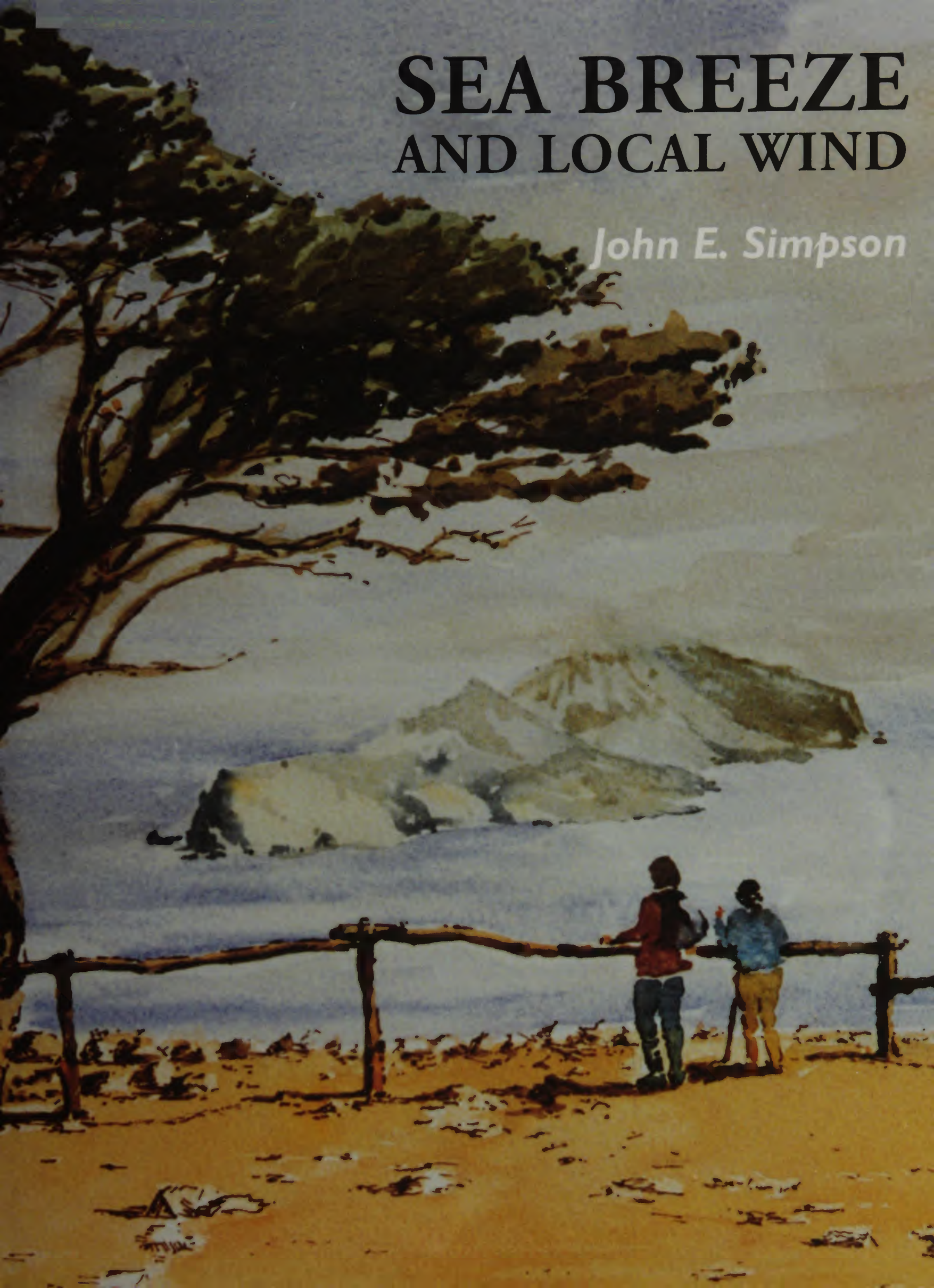


# SEA BREEZE AND LOCAL WIND

*John E. Simpson*



The sea breeze affects our lives in many ways; it controls our local weather, not only on the coast but also in many districts inland. Air pollution and smog, the distribution of airborne insect pests and the spread of pollen are all controlled by the sea breeze. In the world of sport it is important to glider pilots, sailors and surfers, and balloonists.

In this book we see how radar, lidar and satellite photography have helped to forecast and map the sea breeze and the all important 'sea-breeze front'. The book ends with a description of laboratory experiments, mostly carried out by the author and his co-workers, and a simple summary of theoretical models. This book will be welcomed by those researching in the subject but will also be valuable to the general reader who is interested in local weather and the natural environment.

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## **Sea breeze and local winds**

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JOHN E. SIMPSON

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# Foreword

Everyone depends on the atmosphere for their breathing, for its protection of the earth's surface from the solar radiation, its winds for ventilation and transport, its rain which feeds the crops and its clouds which help prevent us freezing or roasting. Of course there have been many books ranging from the most popular to the most learned on the atmosphere and its motion. But few books have focussed on the special features of the atmosphere caused by the effects of the sea on the climate and weather of land areas near the coasts. Since most people in the world live within 200 km of the coasts, it is not surprising that this aspect of meteorology has been important since the time of the ancient Greeks.

John Simpson has always been an active meteorologist, during his career as a glider pilot, a science teacher and latterly a university research scientist, and an excellent photographer. I have known him as a colleague at Cambridge over the past 17 years and was guided by him to see the atmosphere with new eyes. Firstly we all learnt, after he arrived in Cambridge, that indeed sea breezes reached us at about 7pm (7 arrived in the remarkable summer of 1976). He had set up a set of stations between us and the coast to track its movement. He also began to interest a number of colleagues to join with him in a series of laboratory experiments that quite changed the scientific understanding of 'gravity currents', which are the basic mechanism for driving the cool sea breezes inland. He has received visitors from far and wide and had an enormous correspondence; there is no sea breeze in the world that he has not heard about. This book is an excellent account of them; their history, their different types depending on the coastline or the synoptic situation, their connection with local weather such as clouds and rain, their effects on pollution, aircraft and bird flight, their measurements which nowadays includes radar, and finally some of the laboratory studies at Cambridge and elsewhere.

*Professor Julian Hunt, FRS  
Chief Executive, Meteorological Office, Bracknell*

# Preface

I first met the sea breeze over 50 years ago when, due to my ignorance of its existence, I landed a glider downwind after a long flight to the east coast. The result of this ignorance was nothing worse than an over-shoot into a field of beans.

