Medium-Scale Tropopausal Waves Visualized by Upper-Level Clouds to the East of the Tibetan Plateau

Yasu-Masa KODAMA, Kuniko EGAWA\textsuperscript{1}, and Minako TAKAHASHI

Department of Earth and Environmental Sciences, Graduate School of Hirosaki University, Hirosaki, Japan

(Manuscript received 9 April 2007, in final form 11 December 2007)

Abstract

We examined upper cloud variation over East Asia and the western North Pacific using 3-hourly Geostationary Meteorological Satellite infrared (GMS-IR) observations between 1988 and 1997. Of particular focus was the relationship to medium-scale tropopausal waves (MTWs) developed near the tropopause around mid-latitude westerlies. One- to two-day variation in upper clouds was significant throughout the year, except in summer because of eastward-traveling upper cloud systems developing in the southerly of MTWs. This finding confirms a previous theoretical prediction of southerly updraft appearance. The largest 1-day variation in upper cloudiness occurred over the Tibetan Plateau. Large variation also occurred over the China Plain to the east of the Tibetan Plateau and over the East China Sea, but less variation occurred over Japan and the western North Pacific to the east. Since appearance of cloud systems of MTWs near the eastern edge of the Tibetan Plateau is diurnally regulated, the phases of 1-day variation of cloud systems of MTWs over the China Plain are determined by the eastward phase speed of MTWs and the distance from the Tibetan Plateau. When the phase speed of MTWs is uniform, systematic phase delay of diurnal variation in upper cloudiness is significant over China Plain, which has been observed as a distinct phenomenon (Asai et al. 1998). The phase-locked appearance of MTW cloud systems can be ascribed to diurnal variation in upper-tropospheric circulation around the Plateau, which is related to updrafts that develop in the afternoon over the Plateau. This suggests that thermal forcing over the Tibetan Plateau may initiate MTWs and affect their behavior over East Asia, where the magnitude of 1-day variation is larger than that of MTWs in other mid-latitude regions.

1. Introduction

The improved time resolutions of satellite and objective analysis data allow the analysis of short-period (1–2 days) atmospheric waves. Sato et al. (1993) found that medium-scale tropopausal waves (MTWs) can be trapped near the tropopause and propagate eastward along the high-latitude side of upper westerly jets. Such MTWs have been frequently observed in the mid-latitudes over the North Pacific, North Atlantic, and South Indian oceans (Hirota et al. 1995; Sato et al. 2000). These waves occur throughout the year, but intensify between fall and spring over the North Pacific and Atlantic oceans. Over the western North Pacific, MTWs are most intense in spring and appear around the northeastern edge of the Tibetan Plateau. The MTW amplitude increases to the east of 110°E toward a maximum in the eastern Pacific (Yamamori et al. 1997). MTWs are significant along the subtropical jet over the North Pacific and along the polar frontal jet over the North Atlantic and South Indian oceans (Sato et al. 2000). Over Japan in spring, MTWs have a horizontal scale of 2100 ± 300 km, propagation speed of 22 ± 2 m s\textsuperscript{-1}, which is much faster than synoptic-scale

\textsuperscript{1} Present affiliation: Marine Information Research Center, Japan Hydrographic Association

Corresponding author: Yasu-Masa Kodama, Department of Earth and Environmental Sciences, Graduate School of Hirosaki University, Hirosaki, 036-8561, Japan
E-mail: kodama@cc.hirosaki-u.ac.jp
©2008, Meteorological Society of Japan
waves in the mid-latitudes, and time period of close to 1 day (i.e., \(26 \pm 3\) h; Sato et al. 1993). The time periods of MTWs vary from 1 to 2 days depending on the region. For example, over the western North Atlantic in winter, the time period is \(33 \pm 5\) h, although the phase velocity is \(20 \pm 5\) m s\(^{-1}\) (Hirota et al. 1995), which is similar to that over Japan.

