1. INTRODUCTION

The sea breeze is a well studied yet hard to forecast meteorological phenomena. It is defined as an onshore wind formed near the coast as a result of differential heating between the air over the land and air over the sea.

It is generally accepted that on a sunny day the land absorbs short wave radiation and the temperature of the air above the land is forced to rise. The air temperature can vary by about 10°C between day and night. Whilst the sea surface also receives an input of heat it does not warm so quickly due to its lower thermal capacity, the temperature will not change more than 2°C between day and night (Arya, 1999).

A horizontal pressure differential forms as lower pressure is found over the land where air is rising and as a result sea air flows from the higher pressure to the lower pressure replacing the rising land air as seen in Figure 1.

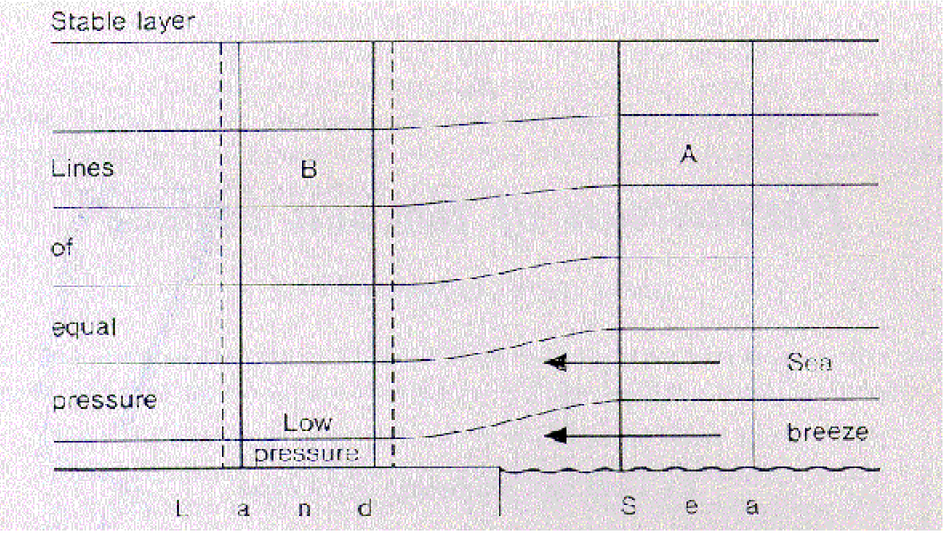


Figure 1: Heating over the land causes an expansion of the column B forming lower pressure at the surface. Air travels from the higher pressure over the sea to the land and there is a return flow aloft. Taken from Simpson (1994) p8.

The air from the sea is found to be cooler and more humid than the land air it replaces. Therefore on a hot summer's day it is often found that there is a cooling onshore breeze at the coastline which develops during the day.

The leading edge of a sea breeze, where the moist sea air meets the less dense drier land air, can form a sea breeze front (SBF). The front is often found to have a raised head like structure with air moving up at the front vertically (Koschmieder, 1936). Often a sea breeze front can be easily identified by a distinct line of cumulus cloud where air has been forced to rise up the front and condenses forming a band of cloud, as is visible in figure 2.

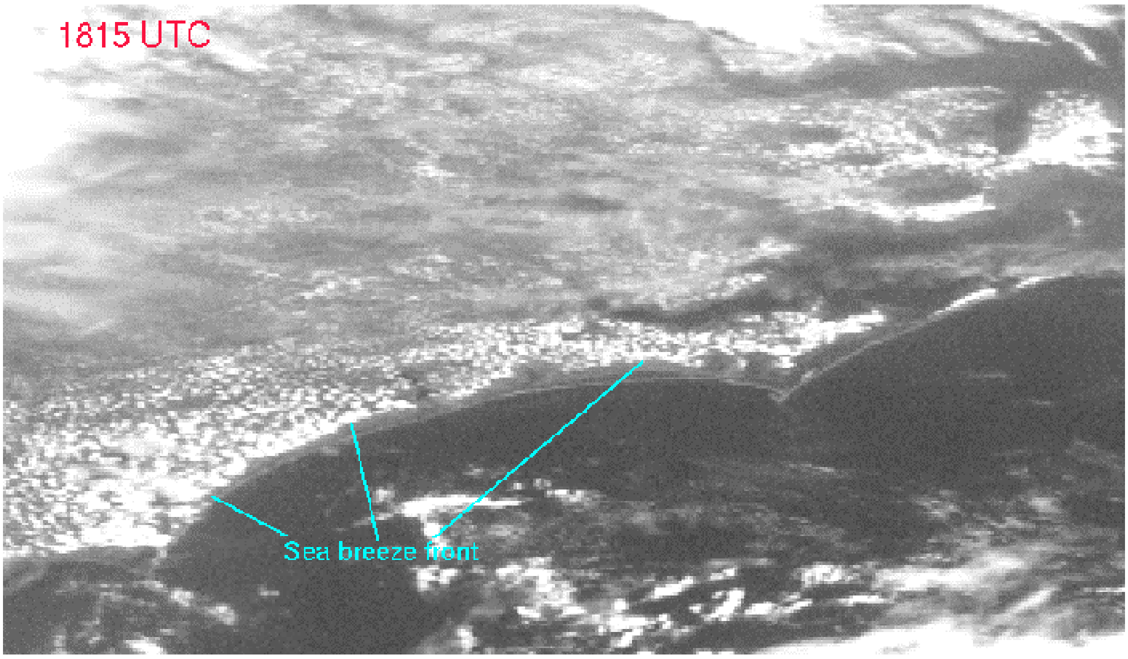


Figure 2: Satellite picture of a sea breeze front taken on the coast of North Carolina using the visible channel of the GOES-8 imager which has a spatial resolution of 1 km. Taken from WxWise (2004).

The front is often marked with a change in parameters such as humidity, temperature, wind speed and direction due to the change in air mass. These differences can be measured as the front passes at sea level and also at some height above the surface.

The sea breeze is an important mechanism for pollution transport in coastal regions (Physick, 1980). Also in some parts of the world it is an important transport medium for pests and insects (Rainey, 1969). Knowledge of local winds that may develop during the day is essential for aircraft due to the possibility of updrafts. Additionally the sea breeze is very useful for sailors who may make tactical decisions based on the likelihood of a sea breeze developing (Simpson, 1994).

In some countries sea breezes may occur almost daily due to very settled weather patterns however in countries like the UK where the weather is very changeable the likelihood of a sea breeze developing is far less predictable and many factors have to be taken into account.

It is clear that to be able to forecast whether a sea breeze will develop, when a sea breeze front will advance and the likely strength of the resulting winds is important in coastal areas. Despite numerous studies covering the subject, forecasting sea breezes is far from efficient and there is potential for much improvement. There are still many aspects of sea breezes that have had little research although there has been a lot of advancement recently as a result of improvements in technology allowing for finer structures to be investigated, however the work is still far from complete.

2 LITERATURE REVIEW

Sea breezes can be studied at various scales. On the macroscale the effects of synoptic conditions on the development of a sea breeze and its subsequent movement inland can be considered. This can be on a scale of 100s of kilometres and on a timescale of days (eg. Simpson,1977; Arritt, 1993). The sea breeze can be considered on an intermediate scale as a circulation cell with a scale of around 100km which extends inland and out to sea. The intermediate circulation cell is often studied using aircraft to gain a better picture through the whole cell (Finkele et al, 1995; Wood et al, 1999). The timescale for the development to breakdown of the circulation cell can be a few hours to a day.

Reducing the scale of study some more, many studies have focused on a scale of 10 - 20km considering the features of the front and head structures only (eg. Simpson, 1994; Chiba 1993). Finally, studies have advanced recently to investigate the wave scale which is on a much smaller level at less than 1km and on shorter timescales, usually under and hour and sometimes a matter of minutes. Much of this work features numerical studies (eg Sha et al, 1991; Ma Yimin & Lyons, 2000) looking at small scale features of turbulence at the sea breeze front.

2.1 Synoptic Scale

The synoptic conditions have a large influence on the development of a sea breeze and its subsequent movement inland.

Some of the earliest investigations of sea breezes were made by Koschmeider in 1936 who suggested that an offshore synoptic wind was required for a sea breeze to form. However it was later discovered that sea breezes still occurred on days with onshore winds and that a front could still form and be detected although it may not be as obvious as when there is an opposing synoptic wind (Pedgely, 1958).

A thermally driven wind that develops on a warm sunny day is dependent on the strength and direction of the wind before the sea breeze forms, as investigated by Est oque in 1962 whose simulation study looked at winds of the same strength from 4 directions along shore and perpendicular to the shore. The findings were that an onshore synoptic wind suppressed the sea breeze system producing a weaker flow than an offshore wind, which enhanced the effect, producing a stronger circulation overall.

Arritt (1993) advanced these findings further with his study investigating the effects of winds of varying strengths and directions. The numerical study meant that all other factors were kept constant apart from the synoptic wind conditions. The findings of this study were that the strongest sea breeze flow was found on days when offshore synoptic winds were light. Conversely, if the synoptic wind was an onshore direction but less than 3m/s then the sea breeze did not weaken, however any wind stronger than this acted as a suppressant to the sea breeze flow as described by Estoque (1962). The numerical situation can be quite unrealistic as it ignores many factors that may have an effect on the sea breeze such as topography and convergence in channels. However in this case the results have been subsequently observed by many other studies including Simpson (1977) described below.

The building of the sea breeze has been considered. However another factor that is dependent on synoptic flow is the distance inland the sea breeze can penetrate. Simpson’s 1977 study on the south coast of England found that the sea breeze can travel up to 100km inland on certain days. However on other days the sea breeze will remain offshore and not penetrate inland at all. Over 12 years between 1962 and 1973 studies of sea breezes and their fronts from the South Coast were monitored and their inland penetration recorded.

Simpson’s study concluded that the penetration of the sea breeze was dependent on the density difference across the sea breeze front. A temperature difference of 3 degrees between the sea and land air is equivalent to a 1% density difference (Simpson, 1994). This study led the way in the thought of the sea breeze as a density or gravity current which will be explained further in the next section.

In addition to the density difference the effects of synoptic winds on the rate of penetration inland of the sea breeze was investigated by Simpson (1977). The results back up findings from Arritt's (1993) numerical simulation. On days of strong opposing flow a sea breeze may not advance inland at all however on days of light to moderate opposing flow a sea breeze may advance far inland.

For example Simpson (1994) describes how a sea breeze on a day with light opposing winds first passed overland before 0900UTC and by the afternoon the front was travelling at 8km/h and reached 45km inland by 1700 UTC. The front then continued to travel inland until later in the evening. However given a day with moderate offshore flow of 7m/s a sea breeze front did not advance inland until 1500 UTC and the front oscillated backwards and forwards over this inland point. It was only in the evening that the sea breeze advanced inland properly and was traced at about 2000 UTC 25km inland. Finally on days with onshore synoptic conditions the front tends to develop later in the day though it still has the capability to travel far inland in the evening.

The findings of these studies show that on days when there is opposing flow the horizontal temperature difference and therefore density difference across the sea breeze front is greatest (Atkinson, 1981). There is horizontal convergence of the synoptic and sea breeze winds where they meet and the result of the horizontal convergence is a zone of frontogenesis, which is the increase in strength within the fluid of density and other parameter gradients (Reible et al,1993). Frontogenesis is strong on days of opposing flow and weaker when there is synoptic onshore flow.

2.2 Circulation Cell Scale

This leads us to studies of a slightly smaller scale where the sea breeze system can be thought of as a circulation cell that develops during the day due to differential heating between the land surface and the sea. Not only is there a flow inland at low levels but there is a return flow from the land to the sea above the sea breeze causing the whole system to be thought of as a convective cell with a depth of 50 to 300 metres (Simpson, 1994) as can be seen in Figure 2.1.

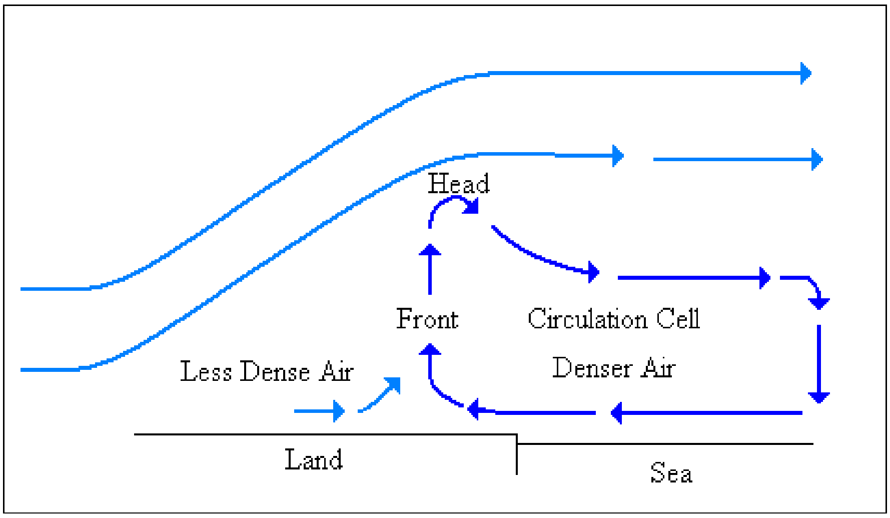


Figure 2.1: Circulation cell diagram. Shows updraughts at the front and raised head.

The cell increases in size and expands inland and seaward and can be in the order of 100km (Finkele et al, 1995). The circulation cell depth is restricted by the depth of the mixed layer which is usually about 1-2km deep (Reible et al, 1993).

As already mentioned the boundary between the land and sea air and the position of the sea breeze front can be identified by a change in meteorological parameters such as wind direction, temperature, humidity and wind speed. This is the leading edge of the circulation cell.

The top of the circulation cell is difficult to define but is thought to be the point where the specific humidity regains the value equal to the air opposing the frontal flow (Finkele et al, 1995). It can be difficult to identify the top of the circulation cell due to the updrafts often found at the front which push air up to higher levels than the top of the cell. In addition there are waves found in the head area which add to the difficulty in defining the upper boundary. These phenomena often affect the specific humidity due to some mixing (Finkele et al, 1995).

The sea breeze can be thought of in terms of a gravity current once a front has been formed where a denser fluid, in this case the sea air, pushes underneath the less dense land air and propagates forward (Simpson et al, 1977). A head may be formed in the frontal region due to the wind behind the front travelling faster than the speed of the front and therefore there is convergence at the front between the sea air and land air forcing the cooler sea air to rise up the front. The raised head is about twice the depth of the flow behind (Simpson & Britter, 1980).

2.3 Front & Head Scale

There are many smaller scale studies that have taken place, particularly recently due to the advance in technology, allowing measurements to be taken on much smaller scale that concentrate on the activity in the sea breeze head and front only. These studies look at the frontogenesis and frontolysis (breaking down of the sea breeze front). The study by Reible et al (1993) looks at the development of sea breeze fronts over 4 summer days in southern England. Once again the effect of different synoptic conditions were considered but this time only the frontal development was studied.

For instance, one day the synoptic wind was the same direction as the sea breeze and there was only weak frontogenesis due to less convergence at the front. In addition as the development of the front started later in the day, turbulent activity on land, as a result of intense heating, inhibited the fronts advance onshore. It is only late in the day when the solar radiation is reduced that the front advances inland, though it is found to penetrate quite far inland during the evening.

On a day with opposing wind conditions there is more convergence at the front and the front is found to develop earlier in the day. Although the front is strong it may also be prevented from travelling far inland due to the opposing winds and also turbulent activity onshore. Likewise it may only advance inland as the turbulence onshore decreases.

Much of the work on gravity currents and the head of the sea breeze has been conducted using water tank experiments detailed in Simpson's (1994) book. The density currents are generated by forcing the advance of a denser liquid (eg salt water) through a less dense liquid (eg water). There is mixing as a result of the shear at the head of the current and turbulent activity takes place there tending to reduce density differences between the two fluids as will be discussed further and was described by Linden and Simpson in 1986.

Updrafts into the head are a result of convection from the surface and produce turbulence (Reible et al,1993). The turbulence can work to destroy the density difference due to the mixing of upper air into the sea breeze and the frontal zone. It is well documented that as a front moves inland it may become harder to identify due to less pronounced changes in the parameters as a result of mixing (Simpson, 1977).

The depth of the head has also been well studied and can reach up to 700m from the surface. If there is opposing synoptic wind the head profile is extended and its height reduced as seen in the photographs from a laboratory experiment (Figure 2.2 diagram b). If the opposing wind is strong enough it can retard the flow and may even bring it to rest (Simpson, 1994).

