On Fronts in Central Europe

K. P. Hoinka

Institute of Atmospheric Physics, German Aerospace Research Establishment (DFVLR), D-8031 Oberpfaffenhofen, Federal Republic of Germany

(Manuscript received 21.02.1985, in revised form 22.08.1985)

Abstract:

In this study a classification of cold and warm fronts occurring in central Europe based on synoptic conditions is presented. A 'southwesterly' type, a 'westerly' type and a 'northwesterly' type of fronts are related to characteristic mesoscale weather close to the Alps.

Using a ten-year time-series of fronts at a single station (Munich) close to the Alps, it is observed that cold fronts occur on an average of 54 days per year while warm fronts occur on 19 days per year. The number of cold fronts per month is about the same for all seasons. The number of warm fronts has a summer minimum. The seasonal ratios of cold fronts to warm fronts is about five to one in summer and two to one in winter. The precipitation linked with cold fronts is estimated to be about 40 % of the annual precipitation rate, supplemented by 10 % connected with warm fronts.

Averaged pre- and postfrontal profiles of temperature and mixing ratio based on rawinsonde observations show only for the cold-frontal event significant differences in the lower troposphere. With the passage of a cold front the temperature decreases by about 4 °C and the dewpoint temperature decreases by about 3 °C. The fall in height of the tropopause is about 1000 m.

Zusammenfassung: Über Fronten in Mitteleuropa

In der vorliegenden Arbeit wird eine Klassifikation von Fronten über Mitteleuropa vorgestellt, die auf den synoptischen Bedingungen der Großwetterlage beruht. Dabei werden Fronten vom 'Südwest', 'West' und 'Nordwest' Typ unterschieden und das dabei auftretende mesoskalige Wettergeschehen, beeinflußt von den Alpen, beschrieben.

Ausgehend von einer Zehnjahres-Periode von Frontenbeobachtungen in München, wird eine Klimatologie von Fronten erstellt, mit dem Ergebnis, daß an 54 (19) Tagen pro Jahr Kaltfronten (Warmfronten) auftraten. Die Anzahl der Kaltfronten pro Monat ist zu allen Jahreszeiten ungefähr gleich, während sich für Warmfronten im Sommer ein Minimum zeigt. Im Sommer gibt es fünfmal soviel Kaltfronten wie Warmfronten, während im Winter das Verhältnis zwei zu eins ist. Der Niederschlag an Kaltfronten beträgt 40 % des jährlichen Niederschlages, ergänzt durch 10 % Niederschlag an Warmfronten.

Gemittelte prä- und postfrontale Profile der Temperatur und des Mischungsverhältnisses zeigen, daß nur bei Kaltfronten signifikante Unterschiede in der unteren Troposphäre festzustellen sind. Zwischen dem präfrontalen und dem postfrontalen Zustand nimmt die Temperatur ungefähr um 4 °C und der Taupunkt um 3 °C ab. Die Höhe der Tropopause sinkt bei Durchzug einer Kaltfront um 1000 m.

Résumé: Au sujet des fronts en Europe Centrale

On présente une classification des fronts froids et chauds d'Europe Centrale en fonction des conditions synoptiques. On distingue les types «Sud-Ouest», «Ouest» et «Nord-Ouest», ainsi que les types de temps caractéristiques de mésoéchelle qui leur sont associés à proximité des Alpes.

En utilisant dix années d'observations des fronts en une seule station (Munich) voisine des Alpes, on observe que les fronts froids se produisent, en moyenne, 54 jours par an contre 19 pour les fronts chauds. Le nombre

0005-8173/85/04 0560–12 $ 03.00/0

mensuel de fronts froids est à peu près le même, quelle que soit la saison. Le nombre de fronts chauds est minimum en été. Le rapport saisonnier des fronts froids aux fronts chauds est de cinq à un en été et de deux à un en hiver. On estime que les précipitations associées aux fronts froids représentent environ 40 % des précipitations annuelles auxquels s'ajoutent 10 % pour les fronts chauds. Les profils moyens de température et les rapports de mélange obtenus par radiosondages avant et après le passage des fronts ne montrent des différences significatives que pour les fronts froids dans la basse troposphère. Lors du passage d'un front froid, la température diminue d'environ 4 °C et la température du point de rosée d'environ 3 °C. L'affaissement de la tropopause est de l'ordre de 1000 m.

1 Introduction

Because of their importance in producing significant weather, atmospheric fronts have been studied extensively. In the definition of that what is meant by fronts diverging ideas exist between practizing forecasters, fluid dynamicists and dynamical meteorologists. In the original polar-front theory, fronts were described as layers separating air masses of different origins (PALMEN and NEWTON, 1969). These layers are characterized by a narrow zone of large temperature gradient, a shift in wind direction and a kink in the isobars (PETTERSSEN, 1958). Fluid dynamicists often consider fronts as a transition zone between two fluids of different densities (SIMPSON, 1969). However, surface fronts are never real discontinuities in the temperature and thus in the pressure gradient field. For the definition of a surface front we might choose the position of the maximum of the horizontal gradient of potential temperature, or that of vorticity or even that of the convergence of wind. We call the zone in the trough including all three maxima frontal "transition zone". This frontal zone corresponds with what the analysts define as a front. The zone extends about 200 km wide or two hours in time scale. The beginning of it is not easy to find, its end, however, is clearly defined when the pressure starts to steadily increase.

Most work deals with fronts over the sea or over flat terrain and sometimes with a transition from sea to land. However, the impact of orography on fronts has received much less attention. Fronts from the Pacific which enter North America in the winter tend to weaken as they cross the Rocky Mountains, but many redevelop to the east of the mountain range. The southerly buster is a particularly abrupt form of a cold front which occurs frequently in the coastal region of southeast Australia. Observational evidence indicates that it is associated with the deformation of a cold front caused by its interaction with the coastal mountains. In southern Germany north of the Alps, eastwards moving fronts are deformed, retarded or even diminished in intensity by the Alps.

