Global Characteristics of Medium-Scale Tropopausal Waves Observed in ECMWF Operational Data

KAORU SATO*
Department of Geophysics, Faculty of Science, Kyoto University, Kyoto, Japan

KAZUTAKA YAMADA
Japan Meteorological Agency, Tokyo, Japan

ISAMU HIROTA
Department of Geophysics, Faculty of Science, Kyoto University, Kyoto, Japan

(Manuscript received 12 February 1999, in final form 10 March 2000)

ABSTRACT

Global characteristics and seasonal variation of medium-scale (zonal wavelengths of 2000–3000 km) waves observed around the midlatitude tropopause are examined using 6-hourly European Centre for Medium-Range Weather Forecasts operational data over four years (1990–93), covering both hemispheres. Medium-scale waves and synoptic-scale waves are extracted using time filters and their characteristics are compared. Hovmöller diagrams indicate the existence of medium-scale waves in the Southern Hemisphere as well as in the Northern Hemisphere. The zonal wavelengths of medium-scale waves are slightly larger in the Southern Hemisphere than in the Northern Hemisphere. Medium-scale waves are mostly active in three regions: the North Atlantic in winter (Dec–Jan–Feb), the North Pacific in spring (Mar–Apr–May, MAM), and the south Indian Ocean in autumn (MAM). These regions are roughly corresponding to and slightly downstream of storm tracks where synoptic waves are dominant. Significant differences in seasonal variation of the intensity between the two kinds of waves are also found.

The maximum of wave amplitudes is seen around the tropopause at latitudes slightly higher than the jet stream axis, where the meridional gradient of the quasigeostrophic potential vorticity (QPV) is maximized. The positive large QPV gradient is attributed to the atmospheric structure around the midlatitude tropopause that is located in vertical westerly shear of the jet stream. This fact suggests that the medium-scale waves are waves trapped around the midlatitude tropopause.

1. Introduction

Using recently available operational analysis data such as data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and Japan Meteorological Agency (JAM), and products from weather prediction models having fine time intervals, phenomena with short periods of 1–2 days became analyzed in detail. Such short-period disturbances usually have small horizontal scales.

Sato et al. (1993, hereafter referred to as SEH93) discovered the existence of small horizontal-scale waves traveling eastward in the midlatitude upper troposphere over east Asia, with the aid of wind data with a fine time interval of about 3 min observed by the middle and upper atmosphere (MU) radar (35°N, 136°E), which is a mesosphere, stratosphere, and troposphere (MST) radar, and three-hourly data from the Japan Spectral Model of JMA in the spring of 1990. A statistically meaningful isolated peak corresponding to the small-scale waves was recognized in frequency power spectra of meridional wind fluctuations for both radar and model data. The wave period was estimated at about 26 h. An estimate of a 95% significant interval of the spectra indicated that there is a statistically meaningful spectral gap between this peak and a peak due to synoptic-scale waves with wave periods of about 4 days (See Fig. 5 of SEH93). The waves appeared in a latitudinal band of 30°–40°N slightly to the north of the subtropical jet stream axis. The zonal wavelength was about 2100 km.
The waves have a geostrophic and hydrostatic nature. Since the waves have horizontal scales that are smaller than the synoptic scale (4000–6000 km) and larger than the mesoscale (<1000 km), we call them the medium-scale waves. The zonal phase velocity of 22 m s\(^{-1}\) is about twice as large as that of synoptic-scale waves, which are also dominant in this season. The difference in phase velocity means that the medium-scale waves are not due to the higher harmonics of the synoptic-scale waves. The vertical structure of medium-scale waves is almost barotropic and different from the baroclinic structure of synoptic-scale waves. These results suggest that there exist medium-scale waves with a period of about 1 day in the midlatitude upper troposphere, which can be distinguished from synoptic-scale waves.

It should be noted that the term medium-scale waves has been used so far to refer to a few different scales of waves. Waves with a zonal wavelength of about 2000 km observed in the lower troposphere during midwinter in Japan (e.g., Nitta et al. 1973), and disturbances with horizontal scales of about 2000 km observed in the lower troposphere along the Baiu front (e.g., Matsumoto et al. 1970; Akiyama 1990) are called medium-scale waves. These medium-scale waves are discussed theoretically by Gambo (1970) and Tokioka (1970) in a framework of baroclinic instability of the atmosphere with small Richardson number. These medium-scale waves have horizontal scales similar to those examined in SEH93, but they can be distinguished from those by their dominant height region (around the tropopause for medium-scale waves in SEH93). Another usage of medium-scale waves refers to waves having zonal wave-numbers of 5–7, which are dominant in the Southern Hemisphere summer (e.g., Salby 1982; Randel and Stanford 1985; Hirooka et al. 1988).