Sato et al. (1998) proposed that an MTW is a type of Rossby wave trapped near the tropopause and maintained by a restoring force of vertical motion, which works under a strong vertical gradient of stability near the tropopause around the poleward side of upper westerly jets. Yamamori and Sato (1998) confirmed a theory for MTWs over East Asia within a framework of quasi-geostrophic potential vorticity. The theory predicts that updraft is accompanied by northward wind and downdraft by southward wind. However, observations have not yet confirmed such vertical motion accompanying MTWs. Visualizing updraft by upper cloud variation is useful to confirm this theory; this was the first purpose of this study.

The energy sources of MTWs are not yet fully known. Yamamori and Sato (2002) showed that an MTW is amplified by vertical coupling with a synoptic-scale baroclinic wave as it passes over the MTW. They noted that this process works when the MTW has finite amplitude and that the process initiating MTWs should be clarified. Shigehisa et al. (1999) theorized that atmospheric heating may generate MTWs. Strong atmospheric heating over the Tibetan Plateau may contribute to MTW formation over East Asia, but this process has not yet been examined. Thus, the second purpose of this study was to investigate whether diurnally altered heating over the Tibetan Plateau contributes to MTW initiation. To do this, we analyzed the relationship between variation in cloudiness and the v-component of wind variation using a cross-spectrum analysis method.

Asai, Ke, and Kodama (1998) described a systematic eastward phase delay in the diurnal variation of upper cloudiness over East Asia, east of the Tibetan Plateau. Hereafter, we refer to this as the AKK (Asai, Ke, and Kodama) phenomenon. A similar eastward phase delay has also been found in the diurnal variation in precipitation over the Great Plains of the USA, east of the Rocky Mountains (Riley et al. 1987). In both phenomena, the phase speed is approximately 20–30 m s\(^{-1}\), which is much faster than the phase speed of synoptic-scale waves. However, the mechanisms seem to be quite different in the two regions. East of the Rockies, this phenomenon is observed only in the warm season (Riley et al. 1987) and has been ascribed to eastward-traveling meso-scale convective systems (MCSs) originating over the Rockies at dusk (Bosart and Sanders 1981; McAnelly and Cotton 1989; Ahijevych et al. 2001). To the east of the Tibetan Plateau, eastward phase propagation is significant in spring (Asai et al. 1998), when MCSs do not develop. Thus, our third purpose was to clarify the mechanism of the AKK phenomenon in relation to cloud systems maintained by the diurnally regulated MTW.

We show that part of the MTWs over East Asia and the western North Pacific can be visualized as an upper cloud system, which can be detected by infrared (IR) cloud images observed by Japan’s Geostationary Meteorological Satellite (GMS). Upper cloud appears in the upper southwesterlies, where updraft is predicted by MTW theory. Such MTWs visualized by upper cloud are frequently observed over East Asia and the western North Pacific, especially in winter and spring. The passage of upper clouds associated with MTWs is regulated diurnally and coherently and causes the AKK phenomenon observed over the China Plain.

2. Data

We used 3-hourly brightness temperature (TBB) data at a \(1^\circ \times 1^\circ\) (lat. \times long.) grid scale derived from GMS-IR observations complied by the Meteorological Research Institute-Japan Meteorological Agency (MRI-JMA) and 6-hourly \(2.5^\circ \times 2.5^\circ\) (lat. \times long.) reanalysis data from the National Centers for Environmental Prediction-the National Center for Atmospheric Research (NCEP-NCAR). Both data are transformed into \(2^\circ \times 2^\circ\) (lat. \times long.) grid for comparison. The study period was the 10 years from 1988 to 1997. We also analyzed 3-hourly GMS IR cloud images on 21 and 22 March 1997 to observe the upper cloud distribution around the MTW. The image data were obtained from the data archives of Weather Home, Kochi University, Japan (http://weather.is.kochi.ac.jp).

3. Relationship between MTWs and variation in upper cloudiness

Figure 1 shows the fields of the northward component of 250-hPa wind and TBB derived from GMS-IR observations at 9 UTC on 16 April 1990. The former is after Fig. 7 of Sato et al. (1993), and was high-pass filtered (< 2 days) to pick up the
MTW. The latter was non-filtered because cloud systems accompanying the MTW are detectable in the unfiltered field. As described by Sato et al. (1993), systematic alternation of southerlies and northerlies at an interval of 2000 km, corresponding to an MTW, was found along 35°N. Areas of TBB < −30°C are a proxy for upper-level cloud shields that appear in the lower-latitude portions of the southerlies.