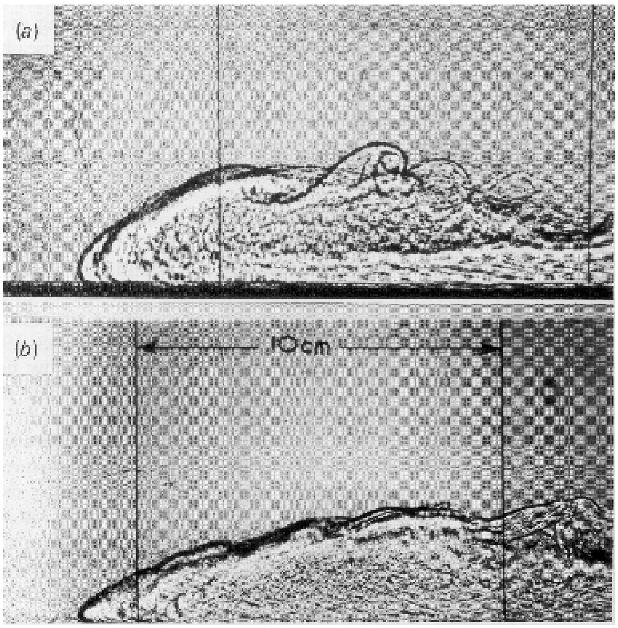


Figure 2.2: Gravity currents reproduced in the laboratory. A) shows a front with no opposing flow and b) is a front formed with a head wind. (Adapted from Simpson, 1994).

Another form of instability found at the sea breeze front is the formation of lobes and clefts (Simpson, 1994)(figure 2.3). The lobes advance forward at the front and are divided by clefts in the flow. They are formed as the flow moves forward and some lighter fluid from the opposing flow is over run. The lighter fluid tries to resurface causing instability at the leading edge of the flow. The lobes tend to expand to a maximum width before they start to split to form a new cleft.

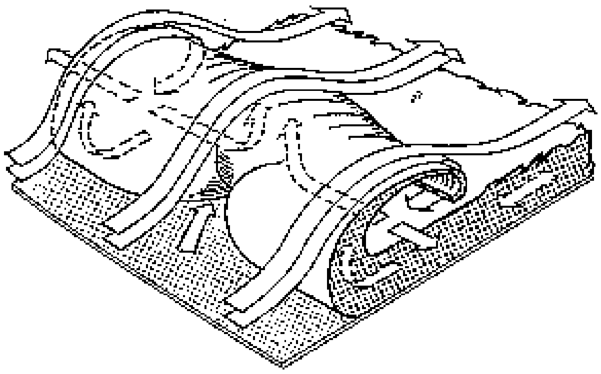


Figure 2.3: diagram of the sea breeze front showing the division at the leading edge of lobes and clefts. Taken from Simpson (1994) p29.

It has been suggested that the sea breeze frontal velocity can be found using the following equation (2.1) (Simpson & Britter, 1980):

$$U_f \sim 0.87\, U_{sb} + 0.59\, U_g \qquad \text{Equation (2.1)}$$

U_g = Geostrophic wind speed (m/s)
U_{sb} = Sea breeze wind speed (m/s)
U_f = Speed of Sea Breeze Front (m/s)

Equation (2.1) shows that the frontal velocity is a balance of the sea breeze velocity and the velocity of the synoptic wind. It is important to note that turbulent activity will reduce this value due to the mixing of the sea air and land air that will occur, slowing the advance forward. It may be possible to add an extra term to the equation to allow for the effects of turbulence, however at this stage we do not know enough about the detail of the turbulence. Therefore we can conclude that the development and inland penetration of the sea breeze front is a balance of the horizontal convergence of the winds and turbulent activity at the front.

2.4 Wave Scale

The findings so far have brought the scale of studies of sea breezes down to wave scale looking at the turbulent activity and its effects in finer detail. An important finding of the laboratory experiments looking at gravity currents is the discovery that a Kelvin Helmholtz Instability appears to occur around the frontal area (Linden & Simpson, 1986). This has important consequences for mixing in the frontal area and therefore frontal development as a whole.

Kelvin Helmholtz instabilities are found when there are denser fluids underneath less dense fluids with a shear layer in the middle. This situation arises at the top of the sea breeze head where there is sea air underneath the land air. Kelvin Helmholtz instabilities which have been simulated in many laboratory studies (Thorpe, 1973) are found in regions of strong shear and where the Richardson's number is less than 0.25. The Richardson's number is a measure of the stability of the flow and can be calculated using the equation (2.2):

Gradient Richardson's Number

$$Ri = \underbrace{\frac{g}{\theta}\frac{\partial\theta}{\partial z}}_{a)} \Big/ \underbrace{\left(\frac{\partial u}{\partial z}\right)^2}_{b)} \qquad \text{Equation (2.2)}$$

g = gravity

θ = potential temperature

u = velocity

z = vertical distance

The value given by the Richardson’s number is a balance of buoyancy which acts to suppress turbulence as it tries to oppose gravity (part a), and a shear production term (part b), that promotes turbulence (Stull, 1983). If the Richardson’s number can be calculated at the point where the shear exists then we can conclude whether the disturbance is caused by a Kelvin Helmhotz instability.

Stull (1983) describes the process of Kelvin Helmholtz instabilities. Once the critical Richardson’s value is reached the flow becomes unstable and waves begin to form, the waves increase in size until they begin to break. The direction the crests take is normal to the line of the shear. The waves cause the less dense fluid to be pulled underneath the denser fluid and this forms patches often called ‘cats eyes’ as can be seen in figure 2.4.

The mixing of the different fluids is a result of the areas of instability which cause turbulence in each wave. This in turn reduces the shear and makes the layer stable once more. If the Richardson’s number is increased above the critical value the layer is said to be stable and the turbulence is eliminated. Therefore the turbulence acts to eliminate itself.

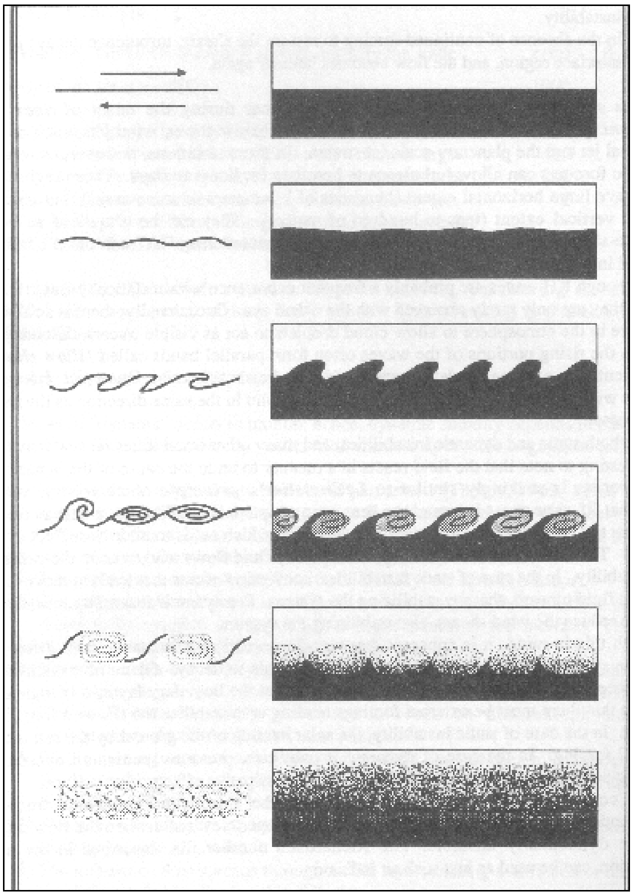


Figure 2.4: Diagram of evolution of Kelvin–Helmholtz waves. From Stull (1983).

It can be very hard to observe Kelvin Helmholtz Instabilities in the atmosphere although they are sometimes seen at the top of clouds figure 2.5.

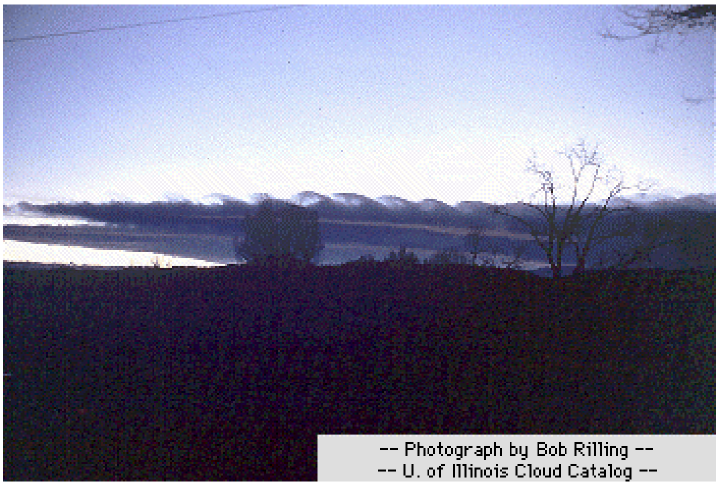


Figure 2.5: Kelvin Helmholtz billows at the top of a cloud (WW2010-University of Illinois, 2004).

Often the instabilities are reproduced in laboratory experiments. This can be see n from Simpson's tank experiment showing the advancing gravity current (fig 2.6). The upper layer of less dense fluid has been dyed. The Kelvin helmholtz waves can be seen as light is shone on the liquid containing a fluorescein.

Figure 2.6: Gravity current tank experiment. Current moves from right to left. From Simpson (1994).

The Kelvin Helmholtz Instability seems to take place at the top of the sea breeze front and cause disturbances that take the form of vortices or billows which propagate away from the front (fig 2.7). These can also be seen in figure 2.6 showing the gravity current. On the right hand side of the diagram there is evidence of a billow which is breaking down and this billow may have an effect on surface parameters.

Many papers written on the subject of sea breezes have commented on waves observed behind the front (eg. Finkele et al, 1995; Reible et al, 1993) although it remains unclear if these waves are definitely a result of Kelvin Helmholtz instabilities. There seems to be a lack of knowledge about the instabilities and the only method used so far to confirm their identity is by measuring the Richardson number at the point of the shear to see if it is less than the critical value.

It is very difficult to calculate a Richardson's number as it requires measurements of variables at the exact point where the strong shear exists and the instabilities form (Sha et al, 1991). This has mainly been carried out using numerical simulations which have been limiting in their applicability to reality due to a number of factors that are discussed later. The ability to recreate the Kelvin Helmholtz instabilities in the laboratory and in numerical simulations does help and has led to many accepting the theory but does not prove definitely that they exist in the sea breeze head.

In a high spatial resolution two-dimensional numerical model used by Sha et al (1991) the Kelvin Helmholtz Instability and other structural features of the sea breeze head were recreated. The instability that was produced from the numerical simulation had a Richardsons number of less than 0.25 and was concluded to be a Kelvin Helmholtz Instability.

Vortices that formed behind the front are known as Kelvin Helmholtz Billows (KHB). These billows were formed close to the front edge of the head region and then propagated along the 'zero velocity boundary' away from the front. The 'zero velocity boundary' is defined as the line where the horizontal velocity of the sea breeze is zero (Sha et al, 1991) and is illustrated in figure 2.7. Kelvin Helmholtz billows (KHBs) were observed increasing in size as they moved backwards in relation to the frontal movement. The KHBs later started to disintegrate and decrease in amplitude and eventually disappear altogether.

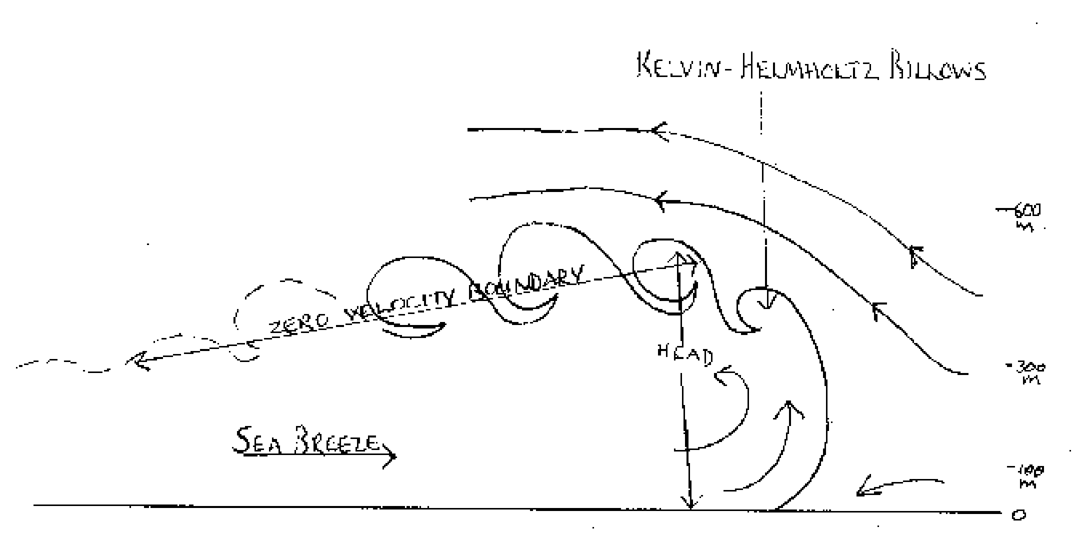


Figure 2.7: Diagram of Sea Breeze front showing 'zero velocity boundary', and Kelvin Helmholtz Billows.

The KHBs that were produced by the numerical simulation cause mixing between the sea breeze and upper air as they start to break down, as described by the Kelvin Helmholtz theory. They create friction along the top of the sea breeze head and are an important factor in controlling its structure. Furthermore it is suggested that the mixing that the KHBs cause can slow the propagation of the sea breeze (Buckley & Kurzeja, 1997).

Not all numerical simulations have been able to recreate Kelvin Helmholtz billows. Mitsumoto et al (1983) used a temperature controlled tank experiment to reproduce many of the intricate structures in the sea breeze head but were unable to produce billows. Although many of the numerical simulations produced features that appear consistent with observational studies there are a few problems with them that make the numerical studies unrealistic and suggest that it may not be ideal to compare the results of the simulation to the real environment.

Sha et al (1991) suggested that their two dimensional model may produce Kelvin Helmholtz Billows that are unrealistically sized and the waves created could be too large amplitudinally. This may be true, especially when compared with the waves produced by 3-dimensional models such as Droegemeier and Wilhelmson's (1987) thunderstorm outflow model which yielded a higher ratio between the wavelength and amplitude of the waves. Buckley and Kurzeja (1997) simulated the nocturnal sea breeze using a 3-dimensional model and found that Kelvin Helmholtz billows were produced although they were not consistent with other studies, mainly due to the low resolution used in the study.

It is thought that the three dimensional model is better at recreating parameters such as radiation, complex terrain and vegetation accurately however the spatial resolution used in a numerical model is critical when trying to recreate Kelvin Helmholtz billows (Buckley & Kurzeja, 1997). Sha et al (1991) used a resolution of around 100m close to the sea breeze front producing the most realistic results and they also commented that it is important to choose a suitable numerical smoothing coefficient. Furthermore, thermal convection in the air surrounding the sea breeze cannot be simulated well unless the resolution is correct and is very fine. Also in the real atmosphere the growth of the head is restricted by an inversion at the top of the head and this is has not been simulated well in numerical models (Droegemeier and Wilhelmson,1986).

Investigations have taken place to compare the results from numerical simulations, laboratory and observational studies to assimilate them and provide further proof that the oscillations produced by the numerical simulations and those observed in observational studies are Kelvin Helmholtz billows. Sha et al (1991) looked at the wavelengths of the various waves and produced the ratio between maximum amplitude of the waves and their horizontal wavelengths. They went on to compare these with other studies yet there is little agreement between the studies. Data from observational studies, used for comparison has been taken from aircraft data from higher levels in the sea breeze, for example, the study by Wood et al (1999) is very useful as it creates a 2 dimensional picture of the system.

Studies on thunderstorm outflows found that Kelvin Helmholtz Billows caused changes in the surface wind speed and pressure (Droegemeier & Wilhelmson, 1987) and therefore it seems possible that as the sea breeze front passes a point oscillations in certain variables at the ground surface may be detected. This has been found in numerical studies (eg Sha et al, 1991) however there has been very little work done in observational studies except for a single study looking at tropical sea breezes, which described pressure oscillations at the surface (Donn et al, 1956).

The numerical simulation by Sha et al (1991) was used to investigate the effects of the Kelvin Helmholtz billows on the rate of movement inland by the front. They found that the Kelvin Helmholtz instability is not visible at all stages of sea breeze front and sometimes the turbulent activity almost destroys the front. When the sea breeze front meets the thermal convection taking place over the land the turbulence is increased before the front passes. This causes so much mixing that the front decays and is slowed down on its journey inland.

The effects of the turbulence in the head have been highlighted and it is clear that there are a lot of gaps in the research as there are no definitive conclusions.

