Northward Ageostrophic Winds Associated with a Tropical Cyclone.  
Part 2: Moisture Transport and Its Impact on PRE

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Abstract

Heavy rainfalls often occur when a tropical cyclone (TC) exists on the sea off the south coast. These pre-typhoon rainfalls (PRE) are associated with the northward moisture transport ahead of the TC. In this paper, we examine the northward moisture transport by the ageostrophic winds associated with typhoon T0918 (Melor) and its impact on PRE. According to a numerical simulation conducted in the previous study (Saito 2019), we analyzed the northward moisture fluxes by reproduced geostrophic and ageostrophic winds. Although the southerly ageostrophic winds are dominant mainly in the upper levels, the ageostrophic winds contribute to enhance the poleward water vapor transport for the upper and middle levels above 3 km.

To see the impact of the ageostrophic moisture transport on PRE, we conducted a sensitivity experiment where the model moisture in middle and upper levels over the sea off the south coast of western Japan was reduced. Precipitation over western Japan was decreased about 30\% when the contributions in moisture fluxes by ageostrophic winds were removed. This result suggests that the northward ageostrophic winds associated with a TC enhance PRE by moistening the middle and upper atmosphere.

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1. Introduction

It is well-known that heavy rainfalls in Japan often occur when a typhoon exists on the sea off the south coast of Japan. For examples, typhoon T0014 (Saomai) existed about 400 km east of Okinawa in case of the Tokai heavy rainfall in September 2000. These pre-typhoon rainfalls are also known in other countries and called as ‘PRE’ (Cote 2007; Gallarneau et al. 2010; Bosart et al. 2012; Byun and Lee 2012). Schumacher et al. (2011) pointed out that PRE is enhanced by a broad region of deep tropical moisture that is transported poleward ahead of the recurving TC. In Japan, this northward transport of moisture is referred as a remote effect of the typhoon, which stimulates the front over Japan\textsuperscript{1}. However, the northward emission of warm and humid air from the typhoon crossing the contours is impossible in the geostrophic wind balance, and the reason why the moisture is transported northward from the typhoon was not clarified (Kitabatake 2012).

Ageostrophic winds were first discussed as a vertical circulation associated with a synoptic frontal zone. Near the baroclinic zone, the relationship by the Sawyer (1952) and Eliassen’s (1962) secondary circulation in the jet-streak four quadrant model is well known as the dynamical origin (Shapiro and Keyser 1990). Lim et al. (1991) analyzed the structure of the ageostrophic wind field in baroclinic waves and showed that the finite meridional wind of the baroclinic jet and its associated wave disturbances is the key factor in the distribution of the ageostrophic wind. Another topic on ageostrophic winds is the low-level jet. Diabatic heating with the precipitation process induces the pressure gradient force forcing the mesoscale convective system, which affects the jet streaks in the upper and lower troposphere (Uccellini and Johnson 1979).

Above mentioned mechanisms on ageostrophic winds were not discussed to explain the northward moisture transport associated with a TC. Recently, Saito (2019) examined the origin of distinct ageostrophic northward winds observed over western Japan in September 2009, when typhoon T0918 (Melor) existed off the south coast of Japan. These southerly winds were reproduced by a numerical experiment using the Japan Meteorological Agency nonhydrostatic model (JMA-NHM). They examined the mechanisms of the ageostrophic winds and showed that the northward winds were dynamically induced by the acceleration vectors of horizontal winds when the typhoon approaches a baroclinic zone from south.

Although Saito (2019) successfully elucidated the origin of the observed ageostrophic winds associated with a typhoon, the reproduced northward ageostrophic winds were mainly dominant in the upper level. Since the most part of the water vapor exists in the lower troposphere, southerly winds in upper levels may not change the precipitation substantially. Indeed, Kato (2018) has pointed out importance of the lowest level moisture for moist convection leading to heavy rainfalls in East Asia. Meanwhile, Takemi (2007) examined a sensitivity of squall-line intensity to environmental moisture condition, and showed that the case with dry middle layer produced a weaker squall line than with moist middle layer when CAPE is unchanged. The question on “how PRE is modified by the northward moisture transport by the ageostrophic winds associated with a TC?” was remained.

In this paper, as a second part of Saito (2019), we address the northward moisture transport by the ageostrophic winds associated with a TC and its impact on PRE. In Section 2, we remind the northward ageostrophic winds observed with typhoon T0918 (Melor) and results of Saito (2019). In Section 3, northward moisture fluxes by ageostrophic winds are quantitatively analyzed. In Section 4, a sensitivity experiment to see the influence of upper and middle level moisture on PRE is conducted. Summary and concluding remarks are given in Section 5.