In the early twenties PEPPLER (1925) was the first to emphazise the particular characteristics of cold fronts in southern Germany. STEINACKER (1982) has shown one example of a front which was deformed by the Alps. Very recently DAVIES (1984) has shown by an analytical model that the speed of a cold front is decreased at the windward side of a barrier and increased at the lee side. However, our knowledge of the structure of cold fronts which are modified by the Alps in southern Germany is limited. The speed of the fronts, their spatial characteristics, as well as the frontal circulation and its associated precipitation are not well known. In the near future it is necessary to perform field experiments to study fronts in the vicinity of the Alps. As a preliminary step towards a detailed study of the fronts in central Europe it is necessary to consider the importance of frontal weather on the climate of this region.

Recently, FRAEDRICH et al. (1985) presented a statistical analysis of frontal events for Berlin, which is located about 700 km north of the Alps. ERIKSON (1963) documents summer and winter averages of frontal events over Hamburg, which is located about 200 km west of Berlin. Another relevant statistical analysis (FLOCAS, 1984) shows the annual frequency of fronts over southern Europe and the Mediterranean Sea, including the area north of the Alps. It shows an increase of about 50 % of frontal occurrence going from north-west France to Hungaria. This result is not convincing because most fronts enter Europe from west to north-west and therefore, the number of fronts should decrease eastwards. The last two studies exhibit the basic problems in evaluating statistics of frontal events. They are, to a certain degree, subjective, depending on the definition of frontal features and depending on the regional interest of the weather services. Therefore, we carry out a statistical analysis of frontal events at Munich, located about 100 km north of the baseline of the Alps. The analysis has been done to provide statistical material for further research.

At first we present in this paper a classification of cold and warm fronts which occur in this area. This classification is based on the synoptic environment in which these fronts occur. We describe qualitatively the different front types and its associated synoptic-scale weather as well as the meso-scale weather linked with the front itself.

In the next section we study the yearly, seasonal and monthly occurrence of fronts in southern Germany, based on a ten-year record between 1968 and 1977, and investigate their contribution to the total precipitation. A classification of rainfall is usually based on its formation: orographic, cyclonic (or frontal) or convective; all three classes occur in southern Germany. In the present study the proportion of frontal rainfall is determined for Munich, for the above period.

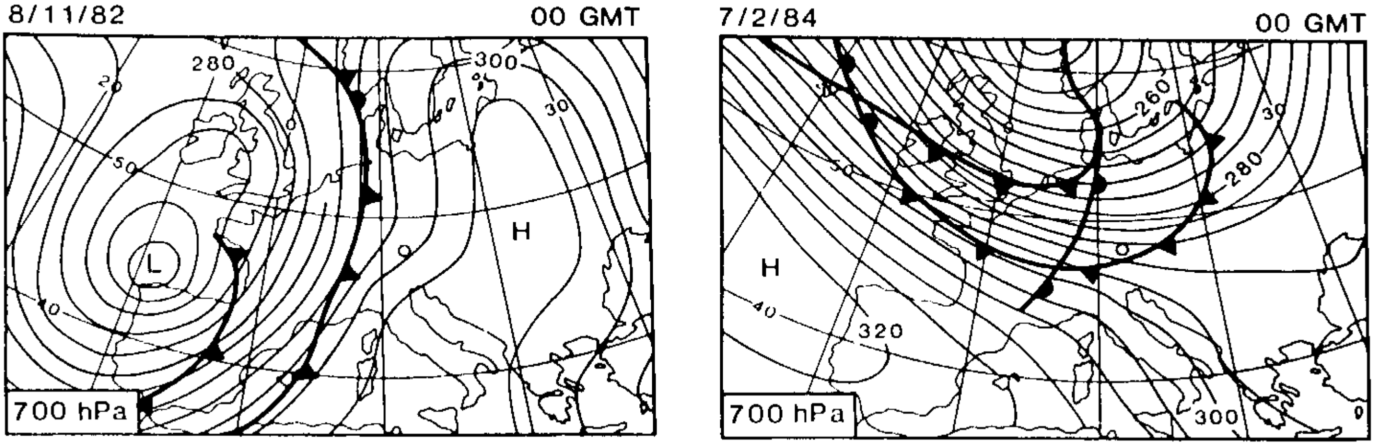
Finally, statistics of the prefrontal and postfrontal troposphere above Munich are evaluated. This analysis is based on rawinsonde observations taken between 1974 and 1977. Surface measurements provided by the German Weather Service are used to complete the statistical analysis. The analysis of the occurrence of fronts, the associated precipitation and the statistical analysis have shortcomings as they are based on the records of ten years or less – a very small statistical sample. However, at present no studies describe the statistical features of fronts influenced by the Alps in central Europe.

2 Synoptic Classification

The cold fronts occurring in the northern vicinity of the Alps can be subdivided into three types depending on the synoptic-scale flow over Europe: a 'southwesterly' Type, a 'westerly' Type and a 'northwesterly' Type. In Figure 1 examples of the three types of cold fronts are given showing the corresponding 700 hPa charts at 00 GMT. Also shown are the surface front positions at 12 GMT on the preceding day as well as at 12 GMT on the same day.

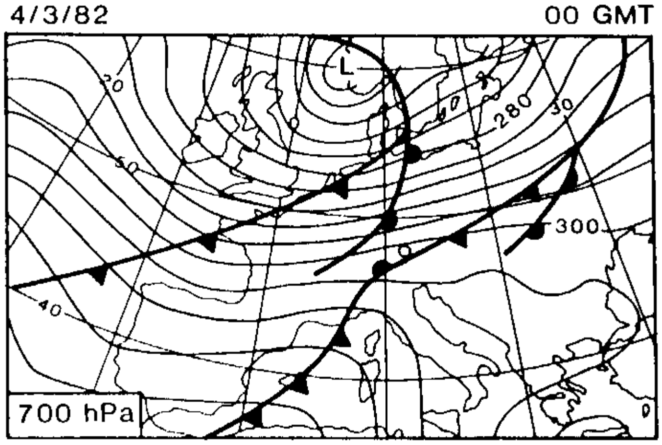
In the southwesterly case (Figure 1, a) a low is located above the eastern Atlantic Ocean. In this case in the prefrontal area south-foehn occurs north of the Alps. The basic weather development for the area north of the Alps is at first foehn, followed by a synoptic-scale trough and later bad weather at the west of the trough. The turn of the geostrophic wind with the frontal passage is from southwest to west or even northwest. The prediction of the movement of this type of front is very difficult. In particular, when secondary wave disturbances occur along the front, the front tends to become stationary.

