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Full Length Research Paper

Effects of Sea Breezes and Local Topography on Pollutant Dispersion in Swansea, UK

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Abstract

Swansea is the wettest city in the UK and has an NO_2 problem due to traffic. It benefits from an advanced air quality monitoring system. In a coastal area like Swansea, the difference on heating can have a large impact on the weather by the formation of the sea and land breezes. These, coupled with the presence of a windier climate in general, impact upon the dispersion of pollution in the city. Nevertheless, mountains are associated with up and down wind (katabatic airflow), causing air containing pollutants to be spread horizontally, reducing the potential for dispersion. The aim of this research is to investigate sea and land breezes of the city of Swansea in relation to topography and in conjunction with urban air quality, together with pollutant exceedences associated with specific weather conditions. Such a phenomenon clearly occurred on 1st and 2nd June 2008 during a summer of otherwise rare sea breezes occurrence. High concentrations of NO_2, O_3 and PM_{10} were recorded during the middle of the night between 23:00 hours on 1st June and 01:00 hours on 2nd June, when the sea breeze changed into a katabatic wind, returning Swansea's pollutants to the city under these specific meteorological conditions.

Key words: *Weather, Air pollution, Topography, Sodar, Mast.*

Introduction

Sea breezes are important factors affecting pollution, particularly on the local scale. They occur due to differential heating of the air over a region where a large body of water and land meet (Simpson, 1994). They are a phenomenon mostly associated with summer because they are driven by the inland convection currents caused as the land heats the air. The resultant thermal low draws in breezes from the sea, and these have important effects on pollution. During the night-time, sea breezes can reverse and return as a land breeze, together with pollutants collected during the day. Katabatic winds are a function of complex terrain and represent downslope flows of dense cold air. In coastal areas katabatic flows may reinforce night-time land breezes (Kambezidis et al., 1998; Simpson, 1994).

Sea breezes have potential consequences for the local air pollution of cities on the coast as they tend to complicate and even override prevailing wind patterns, and the situation is further complicated when a city is sited at the foot of a range of hills. This is the case for Swansea, immediately to the north of which lies the Welsh mountains, so, locally, sea breezes play an important role in the behaviour of coastal (and even inland) pollution (Aggarwal et al., 2004; Maalej et al., 1997). This situation is similar to Los Angeles in USA (Simpson, 1994), Athens in Greece (Kambezidis et al., 1998; Lalas et al., 1983) and Auckland in New Zealand (Khan et al., 2009), which are all surrounded by high mountains and sea.

The role of moving sea breeze fronts on air quality over coastal and inland pollution areas, was investigated by Maalej et al. (1997), through numerical simulation of the transport/chemistry of air pollutants, using detailed structures of eddy diffusivity, temperature and flow fields associated with such fronts. This study of air pollution in the region of Sfax, an industrial town on the Mediterranean shores of Tunisia, showed that local circulation dominated the flow in summer, favouring the transport of CO from the coast toward the rural areas inland. The accumulation of pollutants at night was returned and diffused on the following day by the diurnal evolution, together with the newly emitted pollutants.

The effect of sea breezes was analysed with photochemical pollution (SO_2, NO, NO_2, O_3 and CO) for two typical days in August 1981 in Athens, Greece (Lalas et al., 1983). The study also examined the vertical structure of the atmospheric boundary layer, the pollution emission rates and wind data with well-defined sea-breeze circulation. As inversion layers descend or disappear, abrupt changes and short-period oscillations in concentrations are found, and can be explained by a simple multilayer box model. The diurnal variation and considerations based on simple ground-level wind trajectories indicate that recirculation of pollutants by the sea-breeze cell takes place, possibly aided by the small size of the Athens basin and the surrounding mountains. The passage of the sea-breeze front seems to have no direct effect. No day-to-day pollution accumulation is noticed. The passage of the sea-breeze front does not affect the pollutant concentrations immediately, although reduction, i.e. cleansing action, does occur but this is due to stronger dispersion caused by higher wind speeds.

Kambezidis et al. (1998) were highlighted the effect of sea breezes on air pollution over the greater Athens area. Ground-based measurements in the area showed that northerly wind flows during summertime played a dispersion role in a coastal urban area. The research gave profiles of O_3 and NO_2 on sea breeze and non-sea breeze days, and found these pollutants for the first time at a height of 1200m above ground. During night-time, the surface winds are from the north with moderate-to-weak speeds. Katabatic winds prevail in the mountains north of the basin. During sea breeze conditions, O_3 was convected to altitudes comparable to the height of the surrounding mountains, thus causing maximum concentrations aloft in the second-half of the day. NO_2, however, did not show the same pattern; relatively low values of this pollutant are found aloft, probably due to planes flying at low altitudes during landing/taking-off procedures. During non-sea breeze days, the O_3 field was rather homogeneous; maximum values were observed at altitudes lower than those on sea breeze days.

