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The sea-breeze at Darwin: a climatology

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Summary

The characteristics of the diurnal cycle of the sea-breeze at Darwin are examined and compared for different times of the year, with the aid of tables and diagrams depicting the frequency, time of onset and decline, direction, strength, and sense of rotation. The relationships between the evolution of the sea-breeze, and the diurnal and seasonal variation of the boundary layer in the Darwin region are discussed.

1. Introduction

The sea-breeze is a thermally driven circulation (Atkinson 1981) dependent on land–sea temperature differences which vary diurnally, according to the diurnal changes in land temperature, and seasonally, according to the seasonal changes of sea surface temperatures (SSTs) and land temperatures. The purpose of this study is to develop a climatology of the sea-breeze at Darwin, and to suggest some reasons for its behaviour.

Darwin is situated on the central northern coastline of Australia (12° 26′S, 130° 52′E) (see Fig. 1). North-westerly monsoon flow prevails during the summer months (December–February) whilst south-easterly trades of continental origin predominate for the rest of the year. There are many inlets and indentations in the shoreline around Darwin but it runs roughly from a south-west to a north-east direction. Consequently, the north-west is the most favourable, though not exclusive, direction from which the sea-breeze develops.

2. Selection of data

The data used for this study were obtained directly from Bureau of Meteorology Dines anemograph charts for Darwin Airport and cover the 5-year period 1980–84 inclusive. The aerodrome where the meteorological readings are taken is 28.7 m above sea level and approximately 5 km from the sea-shore.

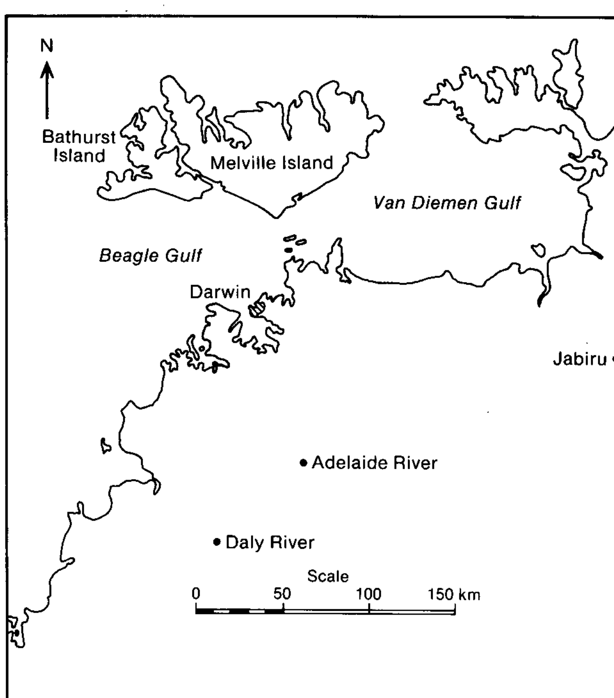

Figure 1. The area around Darwin showing places mentioned in the text.

3. Onset, duration and decline

A clear-cut start and finish to the sea-breeze is sometimes difficult to determine, especially during the wet season months of November–February inclusive, when there is an almost continuous north-westerly airflow over Darwin. This made it necessary to examine the daily anemograph charts and subjectively allocate times for the onset and cessation of the sea-breeze. In many cases, the duration time could only be determined when the wind speed fell to zero or the wind direction changed so that it could no longer be called a sea-breeze.

The onset time of the sea-breeze varies greatly from month to month and even day to day, especially during the dry season. This marked variation can be seen by examining Table I. As the wet season draws to a close, the almost continuous westerly airflow starts to break down — sea-breezes become easy to distinguish due to the abrupt change in wind direction and have a very distinct onset time.

The month of March can be seen as a transition period between the westerly and south-easterly regimes. The figures in Table I show that March has a bi-modal distribution of onset times. The major peak between 0900–0959* is probably the result of the downward mixing of the westerly gradient wind as the boundary layer heats up. The second peak between 1300–1359 would indicate the percentages of 'true' sea-breezes or those formed with an opposing gradient wind.

As the dry season becomes established and the south-easterly trades strengthen, the onset of the sea-breeze becomes later, being most frequent around 1230 in April and 1630 in July. During August there is a re-emergence of the bi-modal onset pattern — the trade winds sometimes weaken and occasionally give way to westerlies. Gradient winds with westerly components become more frequent through September and October due to the development of an inland synoptic-scale heat low.

The 0900–0959 onset maxima may be due to downward mixing of westerly gradients, or in times of light gradient winds may be a true early sea-breeze induced by the large land–sea temperature contrast during these months (see Figs 2 and 3(b)). The maxima between the hours 1300–1359 is evidently a common time of onset with opposing (easterly component) gradient winds.

Table II shows the percentage frequency of the duration of sea-breezes. It can be seen that between September and March inclusive, the majority of sea-breezes last in excess of 8 hours, whilst from November to February inclusive, north-westerly winds blow almost continuously. The life of the sea-breeze is abruptly shortened during the dry season. In April, only 17% of them last for 8 hours or more; in May the majority have a life span of less than 5 hours, while in June and July most have a life span of less than 6 hours.

An appreciation of inland temperatures and their likely effects on the development of sea-breezes can be obtained by considering the inland stations Jabiru Airport (12° 40′S, 132° 54′E) or Daly River (13° 41′S, 130° 38′E) which are over 50 km from the coast compared with Darwin which is 5 km inland.

Fig. 2 shows the average seasonal SST—land temperature difference using composite maximum temperatures from Jabiru Airport and Daly River. A minimum SST—land temperature difference of around 3.5 °C occurs in June, and a maximum difference of around 9 °C occurs during September and October.

Figs 3(a) and 3(b) show the average diurnal land—sea temperature contrasts that can be expected during the periods of minima (June) and maxima (September) respectively. The shaded area above the SST line gives an indication of the thermal energy available to drive the sea-breeze. The average daily period during which this thermal energy is available is from 1200 to 1800 (6 hours) in June and 0900–1930 (10½ hours) in September.

Table I. Percentage frequency of onset times of the sea-breeze at Darwin Airport

Month	Time of onset								
	0900–0959	1000–1059	1100–1159	1200–1259	1300–1359	1400–1459	1500–1559	1600–1659	1700–1759
Mar.	33	9	7	6	19	10	8	6	2
Apr.	4	5	15	20	11	14	10	16	5
May	2	1	7	6	10	16	18	22	19
June	5	3	2	7	19	17	18	20	10
July	3	5	5	10	12	14	19	23	9
Aug.	14	7	11	18	14	16	15	4	1
Sept.	27	13	12	12	18	12	3	3	0
Oct.	40	13	18	11	5	7	4	2	0
Nov.–Feb.	Almost continuous north-westerly flow								

* All times referred to in this paper are local time.

Taking into account the inertia of the sea-breeze circulation, these periods relate reasonably well to the data given in Tables I–III.

Table III shows that the vast majority of sea-breezes dissipate between 1800 and 2200 during the months of April–September. In fact the most frequent time of dissipation in May and June is between 1900 and 1959, which is 1–1½ hours after sunset, and 1–2 hours after the average inland temperature has fallen below the SST.

Sea-breezes that continue to blow after 2200 do so with the assistance of the gradient wind. The direct influence of the westerly monsoons can be seen by the

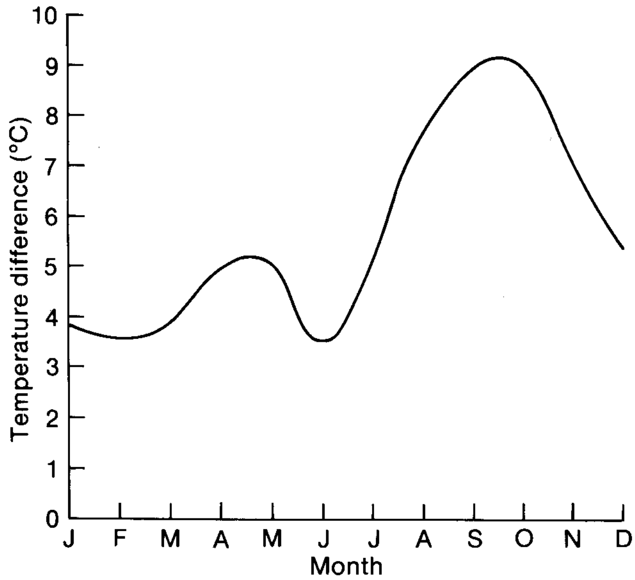

Figure 2. Variation of the diurnal maximum land–sea temperature difference in the Darwin region based on monthly values of average daily maximum temperature (composite of Jabiru and Daly River). (Australian Bureau of Meteorology 1988).

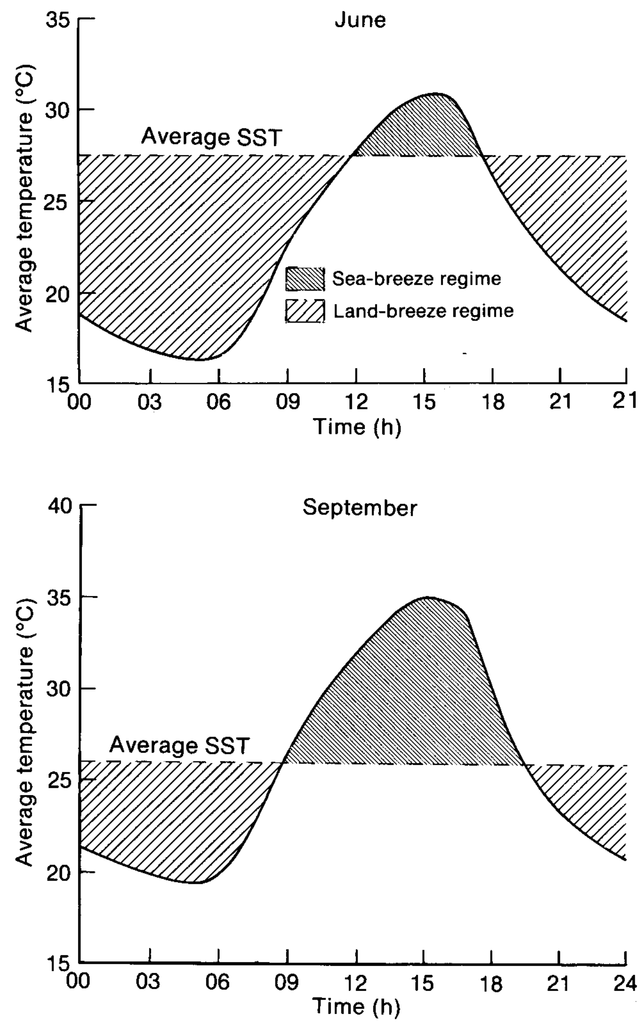

Figure 3. Average diurnal temperatures (as Fig. 2) and the average sea surface temperature off Darwin for the months indicated.

Table II. Percentage frequency of the duration of the sea-breeze to the nearest whole hour at Darwin Airport

Month	Duration (hours)							
	1	2	3	4	5	6	7	≥8
Mar.	Over 50% exceed 8 hours							
Apr.	2	7	10	17	11	19	16	17
May	5	16	19	19	13	9	11	7
June	5	13	12	17	19	13	8	12
July	2	11	17	10	18	14	12	16
Aug.	0	0	3	8	15	17	13	45
Sept.–Oct.	Over 50% exceed 8 hours							
Nov.–Feb.	Almost continuous north-westerly flow							

Table III. Percentage frequency of the decline times of the sea-breeze at Darwin Airport

Month	Time of decline						
	1600–1659	1700–1759	1800–1859	1900–1959	2000–2059	2100–2159	After 2159
Mar.	Over 50% continued after 2159						
Apr.	8	6	20	30	24	6	7
May	1	0	29	45	10	11	3
June	0	0	14	43	27	12	5
July	0	0	15	33	26	12	16
Aug.	0	0	10	29	18	14	29
Sept.–Oct.	Over 50% continued after 2159						
Nov.–Feb.	Almost continuous north-westerly flow						

substantial increase in the percentage of onshore breezes which continue after 2200 during August, until they become an almost continuous occurrence from November to February, making it impossible to distinguish the sea-breeze from the predominant westerly airflow.

4. Direction

It is well known that the direction of the sea-breeze is influenced by local topography, the strength and direction of the gradient-level wind, and Coriolis force (Atkinson 1981). In sunny conditions with light offshore gradient winds (usually less than 5 m s^{-1}), and as a direct response to the horizontal temperature gradient caused by the unequal heating of the land and sea surfaces, the sea-breeze initially tends to blow perpendicular to the coastline. The data shown in Table IV confirms this, with the most frequent initial direction being from the north-west. However, under the influence of strong east to north-east gradient winds, the sea-breeze also frequently develops in the north to north-east sector.

The dominance of the west to north-westerly monsoon during the months of November–March inclusive, makes it difficult to distinguish the sea-breeze circulation from the general westerly airflow. Fig. 4 shows the mean speed and direction of the surface wind at Darwin Airport during these months. In November, the south-easterly trades can still be seen to influence the surface wind in the morning between 1000 and 1100, while from December to March, and apart from the occasional interruption, they blow almost continuously from the north-west sector.