The foehn leads to less cloud formation in the lower troposphere than usually expected in prefrontal areas. The foehn air located north of the Alps replaces the rest of polar air which was transported towards the Alps. This foehn air mass is very dry in a surface layer of about 3 to 4 km. This layer cannot support cloud formation or precipitation. Consequently, the approaching convergence line is usually not linked with clouds or precipitation. This foehn effect can be observed far north, sometimes up to a distance of 200 km north of the Alps. After the breakdown of the foehn the polar air mass is advected towards the Alps behind the front and is blocked by the Alps leading to frontal precipitation augmented by the orography. It is the experience of forecasters in southern Germany that there is less precipitation and less cloudiness in the prefrontal area, presumably associated with the foehn, more rain in the postfrontal area, presumably because of uplift in the presence of blocking by orography.



(a)

(c)



(b)

● **Figure 1**

The 700 hPa analysis for a 'southwesterly' type of a cold front (a), 'westerly' type (b) and 'northwesterly' type (c). The isochrones show the surface front positions at 12 GMT of the preceding and the same day. The small circle indicates the location of Munich.

The westerly type (Figure 1, b) is characterized by a steering low in the northern Atlantic Ocean. The wind turns usually from west to northwest/north and sometimes from northwest to west with the frontal passage. In case of a deepening trough lee cyclogenesis is frequently observed in the Gulf of Genoa. The prediction of this frontal type is not difficult; these fronts are usually moving rapidly.

The northwesterly type of cold front (Figure 1, c) is characterized by a blocking ridge of high pressure located above the eastern Atlantic Ocean. The wind direction turns from northwest to north/northeast with the frontal passage. In the winter these fronts are linked with advection of dry and very cold Arctic air leading to some snow in the blocking area north of the Alps. In summer more humid air is transported towards the Alps. With the lifting of the air mass and the corresponding destabilization, rain and thunderstorms may develop in connection with these fronts. At the southern edge of the Alps with a northerly flow, a north-foehn is frequently observed. This is associated with a decrease in cloudiness in northern Italy.

Three types of warm fronts are experienced in central Europe: a 'southwesterly' type, a 'northwesterly' type and a 'southeasterly' type. The southwesterly type generally precedes the corresponding cold front type, but in most cases this type of a warm front has little significant weather associated with it. The northwesterly type is linked with a northwesterly cold front. In this case, if the warm front is active, precipitation may occur due to lifting close to the orography. The prediction of this type of warm front is difficult.

Finally, a warm front is sometimes connected with a so-called 'Vb-situation'. At the end of the last century a statistics of the main tracks of European cyclones was carried out. About ten different tracks were found to be characteristic for Europe. However, only one track remained by name, the 'Vb-track', which characterizes cyclones generated above the Gulf of Genoa and then moving towards Hungaria. These events are termed by 'Vb-situation' and they are associated with moist warm air moving towards the Alps from southeast. Sometimes heavy precipitation over two to three days can occur if this warm moist air glides up on a dry cold air mass located north of the Alps. However, these situations are not always linked with a sharp transition zone (warm front); more generally they are characterized by advection of moist air.

Occlusions occur in central Europe very seldom, which is due to the fact that the tracks of the mid-latitude cyclones and their occlusions are too far north. In summary, it is noted that the weather associated with warm fronts is usually more benign than that of the cold fronts. the influence of the Alps on the development, movement and decay of cold and warm fronts is at present not well understood. Only the effects of foehn and blocking on fronts in this area are understood qualitatively.

3 Climatology of Fronts

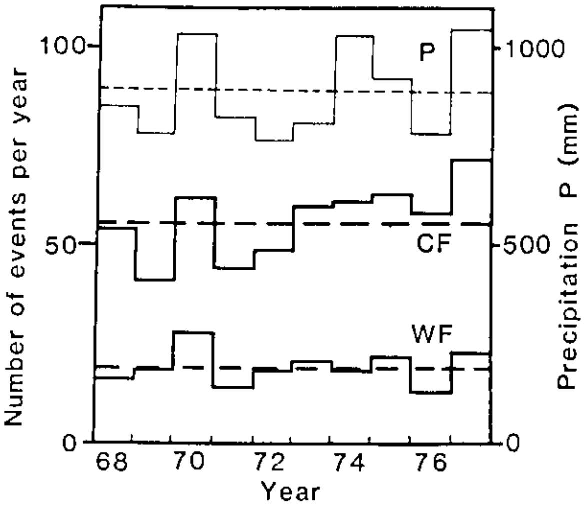
The observation period is from 1968 to 1977. The data are taken from the 'Südbayerischer Wetterbericht' where the meteorological observer at Munich records each day which has a frontal passage. We distinguish between cold fronts, warm fronts and no frontal events. A further subdivision of the fronts has not been carried out because particular characteristics could not be determined with the available data. During the chosen period only 16 occlusions occurred at Munich. Due to the fact that most events of this small sample were not recognized unambiguously to be associated with a cold front or a warm front, we ignored these events. These events were considered to belong to the sample of no frontal events. The precipitation data are collected at a station located in the western suburbs of Munich. The day to day precipitation record relates to the 24-hr period from 0700 hr to 0700 hr (local time).

Although we should test whether the climatic character of the chosen period is normal or extreme, few climatic values are available. In Figure 2 the number of cold fronts, warm fronts and the annual precipitation rate (P) is given for Munich. The amount of annual precipitation is close to the long term annual mean of 952 mm. It can be seen that there are three very wet years (1970, 1974 and 1977) and three very dry years (1969, 1972 and 1976) in the ten-year sample. In the ten-year average, 54 days with events of cold frontal type and 19 days with events of warm frontal type are estimated. FREUER (1981) estimated that about 52 cold fronts and 78 warm fronts occur per year in Berlin. SHAW (1962) has shown that in England warm frontal events occur more frequently than the cold fronts, while GENSLER (1957) found that further south, in Switzerland, a larger proportion of cold fronts are observed. Our finding that cold fronts dominate over warm fronts in southern Germany is consistent with the earlier studies.