My later experience of the sea breeze was obtained in gliders, finding out the nature of the sea-breeze front. This led to a career in Applied Mathematics developing an interest in the physics of the atmospheric boundary layer, backed up with laboratory experiments. In all this, aspects of the sea breeze kept turning up.

The first nine chapters of the book are aimed at the general reader; they deal with the behaviour of the sea breeze and details which can be seen both from the ground and from the air. Other local winds, some of which are closely related, are also dealt with in this section. It is shown that the sea breeze affects the lives of humans in many ways, for example in the distribution of pollution and in the ways in which people spend their leisure time. The last three chapters are slightly more technical and deal with measurements of sea-breeze phenomena.

I am grateful to Professor Julian Hunt for writing the Foreword to this book and for the help of Professors R.S. Scorer, Herbert Huppert and to Drs. Anthony Edwards and John Chapman for reading the text and for their helpful comments. My thanks go to Margaret Downing for her able preparation of the diagrams and to Jason Newling for photographic work.

Ken Griffin's water colour of the 'sea breeze tree' on the coast of Majorca inspired the design for the cover of the book.

# 1

## *The sea breeze*

### 1.1 Introduction

The ‘sea breeze’, which flows inland at the coastline on fine days, is caused by the temperature difference between the hot land and the cool sea. This difference increases during the day and produces a pressure difference at low levels in the atmosphere, which causes the low-level sea-breeze to blow. At night this pressure difference disappears and is sometimes reversed, causing a ‘land breeze’. Of these daily alternating winds the sea breeze is the much stronger effect.

At the coast of many hot tropical countries, where the overall pressure gradient is steady from day to day, the arrival of the sea breeze can be expected regularly every day at the same time, reaching a strength of 6 or 7 m s<sup>-1</sup>. In temperate climates the sea breeze also blows on sunny days, but winds from different directions caused by the movement of depressions and anticyclones often modify its development. The sea breeze will start to blow when the temperature difference between the land and sea is large enough to overcome any offshore wind. For example, on the coast of southern England on a calm day a temperature difference of 1 °C is large enough for a sea breeze to form, but to overcome an offshore wind as strong as 8 m s<sup>-1</sup> a temperature difference of 11 °C is needed (Watts, 1955).

Early in the day, soon after its onset, the depth of the sea breeze may be less than 50 m and the wind just above it can be blowing in the opposite direction. This is shown clearly in figure 1.1, where all the plume from the lower chimney (75 m) is contained in the sea breeze. The plume from the taller chimney, (150 m) all moves in the opposite direction to the low-level breeze. As the day develops, so does the thickness of the sea breeze, often reaching a depth of 300 m. Later in the day the direction of the wind shifts a little due to the Earth’s rotation, veering a few degrees in the Northern Hemisphere.

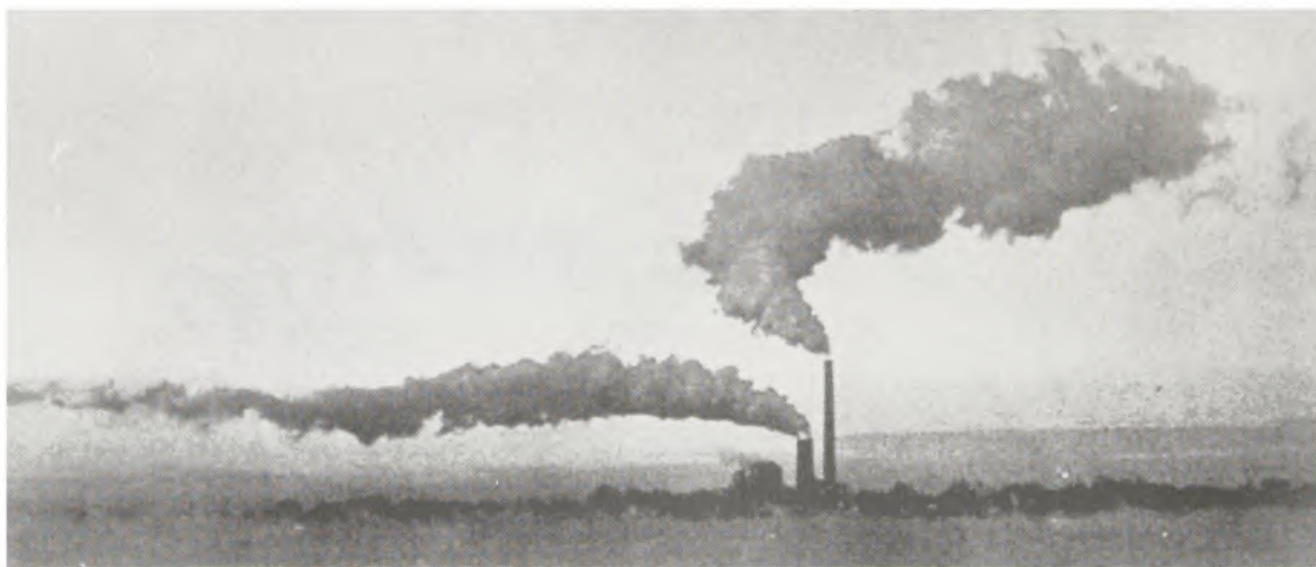


Figure 1.1. The depth of the sea breeze illustrated by smoke plumes. The plume from the lower chimney, height 75 m, is all contained in the low-level breeze; that from the taller chimney all moves in the opposite direction. (Photo by Ralph Turncote.)

Fresh sea breezes appear to be a pleasant feature of life near the coast, however they may have harmful effects on the distribution of pollution. In California, for example, the sea breeze generally has a 'purging' effect, but the stable layering together with the diurnal reversal of both the mountain–valley and land–sea breeze are a problem, maintaining dangerous concentrations of pollution at Los Angeles and other towns on the coast. The city of Athens gives another important example of the daily return of pollution each afternoon.

Sea-breeze 'smog' is also a feature of some parts of England, where the arrival of the sea breeze may appear as a wall of smoke, as shown in figure 1.2, which was taken from the air near Middlesbrough (Eggleton & Atkins, 1972).

Airborne insect pests such as locusts and aphids find the sea breeze useful since it may protect them from being blown out to sea on days when the overall wind is towards the ocean.