Swansea is the wettest city in the UK with an annual average rainfall of 1100mm (Seth, 2009a, b). It is generally milder, wetter, cloudier and windier than the midlands of Great Britain (Wheeler and Mayes, 1997 ; Hulme et al. 1997). This area is subject to oceanic influences, and some orographic precipitation is also generated. The city has a maritime climate, generating large amounts of precipitation. Regions exposed to maritime climates are also windy climates. Winds blow from both south and west, with a relatively high frequency of strong winds. These coastal winds can affect temperature because of the heat conserving properties and mobility of oceanic water (Wheeler and Mayes, 1997).

Thus, the weather in Swansea Bay is mostly affected, throughout the year, by the southwest winds from the Atlantic. The area avoids extremes heat or cold and summers are generally cool while winters remain mild. In a coastal area like Swansea, the differential heating between land and sea can lead to greater frequency of sea and land breeze systems when compared to many cities in the UK. These, coupled with the presence of a windier climate in general, impact upon the dispersion of pollution in the city. On the other hand, cold air drainage from neighbouring high ground has the potential to stabilise the urban atmosphere, reducing the potential for dispersion. The terrain behind Swansea, although complex and mountainous, is generally thus: the southern coastal range of the Welsh mountains rise to approximately 270m within 5km of the coast.

One of the most novel purposes of this study is to analyse meteorological vertical profile data (Sodar and Mast) at their locations in Swansea, as they are potentially powerful demonstrators of key circulations in the local atmosphere in that coastal city; the possible influence of sea breezes and katabatic winds will be discussed.

Materials and Methods

Study Area

Swansea lies in the South West of the UK (Fig. 1), on the South Wales coast. It is in a unique location; its sandy bay provides a gateway to the Gower Peninsula (Swansea City Council, 2000). The City and County of Swansea unitary authority covers a mixed area of extensive coastline, open moorland, rural villages and the city of Swansea. There is a population of around 227,100 living within the Swansea City Council boundary in 2001. Swansea has the third highest population of the 22 Welsh Unitary Authorities, representing almost 8% of the total population in Wales (Govier and Morgan, 2004a), and so is subject to high traffic volumes especially at commuting rush-hours.

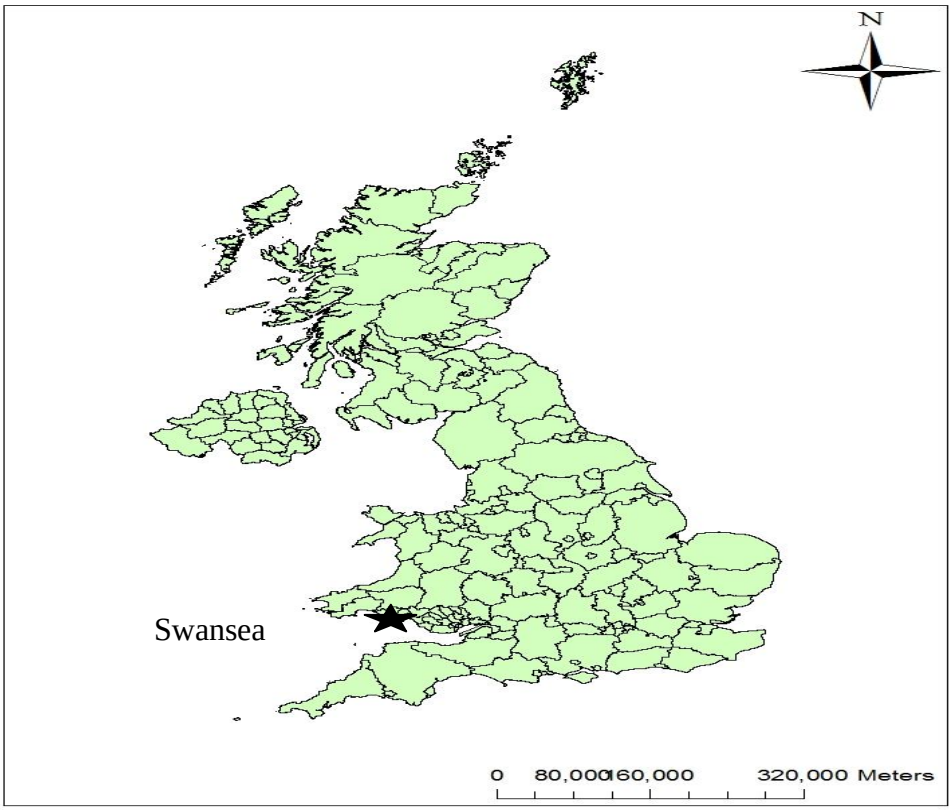


Figure 1. Location of Swansea city.

Instrumentation and Measurement

Swansea has many weather stations, however, this study was focused on the Mumbles Head station which is located in Swansea Bay to the southwest of the city centre (Fig. 2), on top of a small hill. The station is about 10m above ground and 20m distance from the road and is exposed to coastal weather typical of the south-western parts of the UK. This station is a synoptic network type.