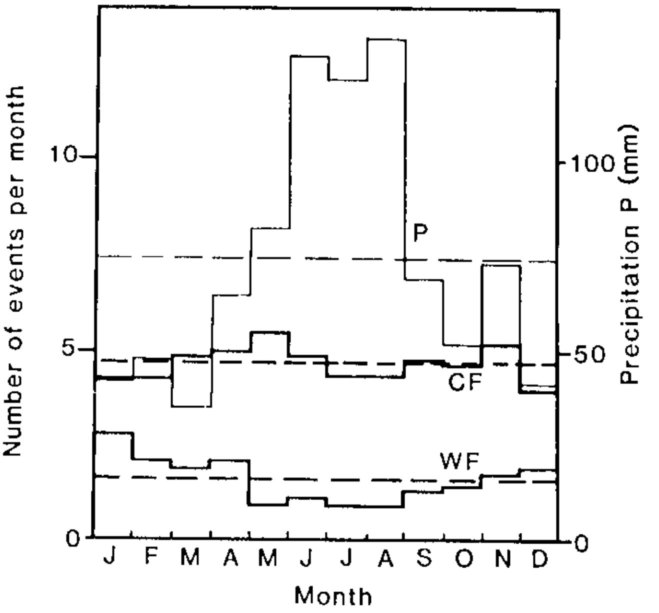
In southern Germany the annual amount of precipitation appears to be linked to the number of fronts that occur there (Figure 2). In Figure 3 the average monthly number of front events and precipitation is given. The annual variation of numbers of cold fronts does not vary widely. In case of warm fronts a weak summer minimum can be seen. However, the monthly precipitation shows a maximum in summer. This maximum is caused by a strong portion of convective precipitation during the summer time.

From Figure 3 a ratio of cold fronts to warm fronts is about 5:1 (summer) and 2:1 (winter). ANIOL (1973) reported for southern Bavaria a ratio of about 10:1 (summer) and 3:1 (winter) of advection of cold air against that of warm air. This is due to his classification of cold air advection which includes cold front events as well as blocking events which force orographic precipitation. His warm air advection events include warm frontal events as well as upgliding of warm air on cold air (e.g. Vb-situations). Because he has only considered a two-year sample, these results are inconclusive.

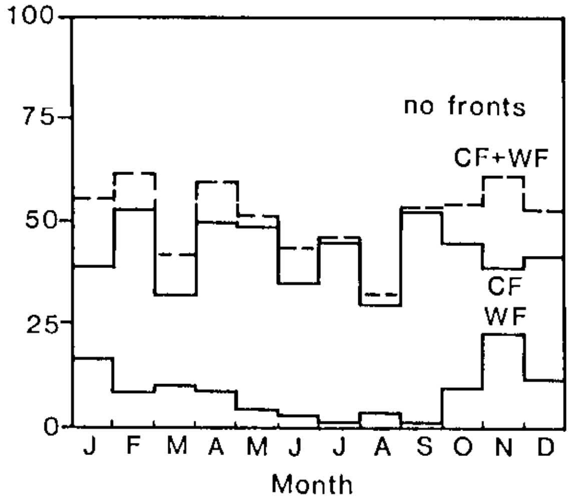
By using the percentages rather than actual measurements, the relative importance of specific types of rain can be compared more readily between the different months. We have subdivided the total monthly



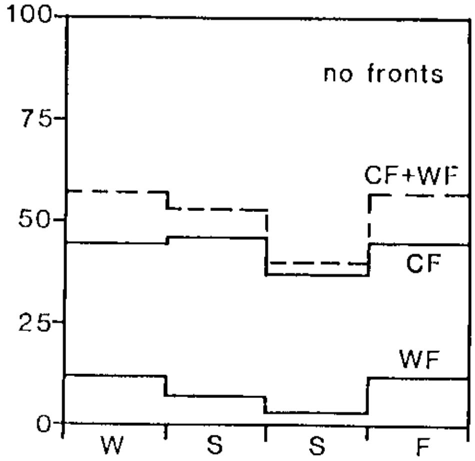
- **Figure 2** The number of cold fronts (CF), warm fronts (WF) and total amount of precipitation (P) at Munich between 1968 and 1977. The broken lines stand for the corresponding average over the entire period.



- **Figure 3** Same as Figure 2, but for the annual variation.



- **Figure 4** Proportion (%) of monthly precipitation due to cold fronts (CF), warm fronts (WF) and events without fronts (orographic and convective precipitation).



- **Figure 5** Same as Figure 4, but seasonal.

amount of precipitation into three categories: precipitation linked with cold front events, with warm front events and with those events without fronts. The result is shown in Figure 4. The mean annual precipitation due to cold fronts (warm fronts) is about 40 % (10 %) of the total precipitation. FLOHN and HUTTARY (1950) have shown that 8.6 % of the annual precipitation is due to precipitation during Vb-situations in Munich. Thus, 50 % of the total amount of precipitation results from frontal events. A similar situation exists for northern England where rather more than half the rain can be described as frontal, divided fairly equally between warm front, warm sector and cold front.

The total amount of the frontal precipitation is smaller during the summer months and higher during the rest of the year. However, this is not clear from Figure 4. Therefore, we look next on the seasonal dependency of the frontal precipitation. Using the four standard climatic seasons, a marked distinction between summer and the other seasons is shown in Figure 5. In summer the portion of frontal rain falls below 40 % of the total monthly amount. The rest of 60 % is due to convective and orographic causes. A similar result is reported for northern England by SHAW (1962), where for various stations the minimum of seasonal percentage was determined for the summer and maximum values for winter and autumn.

The three summer months are outstanding in that they have less precipitation in percentage, but similar numbers of fronts as the other months. However, the total amount of precipitation is much larger during the summer months and therefore the absolute amount per frontal event during the summer is much larger than during the rest of the year. This is not surprising because in summertime thunderstorms develop along a line of a cold front causing heavy rain. This means that summertime convective activity supports the frontal circulations and leads to more precipitation.

The precipitation linked with cold fronts and warm fronts has different characteristics, as shown by ANIOL (1974) using data from a station north to the Alps (Hohenpeissenberg) located roughly between Munich and the baseline of the Alpine barrier. A narrow spectrum is linked with warm fronts with most drops between 0.3 and 0.8 mm in diameter. The drop spectrum in cold fronts is much broader. The droplets vary between 0.3 and 4.1 mm in diameter with about 50 % between 0.9 and 1.4 mm. MARSHALL and PALMER (1948) have shown that the intensity of the precipitation event increases with increasing broadness of the spectrum. Therefore, the drop spectrum measured in connection with cold fronts suggests heavier precipitation rates than those for warm fronts. This is observed and confirmed above. FRAEDRICH et al. (1985) found similar results.