The developing sea breeze in calm weather gradually extends further out to sea as well as inland. On days with an offshore wind the sea breeze may also eventually spread inland, but this will happen later during the day and may be associated with a sudden squall. In an early account of the sea breeze at Cohasset, Massachusetts, Appleton, (1892) described how white-caps were seen on the sea as the interaction between the prevailing winds and the sea breeze produced a sharp sea-breeze front, moving slowly towards the land.

At about the same time in history the arrival and penetration of the sea breeze into the coastal area near Boston was investigated by a group from Harvard College Observatory (Davis, Schultz & Ward, 1890). Over 100 people took



Figure 1.2. The advancing front of the sea breeze, seen as a wall of smoke. Taken from a glider, south-west of Middlesborough, 8 August 1966. (Photo by M. Randle.)

part in making observations over a total period of three months, and the advance of the sea breeze inland was tracked on 30 occasions. This was a remarkable undertaking when we bear in mind that it had to be carried out without the use of telephones or automobiles. Figure 1.3 is an example of the results, showing the inland penetration of the sea breeze on 26 July 1887.

In hot countries the arrival of the sea breeze is very welcome as a gust of cooling wind in the hottest part of the day. In parts of Australia it is known as ‘the Doctor’. In West Pakistan, for example, the sea breeze is well known locally at points inland for its tempering effect on the fierce summer heat. At Hyderabad, in Sind, 170 km inland, every house has a ‘wind catcher’ – a wooden tunnel built above the roof-tops to channel the cool sea breeze, which arrives in the evening, into the rooms below. These structures and other examples of wind catchers are described in Chapter 8.

## 1.2 Sea-breeze clouds

The convergence of the winds near the sea-breeze boundary must cause air to rise, which often condenses and forms clouds. The extent of the sea breeze can sometimes be deduced from the presence of distinctive clouds which form in this zone. A line of cloud parallel to the coast on an otherwise cloudless day is a clear sign of the boundary of the sea breeze, the so-called ‘sea-breeze front’.

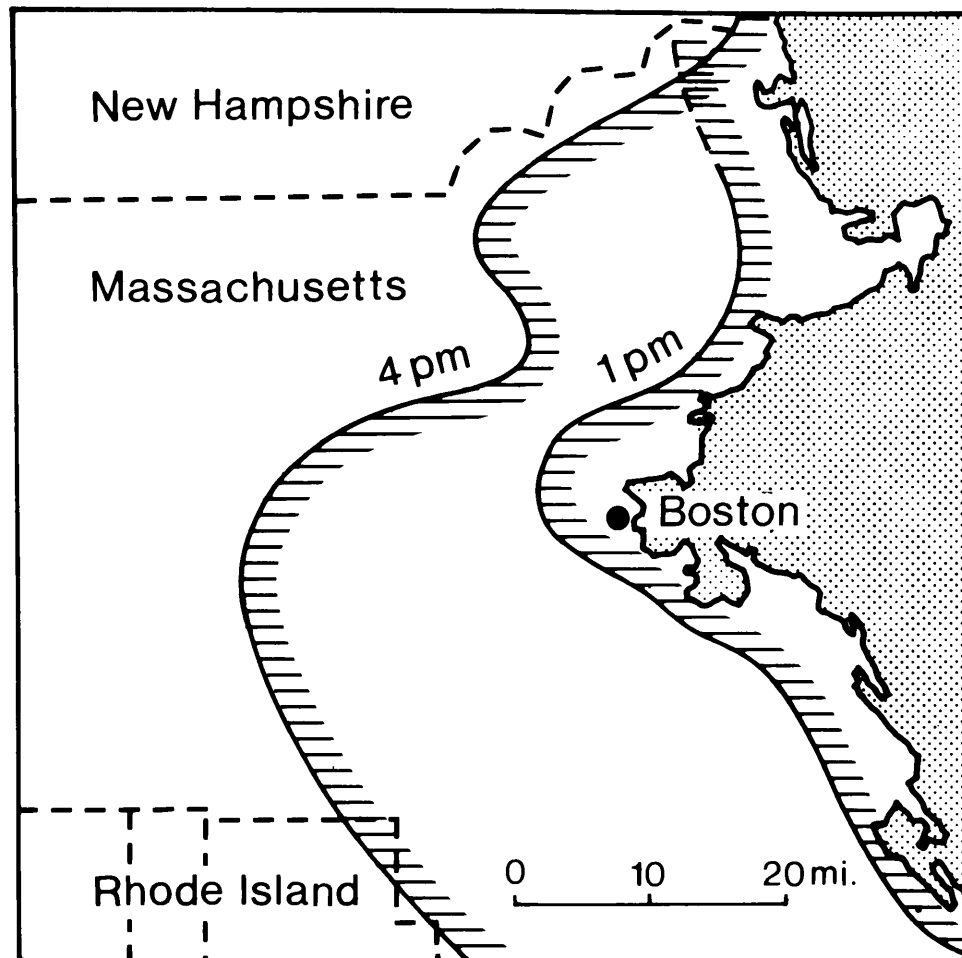


Figure 1.3. The boundary of the sea breeze, measured at 1300 h and 1600 h on 26 July 1887. (After Davis, Schultz & Ward, 1890.)

The interpretation of cloud patterns often makes it possible to see how far the sea breeze has spread inland. An example of this is given in figure 1.4, a view from the air soon after taking off from Gatwick in southern England, just before reaching the south coast. On the left the sky is full of small cumulus clouds uniformly spaced above the heated ground and indicating thermals of rising air. The sea is just out of sight on the right, and the air in the sea breeze is cloudless, but at the weak convergence zone between the land- and sea-air a line of larger cumulus clouds can be seen.

In different parts of the world, for various reasons, these convergence lines can be very intense and develop large banks of clouds, causing rain and even thunderstorms. In such localities the presence of the sea breeze has a marked effect on the climate.

### 1.3 The sea breeze in history

The Greeks did not like being on board ship at night, but nevertheless they would set sail after sunset to take advantage of the land breeze. This was also





Figure 1.4. The boundary of the sea breeze, which is blowing from the right, is marked by the edge of the cumulus clouds. Seen from the air just south of Gatwick.  
(Photograph courtesy of Colin Street.)

the custom of many fishermen of the Greek islands who would later use the sea breeze to return to port in the morning.