This research was considered two air quality monitoring stations (Morfa and Morriston) as shown in Figure 2. The Morfa monitoring station is sited inside the Hafod AQMA close to an important local traffic junction, the Morfa roundabout, which itself is located in the Lower Swansea Valley (Swansea Authority, 2000). The Morriston Groundhog station is a roadside one, sited on the southbound access slip road to the busy A4607 dual carriageway at Morriston Underpass (Govier and Morgan, 2004b).

There are two profile stations (Sodar and Mast) were focused in this study. The Sodar is located in the Lower Swansea Valley area in a Reserve Forces (Territorial Army) Base at Morfa and is approximately 10m above sea level and also within the Hafod Air Quality Management Area (Fig. 2). The area has complex terrain surrounding the site as it is located in the Lower Swansea Valley, bounded to the east and west by high valley sides, which heavily influences the prevailing meteorological conditions. Data are recorded with an integration of 15 minutes. Data are recovered starting from 30m above ground level, up to a maximum height of 300m; the data are recorded at 15m intervals between these two heights. The Sodar is worked like acoustic radar, transmitting sound pulses that are reflected by the temperature structure in the air. Detecting signals from the reflected Doppler-shifted pulses, the system can derive and present important information concerning wind speed, direction and turbulence. The Mast is located in Cwm Level Park in Landore within the Hafod Air Quality Management area (Fig. 2) and is approximately 30m above sea level. This 30m Mast allows data to be gathered with an integration period of 1 minute, measuring temperature and wind profiles in the lowest atmospheric layer in the valley. This research was also indicated Sea-level pressure charts, Radiosonde ascent charts for upper air stations, Satellite images for UK weather and Geographical Information System (GIS) maps.

Figure 2. Air quality, profile and weather stations in Swansea.

Results and discussion

Swansea's pollution levels may be ameliorated by the presence of sea breezes, carrying pollutants inland. The development of sea breezes strongly influences the distribution of the air pollutants in many cities around the world (Clappier and Martilli, 2000; Grossi and Thunis, 2000; Kambezidis et al., 1998; Khan et al., 2009; Lalas et al., 1983; Lu and Tuco, 1994; Nester, 1995; Simpson, 1994). Figure 3 was shown the recorded NO_2 concentrations for Morriston and Morfa for a 48-hour period. 01-06-2008 was a Sunday so the traffic was reduced, but the recorded concentrations of NO_2 during the day (when traffic volumes were higher) were lower than during the night. Figures 4 and 5 were confirmed the presence of a sea breeze between 11:00 and 19:00 hours explaining this. 02-06-2008 was a Monday and higher levels of NO_2 were to be expected but Morriston clearly shown that during the middle of the day, the recorded NO_2 levels actually fell. Figures 6 and 7 were analysed the Sodar and Mast data for the next day, which provided evidence for the presence of a sea breeze between 09:00 and 16:00 hours, and this would explain the apparent cleansing. The NO_2 recorded at Morfa did not show this but the levels are still well below the hourly objective standard of 200µgm^{-3} (Defra, 2008).

Additionally, O_3 measurements from Morriston station in Figure 3 was shown a trough at 22:00 hours on 1st June, coinciding with the NO_2 peak, followed at 00:00 hours on 2nd June by an O_3 peak coinciding with the NO_2 trough. Thus, some form of reversal has taken place, and this will be explained shortly. This night-time O_3 peak, because of its levels, also shown that the reversal was not only returned O_3 and NO_2 but may also be carryed O_3 from elsewhere and transfered this pollutant to Swansea.

These two days were typical of the season and fairly represent the recorded data i.e. they are unexceptional. Nevertheless, this 48-hour period was noteworthy because it shown that at 22:00 hours an NO_2 peak was recorded at Morriston station, and at 00:00 hours another was recorded at Morfa station. One would have expected night-time levels to reflect the lower traffic volumes, but on this occasion, between the aforementioned day-time sea breezes, and in the middle of the night, the Sodar data (Figures 4 and 6) was shown that between 23:00 hours on 1st June and 01:00 hours on 2nd June there was a land breeze descending from the mountains behind Swansea (a katabatic wind). A night-time katabatic wind was typical for this topography (Helmis et al., 1986; Price, 2005; Singal, 1993); a day-time sea breeze, driven in part by an inland thermal low (caused by heated air rising), returned at night, descending from the hills behind the city. The sea breeze in this case was a phenomenon occurring at speeds of up to $3ms^{-1}$ (as evidenced by Sodar data in Figure 4) but the returning katabatic wind was a phenomenon occurred only at speeds of between 1 and $2ms^{-1}$. Thus, the katabatic wind was lighter than the sea breeze, and this was important because if the katabatic wind had been stronger than the sea breeze, it would have carried the pollutants out to sea, and no night-time pollutant peak would have been monitored.