As a subsequent work to SEH93, Hirota et al. (1995, hereafter HYS95) showed the existence of medium-scale waves similar to those of SEH93, based on the analysis of 6-hourly ECMWF operational data in the North Atlantic region in winter (January and February) of 1990. The vertical structure and relation to the background zonal flow are essentially the same as those shown by SEH93, suggesting that the waves are ubiquitous.

Yamamori et al. (1997, hereafter YSH97) indicated a few other important differences between the dynamical features of the medium-scale waves and synoptic-scale waves using data over one year (1985) at a time interval of 1 h from a regional climate (nested) model covering the region of east Asia to the mid-Pacific (see Sasaki et al. 1995). First, the seasonal variation of wave intensity is different: the medium-scale waves are most active in spring, while synoptic-scale waves are active in spring and autumn. Second, the medium-scale wave amplitudes are maximized around the tropopause and little signal is observed near the ground, while synoptic-scale waves have vertical structures extending in almost the entire troposphere. Third, phase velocities of the medium-scale waves near the tropopause are always faster than those of synoptic-scale waves during the year. YSH97 also indicated that the phase velocity of the medium-scale waves has an annual variation: the waves are faster in winter (~24 m s\(^{-1}\)) and slower in summer (~15 m s\(^{-1}\)) in association with the seasonal variation of subtropical jet strength. Note that their Figs. 2–4 show another clear example indicating coexistence of two kinds of waves, that is, synoptic-scale and medium-scale waves in a series of longitude–height sections of meridional winds.

The medium-scale waves around the midlatitude tropopause may be identical to short-wavelength troughs moving eastward in the upper levels in the troposphere, which can be precursor disturbances to the cyclogenesis (e.g., Palmén and Newton 1969; Bluestein 1993; Carlson 1991). The small-scale troughs are frequently referred to as short waves, so as to be distinguished from long (synoptic scale) waves. Sanders (1988) compiled the statistics of the mobile troughs in the Northern Hemisphere by subjectively tracking bends in 500-hPa 522-dam geopotential height contours. His study was refined recently by Lefevre and Nielsen-Gammon (1995) with an objective method applied to twice-daily National Meteorological Center (NMC, now known as the National Centers for Environmental Prediction) data over 20 yr. The lifespan was 5.3 days on the average and 44 days on the maximum. The typical wavelength and eastward phase speed are 2500 km and 15 m s\(^{-1}\), respectively. However, they traced movements of individual mobile troughs on synoptic maps and were not concerned much with whether those troughs have characteristics of “waves” as we analyzed.

Rivest et al. (1992) considered theoretically the dynamics of the short waves in the quasigeostrophic framework and showed that these waves are quasi modes that are basically equivalent to the neutral normal modes of the Eady problem that are trapped into the positively infinite meridional gradient of quasigeostrophic potential vorticity (QPV) at the tropopause.\(^1\) The upper edge modes are aligned vertically and have phase speeds greater than the unstable modes. These characteristics are similar to the medium-scale waves as examined by our previous studies. The intrinsic nature of the neutral normal mode is considered as a perturbed QPV at the tropopause due to north–south displacement of air parcels. Thus the mode exists at the tropopause even if the rigid lid of the Eady problem is replaced with the stratosphere and becomes a “quasi” mode in a system with nonzero meridional gradient of planetary vorticity \(\beta\), as shown by Rivest and Farrell (1992).

Sato, et al. (1998, hereafter SYM98) indicated that the meridional gradient of QPV is maximized around

\(^1\) The tropopause considered here is the level at which the static stability changes drastically between the troposphere and stratosphere as conventionally defined.
the tropopause at slightly higher latitudes than the jet stream core where the medium-scale waves have largest amplitudes. They examined trapped modes theoretically in the quasigeostrophic framework, similar to Rivest and Farrel (1992) and Rivest et al. (1992). The meridional gradient of the background QPV ($\overline{q}_y$) is composed of three terms:

$$\overline{q}_y = \beta - \overline{\pi}_y - \left( \frac{f_0}{N^2} \overline{\pi}_z \right),$$

where $\overline{u}$ is the background zonal wind, $f_0$ the Coriolis parameter, and $N$ the Brunt–Väisälä frequency. The three terms correspond to meridional gradients of the planetary vorticity, relative vorticity, and stretching vorticity, respectively (Holton 1992). The last term is further divided into two terms:

$$-\left( \frac{f_0}{N^2} \overline{\pi}_z \right) = -\left( \frac{f_0}{N^2} \overline{\pi}_{zz} - f_0 \overline{\pi}_z \overline{\pi}_y \right).$$

