A synoptic climatological classification of winter precipitation in Victoria

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The major synoptic types responsible for Victoria's winter (June-September) precipitation are described, and their relative contribution to rainfall in different geographical areas of the State assessed using a five-station pluviograph network. Five distinct synoptic types are recognised: (a) cold frontal systems interacting with cloud masses of low latitude origin (I fronts); (b) frontal systems not interacting with low latitudes (NI fronts); (c) post-frontal; (d) cold lows; (e) warm lows. The relative contribution of each type varies substantially around the State: individual types tend to be most significant in areas with a relatively good exposure to low-level winds accompanying the system, while their influence is reduced in areas leeward of topographical barriers. The majority of rainfall in northern Victoria is contributed by I fronts, and in eastern Victoria, by cold (cut-off) lows. Rainfall in southern Victoria has more varied origins but with the exclusively mid-latitude types, NI fronts and post-frontal, assuming greater significance than elsewhere. In particular, the post-frontal type becomes important in hilly locations exposed to the west-southwest. Attempts are made to explain the rainfall distributions associated with the various synoptic types by drawing analogies with northern hemisphere field-studies on orographic precipitation modification.

Introduction

Why undertake a synoptic climatological analysis of Victorian rainfall?
Because Victoria is the site of significant agricultural, water and forestry resources, elucidation of the synoptic factors controlling the State's rainfall and its variations is clearly important. However, although attempts to understand (and predict) interannual fluctuations in Victorian rainfall date back to the early years of this century (e.g. Quayle 1910; Hunt et al. 1913), little attempt was made until recently to identify specific synoptic or circulation types producing the rainfall and controlling its variability, much less to quantify these effects. For example, meteorologists have long been aware that northern Victorian winter-spring rainfall is subject to a marked tropical influence, reflected in strong correlations between rainfall and Darwin pressure, or the related Southern Oscillation Index (e.g. Quayle 1929; Nicholls and Woodcock 1981; McBride and Nicholls 1983). Yet the few attempts to describe synoptic or circula-  

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torian winter rainfall and evaluates the relative contribution of each synoptic type to rainfall over the State.

The nature of synoptic climatological studies — some examples

Synoptic climatological studies, in which climatic elements such as precipitation are related to particular synoptic or flow types, are a particularly useful means of analysing causes of rainfall and its variability and have been employed extensively for this purpose overseas, especially in Europe and the British Isles. Indeed, Yarnal (1985) considers that synoptic climatological methods should be an ideal approach to the study of regional climatic variability. For instance, Lamb's (1950) seven-type categorisation of surface flow patterns (five based on wind directions, two on isobaric curvature) is a particularly well-known synoptic classification scheme which provided the basis for many subsequent analyses of rainfall in Britain (e.g. Murray and Lewis 1966; Perry 1968, 1969; Jones and Kelly 1982) and Ireland (Houghton and O’Cinneide 1976). Other British synoptic climatological works have related rainfall to, among other things, cyclone tracks (e.g. Thomas 1960) and intensities (Lawrence 1973).

European examples include an analysis by Flocas (1984) of annual and seasonal frontal frequencies over south central Europe and the Mediterranean, while Fraedrich et al. (1986) compiled statistics on the frequency of, and precipitation amounts associated with, various components of mid-latitude cyclones affecting Berlin. In the United States, synoptic climatological approaches have been used to relate atmospheric circulation to precipitation over specific regions by, for instance, Lund (1963) (the northeastern United States); Barry et al. (1981) (western United States); and Yarnal (1984, 1985) (the Pacific northwest). A thorough exposition of synoptic climatological techniques and their applications (prior to 1973), based primarily on northern hemisphere work, has been given by Barry and Perry (1973).

