Climatology of Mesoscale Warm and Cold Fronts in the Kanto Plain

by

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Abstract

A statistical analysis is made of mesoscale warm fronts (MWFs) and mesoscale cold fronts (MCFs) in the Kanto plain by using hourly surface data covering eleven years. A series of objective criteria are used to select 190 MWFs and 177 MCFs, and composite analyses are made of their local structure, seasonal and diurnal variabilities, and the larger-scale environment.

MWFs are associated with southeast-southwest winds or northwest winds blowing against a shallow cold-air pool having a depth of a few hundred meters. The MWF associated with southeast-southwest winds corresponds to the warm-air intrusion during the passage of a cyclone, while the MWF associated with northwest winds corresponds to a strong northwesterly surge. The frequency of MWFs is highest between 06 and 12 JST.

The MCF generally occurs during a cold-air surge. From late autumn to winter, the MCF is mainly associated with northwest winds accompanied by shallow cold air in its leading edge, and is more frequent in the nighttime than in the daytime. From spring to summer, MCFs associated with northeast or east winds are more frequent than those associated with northwest winds, and have a strong tendency to occur in the afternoon.

1. Introduction

In this article we define the mesoscale front (MF) as a transition zone of wind and temperature having a width of a few tens of kilometers or less. The semi-geostrophic theory (e.g. Hoskins and Bretherton, 1972) predicts that a synoptic-scale front can be contracted into a MF as documented in a number of observational studies (Ogura and Portis, 1982; Shapiro, 1984; Bond and Fleagle, 1985). However, many MFs in a region of complex terrain may reflect the effect of topography also. A locally intensified front has

been found to form due to differential surface heating across a coastline (Bosart, 1975; Nielsen, 1989; Nielsen and Neilley, 1990; Physick, 1988; Garratt *et al.*, 1989) and/or dynamical effects of orography (Colquhoun *et al.*, 1985; Hoinka *et al.*, 1990; Hartjenstein and Egger, 1990). As a result the climatology of MFs is expected to show regional characteristics according to the topographic environment.

The Kanto plain is bounded by the Pacific Ocean on the east and south and by the Central Mountains on the northwest (Fig. 1). A large number of publications have been issued on the local wind systems in this region. Under weak gradient winds and fair weather, the surface wind fields are characterized by diurnal varia-

Fig. 1 (a) Topography of central Honshu. Areas above 150m, 300m, 600m and 1200m are hatched with increasing tones. (b) Topography of the region bounded by dotted lines in (a). The stations used for the analysis of Figs. 4 and 15 are shown in large “+” symbols, and those used for the analysis of Fig. 6 are shown in “x” symbols. The stations presented in the time sections in Figs. 5 and 16 are shown with dots. Other AMeDAS stations used for our analysis are shown with small “+” symbols. The site of the Meteorological Research Institute and the Aerological Observatory of Tateno is denoted by “△”. Mt. Tsukuba is denoted by “☆”.

tion related to the thermal high and low over the Central Mountains (Kimura, 1985; Kondo, 1990) and the land/sea breeze in coastal regions (Fujibe and Asai, 1984; Nakane and Sasano, 1986). Under strong pressure gradient, surface winds exhibit complicated patterns (Kawamura, 1977) associated with a number of convergence lines (Yoshino, 1975; Nomoto, 1975). However, wind fields in the presence of synoptic-scale disturbances have remained much less investigated except for a number of studies on cold fronts (Sugiura, 1974; Sakakibara, 1983; Yamamoto, 1984; Fujibe, 1991) and coastal fronts (Fujibe, 1990a, b).

In this article we aim at documenting the collective features of MFs in the Kanto plain by using the hourly data from the AMeDAS (Automated Meteorological Data Acquisition System) network. In view of the limitation in the resolution and reliability of the data, we

restrict our analysis to intense, traveling MFs detected from an abrupt change in wind and temperature. Such MFs are naturally classified into warm and cold fronts. Hereafter we call them “mesoscale warm fronts (MWFs)” and “mesoscale cold fronts (MCFs)”, respectively. We make composite analyses in search of their local structure, seasonal and diurnal variabilities, and relationship to the larger-scale fields.

2. Data and procedure of analysis

2.1 Data

The AMeDAS network covers the Kanto plain with resolution of ~ 20 km (Fig. 1b). Hourly data of wind direction, wind speed, temperature, duration of sunshine and precipitation are recorded at units of 16 points of the compass, 1 m s^{-1} , 0.1°C , 0.1 hour and 1 mm, respectively. Our analysis is made for the

period 1979–1989. Temperature is adjusted to the sea level with a lapse rate of 5°Ckm^{-1} .

At the meteorological tower of the Meteorological Research Institute (MRI; Δ in Fig. 1b, 24.5m above the mean sea level), wind and temperature are observed at levels of 10, 25, 50, 100, 150, 200 and 213m above the ground. Hourly data are available on a data file for 1979–1986.

At the Aerological Observatory of Tateno, which is close to the MRI, upper-level sounding is made every six hours for wind and twice daily for temperature and humidity.

2.2 Selection of MWFs and MCFs

Detection of MFs is made by using a simple algorithm which seeks for a line of wind and temperature change associated with inflow from outside the plain. The condition of inflow is defined on the basis of the wind data at four stations on the periphery of the plain (Choshi, Tateyama, Maebashi and Mito; CH, TA, MA and MI in Fig. 1b) in the following manner:

- (a) The wind direction at Choshi is between ENE and SW with wind speed of 5ms^{-1} or more (in this article the range of wind direction is indicated clockwise, so that “between ENE and SW” means the range from ENE through SE to SW).
- (b) The wind direction at Tateyama is between E and WSW with wind speed of 5ms^{-1} or more.
- (c) The wind direction at Maebashi is between WSW and NNE with wind speed of 3ms^{-1} or more.
- (d) The wind direction at Mito is between NNW and ESE with wind speed of 3ms^{-1} or more.