The tropopause level depends on latitude. In particular, the tropopause level changes drastically around the latitude of the westerly jet core to maintain the thermal wind balance. The tropopause is located at a height of about 17 km at lower latitudes and about 9 km at higher latitudes, which is higher and lower than the level of westerly jet core (about 11 km), respectively. Thus, the vertical shear of westerly wind is positive at the tropopause at higher latitudes, namely at the midlatitude tropopause. Therefore the second term of the meridional gradient of stretching vorticity in (2) is largely positive around the midlatitude tropopause where the vertical gradient of $N^{-2}$ is largely negative. By solving an eigenvalue problem for multilayer models with various basic state parameters, they showed that properties of trapped waves in realistic situations coincide well with observations.

Using observation data with fine vertical resolution from radiosondes and the MU radar, Yamamori and Sato (1998) examined preferable phases of synoptic-scale waves as the background of medium-scale waves. It was shown that the vertical gradient of the static stability around the tropopause is larger in ridge phases than in trough phases and that the medium-scale waves are more clearly observed in ridge phases. This result is consistent with the theory that a necessary condition for the existence of medium-scale waves is a large positive gradient of QPV, which is attributed to the large gradient of stretching vorticity.

In our previous studies, we used a time filter to extract medium-scale waves, although there are various methods to divide disturbances and the background field. Held (1999) gave a caution for the use of a time filter, giving an interesting example (Fig. 2 of his paper). He considered a simple vortex street, a double row of isolated vortices with the row of cyclones displaced northward from the row of anticyclones. If we take a time mean as a background field, the perturbation field has different phase structure from the vortex street. This is because the background is a zonal jet stream with non-zero vorticity, which is originally from a vortex street itself. So in this case, we fail to extract the vortex street as a disturbance using the time filter. However, it should be noted that this is also the case when we take a zonal mean as a background (namely, using a spatial filter). To extract the vortex street as a disturbance, we need to consider the background field with zero vorticity. This is possible when we take a time and meridional mean or a zonal and meridional mean, for example.

For the data analysis of phenomena in the real atmosphere, it is not self-evident which filter is the best to extract disturbances. All that we can show is how well the physics of the phenomena is described by applying the selected filter.

As described in detail above, we have shown in our previous studies that medium-scale waves with different characteristics from synoptic-scale waves exist in various regions and in seasons. The purpose of the present study to show how globally the medium-scale waves are distributed by analyzing 6-hourly ECMWF operational data over four years, from 1990 through 1993, in both the Northern Hemisphere (NH) and Southern Hemisphere (SH). Moreover, as also described, we considered the mechanism of the existence of medium-scale waves. The second purpose of the present study is to examine how well the background condition is consistent with the physics of the medium-scale waves, based on the data analysis.

A brief description of the data and method of analysis is given in section 2. Global characteristics of the medium-scale waves are shown in comparison with those of synoptic-scale waves in section 3. The background field of the medium-scale waves is examined in section 4. The results are discussed in section 5. Summary and concluding remarks are given in section 6.

2. Data and method of analysis

The data used are ECMWF operational data (ECMWF–Tropical Ocean Global Atmosphere upper-air analysis uninitialized data) with a time interval of 6 h (0000, 0600, 1200, and 1800 UTC). The data are distributed on a $2.5^\circ \times 2.5^\circ$ horizontal latitude and longitude mesh at pressure levels of 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, and 10 hPa. The dataset covers four years from 1 January 1990 through 31 December 1993, which is sufficient to examine overall characteristics of global distribution and seasonal variation of medium-scale waves.

The parameters characterizing medium-scale waves such as wave period and phase velocity are considered to be related to generation mechanisms and background fields. In fact, YSH97 showed that the phase velocity has a seasonal variation similar to that of the subtropical jet stream, as described in section 1. Thus the wave
3. Global characteristics of medium-scale waves

a. Hovmöller diagrams

Figure 2a shows the Hovmöller diagrams of the SW geopotential height component during 1990. The displayed component is an average for latitudes of 45°–55°N at the 300-hPa level in which the amplitudes are maximized, as shown in section 4. The latitudinal average makes the picture of medium-scale waves with nearly meridional phases more conspicuous, since amplitudes of the other phenomena with tilted phases are reduced. Eastward migrating waves are clearly observed at any longitude and in all seasons except summer. The thick solid and dashed lines indicate phase lines with phase velocities of 20 and 10 m s\(^{-1}\), respectively. Dominant phase velocities are close to 20 m s\(^{-1}\) and larger than typical phase speeds of 12–15 m s\(^{-1}\) for synoptic-scale waves in the NH (e.g., Wallace et al. 1988). Phase velocities seem small in summer when the background wind is weak. This result is consistent with previous studies of medium-scale waves (SEH93, HYS95, YSH97). Several phases can be traced over 180° of longitude in January and in November. The corresponding lifetime of the medium-scale waves is about 8 days.

