periods to yield calculated 12-h changes in the geostrophic $u$-component.
wind, using the trapezoidal rule. These were compared to the analyzed changes in geostrophic $u$-component wind, evaluated using centered time differences of the geostrophic $u$-component wind, over the corresponding 12-h periods. Attention is focused here on wind changes at the 500-hPa level.

Following Watson and Colucci (2002) who used a modified version of the blocking detection approach of Tibaldi and Molteni (1990), blocking is defined as the persistence (of at least 5 days) of negative zonal index (500-hPa geopotential heights are higher at 60°S than at 40°S) spanning at least 20° of longitude. Here block onset is defined by the first day on which this definition is satisfied for a particular episode. The block-onset region is defined as a rectangle box, which is confined within the 40°–60°S latitude band and (equal or greater than) 20° longitude band that satisfy the blocking detection algorithm. Unlike Dong and Colucci (2005) who selected 30 blocking cases for their study, in the present study, only those blocking cases detected after 1972 are chosen given that the addition of satellite data to the observational system started around 1972. In total, 14 SH blocking events are selected and comprehensively examined with the NQG zonal wind tendency in Eq. (8). The geostrophic $u$-component wind tendencies in Eq. (8) are resolved into contributions from individual forcings as discussed earlier. The wind tendency equation is solved numerically by three-dimensional relaxation over the volume bounded laterally by the whole SH plane and vertically by 1000 and 10 hPa every 6 h during periods of interest. In the relaxation procedure, the partitioned geostrophic $u$-component wind tendencies are set equal to zero on the volume boundaries for simplicity.

Table 1 shows the total analyzed and individually calculated 12-h geostrophic $u$-component wind tendencies due to each forcing elucidated in Eq. (8) averaged over the respective block-onset regions among 14 SH blocking events during the 5-day preblocking period. In all blocking events, the total analyzed wind tendencies have negative values indicating a weakening of the geostrophic westerlies prior to block onsets. It is evident that the QG forcings, $F_{V1}$ and $F_{V3}$, are generally one order of magnitude greater than all NQG forcings. In most blocking cases, the QG forcings consistently contribute to the weakening in the geostrophic westerlies, reflected in the negative wind tendency values. The mean magnitude of quasigeostrophically forced wind tendencies over all 14 SH blocking cases is, therefore, close to the corresponding mean absolute value.

All NQG forcings, shown in Table 1, are generally smaller than the QG forcings. The NQG forcings tend to exhibit alternating contributions to the weakening in the geostrophic westerlies. In terms of the pattern correlation, 8 out of 14 blocking cases are featured with moderately improved pattern correlation between total analyzed and NQG wind tendencies, compared to the QG counterpart. This indicates that, generally speaking, the QG model is satisfactory to qualitatively account for SH blocking events. Nevertheless, there are cases that are featured

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with relatively large NQG forcing such as forcing of geostrophic advection of ageostrophic relative vorticity \((F_{V2})\) in the 1973 and 1974 blocking cases as shown in Table 1. In these cases, the \(F_{V2}\)-induced wind tendency has a magnitude close to, or even greater than, that of the wind tendency forced by the equivalent QG thermal advection forcing \(F_{T1}\). The other ageostrophic forcing term, \(F_{V3}\), generally features a smaller magnitude than \(F_{V2}\) and tends to have an opposite sign compared to \(F_{V2}\). In the following section, therefore, we will focus our attention to the \(F_{V2}\) forcing, which is the largest NQG contribution in most blocking cases.

4. Geostrophic advection of ageostrophic relative vorticity

Following the generalized height equation, shown in Eq. (7), it implies that, in the SH, the anticyclonic ageostrophic relative vorticity advection \((-V \cdot \nabla p\zeta_a > 0)\) is associated with the local geopotential height rises, whereas the cyclonic ageostrophic relative vorticity advection \((-V \cdot \nabla p\zeta_a < 0)\) associated with the local geopotential height falls. Therefore, the strengthening of the geostrophic easterlies (or weakening of the geostrophic westerlies) should be accompanied by a poleward-increasing anticyclonic ageostrophic vorticity advection, as schematically illustrated in Fig. 1.