Figure 2 shows a 6-hourly time-sequence of the high-pass filtered (< 2 days) v-component of wind at 250 hPa and non-filtered TBB fields on Fig. 1. High-pass filtered meridional wind at 250 hPa at 9 UTC, 16 April 1990, after Sato et al. (1993) (upper panel) and the non-time-filtered 3-hourly brightness temperature (TBB) field obtained from GMS IR observations at the same time (lower panel). The TBB field includes an upstream portion. Contours of TBB less than or equal to −30°C (higher than −30°C) were shown by thin solid (dashed) lines. Thick contours indicate 3000 m MSL.

Fig. 2. Six-hourly time sequence of the 250-hPa v-component of high-pass filtered wind (< 2 days) and unfiltered TBB on 16 April 1990. Shading indicates positive wind and TBB lower than −30°C corresponding to upper cloud shields. Interval of thin contours is 4 m s⁻¹ for wind and 10°C for TBB. Thick contours indicate 3000 m MSL.
Fig. 3. Quasi 3-hourly GMS IR images between 21 and 22 March 1997 as an example of cases when eastward propagation of the MTW cloud systems was clearly observed. The positions of three cloud systems are shown. Thick contours indicate 3000 m MSL.
16 April 1990. The maximum amplitude of MTWs was located 5° higher than the westerly core, which occurred in the tropopause gap (Sato et al. 1998). Low TBB areas are located in the lower-latitude portion of the southerly areas, and both areas propagate eastward coherently by ~25° per day, corresponding to a phase speed of ~30 m s⁻¹, as proposed by Sato et al. (1998). This is consistent with MTW theory, which predicts updraft in southerlies and downdraft in northerlies near the tropopause (Sato et al. 1998), because upper clouds are likely to appear in the updraft in the upper troposphere. Upper clouds, however, appeared in the lower-latitude portion of the southerly. This feature cannot be explained by the MTW theory. A possible mechanism will be discussed in Section 6.

Figure 3 shows 3-hourly GMS-IR cloud images between 21 and 22 March 1997, when eastward-traveling cloud systems accompanied by MTWs were observed. The cases in 1997 are shown because we could not obtain the image data in 1990. The cloud system 'A' can be traced from southern China at ~115°E at 00 Z to ~135°E on 30°N at 16 Z on March 21, where it caught up with a synoptic-scale cloud system to the south of Japan. Another cloud system, referred to as system 'B,' appeared at 108°E to the east of the Tibetan Plateau at 09 Z on March 21. It then propagated eastward and caught up with a synoptic-scale cloud system 'C' at 135°E at 16 Z on March 22. System B passed over system C and propagated eastward over the western North Pacific even after 00 Z on March 23 (not shown). Such fast-moving cloud systems in GMS IR observations have also been reported by Hagiwara (1984). Figure 4 shows the surface weather chart at 00 Z on March 22. Cloud system B was accompanied by no surface depression, whereas cloud system C developed around a surface depression. This indicates that system B was an upper system associated with an MTW, whereas system C was a synoptic-scale trough that extended throughout the troposphere.

Figures 5a and 5b show Hovmoller diagrams of upper cloudiness, non-filtered and band-pass filtered (0.75–2 days), respectively, along 30°–40°N in April 1990. Here, upper cloudiness is defined as the fraction of upper cloud cover with tops of TBB lower than ~30°C in a 2° × 2° (lat. × long.) area. In the non-filtered cloudiness diagram, standing diurnal oscillation, along with several eastward phase propagations, dominated over the Tibetan Plateau to the west of ~100°E, and eastward phase propagation dominated to the east of ~100°E. Phase propagation was divided into two categories based on phase speed: slow (~10 m s⁻¹) and fast (25–30 m s⁻¹). The former was observed between 6 and 18 April over the study area and was associated with a synoptic-scale wave, which was confirmed by NCEP-NCAR re-analysis data (not shown). The latter was observed more frequently throughout the month, except for several short periods when cloudiness was small. The fast eastward propagation of cloudiness was superimposed on the slow propagation maintained by synoptic-scale wave.