Hovmöller diagrams for SW in the SH are shown in Fig. 2b. The latitudinal average was made for 50°–60°S where SW amplitudes are maximized (see section 4). The eastward migrating waves are also clearly seen in the SH and the amplitude is larger than in the NH. In particular, the wave amplitudes are large and wavy structure is clear in spring and autumn. The phase speeds are about 20 m s\(^{-1}\) and faster than phase speeds of synoptic-scale waves (~12 m s\(^{-1}\)) (e.g., Berbery and Vera 1996). The phases can be traced over a longer time period in the NH, and sometimes a phase travels around the globe more than once.

b. Zonal wavenumber spectra

Power spectra versus zonal wavenumber (k), \(P_s(k)\), were obtained for SW geopotential height components averaged over the same latitude range as Hovmöller diagrams for each month. An average of the power spectra over four years is shown as a function of month in an energy content form for the NH and SH in Figs. 3a and 3b, respectively. To see the seasonal variation clearly for both hemispheres, two cycles of the year are drawn.

Dominant zonal wavelengths are the medium scale, namely about 2500 km for the NH and 3000 km for the SH. Power spectra for LW components \(P_s(k)\) are shown in Figs. 3c and 3d for the NH and SH, respectively. Dominant wavelengths are about 3000–5000 km in both hemispheres.

In the NH, the zonal wavelength of the SW component is larger in winter and smaller in summer. The spectral amplitude is maximized in winter for \(P_s(k)\), while double peaks in autumn (Sep–Oct–Nov, SON)
FIG. 2. Hovmöller diagram of geopotential height components of medium-scale waves averaged for (a) latitudes of 45°–55°N and (b) 50°–60°S. Thick solid and dashed lines show phase speeds of 20 and 10 m s⁻¹, respectively.

and spring (Mar–Apr–May, MAM) are observed for $P_s(k)$. The SW spectra $P_s(k)$ in the SH are generally larger than in the NH. There is not so much annual variability in the SH. It is rather clear that spectral amplitudes in the SH are maximized twice a year in spring (SON) and in autumn (MAM), although the autumn peak is larger. There is seasonal variation in the zonal wavelength; that is, it is smaller in autumn than in spring. The spectra of $P_s(k)$ are also maximized twice a year.
However there are a few notable differences from $P_s(k)$: the difference in spectral amplitudes between spring and autumn peaks is small; the spring maximum appears about two months later (in Oct) than for $P_s(k)$ (in Aug); the seasonal variation of the zonal wavelength is more apparent.

c. Global distribution of wave intensity

In order to examine global distribution and seasonal variation of the intensity of medium-scale and synoptic-scale waves, the mean squares of the SW and LW geopotential height components were calculated for every
month, which are hereafter referred to as $P_s$ and $P_L$, respectively.

1) TIME–LATITUDE SECTIONS

The average over four years of the zonal mean $P_s$ at the 300-hPa level for each month is shown as a contour map in the time–latitude section of Fig. 4a. Thick solid curves are contours of 30 and 40 m s$^{-1}$ of the zonal mean of horizontal wind speed ($\sqrt{U^2 + V^2}$, where $U$ and $V$ are mean zonal and meridional wind components, respectively) at 200 hPa, indicating the latitudinal position of jet stream axis. The average over the whole year is shown with a thin curve for $P_s$ and a thick curve for the horizontal wind speed as a function of latitude on the right. In general, the wave intensity is maximized in the latitudinal region of 40°–70° in both hemispheres. The latitudinal distribution of $P_s$ in the NH is broader, having a peak at lower latitude than in the SH. This is the basis of latitudinal bands chosen for Hovmöller diagrams and zonal wavenumber spectra shown in sections 3a and 3b.