An outstanding case in Greek history of the use of the sea breeze was by the Athenian leader Themistocles, the commander of the Greek forces at the naval battle of Salamis in 480BC, where both the place and time for the battle were wisely chosen (Plutach, transl. 1892). The place was the channel between the island of Salamis and the mainland, the time chosen was when a brisk wind would start to blow from the open sea (a sea breeze) and raise waves in the narrow channel. The rough water did not inconvenience the Greek ships, which were solidly constructed and lay low in the water. The Persian ships, with lofty sterns and decks, were clumsy and unwieldy and managed poorly in high waves. Therefore, when the wind reached a fair strength the Greek commander ordered attack and the Persian fleet were shattered in the ensuing battle.

Another military use of the sea breeze is recorded about 2000 years later during the American Civil War when balloons were used for aerial reconnaissance (Haydon, 1941). John La Fountain was the first man with the Union



Army to make free reconnaissance flights over enemy territory. He would drift eastwards across the enemy lines when the sea breeze near ground level favoured him, then discharging ballast he relied on the prevailing westerly air stream at higher levels to carry him back. He repeated this feat many times, but had a narrow escape when Union troops seeing a balloon coming from Confederate territory took him for an enemy.

#### 1.4 The onset of the sea breeze

As a summary of the general features of the sea breeze we cannot do better than quote this description by the sea-captain William Dampier from his *Voyages*

These sea breezes do commonly rise in the Morning about Nine-a-Clock, sometimes sooner, sometimes later: they first approach the Shore so gently, as if they were afraid to come near it, and oft-times they make some faint Breathings, and as if not willing to offend, they make a halt, and seem ready to retire. I have waited many a time both Ashore to receive the Pleasure, and at Sea to take the Benefit of it.

It comes in a fine, small, black Curl upon the Water, when, as all the Sea between it and the Shore not yet reached by it, is as smooth and even as Glass in comparison; in half an Hour's time after it has reached the Shore it fans pretty briskly, and so increaseth gradually till Twelve a-Clock, then it is commonly strongest, and lasts so till Two or Three a very brisk Gale; about Twelve at Noon it also veers off to Sea Two or Three points, or more in very fine Weather. After Three a-Clock it begins to die away, and gradually withdraws its force till all is spent, and about Five a-Clock, sooner or later, according to the Weather is, it is lull'd asleep, and comes no more till the next morning.

Land breezes are quite contrary to the sea-breezes; for these blow right from the shore, and as sea breezes do blow during the day and rest during the night; so on the contrary, these do blow in the night and rest during the day, and so they do alternately succeed each other.

(Dampier, 1670)

William Dampier gave a clear account of the sea breeze from the point of view of the professional sailor; slightly different stories might be expected from an experienced air-pilot or from a student of air pollution. Much of their knowledge could be valuable for a weather-wise person only interested in making the best of a sea-side holiday.

# 2

## *Formation of the sea breeze*

### 2.1 Land and sea-breeze generation

Aristotle believed that wind was a 'dry exhalation' and because no such exhalation could be expected to originate from the damp sea, he had difficulty in explaining the generation of the sea breeze without the idea of the rebounding of land breezes at obstacles. The need to introduce the complicated factors of obstacles and reflux is reminiscent of the need met at a later date by the astronomer Ptolemy for introducing epicycles to make his geocentric system of the planets fit the observations.

More convincing to the modern mind, but still not entirely satisfactory, is the simple picture given in many school geography books of the air rising above the heated land, leaving a gap to be filled in by the inflowing sea breeze.

Figure 2.1 gives the generally accepted explanation of the development of the pressure field which gives rise to the low-level sea breeze. When the sun shines, the sea surface temperature changes very little, but the land becomes hotter and convection currents of air distribute heat through several thousand feet above the ground. No changes occur above a certain height, so the sideways expansion of each column of air above the land, B, produces changes in pressure which are transmitted sideways with the speed of sound. The resulting pressure difference at low levels is responsible for the onset of the sea breeze.

A weaker return flow aloft is necessary to balance the system.

### 2.2 Pressure patterns and the sea breeze

The growth and extent of the pressure field at any point is of primary importance as it supplies the driving force for the sea breeze. If barometer readings are carefully examined in very calm weather, when no appreciable synoptic changes

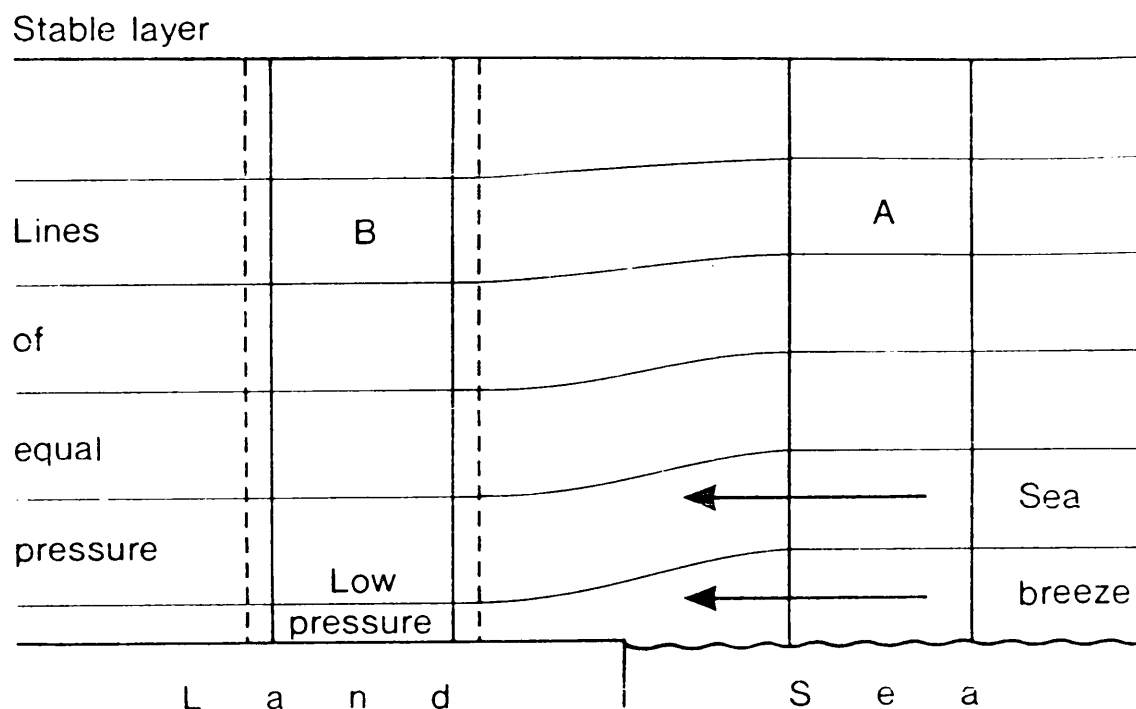


Figure 2.1. Development of the pressure field which gives rise to the sea breeze at lower levels. A column of air above the land, B, is heated by the sun and must expand sideways, as shown by the dashed lines. A column above the sea, A, is unaltered. This causes a pressure difference at low levels which gives rise to the sea breeze.

are taking place, a daily variation of surface barometric pressure can be detected. If averages are taken over a period of several hundred days at any particular place it becomes clear that a regular 'atmospheric tide' exists.