Figures 5c and 5d show the unfiltered and high-pass filtered (<2 days) v-component of wind at 250 hPa. When the fast-phase propagation had significant variation in cloudiness, large cloudiness and southerlies moved eastward coherently in the band- or high-pass-filtered fields (e.g., 140°–160°E on 15–17 April, 110°–130°E on 26–30 April) (Figs. 5b and 5d). Over the Tibetan Plateau west of 100°E, standing variation was dominant, although eastward phase propagation was also found with the passing of large-amplitude (>2 m s⁻¹ or <−2 m s⁻¹ in high-pass filtered v-component of wind) MTWs (e.g., 13–16 April). Not all MTWs are visualized as upper cloud systems to the east of 110°E. For example, cloudiness was small on 14–18 April between 115°E and 130°E, when MTWs were significant in the 250-hPa wind field. Downdraft at the rear of a large-scale trough may have prohibited the visualization of the MTW by upper clouds.
Nevertheless, many of the MTWs to the east of the Tibetan Plateau were accompanied by upper cloud systems. Hereafter, such eastward-traveling upper cloud systems accompanied by MTWs are referred to as “MTW cloud systems.”

To examine the phase relationship between variation in cloudiness and the v-component of wind in MTW and synoptic time-scales, temporal variation in upper cloudiness and the northward component of 250-hPa wind at 30°N and 150°E were compared for variation over 0.75–2 days (MTW time-scale) and 3–6 days (synoptic time-scale) (Fig. 6). In MTW time-scale variation, many peaks of upper cloudiness agreed with the southerly peaks. This is consistent with MTW theory, which predicts updraft accompanied by an upper southerly. In synoptic time-scale variation, many peaks of upper cloudiness preceded the southerly peaks by half or one day (e.g., 4–5 April, 8 April, 17–18 April, and 23–24 April), although several exceptions were observed. In the next section, we confirm relation between phase lag and time-scale of variances statistically using cross-spectrum analysis, and examine the consistency to the theories of the MTW and baroclinic wave.

Figure 7 shows Hovmoller diagrams of the unfiltered upper cloudiness and high-pass filtered v-component of wind at 250 hPa, as in Figs. 5a and 5b, except it depicts in January, July, and October in 1990 to describe seasonal change in the behavior of MTW cloud systems. To the east of 100°E, fast eastward-traveling cloud systems accompanied by an upper southerly (i.e., MTW cloud systems) were observed throughout the year, although the large-amplitude v-wind variation (> 2 m s⁻¹ or < −2 m s⁻¹) at the MTW scale was less frequently observed in summer and fall, consistent with seasonal changes in MTW activity (Yamamori et al. 2003).
1997). In summer diurnal variation of upper cloudiness was large over the Tibetan Plateau and did not propagate toward China Plain (100°–120°E), except several MTW cloud systems propagated eastward (~6 July and 18–20 July). In fall, diurnal variation of upper cloudiness was suppressed over the Tibetan Plateau and upper cloudiness decreased over the whole study areas, although eastward propagations of the MTW cloud system were sporadically observed. A climatological study pointed out that upper cloudiness decreases over East Asia including the Tibetan Plateau and the western North Pacific in fall (Kodama and Asai 1988); further study is necessary to clarify the mechanisms of upper cloud decrease in fall and its relation to the MTW cloud systems.

4. Spectral analysis of variation in cloudiness and upper wind

In the previous section, we showed coherent variation between the v-component of wind in the upper troposphere and upper cloudiness for several cases in 1990. In this section, we examine the statistical relationship between the variation in upper wind and cloudiness by cross-spectral analysis using the 10-year data.

To examine seasonal dependency, Fig. 8 shows the distribution of the variance of upper-cloudiness, which was obtained from power spectrum calculated using fast Fourier transform (FFT) algorithms for six 64-day periods, starting on the first day of odd-numbered months. The power spectrum in each period was calculated for each year between 1988 and 1997 and then averaged over the 10 years for each 64-day period.