Table IV. Percentage frequency of the initial direction from which the sea-breeze develops at Darwin Airport

Month	Initial direction of the sea-breeze			
	W	NW	N	NE
Apr.	22	39	11	28
May	12	32	24	32
June	14	47	18	21
July	7	41	34	18
Aug.	7	46	20	27
Sept.	7	41	33	19
Oct.	18	46	25	11
Nov.–Mar.		See Fig. 4		

The direction of the sea-breeze during the months April–October inclusive does not remain as constant as that depicted in Fig. 4, frequently veering after onset before backing several hours later.

Neumann (1977) found that the rate of local turning was primarily due to three effects:

(a) the Coriolis force,

(b) the cross product of the horizontal mesoscale pressure gradient (approximately equivalent to the diurnal heating/cooling of the land relative to the sea) and the velocity of the sea-breeze, and

(c) the cross product of the horizontal large-scale pressure gradient (assumed not to be affected by the diurnal heating) and the velocity of the sea-breeze.

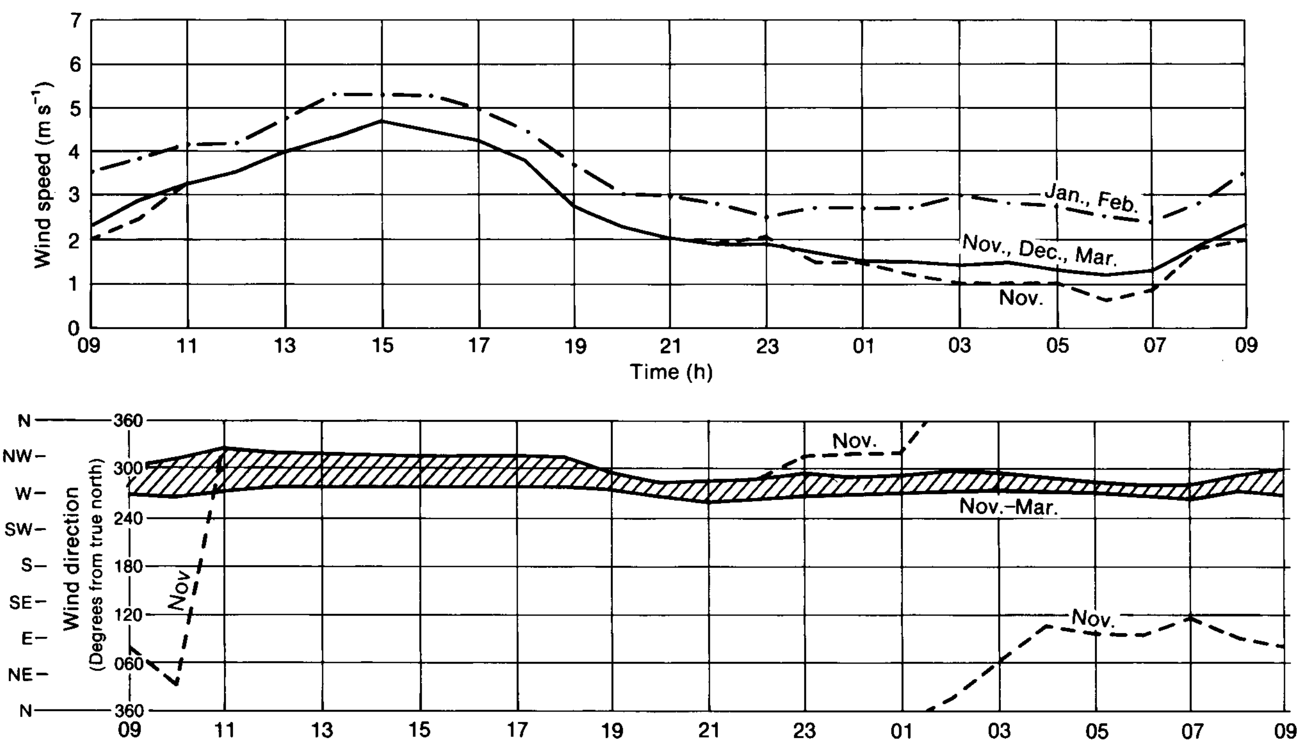

Figure 4. Mean speed and direction of the surface wind at Darwin Airport in a 24-hour period for the months from November to March inclusive.

Thus the rate of turning is governed by:
(a) the diurnal variation of the temperature over the land,
(b) the horizontal pressure gradient, and
(c) the strength of the sea-breeze.

Table V shows that during the months of April–October inclusive, only 37% of the sea-breezes held a steady direction during their life cycle and that of these, 86% originated in the north-east sector.

The synoptic-scale horizontal pressure gradient over Darwin is markedly higher for north to north-east sea-breezes and these seldom rotate during their life cycle. A clearer understanding of the turning of the sea-breeze can be obtained if those sea-breezes that developed in the north to north-east sector are excluded.

Mean hourly wind vectors were determined for days when the sea-breeze developed in the north-west quadrant during May and June, and September alone, and plotted on polar diagrams. The resulting hodographs are shown in Figs 5(a) and 5(b) and show the rotation of the sea-breeze during a 24-hour period, from which it is apparent that the pattern of diurnal rotation of the sea-breeze varies with the time of the year.

In both hodographs, the sea-breeze first veers toward the north soon after developing then backs a few hours later. During the middle of the year (Fig. 5 (a)) the sea-breeze continues to back (even though the wind speed is low) until either a land-breeze is established or the south-easterly trades resume their flow. Later in the year, around September when the south-easterly trades are weaker (Fig. 5(b)), the sea-breeze often becomes west-north-westerly and, although weak, can persist until the early hours of the morning.

Table VI shows some directional characteristics of the Darwin sea-breeze during each month between April and October. The majority of sea-breezes during May and June veer only and do not back before dissipating. During the month of August the mean life-span of the sea-breeze increases significantly (see Table II) and, correspondingly, the number of sea-breezes which back after first veering also increases.

Veering also occurs consistently about 2 hours after the sea-breeze reaches the Airport, irrespective of the actual time of onset. The backing of the sea-breeze on the other hand, takes place at a more definite time of the day, usually between 1720 and 1816.

Table V. Percentage of sea-breezes with a steady direction (to within ±10 degrees) during their diurnal cycle

	Apr.	May	June	July	Aug.	Sept.	Oct.	All months
Percentage of all sea-breezes	42	59	42	44	34	31	17	37
Percentage of sea-breezes in N–NE sector	70	93	86	86	96	89	69	86

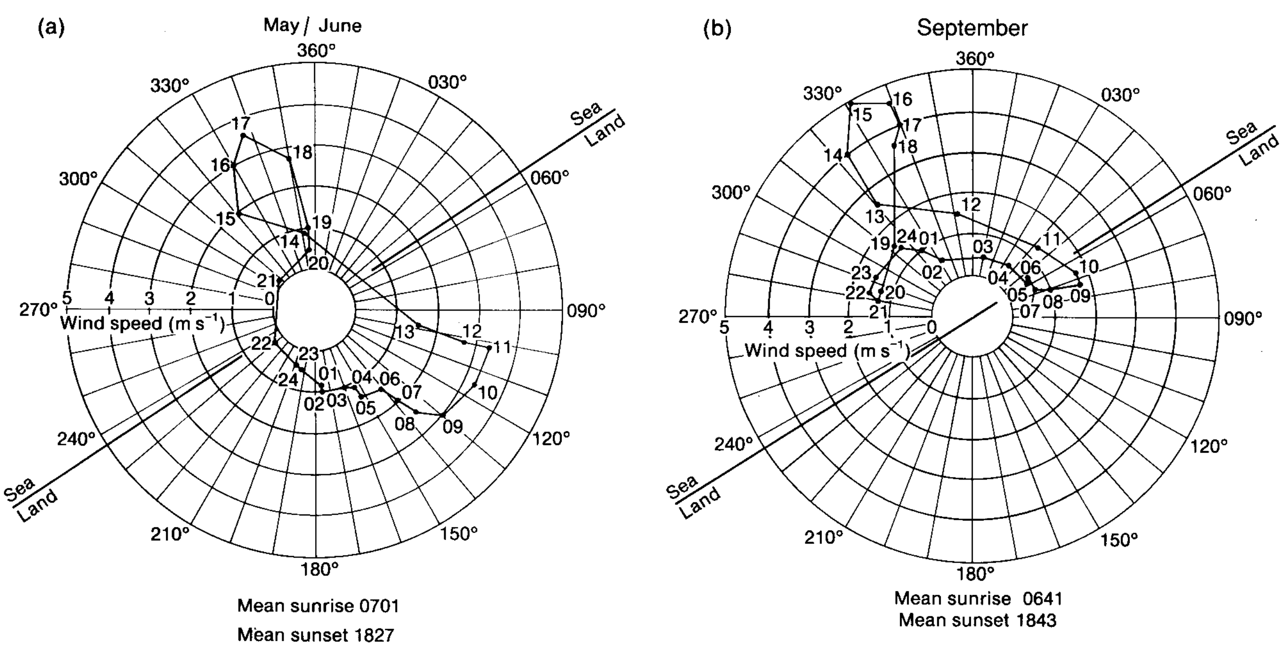

Figure 5. Plotted mean hourly wind vectors for west to north-north-west sea-breeze days at Darwin during (a) May–June, and (b) September. After McCaffery (1966).

Table VI. Percentage frequency and turning time of the sea-breeze at Darwin Airport (excluding sea-breezes that developed in the N–NE sector). VT = average length of time elapsed after development before the sea-breeze veers (hours: minutes), V = average time of day the sea-breeze starts to veer, B = average time of day the sea-breeze starts to back, Nil = doesn't back or veer.

Month	Veers only	Veers/ backs	Backs only	Nil	VT	V	B
Apr.	39	15	29	18	2:04	1508	1737
May	60	14	16	9	1:58	1608	1745
June	71	14	6	9	1:53	1615	1720
July	49	16	23	11	1:47	1612	1747
Aug.	42	26	27	2	2:03	1534	1809
Sept.	39	26	30	5	2:20	1504	1744
Oct.	11	39	44	6	2:36	1406	1816

Coriolis considerations, first incorporated by Haurwitz (1947), dictate that in the southern hemisphere, a sea-breeze should rotate anticlockwise during its life cycle. However, the Coriolis term diminishes greatly in equatorial regions and is a negligible quantity at Darwin's latitude. Notwithstanding this fact, Figs 5(a) and 5(b) show an overall net anticlockwise rotation of Darwin's sea-breeze over a 24-hour cycle. Kusuda and Abe (1989) have pointed out that meteorological effects other than Coriolis force should be taken into account when considering the rotation of the sea-breezes, and have indicated that horizontal advection over time can have a determining effect.

The continued backing of the sea-breeze after sunset is aided by the cool evenings experienced in inland regions during the middle of the dry season. Minimum temperatures reach their lowest during July and conditions become favourable for the development of a land-breeze at night. This in turn effects the behaviour and rotation of the evening breeze, and is one of the distinguishing features between the May/June and September hodographs.

The unusual phenomenon of the sea-breeze veering after initial development is probably due to the close proximity of two large islands, Bathurst and Melville, whose southern coasts are approximately 70 km to the north of Darwin (see Fig. 1). Kimble *et al.* (1946) observed sea-breeze circulations extending 80 km inland and 80 km out to sea in the tropics. This is consistent with observations of visible satellite imagery at Darwin where the sea-breeze front is commonly seen of the order of 80 km inland. Clarke (1989) has shown that a still distinguishable sea-breeze could be found 315 km inland. Given this range of penetration, the initial veering of the sea-breeze in Darwin could be caused by a complex interaction of two distinct sea-breeze cells: a small one set up by the islands, and a second much larger cell generated by the land mass on which Darwin lies.

5. Strength

Walsh (1974) showed that the strength of the sea-breeze is directly related to the amount of thermal energy available to drive the sea-breeze mechanism (numerically depicted by the land–sea temperature contrast). Although the model that Walsh used proved unsuitable for use in Darwin on a daily basis (Lloyd 1988), the strength of the sea-breeze can be shown to be seasonally dependent.

Figs 6 and 7 show the mean speed and gustiness of sea-breezes developing in May/June and September respectively. These are further divided into two groups, (a) those developing in the north-west quadrant, and (b) those developing in the north to north-east sector. Fig. 4 shows the mean speed as well as the direction of the

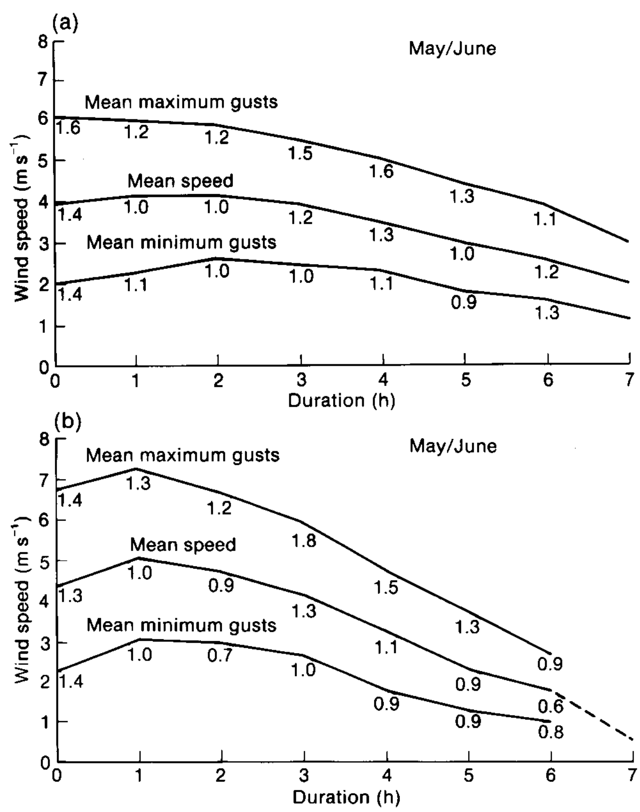

Figure 6. Mean speed and gustiness of sea-breezes developing in (a) the north-west quadrant, and (b) the north to north-east sector during May–June. The numbers below each line are the standard deviations.

surface wind recorded at Darwin Airport during the months of November–March inclusive. The graphs of Figs 6 and 7 represent average speeds; an indication of the variation is presented by listing one standard deviation (SD) for each hour of duration.