This diurnal march of the barometer can be considered as the result of two waves of different origin and character.

One of these, which is a semi-diurnal wave, is analogous to the waves in the ocean produced by the attraction of the sun and moon. In the sea the moon's tidal power is 2.4 times that of the sun but in the atmosphere the sun-tide is 15 to 20 times as strong as the moon-tide.

The second wave is different from the first wave since it has a period of one day and does not depend, like the first wave, only on the latitude and the season. This wave is produced by the variation of temperature in the lower layers of the atmosphere, and is called the thermal wave.

The thermal wave is influenced by the difference in the diurnal variations between land and sea. This difference produces the land- and sea-breeze phenomenon, and brings corresponding variations in the form of the thermal wave.

These waves are illustrated in figure 2.2. Figure 2.2(a) shows the diurnal variation in pressure anomaly at two sites. The total variation is seen to be semi-diurnal and is recorded at the surface both at Jersey in the Channel Islands and at Paris. Figure 2.2(b) shows the difference between the pressure at Jersey,

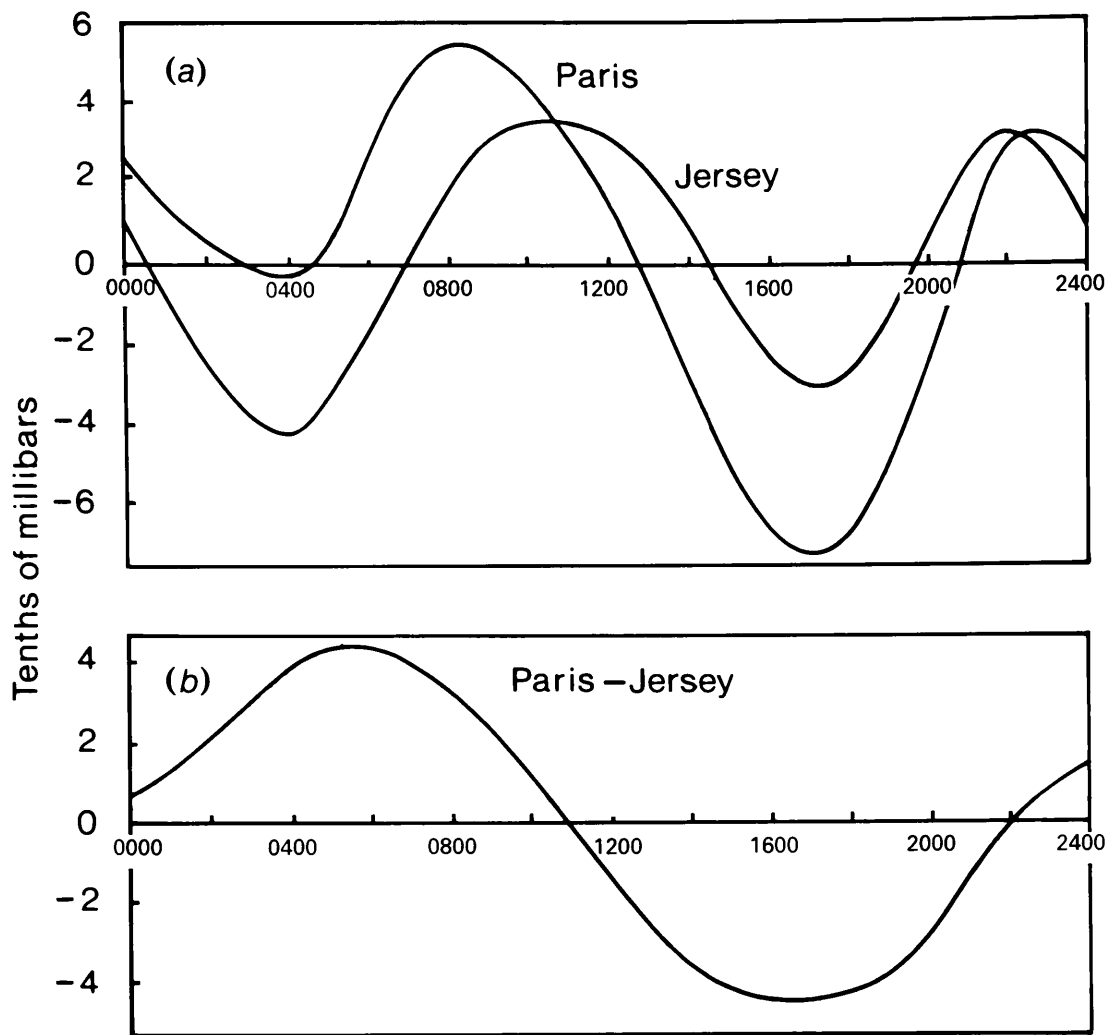


Figure 2.2. (a) Departures from the mean surface pressure in June at Jersey and Paris. Semi-diurnal pressure waves, or aerial tides. (b) Pressure differences between Jersey and Paris. This is a single diurnal wave, related to surface heating.

an oceanic site, and at Paris, which is 160 km inland. The difference is a single diurnal wave.

The spacial variation of the size of this thermal wave across Europe is illustrated in figure 2.3, which shows how the surface pressure changes during a morning in June (Met. Office, 1943). This map shows pressure tendencies at 1300 GMT, i.e. the change between 1000 and 1300 GMT. Note the large negative tendency over Spain and Central Europe due to the divergence of the air above in the middle of the day and even a centre of negative tendency over the British Isles. It can be seen that the tendency at Jersey is 0, and that at Paris is  $-4$ , a difference of about four tenths of a millibar, agreeing with the results of figure 2.2.