Two peaks of the MTW-scale (0.9–2 days) variance over the Tibetan Plateau and the western North Pacific, respectively, in the first half of the year (left panels of Fig. 8). A zone of larger variance extended between the peaks passing through
the islands of Japan, with a minimum variance around Japan. After mid-summer, the variance was largely diminished except over the Tibetan Plateau, although some variance was recovered over the western North Pacific in fall. The middle panels show 1-day (0.9–1.1 day) variance. The right panels illustrate the ratio of the 1-day variance to the MTW-scale variance. Over the Tibetan Plateau, the variance and ratio of the 1-day variance were large throughout the year, although they decreased in fall (Fig. 8k). This is consistent to the seasonal change of the standing cloudiness varia-

Fig. 7. Hovmoller diagrams of upper cloudiness as in Figs. 5a and 5d except for January, July and October, 1990.
tion over the Tibetan Plateau in 1990 (Figs. 5a, 7a, 7c, and 7e). In winter, part of the 1-day variance can be ascribed to diurnal changes in the ground-surface temperature because cold ground is classified as upper cloud when the ground surface is colder than the threshold temperature for detecting upper cloud areas. The variance and ratio of the 1-day variation were not large over the western North Pacific. This means that the predominant period of variation in cloudiness is longer than 1 day over that area. Over the China Plain, the larger variance and ratio of the 1-day variance extended eastward along 30°–35°N from the Tibetan Plateau, except in mid-summer (Figs. 8j and 8p), when the large ratio was interrupted near 105°E. This corresponds to the results shown in Fig. 7c, i.e., diurnal variations of cloudiness over the Plateau scarcely propagated eastward over the China Plain in summer. The upper westerlies, along with MTWs, that pass over the Tibetan Plateau are suppressed in summer. The ratio of 1-day variance were also larger over southeast China (25°–30°N, 110°–120°E) and South Asia to the south of the Plateau between May and October (Figs. 8o, 8p, and 8q). These values represent standing diurnal variation in deep convection caused by the Asian summer monsoon (Murakami 1983) and are not related to the passage of MTW cloud systems.

Figure 9 shows the 10-year averaged power spectral density of variation in upper cloudiness averaged for several 10° × 10° (lat. × long.) areas, along with phase differences between variations.
in upper-cloudiness and in v-component of wind at the 250-hPa level. To obtain stable spectral density, it was calculated for each 2°×2° (lat.×long.) grid and then averaged for each area. The phase difference is defined to be positive when the phase in variation of v-component of wind precedes that of cloudiness variation. The results were obtained by cross-spectrum analysis using the FFT method for a 64-day period between 1 March and 4 May, when the power of MTW-scale (0.9–2 days) variation in cloudiness was largest over the study area (Fig. 8). A significant peak in 1-day variation occurred at 85°–115°E (i.e., over the Tibetan Plateau and China Plain near the eastern edge of the Plateau). For the MTW-scale variation in a 1–2 day period, the phase difference between variation in the upper-cloudiness and in the v-component of 250-hPa wind was close to zero (–0.3 ~ 0.3 radian, corresponding to several hours). For the synoptic-scale variation, which is intensified to the east of 115°E, cloudiness variation preceded upper v-wind variation by approximately 1/8π radian for 3–4 days period and approximately 1/4π radian for 4–6 days period. These results statistically confirmed the results shown in Fig. 6, in which the phase relation between upper cloudiness and upper v-wind changes according to the scales.

We then examine consistency to the corresponding theories. For the MTW-scale variation, the small phase difference between v-component of 250-hPa wind and upper cloudiness is consistent with the theory of MTW, which predicts that upper southerly accompanies updraft in the upper troposphere, because the updraft may form upper clouds. For the synoptic-scale variation, the phase of upper cloudiness variation preceded that of upper southerly variation. In the most unstable mode of baroclinic instability in Eady’s model (cf.,
Fig. 13.4 of Gill (1984), phase of updraft precedes that of v-component of wind near the tropopause, however the phase difference is small (~0.4 radian, approximately 1/8π). Since baroclinic wave accompanies updraft extending throughout troposphere with a maximum around middle troposphere, it is difficult to determine the reference height where updraft is most sensitive to upper cloudiness. If we compared the phase between v-component of wind at tropopause and updraft in the middle troposphere, phase difference is ~0.7 radian, approximately 1/4π, because phase of updraft in baroclinic wave delays with height. Observed phase difference between upper cloudiness and v-component wind falls approximately 1/8π ~1/4π for the synoptic scale variation to the east of 115°E (Fig. 9). This result does not contradict to the Eady’s model.