Additionally ANIOL (1973) has shown for the station Hohenpeissenberg that in summer the duration of precipitation linked with a cold front is longer than that linked with a warm front, whereas in winter cold fronts and warm fronts are similar in duration. Due to the duration of the precipitation events and due to their intensities, the precipitation linked with a cold front is more abundant than that linked with a warm front.

4 Statistics of the Troposphere above Munich

In this section we investigate the statistics of the prefrontal (CF1) and postfrontal (CF2) troposphere in connection with a cold front as well as the prefrontal (WF1) and postfrontal (WF2) atmosphere linked with a warm front. The data used consists of a two-a-day record of soundings taken at Munich between 1974 and 1977. HOINKA (1980) has shown that the mean values of this sample are similar to the long-term climatic means, so that the chosen period could be considered climatically normal.

To subdivide the entire sample into cold fronts, warm fronts and no frontal events, the same data set applied in the last section is used. The indication given by the 'Südbayerischer Wetterbericht' of the time of the frontal events is roughly that the front has passed Munich during the night or during the day. Because the nighttime soundings at 00 GMT should not be compared with the daytime soundings at 12 GMT we have used the soundings to determine the pre- and postfrontal statistics in the following way: if there was a front observed during the day, the prefrontal atmosphere is characterized by the preceding 00 GMT sounding and the postfrontal atmosphere by the following 00 GMT sounding. In case of the passage of a front during the night, the prefrontal atmosphere is described by the preceding 12 GMT sounding as well as the postfrontal atmosphere by the 12 GMT sounding of the following day.

4.1 Treating the Data

For an arbitrary parameter A the sample mean of the sample X are denoted by I(A, X) and the second order moments by II(A, X). The variance $\sigma(A, X)$ is evaluated by

$$\sigma(A, X) = II(A, X)^{0.5}.$$

The 95 % confidence interval of I(A, X) is evaluated by

$$\mathrm{Conf}(A, X) = 1.96 \cdot \sigma(A, X) \cdot M^{-0.5}$$

with M the population of the sample X. The wind statistics are evaluated by using the statistics of u and v. The sample mean of the resultant wind speed V_R is given by

$$I(V_R, X) = (I^2(u, X) + I^2(v, X))^{0.5}.$$

The resultant wind direction of α_R is evaluated using the statistics of u and v. Of climatological interest is the mean wind speed V_M regardless of the direction. Using the mean and resultant wind speed we get the persistence PE

$$PE(X) = 100 \cdot I(V_R, X)/I(V_M, X).$$

The purpose of this study is to determine the statistics of the pre- and post-frontal troposphere. Therefore we have to test the equality of the corresponding means, for instance I(A, CF 1), I(A, CF2) and I(A, NF). The population of the various samples is quite different (about 50 to 1500). Thus we apply the Aspin-Welsh test according to CHOI (1978) to reject or accept the hypothesis: $I(A, X_1) = I(A, X_2)$. In the following the abbreviation AW stands for the rejection (AW = 1) and the acceptance (AW = 0) of this hypothesis. All selected data samples have approximately a Gaussian distribution. Therefore we restrict ourselves in the following to the first and second order moments.

4.2 Tropospheric Statistics

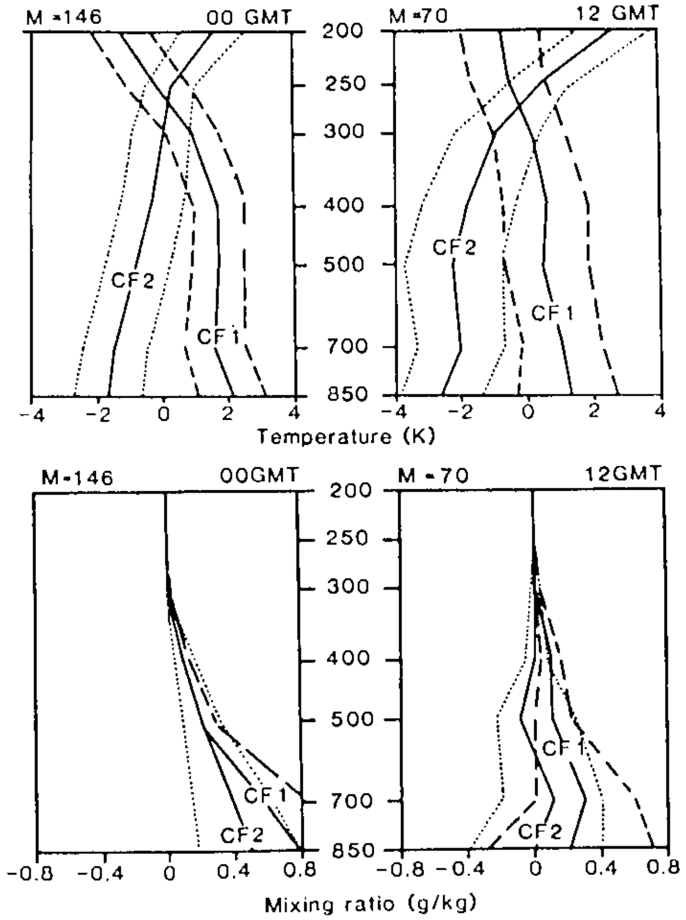
In Figure 6 (top) the tropospheric statistics of the pre-cold-frontal and of the post-cold-frontal atmosphere at 00 and 12 GMT above Munich are given. The temperature differences of the first order moments between the frontal subsample and the NF-sample are shown. The dotted and broken lines indicate the confidence intervals of the first order moments of the corresponding samples. Up to 500 mb the temperature differences are significant between the pre- and the postfrontal troposphere. At 850 mb maximum values up to 3.5 °C are evaluated. Additionally, at 200 mb close to the tropopause a temperature increase is evaluated up to 3 °C indicating that the tropopause has dropped substantially in the postfrontal atmosphere. In Figure 6 (bottom) the mixing ratios are shown. Significant differences could not be derived from the result.