For the period in which any one of (a)–(d) is satisfied, time changes of temperature and wind are examined for 47 stations in the main part of the plain with altitudes below 150m (shown by dots or “+” and “×” symbols in Fig. 1b). For temperature, the departure from the average for the 47 stations is used in order to eliminate the effect of diurnal temperature variation. A frontal passage at a station requires that the

following conditions be satisfied:

- (e) The departure temperature changes by at least 1.5°C in an hour.
- (f) Either the wind direction changes by at least 90° , or the wind speed increases by at least 3ms^{-1} in the same hour.
- (g) The wind direction just after the change is within 45° of that at any one of the upwind stations which satisfy (a)–(d).
- (h) From subjective judgment, the changes (e)–(g) can be recognized as a frontal passage.

If frontal passage is detected at eight stations or more, and can be traced as a propagating line, then the case is selected as representing a MF. A MF associated with temperature rise is defined as a MWF and one associated with temperature drop is defined as a MCF.

This algorithm includes rather severe requirements satisfied by intense MFs only, so that it excludes weak MFs which are difficult to distinguish without a higher degree of subjectivity.

3. Results

3.1 MWFs

(a) Classification

The number of MWFs selected for our analysis is 190. Fig. 2 shows the histogram of the postfrontal wind direction, which is obtained by vector-averaging the winds just after the frontal passage at stations where the front passage is detected. Each graph is stratified with the six-hour precipitation averaged for these stations with the front passage time as the center of the six-hour period. MWFs are separated into two groups with wind directions 90° – 240° and 270° – 360° . We separate the former group into W_{SE} and W_{SW} fronts corresponding to wind directions 90° – 180° and 180° – 240° , respectively. The front associated with winds from 270° – 360° is named the W_{NW} front. The numbers of W_{SE} , W_{SW} and W_{NW} fronts are 20, 114 and 56, respectively.

The classification based on the wind direction alone may not reflect the variable

Fig. 2 Histogram of the postfrontal wind direction (degrees) for MWFs stratified according to the six-hour precipitation amount.

features of MFs. However, more detailed classification calls for more subjective judgment. It is not our purpose to enter into such details at the cost of objectivity, but rather to pick up the representative features common to many cases.

Fig. 3 shows the relation between the postfrontal wind direction and the prefrontal wind direction, namely the wind direction just before the frontal passage. The W_{SE} front tends to be associated with north or northeast wind, while the W_{SW} front can be associated with winds from any direction. The W_{NW} front is typically associated with west or northwest winds, so that its passage results in increase of wind speed with little change in wind direction (as shown later in Figs. 5 and 26).

Table 1 shows the duration of each type of front. More than half of the fronts vanish

Fig. 3 Relation of the postfrontal wind direction and the prefrontal wind direction for MWFs.

Table 1 Duration of each type of MWF: number of cases for each duration range and mean duration.

Type	Total	≤ 6	7-9	10-12	13-18	< 18 (hours)	Mean (hours)
W_{SE}	20	5	6	5	3	1	10.3
W_{SW}	114	30	41	24	16	3	9.3
W_{NW}	56	23	22	7	4	0	7.5

within 9 hours, but some of the W_{SE}/W_{SW} fronts last more than 12 hours. These long-lasting fronts move very slowly against the cold air in the inland region.

(b) Local structure

Fig. 4 shows the composite surface field for the three types of MWF. Each composite field shows the surface field just after the front passage at Tokyo (TO in Fig. 1b). Fig. 5 shows the time-distance section along one of the three lines (YO-CH, MA-KA and UT-TA) shown in Fig. 1b. These composite analyses are made for the cases in which the front passage is detected at any one of the nine stations in the vicinity of Tokyo (denoted by large "+" symbols in Fig.

Fig. 4 Composite field of wind, temperature and precipitation intensity for MWFs just after the front passage at Tokyo. Full barbs indicate 2ms^{-1} and pennants 10ms^{-1} , and circles indicate calm ($<0.5\text{ms}^{-1}$). Temperature is shown by subtracting the spatial average, and isotherms are drawn with 1°C intervals with dashed lines for negative values. The regions with precipitation intensity greater than 9.1, 0.25, 1 and 4mmh^{-1} are hatched with increasing tones.

Fig. 5 Composite time section of wind, temperature and precipitation intensity along the lines shown in Fig. 4 (see Fig. 1b for the location of intermediate stations). The time of reference (0 hour) is the time of front passage at Tokyo. Symbols are the same as used in Fig. 4. Temperature is shown by subtracting the spatial average at the time of reference.

1b). The front passage time at Tokyo is obtained by fitting the front passage time at stations where a front passage is detected by using the least-square method.

The W_{SE} front forms in the northeast-southwest direction associated with southeast winds blowing from the Pacific, and moves toward the northwest. Precipitation of 1mm/(6h) or more is observed except for four cases. There is a slight indication of heavier precipitation in the inland region than in the coastal region.

The W_{SW} front lies in the east-west direction with southwest winds on its south. The calm state on its north is the result of averaging many cases with variable wind directions (Fig. 3). Precipitation is much less frequent than in the case of the W_{SE} front ($\geq 1\text{mm}/(6\text{h})$ in 22 out of 114 cases). In fact, the frequency of precipitation decreases as the postfrontal wind direction turns from east to southwest as seen from Fig. 2.