Sea-breeze strengths under three classifications are now discussed.

5.1 North-westerly sea-breezes

Sea-breezes developing during the latter part of the dry season are on average 2 m s^{-1} stronger than those developing early in the season (compare Figs 6 and 7). The strength of the sea-breeze is dependent on the amount of thermal energy available to drive the sea-breeze mechanism. Fig. 3 shows that the average period during which this thermal energy is available varies from 6 hours in June to 10½ hours in September. Fig. 6(a) shows that those developing in the north-west quadrant during May/June have a mean speed soon after onset of around 4 m s^{-1} (SD 1.4 m s^{-1}) for 2–3 hours before gradually easing off. In September (Fig. 7(a)), sea-breezes attain a mean speed soon after onset of around 4.7 m s^{-1} (SD 1.6 m s^{-1}), they then increase to around 6 m s^{-1} after the first hour, remain steady for the next hour and then gradually ease off. Gustiness is greatest at onset, ranging from 2.0–6.1 m s^{-1} in May/June and 2.3–7.6 m s^{-1} in September.

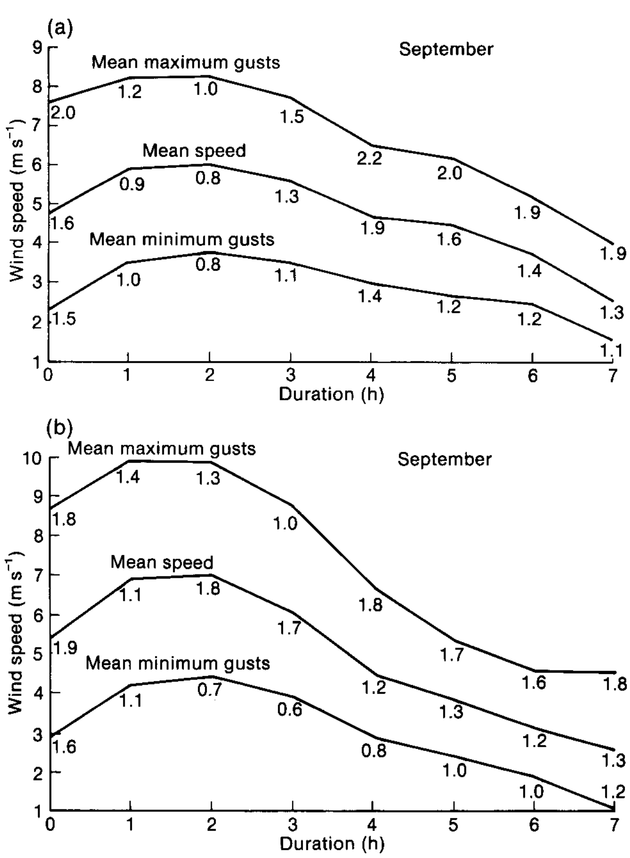

Figure 7. As Fig. 6 but for September.

5.2 North to north-easterly sea-breezes

While sea-breezes are generally stronger during the latter half of the dry season, they also are strongest when they develop in the north to north-east sector. For example, Fig. 6(b) shows that sea-breezes developing in this sector during May/June have a mean speed soon after onset of around 4.4 m s^{-1} (SD 1.3 m s^{-1}). The speed then increases to around 5 m s^{-1} after the first hour and then steadily decreases to less than 2 m s^{-1} during the next 5 hours. In September (Fig. 7(b)), mean speeds soon after onset are around 5.4 m s^{-1} (SD 1.9 m s^{-1}). The mean speed increases to around 7 m s^{-1} after the first hour, then rapidly decreases to around 2.5 m s^{-1} during the next 5 hours. Gustiness is greatest during the first 2 hours after onset for May/June, ranging from 2.3–6.7 m s^{-1}, and for the first 3 hours for September, ranging from 2.9–8.6 m s^{-1} at onset.

5.3 Wet-season breezes

Onshore breezes in the wet season, or more specifically the months November–March inclusive, usually remain north-westerly throughout the day. They attain their maximum strength of around 5 m s^{-1} between the hours of 1400 and 1600, then steadily decline to reach a minimum between the hours of 0600 and 0700 (see Fig. 4).

Daily wind speeds can be highly variable during the wet season, being strongly influenced by the monsoonal flow and local thunderstorm activity. For example, during a strong monsoonal flow, average surface winds speeds of 8–10 m s^{-1} can be sustained for a period of 2–3 days. Wind gusts, generated from inland thunderstorms that move over Darwin, greatly influence the wind speed. This is reflected in the large increase of the standard deviation of the average wind speed from 1.5 m s^{-1} when there is no storm activity, to 7.6 m s^{-1} with storm activity.

6. Conclusion

This study has described the diurnal and seasonal variations of the sea-breezes at Darwin. The different characteristics of the sea-breeze can be grouped into three broad periods: (a) the months from April to July (early to mid dry season), when the land–sea temperature contrast is at a minimum and the south-east trades are at a maximum, (b) August–October (late dry season), when the land–sea temperature contrast reaches a maximum and the south-east trades are losing their influence, and (c) November–March (main wet season) when there is a predominantly north-westerly air flow interspersed with occasional monsoon disturbances.

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Links between convection and waves

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Summary

Observations from gliders and powered aircraft show that in conditions of vertical wind shear there is an interaction between thermal updraughts in the convective boundary layer and wave flow in the stable layer above. Numerical models in two and three dimensions have shown that there can be a feedback between the two types of motion.

1. Introduction

Waves were first observed from gliders in 1933. A theoretical treatment of waves was given by Scorer (1949). For many years waves and thermals were treated as separate phenomena. It was assumed that thermals in the convective boundary layer inhibited the development of waves in the stable atmosphere above. Lee waves were believed to develop towards evening when thermals had died out, and decay during the heat of the day when convection had made the lower atmosphere turbulent.

Before the end of the 1960s pilots had observed that waves could persist even above the tops of large convective clouds. More recently it has been noted that the development of convection within the boundary layer can stimulate the formation of waves higher up. Studies suggest that once these waves have been set off they affect the growth and distribution of cumulus underneath. This is a review of some observations and numerical studies.

2. Early accounts of waves above convective layers

One of the first suggestions that cumuliform clouds could produce gravity waves came from Newton (1960) who wrote that the updraught in cumulonimbus (Cb) clouds could obstruct the horizontal flow of air, and so produce internal gravity waves.

An early observation of waves above cumulus appeared in an article by Bradbury (1963). On this occasion the cumulus tops were limited by a stable layer and winds increased with height while remaining constant in direction.

Waves formed by thermals rising into an inversion were described by Townsend (1966, 1968). He pointed out that vertical shear was important for the development of these waves.

The occurrence of waves aligned parallel to cloud streets was reported by Jaeckisch (1968). A glider had encountered lift in clear air above cloud streets. This lift extended far above the tops of shallow cumulus. The important factor on this occasion was a marked directional shear of wind above the cumulus. At cloud level the wind direction was parallel to the alignment of the cloud streets but above them the direction was approximately at right angles. The lines of cloud appeared to be acting as small ridges stimulating waves in the flow aloft. The wave lift, which was not marked by cloud, lay parallel to the cloud streets (Fig. 1). Since then a number of glider pilots have observed that similar

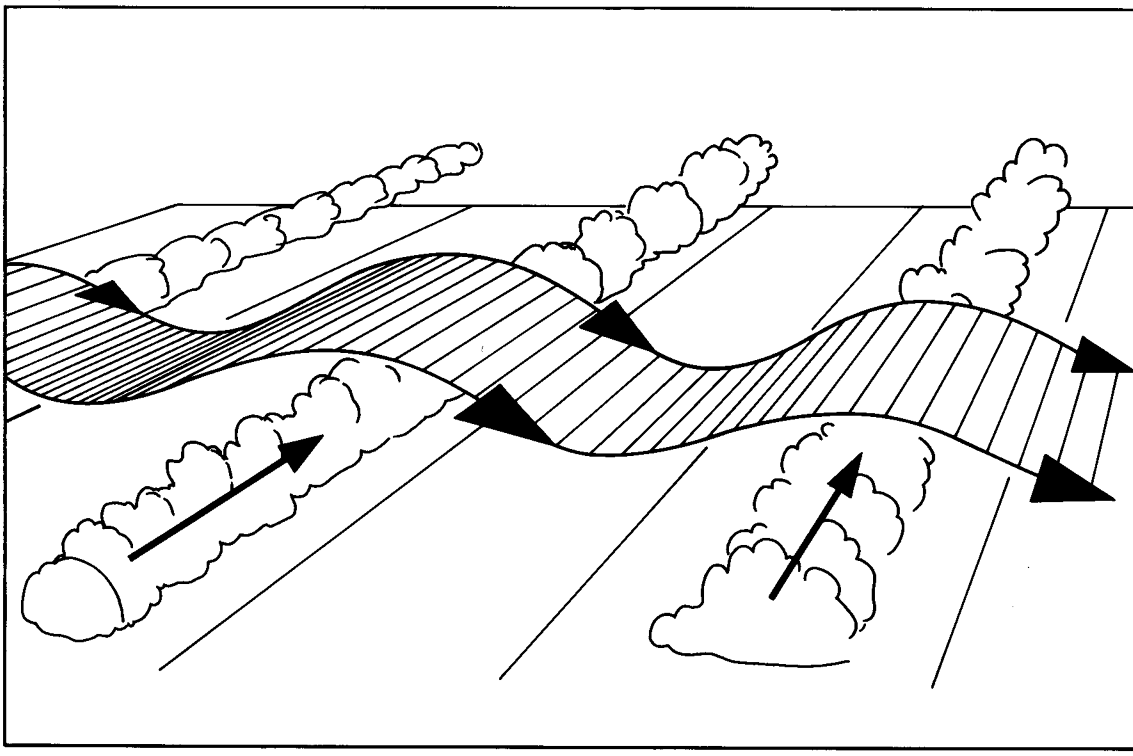


Figure 1. A three-dimensional sketch of waves above cumulus streets when the upper wind direction is at right angles to the wind in the convective layer.

waves can occur, even though the change of wind direction is much less than a right angle.

Cloud streets are not essential for the formation of such waves. Kuettner (1972) reported that waves had also been observed over individual cumulus clouds growing in a vertical wind shear.

3. Observations by glider pilots

3.1 Waves in shear conditions

Reports from glider pilots showed that individual clouds remained vertical while growing but began to tilt in the direction of shear when the updraught ceased. However, fresh thermals often produced new cells on the upshear side (Fig. 2). Such clouds produced transient wave-lift on the windward side. Glider pilots found rising air not only over the top of the cloud but also on the upshear side. This wave-like lift sometimes extended down below the condensation level. A number of pilots who halted their climbs to avoid entering cloud were subsequently able to ascend further in clear air just outside the cumulus. Some pilots found that if they remained circling in clear air just upwind of the cloud a new cell would soon envelop them.

This is different from what is observed in no shear conditions. Then, while the air inside a growing cumulus is moving upward, the edge of the cloud is more often a region of descent. This is usually the case when the cloud contains the kind of vortex-ring circulation proposed by Woodward (1959) and reported in cumulus clouds by Blythe *et al.* (1988).

3.2 Waves above cumulus congestus

Glider pilots have climbed in wave lift above the tops of very large cumulus. Such flights seem to be possible when the glider starts its climb:

(a) before the cumulus has grown large, or
(b) when the convection is temporarily suppressed.

In the first case gliders start by soaring hill-slopes before either thermals or waves have developed. On some days the development of cumulus seems to stimulate waves, and sailplanes are then able to climb in clear air up the windward face of large cumulus. Once at height they can remain in wave lift even if the clouds grow large enough to produce showers.

In the second case the passage of a heavy shower may cause a temporary halt to convection. During this lull, wave flow can descend to low levels and gliders are then able to climb up above the tops of further convective clouds. Heights in excess of 5 km have been reached when the shower clouds were large enough to produce a thunderstorm within 100 km.