When the turbulence occurring before the front ceases, usually when radiative heating over the land stops later in the day, turbulence and mixing decrease allowing the front to penetrate inland faster. In many studies this type of movement has been recorded (Simpson et al, 1977, Clarke 1984) with a slowing of frontal movement in the afternoon and an accelerated frontal movement in the evening.

The discussion of the literature on sea breezes shows that the biggest gaps in research lie in the wave scale and the effects of turbulence on the development of the frontal region and its subsequent movement inland. Despite numerous numerical simulation studies there is little observation in the real environment and the applicability of the findings of these studies is unknown without further research.

2.5 Pollution and The Sea Breeze

Having discussed some of the different scales of research of sea breezes it is important to look at where this research fits in and how it will be useful. To be able to forecast the sea breeze accurately would be very helpful to industry. For example more knowledge of mixing could be useful in coastal pollution dispersion studies. Reible et al (1993) pointed out that pollutants released at ground level may be restricted in their movement by a sea breeze and that if the pollutant is released above the sea breeze there may be little dispersion or mixing into the surrounding air until the circulation breaks down.

Oke (1987) provides a description of a situation where the sea breeze effects pollution dispersion. A pollutant is emitted into stable air moving onshore with the sea breeze, it moves inland until it meets the unstable boundary layer found over land. At this point fumigation occurs and the result is a wall of the mixed up pollutant which appears as the sea breeze front moving inland. In addition some of the pollutant is carried back out to sea in the return flow at the top of the sea breeze cell.

An example where studying the sea breeze pattern is very important is in Athens, (Helmis et al, 1987) as the city has pollution problems due to its location in a basin surrounded by high mountains. The direction and strength of the synoptic wind and the resulting sea breeze front that forms is important to the transport of pollutants inland during the day. It is further complicated by the synoptic conditions from previous days as the remnants from previous days pollutants can react with new pollutants transported inland.

Furthermore Mukammel (1965) discovered that the lake breeze at Lake Erie was the cause of damage to crops of tobacco leaves growing near the shore. It was established that the cause of the crop damage was by ozone however a source for the ozone was unexplained. Mukammel’s study revealed that the ozone was from photochemical reactions over the lake and travelled inland on the lake breeze.

Both these examples show the importance of the sea breeze and that studies from both areas can help piece together the processes affecting the sea breeze and help forecast them in the future.

2.6 Forecasting Sea Breezes

Possible methods of forecasting sea breeze characteristics are discussed by Simpson (1994). So far we have established that the sea breeze is caused by temperature differentials between the land and sea surface and that the synoptic wind has an effect on its development. Therefore it may be possible to compare the air temperature with the mean monthly sea surface temperature to work out the amount above the sea surface temperature the air temperature has to reach for a sea breeze to form. In addition the effect of the opposing wind can be brought into this.

Using this information Biggs and Graves (1962) devised the sea breeze index using dimensionless analysis to balance the forces that cause the sea breeze. Therefore the index takes into account the temperature differences and wind speed and is $U^2/\Delta T$, where U is taken at an inland site and is the unaffected wind velocity and ΔT is the difference between sea surface temperature and air temperature. Once the index number is established for a site using sea breeze data from past events, any number calculated that is lower than the index would be expected to have a sea breeze.

Simpson (1994) found that Thorney island had a sea breeze index of 7. This is considered to be at the high end of the scale as Simpson took the wind speed at 1000m rather than at sea level where Biggs and Graves found the index to be 3 on Lake Erie. The index does not take into account the direction of the wind which as we have previously discussed is very important for the development of the sea breeze. Therefore its applicability is limited but it may be useful in an area where the synoptic conditions are similar from day to day.

Attempts have been made to forecast the rate of inland penetration of the sea breeze (Simpson, 1994) mainly taking into account the wind strength for the day. A lot of local knowledge of the area is required and the results are site specific.

Simpson et al (1977) considered that the state of the tide had an effect on sea breeze propagation due to the changes in sea surface temperature as a result of the ebb and flow of tidal water. They found that that comparing the tidal sine curve for Hayling Island on the South coast of England and the frequency of sea breeze fronts reaching Lasham (50km inland) there was a higher frequency of sea breezes when the high tide was between 1000 – 1600 UTC. It can be concluded that in areas with large intertidal mudflats the state of the tide can be an important factor in forecasting the likelihood of a sea breeze. The temperature of the mudflats will change due to flooding with a different frequency than if they were only affected by radiative heating and the sea surface temperatures will also change frequently (Simpson,1994).

The main problem with trying to make predictions about the sea breeze is the site specificity of each sea breeze prediction. Intertidal mudflats have an effect on the developing sea breeze as do headlands and peninsulas (Simpson, 1994) which cause areas of convergence and divergence. Areas of upland can greatly affect the inland penetration rate of the sea breeze. Furthermore in Great Britain there are many areas where sea breezes clash with other sea breezes on their journey inland, for example sea breezes over north Cornwall often meet those formed on the south coast. Finally sea breezes on islands can be very complex because of such collisions an example of this is the Isle of Wight in the Solent (Watts, 1965) where sea breezes form on the island but also on the mainland only a few miles away therefore the sea breezes can collide, causing strange wind effects.

3 AIMS

A main aim of this investigation is to identify and analyse the sea breezes that occurred on the South of England in 2003. A computer program will be devised to identify the fronts from the high temporal scale data. The sea breeze identification program will be similar to that used in a study in South Israel whereby a computer program was written by Alpert and Rabinovich-Hadar (2003) to identify sea breeze fronts from high temporal scale weather data.

The data will be analysed on two of the scales discussed. Firstly on the synoptic scale the effects of temperature differences between the sea surface and the air temperature will be looked at, to see if there is a relationship between the difference between the two and the formation of sea breezes in this region. The effects of synoptic winds will also be investigated to try to link the influence of the winds and temperature differences to the sea breeze development.

Secondly analysis will take place on the wave scale. Using the days when sea breeze fronts have been identified by the program, certain investigations will take place, in particular the passage of the sea breeze front across a point will be studied to try to identify smaller oscillations in the data. Any oscillations will be looked at in detail and compared with the findings of other studies to try to see if they can be related to Kelvin Helmholtz Instabilities. In particular the results will be compared with the results of the numerical simulation conducted by Sha et al (1991).

Finally the synoptic scale and wave scale will be brought together to investigate any waves or oscillations that occur under the varying synoptic conditions and to see if there are any links between the two scales. This is an area which has not been previously considered. Much of the literature reviewed discusses the possibility of oscillations and their link with Kelvin Helmholtz instabilities but not under what conditions they are formed and any links with the synoptic conditions and characteristics of the waves.

4 METHODOLOGY

4.1 Location

In England there have been several studies looking into features of the sea breeze on the South Coast, most notably Simpson's studies in the 1960s &1970s looking at sea breeze fronts advancing from the coastal station of Thorney Island in Chichester Harbour, Hampshire. The site chosen for this study is in the same area at the entrance to Chichester Harbour and the data is taken from Chimet. Chimet is a weather information system that records weather data from instrumentation on high temporal scale and archives the data. The data is not shore based as the instrumentation is attached to Chichester bar beacon approximately half a mile outside Chichester Harbour entrance as seen in Figure 4.1

Figure 4.1: Chart of Chichester Harbour Entrance showing the Bar Beacon half a mile outside the entrance. Adapted from Chimet.co.uk (2004)

The data is transferred to the RNLI station on Hayling Island by radio modems and updated every 5 minutes. A summary of the data recorded is given in table 4.1.

Measurement	Sensor	Sampling Frequency	Averaging	Reporting Interval
Wind Speed	Anemometer	Every second	5 minutes	Every 5 minutes
Wind Gust	Anemometer	Every second	Taking max of 3-second running average	Every 5 minutes
Wind Direction	Wind Vane	Every second	Vector addition over 5 minutes	Every 5 minutes
Air Temperature	Thermistor	Every second	5 minutes	Every 5 minutes
Sea Temperature	Thermistor	Every second	5 minutes	Every 5 minutes
Barometric Pressure	Barometric Pressure Transducer	Every minute	5 minutes	Every 5 minutes
Tidal Height	Pressure Transducer	Every second	5 minutes	Every 5 minutes
Wave Height(average)	Pressure Transducer	Every second	15 minutes	Every 5 minutes
Wave Height(maximum)	Pressure Transducer	Every second	15 minutes	Every 5 minutes
Wave Period	Pressure Transducer	Every second	15 minutes	Every 15 minutes

Table 4.1 : Summary of measurements taken by Chimet.
Adapted from Chimet.co.uk (2004)

Chichester Harbour has a tidal range of about 4m and the bar beacon is affected by tidal movements. The depth of water at the beacon varies from 4.5 m to 1.75 m and depending on the state of the tide, slightly less than within the harbour. This varying depth at the recording station will affect the sea surface temperature that is recorded and it will not be truly representative of the real sea surface temperature as shallower water will be warmer.

This study will look at data recorded in 2003. The summer of 2003 was when the highest ever temperature was recorded in the UK. Overall 2003 had a warm and dry and sunny summer and the weather was particularly settled throughout August. As there is an overall trend for increase in temperature in the UK over the last 20 or 30 years it will be interesting to compare the results of Watts study in 1965 to the results of the study in 2003.

4.2 Evidence of Sea Breezes in Chimet Data

It is important that sea breeze features can be identified within the data and it is possible to do this by graphing variables for a day when a sea breeze could be expected. This was carried out for the 24th of June, the synoptic conditions for this day are shown in figure 4.2 which shows high pressure to the south west of the UK dominating the conditions on the south coast. The synoptic conditions for the day were light offshore breezes and clear skies.

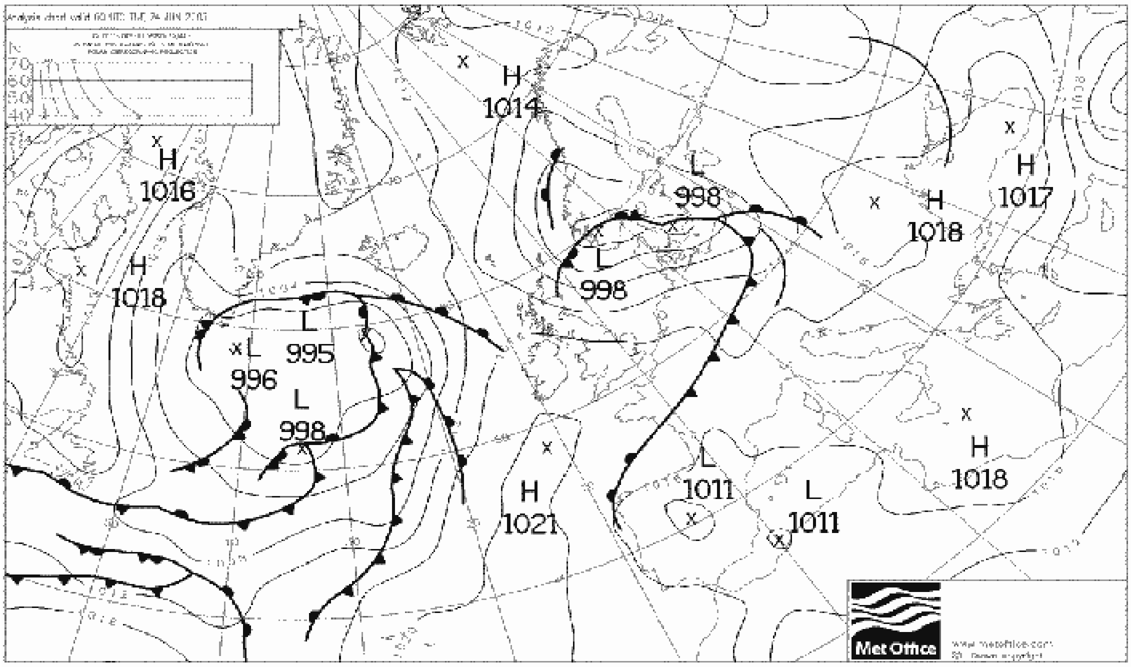


Figure 4.2: Synoptic Analysis chart for the 24th June 2003 with dominant high pressure to the south west of the UK. (Wetterzentrale, 2004)

The output from the Meteorological Office unified model for the 24th June (Figure 4.3) shows that forecasters had identified the possibility of the development of the sea breeze. Furthermore the map shows the main wind patterns in the UK on a day when a sea breeze develops against light opposing winds.

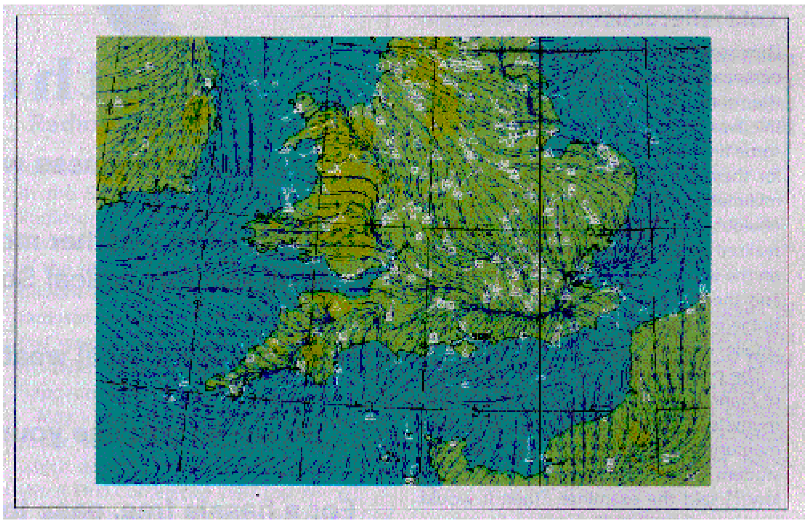
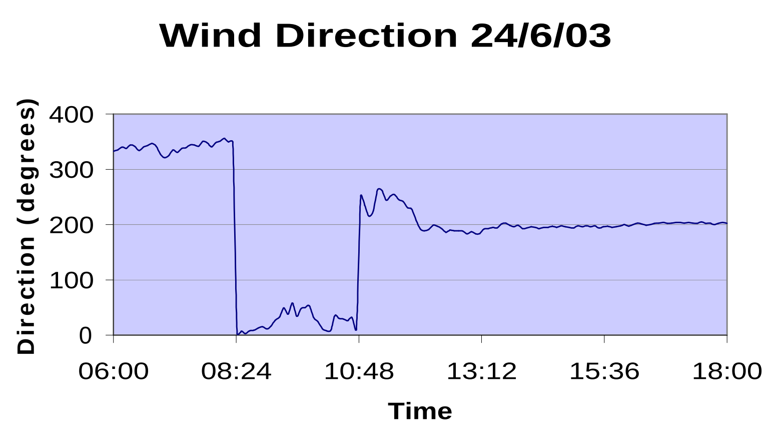


Figure 4.3: Output from the Met Office Unified Model at 1500UTC, 24/6/03. From Galvin & Dominy (2003).



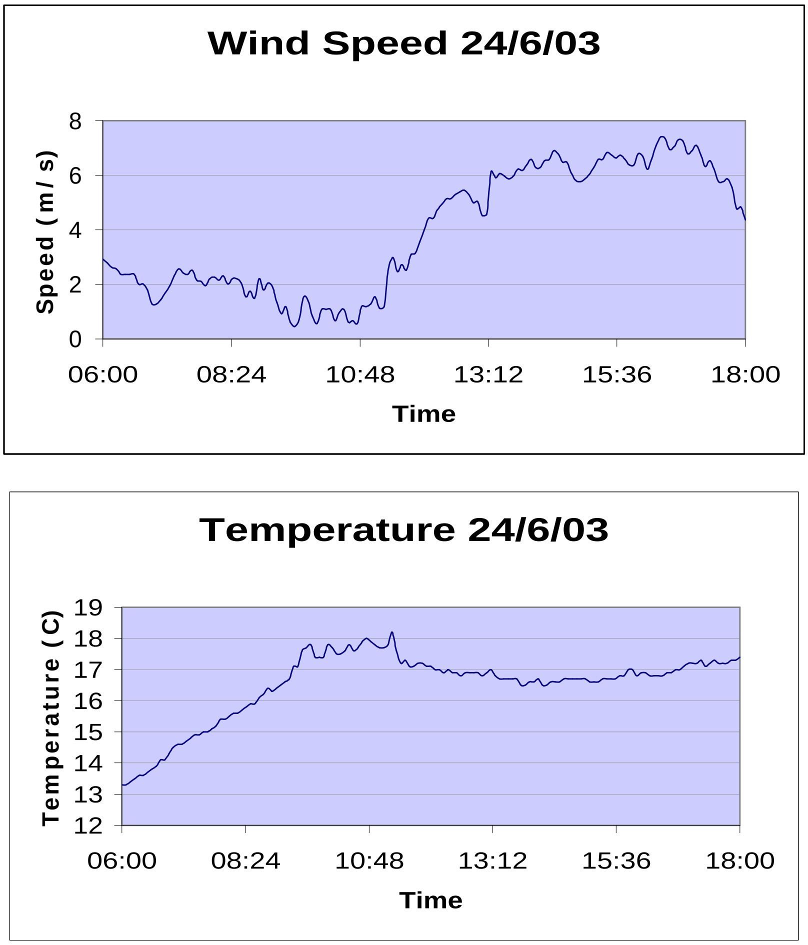


Figure 4.4 : Graphs of wind direction, speed and temperature from Chimet data on 24/6/03.