The latitude with large $P_s$ values varies annually in the NH and semiannually in the SH. The dominant latitude for the NH is slightly higher in late summer and lower from winter to spring, while the dominant latitude for the SH is higher around the equinox and lower around the solstice. Thus, there is a marked contrast between the NH and SH in that the dominant latitude is lower (higher) when $P_s$ is maximized in the NH (SH).
The subtropical jet is situated around the latitude of 30° in both hemispheres, and a double jet structure is seen in the spring in the SH. Of the double jets, the higher-latitude one is called the polar-front jet stream. The peak latitude of \( P_s \) in the Southern Hemisphere seems to correspond roughly to the polar-front jet axis. The relative location of the jet and large \( P_s \) region as a function of longitude will be discussed in detail later.

Figure 4b shows a time–latitude section of zonally averaged \( P_L \). It is noted that the density of contours in Fig. 4b is almost the same as in Fig. 4a, although the contour intervals are 10 times as large as those for \( P_s \). This means that LW amplitude is about three times as large as that of SW. Overall characteristics seen in seasonal variation and latitudinal distribution of \( P_L \) are similar to those of \( P_s \). For example, the equatorward shift in summer and winter in the SH is seen also for \( P_L \) as indicated by a comprehensive work of storm tracks in the SH by Trenberth (1991).

2) Time–Longitude sections

Longitudinal distribution of \( P_s \) and \( P_L \) in each hemisphere is shown in Fig. 5, where \( P_s \) and \( P_L \) are averaged over a latitude range of 30°–70° and over four years at each month. The average over the whole period is shown on the right of each figure.

For \( P_s \), the wave intensity is strong over the Pacific (about 150°E to 120°W, hereafter referred to as NP), over the Atlantic to Europe (about 90°W to 50°E, hereafter NA) in the NH (Fig. 5a), and over the Indian Ocean (about 10°–120°E, hereafter SI) in the SH (Fig. 5b).

Although \( P_s \) values in the two regions in the NH are maximized in the time period from autumn to spring,
the seasonal variation seems slightly different. An isolated peak is seen twice a year in late autumn and spring in NP, while a broad peak is centered in winter in NA.

On the other hand, $P_s$ in the SH has one maximum longitudinally in SI, and hence the characteristics there reflect seasonal variation of the zonal mean wave intensity in the SH as shown in Figs. 3 and 4.

The longitudinal distribution of $P_L$ (Figs. 5c and 5d) is fundamentally similar to that of $P_s$; areas having large values are NP, NA, and SI which are called storm tracks. A notable difference in the longitudinal distribution between $P_s$ and $P_L$ is that large $P_s$ spreads eastward more than $P_L$ in any region. The difference between $P_s$ and $P_L$ in each of NP and NA is also worth noting. There are two maxima in autumn to spring in NA for $P_L$ while only one maximum is seen for $P_s$. In NP, two maxima are observed for $P_s$ as for $P_L$ but with a difference in the timing. The first maximum is observed in December for $P_s$ but in November for $P_L$. The midwinter minimum is seen in February for $P_s$ but in January for $P_L$. The second maximum is in March for both $P_s$ and $P_L$. Thus the time interval between the two maxima in the time period from autumn to spring is longer for $P_L$ than for $P_s$. The existence of a midwinter minimum for $P_L$ is indicated by Nakamura (1992).

Next, to see year-to-year variation, time–longitude sections of $P_s$ over the four years are shown in Fig. 6. The characteristics of $P_s$ and $P_L$ described above for the 4-yr average are commonly observed for each year, although intensity and longitudinal distribution are slightly dependent on the year. First, large $P_s$ is observed in NP, NA, and SI in any year. Second, the two separated maxima in winter and in spring in NP are seen in any year. Third, the winter maximum in NA is separated into two in some years, but the time interval between the two maxima is small compared with that in NP.
Spectral characteristics and latitudinal distribution seen in the 4-yr average in Figs. 3 and 4 are also commonly observed in each year.

3) POLAR STEREO PROJECTION MAPS IN ACTIVE SEASONS

To see detailed distributions of $P_s$ and jet stream strength, polar stereo projection maps are shown. Figures 7a, 7b, and 7c are for the winter (Dec–Jan–Feb, DJF) of the NH, when $P_s$ is maximized in NA and NP, for the spring (MAM) of the NH having large $P_s$ values in NP, and for the autumn (MAM) of the SH when $P_s$ is maximized in SI, respectively. Thick curves show the seasonal mean of horizontal wind speed at 200 hPa as an indicator of jet streams.