The W_{NW} front is accompanied by north-west winds blowing from the northwestern part of the plain. The structure of the front is not clearly seen in Figs. 4 and 5; in fact this type of front is usually most conspicuous in the north-western part of the plain and tends to become less obvious as it moves southeast (e.g. Fig. 26b). Precipitation is rare during the passage of the front ($\geq 1\text{mm}/(6\text{h})$ in 3 out of 56 cases).

Fig. 6 shows the vertical time section at the MRI tower and the AMeDAS station of Mt.

Tsukuba ($\star$ in Fig. 1b, 868m above the mean sea level) for the period 1979-1986. This analysis is made for the cases in which the front passage is detected at any one of the six surrounding stations denoted by " $\times$ " in Fig. 1b. Before the front passage, there is a cold-air pool below the height of a few hundred meters, above which the wind direction agrees with the postfrontal wind direction. After the front passage, the cold-air pool disappears and the wind direction becomes nearly uniform throughout the boundary layer.

In the following analysis (Figs. 7-12 except Fig. 9) we represent the front passage time by the average for the stations where a front passage is detected. Fig. 7 shows the relation of the postfrontal wind direction and the 850hPa wind direction at Tateno stratified according to the 850hPa wind speed. Among six-hourly data of the 850hPa wind, those at the observation time nearest the front passage time are shown. The postfrontal wind direction roughly agrees with the 850hPa wind direction with wind speed exceeding 10ms^{-1} in most cases. These facts indicate that the MWF is the boundary of a deep layer of strong wind and a shallow cold-air pool.

(c) Seasonal and diurnal variations

Fig. 8 shows the season-time of the day diagram for each type of MWF. Stratification with precipitation amount is made in the same way as in Fig. 2. The W_{SE} front is observed

Fig. 6 Composite vertical time section of wind and potential temperature ($T + \Gamma_d z$; Γ_d is the dry adiabatic lapse rate) at the MRI tower and Mt. Tsukuba (MT). The time of reference is the front passage time at the MRI. Symbols are the same as those used in Fig. 4. Potential temperature is shown by subtracting the spatial average temperature at surface at the time of reference.

mainly in spring and autumn. The W_{SE} fronts in spring accompany extratropical cyclones, while six out of the seven cases between June and October accompany tropical cyclones. The W_{SW} front can be observed in any season, but is more frequent from late autumn to early spring

(91 out of 114 cases are observed during the six months November–April). The W_{NW} front is most frequent in cold seasons (37 out of 56 cases are observed during the four months December–March).

The mean location of the W_{SW} front varies according to seasons. Fig. 9 shows the composite time section for the W_{SW} front for October–January and April–August. For October–January, the front moves from the south coast to the central part of the plain with the northern region dominated by cold air. For April–August, the southern part of the plain is dominated by southwest winds from the beginning, and the front moves northward from the central part of the plain. However, there appears to be no essential difference in the vertical structure of the front (not shown).

We can also observe in Fig. 8 that the frequency of the W_{SW} and the W_{NW} fronts has a distinct maximum between 06 and 12 JST (65 out of 114 W_{SW} cases and 23 out of 56 W_{NW} cases), although the small number of W_{SW} cases with substantial precipitation ($\geq 1\text{mm}/(6\text{h})$) show little diurnal variation. The four W_{SE} fronts with precipitation less than $1\text{mm}/(6\text{h})$ are also clustered in this time of the day. Thus the MWF is generally most frequently observed between 06 and 12 JST if precipitation is weak or absent.

Fig. 7 Relation between the postfrontal wind direction and the 850hPa wind direction at Tateno stratified according to the 850hPa wind speed.

Fig. 8 Scatter diagram for the seasonal and diurnal distribution of MWFs. Data are stratified with six-hour precipitation amount, and also with the mean latitude of the front for the W_{SW} and W_{NW} fronts.

Fig. 9 Same as Fig. 5 but for the W_{sw} front in October-January and April-August.

Fig. 10 Histograms of the 850hPa wind speed for each type of MWF stratified according to the front passage time.

Fig. 10 shows the histogram of the 850hPa wind speed stratified according to the front passage time. Ranks of lower wind speed include 06-12 JST cases at a higher percentage. For example, out of 48 W_{sw} fronts which occur when the 850hPa wind is weaker than 15ms^{-1} , 41 cases occur during 06-12JST. This indicates that the threshold wind speed for the occurrence of the MWF is lower in late morning than in other time of the day.

(d) Larger-scale fields and parameters

Fig. 11 shows the composite pressure field based on six-hourly data of sea-level pressure at observatories of the Japan Meteorological

Agency (JMA). Data at the observation time nearest the front passage time are used in constructing the composite field. The W_{se} front occurs to the east of a cyclone embedded in a north-south oriented trough over western Honshu. The W_{sw} front occurs to the south of a low, which is typically located over the Sea of Japan (e.g. Fig. 26). In both cases, the cold air in the inland Kanto plain is isolated in the field of widespread warming which is shown by hatching. In the case of the W_{se} front the region of cold air corresponds to a pressure ridge extending southwestward from a high located to the east of Honshu, while in the case of the W_{sw} front a pressure ridge extends

northeastward from a high located to the south of Honshu. Since the pressure excess in the northwestern part of the Kanto plain is ~ 0.5 hPa and the inland-coast temperature difference is a few degrees, the depth of the cold air can be estimated to be several hundred meters, in rough agreement with the result in Fig. 6.

The W_{NW} front corresponds to a strong northwesterly wind surge accompanied by widespread cooling. The warm frontal character is therefore a local feature in the field of cold-air advection. In fact, the surface temperature over the Kanto plain begins to drop a few

hours after the passage of the W_{NW} front (Fig. 5).