The graphs in figure 4.4 are plots of the Chimet data recorded on 24th June and show evidence of a sea breeze front at about 1100UTC due to the change in wind direction by around 0°- 50° to 200°. The first jump in wind direction is a small change from just less than 360 to 0 degrees and does not represent a large change like the second jump. In addition there is also a drop in temperature and the increase in wind speed after this time.

As it is not practical to plot the data for the entire year, a program using excel has been devised in an attempt to identify all the sea breeze fronts in the data. The data can be copied and pasted into the spreadsheet and the sea breeze frontal time will be picked out. Criteria will be devised to correctly identify the front.

4.3 Criteria for Sea Breeze Identification.

The criteria used in the computer program for the identification of the sea breeze front were chosen based on criteria used by Alpert and Rabinovich-Hadar (2003) in their program to identify sea breeze fronts on the Israel coast. These conditions are selected on the basis that the sea breeze front is accompanied by a drop or steadying in temperature, an increase in wind speed and a change in wind direction, as shown previously.

The criteria devised are as follows:

- Wind Direction: the end of a change in wind direction of greater that 40^{o} within 15 minutes.
- Wind Speed: the beginning of an increase in wind speed of greater than 0.75m/s over 35 minutes.
- Temperature: the beginning of a decrease or stabilisation in temperature over 15 minutes.
- Gustiness: The 8th largest gustiness value for the day was compared with gustiness values throughout the day. Gustiness values greater than the 8th largest were flagged as possible indicators of the front since the SBF coincides with an increased gustiness.

In most cases, except for the wind direction, 20 minute running averages have been used to smooth the data and make sure changes are genuine and not just small oscillations. However, this may effect the timing of the fronts arrival as the averages may move the time of any changes back.

The program is created on an excel spreadsheet and the data is input for each day. Columns are produced that flag either a zero or one value if the criteria are met. It was decided that the wind direction being onshore is a compulsory flag and that this criteria must produce a one in order for the program to count it as a sea breeze event. From the

Ordnance Survey map the onshore direction is between 100 – 260^{o} (Ordnance Survey, 1988). This is useful in eliminating some changes that result from other phenomena like synoptic fronts.

In addition, three of the other four criteria flags must produce a ‘1’ for a sea breeze front to be counted. In many cases there is an onshore breeze before the sea breeze front comes through and this will not create a sufficient change in wind direction to change the direction flag to a ‘1’. Furthermore not all sea breezes will cause a flag to turn to 1 and so allowing just three values to equal ‘1’ allows for some anomalies. It is found that the use of three flags is successful in eliminating most non sea breeze front features.

Alpert and Rabinovich-Hadar (2003) and others who have studied data to identify sea breeze fronts have used a humidity parameter as well however this was unavailable from Chimet. This would have been a useful indicator as the sea breeze is usually found to be a moister air mass than the dryer land air and the beginning of an increase or stabilisation in relative humidity could have been used as an extra flag.

Gustiness is a measure of the turbulence in the wind speed and is calculated as the ratio between the wind speed standard deviation and the average wind speed.

$$\text{Gustiness} = \sqrt{\frac{(u'^{2})}{\overline{u}}}$$

Here u’ is the difference between the 5 minute value of wind speed and the 20 minute running average wind speed at that time and u is the average wind speed.

The flags change to values of one at the beginning of a sufficient change in the variable except for wind direction when the end of the change is used to indicate the arrival of the sea breeze front. This procedure is similar to that of other investigations (Chiba, 1993) and is an attempt to fit the arrival of the front into the shortest time period. The timing of the front passing is variable and depends somewhat on its how it has been generated and how much it has developed.

4.3.1 Points about the criteria

Some parameters have been modified from the indicators used by Alpert and Rabinovich-Hadar (2003) due to climatological differences in location. In their study they expected a change in wind speed of over 1.5 m/s in 35 minutes as they found the average total increase in windspeed to be 4-5 m/s, this is too large for this study as the wind increase is rarely this great. In addition in the Israel study a change in direction of 45 ^{o} in 15 minutes was expected however in certain cases this was too large so it was modified slightly in this study to 40^{o}.

There have been several problems associated with the criteria chosen and many refinements to the program have been made over the course of the study although it is impossible to eliminate all anomalies. For example one complication in writing the criteria for wind direction occurs because excel did not recognise that a change from 360^{o} to 5^{o} is only a change of 5 degrees. Additional criteria were successfully programmed in to overcome this problem.

Although gustiness is a useful parameter for identifying the front, a problem found in both this study and in the study of Alpert and Rabinovich-Hadar (2003) is that the value of gustiness is very large even when there is little change in the wind if the wind is very slack ie. close to 0 m/s.

Unfortunately two weeks of Chimet data from the 17th July – 1st August 2003 was unavailable and this leaves a certain amount of uncertainty, as this is a period where several sea breezes would be expected. The data used gave a full range of sea breezes throughout the summer season and have allowed a detailed analysis to take place. The criteria devised have been found to be generally good at identifying sea breeze fronts.

4.4 Non sea breeze fronts

Quite often the program picks up indications of a front late in the afternoon when a sea breeze front would not really be expected to develop as radiative heating would have been reduced by this point. For example on the 22nd of June the program detects a front at 1730. By looking at the data for this day in table 4.2 we can see that there was a change in direction at 1730 and that there was a decrease in temperature and an increase in wind speed at this time which caused the flags to produce enough values of one for the program to think it was a sea breeze front.

Date	Time	Wind speed (knots)	Wind direction	Temperature
22/6/03	17:00	2	181	18.4
22/6/03	17:05	0.8	56	18.4
22/6/03	17:10	2.4	88	18.4
22/6/03	17:15	0.8	82	18.5
22/6/03	17:20	1.7	91	18.6
22/6/03	17:25	3.6	113	18.6
22/6/03	17:30	2	124	18.8
22/6/03	17:35	2.5	118	18.9
22/6/03	17:40	5.7	122	18.5
22/6/03	17:45	4.5	108	18.4
22/6/03	17:50	5	88	18.3
22/6/03	17:55	5	94	18.2
22/6/03	18:00	5.5	95	18

Table 4.2: data from Chimet for 22 nd June 2003 shows a change at 1730 which caused the program to detect a sea breeze front.

However looking at the synoptic chart on this date at 0000 UTC (fig 4.5) the synoptic conditions do not resemble those for which a sea breeze may be expected. There are two low pressure systems to the west of the UK with a cold front advancing across the country. It is possible that the front the program is identifying as a sea breeze front is the cold front sitting out to the west of Ireland at the time of the synoptic chart.

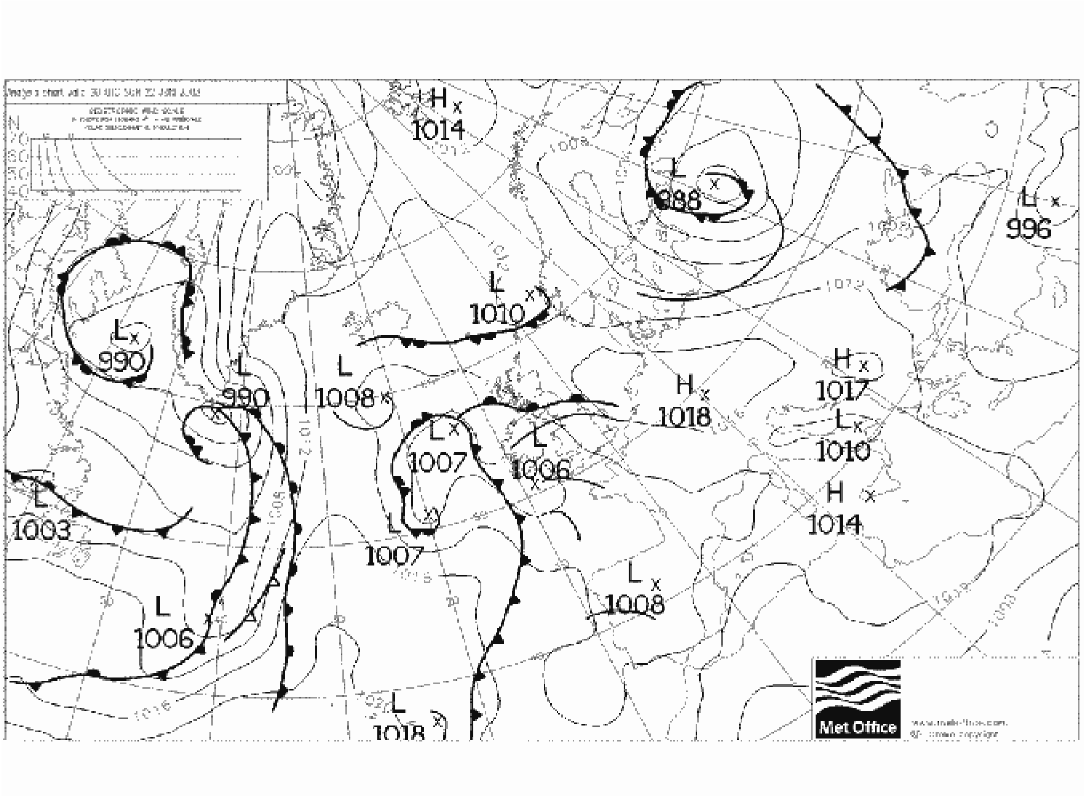


Figure 4.5: Synoptic chart for the 22nd June 2003 0000UTC. (Wetterzentrale, 2004)

4.5 Identification of oscillations

As noted by Sha et al (1991) the passage of Kelvin Helmholtz billows from above will have effects on surface parameters such as wind speed, pressure and temperature. Using the days identified by the program as having sea breezes it will be possible to look at the passage of the front more closely to try to identify any oscillations or wave like patterns in the surface parameters.

Graphs can be drawn using the time and speed of the passage to construct distance graphs showing the various parameters and any changes before or after the passage of the front across Chimet. The graphs are constructed using data from 30 minutes before the front to 30 minutes after the front to look at the details of the wind speed, pressure and temperature, at the time when the front crossed Chimet. Rather than using time versus the variable we will convert it to distance so that we can see the wavelengths of any oscillations and read these from the graphs. This method has been used by Simpson (1994) to visualise details of the frontogenesis.

If there are any wave like oscillations present these should be visible in this time period as it is expected that they could be seen directly after the front because they are produced at the top of the frontal head as described in section 2.4.

The methodology described was put into action and allowed analysis of the sea breezes that were detected in the data from April to September 2003.

5. ANALYSIS

As previously discussed sea breeze studies have taken place on a variety of scales and this analysis section will be useful in examining the features of the sea breeze reaching Chichester Harbour on a couple of different scales. Initially large scale synoptic weather and its effects on the development of the sea breezes on different days will be examined. Secondly, any wave scale features will be identified and discussed further with a view to comparing them with the findings of other studies.

5.1 Total number of sea breezes

The program devised to detect sea breeze fronts was run using Chimet data from April to October for 2003. The results can be seen in full detail in Appendix 1. A summary of the number of sea breezes is shown in table 5.1.

Month	April	May	June	July	August	Sept.	October
No. of sea breezes	6	14	16	10 *	10	10	4

Table 5.1: shows the distribution of sea breeze days in 2003. *2 weeks data was unavailable in the second half of July.

There are 70 sea breezes picked up by the program in total. This includes 6 that occur at suspicious times for a sea breeze (ie. after 1600 UTC). An example was discussed previously in section 4.4 when the sea breeze was detected at 1730. There are two weeks of data missing for the second half of July and so it can be concluded that there were about 70 sea breezes in total during the summer season 2003.

Watts (1965) gave the number of days with sea breeze activity at Thorney Island as 75 between April and September inclusive in one year. The results of this study include October and show that there were 4 sea breezes in October so the total can be taken as 66 between April and September. This is slightly lower than Watts' (1965) results and could be due to the program not detecting some fronts or a lower number of sea breeze fronts occurring on the south coast.

5.2 Temperature Effects on sea breeze development

5.2.1 Annual variations

The distribution of sea breezes throughout the year is explained by the difference in air temperature and sea surface temperature (table 5.1). The greatest difference between the two would be expected in May and June when the air temperatures can be in the late teens or early twenties on sunny days and the sea surface temperature is still quite low as it takes longer to increase in the summer months. As a result a greater temperature differential develops.

If the missing data in the second half of July followed the same pattern as occurred in the first half of the month, July would be expected to have had the greatest occurrence of sea breezes. It is suspected that the number of sea breezes in the latter half of July would decrease due to an increase in sea surface temperatures reducing the temperature differential.

Figure 5.1 shows the daily minimum and maximum air temperature over land and daily average sea surface temperature, all the variables were measured by Chimet. The sea surface temperature follows some of the small peaks and troughs that the air temperature traces. This illustrates that due to the shallow nature of the water where the data is recorded, it is not representative of the sea surface as a whole as the sea surface temperature graph would be expected to be smoother and not to follow the air temperature so closely. However the graph does show that the highest air temperatures relative to the sea surface temperature occur in late June and early July.

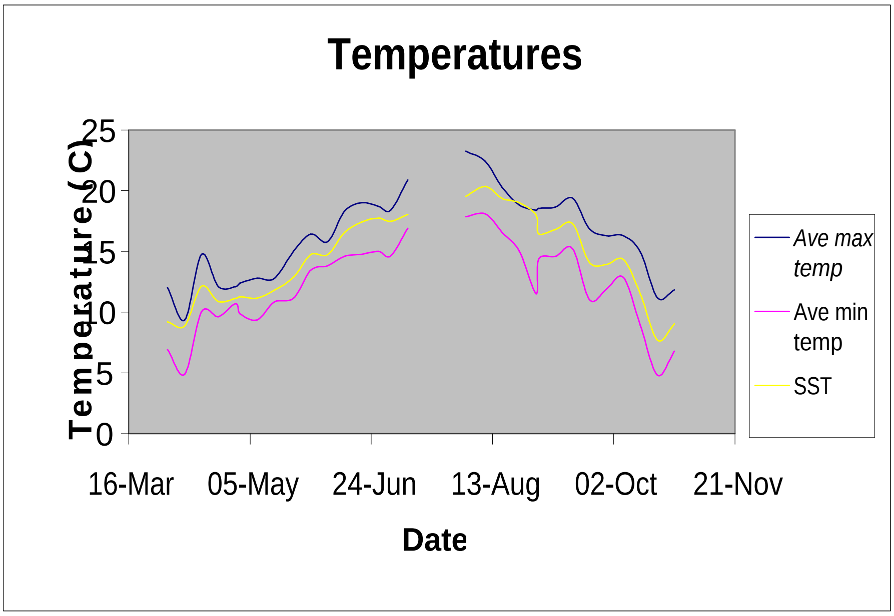


Figure 5.1: Graph of temperature data taken from Chimet. Sea Surface temperature is the weekly average. Average minimum and average maximum are also the average for the week. Full results in Appendix 1.

Figure 5.2 shows a graph of sea surface temperatures for the South West of England (A1 SST website) compared to the values taken at Chimet and shows that the values recorded may be unrealistically high in the summer months and that the actual sea surface temperatures are a few degrees lower. This is due to the shallow water at Chimet, the water is becoming warmer than the actual sea surface temperature. Although until mid June the Chimet sea surface temperatures are reasonably similar to the temperatures recorded off the south west of the UK.

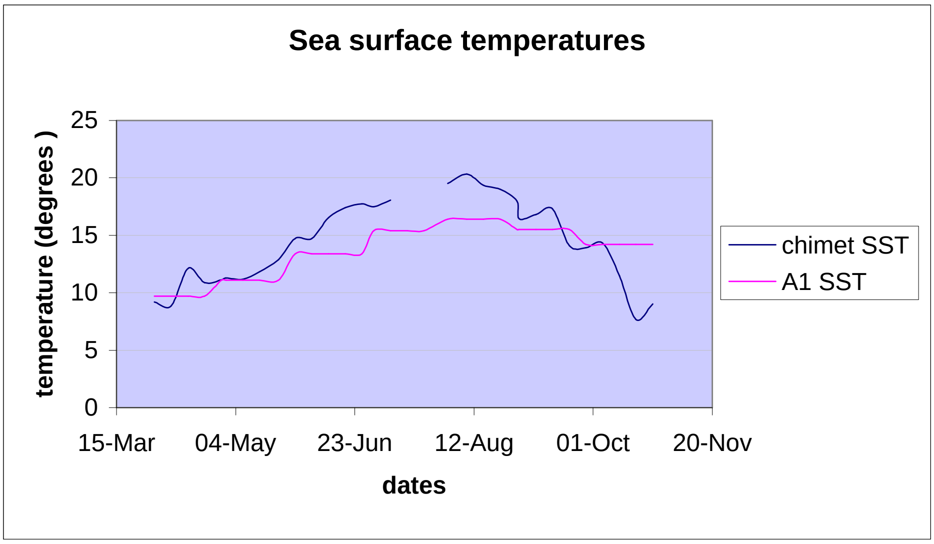


Figure 5.2: Graph of the difference between Sea surface temperatures recorded at Chimet and sea surface temperatures for the SW England. Data fromChimet.co.uk (2004) and AI Surf (2004).