There are several common characteristics seen in areas having large $P_s$ values in Fig. 7. First, the large $P_s$ areas are located downstream of the jet. It is worth noting here that the longitudes where $P_s$ is dominant in NP are shifted westward by 15° from winter to spring, although the jet stream does not move significantly. Thus the longitudes of the maximized $P_s$ region and the jet stream are particularly apart in the winter in the NP region. Second, in NA and SI where subtropical and polar-front jet streams exist at separated latitudes, $P_s$ is large only around the latitude of the polar-front jet. Third, the large $P_s$ regions are located at slightly higher latitudes by about 5° of the jet stream axis, which is consistent with the previous studies (SEH93, HYS95, YSH97). It should be noted that this relative location is not clear in the latitudinal distribution of the zonal mean $P_s$ and the zonal mean horizontal wind speed that is shown in Fig. 4.

Polar stereo maps are also shown for $P_L$ in Fig. 8. Observed distribution of $P_L$ is similar to its climatology shown by Nakamura (1992) for the NH. Latitudinal distribution of $P_L$ is similar to $P_s$ in the sense that large $P_L$ values are observed at latitudes higher than the jet stream by several degrees. However, there is a significant difference in longitudinal distribution between $P_s$ and $P_L$. Most $P_s$ maxima in NP, NA, and SI are located...
downstream of the $P_s$ maxima. An extreme is seen in NP in the winter (DJF) of the NH.

4. Background atmosphere of medium-scale waves

In this section, we make a statistical analysis using the ECMWF data over the four years at all levels, in order to confirm that the characteristics of the background field of medium-scale waves indicated by previous papers of SEH93, HYS95, and YSH97 are common. Monthly mean $P_s$ and background fields are examined for each latitude–height section where the $P_s$ maximum takes a value greater than 400 m$^2$.

Figure 9 shows histograms of pressure level ($p$), potential temperature ($\theta$), Ertel’s potential vorticity (EPV), horizontal wind ($|V| = \sqrt{U^2 + V^2}$), and the vertical shear ($U_z$) in which $P_s$ is maximized in the latitude–height section at each longitude for (a) the NH and (b) the SH. Only cases having $P_s$ maximum greater than 400 m$^2$ are included for statistical significance.
FIG. 10. Scatter diagrams of $P_S$ (upper panels) and $P_L$ (lower panels) vs horizontal wind speed in regions of (a) North Pacific (120°E–120°W), (b) North Atlantic (90°W–30°E), (c) south Indian Ocean, and (d) North Pacific (130°–170°E). Open squares, closed squares, crosses, and closed circles denote winter (DJF for the NH and JJA for the SH), spring (MAM for the NH and SON for the SH), summer (JJA for the NH and DJF for the SH), and autumn (SON for the NH and MAM for the SH) cases, respectively.

shear of zonal wind ($U_z$) at the latitude and longitude of $P_S$ maximum. Results are shown separately for the NH and SH.

The mode of the pressure level is 300 hPa, which is the reason why the 300-hPa level was chosen for global distribution analysis in previous sections.

The potential temperature and EPV are invariant for Lagrangian motions in adiabatic and frictionless flow. The medium-scale waves are dominant in the region with potential temperature of 315–320 K and EPV of 1–3 PVU (potential vorticity units, $10^{-6}$ km$^2$ kg$^{-1}$ s$^{-1}$) in the NH and −3 to −1 PVU in the SH. Since the levels having absolute values of 1–3 PVU roughly correspond to the tropopause (Hoskins et al. 1985), this result indicates that the medium-scale waves in both hemispheres exist around the tropopause.

As for the background wind condition, the magnitude of mean horizontal flow preferred by the medium-scale waves is in a wide range of 20–40 m s$^{-1}$. It is worth noting that the preferred vertical shear of the mean flow is mostly positive. This means that the tropopause where the medium-scale waves are dominant is on the poleward side of the jet stream core, as explained in section 1.

Scatter diagrams to show the relation of $P_S$ and $P_L$ to the background horizontal wind are given in Fig. 10. The averages for NP, NA, and SI are shown in Figs. 10a, 10b, and 10c, respectively. The result for the same longitudinal area in NP as examined by Nakamura (1992) for $P_L$ is also shown in Fig. 10d. Open squares, closed squares, crosses, and closed circles denote winter [DJF for the NH and Jun–Jul–Aug (JJA) for the SH], spring (MAM for the NH and SON for the SH), summer (JJA for the NH and DJF for the SH), and autumn (SON for the NH and MAM for the SH) cases, respectively.