5. Relation of MTWs to variation in diurnal cloudiness over East Asia

In this section, we examine the mechanism of the AKK phenomenon by considering the roles of MTW cloud systems. To demonstrate the phenomenon, Fig. 10 illustrates the diurnal variation in cloudiness in April averaged for 10 years between 1988 and 1997. The cloudiness anomaly from the daily mean was averaged between 30°N and 40°N at every 2° in longitude between 90°E and 130°E. Over the Tibetan Plateau to the west of 100°E, upper cloudiness reaches a maximum at ~12 UTC corresponding to ~18 LT (local time) each year. Eastward phase propagation, which corresponds to the AKK phenomenon, was observed each year between 102°E and 110°E, except in 1997. To the east of 110°E, the AKK phenomenon was observed in most years. The behavior of the AKK phenomenon, however, changed largely from year to year. The eastward phase propagation can be traced to 130°E only in 1988, 1990, and 1992–1995. The phase speed of the propagation was not constant; it was lower (~20 m s⁻¹) in 1992 than in the other years (~30 m s⁻¹). Using 10-year upper cloudiness data, we confirmed that the AKK phenomenon was observed in most months, except in summer and fall (not shown).

To examine the relationship between the AKK phenomenon and MTW cloud systems, Hovmoller diagrams of upper cloudiness and the high-pass filtered v-component of wind in April were compared between 1992 and 1997, in which years the AKK phenomenon was clear and obscure, respectively (Fig. 11). In April 1992, several MTW cloud systems were observed. In this month, the phase speed of these systems was lower than usual (~20 m s⁻¹), which may have caused the lower phase velocity of the AKK phenomenon (Fig. 10). The mean westerly at 250 hPa, which advected the MTWs, was 33.4 m s⁻¹ and lower than the average for other years (37.3 m s⁻¹) over 30°–40°N, 105°–130°E. Yamamori et al. (1997) noted that the phase speed of an MTW was less than that for the 250-hPa westerly, but changed along with the variation in westerly wind speed (Fig. 11 of Yamamori et al. 1997). In April 1997, several MTW cloud systems were observed; however, the phase speeds of these systems were not uniform. This incoherency obscures the AKK phenomenon in this month. In April 1990, the phase speeds of several MTW cloud systems were uniform (Figs. 5a and 5d), and the AKK phenomenon was clearly observed over the western North Pacific.

For the AKK phenomenon to be observed clearly, not only the phase speed of the MTW cloud systems, but the phase of diurnal variation should be coherent. Thus, the MTW cloud systems must appear in a specified time near the eastern edge of the Tibetan Plateau, the starting point of eastward propagation of the AKK phenomenon. Figure 12 shows histograms of the number of days in April 1990 classified by the time (UTC) when the maximum cloudiness and the maximum southerly at 250 hPa were observed. If the maximum cloudiness was less than 10%, the day was not counted because MTW cloud systems may not have passed; however, all days were counted for the time of maximum v-component wind because MTWs were observed in most of these periods. To reduce the influence of cloud variation in a scale smaller than the MTW-scale, the day was counted for every 2° × 2° (lat. × long.) grid between 30°–40°N along each longitude line and then averaged over 30°–40°N for each line. At 90°E over the Tibetan Plateau, maximum cloudiness appeared most frequently at ~9 UTC, corresponding to ~15 LT. To the east of 105°E, the most frequent time delayed toward the east, i.e., ~12 UTC at 105°E, 21–0 UTC at 110°E, 6–9 UTC at 120°E, and ~0 UTC at 130°E. The secondary peak at 0 UTC corresponding to 6 LT at 90°E and 105°E may ascribed to misclassification of cold ground surface over the Plateau in early morning. To the east of 110°E, the most frequent time of maximum cloudiness almost agrees with that of the maximum
southerly. This indicates that both the maximum v-wind and the maximum cloudiness, which indicate the passage of an MTW cloud system, were diurnally regulated and coherent to the east of the Plateau. Because the most frequent time of maximum cloudiness was almost consistent with that of the mean diurnal variation in cloudiness in this month (the third panel of Fig. 10), the AKK phenomenon over the China Plain can be ascribed to coherent, diurnally regulated passages of the MTW cloud systems.