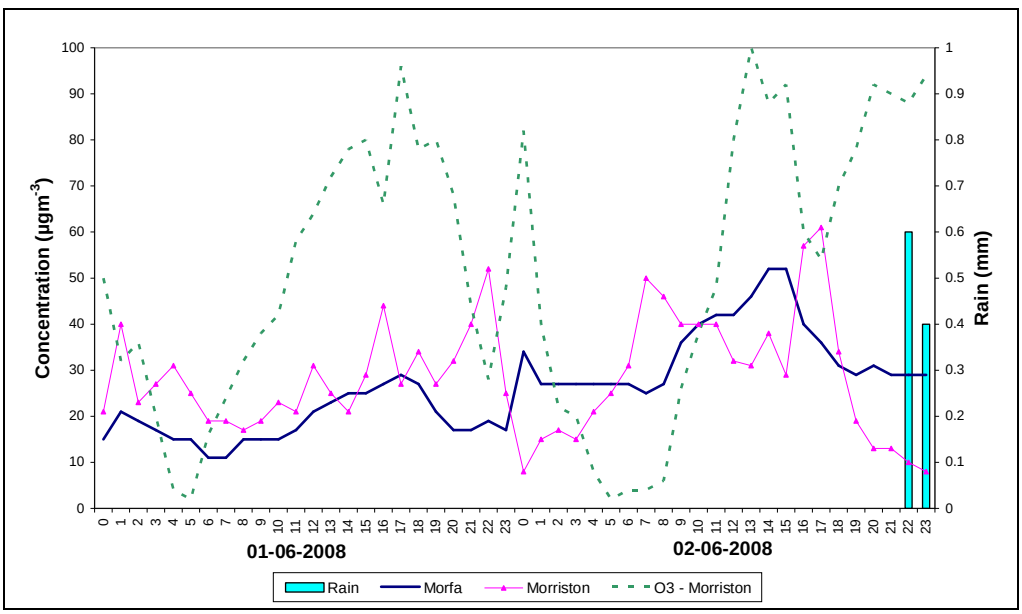


Figure 3. Hourly comparison of NO_2 concentrations between Morfa and Morriston stations. Hourly O_3 concentrations for Morriston station. Hourly total rain for Mumbles Head station. 01st - 02nd June 2008.

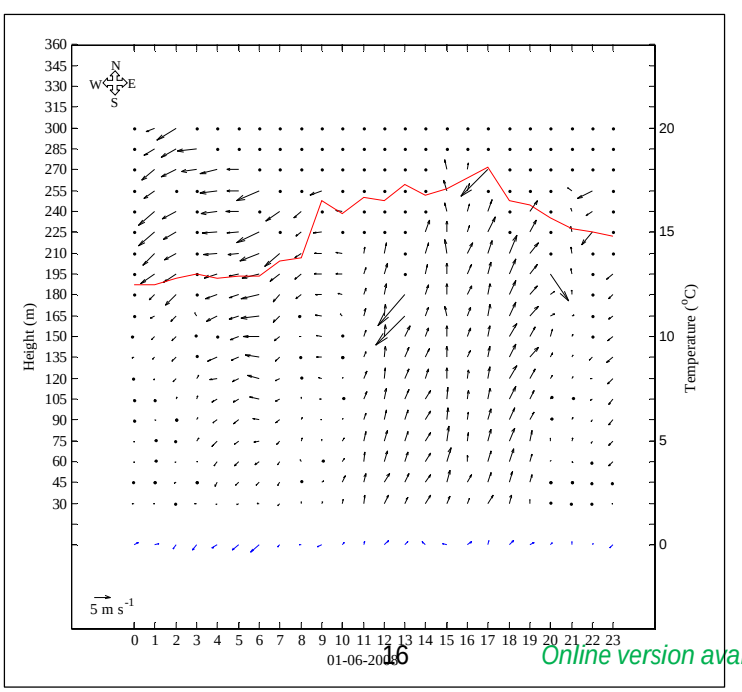


Figure 4. Passage of sea breeze front during the afternoon of 01st June 2008. Black arrows show the winds measured by the Sodar at 19 levels between 30 and 300m. Blue arrows show winds measured at the Mumbles Head site at 10m above ground. The length of the arrow is proportional to the wind speed. A scale arrow is shown in the bottom left. The arrows point in the direction the winds flowed. A compass is provided in the top left. The red line shows 10m air temperature measured at Mumbles Head station.