In the southern hemisphere, most attempts to analyse rainfall variability using synoptic approaches have been concentrated near the land areas of South Africa (e.g. Vowinckel 1955; Tyson 1981, 1984; Dyer 1982; Harrison 1984), New Zealand (e.g. Kidson 1969; Salinger 1980), and over various regions of Australia — e.g. Hobbs (1971) for northeastern New South Wales; Wright (1974a,b) for southwestern Australia; and Sumner and Bonell (1986) for northern Queensland. Various attempts have been made to describe the major synoptic, or ‘storm’, types affecting southeastern Australia, including Victoria. Among the older works, Quayle (1910, 1915) classified storm types affecting Victoria according to their location of origin, distinguishing between ‘Antarctics’ (essentially extratropical systems), and ‘monsoons’ (depressions or troughs of low latitude origin). However, their influence on Victorian rainfall was described in only a very qualitative fashion. Similarly, Hunt et al. (1913) described well the synoptic characteristics of drought and wet years in northern Victoria, but again only in very general terms. Taylor (1918, 1920) subsequently made some attempt to quantify the relative contributions of major storm types to Victorian rainfall, finding ‘Antarctics’ (which covered all types of mid-latitude frontal systems) to be most important, followed by troughs, then ‘east coast lows’.

Among more recent studies, Derbyshire (1971) described the precipitation-producing characteristics of seven storm types affecting southeastern Australia, and Haslett (1977) related Melbourne rainfall to certain features of SLP distributions, fronts and cyclone tracks around latitude 35°S. Lajoie (1980) investigated the effect of several synoptic features on rainfall around Horsham (northwestern Victoria), noting that cold fronts and depressions proved most effective in producing heavy rainfall here when coupled with lower latitudes. Budin (1985) discussed circulation conditions associated with years of heavy and light snowfall over the Australian Alps. Adopting a slightly different approach, Wright (1971) included southeastern Australian data in an attempt to relate Australian rainfall to 500 hPa circulation, and Ohis (1980) related Australian rainfall to blocking over various longitude bands, obtaining reasonably high correlations between southeastern Australian winter-spring rainfall and blocking over and east of eastern Australia.

The present study

The present paper describes a simple classification system for rain-bearing synoptic types affecting Victoria and assesses the average contribution of each type to winter rainfall based on the period 1971–82. The bulk of Victoria’s annual precipitation is normally received in the winter half-year (May through October); rainfall variations are of particular significance during this period since it is the time when major water supply areas are replenished, germination and growth of most important crops takes place, and the quality and yield of pastures/hay are largely determined. It was essentially for this reason that the winter season was selected for this study, where, following Taljaard (1967), ‘winter’ encompasses the four months June through September.

The next section describes Victoria’s topography and winter rainfall distribution. A network of pluviograph stations used to assess areal rainfall variability is then introduced, and the synoptic
classification scheme and analysis procedure are described. The following section describes the contribution of each synoptic type to total rainfall, and discusses spatial and within-season variability. The important role of topography in modifying rainfall distributions associated with the various synoptic types is then discussed, and finally the study's major results are summarised.

The study area

Topography
Figure 1 shows the topographical distribution of southeastern Australia and locations of places mentioned in the text. Victoria's most important topographic feature is an east-west range of mountains across the State's centre (the Great Dividing Range) which increases from about 500–1000 m in the west to around 1500 m in the east and acts as an important climatic divide. Most of northwestern Victoria is topographically featureless while an extensive plain runs along the southwest coast. The Grampians are evident as an isolated outcrop at the far western edge of the Divide, while in southern Victoria two other relatively isolated features stand out: the Otway Ranges in southwestern Victoria and the Strzelecki Ranges in West Gippsland. Despite reaching elevations of only 500–700 m these features are nevertheless important local influences on rainfall (Hunt et al. 1913, pp. 24–25).

The synoptic classification and analysis methods

The contribution made by each of several synoptic types to total winter rainfall, and the average amount per episode, were determined for several stations representing different climatic regions of Victoria. This involved identifying the synoptic type responsible for each winter rainfall episode in Victoria over the study-period 1971–82, and evaluating the associated rainfall at each station. Hourly pluviograph data were used for the latter purpose as experience showed that very often individual episodes could not be adequately delineated without this degree of temporal resolution.