To clarify the mechanisms of diurnally regulated formation of the MTW cloud systems near the eastern edge of the Tibetan Plateau, the relation-
Fig. 11. As in Figs. 5a and 5d, except for April 1992 (upper panels) and April 1997 (lower panels).

Fig. 12. Histogram of the times of maximum high-cloudiness for the five 10° × 10° (lat. × long.) areas (upper panels) in April 1990. As in the upper panels except for the maximum southerly of the high-pass filtered (< 2 days) v-component of wind at 250 hPa (lower panels).
ship between diurnal variations in upper cloudiness, the v-component of wind at 250 hPa level, and large-scale circulation around the Tibetan Plateau were examined. Figures 13 and 14 show composite anomaly fields of 250 hPa wind and upper cloudiness, and vertical p-velocity at 400 hPa, respectively, at four times of day (i.e., 0, 6, 12, and 18 UTC) averaged for April 1990. Figure 13 shows that upper cloudiness over the Tibetan Plateau rapidly increased at 12 UTC. The positive anomaly of cloudiness shifted eastward at the eastern edge of the Plateau (~105°E) at 18 UTC and then propagated eastward at 110°E at 0 UTC and 115°E at 6 UTC. The positive anomalies of cloudiness observed at 12 and 18 UTC around the Tibetan Plateau were not accompanied by upper southerlies. To the east of 110°E after 00 UTC, a positive anomaly of cloudiness was accompanied by an upper southerly. Figure 14 shows that divergent wind accompanied by anticyclonic rotation and updraft dominated over the Plateau at 12 UTC. At 18 UTC, convergent wind and downdraft appeared, but anticyclonic circulation still remained around the eastern edge of the Tibetan Plateau. Convergent wind continued over the Plateau at 0 UTC, and cyclonic circulation centered at the eastern part of the Plateau developed. Updraft appeared over the Sichuan basin (~105°E), but was accompanied by cyclonic wind. The cyclonic circulation formed a strong southerly around 110°E over the China Plain. At 6 UTC, large-scale cyclonic circulation dominated over the Plateau, but updraft had begun in the southern portion of the Plateau. It seems that the diurnal variation in wind at 250 hPa around the Plateau can be ascribed to divergence along with mid-tropospheric updraft at 6 and 12 UTC and convergence along with downdraft at 18 UTC and 0 UTC over the Plateau and eastward advection of vortices over the China Plain. As a result, the southerly was intensified at 0 and 6 UTC and the northerly at 12 and 18 UTC over the China Plain at around 110°E, where upper cloudiness

Fig. 13. Monthly averaged wind at 250-hPa and upper cloudiness anomaly averaged at 0 UTC (a), 6 UTC (b), 12 UTC (c), and 18 UTC (d) in April 1990. Thin dashed contours indicate negative anomaly of cloudiness. Thick contours indicate 3000 m MSL.
increased at 0 UTC. Similar features were found in 10-year averaged composite fields in April.

Figure 15 shows the 10-year averaged variance in v-component of wind at 250 hPa in 64 days between 1 March and 3 May. As described by Yamamori and Sato (2002), a large MTW-scale (0.9–2.0 days) variance was concentrated along storm tracks over the North Pacific and North Atlantic (upper panel). The large variance of 1-day (0.9–1.1 day) almost agrees with large MTW-scale variance. Note that the increase in 1-day variance downstream of the Tibetan Plateau is steeper than the MTW-scale variation (middle panel). Over the China Plain and East China Sea in the downstream of the Tibetan Plateau, the contribution of 1-day variance to total MTW-scale variance is 0.2–0.3, which is larger than that along the storm track over the east coast of North America and the western North Atlantic (0.1–0.15; bottom panel). This is consistent with differences in the predominant frequency of MTW between the two regions, as introduced in Section 1 (Sato et al. 1993; Hirota et al. 1995). The contribution of 1-day variance is large within ~3000 km of the eastern edge of the Tibetan Plateau and decreases over the North Pacific to the east of Japan. This east-west contrast is similar to that in the 1-day variance of upper cloudiness shown in Fig. 8.