In the mid troposphere there is no significant difference between the post- and pre-frontal sounding. This is due to the fact that the time lapse rate between two soundings is 24 hrs. The tilting angle of the fronts is between 1° and 2°. Assuming a frontal speed of 10 m/s, after 5 hrs, the front has moved about 200 km and the post-frontal cold air is about 7 km shallow. This means that the pre-frontal atmosphere is replaced by the post-frontal airmass only up to 7 km.

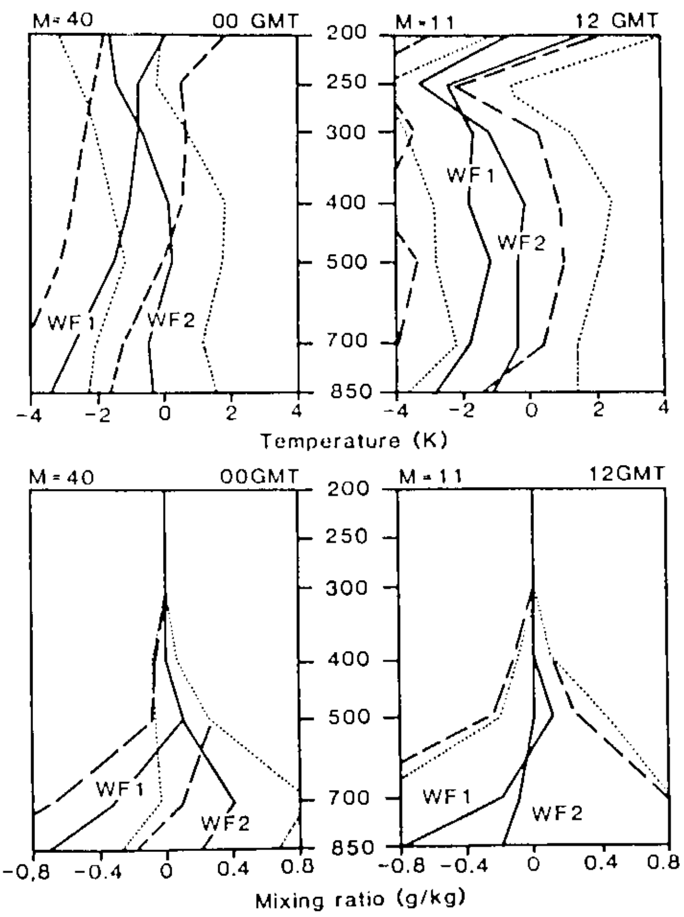
The number of daytime fronts is about double the number of nighttime fronts. This needs some explanation. All fronts which could be clearly located between 5 am and 7 pm due to the information of the observers were considered to be daytime fronts. The time of passage of the nighttime fronts are less exact. A similar result reported FREUER (1981) for Berlin.

Figure 7 shows the statistical sounding which is linked with a warm front. In this case no significant differences are evaluated neither for the temperature nor for the mixing ratio. This might be an effect of the well known fact that warm fronts are not that effective in producing severe weather in southern Germany. This fact should result in less significant statistics than in the case of the cold fronts associated with stronger weather.

Because there is no significant difference between the statistics of no-frontal events (NF) and those associated with warm fronts (WF1, WF2), we restrict ourselves in the following to the statistics associated with cold fronts (CF1, CF2). The absolute values of these statistics are given in the Appendix.



- **Figure 6** Vertical profiles of differences I(A,CF1) I(A,NF), I(A, CF2) I(A, NF), for cold fronts (see Section 4.1). The top figure shows the temperature differences (K) and the bottom figure the differences in mixing ratio (g/kg). M is the population of the subsample. The abbreviations stand for the subsamples: without frontal events (NF), prefrontal cold front (CF1), postfrontal cold front (CF2). The dotted and broken lines show the corresponding confidence intervals. The sample size is given by M.



- **Figure 7** Same as Figure 6, but for warm fronts.

Observations suggest that the pre- and post-frontal atmosphere have different stability characteristics. The destabilization by lifting the warmer air by the colder in the frontal zone cannot be considered here using the available data. These frontal zones extend about 200 km. The time difference between two comparable soundings is 24 hrs which is too large to pick up these small scale differences. However, a mean stability measure, the Brunt Väisälä frequency N, where $N^2 = g \cdot (\partial\theta/\partial z) \cdot \theta^{-1}$, can be taken from the statistical profiles. The mean stability for the layer between 2 and 8 km increases with the passage of a cold front from $N = 0.0105\ s^{-1}$ to $N = 0.0112\ s^{-1}$. This is only a slight increase, however, it shows a clear tendency because in the entire troposphere the warm air is replaced by cold air.

4.3 Surface Statistics

In Table 1 surface statistics are given for the subsamples containing no frontal events, pre-cold-frontal and post-cold-frontal for 00 and 12 GMT. The mean pressure for the pre- and post-cold-frontal situation is significantly smaller than for no frontal events and confirms that these fronts occur in

Table 1 Surface statistics of pressure (p), temperature (T), dewpoint temperature (T_d) and mixing ratio (m) at Munich for the period 1974–1977. The means (I) and their 95 % significance levels (S) are given. The AW stand for the acceptance (AW = 0) or rejection (AW = 1) of the hypothesis, that the compared first order moments are equal. The abbreviations stand for the subsamples: without frontal events (NF), prefrontal cold front (CF1), postfrontal cold front (CF2), prefrontal warm front (WF1), postfrontal warm front (WF2).