Fig. 12 shows the time series of several parameters at surface and the 850hPa level. The average front passage time is used as the time of reference (0 hour). The surface temperature and precipitation amount are obtained by averaging the data at 47 stations in the Kanto plain. The cloud amount is obtained from the three-hourly observation data at Tokyo. The 850hPa temperature and equivalent potential temperature (θ_e) are obtained from the half-daily sounding at Tatenos. These are used after

Fig. 11 Composite field of sea-level pressure and surface wind. Wind is shown in the same manner as in Fig. 4. Pressure is shown by subtracting the spatial average for the region, and isobars are drawn at 1hPa intervals with dashed lines for negative values. The regions in which temperature has risen by 1°C and 3°C during the previous 24 hours are hatched with increasing tones.

Fig. 12 Composite time series of surface and 850hPa parameters for MWFs. Arrows indicate the 850hPa wind with full barbs for 5ms^{-1} . Temperature (T_{surface} and T_{850}) and equivalent potential temperature (θ_{e850}) are shown by subtracting the 48-hour averages at the 850hPa level.

interpolating hourly values by using the cubic spline functions of Akima (1970). The W_{SE} front is associated with strong south winds and warming at the 850hPa level, where temperature becomes highest about 9 hours after the occurrence of the front. The W_{SW} front occurs in the later stage of warm-air intrusion associated with southwest winds at the 850hPa level. On the other hand, the W_{NW} front occurs simultaneously with the beginning of the temperature drop and the onset of the northwest wind at the 850hPa level. The opposite temperature change between surface and the 850hPa level confirms that the warm frontal character results from the transition of the boundary-layer structure.

3.2 MCFs

(a) Classification

The number of MCFs is 177. Fig. 13 shows the distribution of the postfrontal wind directions. MCFs correspond to wind directions between 255° and 135° except for three cases. We define C_{NW} , C_{NE} and C_E fronts corresponding to wind directions 255° – 15° , 15° – 75° and 75° – 135° with 97, 53 and 24 cases, respectively. Precipitation of 1mm/(6h) or more is observed in nearly half of the cases (39/97) of the C_{NW} front but is less frequent as the wind direction turns toward the east (8/53 for the C_{NE} front and 1/24 for the C_E front).

Fig. 14 shows the relation between the postfrontal wind direction and the prefrontal wind direction. The C_{NW} front is mostly associated with southwest winds. The C_{NE} front also tends to be associated with southwest winds, although there is considerable scatter in the prefrontal wind direction. The C_E front tends to be associated with northerly winds.

Table 2 shows the duration of each type of MCF. In comparison to the MWF, the MCF tends to be short-lived. In particular, more than half of the C_{NW} fronts (59/97) disappear within 6 hours.

(b) Local structure

Fig. 15 shows the composite surface field for the three types of MCF at the front passage time at Tokyo. Fig. 16 shows the time-distance

Fig. 13 Same as Fig. 2 but for MCFs.

Fig. 14 Same as Fig. 3 but for MCFs.

Table 2 Same as Table 1 but for the MCF.

Type	Total	≤6	7-9	10-12	13-18	<18 (hours)	Mean (hours)
				(number of fronts)			(hours)
C _{NW}	97	59	27	6	5	0	6.5
C _{NE}	53	15	26	10	2	0	7.8
C _E	24	7	14	3	0	0	7.3

section along one of the three lines (CH-YO, KA-MA and TA-UT) shown in Fig. 1b. The C_{NW} front is located in the northeast-southwest or east-west direction, while the C_{NE} front is located in the east-west or southeast-northwest direction. The C_E front is directed in the north-south direction and moves westward.

Fig. 15 Same as Fig. 4 but for MCFs.

Fig. 16 Same as Fig. 5 but for MCFs.

In order to evaluate the vertical structure of the front, we compare the postfrontal wind direction and the wind direction at the 850hPa level at Tateno. Fig. 17 shows their relation stratified according to the 850hPa wind speed. Considering the possibility of a time lag in the front passage at upper levels, the 850hPa wind data 12 hours after the surface front passage are shown. For the C_{NW} front, the 850hPa wind direction is mostly from the west or north with wind speeds exceeding 10ms^{-1} in nearly half of the cases (43/92). For the C_{NE}/C_E front, the 850hPa wind is weaker than 10ms^{-1} in most cases (39/52 and 21/24, respectively) and tends to blow from the westerly direction. This indicates that the C_{NW} front tends to be associated with a deep and strong northwesterly surge, while the C_{NE}/C_E front tends to be associated with a shallow northeast-east wind with its top lower than the 850hPa level.

Fig. 18 shows the vertical sounding at Tateno at 21 JST for six cases in which C_{NW} and C_E fronts occurred in the afternoon. For C_{NW} fronts, the top of the northwest wind is typically around the 800hPa level. The northwest wind layer is slightly more stable than the layer

Fig. 17 Relation between the postfrontal wind direction and the 850hPa wind direction 12 hours after the front passage stratified according to the 850hPa wind speed.

Fig. 18 Vertical sounding at 21 JST for six cases of the C_{NW} (upper) and C_E (lower) fronts.

above, but the frontal inversion is not obvious. In comparison, the top of the east wind associated with the C_E front is between the 950hPa and the 900hPa level, and is often capped by a well-defined inversion layer. The shallow cold air surmounted by inversion is the general feature of the C_{NE} front also (not shown).

(c) *Seasonal and diurnal variations*

Fig. 19 shows the season-time of the day diagram of each type of MCF. The C_{NW} front is observed in any season although rare in summer, while the diurnal variability and the position of the front show considerable seasonal differences. From late autumn to winter, the C_{NW} front is more frequent in the nighttime than in the daytime and is mostly observed in the southern part of the plain. In spring and summer, the C_{NW} front is most frequent in the afternoon and is mainly observed in the northern plain. For example, out of the 41 cases in the four months October–January, 25 occur in 18–06 JST and 34 occur south of the 35.8°N line, while out of the 29 cases in the five months April–August, 20 occur in 12–18 JST and 20 occur north of the 35.8°N line.