2. Ageostrophic winds associated with typhoon T0918 (Melor)

When the typhoon T0918 (Melor) approached Japan, distinct ageostrophic southerly winds were observed over western part of Japan. Figures 1a and 1b show 300 hPa and 500 hPa height fields by the JMA operational global analysis and observed winds at

\textsuperscript{1}See Supplement 1 of Saito (2019): https://www.jstage.jst.go.jp/article/sola/15/0/15_2019-040/_supplement/_link/15_2019-040_1.pdf.
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These southerly winds are seen also in 500 hPa level, while at 850 hPa level, horizontal winds are basically along the height contours. At surface (Fig. 1c), horizontal winds are east-northeasterly, crossing the contours toward the typhoon center.

Saito (2019) examined the cause of the ageostrophic winds and showed that they are dynamically induced by the acceleration vector of horizontal motion of the air (Haltiner and Martin 1957; Ogura 1978, 2000). In northern hemisphere, the direction of the ageostrophic wind is leftward of the direction of the acceleration vector. Sensitivity experiments showed that precipitation enhanced the northward ageostrophic winds but its effect was not primary over western Japan. Orographic effect was negligible for occurrence of large scale northward ageostrophic winds.

Although Saito (2019) presented the dynamical origin of the northward ageostrophic winds associated with a typhoon, quantita-
tive evaluation of the northward moisture transport and its impact on PRE was not given.

3. Northward moisture fluxes by ageostrophic winds

In this section, we checked northward moisture fluxes by horizontal winds and contribution of ageostrophic wind components in the experiment by Saito (2019). Figure 2 shows horizontal winds and their southerly components at $z = 1, 3, 5, 7,$ and $9$ km levels simulated by JMA-NHM for 00 UTC 7 October 2009 (FT = 6). b) Same as in a) but for northward moisture fluxes. (νν′). c) Same as in b) but for geostrophic wind components. d) Same as in b) ageostrophic wind components (νν′).

Fig. 2. a) Horizontal winds (arrows) and their $v$-components (colour shade) at $z = 1, 3, 5, 7,$ and $9$ km levels simulated by JMA-NHM for 00 UTC 7 October 2009 (FT = 6). b) Same as in a) but for northward moisture fluxes. (νν′). c) Same as in b) but for geostrophic wind components. d) Same as in b) ageostrophic wind components (νν′).

In this section, we checked northward moisture fluxes by horizontal winds and contribution of ageostrophic wind components in the experiment by Saito (2019). Figure 2 shows horizontal winds and their southerly components at $z = 1, 3, 5, 7,$ and $9$ km levels simulated by JMA-NHM for 00 UTC 7 October 2009 (FT = 6). As seen in Fig. 1, southerly winds over western Japan are more distinct at upper levels and most dominant at $z = 9$ km. Around the typhoon, dipole patterns of $v$-component are obvious below $7$ km, which corresponds to the cyclonic circulation around the typhoon center. Supplement 1 depicts geostrophic and ageostrophic components of the northward winds. In geostrophic winds (Supplement 1a), these dipole patterns are more evident while southerly winds over western Japan in upper levels are weaker. In ageostrophic winds (Supplement 1b), anti-cyclonic dipole patterns are seen around the typhoon. These opposite circulations correspond to the gradient wind decetration, that discussed in Saito (2019) (see their Fig. 4a). Southerly ageostrophic winds over western Japan are more distinct in upper levels, and apparently contribute to enhance the $v$-component of horizontal winds. In the lowest level ($z = 1$ km), ageostrophic winds are northerly over western Japan. These northerly winds in the boundary layer are driven by the balance of the pressure gradient force toward the typhoon, Coriolis force and the surface friction.

Color shade of Figs. 2b, 2c, and 2d depicts horizontal distribution of the northward moisture flux $(\rho q v)$ by the southerly horizontal winds at $z = 1, 3, 5, 7,$ and $9$ km levels. Here, $\rho$ is the density, $q$ the mixing ratio of water vapor, and the northward moisture flux at a specific level is evaluated by the sum of moisture fluxes at vertically adjacent levels (Supplement 2). Patterns of the northward moisture fluxes are basically similar to those of the
southerly winds (Supplement 1), but at \( z = 9 \) km, a large area of the northward moisture flux is seen over the sea off the south coast of western Japan, reflecting horizontal distribution of water vapor. Around this area, the ageostrophic winds seem contribute more in the upper levels as foreseen by Fig. 2.