3.3 Transverse waves over cloud streets

It is easy to visualize how parallel waves may form when the wind aloft blows across streets of cumulus. It is harder to see why transverse waves should be found when the wind direction aloft remains parallel to the streets. However, wave bars can be found on satellite pictures even when the flow is parallel to the alignment of the hills. For example, wave bars aligned north-north-west to south-south-east can form over Bantry Bay in Ireland when the west-south-westerly wind is

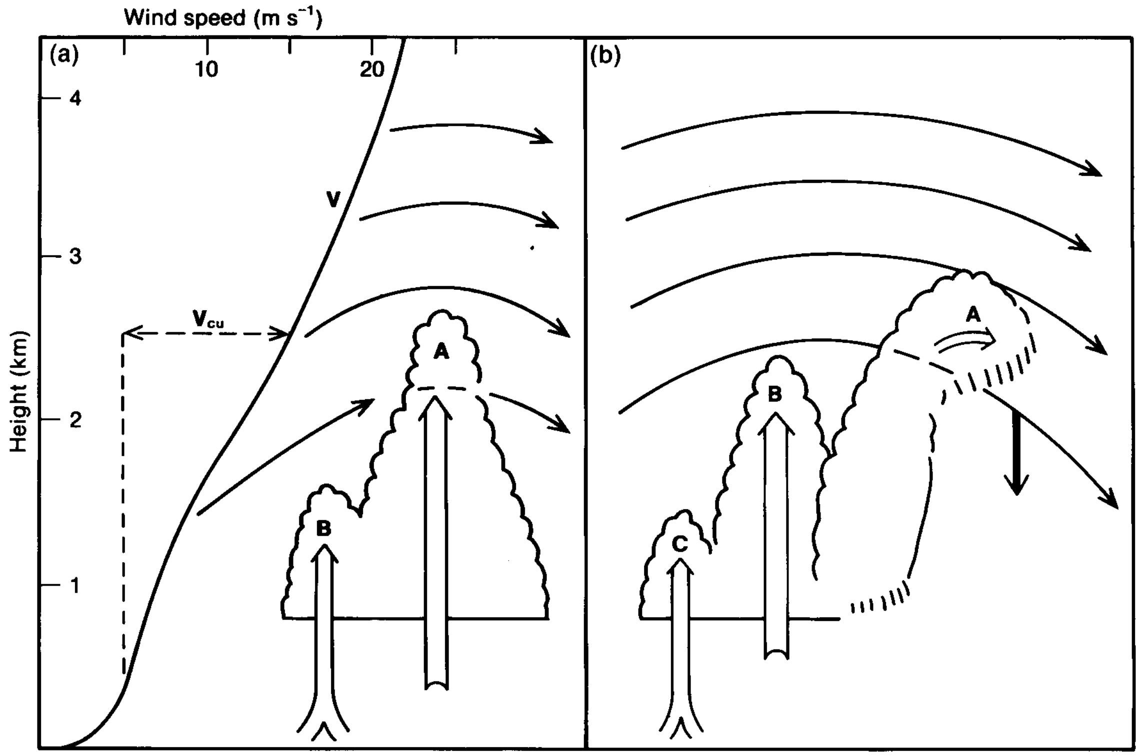


Figure 2. Waves over an isolated cumulus growing through a vertical wind shear. Individual thermals are labelled A, B and C. (a) shows an early stage with thermals at A and B, (b) shows the original cloud tilting and decaying when thermal A has ceased but a fresh thermal forming at C on the upshear side of the cloud. The variation of wind speed with height is shown on the left-hand side of (a), V_{cu} is the velocity of the cloud top relative to its base.

parallel to the peninsulas there. Evidently the preferred alignment of these waves is across the wind and it does not matter whether the starting impulse comes from a series of peninsulas sticking out into the flow or a long ridge at right angles to it.

Observations by pilots suggest that such transverse waves are common above cloud streets. They occur when the tops of cumulus are restricted by a stable layer and the wind speed increases with height while maintaining a constant direction. Fig. 3 shows a simplified version of the pattern. When the air aloft is too dry for lenticular clouds to develop, the position of wave crests is generally marked by a thickening in the lines of cumulus and a rise in the level of cloud tops. A description of these waves encountered by glider pilots over the United Kingdom appeared in an article by Bradbury (1984).

The conditions for transverse waves are also favourable for the development of orographic waves, and many of the transverse waves observed over the United Kingdom do seem to be initiated by hills. However, these waves are not rigidly controlled by the shape and alignment of major ridges. The unstable air often extends so far above the mountain tops that there seems to be no direct link between the underlying topography and the wave pattern aloft. It seems that the first wave is stimulated by stronger convection over the mountains. If the wave energy is trapped below a zone of very strong upper winds a regular pattern of wave bars can extend downstream with little regard for the underlying topography. The tendency for regular waves to extend across an area of irregular mountains has been mentioned by Scorer and Verkaik (1989).

3.4 The mobility of transverse waves

Most purely orographic waves usually appear long before convection begins and remain anchored to some feature of the topography for long periods.

Pilots' observations show that on days of deep convection the waves did not develop until cumulus clouds had formed. Waves which depend on the growth of convective clouds are not very stable and pilots find them less reliable than purely orographic waves. An example of a moving wave above cloud streets was reported by Purnell (1977). He encountered a cloudless transverse wave above cumulus streets whose tops were about 2400 m. The wave lift reached 4300 m near Basingstoke, at least 150 km downwind of the Welsh mountains. The region of lift appeared to be drifting slowly downwind so it seems that this wave was not anchored to any topographical feature.

Absence of visible wave bars can make it difficult to confirm the presence of such waves on satellite pictures. Even when wave clouds do appear there is nothing to show if they are stationary or moving.

4. Satellite pictures of transverse waves over cloud streets

Figs 4–6 illustrate the cloud patterns seen when transverse waves formed above cloud streets. Figs 4 and 5 are of Scotland when a north-westerly flow covered the country. Cumulus streets formed as soon as the air

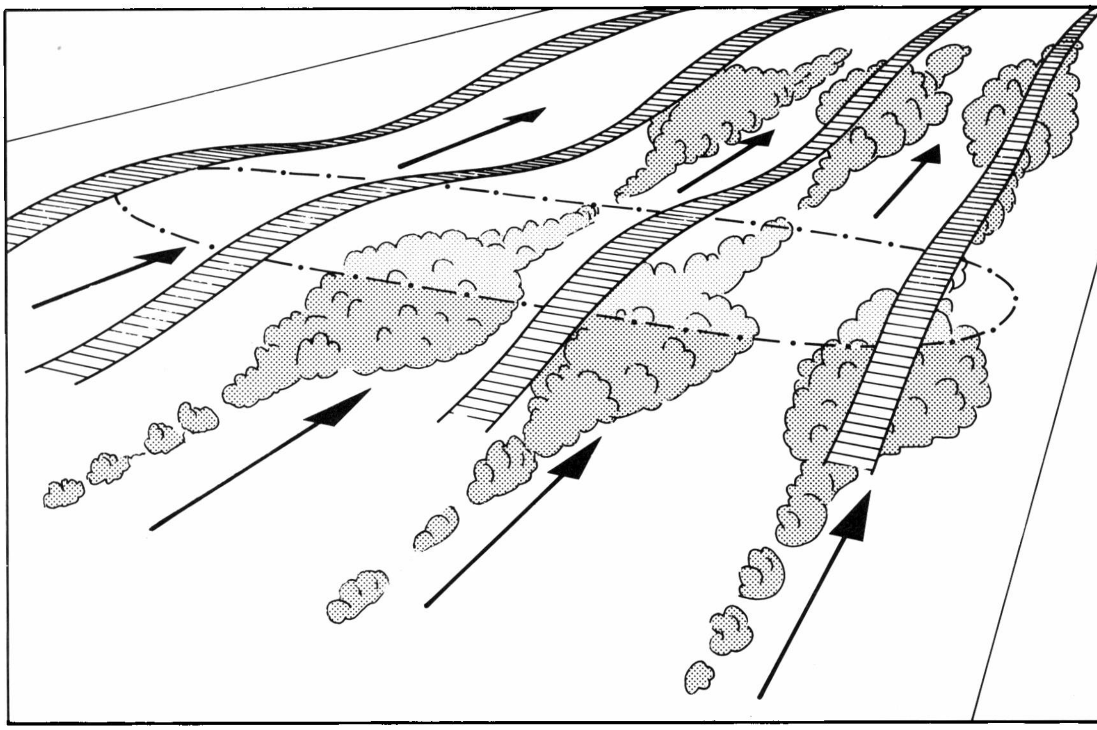
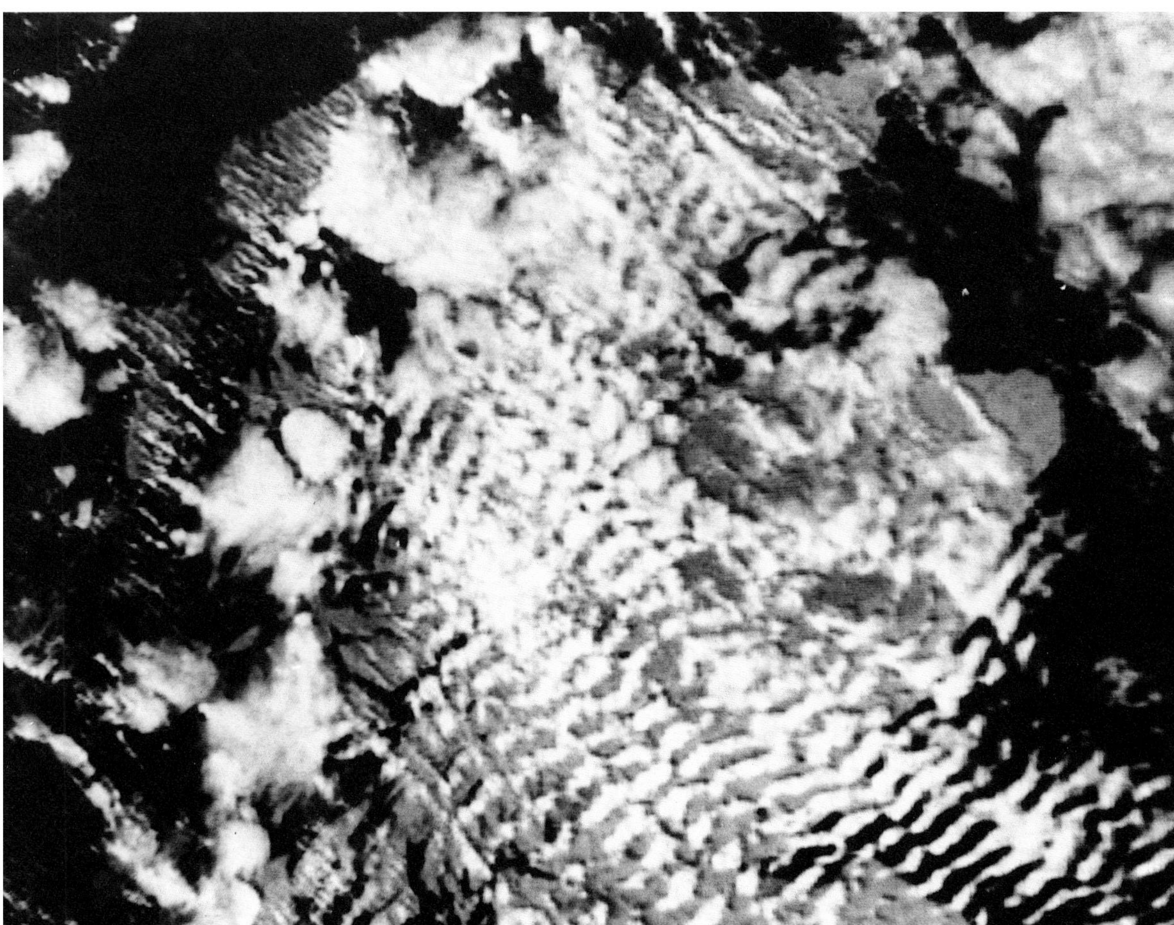
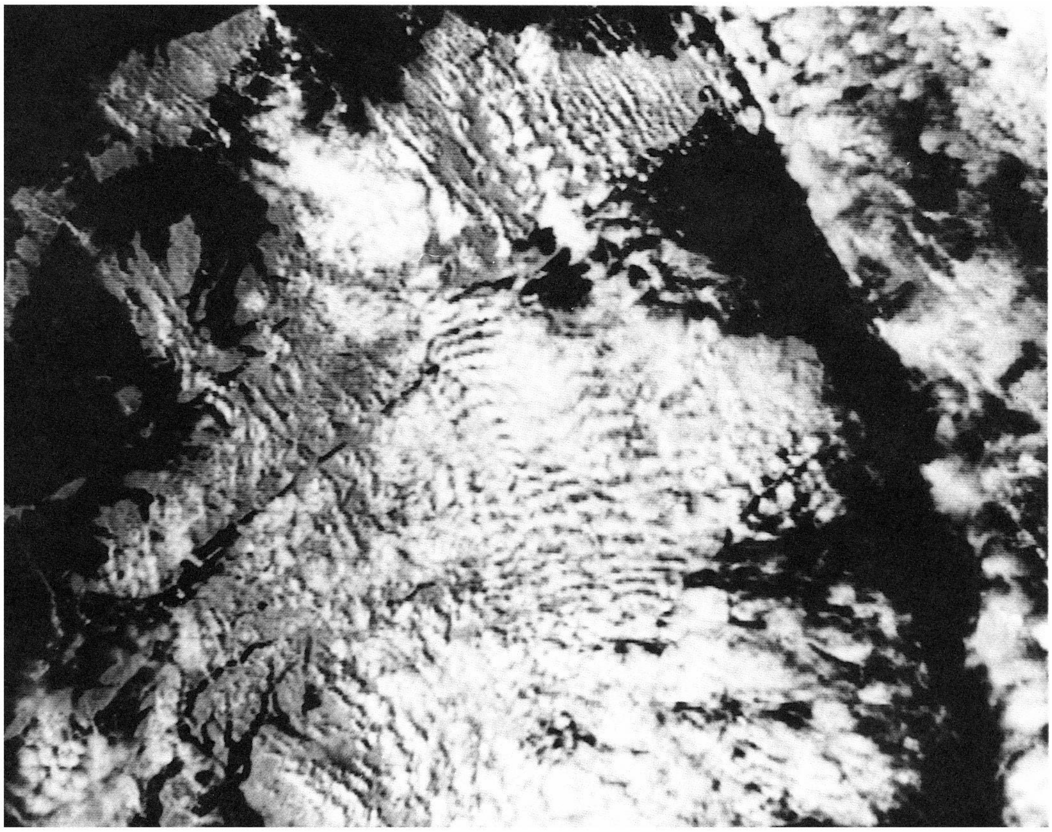


Figure 3. A three-dimensional sketch of waves with lines of peaks and troughs at right angles to lines of cumulus. The region within the dash-dot line shows where lenticular cloud may occur if the air aloft has sufficient moisture.