Fig. 20 shows the composite surface and vertical time sections for the C_{NW} front for October–January and April–August. In October–January the C_{NW} front typically moves from

the central part of the plain to the south coast with the northern part of the plain covered by cold air all the time. The cold air is very shallow (~ 200 m) for a few hours after the frontal passage, although it soon becomes deep as observed from the onset of the northwest wind at Mt. Tsukuba. Aside from the direction of the movement, the spatial structure of the leading edge of the front is similar to that of the W_{SW} front. Precipitation is relatively infrequent (13 out of 41 cases) and does not well correspond to the position of the front. On the other hand, the C_{NW} front in April–August arrives from the northwest corner of the plain accompanied by cold air deeper than Mt. Tsukuba. Precipitation is more frequent (15 out of 29 cases) than in October–January and roughly corresponds to the front.

The C_{NE} and C_E front shows a strong tendency to occur from spring to summer and between 12 and 18 JST. Of the 53 cases of the C_{NE} front, 35 occur between 12 and 18 JST. The C_E front is restricted to the seven months from March to September, and 21 out of 24 cases occur between 12 and 18 JST.

(d) *Larger-scale fields and parameters*

Fig. 21 shows the sea-level pressure field around central Honshu. The higher pressure toward the northwest is common to the three types of front. Thus the MCF generally occurs

Fig. 19 Same as Fig. 8 but for MCFs. Stratification with latitude is made only for the C_{NW} front.

Fig. 20 Same as Figs. 5 and 6 but for the C_{NW} front in October-January and April-August.

Fig. 21 Same as Fig. 11 but for MCFs. Hatching indicates the area in which temperature has dropped during the preceding 24 hours, with double hatching for a drop of more than 2°C .

in the situation of a cold-air surge. The pressure gradient is strongest for the C_{NW} front and weakest for the C_E front, although slightly weaker than in the case of the W_{NW} front even for the C_{NW} front. The direction of the geostrophic wind has a larger easterly component in the case of the C_{NE}/C_E front than for the C_{NW} front, but nevertheless the wind direction in most regions of Honshu is northwest or north. In other words, the easterly wind associated with the C_{NE}/C_E front is a local feature corresponding to the mesolow to the west of the plain.

In view of the strong diurnal variation in the frequency of the C_{NE}/C_E front, it is worth examining whether the mesolow is observed irrespective of the time of the day or only in the

afternoon. Fig. 22 shows the pressure field at 03 and 15 JST for the C_{NE} front which occurred during 00–06 JST and 12–18 JST, respectively. A mesolow exists to the west of the Kanto plain in both cases, and also in other time of the day (06–12 JST and 18–24 JST) not shown here. Therefore diurnal heating is not necessary, although may be favorable, for the formation of the mesolow.

Fig. 23 shows the time series of surface and 850hPa parameters. The C_{NW} front coincides with the beginning of the temperature drop at the 850hPa level, while the occurrence of the C_{NE} and C_E fronts delays the beginning of the 850hPa temperature drop by 6–12 hours and 12–18 hours, respectively. According to surface weather maps, most C_{NW} fronts agree with the

Fig. 22 Sea-level pressure field at 03 and 15 JST for the C_{NE} front which occurred during 00–06 JST and 12–18 JST, respectively.

Fig. 23 Same as Fig. 12 but for the MCF.

Fig. 24 Composite field of cloud amount (%) and wind every six hours before and after the occurrence of the C_E front. Contour intervals are 5%, and dashed lines indicate values less than 60%. The meaning of the hatching is the same as in Fig. 21.

passage of a synoptic-scale cold front or a secondary meso- α -scale trough, while most C_E fronts occur well north of a synoptic-scale cold front drawn in weather maps. The C_{NE} front sometimes corresponds to the passage of a synoptic-scale cold front oriented in the east-west direction, and sometimes occurs more than a few hours after the cold frontal passage.

The C_{NW} front coincides with the time of maximum precipitation, and is followed by a decrease in cloud amount. In contrast, the C_E front tends to occur under fair weather followed by an increase in cloud amount. Fig. 24 shows the distribution of cloud amount every six hours before and after the C_E front passage. Before the passage of the front, the Kanto plain is a region of localized low cloudiness (<50%) with temperature higher than the climatic normal. On the average for the 23 cases of the C_E front (except for a case in the nighttime), the daily maximum temperature at Tokyo is higher than the climatological normal by 2.4°C. After the passage of the C_E front, the Kanto plain becomes a region of high cloudiness (>70%) which is sometimes accompanied by weak but continuous precipitation (Fig. 23). This is a type of the "northeasterly cloudy weather" notorious among the forecasters.

The cloudiness after the passage of the C_E front corresponds to low stratus over the inversion layer above the easterly wind (Fig. 18). For the six cases shown in Fig. 18, the average low cloud amount (Nh in the weather

report) is 6/8, and the cloud base is below 1km except for the case on 10 March 1985. The top of the cloud layer is usually low, as suggested from the low humidity above the 700hPa level.

Fig. 25 shows an example of the C_E front on 11 April 1987. At 09 JST 11 April, the synoptic-scale cold front had already moved to the east of Honshu, and the Kanto plain was dominated by northwest winds. The 850hPa temperature at Tateno had dropped by 5°C after 21 JST 10 April. However, surface temperatures in the Kanto plain remained high until the arrival of the C_E front in the afternoon. This was followed by increase in low clouds and weak rain, which lasted throughout 12 April.