Figures 3a−3c show vertical profiles of the water vapor mixing ratio \( q_v \), water vapor density \( \rho q_v \), northward wind component \( v \) and moisture flux \( \rho q_v v \) by (a) horizontal wind \( v \), (b) geostrophic wind component \( v_g \), and (c) ageostrophic wind component \( v_a \) averaged over a rectangle area around and off the south coast of Japan \((130^\circ E−137^\circ E, 30^\circ N−33^\circ N)\). The northward ageostrophic winds seem contribute more in the upper and middle levels above 3 km. Moisture flux by ageostrophic winds gradually decreases with the height. The northward geostrophic winds (Fig. 3c) increase with the height and attain the maximum \((19 \text{ m s}^{-1})\) at \( z = 9.6 \) km. As shown in Supplement 1c and Fig. 2d, \( v_g \) becomes negative in lower levels. Moisture flux by ageostrophic winds is positive above 3 km. Since water vapor decreases with the height, the moisture flux by ageostrophic winds does not increase with the height. Still, it contributes to enhance the poleward water vapor transport in the upper and middle levels above 3 km. Figure 3d shows vertical profiles of \( v_g \), \( v_a \), and the ratio of \( v_a \) to \( v \) as the contribution of geostrophic wind component in southerly winds. Here, we plotted the values of \( v_a/v \) only for above 3 km. These values are used as a reduced function for water vapor in the sensitivity test in the next section.

4. Impact of northward moisture transport by ageostrophic winds on PRE

4.1 Design of the sensitivity experiment

In order to respond to the question “how PRE is modified by the northward ageostrophic winds associated with a TC?”, in this section we conduct a sensitivity experiment. Since the geostrophic and ageostrophic winds are coupled by dynamics, it is impossible to evaluate their effects independently. As an alternative expediency, we checked the impact of moistening of the atmosphere in the middle and upper levels on PRE. Considering the fact that the northward ageostrophic winds are dominant in the upper and middle levels, we reduced the model moisture in middle and upper levels according to the contribution of the ageostrophic wind in the northward wind.

Supplement 3 illustrates a schematic chart of the sensitivity experiment. Saito (2019) conducted numerical experiments of the event of T0918 (Mellor) using JMA-NHM (Saito et al. 2006, 2007; Saito 2012) with a horizontal resolution of 10 km. Initial condition was given by the JMA operational mesoscale analysis at 1800 UTC, 6 October 2009, and boundary conditions were given by the 6 hourly JMA’s operational global model forecasts initiated by global analysis at 1800 UTC, 6 October. The horizontal domain size of the numerical experiments was 3,600 km × 2,880 km and the number of vertical levels was 50. The 3-ice bulk cloud microphysics scheme which predicts six water species (Ikawa and Saito 1991) and a modified Kain-Fritsch (K-F) convection parameterization scheme (Yamada 2003) are simultaneously employed as the precipitation process. The Mellor-Yamada-Nakanishi-Niino
level-3 turbulent closure model (Nakanishi and Niino 2006) is implemented as the boundary layer scheme. These specifications were almost the same as in the JMA’s operational mesoscale model (MSM) as of 2009 except the horizontal resolution and time interval of the lateral boundary condition update. Six-hour forecasts were conducted in Saito (2019) from 1800 UTC 6 October 2009 to reproduce the ageostrophic winds at 00 UTC 7 October. In this paper, we adopt the restart option of JMA-NHM and output a restart file at 00 UTC 7 October (FT = 6). Then, we restart the model from FT = 6 to FT = 18 with and without modifications of the water vapor filed of the restart file. We regard the model run without modification of the restart file as the control (CNTL), and one with modified water vapor as the test (TEST). The forecast of CNTL until FT = 12 is identical to the result of Saito (2019).

In TEST, water vapor of the restart file in middle and upper levels above 3 km over the rectangle area around and off the south coast of western Japan (130°E–137°E, 30°N–33°N) was decreased by multiplying the reduced function, the ratio of the geostrophic wind in the northward wind components \( \frac{v_g}{v} \). Figure 4a shows vertical profiles of the water vapor mixing ratio in CNTL and TEST over the rectangle area. The total water vapor in the rectangle area was $113.13 \times 10^6$ tons in CNTL and $103.94 \times 10^6$ tons in TEST. This decrease of total water vapor (9.19 × $10^6$ tons) corresponds to 4.59 mm in the averaged precipitable water vapor (PWV), and 8.1% of PWV in CNTL (56.5 mm).

Figure 4b compares the relative humidity (RH) in the two experiments. Although the change of the mixing ratio is not large, above 6 km, RH was decreased from above 80% to below 60%.
Figure 4c indicates vertical profiles of the temperature and the potential temperature. In this area, the temperature lapse rate is about 5.5 °C/km in the most troposphere, and no specific inversion layer is seen. Level of 0°C is about 4.2 km. The equitable potential temperatures (Fig. 4d) of TEST decreased by about 3 K compared with CNTL in middle and upper levels from z = 4 to 9 km. However, the change of CAPE was not so large as from 979.4 J/kg to 953.8 J/kg (2.6%), because the equitable potential temperatures at the lower levels are unchanged.