Nakamura showed that the correlation between $P_L$ and background horizontal winds is positive for winds smaller than 45 m s$^{-1}$ and negative for larger winds. Thus, in winter when the horizontal wind is strongest, $P_L$ becomes smaller. Such a tendency is seen also in our analysis (Figs. 10a and 10d for $P_L$), although the threshold value of horizontal wind for positive and negative correlation areas is small ($\sim$35 m s$^{-1}$) compared with Nakamura’s result ($\sim$45 m s$^{-1}$). However, this tendency is not clear for $P_S$. The distribution for NP is rather linear (Figs. 10a and 10d). It is also worth noting that the preferred horizontal wind for $P_S$ is weaker than that for $P_L$, particularly in winter. Wind speeds and wave intensity in NA (Fig. 10b) are also positively correlated.

The reduced wave intensity in winter (open squares in Fig. 10c) is also observed in SI for both $P_S$ and $P_L$, but the situation is different from that of NP, because the background horizontal wind is also weak in winter in SI. As shown by van Loon (1967), the polar-front jet in the SH is maximized twice in a year, namely, in spring and autumn, when $P_S$ and $P_L$ are maximized. However, the positive correlation for $P_S$ is not clear in SI compared
with NP and NA. This is because, in SI, $P_s$ values are larger in autumn than in spring, although the horizontal wind magnitudes are almost the same. On the other hand, weak positive correlation is seen for $P_L$, which has comparable maxima in autumn and spring. The preference of weaker wind speed for $P_s$ compared with $P_L$ can also be seen in SI.

5. Discussion

a. The trapping of medium-scale waves in the midlatitude tropopause

The medium-scale waves as examined in previous studies have amplitudes maximized around the tropopause on the poleward side of jet streams (SEH93, HYS95). The amplitudes become halved at 700 hPa and little signal of medium-scale waves is seen at the surface (YSH97). The structure is almost barotropic. A possible maintenance mechanism of medium-scale waves having such characteristics is that the medium-scale waves are trapped into a localized large positive peak of horizontal (mostly meridional) gradient of QPV around the mid-latitude tropopause (Rivest et al. 1992; Rivest and Farrell 1992; SYM98). According to the theory, the modes trapped in the peaky QPV gradient have a different dispersion relation than Rossby waves in a flow having a uniform QPV gradient.

SYM98 suggested that the localized positive peak of the QPV gradient could be attributed to a term of large gradient of stretching vorticity, that is, $f \frac{\partial \mathbf{u}}{\partial \mathbf{z}} (1/N^2)$, around the tropopause on the poleward side of the jet stream, as explained in section 1. The results of preferable background fields for the medium-scale waves obtained in this study are consistent with this theory: that is, the medium-scale waves are dominant at the tropopause (EPV of 1–3 PVUs) where $u_z$ is positive (Fig. 9).

A typical example showing that medium-scale waves are trapped into such a large gradient of potential vorticity is presented in Fig. 11. The top, middle, and bottom panels of Fig. 11 show polar stereo maps of the SW geopotential height component, unfiltered EPV, and EPV having periods longer than 2 days, respectively. All maps are drawn on the same potential temperature ($\theta$) surface of 315 K, where the medium-scale waves are dominant. The regions where EPV values are in the range of 1–3 PVUs corresponding to the tropopause are darkly shaded. Note that when quasigeostrophic scaling holds, the horizontal gradient of QPV on the $z$ surface and that of EPV on the $\theta$ surface are proportional (Charney and Stern 1962). According to theoretical interpretation by SYM98, in this case, it is rather better to say that since the 315-K potential temperature surface and the tropopause surface cross at a midlatitude in the meridional cross section (e.g., Fig. 9.1 of Andrews et al. 1987), the large vertical gradient of EPV around the

![Fig. 11. Polar maps at 315 K at 0000 UTC 29 Jan 1990 in the NH for (a) short-period component of geopotential height, (b) unfiltered ErTEL's potential vorticity, and (c) long period (>2 days) component of EPV. Small and large dashed circles show latitudes of 60° and 30°N, respectively. Contour intervals are 20 m for (a) and 1.5 PVU for (b) and (c), respectively. Regions having EPV in the range of 1.5–3 PVUs are hatched.](image-url)
midlatitude tropopause is seen as a large meridional gradient of EPV on this \( \theta \) surface.

Compared with the top and bottom panels of Fig. 11, we can see about three wavelengths of medium-scale waves along the tropopausal region from 35°N, 170°E–40°N, and 100°W having dense EPV contours. It should be noted here that the large EPV horizontal gradient is localized vertically as well as horizontally around the midlatitude tropopause. Therefore the midlatitude tropopause on the poleward side of the jet stream is a duct in both vertical and horizontal directions for medium-scale waves.