3.3 Combination of fronts

More than one MF often occurs in sequence during the passage of a synoptic-scale cyclone. We define "sequential fronts" as those in which the latter front begins within 12 hours of the ending of the former. If two fronts coexist for three hours or more, we call them "simultaneous fronts".

The combination of fronts can be classified into following types, where the symbols " $\rightarrow$ " and "+" indicate sequential and simultaneous fronts, respectively:

- (a) Warm southerly $\rightarrow$ cold northerly (39 cases)
 - $W_{SW} \rightarrow C_{NW}$ (30 cases)
 - $W_{SE} \rightarrow C_{NW}$ (3 cases)

Fig. 25 (a) Surface pressure map (hPa) at 09 JST 11 April 1987. The position of the synoptic-scale front at 21 JST is shown by a dashed line. (b) Surface wind and temperature (°C) at 15 JST 11 April. (c) Time section of surface wind and temperature (°C) on the YO-CH line. Symbols in (b) and (c) are the same as in Fig. 4, but hatching indicates the region with precipitation intensity exceeding 0.25mmh^{-1} .

- $W_{SW} \rightarrow C_{NE}$ (6 cases)
 (b) Warm southerly $\rightarrow$ warm northerly (17 cases)
 $W_{SW} \rightarrow W_{NW}$ (15 cases)
 $W_{SE} \rightarrow W_{NW}$ (2 cases)
 (c) Warm northerly and cold northerly (17 cases)
 $W_{NW} + C_{NW}$ (11 cases)
 $W_{NW} \rightarrow C_{NW}$ (1 case)
- $C_{NW} \rightarrow W_{NW}$ (5 cases)
 (d) Others (6 cases)
 $W_{SW} \rightarrow W_{SW}$; $W_{SE} + W_{SW}$; $W_{SW} + C_{NW}$; $W_{NW} \rightarrow C_{E}$; $C_{NW} + C_{NE}$; $C_{NE} + C_{NE}$ (each 1 case)

The number of fronts involved in these relationships is 128. Among them, 122 occurred between October and April and account for 44% of the total MFs during these seven

months. The three-front combination of (a), (b) and (c) is found in ten cases. If we allow for weak MFs which have been omitted by our algorithm (Section 2.2), the number of combined fronts becomes still larger.

It can be seen from Figs. 9a and 20a that the W_{SE} and C_{NW} fronts typically occur in sequence during a temporal intrusion of warm air from the south coast. Thus the combination (a) is usually associated with the movement of a single MF. On the other hand, each of the combinations (b) and (c) involves two MFs, one in the southern Kanto plain and the other in the northern plain with a region of trapped cold air in between. It is interesting that the sequential relationship of $W_{NW} \rightarrow C_{NW}$ is rare (only one case) in (c). In fact, the time of the onset of the W_{NW} front is later than that of the C_{NW} front in 14 cases out of the 17 cases in (c). In other words, the warm air begins to retreat from the southern plain before being swept away by the strong northwest winds.

Fig. 26 shows an example of W_{SW} , C_{NW} and W_{NW} fronts on 30–31 December 1985. As a cyclone passed the Sea of Japan, warm air spread over the southern Kanto plain accompanied by a W_{SW} front, and went back in the form of a C_{NW} front on the morning of 31 December (Fig. 26c). The northern part of the plain remained covered by cold air until a surge of strong northwest winds on the morning of 31 December. This was accompanied by a temperature rise, namely a passage of a W_{NW} front. From 06 to 09 JST 31 December, the C_{NW} and W_{NW} fronts coexisted with the region of cold air trapped between them (Fig. 26b). The vertical section (Fig. 26d) indicates that this cold air was only about 100m deep. At Mt. Tsukuba (not shown), the wind changed from southwest to northwest at around 09 JST 31 December with a temperature drop of $\sim 2^\circ\text{C}$. This seems to correspond to the passage of the synoptic-scale cold front, but there was no other remarkable change in wind and temperature. Therefore the complicated behavior of MFs was essentially a boundary-layer feature related to the shallow cold air.

4. Discussion

4.1 MWFs

The MWF is characterized by shallow cold air corresponding to a localized airmass. Fujibe (1990b) statistically verified the presence of a cold-air pool in the inland region during a cyclone passage in the cold season. This explains the higher ratio of the number of MWFs to that of MCFs in comparison to other regions in middle latitudes, where cold fronts are a few times more frequent than warm fronts (e.g. Hoinka, 1985).

The structure of the W_{SE}/W_{SW} front satisfies the definition of a coastal front, which is defined as a MF between maritime air and a colder airmass trapped inland (Nielsen, 1989). Fujibe (1990a) showed that the coastal front in the Kanto plain tends to move inland under strong onshore winds. This is nothing other than the W_{SE}/W_{SW} front described in this paper. Nielsen (1989) attributed the formation of coastal fronts to the land-sea differential heating and/or the orographic blocking of low-level air, while Bell and Bosart (1989) emphasized the activity of large-scale tropospheric disturbances during the generation of intense coastal fronts. In our analysis, the W_{SE}/W_{SW} front occurs during the temperature rise at the 850hPa level, which implies the presence of the synoptic-scale frontal zone in a wide sense. Therefore both topography and large-scale baroclinicity are likely to contribute to the generation of a strong MWF.