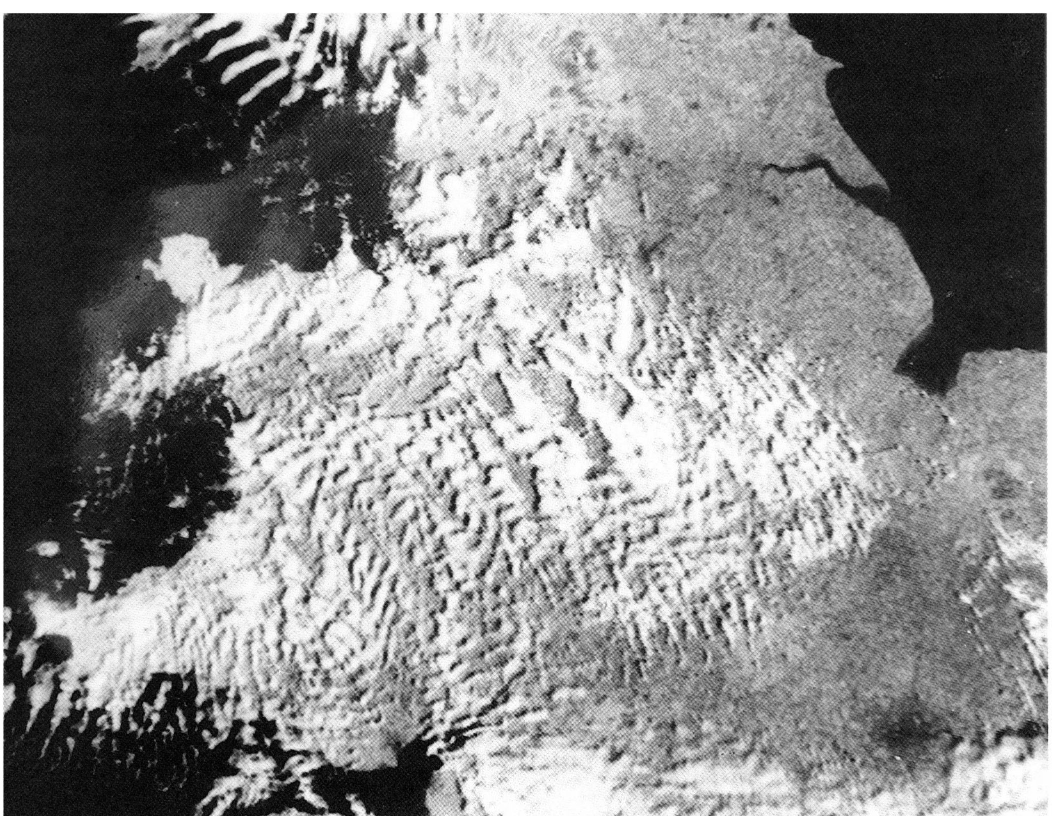
VHRR picture by courtesy of University of Dundee

Figure 4. Cloud streets and transverse waves over Scotland 1538 UTC 21 August 1980.



VHRR picture by courtesy of University of Dundee

Figure 5. Cloud streets and transverse waves over Scotland 1515 UTC 23 August 1980.



VHRR picture by courtesy of University of Dundee

Figure 6. Cloud streets and transverse waves over Wales and the Midlands of England 0838 UTC 21 August 1980.

reached land and transverse wave bars developed over the mountains. It seems evident that most, if not all, the visible waves were due to the mountains. However, in several places streets can be seen to persist under the wave clouds. This indicates that the helical circulation associated with cumulus streets was too deep to be disrupted by passage over the mountains. Where wave motion fails to produce transverse bars of cloud, the streets develop thicker patches in phase with the wave. This can be seen downwind of Cape Wrath.

Fig. 6 shows the pattern over Wales and the Midlands. Here the wave bars are neither so regular nor so prominent as over Scotland but there are several regions where transverse waves can be seen across lines of cumulus. In the region south-east of Birmingham there are transverse bands which do not seem to have any close association with the alignment of mountain ranges upstream. Over level ground the cloud streets sometimes appear to extend further downwind than the wave bars.

5. Importance of vertical wind shear

A growing cumulus can rise almost vertically even if it encounters a strong shear of wind. Kuettner *et al.* (1987) found a difference in velocity of 8–10 m s^{-1} between the interior of an active cumulus and the free air surrounding it. Although some of the environmental air may be entrained into the cloud, much of the flow is deflected over the top thus producing a vertical motion in the clear air above.

Lemone (1989) showed that strong shear tends to inhibit the growth of the weaker members of a field of cumulus but enables stronger ones to grow very much larger than they would in an atmosphere without shear. The shear increased both the horizontal dimensions and the life-time of the cumulus and suggested that the size to which a cumulus can grow may be a function of the shear. This effect could be attributed to wave development aloft, a theory also supported by Balaji and Clark (1988).

6. Exploration by powered aircraft

Although sailplanes are useful for detecting very small vertical motions they cannot make a thorough exploration of these waves. Powered aircraft are necessary to carry out a proper survey of wave–thermal interaction. Such a survey was carried out over Nebraska, USA, in a region 250–450 km east of the Rocky Mountains and reported by Kuettner *et al.* (1987).

Flights were made above long streets of cumulus when the wind direction changed by as much as 75 degrees between the cumulus level and the stable flow above. A vertical wind shear in excess of 3 m s^{-1} km^{-1} was observed. A surprising discovery by these flights was the vertical extent of waves. Wave oscillations were found to extend above 9 km (the height limit of the aircraft used). Vertical motions were in the range 1–3 m s^{-1} and the horizontal wavelengths varied between 5 and 15 km.

7. Numerical models

Although mathematical models of large-scale weather systems have existed for over 40 years it is only in the last 10 years that features as small as individual thermals could be resolved successfully. An early account by Mason and Sykes (1982) described a numerical model of horizontal roll vortices. This model also produced gravity waves which were very sensitive to the orientation of the rolls.

Some years later Clark *et al.* (1986) published the results from a two-dimensional model. This was used to investigate the developments when the upper winds blew across cumulus streets. The model results agreed well with observations made by aircraft and reported by Kuettner *et al.* (1987).

This line of research was extended by Balaji and Clark (1988) who showed that gravity waves could be formed in the stable layer aloft by excitation from convective eddies in the planetary boundary layer. Once formed these waves began to modulate the convection; in some circumstances very much larger cumulus could be produced after the waves had formed.

Although a rather different line was followed by Bretherton and Smoliarkiewicz (1989), their model also showed that a growing cumulus could produce a circulation in the environment which appeared to be due to spreading gravity waves.

Two dimensions are inadequate to describe developments in and above a field of cumulus so a three-dimensional model was developed by Hauf and Clark (1989). The changes produced by the extra dimension were:

(a) The long lines of cumulus used in the two-dimensional model were replaced by individual clouds scattered over the whole area.

(b) There was competition between longitudinal rolls forming cloud streets along the shear and transverse gravity waves aligned at right angles to these streets.

(c) The gravity waves tended to destroy the cloud streets but there still remained weak elements aligned along the shear. The pattern has been described as having a 'varicose-like' structure. Fig. 6 shows such a pattern over the Midlands of England.

8. Stages of development shown by numerical models

The numerical models showed the following sequence of events as convective eddies and waves interact:

(a) Surface heating sets off thermals which rise to the top of the convective layer and deform the interface producing undulations which act like hills to the flow above. Initially the size and spacing of these undulations depends on the characteristics of the boundary layer. Typically the wavelength of these undulations is about twice the depth of the convective layer.

(b) Gravity waves are set off by the flow of air across these undulations. The waves propagate upwards at 4–5 m s^{-1} and can reach the tropopause in less than an hour. However, it may take several hours for a quasi-steady state to develop throughout the troposphere. If the high-level winds are very strong the waves may be trapped below the tropopause and propagate long distances downstream. If they are not trapped, some wave energy may extend into the stratosphere. The horizontal wavelength shows wide variations but typically averages 9 km.

(c) Internal gravity waves then start to influence the growing thermals in the convective boundary layer. Convection is enhanced in regions beneath upward wave flow and inhibited where the waves impart a downward motion. As a result, new convective cells grow on the upshear side of the clouds. Any clouds which find themselves beneath the descending current are suppressed and presently disappear. Since the gravity waves usually have a wavelength greater than the initial spacing between cumuli, the waves slowly alter the size of eddies in the boundary layer. The distance between thermals in the boundary layer eventually adjusts to fit the length of the gravity waves aloft.

(d) If the convective layer is deep some cumulus may grow very much larger while others are totally suppressed.

The sequence is shown schematically in Fig. 7 which indicates vertical motions at several levels. Convective up- and downdraughts start at A. At B smoother wave flow starts in the stable layer at and above 2 km. At point C the feedback from waves aloft starts to dominate the eddies in the convective layer. The cumuli grow larger and are spaced further apart.

9. Effects of variations in shear and depth of instability

The cumulus clouds tend to grow on the upwind side and decay on the downwind side under the influence of the waves above. If the convective layer is shallow the movement of waves aloft is likely to reduce the life of individual thermals rising from the ground and clouds remain small. With a deeper convective layer a few of the cumuli grow large because they happen to be in phase with the wave lift above. Once a cumulus exceeds a certain size the favoured cloud continues to grow at the expense of smaller clouds all round. Continued growth then influences the gravity waves above and a positive feedback is established.

If there is no vertical shear the thermals produce hardly any gravity waves in the stable layer. The waves which do occur tend to move outward along the interface (like ripples on a pond) without propagating upwards.

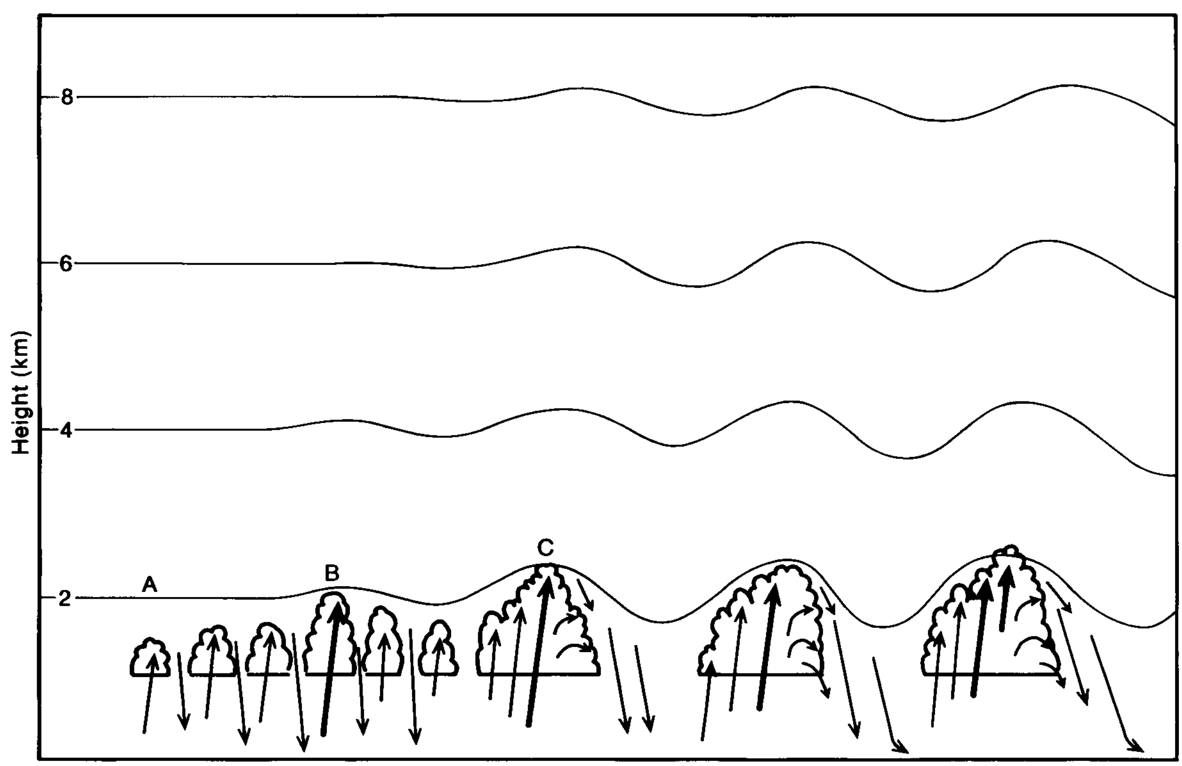


Figure 7. Height-time diagram showing schematically the development of thermals in the convective layer at A followed by upward propagating waves in the stable layer at B. The spacing of convective eddies becomes dominated by wave flow aloft beyond C.