Examination of the calculated wind tendency due to \(F_{V2}\) from Table 1 reveals two categories of blocking cases, one contributing to the weakening in the geostrophic westerlies (hereafter \(F_{V2}\)-favoring blocking cases) and the other contributing to the strengthening in the geostrophic westerlies (hereafter \(F_{V2}\)-opposing blocking cases). In the present study, the 1974 and 1973 blocking cases, which represent the typical blocking events from these two categories, are selected for closer examination. Furthermore, the composite of \(F_{V2}\)-favoring and \(F_{V2}\)-opposing blocking cases will be discussed.

a. June 1974 blocking case (\(F_{V2}\) favoring)

The evolution of the June 1974 blocking case is illustrated in Figs. 2a–f, from 5 days prior to block onset through the block-onset day. A blocking pattern was analyzed at 500 hPa over the southeastern Pacific Ocean on 25 June 1974, resembling the Greek letter \(\Omega\). The geostrophic westerly flow upstream of the block-onset region began to split into northern and southern branches on 20 June as shown in Fig. 2a. A ridge developed over South America during the following days, accompanied by a cyclonic vortex forming on the west flank on 24 June. The geostrophic easterly flow began to appear over the block-onset region on 25 June and kept strengthening through 27 June (not shown).
eastward-increasing meridional gradient of the ageostrophic relative vorticity (from $\partial \zeta / \partial y < 0$ to $\partial \zeta / \partial y > 0$), as depicted in Fig. 3b, with the geostrophic winds overlaid. Accordingly, this is associated with the anticyclonic ageostrophic vorticity advection poleward of the cyclonic ageostrophic vorticity advection, as shown in the schematic illustration Fig. 1. In association with this advection pattern, a dipole of the calculated geopotential height rises poleward of the height falls is expected over the block-onset region, shown in Fig. 3c. The calculated weakening of the geostrophic westerlies is, therefore, readily observed in Fig. 3d, which contributes to the weakening of the total analyzed geostrophic westerlies (map not shown).

Fig. 2. The 500-hPa height analysis on (a) 20, (b) 21, (c) 22, (d) 23, (e) 24, and (f) 25 Jun 1974, all times 0000 UTC. The block-onset day is 25 Jun 1974. The block-onset region ($60^\circ$–$40^\circ$S, $95^\circ$–$72.5^\circ$W) is outlined by a rectangle. The contour interval is 60 m.
In a similar fashion, the evolution of April 1973 blocking case is presented in Fig. 4 for the 5-day pre-blocking period and block-onset day. A blocking was objectively detected on 24 April 1973 over the southeastern Pacific Ocean as shown in Fig. 4f. During the 5-day preblocking period, a cyclonic low propagated eastward into the block-onset region as it was followed by an anticyclonic ridge upstream that was intensified one day before the block-onset day. The geostrophic easterly flow began to appear on 23 April over the block-onset region and persisted throughout 28 April (not shown). In opposition to the aforementioned June 1974 blocking case, in which the block-onset region is objectively detected on the west flank of the anticyclonic

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**FIG. 3.** The 500-hPa (a) ageostrophic wind, (b) ageostrophic relative vorticity (contour interval $1 \times 10^{-6}$ s$^{-1}$) overlaid by the geostrophic wind, (c) calculated equivalent $F_{V2}$-induced height tendencies [the contour interval is 2 m (12 h)$^{-1}$], and (d) calculated $F_{V2}$-induced geostrophic zonal wind tendencies [the contour interval is 1 m s$^{-1}$ (12 h)$^{-1}$], on 22 Jun 1974. A wind vector scale is provided in the lower right-hand corner of (a) and (b), respectively, in units of m s$^{-1}$. The entire plotting area is the block-onset region.
blocking ridge, the April 1973 blocking case is characterized by the block-onset region detected on the east flank of the anticyclonic blocking ridge.

Attention will be focused on 23 April 1973, one day prior to block-onset day, due to the large calculated $Fv^2$-induced wind tendencies on this day. Zoomed into the block-onset region, Figs. 5a–d clearly depict the negative contributions of $Fv^2$ to block onset by inducing the strengthening of the geostrophic westerlies over the block-onset region. As a pronounced cyclonic low dominated over the block-onset region on 23 April, shown in Fig. 4e, this is associated with subgeostrophic

![Fig. 4](image-url)
winds (ageostrophic winds pointing opposite to the geostrophic winds) over the block-onset region as displayed in Fig. 5a. The corresponding ageostrophic anticyclonic curvature at the center of the block-onset region, along with the background geostrophic cyclonic flow, leads to a dipolar advection pattern of cyclonic ageostrophic vorticity advection situated poleward of the anticyclonic ageostrophic vorticity advection as displayed in Fig. 5b. This pattern is opposite to the block-onset-favoring pattern of ageostrophic relative vorticity advection shown in the schematic illustration Fig. 1. Accordingly, a dipole of the calculated geostrophic height falls poleward of the height rises is expected in the block-onset region, which is confirmed by Fig. 5c. In consequence, a strengthening of the geostrophic westerlies due to the advection of ageostrophic relative vorticity by the geostrophic flow is found in Fig. 5d.
5. Composite analysis