It may be recommended to distinguish between MWFs associated with synoptic-scale fronts and those having a more localized character. By examining individual cases, we in fact find some MWFs coinciding with synoptic-scale warm fronts in surface weather maps, although many others occur well apart from synoptic-scale fronts. Even in the former cases, however, the MWFs are substantially sharper than a typical warm front in middle latitudes, suggesting the importance of topographic effects in sharpening a front locally. Moreover, the warming at the 850hPa level is observed in many cases of MWFs irrespective of the position of the synoptic-scale fronts. Thus it is

Fig. 26 (a) Surface weather map at 21 JST 30 December 1985. The positions of the synoptic-scale front at 09 JST on 30 and 31 December are shown by dashed lines. (b) Surface wind and temperature at 06 JST 31 December. (c) Time section on the MA-KA line. (d) Vertical time section of wind and potential temperature at the MRI tower.

not practical to classify these MFs into local fronts and synoptic-scale fronts, although there can be differences in the relative contributions of local and large-scale factors.

As for diurnal variation, Fujibe (1990a) showed that the coastal front in the non-rainy case tends to shift inland in the daytime. This corresponds to the maximum frequency of MWFs in 06–12 JST. There can be two ways in which daytime heating causes the front to move inland. In the first place, the warming of the cold-air pool will destroy the stable stratification which has prevented the strong low-level wind to reach the ground. In the second place, the warming over the land will increase the landward pressure gradient force. At present it is not certain which effect is the more important. Apart from the mechanism, the daytime inland movement of the W_{SE} / W_{SW} front may be mistaken for a sea-breeze front unless the temperature field is carefully analyzed.

The W_{NW} front occurs in the field of a strong cold-air surge. The temperature rise is associated with the destruction of the surface cold-air pool and is confined within the lowest few hundred meters. A similar phenomenon is found in southern Germany when a cold-air pool is destroyed at the passage of a cold front (Hoinka *et al.*, 1990). The frequent occurrence of the W_{NW} front in the northern Kanto plain may be due to the adiabatic warming as the northwest wind blows down the Central Mountains, namely a foehn effect.

4.2 MCFs

The MCFs generally occur during the northwesterly cold-air surge in the synoptic field. However, the features of fronts differ considerably among the cases, especially according to seasons.

From late autumn to winter, the C_{NW} front typically corresponds to the retreating stage of the W_{SW} or W_{SE} front which has penetrated into the plain. On one hand the retreat coincides with the change in the synoptic-scale pressure field at the passage of a cold front, while on the other hand it is related to the diurnal cycle characterized by the development of the cold-air pool in the nighttime. The cold air is very

shallow (100–200m) before the arrival of deep cold air (Figs. 20 and 26).

In comparison, the C_{NW} front in spring and summer better fits the classical picture of the cold front with respect to the deep cold air at the leading edge and the precipitation in the postfrontal region (Figs. 18 and 20). This type of front is most frequent in the afternoon. This may be a general feature of cold fronts over the land, since Hoinka (1985) also showed that the cold frontal passage in southern Germany is about twice as frequent in the daytime (07–17 LST) as in the nighttime. A possible reason for the afternoon maximum is the unstable stratification of the daytime boundary layer, in which surface parameters are more sensitive to the transition in the free atmosphere than in the nocturnal boundary layer (Sturman *et al.*, 1990). Another possible reason is the generation of convective precipitation which results in a sharp cold frontal head due to evaporative cooling. In fact, some MCFs in spring and summer are associated with heavy thunderstorms accompanied by strong gust fronts and/or downbursts (e.g. Tabata *et al.*, 1991).

In spring and summer, however, cold air arrives in the Kanto plain more often from the northeast or east than from the northwest. This may partly be attributable to the large-scale environment in the warm season, in which cold air tends to arrive from the cold maritime region northeast of Honshu. However, Fig. 21 reveals that the easterly wind accompanying a C_{NW} / C_E front is a local feature in the Kanto plain. It is likely that the Central Mountains block the shallow cold air arriving from the northwest and deflect it around their northern corner.

Northeasterly cold fronts are frequently observed in regions east of mountain ranges with shallow (1–2km) cold air as the common feature (Bosart *et al.*, 1973; Colquhoun *et al.*, 1985; Howells and Kuo, 1988; Sturman *et al.*, 1990; Triet *et al.*, 1990; Chen and Hui, 1990; Smith *et al.*, 1991). According to Bosart *et al.* (1973), the “back-door front” east of the Appalachians is mainly encountered in the warm season (most frequent in June) and often breaks the heat wave in the eastern states, but

is rarely accompanied by heavy precipitation. This description applies to the C_{NE}/C_E front quite well. The C_{NE} front and the C_E front have many common features, although the former tends to be more closely related to the synoptic-scale cold front, while the latter tends to have the character of a local front in the post-cold-frontal region. As seen from Fig. 25, the northwesterly foehn in the lee of the Central Mountains may contribute to the high temperature before the arrival of a C_E front. This situation is like the case of the Colorado "upslope cold front" (Young and Johnson, 1984; Boatman and Reinking, 1984), which moves westward against the west wind in the lee of the Front Range of the Rockies.

The C_{NE}/C_E front occurs predominantly in the afternoon under relatively fair weather associated with inland penetration of shallow, cool maritime air. In this respect it may look like a sea-breeze front. However, it has a number of features deviating from a typical sea-breeze front. In the first place, the easterly wind continues until midnight or even until the next day in some cases, resulting in a temperature fall on the synoptic time scale. In the case shown in Fig. 25, the daily maximum temperature at Tokyo was 19.6°C on 11 April, but it dropped to 9.0°C on 12 April. On the average for the 23 C_E fronts, the daily maximum temperature at Tokyo drops by 5.4°C the next day. In the second place, the easterly wind is often colder than the sea surface near the Kanto plain. According to the "Ten-day marine report" published by the JMA, the sea surface temperature along the east coast of the plain was 8–12°C in the first twenty days of April 1987. This was a few degrees higher than the air temperature after the midnight of 11 April, when the temperature was higher in the coastal region than in the inland region (Fig. 25c). This indicates that the sea surface was a heat source, which is the situation just opposite to the sea breeze. It is also to be noted that some C_{NE}/C_E fronts occur in the nighttime, although rarer than in the afternoon.