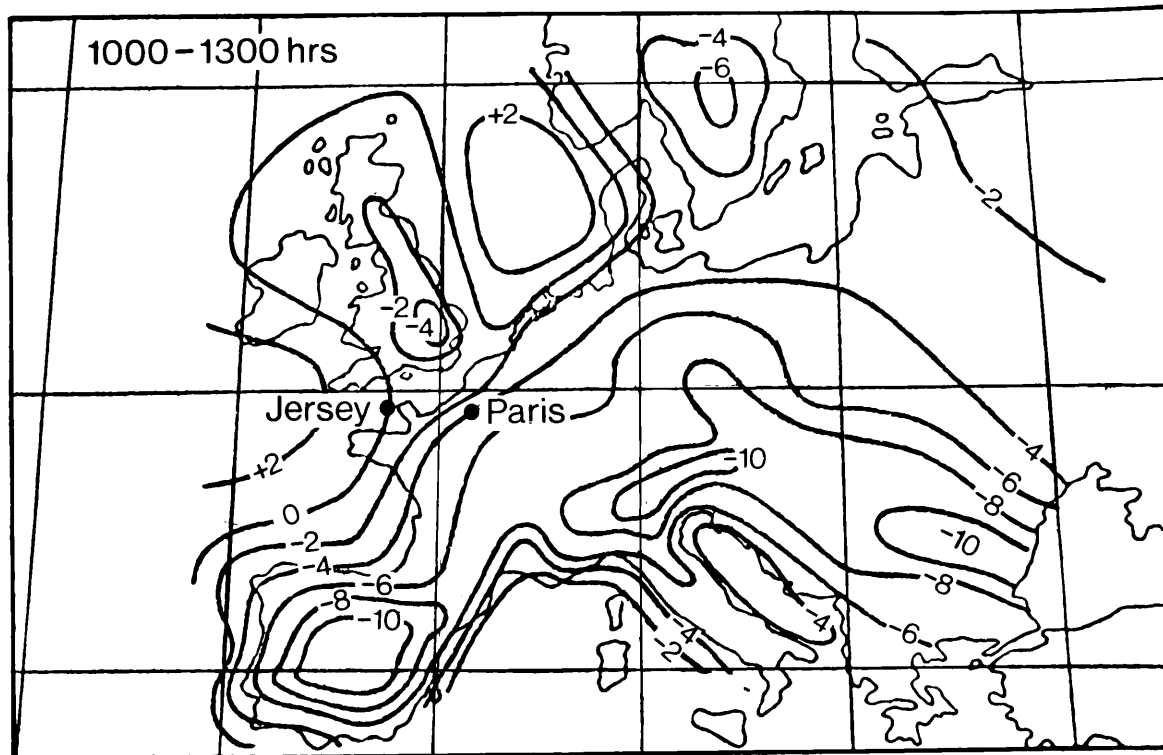


Figure 2.3. Surface pressure changes in Europe between 1000 and 1300 GMT in June. Units are tenths of a millibar; the positions of Jersey and Paris are marked.  
(After Met. Office 1943, unpublished.)

### *2.21 Diurnal temperature and pressure changes*

The sea breeze does not necessarily depend on high surface temperature since it is the changes in temperature which are important.

Sometimes these temperature changes may be very great, for example tests made in Arizona have shown that during the day black asphalt reaches a temperature  $19^{\circ}\text{C}$  above normal surroundings. It has been suggested that a large area of black asphalt near the coast would induce a sea-breeze circulation, leading to cloud formation and rain (Black & Tarny, 1963). Calculations suggest that the optimum length would be 50 kilometres inland from the shore, with a width  $\frac{1}{10}$  to  $\frac{1}{3}$  of the length. One acre of asphalt should be sufficient for three acres of arable land. Suitable large-scale test sites would be in Libya, Venezuela or W. Australia.

In countries such as Britain the daily temperature changes are much less than this. Typical mean temperature changes here in June between 0900 and 1500 GMT amount to only about  $2^{\circ}\text{C}$  towards the centre of the country.

The pressure drop during the same time shows very similar contour lines to those of temperature rise, with the minima inland.