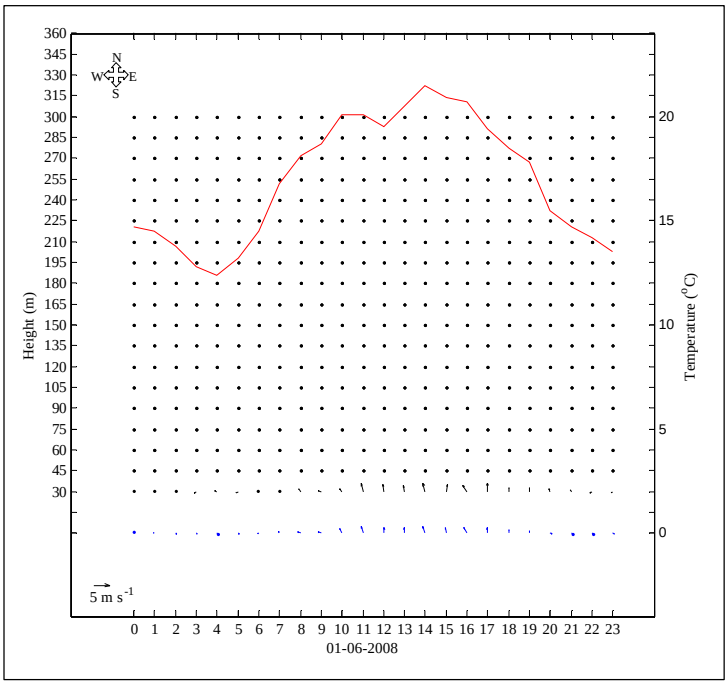


Figure 5. Passage of sea breeze front during the afternoon of 01st June 2008. Black arrows show the winds measured by the Mast at 30m above ground. Blue arrows show winds measured by the Mast at 10m above ground. The red line shows 2m air temperature measured by the Mast.

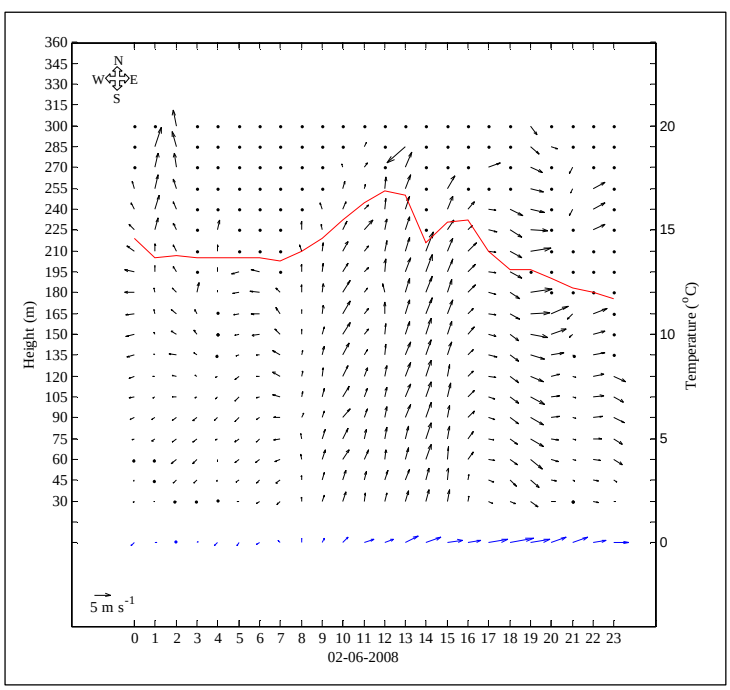


Figure 6. Passage of sea breeze front during the afternoon of 02nd June 2008. Black arrows show the winds measured by the Sodar at 19 levels between 30 and 300m. Blue arrows show winds measured at the Mumbles Head site at 10m above ground. The length of the arrow is proportional to the wind speed. A scale arrow is shown in the bottom left. The arrows point in the direction the winds flowed. A compass is provided in the top left. The red line shows 10m air temperature measured at Mumbles Head station.

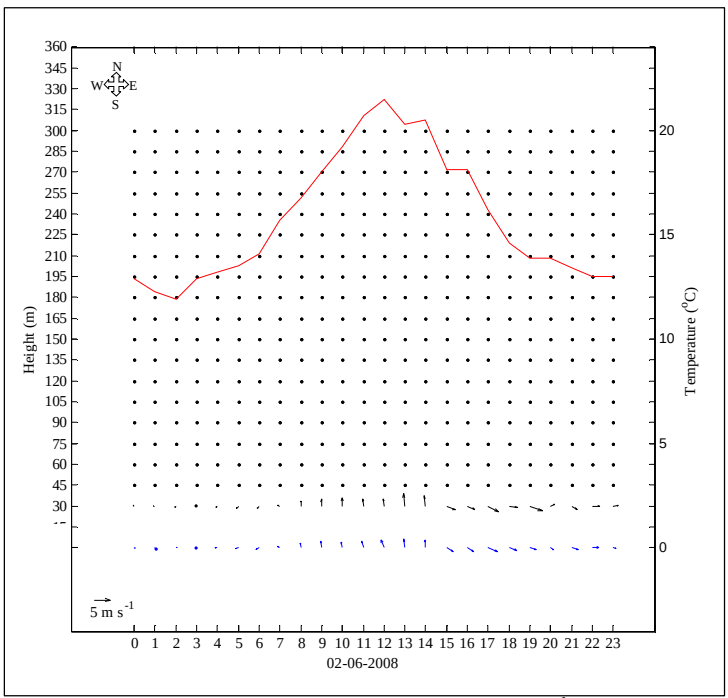


Figure 7. Passage of sea breeze front during the afternoon of 02nd June 2008. Black arrows show the winds measured by the Mast at 30m above ground. Blue arrows show winds measured by the Mast at 10m above ground. The red line shows 2m air temperature measured by the Mast.