The pluviograph station network
The pluviograph stations used in assessing the geographical dependence of rainfall/synoptic-type relationships are shown in Fig. 1 (numbers in brackets represent each station's average winter

Winter precipitation
Figure 2 presents Victoria's mean June to September precipitation. Amounts range from 100–150 mm in the far northwest to 400–600 mm in the foothills of the northeastern ranges, and up to 1000 mm in alpine areas. In southern and southeastern Victoria amounts increase from 250–300 mm on the plains to 400–600 mm on the southwestern Divide. The Otway and Strzelecki Ranges, well exposed to the west-southwest, stand out as relatively wet areas, with the former receiving up to 900 mm. Two areas of markedly reduced rainfall are evident in southern Victoria; one extending west from Melbourne to around Geelong, the other around Sale. In both cases rainfall in westerly flow is reduced substantially by uplands to the northwest and southwest (Hunt et al. 1913; Pittock 1977).
rainfall between 1971–82). Details of the stations are as follows:

1. **Melbourne:** Taken as representative of a flatland station in southern Victoria. However, due to its relatively sheltered location downwind of hills to the northwest and southwest, Melbourne’s winter aggregate rainfall of 196 mm is below average for southern Victoria.

2. **Wangaratta:** Assumed typical of the northern and northeastern Victorian plains country. Winter rainfall amounts to 254 mm.

3. **Mildura:** Represents northwestern Victoria; winter rainfall totals 99 mm. Although somewhat drier than most of the northern and northwestern Victorian plains country, the synoptic processes affecting Mildura would be common to most of this area.

4. **Sarsfield East:** Represents eastern Victoria, long recognised as climatically dissimilar to the rest of the State. Winter rainfall is moderate, 237 mm.

The first four stations are located in flat country, and are free of local orographic influences. Two other stations, with unfortunately incomplete records, were included to study the effects of orographic rainfall enhancement in southern Victoria:

5. **Wyeapoinah:** An exposed, elevated (540 m above sea level) station in the Otway Ranges in southwestern Victoria, taken as representative of several relatively isolated, hilly areas in southern Victoria providing close to optimum conditions for rainfall from wintertime synoptic systems. The difference this makes is indicated by the winter aggregate of 896 mm, several times greater than at the other stations. Although only eight years of data were available at this station (1974–81), compared with twelve at the other four, differences in synoptic-type statistics for other stations (Melbourne and Wangaratta) over the periods 1974–81 and 1971–82 were only very minor. It is assumed the same consistency would apply at Wyeapoinah, so that reasonable comparisons can be made between this station and the others.

6. **Upwey:** Situated at an altitude of 220 m on the southern side of the 600m Dandenong Ranges 30 km east of Melbourne; data were available for the period 1971–80. Mean winter rainfall totals 345 mm, considerably greater than at Melbourne.

The analysis in this paper is mostly based on results from the first five stations, with Upwey being introduced in a later section to investigate orographic influences within the Port Phillip region. It would have been instructive to also include stations representative of the mountainous regions in northeastern Victoria and exposed low-level areas of southern Victoria, but data in appropriate form were not available for stations in these regions over the study period. Nevertheless, recent studies (Wright 1987; Whetton 1988) have shown that the chief statistical patterns of Victorian rainfall variability are centred in regions represented by the existing stations; hence the network described is felt to be sufficient to capture the significant features of rainfall variability within Victoria.

### The synoptic classification

The synoptic classification scheme employed is based on the author’s experience of commonly-observed synoptic types, and as such is subjectively based. An alternative approach would be to classify synoptic types using objective methods (e.g. Lund 1963; Kirchhofer 1973; Yarnal 1985), however, the subjective approach is preferred here as the synoptic types described are all easily recognisable on daily synoptic charts and are not subject to ‘within-type variability’ (i.e. a tendency for particular types to disappear from one data period to the next), an acknowledged problem with objectively-derived classifications (Yarnal 1985).