The unfiltered EPV map in the middle panel of Fig. 11 shows that the medium-scale waves make the tropopause meander. This meandering feature around the tropopause is not seen in the filtered EPV map in the bottom panel of Fig. 11. The horizontal displacement of the tropopause due to the medium-scale waves amounts to about 1000 km in the horizontal. This wavy structure of the tropopause continues over four days, and the phase velocity is about 22 m s\(^{-1}\) (not shown). Although this example gives one of the clearest cases having large amplitudes (see Fig. 2), the observed horizontal displacement suggests the possible contribution of medium-scale waves to the mixing of substances across the midlatitude tropopause.

6. Summary and concluding remarks

Global distribution and seasonal variation of medium-scale (2000–3000 km) wave activity at 300 hPa were investigated by using 6-hourly ECMWF operational data over four years of 1990–93. The mean square of geopotential height fluctuations was used as an index of wave intensity. There characteristics were compared with those of synoptic-scale waves. The medium-scale waves and synoptic-scale waves were defined as fluctuations with wave periods shorter than 42 h and 2–6 days, respectively. Results are summarized as follows.

1) The medium-scale waves exist in the latitudinal band of 40°–70° in the SH as well as in the NH.
2) A typical zonal phase velocity of the medium-scale waves is about 20 m s\(^{-1}\), although it depends on latitudes and regions. The phase velocity is faster than that of synoptic-scale waves. Dominant zonal wavelengths are 2500 km for the NH and 3000 km for the SH.
3) An equatorward shift of the dominant region of medium-scale waves is observed twice a year in summer and in winter in the SH when the polar-front jet is weak, while the equatorward shift is observed only in winter to spring in the NH when the subtropical and polar-front jets are strong.
4) The medium-scale waves are dominant in three regions, the North Atlantic, North Pacific, and south Indian Oceans, where a strong jet stream (the polar-front jet for NA and SI, and the subtropical jet for NP) is situated.
5) The medium-scale wave intensity is strong from autumn to spring in NA and NP, although the detailed seasonal variation is different. The maximum of the wave intensity is observed in midwinter in NA. A weak minimum in late winter is observed in NP. There are two separated maxima in autumn and spring in SI, and the autumn maximum dominates the spring one.
6) The medium-scale waves are dominant at latitudes slightly higher than the jet stream core by several degrees and on the downstream side of the jet.
7) The overall features of the medium-scale waves in terms of dominant regions and seasonal variation are similar to those of synoptic-scale waves, though...
some notable differences are seen. An important difference is that the medium-scale waves are dominant in the regions slightly more downstream of the strong westerly jet compared with the synoptic-scale waves.

Further analysis was made statistically to examine characteristics of the background atmosphere using data at all pressure levels from 1000 to 10 hPa. The medium-scale waves are dominant at the pressure level of 300 hPa, the potential temperature level of about 315 K, and the location where the background horizontal winds are in a range of 20–40 m s⁻¹. Preferred EPV of 1–3 PVUs and positive vertical shear of the background horizontal wind indicate that the medium-scale waves exist around the midlatitude tropopause on the poleward side of the jet stream. This result supports the theory by SYM98 that the medium-scale waves are trapped into the midlatitude tropopause where the meridional gradient of QPV is maximized. In fact, the medium-scale waves were observed as meandering tropopause on the map of EPV on the surface of θ = 315 K.

However, there are several remaining issues that should be investigated. One is the generation mechanism of the medium-scale waves. Judging from the longitudinal difference between dominant regions of SW and LW, synoptic-scale waves may contribute to the generation of medium-scale waves. Another issue is why the medium-scale waves have large amplitudes only near the polar-front jet but not near the subtropical jet in NA and SI. Detailed difference in the atmospheric structure and disturbances between these two kinds of jet stream should be examined. Moreover, the time filter used in this study may not distinguish medium-scale waves from the other phenomena such as streamers for which nonlinear processes are important (Appenzeller et al. 1996) and relatively small-scale baroclinic waves, which are dominant in NA (Ayrault et al. 1995). It is important to study further details on the relation between medium-scale waves and these phenomena having similar temporal and spatial scales.

Acknowledgments. The authors thank the editor, J. R. Gyakum, and anonymous reviewers for their critical reading of the manuscript and valuable comments. Thanks are also due to M. P. Lelong for her suggestions to improve the English expression of the original manuscript. The data used in this study were provided by ECMWF. This study was supported by Grant-in-Aid for Scientific Research (A)(2)08404026 of the Ministry of Education, Science and Culture, Japan.

REFERENCES