Therefore the C_{NE}/C_E front should be regarded as associated with the intrusion of a large-scale cold air mass originating from a

substantially high latitude, although the role of diurnal heating seems to be important as a trigger to the inland penetration of the cold air. Fujibe (1991) documented some remarkable examples of diurnal modulation on the movement of cold fronts. In one of his cases, a cold front displayed an oscillatory movement in central Honshu, resulting in repeated C_{NE} frontal passages on the afternoons of the two successive days (3–4 September 1984). Physick (1988) made a numerical experiment on the effect of the daytime thermal contrast across a coastline in enhancing and accelerating a cold frontal system. Our analysis suggests the importance of a similar effect from a statistical viewpoint.

We find from these considerations that we have failed to detect typical sea-breeze fronts. This is because the sea-breeze front is weaker and more localized than is resolved by the hourly AMeDAS data. For example, Gamo (1991) showed that a sea-breeze front is rarely accompanied by a drop but only by a "leveling off" in the hourly time series of temperature. On the other hand, Ishikawa *et al.* (1986) detected many wind shift lines by using a dense anemometer network developed in the eastern Kanto plain, including sea-breeze fronts coming from the east coast. These appear to be MFs of smaller scales than is described in this paper, but we have little knowledge of the general features of MFs on this scale.

5. Summary

The features of the MWFs and MCFs described in this paper are summarized in Table 3. These MFs occur during the passage of synoptic-scale disturbances, and in this sense they are related to the large-scale frontal zone. However, they are more or less influenced by various mesoscale processes including

- (1) the shallow cold-air pool in the field of warm-air advection,
- (2) the northwesterly foehn in the lee of the Central Mountains,
- (3) deflection of cold air around the northern corner of the Central Mountains, and
- (4) diurnal heating and cooling of the land.

Table 3

Type	Wind direction	Number of cases	Preferred season	Preferred time of the day	Typical depth of the cold air	Synoptic condition
W _{SE}	90-180°	20	Spring and autumn	(06-12 JST)	A few hundred meters	East of a cyclone
W _{SW}	180-240°	114	Autumn-spring	06-12 JST	A few hundred meters	Warm sector
W _{NW}	270-360°	56	Winter	06-12 JST	A few hundred meters	Cold-air outbreak
C _{NW}	255- 15°	97	Autumn-spring	\$	A few kilometers #	Cold-air outbreak
C _{NE}	15- 75°	53	Spring-summer	12-18 JST	~1km	Weak cold-air outbreak
C _E	75-135°	24	Spring-summer	12-18 JST	~1km	Weak cold-air outbreak

\$ Nighttime in late autumn-winter; 12-18 JST in spring-summer.

In late autumn-winter, a few hundred meters at the leading edge.

These processes are typically related to the features of

- (1) the three types of MWFs and part of the C_{NW} front,
 - (2) the W_{NW} front and the prefrontal condition of the C_E front,
 - (3) the C_{NE} and the C_E front, and
 - (4) all types of fronts,
- respectively. Naturally these are only the rough outlines of MFs which involve all kinds of variabilities among the cases.

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関東平野に現れるメソ温暖・寒冷前線の気候学

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11年間のアメダス資料を使って、関東平野に現れるメソ温暖前線とメソ寒冷前線の統計的な調査をした。ここで言うメソ前線とは幅 20~30 km 以下の気温・風の急変線のことであり、その基準としては、1 時間に 1.5°C 以上の気温変化を伴う風向・風速の変化が 8 地点以上に現れることを条件とした。この条件を満たす 190 例のメソ温暖前線と 177 例のメソ寒冷前線を対象として、発現頻度や形態の季節変化・日変化、総観場との対応関係を調べた。

メソ温暖前線は低気圧前面の南東風、暖域の南西風あるいは寒気吹き出し時の北西風に伴って現れ、これらが平野部に存在する薄い(数百 m 以下)冷氣層を侵食していく形態をとる。南東風前線は主に春の温帯低気圧と秋の台風の時に現れ、降水を伴うことが多い。南西風前線は 1 年を通じて現れるが秋~春に多く、秋~冬は主に南関東に、春~夏は北関東に現れる。北西風前線は 12~3 月に多く、平野北西部から強い北西風が吹き出してくる時に現れる。降水がある場合を除き、メソ温暖前線は 6~12 時に最も頻度が高い。

メソ寒冷前線は一般に寒気吹き出し時に現れるが、北西風以外に北東~東風に伴うものもある。北西風前線は厚い(~2 km)寒気を伴っているが、晩秋~冬にはメソ温暖前線として北上してきたものが寒冷前線となって南下していくことが多く、(1)先端部では寒気がごく薄い(~200 m)、(2)夜に多い、という特徴がある。一方、春~夏の北西風前線は午後に現れる傾向がある。しかし、春~夏にはむしろ北東~東風前線が平野北東部から侵入してくることが多く、これら(特に東風前線)は(1)総観規模前線の通過から数時間~半日程度遅れて現れる、(2)寒気の厚さは 1 km 程度で、しばしば下層雲伴う、(3)午後に侵入することが圧倒的に多い、などの特徴を持っている。

これらのメソ前線は低気圧通過前後の暖気・寒気侵入に付随して現れるもので、この意味では前線帯内の現象であるが、天気図に描かれた前線と 1:1 に対応するとは限らず、一般的には基本場の傾圧性と地形効果との複合によってできると考えられる。