The classification consists of essentially five types:

1. **(1) and (2) The ‘interacting’ and ‘non-interacting’ frontal types** (Figs 3 and 4). Most fronts affecting Victoria are cold frontal systems, which were subdivided into so-called ‘interacting’ (I) and ‘non-interacting’ (NI) fronts. I fronts (Fig. 3) are those in which cloud masses (at any atmospheric level) originating in tropical and subtropical latitudes (i.e. north of 30°S) within the Australian region are caught up in the circulation of a frontal trough, causing them to move south or southeastward, and thereby affect Victoria. In most cases the low latitude cloud mass, which most frequently takes the form of a ‘northwest cloudband’, amalgamates with the original frontal cloudband prior to reaching Victoria, producing an often extensive band of cloud aligned along and ahead of the surface cold front (Fig. 3). NI fronts (Fig. 4) are simply those in which no such ‘interaction’ with lower latitude cloud masses is observed. The I/NI classification was made by following each frontal cloudband on satellite imagery from the time it passed 90°E until it reached Victoria, and noting whether or not it interacted with a low latitude cloud system. Further details of the classification procedure, and a more complete discussion of the nature and characteristics of I fronts, along with illustrative case studies, may be found in Wright (1988a).

The weather accompanying the two types of front is quite different. NI fronts generally produce brief rain or showers as the front passes, more particularly in southern Victoria. Winds generally tend northwesterly ahead of the front and west to southwesterly behind it, but sometimes remain west to southwesterly throughout a front’s period of influence. By contrast, continu-
ous rain may fall well ahead of surface I fronts within north to northwesterly winds, producing heavy totals over and north of the Dividing Range (Wright 1988a).

Fig. 3 Frontal system approaching southeastern Australia, 27/6/1980. (a) SLP (solid) and 500 hPa (broken) analyses, 0000 UTC, 27/6/1980; (b) satellite imagery (for 2100 UTC, 26/6/1980). Points to note: (1) Although the front is only just entering western Victoria, rain was already falling over northern Victoria and central New South Wales some 400 km ahead of the surface cold front. Rain also extended well inland towards central Australia. (2) The well-defined, high amplitude frontal trough, with pronounced northwesterly to northerly flow at 500 hPa over Melbourne. (3) The link with a 'northwest cloudband' extending back towards the tropical Indian Ocean.

Fig. 4 NI front affecting Victoria, 1/9/1980. (a) SLP analysis, 0600 UTC; (b) corresponding satellite imagery. In this case, a rather strong NI front has just passed through Melbourne. Note the absence of cloud links with lower latitudes, and the confinement of the main frontal cloudband to southern Victoria.

(3) Post-frontal (Fig. 5). This classification refers to showery precipitation in unstable westerly to southerly airstreams, and is quite frequent in Victoria behind significant cold fronts. Substantial precipitation may occur in hilly areas of southern Victoria with a southwesterly exposure, but it is usually insignificant in the north. Post-frontal rainfall is generally increased when an upper-level trough is located over Victoria, or when cyclogenesis over eastern Bass Strait causes strengthening onshore southwesterly flow. In this analysis post-frontal precipitation was defined as precipitation occurring clearly behind an analysed surface cold front, and was normally easily distinguished from the frontal rainband by a break of at least one hour's duration.
(4) Cold lows (Fig. 6). Perhaps better known as 'cut-off' lows, this type may affect Victoria at any time, but occurrences are most frequent in the cooler months. Cold lows are characterised by a well-defined pool of cold air in the middle to upper troposphere, associated with a cyclonic circulation at these levels. The surface isobaric curvature is normally also cyclonic, but may on occasions be straight, or even anticyclonic. In this study a cold low was diagnosed whenever analyses at 500 hPa or higher indicated a closed cyclonic circulation, or at least a local height minimum within a clearly defined trough, at some stage during the system's period of influence on Victoria. Cold lows produce characteristically showery weather, but quite often widespread rain due to upslope may occur in the relatively warm air eastward of such systems (Foley 1956). Well-developed systems may produce heavy precipitation anywhere in Victoria. In particular, systems developing off the east Australian coast (commonly known as 'east coast lows') occasionally produce prolonged heavy rainfall in eastern Victoria (e.g. Foley 1956; Victorian Year Book 1974).