5.2.2 Individual days

Taking a closer look at temperature differences (table 5.2) on individual sea breeze days shows that in the early season the difference between the sea surface temperature and the maximum air temperature seems to be larger for a sea breeze to occur than in mid summer. For example, on the 24 th June the temperature range was 5 degrees during the day but the maximum was only 0.8 degrees more than mean SST. However on the 5 th April the maximum temperature is 14.7 c and the sea surf ace temperature is 9.2 c degrees while the range for the day is 5.4. So the range is similar however the maximum temperature is much greater.

Date	Max. temperature (chimet) (c)	Minimum temperature (chimet) (c)	Temperature Range	Average Sea Surface Temperature (c)
5/4/03	14.7	9.3	5.4	9.2
22/4/03	10.8	7.2	3.6	10.9
6/5/03	13.3	8.1	5.2	11.3
13/5/03	13.6	8.2	5.4	11.2
2/6/03	15.9	13.3	2.6	14.7
24/6/03	18.2	13.3	4.9	17.4

26/6/03	18.7	15.8	2.9	17.4
14/7/03	24.4	17.8	6.6	18.9
6/8/03	21.8	18.7	3.1	19.5
12/8/03	23.3	19.2	4.1	20.4
3/9/03	18.1	15.6	2.5	16.4
14/9/03	18.2	14.9	3.3	16.8
11/10/03	18.4	11	7.4	14.3
29/10/03	12.2	8.1	4.1	9.0

Table 5.2: shows different temperatures on different sea breeze days. The sea surface temperature is the weekly average. Minimum and maximum temperatures are between 0600 UTC and 1800 UTC.

Rather than a relationship between the maximum temperature and sea surface temperature perhaps there is some indication that a relationship between minimum temperature and sea surface temperature exists, or that there is a relationship between the sea breeze occurrence and the temperature range for that day. Looking at the average values for days with sea breezes and no sea breezes (table 5.3) it is clear there is no real pattern. The average temperature range is slightly less for days with sea breezes than those without however the results do not show definite patterns between temperature and sea breeze genesis.

	Average Temperature Range (max.–min.)	**Average Difference between max. temperature & SST**	**Average Difference between SST & min. temperature**
Days with no sea breeze	4.11	1.93	2.19
Sea breeze days	4.02	1.84	2.18

Table 5.3: shows the averages for the Chimet data from April – October 2003.

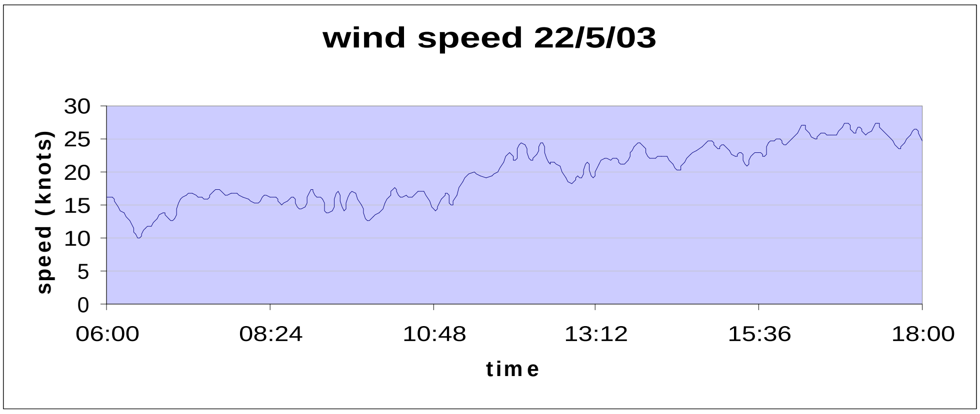
It is well documented in the literature that the sea breeze is caused by the differential between the sea surface temperature and the air temperature, however a relationship is not visible within this data. This indicates that the process that causes the sea breezes to develop and move inland is more complex and suggests that other factors are involved in this case. It was suggested in the literature that there are relationships between synoptic conditions and the sea breeze development and these are explored further in the next section.

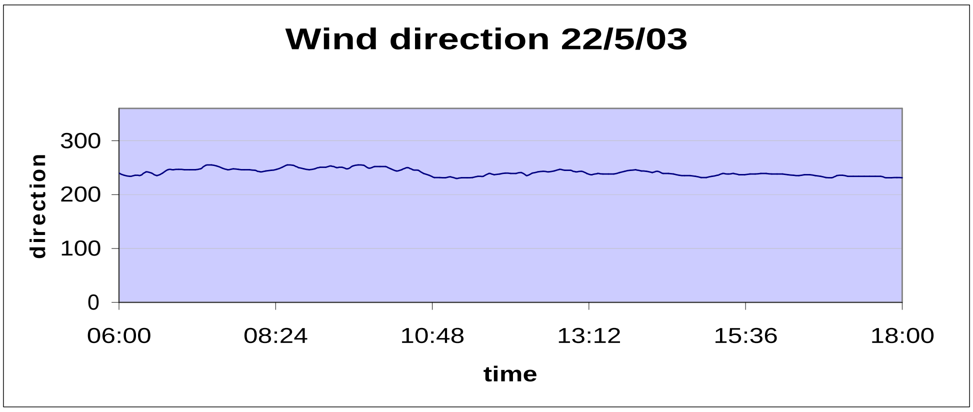
5.3 Synoptic conditions

By looking at various examples from days when the program identified sea breezes we can see if there is a pattern between the time of the front passing Chimet and the synoptic conditions and also if there is evidence of weaker fronts, as would be expected on days with a synoptic onshore breeze.

5.3.1 Onshore Winds

The 22nd May is an example of a day where the synoptic conditions were onshore already and so it is harder to detect the sea breeze front as it is theoretically weaker. Chimet did however detect the front at 1150 UTC.





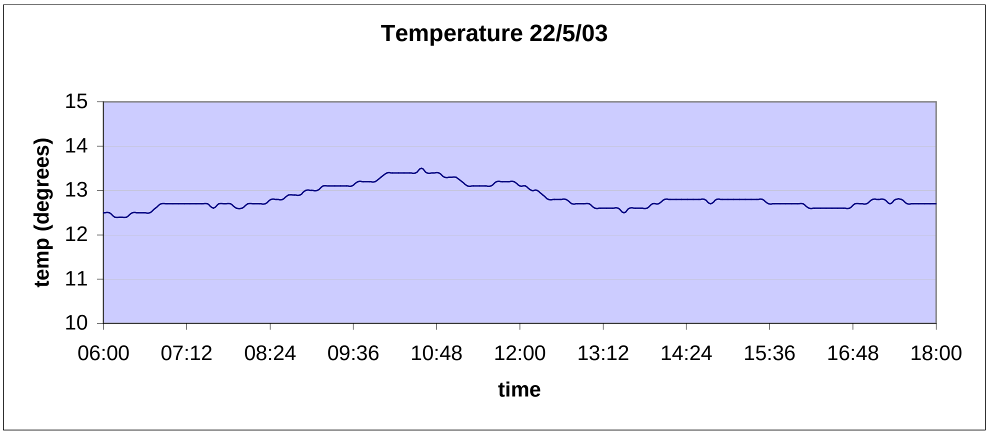
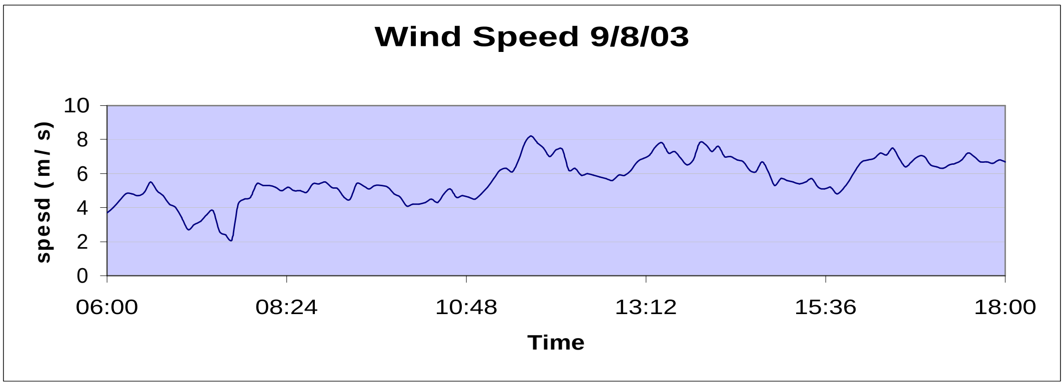
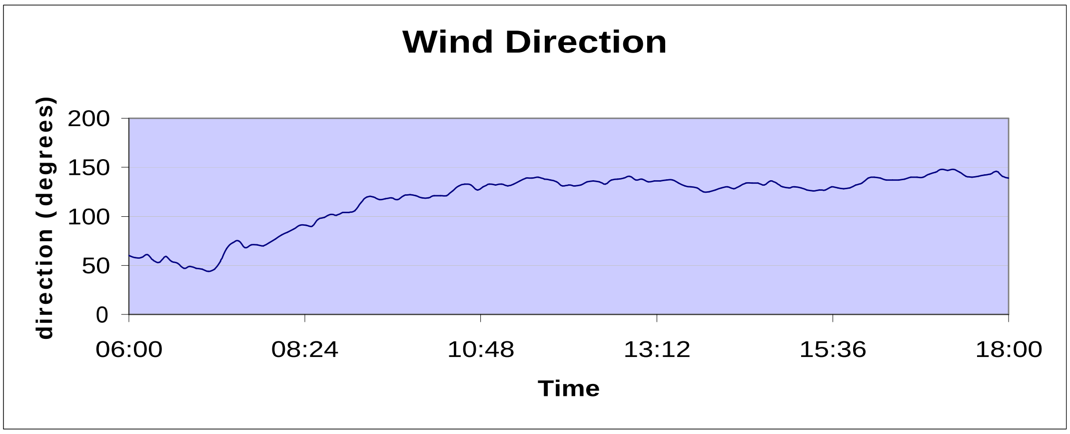


Figure 5.3:Graphs of wind speed, direction and temperature from 0600 – 1800 UTC on the 22/5/03.

An example of a sea breeze front that the program does not pick up as only 3 flags turn to 1 is on the 9th August. Although all the flags apart from 'the change in direction' do change, the timing does not coincide so the program does not record it. However it is a good example of a front on a day when the wind is onshore already as seen in the graphs below. The front seems to pass Chimet at about 1145.





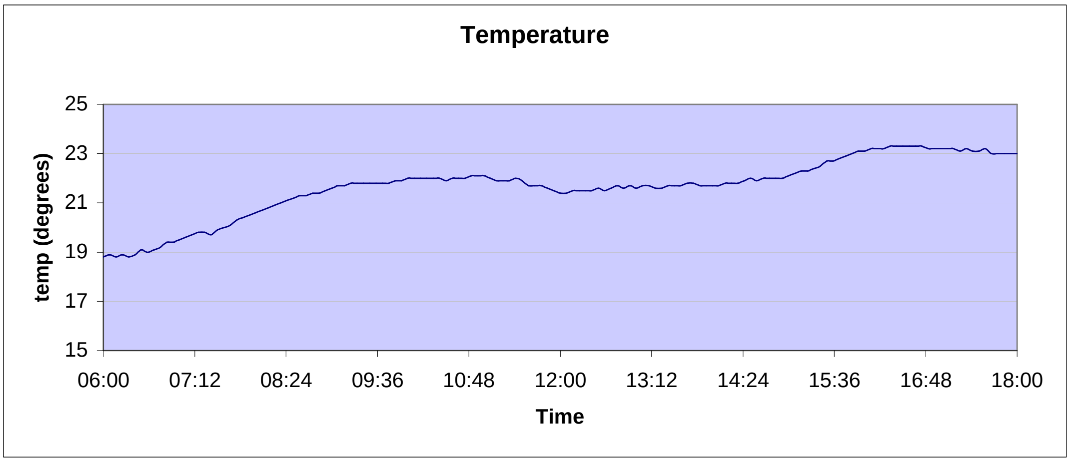


Figure 5.4:Graphs of wind speed, direction and temperature from 0600 – 1800 UTC on the 09/08/03.

The 9th of August sea breeze illustrates the weaker front which is almost undetectable due to weaker frontogenesis on days when the synoptic wind is onshore as was discussed in section 2.1. This is explained by weaker convergence at the front and only a slight density difference across the front. The change in surface variables as the front passes is not so noticeable, making it harder for the program to identify the front.

5.3.2 Seasonality

Arritt (1993) found that the strongest sea breeze frontogenesis takes place on days when the wind is 6m/s in an offshore direction. On the 5 th April 2003 in the morning the winds were offshore (20-30^o) averaging about 5-6 m/s, the maximum temperature was 14.7^{o}C at 1515 UTC and average sea surface temperature that week was 9.7 ^{o}C. The pressure was high at 1032mbars all the typical conditions of a sea breeze formation. The graphs (figure 5.5) show the conditions for the day and the program detected a sea breeze front at 1535.

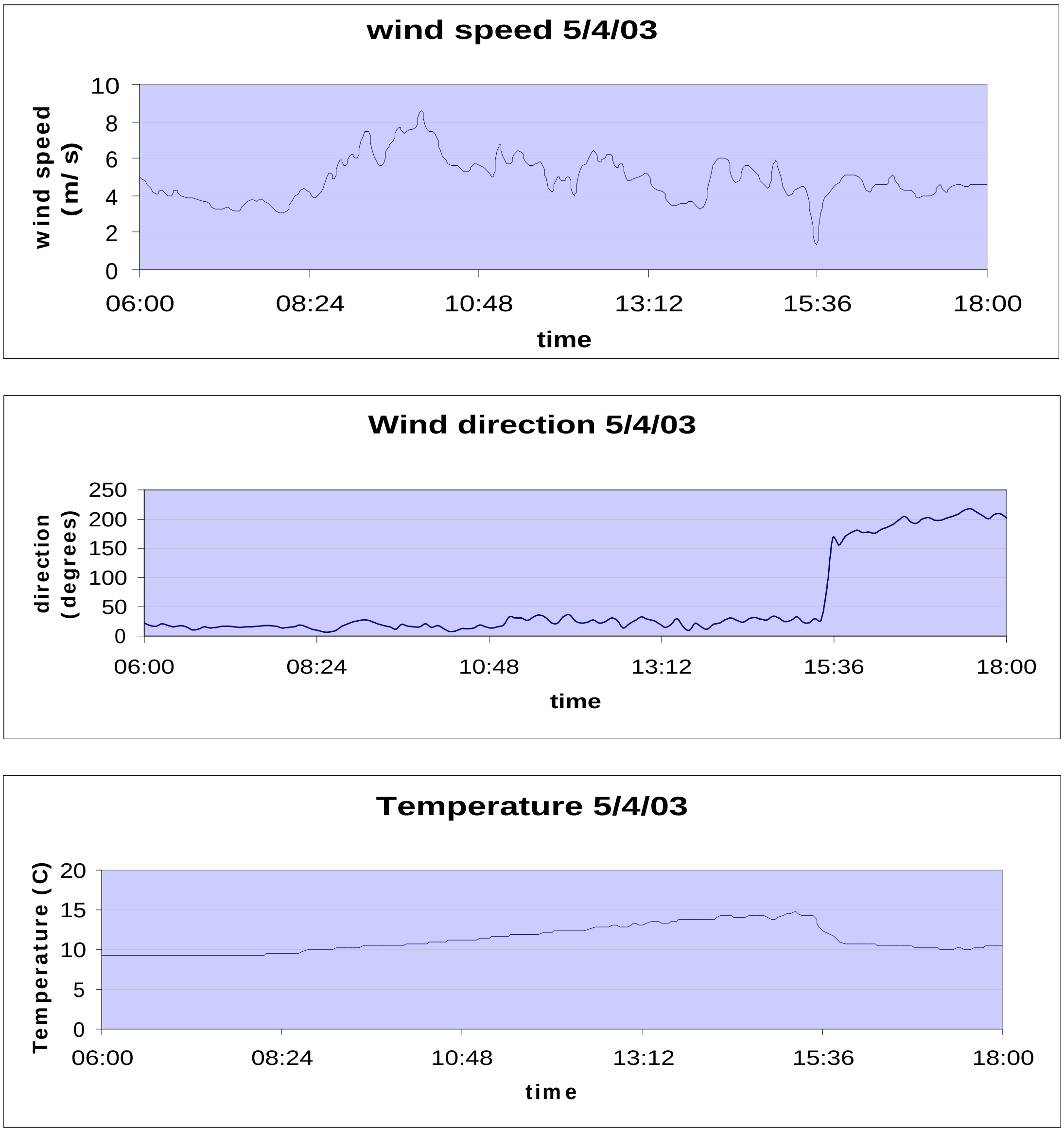


Figure 5.5:Graphs of wind speed, direction and temperature from 0600 – 1800 UTC on the 05/04/03.