1800. 26 July 1963

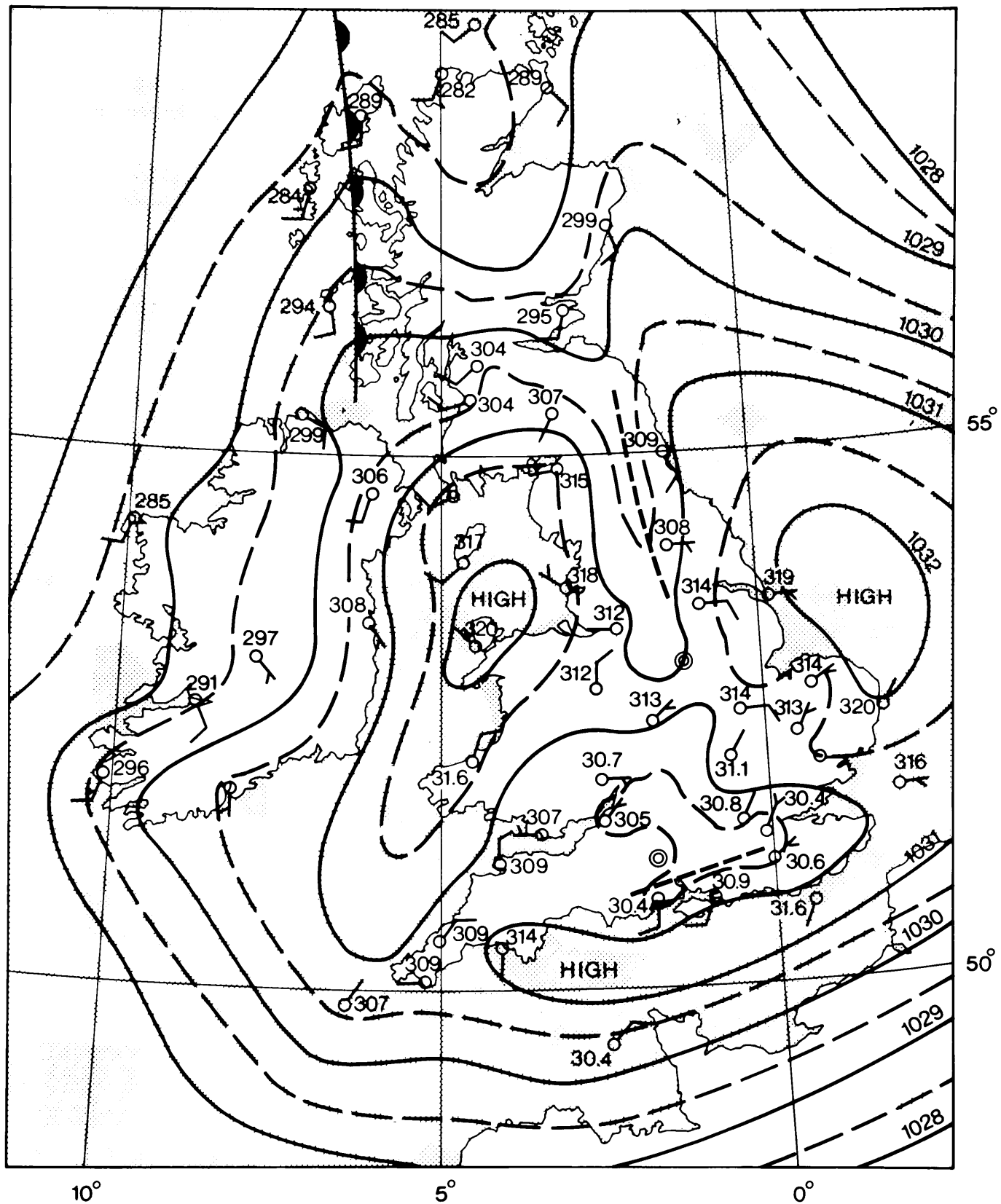


Figure 2.4. Detailed surface pressure field at 1800 GMT, 26 July 1963, a day with strong inland sea-breeze penetration. The two dashed lines, near the north-east and the south coast, show the observed position of the sea-breeze front.

### *2.22 Pressure field on a day of strong sea breeze*

In the course of some sea-breeze investigations in the south of England (Simpson, 1964) numerous charts of the developing pressure field were plotted. Using the hourly charts of the Meteorological Office it was possible to see the development of the pressure pattern not only over the land but also over the sea. One of these maps of pressure contours, made on 26 July 1963, a good sea-breeze day, is shown in figure 2.4. Areas of high pressure appear above the North Sea, English Channel and Irish Sea. The two dashed lines, one near the North East coast and the other in the South, show the position of the boundary of the sea breeze (the sea-breeze front) at 1800 GMT.

### *2.23 Seasonal differences of temperature*

Monthly mean air temperatures and corresponding sea-surface temperatures have been measured in order to examine the probable differences available to drive the sea breeze. Sea temperatures are difficult to measure reliably, but some good long-term station records are available from the US Dept. of Commerce. Figure 2.5 shows the sea-surface temperature curve lagging behind that of the air temperature by about a month, as is normally expected. (Diaz & Quayle, 1980).

## **2.3 Sea-breeze strength and direction: hodographs**

A useful way of presenting measurements of the sea breeze is to use a wind hodograph traced out by the end point of the wind vector as its value changes with time. Hodographs show, at any given locality, a complete 360° turn during the day, provided the overall gradient wind is weak.

In addition to many observational results, there have been theoretical investigations of hodographs in the land-sea-breeze circulation. Pioneering work (Haurwitz, 1947) in a simplified linear model considering friction, Coriolis forces due to the Earth's rotation and inertial forces showed that the hodographs should be ellipses for which rotation is always clockwise (in the northern hemisphere). In this model the sea breeze, which starts blowing at right angles to the shore, gradually veers in direction until by sunset it is blowing nearly parallel to the coastline.

Sea-breeze hodographs measured in the northern hemisphere mostly show a clockwise rotation with time, but there are also stations with a clear anticlockwise direction. Theory suggests that the rotation displayed in hodographs is

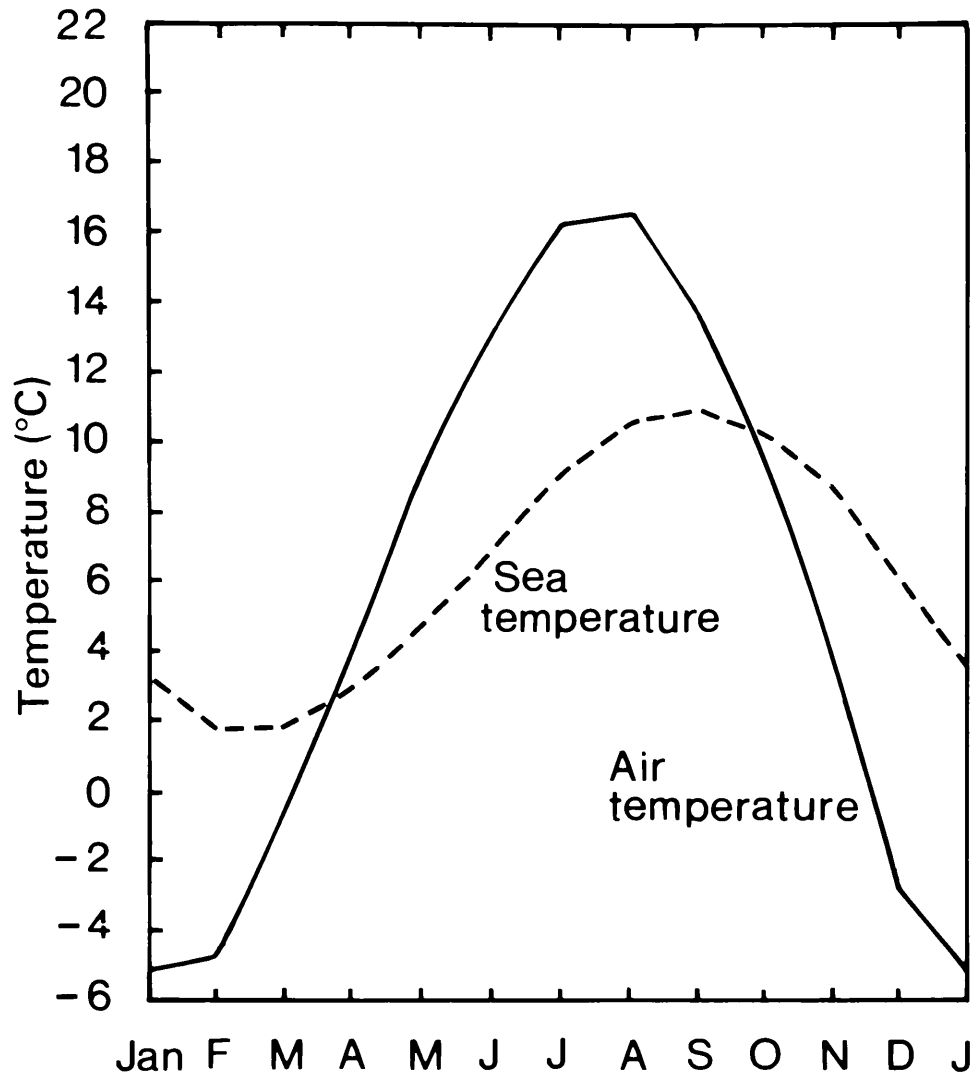


Figure 2.5. To show the difference between land and sea temperature throughout the year, measured at Eastport, Maine. (Average through the years 1927–77.) (After Diaz & Quayle, 1980.)

primarily due to the Earth's rotation, but some other explanation must be found for those with anticlockwise rotation. In the following sections complex coastlines and mountains are shown to be some of the causes of anticlockwise rotation.