It is worth mentioning that Nester (1995) was identified sea breezes near the Attica Peninsula coast in the Greater Athens area, Greece, on 24th May 1990. The researcher was found high concentrations of NO and NO_2 occurred around midnight, when the sea breeze changed to a land breeze between midnight and the early morning hours of 25th May.

The NO_2 peaks at the two stations in Figure 3 during this night did not occur at the same time. This was because of the relative locations of Morfa and Morriston; Morfa is about 2.5km to the south of Morriston. The Sodar and Mast are located close to Morfa station, so the wind speed and direction data and the NO_2 levels data are in concert. However, with the Morriston site being downwind of the Swansea city during the sea breeze and the wind speed being between 1.3ms^{-1} and 3.6ms^{-1}, the NO_2 peak at Morriston station should indeed be approximately 2 hours before Morfa station.

Thus the sea breeze that, on 1st June, was carried the pollutants inland from Swansea experienced a reversal and was returned as a katabatic wind still carrying those pollutants; there was no large source of pollution upwind and inland from Swansea so the pollutants were being returned rather than imported. This reversed breeze did however carry slightly elevated levels of PM_{10} (82µgm^{-3} as in Figure 8), peaking together with the NO_2 peak recorded at Morriston station.

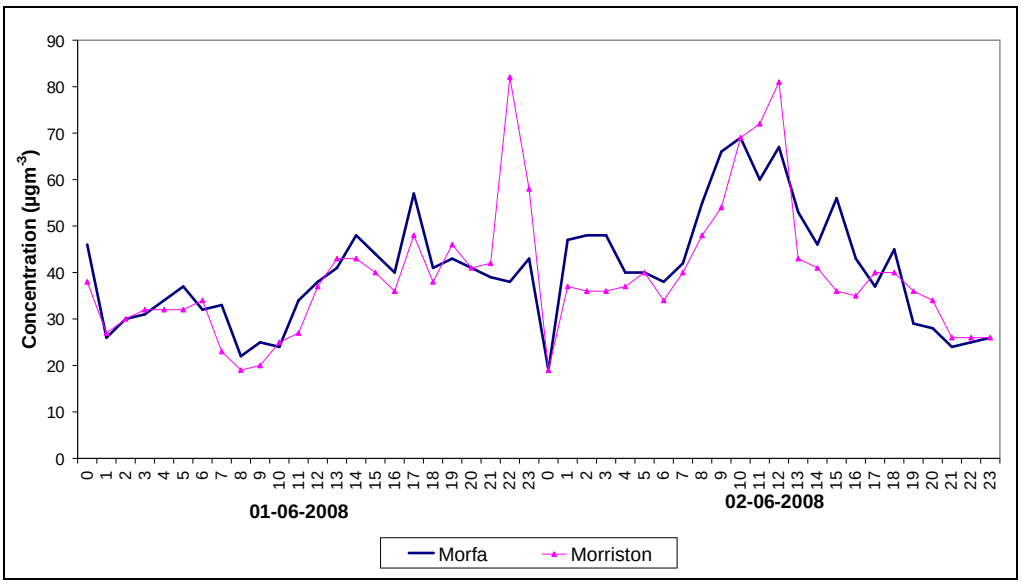
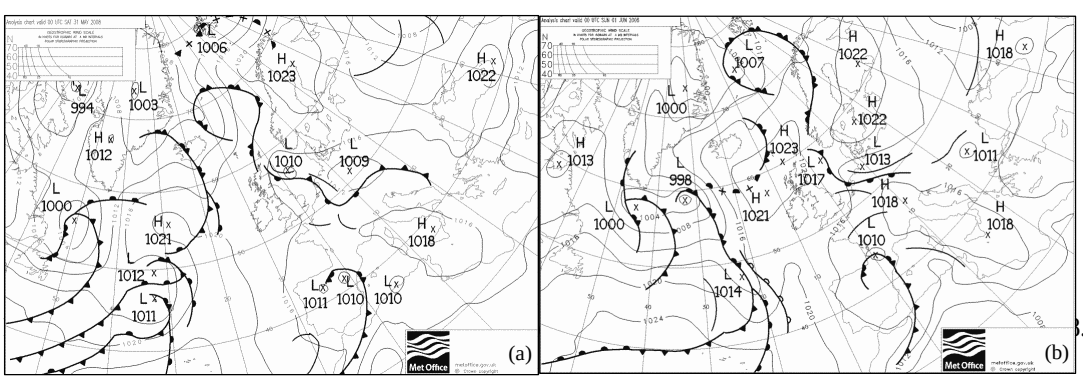


Figure 8. Hourly comparison of PM_{10} concentrations between Morfa and Morriston stations, 01st -02nd June 2008.