Figures 4e and 4f compares the horizontal distribution of water vapor mixing ratios by CNTL and TEST at z = 9 km at the restart time. The reduced water vapor in the rectangle area off the south coast of western Japan is advected northward and affects the precipitation over Japan with time.

4.2 Results of the sensitivity experiment

Figures 5a–5c show hourly precipitation intensity for 0100 to 0400 UTC 7 October 2009 (FT = 7–10) by CNTL, TEST, and the difference (CNTL-TEST), respectively. The spiral rainfalls just in the front side of the typhoon are almost the same, while rainfall intensity around southern coastal areas of Kyushu and Shikoku in TEST decreased obviously. Figure 5d shows the ratio of accumulated precipitation decrease, (CNTL-TEST)/CNTL. The accumulated rain in TEST around southern coastal areas in western Japan decreased to less than 50% of CNTL locally.

Figures 6a and 6b show the 4-hour accumulated rain by CNTL at 0400 UTC, 7 October (FT = 6–10) and the decrease of precipitation in TEST. Accumulated precipitation decreases above 20 mm around some southern coastal areas of Kyushu and Shikoku. In these areas, the ratio of accumulated precipitation decrease exceeded 50%. Figure 7a indicates time evolution of hourly precipitation intensities of CTL and TEST averaged over the red rectangle area. The precipitation intensity decreased about 30% for FT = 8–9. During FT = 6–12, total decrease of rainfall in the rectangle area was 12.38 × 10^6 tons (11.0%; 6.18 mm in average), which exceeded the change of water vapor at FT = 6 in TEST.
(8.1% and 4.59 mm). These results suggest a positive feedback of water vapor change in upper and middle levels on precipitation, and consistent with the results of Takemi (2007, 2014), where convection in a squall line becomes weaker with a dry middle layer.

To address the origin of the decrease of rainfall in TEST, we decomposed the precipitation into two parts; precipitation by cloud microphysics and that by the K-F convection scheme. Figures 6d and 6e show precipitation by cloud microphysics and by the K-F scheme in CNTL, respectively, and Fig. 6f is the ratio of the K-F scheme in total precipitation. In the rectangle area over western Japan (red rectangle), most rains are given by cloud microphysics. Figures 6g–6i show corresponding results by TEST. Precipitation by cloud microphysics over western Japan decreased drastically, while precipitation by the K-F scheme was almost identical. This tendency is also confirmed by the hourly precipitation (Figs. 7b and 7c). Almost all decrease of precipitation in TEST was brought by cloud microphysics.

5. Summary and concluding remarks

As a second part of Saito (2019), we further examined the northward moisture transport by the ageostrophic winds associated with a TC and its impact on PRE. Simulated moisture flux for the case of T0918 was analyzed. Although the northward ageostrophic winds are dominant mainly in the upper levels, the ageostrophic winds contribute to enhance the poleward water vapor transport in the south of western Japan for the upper and middle levels above 3 km.

We conducted a sensitivity experiment where the model moisture in middle and upper levels was reduced according to contributions in moisture flux by the ageostrophic wind components. Even though the northward water vapor transport by the ageostrophic wind is dominant only in the upper and middle levels and the most part of the water vapor exists in the lower troposphere, precipitation over western Japan was substantially decreased when the contributions in moisture flux by ageostrophic winds were removed. The decrease of total precipitation amount in TEST exceeded the decrease of precipitable water vapor, and the most part of the decrease was brought by the cloud microphysics scheme in the model. Our results show that the northward ageostrophic winds associated with T0918 enhanced the pre-typhoon precipitation over western Japan by moistening the middle and upper atmosphere. These new findings may change the conventional perspective on the precipitation intensification mechanism in PRE that a typhoon stimulates the front and enhance precipitation by supplying water vapor in the lower levels.

In our sensitivity test, decrease of rainfall over western Japan in TEST exceeded the decrease of water vapor in upper and middle levels at the restart time. In TEST, we changed water vapor only and used the same kinematic fields as in CNTL. As discussed by Sawyer (1952) and Eliassen (1962), northward ageostrophic winds may yield an upward motion as a secondary circulation, which also likely enhances the pre-typhoon precipitation. Studies on the detailed mechanisms of precipitation intensification by upper and middle level moistening and effect of the secondary circulation caused by the ageostrophic wind on PRE are the future subjects.

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Supplements

Supplement 1. a) Same as in Fig. 2a but for geostrophic wind components (\(v_g\)). b) Same as in a) but for ageostrophic wind components (\(v_a\)).

Supplement 2. Schematic chart on evaluation of northward moisture flux at a specific level and corresponding vertically adjacent levels.

Supplement 3. Schematic chart of the sensitivity experiments.

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