### *2.31 Observed diurnal changes in sea-breeze direction*

The original simple theoretical model was for a straight coastline with uniform conditions inland; in reality, the coastline may not be straight and there may be significant features which can affect the growth of the pressure field which creates the sea breeze.

The combination of two sea breezes originating at two coastlines which



enclose an angle to 70 at Halifax, Nova Scotia, was found to be different from that to be expected on a straight coast (Dexter, 1958). The graphical addition of the two corresponding elliptical hodographs was shown to produce a hodograph very similar to that observed; see figure 2.6.

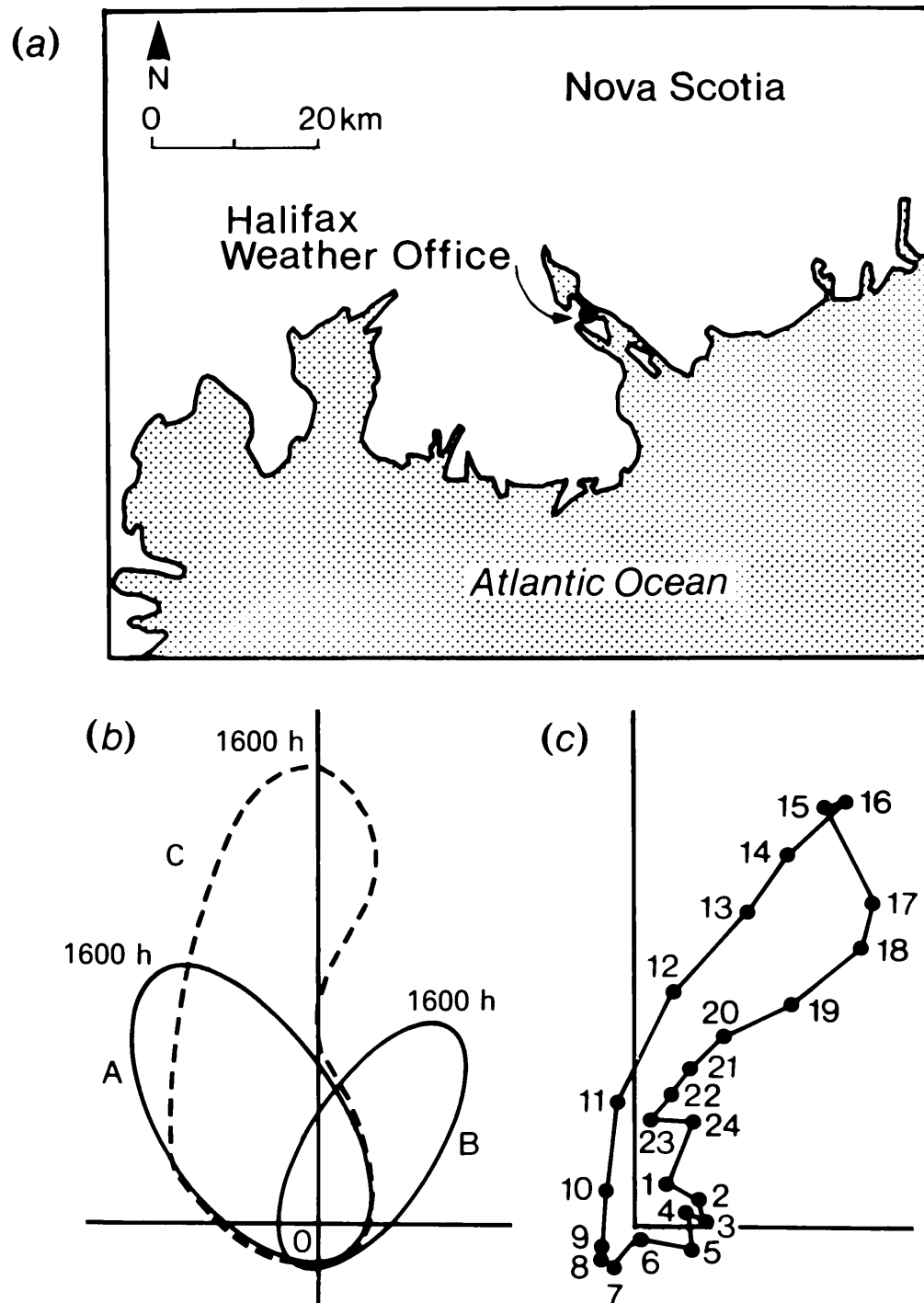


Figure 2.6. The harbour sea breeze and the mainland sea breeze near Halifax, Nova Scotia. (a) Map of the area. (b) Theoretical sea-breeze hodographs. A, Halifax harbour effect; B, the Atlantic effect; C, the sum of A and B, allowing for the periods in which they apply. For example, the wind was nearly from the south at 1600 h. (c) Measured hodograph for June, showing a similar shape to C. The numbers 1–24 represent the times 0100–0000 h. (After Dexter, 1958.)

Gliding and related meteorology have always been important parts of John Simpson's life. In the 1960s when he was teaching physics as a schoolmaster, he made some of the earliest flights of discovery at sea-breeze fronts and began a long series of laboratory experiments on the behaviour of such fronts. He next worked for five years at the Department of Meteorology at Reading University where he flew gliders and light aircraft investigating thermals and sea-breeze fronts.

Since 1974 his work at the University of Cambridge has been on meteorological problems including microbursts and aircraft safety and also on the dispersion in the atmosphere of dense gases. He has published 50 scientific papers on these and other topics.

The first book entirely devoted to the sea breeze; for anyone who looks at the sky and is interested in local weather; for those concerned about pollution and environmental problems; for practitioners of gliding, sailing and ballooning.



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