The above two blocking cases have clearly revealed opposite contributions to block onset from forcing $V_2$. Nevertheless, one may wonder if they are representative of two distinct blocking scenarios in terms of $V_2$ contribution. Therefore, it is worth conducting a composite analysis. Among the selected 14 blocking cases in present study, 9 blocking cases are classified as $V_2$-favoring cases, which feature negative $V_2$-induced zonal geostrophic wind tendencies (weakening in geostrophic westerlies) time-averaged over 5-day preblocking period and area-averaged over the block-onset region, whereas 5 blocking cases are classified as $V_2$-opposing cases, which feature positive $V_2$-induced zonal geostrophic wind tendencies (strengthening in geostrophic westerlies).

Table 2 presents the calculated $V_2$-induced zonal geostrophic wind tendencies over 5-day preblocking period for two classified categories of blocking cases in terms of $V_2$ contribution. It is clear that the composite $V_2$-induced zonal geostrophic wind tendencies is negative in the $V_2$-favoring cases, but positive in the $V_2$-opposing case over the 5-day preblocking period. This is consistent with findings from the previous two blocking case studies. Here we will focus on day 2 for both $V_2$-favoring and $V_2$-opposing composite case studies given that the day 2 is about the middle of 5-day preblocking period.

Figure 6 shows the evolution of 500-hPa geopotential height field for the composite $V_2$-favoring blocking case. Here the longitude and latitude are virtual references in that each blocking case has different block-onset region and the composite block-onset region is an overlay of each individual block-onset region. Figure 6 features the onset and development of an anticyclonic blocking ridge in a way similar to the June 1974 blocking case. Synoptically, this configuration of the geopotential height field bears close resemblance to equatorward cyclonic wave breaking (Gong et al. 2010). Again, attention will be focused on 2 days prior to the block-onset day (day 2). Similar to the April 1973 blocking case, a cyclonic vortex is dominant over the composite block-onset region on day 2. Figure 9 examines contribution of $V_2$ by zooming onto day 2 of the composite $V_2$-opposing blocking cases. Over the middle section of the composite block-onset region, a cyclonic ageostrophic curvature region ($\zeta_\alpha < 0$) is found to be sandwiched by two anticyclonic ageostrophic vortices ($\zeta_\alpha > 0$), as shown in Fig. 9a. With the background dominant northwesterly flow, this leads to a pattern of cyclonic ageostrophic vorticity advection poleward of anticyclonic ageostrophic vorticity advection, as shown in Fig. 9b. Therefore, a local strengthening of the geostrophic westerlies is found over the block-onset region as shown in Fig. 9c. This nicely confirms what is observed in the April 1973 blocking case.

Table 2. Calculated $V_2$-induced 12-h changes in the 500-hPa geostrophic zonal wind (m s$^{-1}$) area averaged over the respective block-onset regions during the 5-day preblocking period for (top) nine $V_2$-favoring blocking cases and (bottom) five $V_2$-opposing blocking cases. Also, composite results are presented at the bottom of each.

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<th>Day 3</th>
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FIG. 6. Composite 500-hPa geopotential height field over the 5-day preblocking and block-onset day (day 0) of nine FV2-favoring blocking cases. The contour interval is 60 m. The composite block-onset region is highlighted by a rectangle.
wind 5 days before block onset, it usually leads to anticyclonic curvature of geostrophic flow over the block-onset region on the block-onset day and, hence, the forcing $F_{V^2}$ usually favors block onset. To the contrary, when the geostrophic flow features northwesterly wind 5 days before block onset, this is usually associated with cyclonic curvature of geostrophic flow on the block-onset day and thus results in an opposing pattern of $F_{V^2}$. Since $F_{V^2}$ is the dominant contribution of NQG forcing, identifying the curvature of geostrophic flow before block onset will facilitate predicting the NQG contribution to block onset.