10. Waves from the tops of cumulonimbi

There are reports of rare occasions when the tops of a vigorous Cb cloud over the USA penetrated the tropopause and set off a train of waves which moved away horizontally. These waves later initiated a further outbreak of convective storms far downwind of the original cloud (Uccelini 1975, Stobie *et al.* 1983).

Small amplitude waves occasionally produce a pattern in the anvil of cirrus blown off the top of a Cb. An example is shown in Figs 8 and 9. The pictures show the anvil cirrus streaming from the top of a maritime Cb over the Indian Ocean south of the island of Gan in the Maldives. The tops of Cb extended up to an easterly jet stream with velocities exceeding 100 kn at levels between 200 and 150 mb. One Cb set off this wave pattern in the cirrus. It was visible for several minutes before lower cloud obscured the view.

Figure 8. Waves in anvil cirrus downwind of a maritime cumulonimbus (Cb) over the Indian Ocean just south of Gan. The tops of a distant Cb had penetrated the equatorial easterly jet where wind speeds exceeded 100 kn.

Figure 9. Westward extension of the same train of waves as that shown in Fig. 8.

11. Conclusions

In an atmosphere with a vertical wind shear the development of thermals in the convective boundary layer can produce obstructions to the horizontal flow. These obstructions act like temporary hills and set off gravity waves in the stable layer. Such waves have been observed to propagate to heights in excess of 9 km and may penetrate the lower stratosphere. Some time after these gravity waves have developed aloft they begin to influence the location of convective updraughts from the surface. Thermals are stimulated beneath regions where wave flow is ascending but are suppressed where wave flow is descending. Thus the location and size of cumulus clouds is modified by the waves. On days of deep convection this effect may result in some cumuli becoming very much larger.

If the depth of convection is limited by a stable layer and cloud streets occur, the waves form parallel to the streets when the winds aloft blow across them. If there is no change in wind direction with height, transverse waves may form at right angles to the cloud streets. Although such waves are influenced by topography they can form even when strong convection extends far above any mountain summits. Then the initial stimulus to wave flow is provided by stronger thermals over the mountains rather than direct coupling between the terrain and the stable air immediately above.

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Real-time analysis of surface wind gusts using radar data: 25th January 1990

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Summary

Methods of estimating gust strengths near showers using radar derived velocities are explained, and possible future operational uses discussed.

1. Introduction

During Thursday 25 January 1990 a deep depression moved rapidly across the British Isles causing widespread damage, disruption to transport and interruption to electricity supplies over southern England and Wales. Forty-seven people are reported to have been killed by falling trees, masonry and scaffolding, in car accidents, and by drowning at sea. The total damage cost is expected to be well over a billion pounds.

Winds gusting to over 85 kn at ground level were recorded, comparable with the severe storm of October 1987. However damage was more severe and the death toll higher than in 1987 as the high winds occurred during the daytime when many people were out of doors, and over a greater area. The Meteorological Office forecasted the event very well, the first indication of an unusually low pressure system being issued 5 days in advance. Warnings of a severe storm were broadcast at midnight on Wednesday night.

Although the widespread destruction caused by the event was not fully reported until around midday on 25 January, the decision was taken during the morning to carry out the real-time analysis of the winds using radar data, employing the research and development versions of the operational Meteorological Office FRONTIERS system now known as Merlin (Browning and Carpenter 1984). The two systems were operated in parallel throughout the day, and the wind analyses and their implications for future operational systems are reported here.

2. Background

Since the early 1950s radar has been used to study the motion of small precipitation areas (see, for example, Ligda and Mayhew 1954, Tatehira *et al.* 1976, Parsons and Hobbs 1983). Unfortunately the movement of radar echoes may be related to the wind velocity at various levels in the atmosphere, and therefore care must be taken in associating echo movement with wind velocity at particular heights.

Bond *et al.* (1981) described a study of the speed of travel of shallow showers during the 1979 Fastnet Yacht Race and other occasions of strong winds. They found that such measurements gave a good indication of the peak surface gusts at exposed coastal locations (see section 6). In discussing the possible operational utility of such measurements, they concluded that radar images with a spatial sampling interval of at least 5 km and a temporal resolution of at least 5 minutes are needed to give reliable velocities from showers which are restricted to a well-mixed boundary layer (≦3 km deep). For comparison it should be noted that 100 kn is approximately equal to 3.1 km min^{-1}. Thus it was likely that an objective cell-tracking procedure was needed. This was confirmed by Monk *et al.* (1987), who also found that an operationally useful indication of the speed and direction of movement of two cyclonic vortices was provided by radar echoes.

In this paper an analysis procedure implemented in real time is discussed. In spite of the restrictions imposed by the availability of radar data only every 15 minutes, it has been possible to derive meaningful analyses which were generated within about 20 minutes of the nominal observation time.

3. Synoptic situation on 25 January 1990

An Atlantic depression underwent dramatic, well forecast, deepening early in the morning and moved north-east over Ireland and southern Scotland with a central pressure of about 955 mb and with a shallow trough extending southwards to the rear of the surface cold front. Radar composite images at 0930 and 1000 UTC on 25 January 1990 are shown in Figs 1(a) and 1(b). The position of the front is indicated in Fig. 1(a) as the three areas of heavy precipitation over south-east and central England. Winds increased as the trough, marked by the precipitation over Wales and Cornwall, approached. Behind this trough winds eased somewhat in the south. A rapid rise of pressure behind the trough over Ireland caused a tightening of the gradient in the north where the strongest winds were from north of west.

4. FRONTIERS velocity analysis facilities

The FRONTIERS precipitation nowcasting system allows the forecaster to derive the velocity of features in

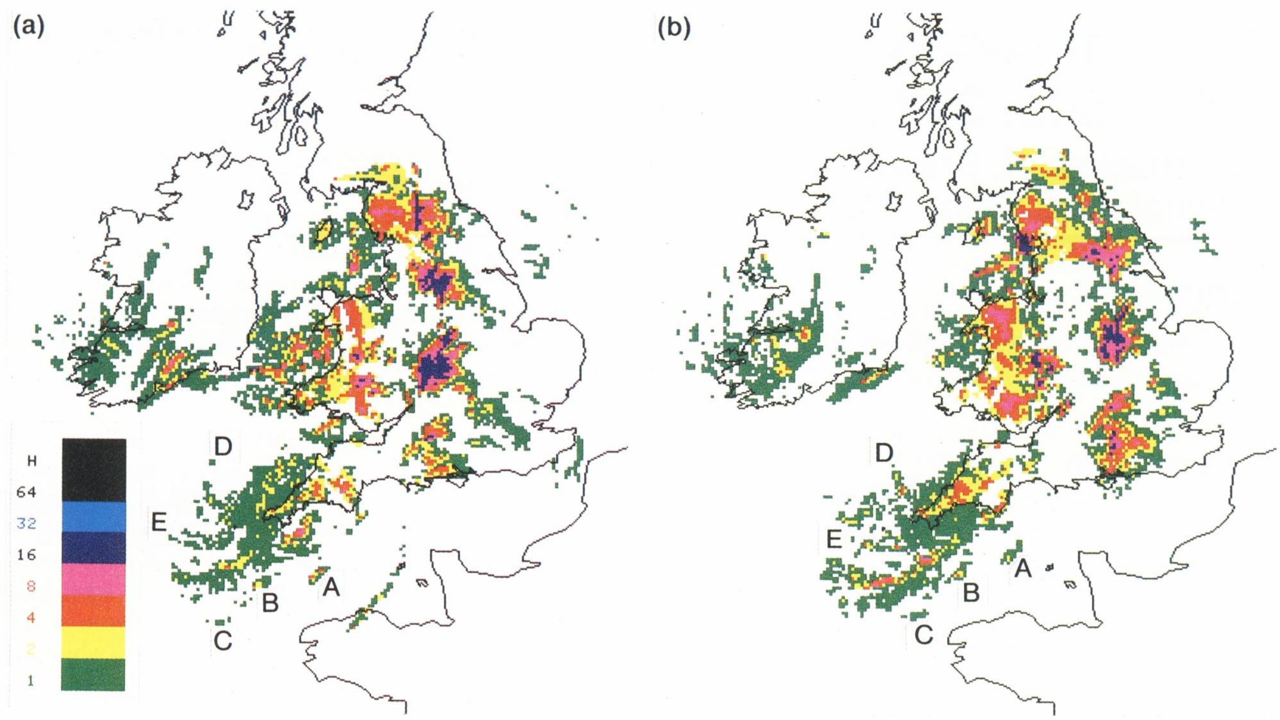

Figure 1. Radar composite images at (a) 0930 and (b) 1000 UTC on 25 January 1990. Each data square is 5 km × 5 km and different colours represent instantaneous rainfall rates (mm h^{-1}) as shown on the colour code given on the left of the images. Cells used to derive echo motion are labelled with the letters A–E on each image.

the radar (or satellite) imagery. At present the methods are only semi-automated and the forecaster interacts with the system through visual display units (VDUs) equipped with touch-sensitive screens. The imagery is presented in colour on a main monitor and control menus appear on alphanumeric VDUs. Radar data are available at 15-minute intervals but forecasts are only produced from data at half-hourly intervals.

Two methods are available for determining velocities, Touch Same Feature (TSF) being the quicker method. The forecaster is invited to touch the same feature in the current and T−30 mins radar pictures and the system computes the velocity from the displacement. The 30-minute interval is a compromise between the need for a significant displacement relative to the 5 km resolution of the radar data and the need to be able to identify the same feature. It is very difficult to use if the target is evolving or other potential targets are nearby.

The preferred method is known as Lagrangian Replay (LR). The forecaster sets up a replay sequence of radar pictures, typically 1–2 hours duration, and touches the same feature on the first and last picture of the sequence. From these touch points the system computes a velocity as for TSF. The entire sequence is then replayed at several frames per second with the computed velocity being subtracted. If the chosen feature remains stationary then its velocity must equal that which is being subtracted. If it is not quite stationary, it can be made so using a joystick attached to the system and the velocity is recomputed. This method is generally more accurate than TSF, especially for low velocities. On this occasion the two methods yielded similar velocities because large displacements occurred over a half-hour period.

5. Echo-velocity measurement and analysis

The velocity vectors shown in Fig. 2 were obtained using the development version of the FRONTIERS system, known as Merlin, which is located in the Nowcasting and Satellite Applications Branch of the Meteorological Office. A speculative measurement made around 1020 UTC gave a velocity of 85 kn for a discrete echo over the English Channel which, bearing in mind the results of Bond *et al.* (1981), indicated the likelihood of severe gusts. Therefore it was decided to operate Merlin in real time to evaluate the number of cell velocities which might be obtained operationally and to compare the measured velocities with observed gusts. Real-time measurements commenced at 1130 UTC and terminated at 1500 UTC. The number of velocities obtained was probably more than would be obtained during operational use of the current FRONTIERS system because the rest of the rainfall analysis normally carried out on FRONTIERS was omitted. Thus about 9 minutes was devoted to echo velocity determination per 30-minute cycle, compared with about 5 minutes available operationally. However the FRONTIERS' software runs more slowly on Merlin because the computer is shared with many other users.