(5) Warm lows (Fig. 7). This type differs dynamically from cold lows in that air near the system's centre is warmer than that surrounding it; hence (from thermal wind considerations), the system's organisation decreases with height. Warm lows generally originate as 'heat low' developments over northern Australia, which occasionally extend or move far enough southward to affect Victoria, where they may produce heavy rain and thunderstorms. Warm lows are therefore mainly a feature of the warmer months but do occasionally occur in winter. Note that this classification does not include cases where a tropical 'dip' or depression is overlain by a cold-cored system — such cases would be classed as cold lows. In this analysis warm lows were distinguished primarily by the presence of a relatively warm low-level air mass over Victoria (as defined by 850 hPa temperatures) and a 1000–500 hPa thickness ridge in close proximity to the surface trough or low. These features are clearly evident in Fig. 7 which also illustrates the systems' tendency to decrease in organisation with height.

Analysis procedure
In this investigation the synoptic types affecting Victoria, and their period of influence, were determined from three-hourly synoptic analyses (National Meteorological Centre, Bureau of Meteorology, Melbourne). Rainfall associated with each system was then determined from the pluviograph records for each station.

A system or type was said to be affecting the State if:
(a) it crossed or extended over central Victoria, even if no measurable rain (≥ 0.2 mm) fell;
(b) it produced measurable rain at one or more of the four main stations (Mildura, Melbourne, Wangaratta or Sarsfield East) even if it never traversed central Victoria.

For further details of the methods used in assigning rainfall to the various synoptic categories, see Wright (1987).
Results

Relative contributions and intensities
Figure 8 summarises each synoptic type’s contribution to winter rainfall at the five stations. Clearly, the I frontal type dominates winter precipitation at the northern Victorian stations, accounting for about half the total amount at each. It is, however, considerably less important in southern Victoria, producing only 15 per cent of rainfall at Weapooahnah and Sarsfield East. The NF frontal type contributes around 15–20 per cent of winter rainfall in most areas, but is slightly more important in southern Victoria and less so in northwestern Victoria.

The post-frontal type contributes substantially to Weapooahnah’s winter precipitation but is less important elsewhere in southern and eastern Victoria, and negligible in the north. The latter result indicates that post-frontal airstreams have already lost most of their moisture by the time they reach northern Victoria. The reduced significance of this type at Melbourne and Sarsfield East compared to Weapooahnah is an effect of orography and exposure, as discussed in the following section.
Table 1. Proportion (%) of total cases of each synoptic type (excluding post-frontal) producing precipitation, and the average amount per case (intensity), at Mildura, Wangaratta, Melbourne, Weeaproinah, and Sarsfield East. AVC1 is the intensity averaged over all systems affecting Victoria, AVC2 is the average amount from just those systems affecting the station. The mean number of occurrences per season is also shown (brackets).

<table>
<thead>
<tr>
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<th>Wangaratta</th>
<th>Melbourne</th>
<th>Weeaproinah</th>
<th>Sarsfield East</th>
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<td>%</td>
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Cold lows make substantial contributions to rainfall at all stations but are especially dominant in the east. Warm lows, on average, contributed little to total winter rainfall but did make important contributions in individual seasons. Such systems were, during this study, confined to the late winter period (August/September).