The literature suggests that on days with conditions like these the sea breeze front would be expected to form earlier in the day suggesting that something prevented it moving inland earlier than 1535. Although the front was formed offshore due to the opposing wind in the morning it would still be expected to push inland earlier. The reason the front did not pass Chimet earlier may be because it is early in the season for sea breezes and it may require longer with a temperature differential before the front forms.

A typical feature of the sea breezes for the first three weeks in April is that despite maximum temperatures well above the sea surface temperature, (for example on the 4th April, the maximum temperature is 18.4 °and the sea surface temperature is 9.2 °C), no sea breeze develops. Looking at this data more closely reveals that moderate to strong northerly or offshore winds are occurring often and this seems to prevent the development of a front or prevents the front moving inland. This is a good example of the importance of wind strength on the movement of sea breeze fronts but also illustrates that the early season sea breezes are not strong enough to overcome opposing moderate winds.

In the data from the 24th June that was previously looked at as an example of a sea breeze in the methodology (figure 4.4) there was a front that formed when the synoptic conditions were around a 2m/s offshore wind (350 – 10°). The program identified the front passing Chimet at 1050. This front could have formed earlier than the example on the 5th April because the sun comes up earlier in June and the early heating will result in formation of the sea breeze. It seems that not only are synoptic conditions important in sea breeze development but also the time of year.

5.3.3 Timing with Onshore and Offshore Winds.

Having looked at the effects of the time of the year on the timing of the frontal development it is important to consider the large scale effects of the synoptic winds on the timing of the front passing Chimet. By comparing the sea breeze fronts that form on days with opposing offshore winds and those with onshore winds we should be able to see that the latter cross Chimet later in the day as described by the literature. This is due to the smaller density difference across the front on days with synoptic onshore winds.

However, as discussed the wind strength also has some bearing on this. If the synoptic wind is strong and opposing the sea breeze it may keep it offshore and stop it crossing Chimet until later in the day. A closer look at some of the details of synoptic winds on days with developing sea breezes are shown in table 5.4. 27 representative sea breeze days, chosen randomly to cover the entire season were investigated.

DATE	TIME OF FRONT	DIRECTION 1 HOUR BEFORE	WIND SPEED 1 HOUR BEFORE (knots)	DIRECTION 30 MINS BEFORE	WIND SPEED 30 MINS BEFORE (knots)
5/4/03	1535	29	10.9	33	9.7
22/4/03	1045	48	0.1	0	0
2/5/03	1355	192	19.8	196	22.4
6/5/03	1205	248	11.6	220	8.9
11/5/03	0730	81	1.3	45	2.3
22/5/03	1150	236	15.7	231	19.8
7/6/03	1330	197	10	195	12
13/6/03	1000	11	3.6	337	3.7
26/6/03	0940	50	8.8	69	7.6
28/6/03	1000	312	5.2	289	3.7
5/7/03	1205	333	3.3	298	5
8/7/03	0720	0	0	0	0
9/7/03	0830	296	1.9	4	1.4
14/7/03	1200	102	11.1	105	11.9
2/8/03	1045	348	4.4	38	3.6
6/8/03	0830	141	3.8	152	5.3
11/8/03	1000	17	4.8	26	3.6
14/8/03	1405	22	5.1	40	3.7
20/8/03	1135	301	6.3	305	4.7
2/9/03	1230	334	1.6	33	0.4
5/9/03	1435	157	7	157	4.9
11/9/03	1300	205	4.7	194	4
14/9/03	1005	74	5.8	75	5.4
20/9/03	1350	127	5.8	124	7.7
24/9/03	1220	109	1.7	0	0
11/10/03	1205	84	0	81	0
21/10/03	1530	230	4.2	246	4.6

Table 5.4: A comparison of wind directions and speeds before the sea breeze on 27 days from 2003 on which a sea breeze occurred. Red represents offshore winds and black onshore winds.

It seems on days with onshore winds between (110 and 260 degrees) the fronts seem to reach Chimet after 1200 and on days where the wind is already offshore (between 261 and 109 degrees) the frontal time is earlier and have usually passed Chimet by 1300. There are several exceptions which will be discussed further.

On the 6th August even although the wind is onshore in the morning the sea breeze front is detected at 0830 which is earlier than expected for these synoptic conditions. A closer look at the data for that day shows very high temperatures overnight maintaining a differential of about 4-5 degrees. It shows that the sea breeze may have been forming for several hours before the front crossed at 0830 and is an exceptional case.

The sea breeze on the 5th April also does not fit the general rule as previously discussed. This is due to the fact it is very early in the season and therefore the front did not evolve until later. Also the 14th August does not fit the rule and this example will be studied more closely.

It is interesting to examine a few cases more closely. The conditions on 28th June, 5th July, 2nd August, 11th August and 14th August are similar with light offshore winds between 1.7 and 2.7 m/s before the front yet they have very different arrival times for the front ranging from 1000 and 1405. The front arrival time for the 28th June and the 11th August is 1000 but the others vary and therefore it is useful to examine other aspects of the weather on that day.

DATE	FRONT TIME	TEMPERATURE (^{o}C)	SST (^{o}C)	PRESSURE
28/6/03	1000	15.1	17.3	1016.4
5/7/03	1205	17.9	17.3	1019
2/8/03	1045	18.7	17.9	1023
11/8/03	1000	24.6	20.6	1016.8
14/8/03	1405	20.6	20	1018.5

Table 5.5: Variables at time of front detected by Chimet

The table of results (table 5.5) is really not showing much pattern except that the 28th June and 11th August have the similar pressure readings. It might be considered that the temperature difference between sea surface temperature (SST) and air temperature is important, however there appears to be an anomaly on the 28th June when the air temperature at the time the front passes Chimet is lower than the SST, but this may be a data error. Otherwise when the difference in temperature is greater, the sea breeze front arrives earlier. The 5th July and 2nd August have almost identical synoptic conditions yet the front arrives earlier on the 2nd August this could be due to the higher pressure and slightly higher temperature on this date.

The analyses of the sea breezes show how it is a complex balance of factors that effect the timing and movement of the front. There are some trends indicating that offshore opposing winds before the sea breeze forms mean the front moves inland earlier due to the greater density difference across the front. However this is effected by the time of year, during the early season when sea surface temperatures are still low and radiative heating is less it may take longer for the sea breeze to develop, so all fronts form later in the day.

5.4 Looking at fronts in detail over time and distance

Having identified the sea breeze fronts that occurred in 2003 and looked at their formation the next objective was to look at them more closely and investigate the finer details of the passage of the front. It is evident on some of the days when sea breeze fronts were identified that there are some oscillations after the passage of the front and even some wave like behaviour before the front passed. Some examples of this will be investigated further.

5.4.1 Examples of Oscillations in Surface Parameters

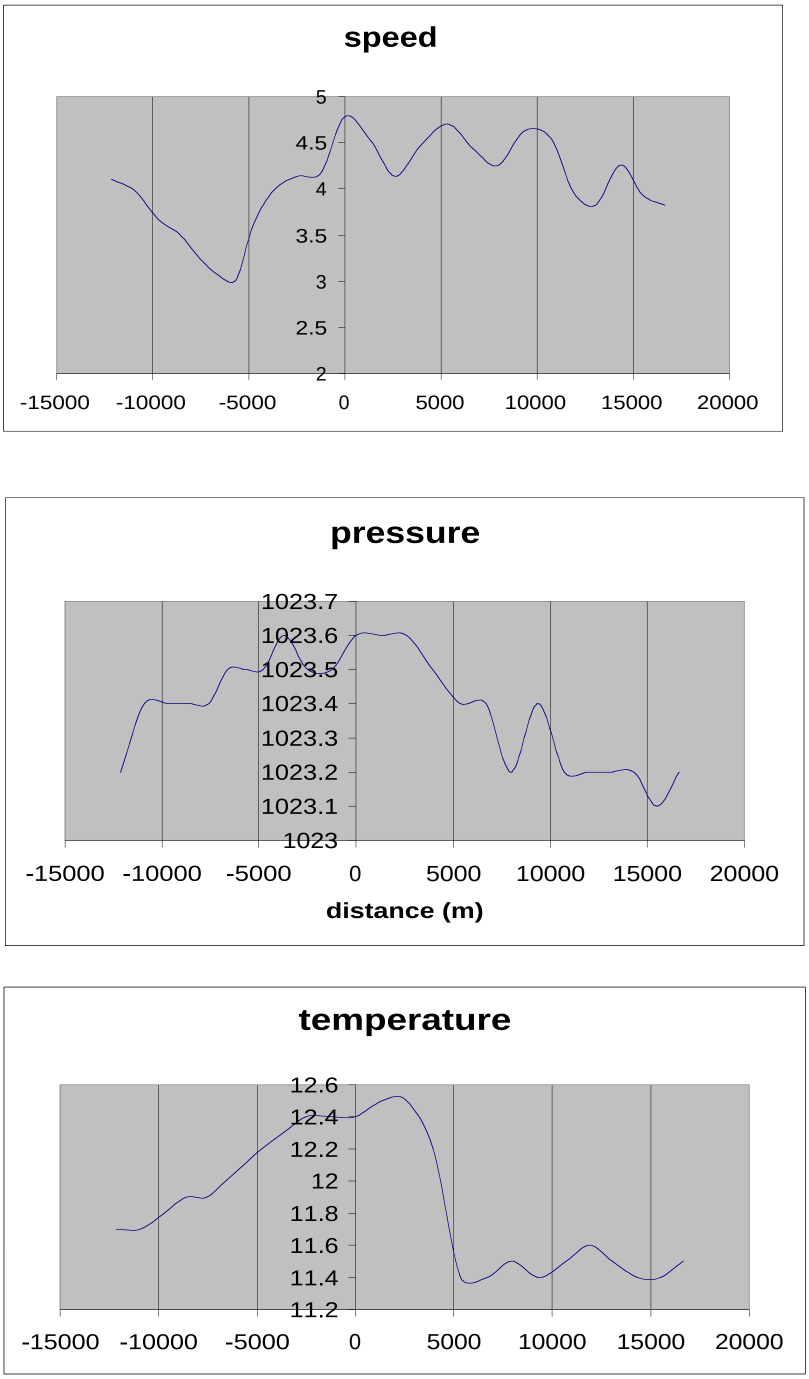


Figure 5.6: Graphs for the sea breeze frontal passage on 6th May 03.

The graphs for the sea breeze on the 6th May show the passage of the sea breeze front, the graphs show definite wave like patterns (fig. 5.6). The zero point on the x -axis is the front passing Chimet, the negative distance is the air inland of Chimet when the front is passing and the positive side of the x -axis is the air out to sea from the position of the front. The main oscillations on this occasion are between 5 –10km out to sea. The waves could be identified in the wind speed, temperature and pressure parameters. The scales are small however there is definite evidence of wave like behaviour. In addition the pressure and temperature waves seem to mirror each other. It is reasonable to find this as we would expect a small pressure decrease as warmer air is mixed in from above due to the Kelvin Helmholtz Billows.

The wavelengths of the oscillations on the 6th May do seem to differ between the different variables. The wavelength for wind speed is 5000m, for pressure there is one main oscillation about 6000m out to sea and this has a wavelength of 3500m. For the temperature parameter the wavelength is 4500m and the oscillation occurs 5250m from the front. The strongest signal is picked up in the wind speed and the oscillations are approximately 0.5m/s in amplitude. The oscillations in pressure are 0.2mbars and in temperature are 0.1 °C and there is evidence to suggest that they get larger further away from the front as Sha et al (1991) described whereby the billows increase in size as they move away from the front along the ‘zero velocity line’. There do not seem to be any oscillations before the passage of the front on this occasion.

Another day when oscillations can be identified is the 12th May 2003 and the graphs of the parameters are shown in figure 5.7.

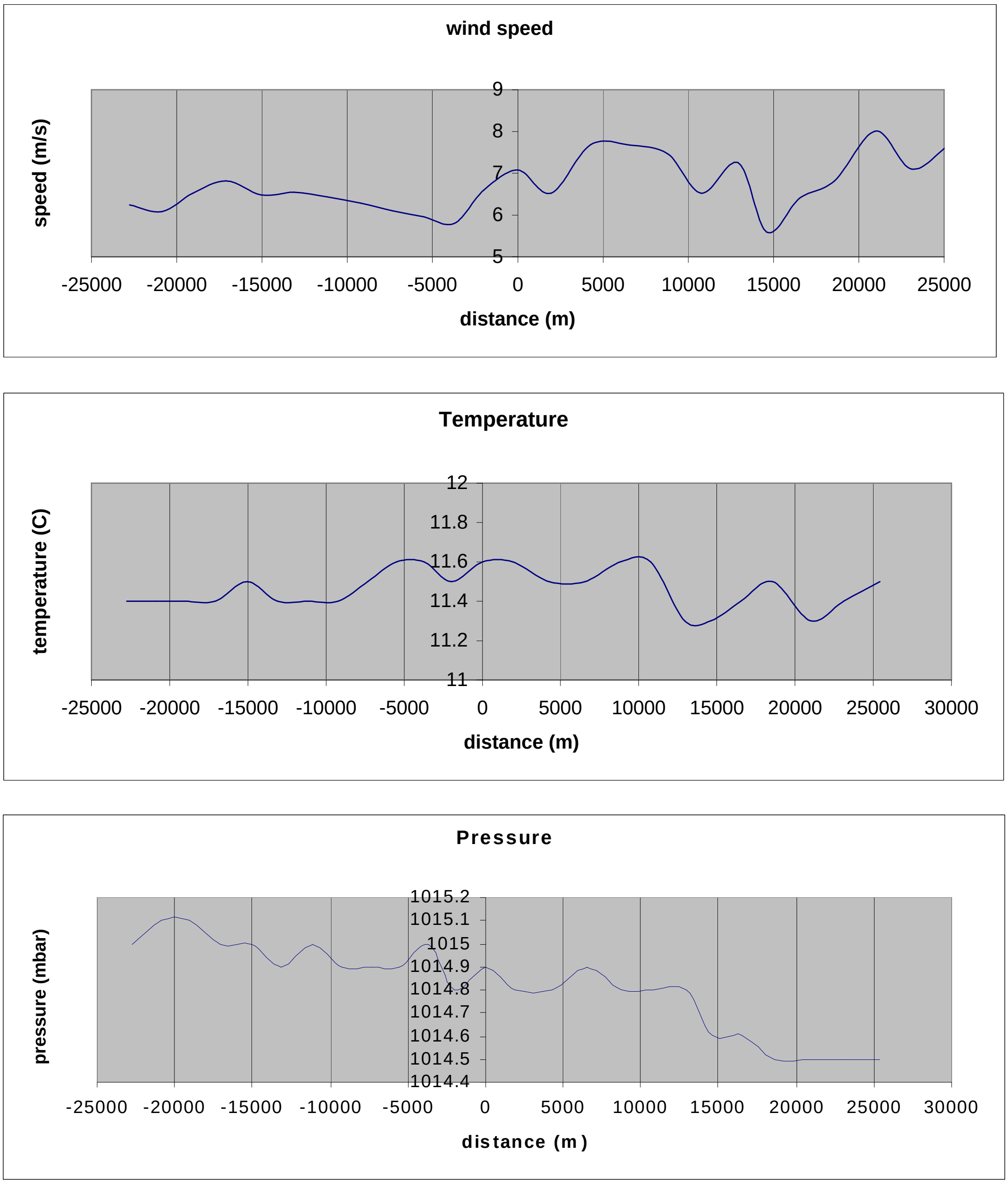


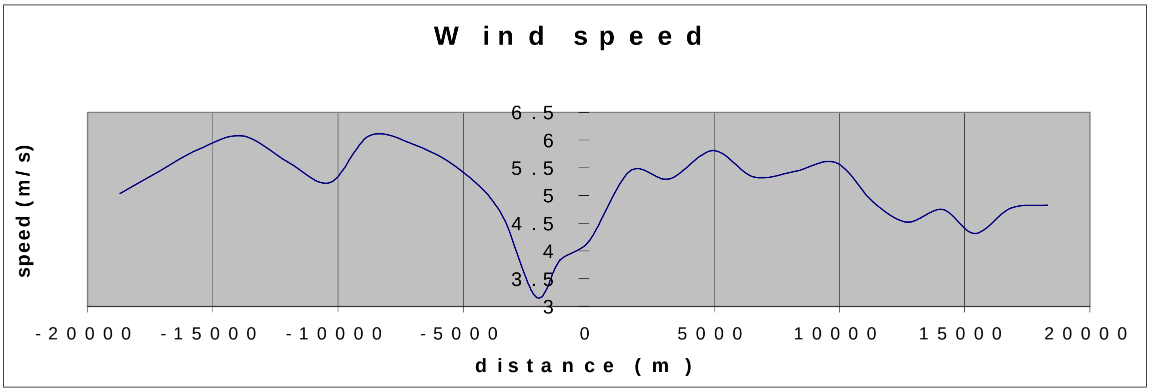
Figure 5.7: Graphs for the sea breeze frontal passage on 12th May 03.