6. Summary and future tasks

Short-period variation in upper cloudiness over East Asia and the western North Pacific was examined using GMS IR observations. Eastward-traveling upper cloud systems with phase speeds faster than those of synoptic-scale waves are frequently observed to the east of the Tibetan Plateau, especially in winter and spring. Upper clouds appear in the southerly area of the MTW, consistent with MTW theory, which predicts updraft in southerlies (Sato et al. 1998). The MTW cloud systems sometimes superimpose on cloud systems with synoptic-scale waves. The predominant time period of cloud variation accompanied by an MTW is longer toward the east, at 1 day over the China Plain to
the east of the Tibetan Plateau and ~2 days over the western North Pacific. Cross-spectral analysis also revealed a statistical phase relationship between upper cloudiness and the v-component of wind that is almost in phase with MTW-scale (1–2 days) variation. This contrasts with synoptic-scale variation in the developing stage, in which upper cloud appears ahead of the upper southerly.

Upper cloudiness increased in the southern portion of southerly of MTW (Figs. 1 and 2). The theory of MTW in quasi-geostrophic framework (Sato et al. 1998) cannot explain meridional change in updraft profiles across a jet core, which may relate to upper cloudiness distribution. Actually, tropopause is higher in the south of the tropopause gap near the jet core. If updraft exists mainly in the troposphere (stratosphere) to the south (north) of the gap, the upper cloud likely appears only in the south portion of the southerly, because upper cloudiness can appear in the troposphere. Further theoretical studies on finer structure of MTW near the tropopause gap are expected.

We also examined the relationship between the MTW cloud systems and the AKK phenomenon, which is a systematic phase delay in diurnal variation in upper cloudiness observed to the east of the Tibetan Plateau observed in the monthly mean field. The AKK phenomenon is ascribed to the coherent passage of the diurnally regulated MTW cloud systems. Because the appearance of the cloud system is quasi-diurnal near the eastern edge of the Tibetan Plateau, the phase is locked over the China Plain to the east of the Plateau when the phase speed of eastward propagation is uniform among the MTW cloud systems. This causes the AKK phenomenon, i.e., systematic phase delay of diurnal variation in the monthly mean field. Over Japan and the western North Pacific, the phase speed and significance of the AKK phenomenon have large variability because few MTW cloud systems propagate over or to the east of Japan, and the AKK phenomenon observed depends on the behavior of these few systems.

Yamamori and Sato (2002) noted the amplification of the MTW by synoptic-scale disturbances through vertical coupling. They also suggested that this process holds for finite-amplitude MTWs and that other processes are necessary to initiate an MTW. We found phase-locked, 1-day variation in upper cloudiness and the v-component of 250-hPa wind over the China Plain and East China Sea. This suggests that diurnal forcing over the Tibetan Plateau affects MTWs at least over East Asia. Further studies should examine possible

---

**Fig. 15.** Ten-year (1988–1997) averaged variance of the v-component of wind at 250 hPa over the midlatitude in the Northern Hemisphere for 64-day period starting from 1 March. The upper panel shows the MTW time-scale (0.9–2 days) variance, the center panel illustrates diurnal (0.9–1.1 days) variance, and the bottom panel illustrates the ratio between the two. Thick contours indicate 3000 m MSL.
mechanisms of atmospheric heating that enforce MTWs over the Tibetan Plateau.

Acknowledgements

We thank Dr. A. Numaguti, who suggested several similarities between the MTW and eastward phase propagation of diurnal variation in upper clouds. We also thank Drs. Sato and Yamamori for their encouragement. Part of this study was carried out under a joint research program of the Center for Environmental Remote Sensing (CEReS), Chiba University. Comments by corresponding editor (Dr. Fujiwara) and two anonymous reviewers were very fruitful for improving the manuscript. The GMS cloud images were obtained from the satellite data archives of Weather Home, Kochi University, Japan.

References