Table 1 displays the proportion of systems producing rainfall at each station relative to the total number of systems of that type affecting Victoria (average seasonal frequency is shown in brackets). Also shown is the average intensity per case — for all systems of a particular type (AVC1), and for only those systems producing precipitation at the station (AVC2). The proportion of rain-producing fronts is, not unexpectedly, greatest at Weeaproinah and least at Mildura; however, the proportion at Sarsfield East is also little better than one in two. The low figures at these stations mainly reflect the relative inactivity there of NI fronts, particularly at Mildura which lies far enough inland to be out of reach of many NI fronts. Average NI frontal intensities are significantly less than those for I fronts at all stations except Weeaproinah, with greatest differences in northern Victoria. Thus, I fronts are generally much more productive north of the Divide than to the south, whereas north-south differences in NI frontal intensity are relatively slight (the high intensities for both frontal types at Weeaproinah are due to orographic enhancement).

An interesting feature of the cold low statistics is that despite this type’s dominance at Sarsfield East, only 75 per cent of events produced rain there, a proportion lower than anywhere else except Mildura. This somewhat surprising result reflects the effectiveness of topography to the west (Fig. 1) in excluding from eastern Victoria the effects of many disturbances producing rainfall elsewhere in the State — especially depressions centred around western Victoria and directing a northwesterly flow across eastern Victoria. However, rainfall from the systems that do affect Sarsfield East is heavier than elsewhere (except at Weeaproinah where orographic lifting is again evidently important). Thus during this analysis, favourable cold low situations quite often produced rainfalls of over 50 mm (and up to 200 mm) at Sarsfield East — with even heavier falls usually occurring further east.

Although warm lows were infrequent during this study, Table 1 suggests they are capable of producing heavy rainfall on occasions, presumably because their low latitude origins favour a significant air mass moisture content (Wright 1987, p. 290). Hence associated rainfall was generally heavier than for cold lows at all stations except Weeaproinah.

Within-season variability

Figure 9 shows each type’s contribution to rainfall in the individual winter months. Within-season variability of synoptic influences is evidently mostly slight, except between June and other months. Thus, except at Melbourne, cold lows contributed a much greater proportion of June’s rainfall than in other months, whereas frontal and post-frontal influence is correspondingly less in June. These differences in cold low and frontal activity reflect an apparent tendency for blocking activity in the Australian region to peak in June (Wright 1987).

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*All references to statistically significant features refer to the 5 per cent significance level.*
Fig. 9 Mean contribution of each synoptic type to total precipitation in each month (June through September), and the whole season, 1971–82.

Discussion of orographic effects

Since the preceding results indicate that Victoria's topography strongly influences rainfall distributions associated with the various synoptic types, this aspect is now discussed further.

General results

Various empirical studies have been conducted on orographic influences in southeastern Australia (e.g. Coote and Cornish (1958) in South Australia; Hounam (1958) in Victoria's Port Phillip region; and Manton (1979) in northwestern Victoria). However there appears to have been no attempt to study detailed mechanisms of orographic precipitation redistribution within southeastern Australia, along the lines of the comprehensive northern hemisphere studies of, for example, Browning et al. (1974), and Parsons and Hobbs (1983). Nevertheless, explanations for the rainfall distributions associated with each synoptic type may be proposed here in terms of results from these more detailed studies.

Firstly, since most I frontal precipitation occurs within prefrontal northerly or northwesterly airstreams, the north-south differences in I frontal rainfall are evidently due to the east-west Divide across the State's centre. I frontal rainfall is predominantly due to upslide (Wright 1988a) and is derived primarily from layer clouds, accompanied by a stable or potentially unstable atmosphere. Significant orographic enhancement has been observed under such conditions in northern hemisphere studies by, for example, Bergeron (1965, 1968) via the 'seeder-feeder' process (in which 'feeder' clouds forming about hills in near-saturated air masses enhance background precipitation from higher, stratiform, 'seeder' clouds), and by Browning et al. (1974) through orographic triggering of mid-tropospheric potential instability. It seems likely that similar mechanisms would apply here. Indeed, consistent with these and other studies on orographic enhancement in western Britain (e.g. Douglas and Glasspoole 1947; Browning et al. 1974; Hill et al. 1981), heavy precipitation was commonly observed over Victoria's northeastern ranges when low-level northwesterly winds ahead of I fronts were strong and moist (as was frequently the case in winter 1981, for instance).