	GMT	p(mb)		T(°C)		T_d(°C)		m(g/kg)		V_M(m/s)		V_R(m/s)		α(deg)		PE (%)
		I	S	I	S	1	S	1	S	1	S	I	S	I	S	
NF	12	1017.3	0.5	11.0	0.5	4.3	0.4	5.6	0.1	3.3	0.1	0.7	0.2	321	20	21
CF1	12	1011.4	1.8	12.7	1.8	4.9	1.4	5.8	0.5	3.7	0.6	1.5	1.0	249	41	41
CF2	12	1013.3	1.9	9.4	1.3	4.0	1.1	5.3	0.5	4.2	0.6	2.5	1.0	265	21	59
NF	00	1018.5	0.5	5.6	0.4	3.4	0.4	5.2	0.1	2.3	0.1	1.0	0.2	219	11	41
CF1	00	1014.6	1.3	8.1	1.0	5.5	1.0	6.0	0.4	3.2	0.4	2.2	0.5	236	14	69
CF2	00	1015.9	1.4	7.0	1.0	4.6	0.9	5.7	0.4	3.8	0.4	2.5	0.6	254	12	67
AW:																
NF /CF1	12	1		1		0		0		1		1		1		–
NF /CF2	12	1		1		0		0		1		1		1		–
CF1/CF2	12	0		1		0		0		0		0		0		–
NF /CF1	00	1		1		1		1		1		1		1		–
NF /CF2	00	1		1		1		1		1		1		1		–
CF1/CF2	00	0		0		0		0		1		1		1		–

Table 2 Same as Table 1, except for statistics of the tropopause.

	GMT	p(mb)		T (°C)		T_d(°C)		m (g/kg)		V_M(m/s)		V_R(m/s)		α (deg)		PE (%)
		I	S	1	S	I	S	I	S	1	S	I	S	I	S	
NF	12	235.4	2.8	- 58.8	0.4	- 64.2	0.5	0.1	0.1	19.9	0.8	8.5	1.4	290	9	43
CF1	12	225.2	9.7	- 60.5	1.2	- 64.4	1.5	0.0	0.0	22.0	2.8	14.8	5.0	248	20	67
CF2	12	255.6	9.8	- 56.5	1.3	- 62.2	1.4	0.0	0.0	27.7	3.3	18.8	6.0	248	19	68
NF	00	235.1	3.0	- 59.0	0.4	- 64.6	0.5	0.0	0.0	19.7	0.9	8.8	1.6	294	10	45
CF1	00	220.8	5.5	- 60.4	0.8	- 65.2	1.1	0.0	0.0	24.8	2.3	16.5	4.1	280	14	67
CF2	00	243.3	6.5	- 57.8	0.9	- 63.6	1.2	0.0	0.0	27.4	2.7	16.0	5.0	269	17	58
AW																
NF /CF1	12	1		1		0		0		1		1		1		–
NF /CF2	12	1		1		1		0		1		1		1		–
CF1 /CF2	12	1		1		1		0		0		0		0		–
NF /CF1	00	1		0		0		0		0		0		0		–
NF /CF2	00	1		0		0		0		1		1		1		–
CF1 /CF2	00	1		0		0		0		0		0		0		–

cyclonic situations. All pre- and post-frontal statistics significantly differ from the no-front-sample, with the exception of the dewpoint temperature and the mixing ratio.

The decrease in temperature with the passage of the cold front is between 1.1° and 3.3 °C. Apart from being a zone of rapid transition in temperature, a front is also a zone of rapid change of pressure and wind. The mean pressure is lower in the prefrontal area than in the postfrontal area. This seems to confirm observations. However, the Aspin-Welsh test shows that most of the differences are statistically insignificant. All wind speeds increase by about 1 m/s with a turn in wind direction of about 17° from south to west. These differences are significant only for the daytime fronts (00 GMT).

4.4 Tropopause Statistics

The outstanding feature of the tropopause in connection with a cold front is that the tropopause is folded near the upper extension of the frontal zone. This leads to a higher tropopause in the prefrontal troposphere than in the postfrontal troposphere. This is corroborated by the statistics given in Table 2. The pressure increases by about 25–30 mb which is equivalent to a drop of about 1000 m. This difference and the temperature difference of about 4 °C (12 GMT), are statistically significant.

Acknowledgement

Peter LANG (DWD, Hohenpeissenburg) is thanked for discussing the precipitation observations at Hohenpeissenberg with me.

References

ANIOL, R., 1973: Niederschlagswetterlagen am Hohenpeissenberg. Met. Rdschau **26**, 184–187.

ANIOL, R., 1974: Z/R Beziehungen und Wetterlage am Hohenpeissenberg. Met. Rdschau 27, 27–29.

CHOI, S. C., 1978: Introductory Applied Statistics in Science. Prentice-Hall Inc., Englewood Cliffs, New Jersey.

DAVIES, H. C., 1984: On the retardation of a cold front. Beitr. Phys. Atmosph. 57, 409–418.

ERIKSON, W., 1971: Über die Häufigkeit meteorologischer Fronten über Europa und ihre Bedeutung für die klimatische Gliederung des Kontinents. Erdkunde **25**, 163–178.

FLOCAS, A. A., 1984: The annual and seasonal distribution of fronts over central-southern Europe and the Mediterranean. J. Climatol. 4, 255–267.

FLOHN, H. and HUTTARY, J., 1950: Über die Bedeutung der Vb-Lagen für das Niederschlagsregime Mitteleuropa. Met. Rdschau 3, 167 - 180.

FRAEDRICH, K., BACH, R. and NAUJOKAT, G., 1985: A single station climatology of central European fronts: number, time and precipitation statistics. Beitr. Phys. Atmosph.

FREUER, Ch., 1981: Häufigkeit der Luftmassen und Frontdurchgänge in Berlin-Dahlem 1972–1980. Beilage zur Berliner Wetterkarte, 57/81, SO 10/81, 1–6.

GENSLER, G. A., 1957: Die Klassifikation der Fronten. La Meteorologie **45/65**. 301–303.

HOINKA, K. P., 1980: Synoptic-scale atmospheric features and foehn. Beitr. Phys. Atmosph. **53**, 486–508.

MARSHALL, J. S. and PALMER, W., 1948: The distribution of raindrops with size. J. Met. **5**, 165–166.

PALMEN, E. and NEWTON, C. W., 1969: Atmospheric circulation systems. New York 1969. pp. 603.

PEPPLER, W., 1925: Die Fronten in Süddeutschland. Das Wetter No. 42, 109–110.

PETTERSSEN, S., 1958: Introduction to Meteorology. New York, pp. 520.

SHAW, E. M., 1962: An analysis of the origins of precipitation in northern England, 1956–1960. Quart. J. Roy. Met. Soc. **88**, 539–547.

SIMPSON, J. E., 1969: A comparison between laboratory and atmospheric density currents. Quart. J. Roy. Met. Soc. **95**, 758–765.