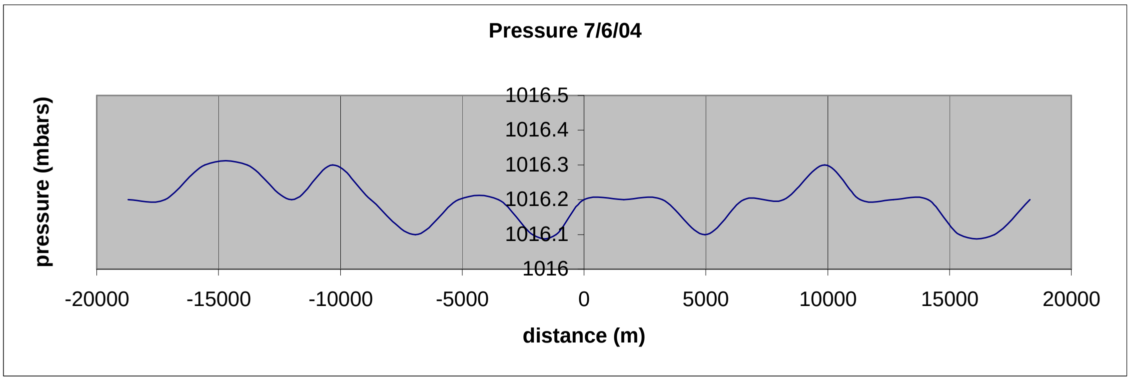
On this occasion the temperature oscillations are far clearer, the wavelength of the oscillation as the front passes is 5km however the wavelength of the next oscillation is 10km and the wavelengths then decrease. The amplitude of the oscillations for temperature are 0.1 degree changing to 0.2 degrees further out to sea away from the front.

On the 12 th May the pressure oscillations show a similar wavelength pattern, expanding further away from the front (fig 5.7). The amplitude of the oscillations are 0.1mb. The oscillations in the wind speed parameter have the same wavelength pattern as the other two parameters, however they are harder to define. The size of the oscillation is 1m/s and does seem to increase further away from the front to 2m/s. On this occasion the temperature and pressure oscillations do not mirror each other exactly but there is a lag of about 1000m with the oscillations in temperature occurring first.

Note that the wind speed and temperature continue to oscillate over 25km from the front whereas the pressure stops oscillating at 19km. It has been found in previous studies (Sha et al, 1991) that oscillations in the pressure field were not detectable and it may be that this is a less sensitive parameter and therefore the oscillations are less visible if the billows are breaking down. In the first example of the oscillations on the 6 th May wavelike features could still be detected at the end of the measurement period.

Furthermore on the 12th May there is a evidence to support some prefrontal oscillations. This can be seen in the pressure field where there is a wavelike feature 10km before the front (Fig 5.6). This seems too far from the front to be related to its passage and is not identifiable in the wind speed field which has proved the most decisive so far.





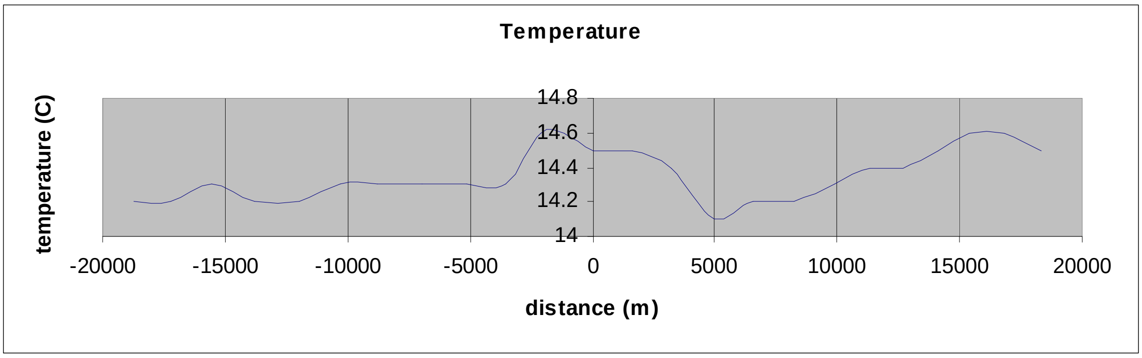


Figure 5.8: Graphs for the sea breeze frontal passage on 7th June 03.

The 7 th June is another example where wave like features can be identified in the parameters around the passage of the front. In this instance there is little evidence in the temperature field except at 5000m behind the front out to sea and it is not as distinctive as the patterns in wind speed and pressure. The wavelengths are less than 5000m as the front passes however, as in the previous example they extend to greater than 5000m before decreasing again.

On the 7 th June there is also evidence of a prefrontal wave with a wavelength of 5000m about 7.5km ahead of the sea breeze front. This is mainly seen in the pressure and speed parameters.

On several days investigated there is no evidence of any oscillations in the surface parameters at all. For example on the 29 th September there was no recorded wind before the front came through therefore the charts only show the air seaward of the front (Fig

5.9). This illustrates that the oscillations are not just random features as there is clearly no evidence of any wavelike behaviour in the surface variables on the 29th September.

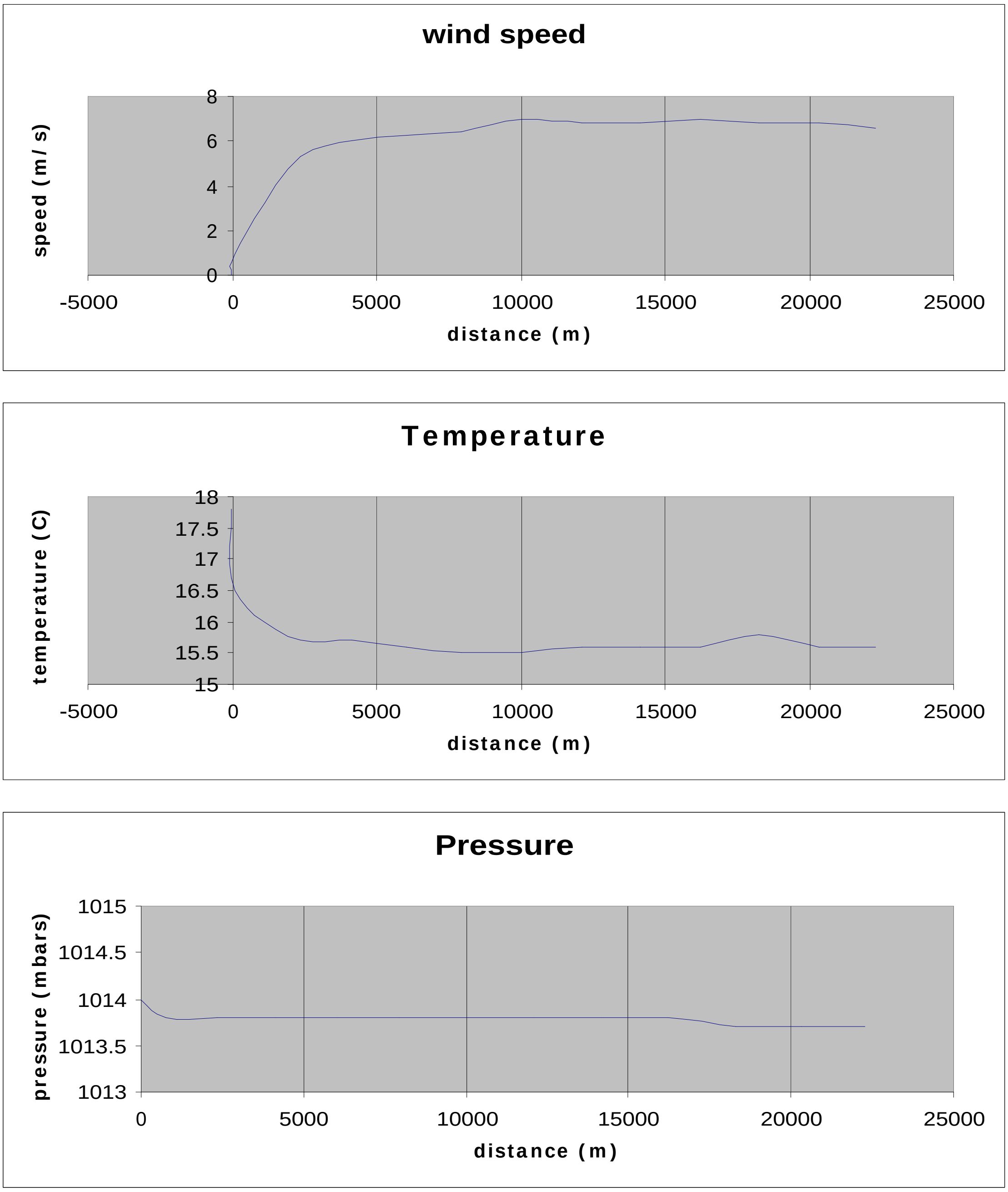


Figure 5.9: Graphs for the sea breeze frontal passage on 29th Sept 03.

The post-frontal oscillations identified in this study can be compared to those found in other studies. Sha et al (1991) found the pressure perturbations to have an amplitude of 0.5hPa. The amplitude of the oscillations in this study are smaller, around 0.1hPa. This indicates that the waves we are finding are smaller than those of the numerical simulation. In contrast the amplitude of the oscillations seen in the South Israel study (Alpert & Rabinovich-Hadar, 2003) are similar to those found here, both studies find the wind speed amplitude is around 0.5m/s and the temperature oscillation is around 0.2°C.

Donn et al (1956) reported pressure oscillations in their observational study. These were of a 25 – 40 minute period. Sha et al (1991) found that the period of oscillations in surface velocity was typically 35 minutes. The period of oscillations in this study is very variable depending on the windspeed on the day as the wavelengths are all around 5km. On the 6th May the oscillations are 20 minutes, on the 12th may they are 12 minutes and on the 7th June 15 minutes. The waves detected in the Israel study (Alpert & Rabinovich-Hadar, 2003) also appear to have a period of around 30 minutes. We are finding shorter periods for all the waves seen in this study. This suggests that the waves found here are slightly different from those of other studies.

Sha et al (1991) also found that the horizontal wavelength of the billows was between 0.5 and 3km although this measurement result applied above the surface. The wavelengths found at the surface in this study have been typically around 5km.

It has been established that there is evidence at the surface of some disturbances from above causing oscillations in speed, pressure and temperature parameters at the time of the front passing Chimet. As it has also been discovered that on certain days there is no evidence of any wavelike behaviour it is now a good idea to try to find any links between days with the oscillations and those without.

5.4.2 Links between Days With and Without Oscillations.

In some cases it is hard to distinguish whether a day has oscillations or not. However a table has been prepared to investigate any relationships between days with oscillations and those without (table 5.6). 14 sea breeze days were chosen to represent a variety of different synoptic conditions throughout the entire season to see if there are any relationships between the days when oscillations could be identified and those when they could not be seen.

DATE	TIME OF FRONT	WIND DIRECTION 1 HOUR BEFORE FRONT	WIND DIRECTION 1 HOUR AFTER FRONT	DIFFERENCE IN WIND DIRECTIONS	EVIDENCE OF OSCILLATIONS
5/4/03	1535	29	205	176	none
6/5/03	1205	248	202	46	definite
7/5/03	0955	281	196	85	none
12/5/03	1005	211	206	5	definite
22/5/03	1150	232	245	13	definite
27/5/03	1010	277	251	26	definite
5/6/03	0830	219	200	19	some
7/6/03	1330	197	182	15	definite
13/6/03	1000	11	213	202	none
18/6/03	0905	246	235	11	definite
24/6/03	1050	32	228	196	some
14/8/03	1405	22	190	168	possible
16/9/03	1055	259	181	78	possible
29/9/03	1350	0	211	211	none

Table 5.6: Table of wind directions before and after the fronts crossed Chimet and evidence of oscillations.

There is evidence to suggest that the days where there is only a small change in wind direction with the sea breeze arriving will have more evident wavelike activity in the parameters at the surface. The days with definite evidence of oscillations all have onshore winds before the front and the change in angle of the wind is less than 50^{o}. The relevance and possible explanation for this pattern will be discussed in more detail later on. As the angle by which the wind changes gets larger the wavelike features become less distinctive and may be a result of random oscillations. Although there is still evidence that the features could be linked with possible Kelvin Helmholtz Billows as the timings of the oscillations between parameters still seem to coincide although their amplitudes are smaller.

There are some exceptions to the conditions that a smaller change in wind direction indicates that oscillations will be visible at the surface and the boundaries are blurred. However, as a general rule it is found that changes in wind direction of less than 50^{o} indicate that oscillations of certain parameters will be visible at the surface. The synoptic wind speed does not seem to have any bearing on whether waves can be identified at the surface. A discussion on possible reasons for this relationship between wind direction change and wave like features will follow.

6 DISCUSSION

6.1 Large Synoptic Scale Effects

The results showed a similar number of sea breezes as the number found in 1965 (Watts, 1965) although there were slightly less in 2003. It is likely that the program is not picking up less distinct fronts as was discovered in the case of the 9th August and may need some slight adjustments to identify less obvious fronts

Due to the unreliable nature of the sea surface temperature data and having not had access to inland temperature data it is difficult to find a relationship between the temperature differential and days on which sea breezes develop. However there is some general evidence toward a trend. There is also evidence to suggest that a greater temperature differential is required for sea breeze development in April and October. This may be due to lower minimum temperatures at this time or less daylight and therefore less prolonged radiative heating in early or late season.

It has been found that weaker fronts develop on days with prevailing onshore winds and that these fronts did not cross Chimet until later in the day. These findings indicate that the strength of the frontogenesis or the density difference across the front is more important than the tendency of the front to form further offshore with opposing synoptic winds.

The formation of the sea breeze front is due to a sensitive balance of synoptic conditions and temperature differentials. The effect of the prolonged synoptic conditions has not been considered here apart from briefly when considering the sea breeze front on the 5th April, which came in later than expected and may have been influenced by the strong opposing winds of the days before. However it must be important in a region as changeable as the UK and could be very useful in explaining difference in times when fronts cross Chimet.

Furthermore not only the difference between the sea surface temperature and the air temperature but also the length of time the differential has existed may be important and is worth some further investigation.

Although we can use a combination of the factors discussed, eg temperature differences, pressure and synoptic winds to help us forecast it is inevitably a very complex process and one where a lot of potential study could take place. More reliable sea surface temperature data would have given us a better picture of the differences between the land air temperature and sea surface temperature for the days with sea breezes. Furthermore a temperature taken from an inland station may also have shown a more reliable picture of the conditions on the particular day in question. The problems with the temperature data may be masking a far stronger relationship between the sea breeze formation and the temperature field as described in other literature on the subject yet unidentified in this study.

A technique to confirm the existence of the sea breeze pre- and post-frontal oscillations used by Alpert and Rabinovich-Hadar was averaging of several consecutive days' data. By averaging the parameters for 8 or 9 days they identified secondary fronts from the results on the graphs. This highlights one of the main differences between their study in Israel and this study on the south coast of Britain. The sea breezes in Israel were extremely predictable and occurred daily throughout the summer at similar times each day. The synoptic conditions were almost constant with only a little change each day therefore this averaging process could be expected to produce reasonable results.

The data used in this study from the Chimet weather recording station illustrates just how variable synoptic conditions are over the south coast of England even in the summer and the variability highlights how difficult it is to predict the sea breeze. It would not be possible to average over several days as it is highly unlikely that we get the same conditions for more than 2 or 3 days and the time of the sea breeze front is extremely changeable. Even in 2003 when the weather was very settled for much of August there is a great deal in variability in the sea breeze formation.

6.2 Smaller scale wave like features

Wavelike features were identified on several days after the passage of the sea breeze front and on occasions pre-frontal waves could also be identified in surface parameters. It is quite possible that the waves after the front were a result of a Kelvin Helmholtz instability at the front, producing billows that propagate away from the front as suggested many times in the literature.