Conversely, 'feeder' clouds, along with small-scale precipitation features embedded within precipitating cloud masses, tend to be destroyed downstream from significant orographic features through topographically-induced divergence/subsidence, and/or obstruction of low-level moisture influxes (Lillywhite 1951; Hobbs et al. 1975; Parsons and Hobbs 1983). This effect would be particularly marked in eastern Victoria, where the 1000–2000 m barrier is probably high enough to upset even the middle-level 'seeder' clouds (Parsons and Hobbs 1983). These factors probably explain the substantial reductions in I frontal rainfall in southern and southeastern Victoria (Table 1): reductions were less marked in southwestern Victoria where relief is lower. These features show up clearly in case studies (Wright 1987, 1988a), while precipitation decreases of similar magnitude by topography of similar size have been observed by Hobbs et al. (1975), Parsons and Hobbs (1983) and others.

Surprisingly, differences in the proportion of NI fronts producing precipitation at Melbourne and Wangaratta were negligible (Table 1). This is most likely because airflows preceding NI frontal troughs generally have a less pronounced northerly component than those ahead of I fronts, so topographically-induced north-south rainfall differences would be reduced. However, NI frontal influence apparently declines with distance from the coast, with considerably less of the rainfall at inland Mildura (some 300 km from the south coast) coming from NI fronts than elsewhere (Fig. 8).

The much smaller proportion of rain-producing NI fronts at Melbourne compared with Weepranginah suggests that Melbourne is effectively shielded from NI frontal influences by the Otway Ranges to the southwest and other high ground to the northwest (Fig. 1). The Hill et al. (1981) study
on orographic influences in the Welsh Hills, which constitute a barrier of similar maritime exposure and height (500–600 m) to the Otways, showed that at times when frontal systems were not producing measurable rainfall on the nearby coast, it was unlikely to be recorded on the hills either. This suggests that the frequency of rain-producing fronts may be only slightly lower on the exposed south coast than at Weeaproinah (although rainfall amounts would naturally be somewhat less). Hence the relatively low proportion of rain-producing NI fronts at Melbourne probably reflects the degree of shielding at a relatively sheltered location within southern Victoria compared with an exposed one. This effect appears to be even greater in southeastern Victoria, where high ground upstream (in relation to the westerly flow in which NI fronts are embedded) reduces frontal influences still further.

Weeaproinah's relatively high post-frontal rainfall reflects particularly marked enhancement of post-frontal precipitation at that station. Parsons and Hobbs (1983) similarly found that, on windward slopes, post-frontal rainbands tend to experience greater enhancement than better organised features such as frontal rainbands. Again, a similar effect probably applies in other relatively exposed hilly regions in southern Victoria, such as the Strzelecki Ranges of south Gippsland and on the southwestern slopes of the Divide. However, shielding may diminish this effect in the hills east of Melbourne, as discussed below. The fact that post-frontal moisture (which is mostly confined to relatively low levels) is precipitated preferentially on the exposed slopes of even minor topographical features, probably explains the reduced significance of this type at Melbourne and Sarrefield East, which lie downwind of such features.

Cold low rainfall was heaviest at Sarrefield East and Weeaproinah (Table 1), both well exposed to moist, onshore low-level airstreams associated with depressions. The additional effect of orographic lifting is evidently considerable at Weeaproinah, which on several occasions during the study received over 100 mm within 24 hours from cold lows. Most heavy falls at Sarrefield East were associated with depressions centred near the east Australian coast or over the Tasman Sea, producing strong, onshore southerly to easterly winds. In these situations heavy rain is often confined to those areas exposed to the south and east. Then, the same topographical features that normally reduce the influence of 'westerly' fronts in southeastern Victoria (Fig. 1), also prevent 'east coast low' influences from extending further west.