6. Discussion

In addition to examining the calculated zonal wind tendencies in the midtroposphere, we also looked at these quantities in the stratosphere. We found an interesting common feature such that the QG model tends to overestimate zonal wind tendency in nearly every blocking event that we examined, compared to the NQG counterpart. For instance, Fig. 11 depicts the comparison of 50-hPa geostrophic zonal wind tendencies from the analyzed field, NQG, and QG computations for the 1999 blocking event 5 days prior to block onset. This blocking event is characterized with a classic dipole blocking structure on the block-onset date. This case has been exclusively studied by Dong and Colucci (2005) so details can be referred to there. On day 5, strong weakening in the zonal wind is observed in the analyzed wind tendency field within the stratosphere as shown in Fig. 11a. The wind tendency field computed from the NQG model, as shown in Fig. 11b, agrees fairly well with the analyzed field both in terms of pattern and magnitude comparison. Nevertheless, it is evident that the QG representation, shown in Fig. 11c, tends to overestimate the calculated zonal wind tendency field. Figure 12 compares QG and NQG model performance in calculating the geostrophic zonal wind tendency averaged over the block-onset region, within the troposphere and stratosphere, respectively, for the 1999 blocking event 5 days prior to block onset. It clearly demonstrates the overestimation by the QG model within the stratosphere. This overestimation issue has been commonly found in many blocking cases selected for the current work, with the overestimation increasing with increasing altitude above the troposphere. In fact, this overestimation problem is consistent with numerous studies on evaluating geostrophic approximation in the stratosphere. Boville (1987) found large errors in eddy momentum and heat fluxes calculated in the stratosphere compared to the troposphere. This study pointed out that these
FIG. 8. Composite 500-hPa geopotential height field over the 5-day preblocking and block-onset day (day 0) of five $F_{V2}$-opposing blocking cases. The contour interval is 60 m. The composite block-onset region is highlighted by a rectangle.
large errors are essentially rooted from substantial overestimation by geostrophic wind approximation. In the stratosphere, especially for mid- and high latitudes, winds are rotational such that that neglecting local curvature effect can cause the geostrophic over-estimate. This is also confirmed by Randel (1987) who compared several methods of calculating horizontal wind fields in the extratropical stratosphere. This study suggested that balance method is superior for evaluating local winds, compared to geostrophic wind approximation, in that the balance method considers the nonlinear effect in wind estimate. Therefore, extra caution needs to be exercised when the QG model is applied to the stratosphere given the large estimating error arising from geostrophic wind.

7. Conclusions

In the current study, we use a generalized geostrophic zonal wind tendency equation to diagnose the non-quasigeostrophic forcings to blocking onset in the SH and compare them to the QG counterparts. In general, the QG model is able to represent the key physical processes associated with blocking onset in the troposphere reasonably well. The consideration of NQG forcings moderately improves the QG representation of block onset in 8 out of 14 blocking events, if evaluated from the pattern correlation with the analyzed zonal wind tendency field. Furthermore, in this work, particular focus is placed on the forcing of geostrophic advection of ageostrophic relative vorticity, $F_{V2}$, which is extensively examined through case study and composite analysis of selected blocking events. In a composite sense, this forcing is found to be the leading NQG forcing among all NQG forcings. In terms of favoring or opposing blocking onset, the forcing $F_{V2}$ appears to have alternative contribution that is dependent upon the curvature of the geostrophic flow within the blocking structure. Generally speaking, the southwesterly flow is usually associated with the $F_{V2}$-favoring effect whereas northwesterly flow is associated with the $F_{V2}$-opposing effect. Therefore, it is important to use the geostrophic flow pattern prior to blocking onset to foresee this ageostrophic forcing to blocking onset. Finally, a pronounced overestimation of the calculated geostrophic zonal wind tendency is commonly found in the stratosphere by using the QG model. The root of this estimation comes from geostrophic wind approximation, which is incapable of representing the rotational wind in the stratosphere satisfactorily (Boville 1987; Randel 1987). Hence, extra caution needs to be used when applying the QG model to the stratosphere.
FIG. 10. 500-hPa geopotential height difference between $F_{V2}$-favoring and $F_{V2}$-opposing composite blocking cases over the 5-day preblocking and block-onset day. The contour interval is 20 m. The composite block-onset region is highlighted by a rectangle.
FIG. 11. Comparison of 50-hPa (a) analyzed, (b) non-quasigeostrophically, and (c) quasigeostrophically calculated geostrophic zonal wind tendencies for the 1999 blocking case 5 days prior to the block-onset date. The contour is 2 m s$^{-1}$ (12 h)$^{-1}$. The block-onset region is highlighted by a rectangle.

FIG. 12. Area-averaged geostrophic zonal wind tendencies [m s$^{-1}$ (12 h)$^{-1}$] over the block-onset region for the 1999 blocking case 5 days prior to the block-onset date within the (a) stratosphere and (b) troposphere. The black, red, and green lines represent the analyzed, nonquasigeostrophically, and quasigeostrophically calculated geostrophic zonal wind tendencies, respectively.
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