Three stages of billow structure have been identified by Sha et al's (1991) numerical simulation. An initial stage occurred directly after the formation of the Kelvin Helmholtz instability. The billow reaches its maximum amplitude in the 'mature' stage and then there is a final break down stage when the billow amplitude decreases again until the billow is destroyed. This behaviour is certainly visible on the days with oscillations in the data in this study. The wavelengths of the oscillations grow as we move away front the front and then decrease once again.

It seems that the oscillations detected in this study do differ to those found in other studies. This may be due to problems with the numerical simulations highlighted in section 2.4. The numerical simulation studies could be producing unrealistic billows. The amplitude of the oscillations are similar to other observational studies but lower than the numerical simulation study.

Observations of waves at the surface in this study have shown that they have a shorter period than both the observational study (Alpert & Rabinovich-Hadar, 2003) and numerical simulations (Sha et al, 1991). This could be due to weaker billows from above in this case, however more work of this kind is required to compare results from observational studies. It is possible that the waves detected in the sea breezes of the South Coast of England are not of the same origin as those of other studies ie. the South Israel study. Until further research takes place this cannot be ruled out.

Sha et al (1991) and other numerical studies have compared the ratio of maximum amplitude to the wavelength and found it very variable depending on the study. If measurements were taken at different heights through the sea breezes it would have been possible to compare the ratios to their findings. Although once again this has not been done in an observational study and so the results could only be compared to the numerical simulation, which as discussed is limiting.

In this study it seems that the best parameter for identifying oscillations at the passage of the front is the wind speed followed by the pressure field. Alpert & Rabinovich-Hadar (2003) found that the waves were identified most easily in the turbulence field followed by wind speed and sometimes temperature. Sha et al (1991) in their numerical simulation found that oscillations could be spotted in wind speed and pressure but not in temperature. These results broadly agree with the findings here although wavy characteristics can also be spotted in the temperature field in this study. The turbulence or 'gustiness' field did not produce any significant findings.

Differences between the best parameter for identifying the oscillations between this study and the numerical simulation can be explained by the unrealistic nature of the simulations. Perhaps in the numerical simulation temperature is not well represented and that is why the oscillations are not identified in this field. Alpert & Rabinovich-Hadar's observational study agrees that wind speed was a good detector and the lack of evidence of oscillations in the turbulence field in this study may indicate that turbulence or 'gustiness' may not have been correctly measured. It seems that pressure is not usually a good indicator of the oscillations however in this case it was. Perhaps in the south Israel study the pressure is more stable and does not change as much as it does on the south coast of England where it was found to be a good indicator of any surface oscillations.

It was not possible to find a Richardson's number for the instabilities as our data was only taken at the surface and therefore we are unable to confirm if the waves are a result of a Kelvin Helmholtz instability. In addition it is likely that a stronger signal of any waves would be found higher up as found by those who studied the fronts at different heights using aircraft (Finkele et al, 1993). Oscillations in surface parameters have rarely been investigated before and it was interesting to find that they were only present on certain occasions. We cannot assume that the waves are a result of Kelvin Helmholtz billows without more evidence.

The pre-frontal waves were also identified in the Israel study (Alpert & Rabinovich-Hadar, 2003) and their existence was explained by a study carried out by Geisler and Bretherton, (1969) who described the sea breeze analytically using the solution of the thermodynamic equation. A perturbation before the sea breeze called a 'forerunner' was found. They expected the forerunner to travel 10km from the front about 30-50 minutes after the front crossed the coastline. This suggests that this is not a suitable explanation for any oscillations before the front in this study as the data is out at sea and the 'forerunners ' only occur inland.

The explanation for pre-frontal oscillations presented by the work of Geisler and Bretherton (1969) has not been referenced by other works. The theory behind it is linear and the sea breeze is a non-linear phenomena and so its applicability is questionable. The only other reference to pre frontal wave activity that can be found is that of Finkele et al (1993) who also identified some wave activity landward of the front yet offered no explanation for the formation of waves. A possible explanation for the oscillations before the sea breeze front is if the sea breeze front had travelled over some land or shallow water area before reaching Chimet. Having checked the depth of water at Chimet when the front passed there is no relationship between shallow water due to lower tidal levels and the incidence of the pre-frontal waves. It is possible that the pre-frontal wave may have been induced if the wind is such a direction that it crossed the Isle of Wight or over many of the sandbank areas near the harbour entrance, which may have made the sea breeze more complex.

6.3 Relationships between synoptic scale findings and wave scale findings

The occurrence of the waves when wind direction does not change much with the passage of the front is hard to explain. The front is thought to be stronger and more distinctive when the synoptic wind opposes the sea breeze and it might be expected that this would result in larger billows propagating away from the front bringing a stronger signal down to surface parameters. This is not the case here. Little work has been done on this subject and it would be interesting to be able to compare the finding with other studies. One possible explanation is suggested by diagrams of laboratory work on gravity currents by Simpson (1994) (figure 6.1).

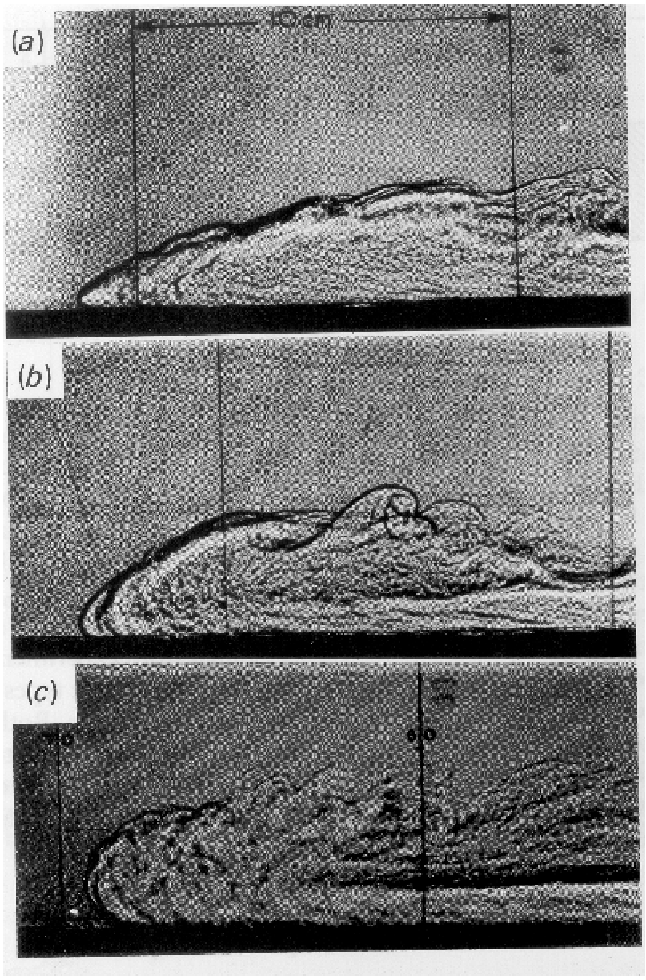


Figure 6.1: Photographs of gravity current heads due to differing synoptic conditions. (a) Head wind, (b) calm conditions, (c) tail wind.

The diagrams in figure 6.1 show the effects of head winds (a), no wind (b) and tail winds (c) on the head of the gravity current and show that for a tail wind the head of the sea breeze is deeper. The billows behind the front look more turbulent in (c) and it looks as if the effects of the billows reach the surface. In contrast the billows induced by the head wind and calm conditions do not appear to reach the surface and the head is more elongated. If this is the case any effects of billows may not cause the surface parameters to change much and the billows could break down earlier.

Another hypothesis is that when the change in wind direction is larger the frontogenesis takes place further offshore because there has been an opposing synoptic wind preventing the sea breeze moving inland. Therefore when the sea breeze front reaches Chimet the billows may have already broken down and turbulence has stopped. Simpson (1994) described how a sharp front develops when mixing is complete and this is found on days of opposing offshore winds. The front then moves inland quicker as the density gradient across the front is great and therefore these fronts accelerate inland.

In contrast when the synoptic wind is onshore the frontogenesis occurs further inland and so when the front passes Chimet the billows are still visible and signals of the billows are detectable at the surface. The front slows down due to the mixing decreasing the density difference across the front and making the front less distinct. This has indeed been found on days of onshore synoptic flow (Reible et al, 1993).

It is unlikely that turbulent mixing has stopped by the time the front reaches Chimet as it would normally be expected to continue until the front reaches the shore and there is potential to study further the effects of instabilities on propagation of the sea breeze front inland. Sha et al (1991) attempted to investigate this in their numerical simulation however there is little observational investigation of this subject with a view to relating it to Kelvin Helmholtz instabilities.

Studying oscillations in surface parameters is a new area of research and is a subject which should be explored more as it is evident that there is some relationship between different synoptic winds and the presence of waves in the surface parameters. It may have important implications for the inland penetration of sea breezes and could help forecast the effects of a sea breeze in the future. It links the studies of large scale synoptic effects on sea breezes and the studies at the small scale investigating the influence of Kelvin Helmholtz instabilities on mixing.

7 CONCLUSIONS

- There were 70 sea breeze fronts detected by the program, which is similar to that of previous studies (Watts, 1965). In addition the distribution of sea breezes throughout the year was as expected with the largest amount in June and July when the greatest differential exists between SST and air temperature.

- The temperature differential between the sea surface temperature and air temperature is accepted as the reason sea breezes form, however a clear relationship between days was not established in this study due to dubious sea surface temperature data. There was evidence that sea breezes did form with less of a temperature differential during mid season. However at the beginning and end of the season a greater difference between the two was required for the sea breeze to develop.

- It was found that on days with synoptic onshore flow the front was less distinctive and harder for the program to pick up than when the synoptic flow was opposing the sea breeze. Furthermore the sea breeze tended to pass Chimet later, after 1200 UTC, than with opposing flows when most fronts pass Chimet before 1300 UTC, although many exceptions were found.

- The sea breeze development is a result of a complicated mix of temperature differential between the sea surface temperature and air temperature and synoptic conditions and it is particularly hard to forecast the sea breeze on the south coast of England where conditions are very changeable. Certain assumptions can be made about the timing of the front depending on the synoptic conditions and time of year, however accurate forecasting is far from possible.

- Wave like oscillations were visible after the front passed at the surface and were most obvious in the wind speed parameter. The wavelengths were larger than other studies have reported and had shorter periods. The amplitudes are consistent with other observational studies. The waves tended to increase in size further away from the front, then decrease again, which is consistent with Kelvin Helmholtz billows increasing in amplitude before breaking down.

- There was also evidence to suggest that there were pre-frontal oscillations on a few occasions and a suitable explanation for these has not been found and would require further investigation.

- On some days there were no oscillations and these days tended to be when there was a greater change in wind direction from the synoptic wind to the sea breeze direction. A possible explanation for this result is suggested from the laboratory work on gravity currents by Simpson (1994) where there is more visible turbulence at surface levels in experiments with head winds. Alternatively the billows may have already broken down before they pass Chimet on days of greater wind direction change.

- Studying the waves at surface level has not previously had much attention and may be important in explaining many sea breeze processes such as movement inland. This is an area which requires further work to explain and confirm the findings from this investigation.

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APPENDIX 1

Summary of Results

#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
5-Apr-03	15:35	3
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
21-Apr-03	6:20	17
22-Apr-03	10:45	2
#N/A	#N/A	0
#N/A	#N/A	0
25-Apr-03	16:50	3
26-Apr-03	7:15	2
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
30-Apr-03	#N/A	0
1-May-03	#N/A	0
2-May-03	13:55	2
3-May-03	#N/A	0
4-May-03	#N/A	0
5-May-03	14:05	1
6-May-03	12:05	1
7-May-03	9:55	1
8-May-03	#N/A	0
9-May-03	#N/A	0
10-May-03	#N/A	0
11-May-03	7:30	2

12-May-03	10:05	2
13-May-03	12:15	2
14-May-03	#N/A	0
15-May-03	#N/A	0
16-May-03	16:50	3
17-May-03	#N/A	0
18-May-03	8:40	1
19-May-03	#N/A	0
20-May-03	#N/A	0
21-May-03	#N/A	0
22-May-03	11:50	3
23-May-03	#N/A	0
24-May-03	#N/A	0
25-May-03	10:10	7
26-May-03	11:05	3
27-May-03	#N/A	0
28-May-03	9:25	3
29-May-03	10:50	8
30-May-03	#N/A	0
31-May-03	#N/A	0
1-Jun-03	6:45	3
2-Jun-03	8:30	3
3-Jun-03	#N/A	0
4-Jun-03	11:25	1
5-Jun-03	8:30	15
6-Jun-03	14:10	2
7-Jun-03	13:30	2
8-Jun-03	#N/A	0
9-Jun-03	#N/A	0
10-Jun-03	9:00	1
11-Jun-03	#N/A	0
12-Jun-03	#N/A	0
13-Jun-03	10:00	4
14-Jun-03	#N/A	0
15-Jun-03	11:00	2
16-Jun-03	#N/A	0
17-Jun-03	#N/A	0
18-Jun-03	9:05	5
19-Jun-03	9:00	1
20-Jun-03	#N/A	0
21-Jun-03	#N/A	0
22-Jun-03	17:30	1
23-Jun-03	#N/A	0
24-Jun-03	10:50	2
25-Jun-03	#N/A	0
26-Jun-03	9:40	2
27-Jun-03	7:10	3

28-Jun-03	10:00	1
29-Jun-03	#N/A	0
30-Jun-03	#N/A	0
1-Jul-03	11:35	1
2-Jul-03	12:35	1
3-Jul-03	16:20	4
4-Jul-03	10:20	5
5-Jul-03	12:05	2
6-Jul-03	10:15	2
7-Jul-03	#N/A	0
8-Jul-03	7:20	3
9-Jul-03	8:30:00 am	3
10-Jul-03	#N/A	0
11-Jul-03	#N/A	0
12-Jul-03	#N/A	0
13-Jul-03	#N/A	0
14-Jul-03	12:00	3
15-Jul-03	#N/A	0
16-Jul-03	7:30	3
2-Aug-03	10:45	2
#N/A	#N/A	0
#N/A	#N/A	0
6-Aug-03	8:30	1
#N/A	#N/A	0
8-Aug-03	9:35	3
#N/A	#N/A	0
10-Aug-03	16:25	1
11-Aug-03	10:00	6
12-Aug-03	10:50	1
	8:30	1
14-Aug-03	14:05	3

#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
20-Aug-03	11:35	3
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
18-Aug-03	17:40	1
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
2-Sep-03	12:30	3
3-Sep-03	11:25	2
#N/A	#N/A	0
5-Sep-03	15:35	4
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
11-Sep-03	13:00	2
12-Sep-03	15:00	2
#N/A	#N/A	0
14-Sep-03	10:05	10
#N/A	#N/A	0
16-Sep-03	10:55	2
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
20-Sep-03	13:50	2
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
24-Sep-03	12:20	2
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
29-Sep-03	13:50	3
#N/A	#N/A	0

#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
11-Oct-03	12:05	4
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
21-Oct-03	15:30	3
22-Oct-03	12:20	2
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
#N/A	#N/A	0
29-Oct-03	15:00	2
#N/A	#N/A	0
#N/A	#N/A	0

week	Ave Max temp	ave min temp	ave SST
1-Apr	12.0285714	6.9	9.20376984
8-Apr	9.34285714	4.9	8.86767928
15-Apr	14.7571429	10.0285714	12.1211864
22-Apr	12.0857143	9.62857143	10.8668654
29-Apr	12.1	10.7	11.12927
1-May	12.4	9.8286	11.27059
8-May	12.785714	9.3571	11.15807
15-May	12.771429	10.829	11.81033
23-May	15.028571	11.157	12.87407
30-May	16.428571	13.443	14.72474
6-Jun	15.814286	13.814	14.71793
13-Jun	18.314286	14.6	16.55127
20-Jun	19	14.771	17.42086
27-Jun	18.72	15	17.7439583
2-Jul	18.385714	14.629	17.47725
9-Jul	20.9	16.9	18.05035
16-Jul			
23-Jul			
2-Aug	23.257143	17.857	19.53602
10-Aug	22.428571	18.086	20.3457
17-Aug	20.2714286	16.5714286	19.3660705
24-Aug	18.8285714	15.0142857	18.9988077
31-Aug	18.4	11.5	17.9857651
1-Sep	18.5428571	14.3571429	16.4447591
8-Sep	18.6428571	14.5857143	16.7979136
15-Sep	19.3857143	15.2142857	17.2940387
22-Sep	16.8571429	11.0142857	14.0923497
29-Sep	16.3	11.9142857	13.914158
6-Oct	16.3	12.8428571	14.3265772
13-Oct	14.9428571	8.9	11.468306
20-Oct	11.1714286	4.8	7.68658718
27-Oct	11.84	6.78	9.03583333