The targets used to find the vectors were ideally small, well defined and long-lasting echoes. The showers ahead of the trough in the English Channel, and to rear, north of the Scillies were easy to follow. Farther north and east

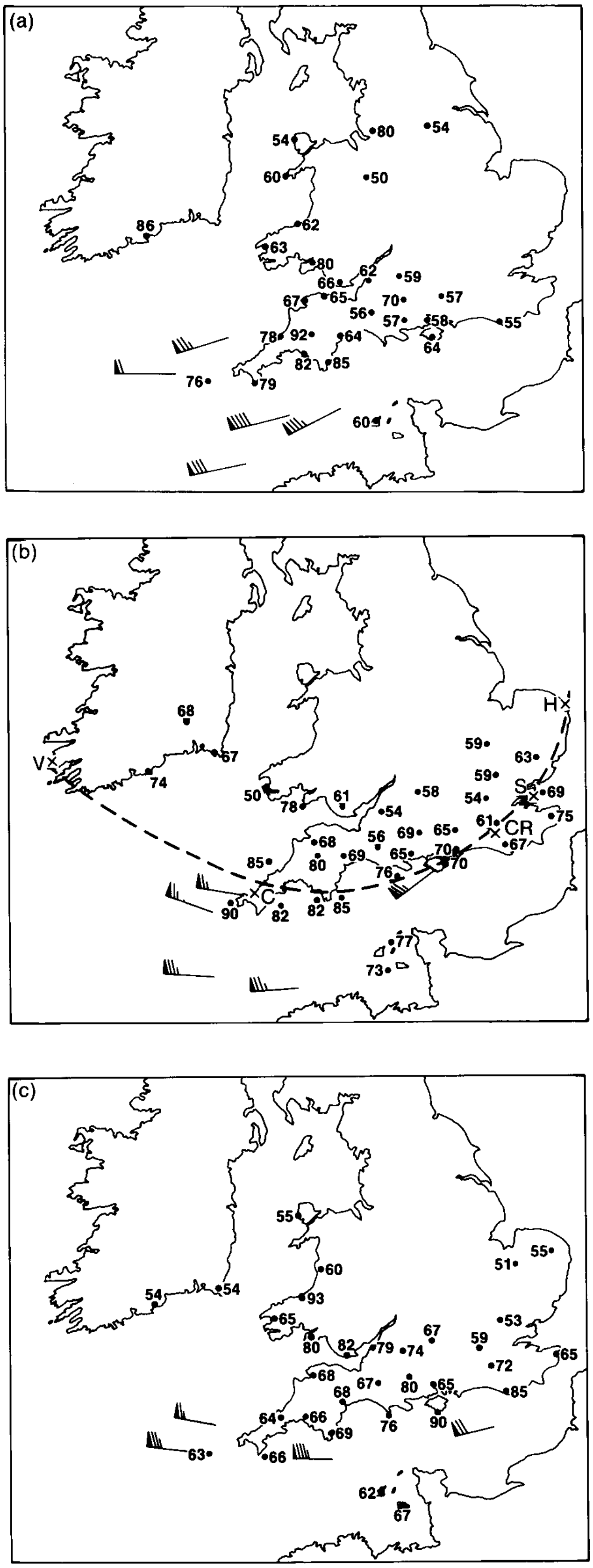

Figure 2. Anemometer measured gust speeds over 50 kn shown as numbers at (a) 1000 UTC, (b) 1200 UTC and (c) 1400 UTC on 25 January 1990. Wind arrows show radar echo speeds derived in real time. In Fig. 2(b) the streamline from Valentia (V) in the west to Hemsby (H) in the east is shown, passing through Camborne (C), Crawley (CR) and Shoeburyness (S) (see Fig. 4).

individual echoes were less discernible and so the analysis concentrated upon the south. The larger areas of precipitation evident in Figs 1(a) and 1(b) were not used because they would be likely to give velocities characteristic of the trough or front which would not necessarily be that of the wind at the top of the boundary layer. Cells lettered A–E in Figs 1(a) and 1(b) were chosen to determine wind speeds, and comparison of their positions in the two figures gives dramatic indication of their movement in only 30 minutes.

Almost all the vectors were obtained using LR because it normally avoids confusion over exactly which feature is being tracked. However, occasionally time was wasted because totally unrealistic velocities were obtained, e.g. 315°/08 kn around Lands End at 1400 UTC. This was the consequence of a stroboscopic effect which can occur with fast moving discrete cells. For example if shower lines are 20 km apart and move 20 km in 15 minutes then little movement would be seen during a replay as one cell was replaced by the next cell upwind.

The results of the analysis at 1000, 1200 and 1400 UTC are shown in Fig. 2. Because the real-time analysis began after gusts of over 60 kn were widespread across the south, it was decided to analyse the 1000 UTC data retrospectively, although the 85 kn vector west of the Channel Islands was obtained in real time. The gusts reported on the synoptic hour are shown as numbers and the echo-derived velocities as wind shafts, with one full feather representing 10 kn. The east-north-east progression of the largest gust is apparent from Fig. 2. The key feature of Fig. 2 is that the echo velocities and largest gusts are of comparable magnitude, as found by Bond *et al.* (1981). However the spatial distribution of the echo velocities does not appear to be particularly illuminating. For example, the gusts of up to 90 kn on the west coast of Cornwall at 1200 UTC are not reflected in comparable upwind velocities (Fig. 2(b)), although comparable velocities were obtained to the south at 1000 UTC (Fig. 2(a)). It was not possible to measure velocities over south-east England and East Anglia in the afternoon, due to power failures at the Wardon Hill and Chenies radars. Therefore it is not possible to determine whether a maximum in echo velocity tracked east-north-east as did the maximum in gust magnitude.

6. Depth of convection

In the study of Bond *et al.* (1981) the agreement between the speed of the showers and the magnitude of the gusts was attributed to the shallow nature of the convection. Thus the echo speed was unambiguously characteristic of the wind speed one or two kilometres above the surface, which could plausibly be brought unmodified to the surface by downdraughts. In addition, the shallow nature of the convection prevented vigorous downdraughts developing which, upon reaching the surface, might have diverged and generated gusts greatly in excess of the shower velocity.

The FRONTIERS system allows the operator to extract quickly the mean and minimum temperature within a designated area from the Meteosat infra-red data. On this occasion only the 1400 UTC satellite data were received into the Merlin system in real time. Then the convective cells which were tracked in the western English Channel were found to have tops at −31 °C, and are very close to the positions identified as a source of atmospherics (lightning). Study of the FRONTIERS archived data showed that earlier the coldest cloud tops being tracked were about −18 °C. Both these values fit well with inversions apparent on the midday ascent from Camborne at around 630 mb and 450 mb as in Fig. 3. Therefore most of the targets used had tops around 3000 m at first, rising to more than 6000 m later.

Since the convection was not particularly shallow, the justification for equating the speed of the showers to the maximum gusts is the absence of shear above 850 mb as indicated by Fig. 3. To confirm that this was a general feature, a cross-section of wind speeds is shown at Fig. 4. The horizontal axis is the nearly circular arc as sketched in Fig. 2(b). This is very nearly a streamline and runs from Valentia (V) in south-west Ireland, through Camborne (C) in Cornwall, and through Crawley (CR) and Hemsby (H) in the south-east of England. Unfortunately neither Larkhill nor Shoeburyness were able to launch balloons successfully around midday, but Hemsby had to launch an extra flight 45 minutes after the first. Allowing 110 km displacement for this delay,

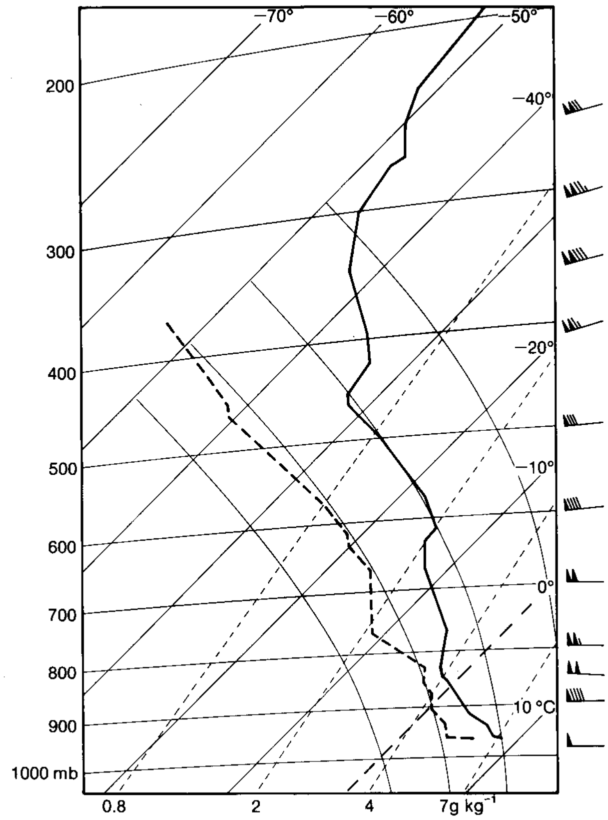

Figure 3. Radiosonde sounding at Camborne in south-west England at 1100 UTC on 25 January 1990. Winds are also shown, traditionally.

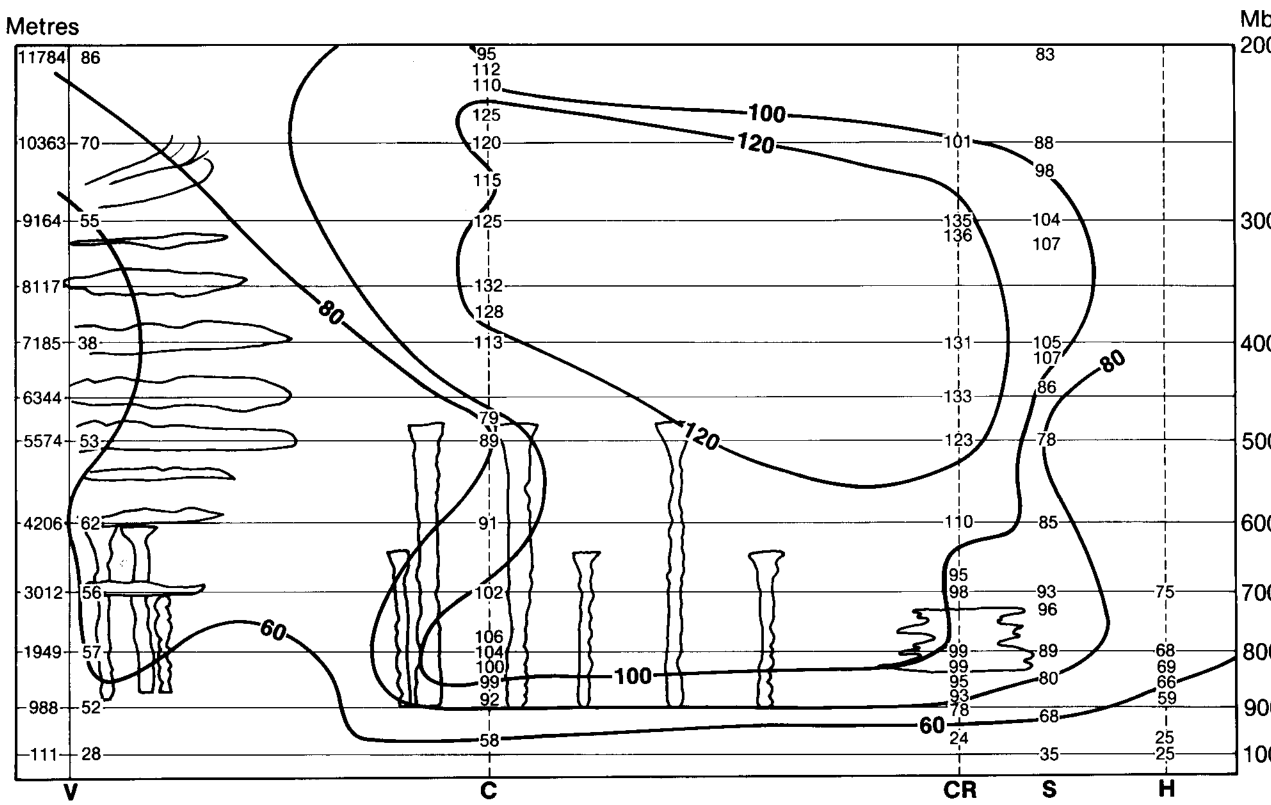

Figure 4. Vertical cross-section at 1200 UTC on 25 January 1990 of the wind speed (kn) approximately along a streamline between Valentia and Hemsby (see Fig. 2(b)). Also shown, schematically, are the extents of the observed clouds.

winds have been included for a location near Shoeburyness.

The cross-section confirms the very strong shear in the boundary layer and the insignificant shear above 850 mb. Thus even if the speed of the echoes is governed by the wind speed at some level between 850 and 600 mb, this should still be a good guide to the wind speed lower down. In fact, for reasons that are not clear, the modal speed of the echoes, which is around 75 kn, is less than the wind above the sheared region, which is around 100 kn.

7. Implications for future operational use

The analysis of winds described in this paper was carried out in real time in parallel with the operation of FRONTIERS in the Central Forecasting Office. The question arises as to whether or not such a dedicated procedure can be combined with the routine analysis of the radar and satellite data embodied in normal FRONTIERS operation.

Clearly the surface winds were the 'problem of the day' as the precipitation was not exceptional, yet precipitation analyses are still required continuously. Therefore it may be that either FRONTIERS must be further automated to allow the forecaster to concentrate on particular problems of severe weather if the need arises, or in such circumstances parallel operation of two (or more) workstations as envisaged by Browning and Golding (1984) must be undertaken. The use of a research system might be appropriate when such severe weather is expected, particularly as the case described in this paper suggests that it might be possible to link the location of the showers to occurrences of falling trees and therefore increased risk of damage and even death.

Constraints on forecaster availability exist at present, and undoubtedly this will be the situation in the future. Hence the multiple workstation approach may not be practical, except for situations in which tasks are very different; for example one workstation for numerical model initialization and another for imagery interpretation. There is scope, however, to develop a future generation of FRONTIERS systems with a capability to operate automatically, producing routine products whilst allowing the forecaster to function in a separate mode, which may be to cope with emergencies or to deal with specific difficult analysis problems. Of particular interest might be the possibility of determining radar echo height and absence of wind shear from three-dimensional reflectivity and Doppler data which may become available in the future generation of operational radars in the United Kingdom. These data, used with numerical model output, offer intriguing possibilities. The need to consider these alternatives is highlighted by the analysis reported here.

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Notes and news

Old views on climate change

The following are extracts from an address which would be topical even today; the speaker and the date are revealed at the end.