Although the Sodar data clearly were indicated a katabatic wind at the time in question, it is necessary to confirm that this was a reversed sea breeze (katabatic wind). Firstly, the Met Office sea-level pressure charts in Figures 9 and 10 were shown that the UK was in a 'col' between pressure systems for the duration of this reversal episode. The pressure chart was also shown isobars spaced widely, which allowed sea breezes to occur on the Swansea coast. There were no significant winds associated with this event over Swansea, and thus the Sodar data must have recorded sea breezes rather than prevailing winds. Secondly, on the 1st June, the dewpoint and absolute humidity shown fluctuations between 07:00 hours and 15:00 hours (Fig. 11). These two parameters were also shown rises on 2nd June 2008 between 09:00 hours and 16:00 hours. These rises in dewpoint and absolute humidity were typical of sea breezes as, at this time of year, the sea is warm, and winds passing over it will pick up moisture. The figure was also indicated that the sea breeze on the second day was more clearly defined and was stronger, and both the presence of sea breezes and their relative strengths were in evidence in the Sodar and Mast data in Figures 4-7. Also of interest is that Figure 11 was given evidence of mist or fog from 00:00 hours to 07:00 hours on 1st and again at 18:00 hours to 00:00 hours on 2nd June 2008, where the air temperature meets the dewpoint. The satellite images in Figure 12 were shown that Swansea on 2nd lay under clear blue skies at lunchtime with a sea fog offshore; good conditions for sea breezes. The image for the previous day was not so clear. Furthermore, at around midnight there was a sudden drop in temperature of nearly 1°C recorded at Mumbles Head station, and this is explained by the arrival of the katabatic wind.



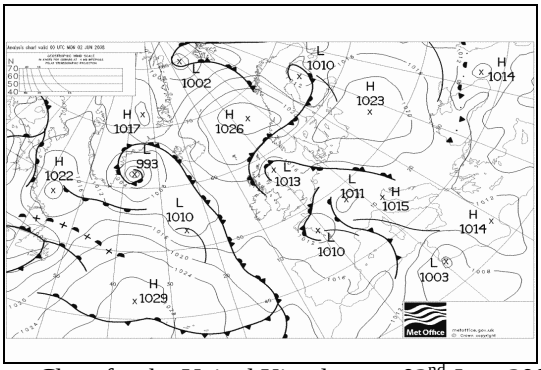


Figure 10. Sea-level Pressure Chart for the United Kingdom on 02nd June 2008.

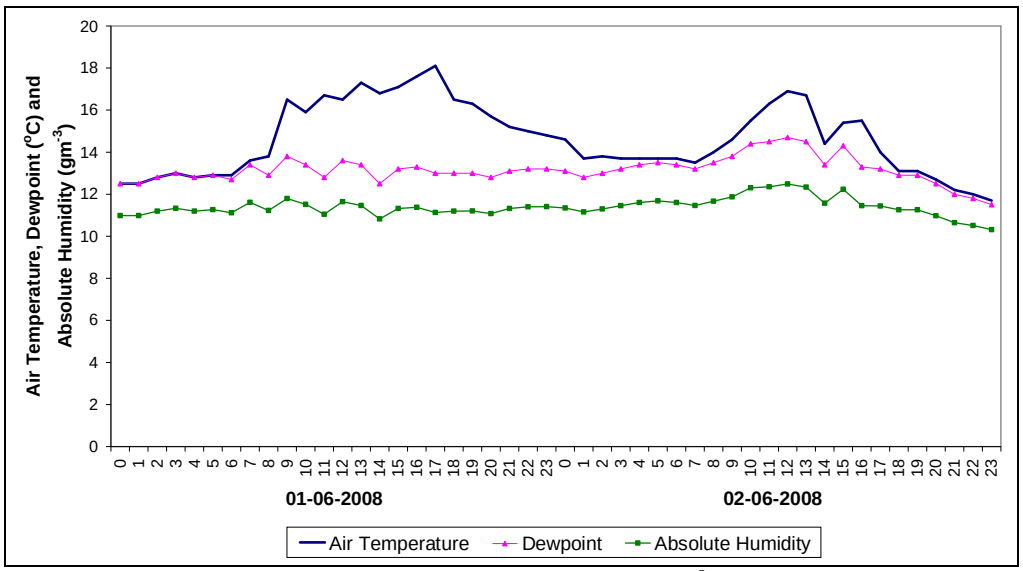


Figure 11. Hourly comparison between air temperature, dewpoint (°C) and absolute humidity (gm^{-3}) for Mumbles Head station, 01st and 02nd June 2008.