Orographic effects within the Port Phillip region
To assess to what extent orographic effects are important within the relatively sheltered Port Phillip region, Melbourne's synoptic/rainfall distribu-
tion was compared with that at Upwey, in the Dandenong Ranges 30 km to the east, over the period 1971–80. It is recognised that differences between these stations will not be due solely to orographic enhancement: for instance west-southwesterly winds incident on Upwey may pick up additional low-level moisture from Port Phillip Bay, whereas in Melbourne, winds from this direction have a more overland trajectory (see Fig. 1). Nevertheless, Upwey's exposure is fairly typical of much of Melbourne's water catchment area in the hills further east, hence the results should provide some insight into orographic influences in this important water resource area.

Figure 10 shows each type's contribution to the stations' winter rainfall and Fig. 11 displays monthly and seasonal values of an 'enhancement' ratio, i.e. the ratio of the two stations' total rainfall for each type. The post-frontal type contributes significantly more of Upwey's rainfall than Melbourne's (Fig. 10) due to preferential enhancement of this type (Fig. 11). Since the post-frontal contribution at Weeaproinah was greater still
be due to improved exposure to west to southwest winds — or even upstream effects from higher mountains further east — the consistent increases with all synoptic types, despite substantial differences in incident wind direction, suggests that the purely orographic effect is considerable. Similar results probably apply to most other parts of Melbourne's water catchment area where greater elevation may allow the post-frontal type in particular to become even more significant.

Summary

This study has shown that the relative significance of the synoptic types producing Victoria's winter precipitation varies substantially between northern, southern and eastern Victoria. A preferred area of influence exists for each synoptic type governed largely by the direction of the accompanying low-level winds and the topographical distribution. The influence of each type on Victoria's rainfall may be summarised as follows.

I fronts, in which low latitude cloud masses amalgamate with extratropical frontal systems, produce about half of northern Victoria's winter rainfall, but much less in southern (and especially southeastern) Victoria because of the east/west oriented Divide. Hence their contribution to southern Victorian rainfall is overshadowed by other synoptic types. NI fronts generally produce lighter rainfall than I fronts but are more frequent. They contribute about 20 per cent of southern Victoria's average winter rainfall, but somewhat less in northern Victoria.

Cold lows contribute substantially to winter rainfall throughout the State accounting for slightly over half of southeastern Victoria's total, and ranking second in importance to I fronts in northern Victoria. Warm lows during this study were confined to August and September: although on average contributing only about 5 per cent of total winter rainfall, they occasionally made important contributions in individual months. It seems likely that this type would become more important in the warmer months. The post-frontal type is significant only in southern Victoria, with distance from the coast and the presence of the Divide minimising its influence in the north. Within southern Victoria, its influence appears greatest in hilly regions with a westerly or southwesterly exposure, with something of a 'rainshadow' effect apparent in downstream areas.

The patterns of orographic rainfall enhancement/depletion observed with each type were consistent with northern hemisphere field studies on orographic influences. In particular, the tendency for I frontal rainfall to be heavy in northern Victoria, but often insignificant in the south, appears explainable partially in terms of topographically-induced convergence and divergence (Lillywhite...
1951), and partially through the 'seeder-feeder' process described by Bergeron (1965, 1968).

Finally, most of these results probably apply to a much larger area of southeastern Australia. The significant I frontal influence on northern Victorian rainfall probably holds over much of inland southeastern Australia where rainfall variability patterns are very similar (Nicholls 1985). However rainfall in Adelaide, with a southwesterly exposure, apparently also depends on southerly component winds (Price 1973). Since southwesterly quadrant flow is associated primarily with the post-frontal, NW, and cold low types (with the low centred east of Melbourne), this observation agrees with the results obtained here for southeastern Victoria, suggesting that these types are also important over at least southeastern South Australia. The strong post-frontal contribution in exposed and hilly portions of southeastern Victoria would probably be even more marked in western Tasmania, where higher mountains (800-1500 m) and improved exposure would favour considerably greater orographic influence than in southern Victoria. Finally, the dominant cold low influence on central eastern Victorian rainfall would also apply to the east coasts of New South Wales and Tasmania, possibly to an even greater extent than at Sarsfields East.

References