'There are, I believe, few persons who have noticed, and who can recollect, the state of the climate of England half a Century ago, who will not be found to agree in opinion that considerable changes have taken place in it; and that our Winters are now generally warmer than they were at that period. My own habits and pursuits, from a very early period of my life to the present time, have led me to expose myself much to the weather in all seasons of the year, and under all circumstances; and no doubt whatever remains in my mind but that our Winters are generally a good deal less severe than formerly, our Springs more cold and ungenial, our Summers, and particularly the latter parts of them, as warm at least as they formerly were, and our Autumns considerably warmer; and I think that I can point out some physical causes and adduce some rather strong facts, in support of these opinions.

Within the last fifty years very extensive tracts of ground, which were previously covered with trees, have been cleared, and much waste land has been enclosed and cultivated; and by means of trenches and ditches and other improvements in agriculture and covered drains, the water which falls from the clouds, and that which arises in excess out of the ground, has been more rapidly and more efficiently carried off than at previous periods. The quantity of water which our rivers contain and carry to the sea in Summer and Autumn, is in consequence, as I have witnessed in many instances, greatly diminished; and upon the estate where I was born, and which I now possess, my title deeds, and the form of the ground, prove a mill to have stood, in the reign of Queen Elizabeth, and probably at a good deal later period, in a situation to which sufficient water to turn a mill-wheel one day in a month cannot now be obtained in the latter part of the Summer and Autumn. Under these circumstances the ground must necessarily become much more dry in the end of May than it could have been previously to its having been enclosed and drained and cultivated; and it must consequently absorb and retain much more of the warm Summer rain (for but little usually flows off) than it did in an uncultivated state; and as water in cooling is known to give out much heat to surrounding bodies, much warmth must be communicated to the ground, and this cannot fail to affect the temperature of the following Autumn. The warm Autumnal rains, in conjunction with those of the Summer, must necessarily operate powerfully upon the temperature of the succeeding Winter; and, consistently with this hypothesis, I have observed that during the last forty years, when the weather of the Summer and Autumn has been very wet, the succeeding Winter has been in the climate of this vicinity generally mild. And that when north-east winds have prevailed after such wet seasons the weather in the Winter has been cold and cloudy, but without severe frost, probably in part owing to the ground upon the opposite shores of the Continent being in a state similar to that on this side the Channel.

Supposing the ground to contain less water in the commencement of Winter on account of the operation of the drains above-mentioned, as it almost always will, and generally must do, more of the water afforded by dissolving snows, and the cold rains of Winter, will be necessarily absorbed by it; and in the end of February, however dry the ground may have been at the Winter solstice, it will almost always be found saturated with water derived from those unfavourable sources; and as the influence of the sun is as powerful on the last day of February, as on the 15th of October, and as it is almost wholly the high temperature of the ground in the latter period, which occasions the different temperature of the air in those opposite seasons, I think it can scarcely be doubted that if the soil have been rendered more cold by having absorbed a larger portion of water at very near the freezing temperature, the weather of the Spring must be, to some extent, injuriously affected. But whether it be owing to the preceding, or other causes, I feel most perfectly confident that the weather in the Spring has been considerably less favourable to the blossoms of Fruit Trees, and to vegetation generally, during the last thirty years, than it was in the preceding period of the same duration; and I shall in conclusion adduce one fact, the evidence of which I think cannot easily be controverted. The Herefordshire farmers formerly calculated upon having a full crop of acorns upon the oaks, which grew dispersed over their farms, once in three years; but a good crop of acorns is now a thing of rare occurrence, upon the value of which the farmer has almost wholly ceased to calculate, even upon those farms which contain extensive groves of Oaks. The trees nevertheless blossom annually very freely, but no fruit is produced. Many causes may be assigned for the diminished produce of Orchards, and of Fruit Trees generally; but the blossoms of the Oak must be now as capable of bearing cold as they were half a century ago, and their failing to produce acorns can only be attributed to the agency of some external cause; and I am wholly unable to conjecture any such cause except the above-mentioned.'

The address entitled 'Upon the supposed changes in the Climate of England' was given on 5 May 1829 to the Royal Society by its President, Thomas Andrew Knight.

Review

Turning up the heat, by F. Pearce. 129 mm × 197 mm, pp. 230, *illus.* London, Glasgow, Toronto, Sydney, Auckland, Paladin Books, 1989. Price £4.99.

The late 1980s were marked by a tremendous rise in public awareness of 'green affairs'. Concern was directed on the one hand towards issues that affected our own back yards — toxic and nuclear waste disposal, food quality — and on the other towards global issues; in particular, human interference with the chemical composition of the atmosphere — the greenhouse effect and the ozone hole. None of these issues look likely to disappear in the near future, and it is hoped that the decade of the 1990s will be marked by positive action to reduce these threats. However, public concern must be matched by public knowledge. To succeed, pressure for change requires a sound basis of scientific understanding. There is therefore a very real need for a literature that will describe, in terms understandable to the intelligent lay-person, the chemical, physical and biological processes which, coming together, have the capacity to constitute environmental threat.

Turning up the heat is a contribution to the non-specialist literature on the greenhouse effect, advertising itself as 'The First Handbook to the Greenhouse Age'. The subject matter ranges widely from the straightforward consideration of the principles underlying the greenhouse effect, through matters as diverse as the death of the dinosaurs and the political debate surrounding the Montreal Protocol. A book with such diverse themes requires a strong structure, and yet the material in one chapter seldom bears any clear link to what has gone before, and what follows.

The book opens with a discussion of the ozone hole (what it is, how it was discovered) and the Montreal Protocol. Chapter 2 looks at the origins of the Earth, and spends some considerable time describing the evolution of the scientific debate that surrounds the Gaia hypothesis. This is followed by two chapters covering (too superficially) desertification, the green revolution, deforestation and other related (?) issues. Then it's back to hard science, with a chapter on cloud formation, the role of algae and dimethyl sulphide. Finally, in chapters 6 and 7, we come to radiative mechanisms which underlie the greenhouse effect, the role of the oceans, feedbacks, and the potential impacts — what climatologists would generally regard as the nuts and bolts of the whole issue. Chapter 8 looks at El Niño Southern Oscillation, and chapter 9 at the causes of Ice Ages, Milankovitch cycles and the role of the deep ocean circulation. Chapter 10 examines the sources of non-CO_2 greenhouse gases, chapter 11 rising sea levels, chapter 12 increasing global populations and chapter 13 possible ways to defuse the greenhouse effect.

As can be seen from the preceding paragraph, my major criticism of this book is its lack of organization. In general, the material is up-to-date and presented in terms possible for the lay-person to understand without dodging the issues or being condescending. There is some tendency to oversimplify, most obvious in the early and, in part, superfluous chapters on African agriculture and the Amazonian rain forests. The author is clearly well-read and well-informed, although not as much as he would perhaps like us to believe — I was interested to read that Alayne Street-Perrot has undergone a sex change. All in all, however, if I was looking for a book to inform my teenage children or my next-door neighbour on the greenhouse effect, this is one that I would be happy to hand over.

J.P. Palutikof

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Operational analysis and prediction of ocean wind waves, by M.L. Khandekar (New York, Berlin, Springer-Verlag, 1989) is an attempt to compile the present state of knowledge of the topic. It aims to satisfy the need for a ready reference on the various techniques and their uses.

Carbon dioxide and global change: earth in transition, by S.B. Idso (Tempe, Arizona, IBR Press, 1989) contains an analysis and review of the many potential consequences of the rising carbon dioxide content of the earth's atmosphere. Included also are 100 pages of references to publications on the many interrelated aspects of the subject.

Noctilucent clouds, by M. Gadsden and W. Schröder (Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong, Springer-Verlag, 1989) includes what is known about noctilucent clouds, drawn from many separate sources. It is aimed at a wide variety of readers.

Weather radar networking, edited by C.G. Collier and M. Chapuis (Dordrecht, Boston, London, Kluwer Academic Publishers, 1990) gives an account of the lectures presented at a COST 73 Project seminar in Brussels on 5–8 September 1989. Almost 60 papers are included on the many aspects of the theory and application of the subject.

Impact models to assess regional acidification, edited by J. Kämäri (Dordrecht, Boston, London, Kluwer Academic Publishers, 1990) divides the subject into terrestrial and aquatic effects, and model reliability and utility. Also included is a chapter on future directions for research.

Satellite photograph — 21 April 1990 at 1445 UTC

The NOAA-11 visible photograph shown in Fig. 1, showing the central and eastern Atlantic, has been reproduced from a picture received on a facsimile machine. The picture shows several frontal zones, each seen by clearly defined bands of cloud. Comparison with the corresponding infra-red image (not shown) indicates that, except near Spain (lower right), almost all the cloud is at low levels.

Apart from the front labelled 'W', all the surface fronts can be located using cloud information — either along the narrow cloud bands ('C' and 'I'), or along the axis of the bright (thickest) cloud ('E'). Front 'I' is associated with a depression which is centred between Iceland and Greenland. South of Iceland, the front is marked by a rope cloud — a narrow filament of cloud associated with low-level line convection. It is unusual to see rope clouds so far north since, near depressions, most middle-latitude fronts are covered by middle/upper-level cloud.

Fronts 'C' and 'E' have become slow moving within a region of high pressure (Fig. 2). Fronts tend to become weak near anticyclones, but as this image shows they may persist as distinct cloud features.

In the cloud-free zone off the coast of south-east Greenland, there is a narrow gap separating a region of thin ice (out to sea) and thick ice (near the coast). Nearer Iceland, a chain of cloud vortices indicates that there is considerable small-scale detail which is not indicated on the synoptic-scale chart shown in Fig. 2.

G.A. Monk

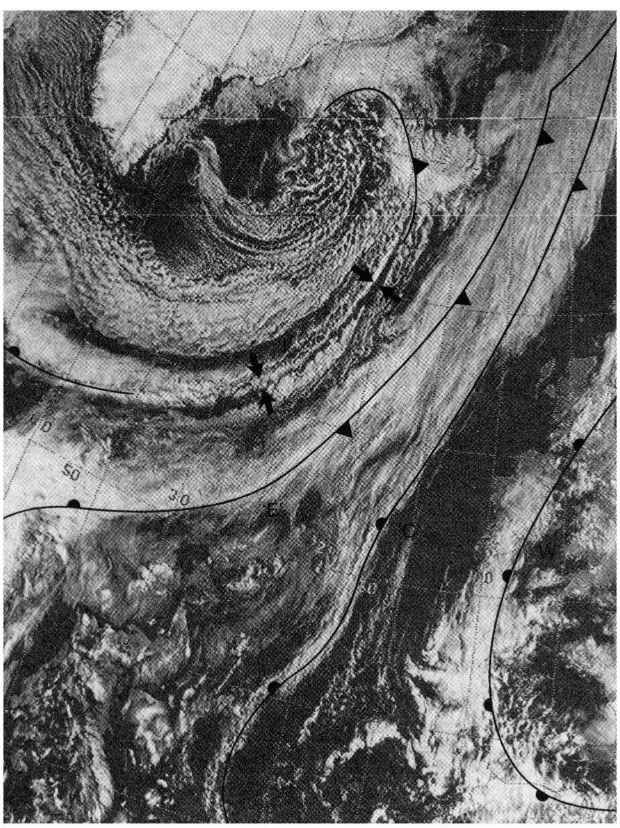

Figure 1. NOAA-11 visible image on 21 April 1990 at 1445 UTC. Frontal positions have been superimposed. South of Iceland, front 'I' is marked by arrows.

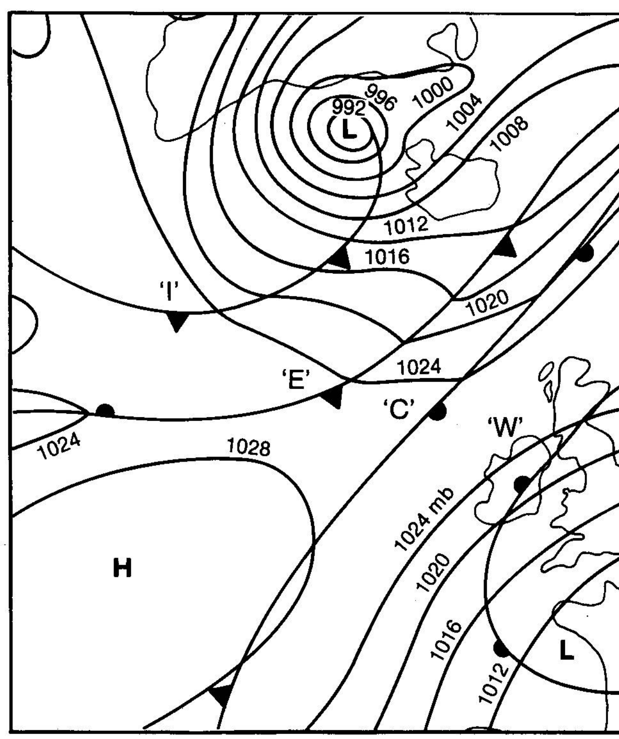

Figure 2. Surface analysis on 21 April 1990 at 1200 UTC.

GUIDE TO AUTHORS

Content

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Preparation and submission of articles

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (Compucorp or IBM-compatible) can be labour-saving, but only a print-out should be submitted in the first instance.

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