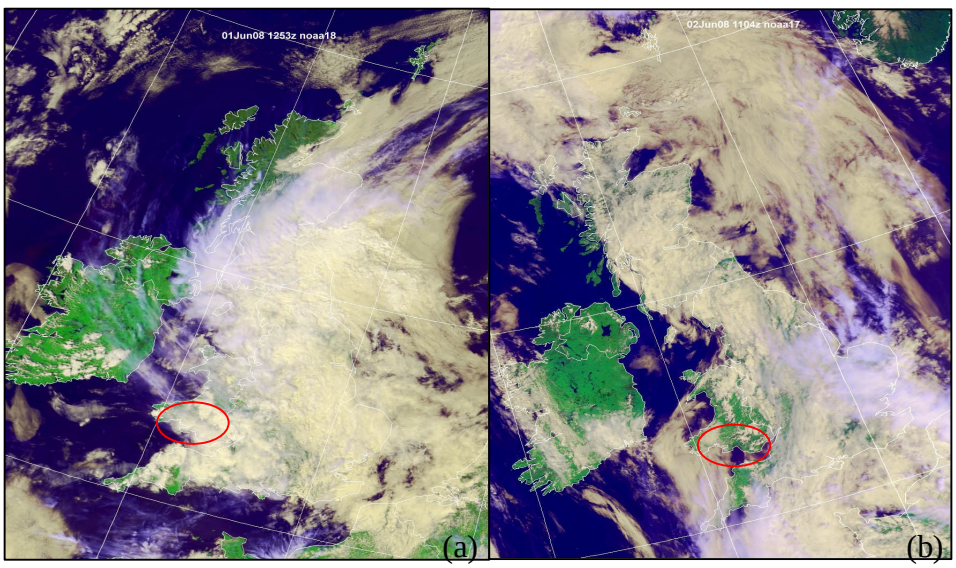


Figure 12. Satellite images from Wokingham Weather website. Red circle is Swansea area. (a) 01st - (b) 02nd June 2008.

In order to substantiate the evidence for sea breeze pollutants being returned on a katabatic wind, carbon monoxide (CO) should also be considered. CO does not chemically react with other pollutants directly so it is instructive to observe its levels in Swansea over the same period (Jacobson, 2002). Figure 13 was indicated that between 21:00 hours and 23:00 hours on 1st, and again between 01:00 hours and 02:00 hours on 2nd, there were CO peaks although there were very few emission sources at that time.

Figure 12 was also clearly shown a trough at midnight, and this was also in evidence for NO_2, O_3 (Fig. 3) and PM_{10} (Fig. 8), all to lesser extents, at similar times (reflecting the relative positions of the measuring stations). This can be explained by a deeper analysis of the Sodar data in Figures 4 and 6, which was indecated that the katabatic wind, occurred at lower levels, dropped in conjunction with a high-level wind prevailing in the opposite direction. This prevailing southerly lasted only for up to a couple of hours, and the katabatic wind then returned. Thus, katabatic winds are a complex phenomenon, as they are affected not only by the topography and the local climatic conditions that create them, but also by macroscale events such as a change in prevailing wind direction or speed (Simpson, 1994).

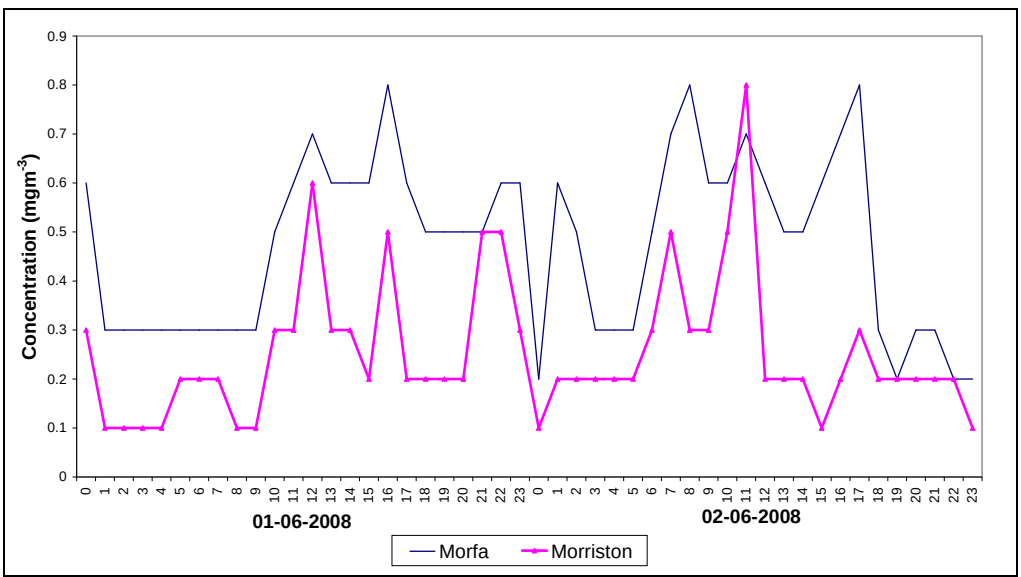


Figure 13. Hourly comparison of CO concentrations between Morfa and Morriston stations, 01st - 02nd June 2008.

Conclusion

The evidence was presented here shown that there was a strong relationship between weather and air quality in urban areas. Sea breezes was often occurred during the day carryed Swansea's pollutants inland. However, these sea breezes were returned, descended from the mountains behind Swansea, at night (as katabatic winds). These katabatic winds were both lighter and cooler than the original sea breezes. Such a phenomenon clearly was occurred on 1st and 2nd June 2008. Moreover, high concentrations of NO_2, O_3 and PM_{10} were recorded during the middle of the night when the sea breeze changed into a katabatic wind, returned Swansea's pollutants to the city under these specific meteorological conditions.

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