STEINACKER, R., 1982: The first ALPEX-SOP cold front on 2 March 1982. In: ALPEX preliminary results. GARP-ALPEX no. 7, 87–98. Obtainable from WMO Geneva.

Appendix

- **Table A1** Statistics of the troposphere above Munich at 00 GMT for the period 1974 to 1977 for daytime cold fronts. For abbreviations see Table 1

p(mb)	T(°C)		T_d(°C)		m(g/kg)		V_M(m/s)		V_R(m/s)		α(deg)		PE(%)
	I	S	I	S	I	S	I	S	I	S	I	S	
NF													
850	4.4	0.4	-2.8	0.5	4.1	0.1	6.7	0.3	2.3	0.6	272	9	34
700	-4.9	0.4	-13.1	0.6	2.4	0.1	8.3	0.4	4.0	0.6	282	7	49
500	-20.9	0.4	-31.1	0.6	0.7	0.0	12.4	0.5	5.2	1.0	290	11	42
400	-32.7	0.4	-42.0	0.5	0.3	0.0	15.5	0.7	6.1	1.3	292	12	39
300	-47.3	0.3	-55.5	0.4	0.1	0.0	19.4	0.9	8.0	1.6	295	12	41
250	-53.9	0.3	-61.9	0.4	0.0	0.0	19.9	0.9	9.0	1.6	296	10	45
200	-56.4	0.4	-64.4	0.6	0.0	0.0	22.1	9.9	11.6	9.9	321	64	52
CF1													
850	6.5	1.1	-0.2	1.1	4.9	0.3	9.6	1.2	7.1	1.6	265	8	75
700	-3.3	0.9	-9.4	1.3	3.1	0.3	11.9	1.2	9.2	1.8	265	9	77
500	-19.2	0.8	-28.2	1.3	0.9	0.1	15.7	1.5	11.0	2.5	271	11	70
400	-31.0	0.8	-38.9	1.2	0.4	0.0	18.5	1.7	12.1	3.1	275	13	65
300	-46.4	0.8	-53.2	0.9	0.1	0.0	22.2	2.2	14.0	3.8	280	15	63
250	-54.1	1.0	-60.9	0.8	0.0	0.0	24.0	2.2	15.4	4.0	279	14	64
200	-57.7	0.9	-64.7	1.6	0.0	0.0	22.3	2.0	15.7	3.5	278	12	71
CF2													
850	2.7	1.0	-0.9	1.1	4.6	0.3	10.4	1.3	7.9	1.8	282	10	76
700	-6.4	0.9	-11.0	1.4	2.8	0.3	12.2	1.3	8.7	2.1	275	11	72
500	-21.7	0.9	-29.8	1.6	0.9	0.1	17.3	1.8	9.9	3.2	271	18	57
400	-33.0	0.9	-40.8	1.3	0.4	0.0	21.8	2.3	11.6	4.1	270	20	53
300	-47.3	1.0	-54.1	1.4	0.3	0.3	27.1	2.8	14.7	5.2	273	20	54
250	-53.7	0.7	-60.5	0.9	0.0	0.0	27.1	2.8	15.8	5.0	272	18	58
200	-54.9	1.0	-63.0	1.7	0.0	0.0	22.8	2.3	14.9	4.0	271	14	65

- **Table A2** Statistics of the troposphere above Munich at 12 GMT for the period 1974 to 1977 for nighttime cold fronts. For abbreviations see Table 1

p(mb)	T(°C)		T_d(°C)		m(g/kg)		V_M(m/s)		V_R(m/s)		α(deg)		PE(%)
	I	S	I	S	I	S	I	S	I	S	I	S	
NF													
850	4.1	0.4	-1.9	0.5	4.4	0.1	6.9	0.4	2.4	0.5	265	8	34
700	-4.9	0.4	-13.1	0.6	2.4	0.1	8.5	0.3	3.8	0.6	272	6	45
500	-20.9	0.4	-30.9	0.6	0.8	0.1	12.8	0.5	5.2	0.9	286	10	41
400	-32.7	0.4	-41.9	0.5	0.3	0.0	16.2	0.6	6.4	1.2	288	10	40
300	-47.4	0.3	-55.3	0.4	0.1	0.0	20.2	0.8	8.1	1.5	293	11	40
250	-54.3	0.3	-61.7	0.4	0.0	0.0	20.4	0.8	9.0	1.5	294	9	44
200	-56.4	0.4	-63.9	0.6	0.0	0.0	17.5	0.7	9.2	1.2	288	7	53
CF1													
850	5.3	1.6	-0.9	1.5	4.6	0.5	8.9	1.5	5.6	2.3	255	22	63
700	-3.9	1.3	-10.6	1.6	2.7	0.3	10.7	1.5	7.9	2.4	254	16	74
500	-20.3	1.4	-28.2	1.5	0.9	0.1	15.2	1.7	9.9	3.4	252	20	65
400	-32.2	1.4	-39.4	1.4	0.4	0.1	19.1	2.3	12.3	4.3	253	20	65
300	-47.4	1.1	-53.5	1.1	0.1	0.0	22.9	3.1	14.9	5.4	252	21	65
250	-54.8	1.0	-60.6	0.9	0.0	0.0	23.3	3.2	15.7	5.4	248	20	67
200	-57.3	1.3	-63.2	1.6	0.0	0.0	20.8	2.6	15.3	4.5	250	17	74
CF2													
850	1.5	1.2	-1.2	1.2	4.4	0.4	9.0	1.5	6.5	2.2	272	12	73
700	-7.0	1.3	-12.1	1.7	2.5	0.3	12.2	1.7	8.9	2.7	261	14	73
500	-23.2	1.4	-30.3	1.8	0.7	0.1	17.1	2.1	11.4	3.8	252	19	67
400	-34.6	1.3	-41.6	1.4	0.3	0.0	22.4	2.8	15.1	4.9	251	19	68
300	-48.4	1.1	-55.0	1.0	0.1	0.0	27.2	3.3	18.2	6.0	250	19	67
250	-53.9	0.9	-60.5	0.9	0.0	0.0	27.0	3.2	19.0	5.8	249	18	70
200	-53.8	1.1	-60.5	1.6	0.1	0.0	21.9	2.6	16.5	4.5	250	16	75