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RESEARCH ARTICLE

Detection of sea-breeze events around London using a fuzzy-logic algorithm

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We present an algorithm for detecting sea breezes based on fuzzy logic, using changes in variables commonly measured at meteorological stations. The method is applied to 1 year's worth of UK Met Office data (2012) measured at several stations around London, UK. Results indicate about a dozen potential events over the year, when matched against corresponding detections at a coastal reference site (Gravesend). In some cases the time lags between corresponding events detected at different stations can be used to characterize the average propagation speed of the sea-breeze front. Advantages and disadvantages of the method are discussed.

KEYWORDS

fuzzy logic, sea breezes, urban meteorology, wind changes

1 | INTRODUCTION

Sea-breeze fronts can propagate considerable distances inland (Simpson, 1994). Yet the incidence and effects of sea breezes in inland cities such as London, UK, are not well documented. Sea breezes can affect air quality (e.g., Papanastasiou and Melas, 2009) and meteorological conditions (Grimmond *et al*., 2004) over coastal cities. Marine intrusions were even found to have implications for urban areas located further inland; for example, Chemel and Sokhi (2012) suggest they might alter urban heat island patterns for London. Therefore, detection of sea breezes could inform the prediction of local weather and air quality.

Several methods have been proposed for detecting sea breezes from single-station time series measurements of meteorological variables, which have been successfully applied to coastal sites (e.g., Borne *et al*., 1998; Alpert and Rabinovich-Hadar, 2003; Plant and Keith, 2007). However, the proposed algorithms have often necessitated somewhat ad hoc decisions on threshold values characterizing changes in the relevant variables. These particular choices may not be applicable to stations further inland, where the influence of the sea-breeze passage is likely weakened by drag and terrain effects, especially over a city. Recent studies have exploited advanced measurement capability such as Doppler weather radar (Suresh, 2007) and satellite observations (Lensky and Dayan, 2012), but these may not always be available.

In this paper we employ a detection algorithm based on fuzzy logic that can in principle be applied consistently for inland as well as coastal stations, using only time series as routinely measured at surface weather stations. We then illustrate the application of the method using a year's worth of data measured at several stations in and around the Greater London area; the results offer some insight into the incidence of sea-breeze events at those locations.

2 | SITES AND DATA

The data set consists of surface observations at 1-min resolution over a whole year (2012) from UK Met Office surface sites (UK Met Office, 2006, 2018) at four locations around Greater London (St James' Park, Heathrow, Northolt and Kenley), one "rural" location (Farnborough) and a coastal reference site (Gravesend; Table 1 and Figure 1). This period has been chosen to coincide with major field campaigns in the ClearfLo (Clean Air for London) project (Bohnenstengel *et al.*, 2015), when extensive measurements of air quality and boundary layer characteristics were made in London. One-minute average data for the following quantities are available: temperature, relative humidity, wind speed, wind direction and gust. Only at St James' Park the data set is limited to temperature and relative humidity.

Figure 2 shows the wind speed observed at Heathrow on a case study day (July 25, 2012), revealing rapid and generally large turbulent fluctuations at the native 1-min resolution. As the sea-breeze detection is based on changes in the observed quantities (section 3), these small-scale fluctuations need to be removed by performing a running average over an interval larger than the small-scale turbulence but not so large as to smooth out larger-scale variations. Tests with different averaging intervals (not shown) found averaging windows of 20 or 30 min to be most suitable. A running average over an interval of 30 min is used in this study.

TABLE 1 Times (UTC) of potential passage of sea-breeze front at six Met Office stations in and around Greater London, UK, identified by the fuzzy-logic algorithm (section 3). Top row shows the total number of dates with an event by station. Last column shows the number of stations at which a detection was made on the same day. Columns are ordered by easting of measurement site from east to west

Date	Gravesend	Kenley	St James Park	Northolt	Heathrow	Farnborough	Total stations
Total days	16	11	12	10	14	6	
March 15, 2012	1543	1725	1626	1657	1802		5
		1842	1834	1919			
			1918				
March 20, 2012	1408		1607	1647	1704		4
March 22, 2012	1513	1301	1623	1727	1441	1646	6
			1702		1746		
			1801				
April 11, 2012	1318			1304	1707	1654	4
				1700		1820	
May 28, 2012	1301		1944		1841		3
	1433						
June 19, 2012	1539				1937		2
June 28, 2012	1425	1607	1740		1703		4
		1724	1945				
		1843					
July 25, 2012	1411	1732		1825	1843		4
		1954					
August 10, 2012	1503	1738	1805	1911	1920	1818	6
		1809					
August 18, 2012	1315	1635					2
September 7, 2012	1531	1858	1644	1950	1944		5
			1832				
			1905				
September 8, 2012	1454		1644	1736	1702		4
			1808				
			1919				
September 13, 2012	1427	1844	1414		1842		4
			1611				
September 15, 2012	1521	1754	1753	1830		1928	5
September 17, 2012	1349	1705	1303		1830	1659	5
			1816				
September 18, 2012	1527	1400	1402	1751	1313	1939	6
		1601	1706				

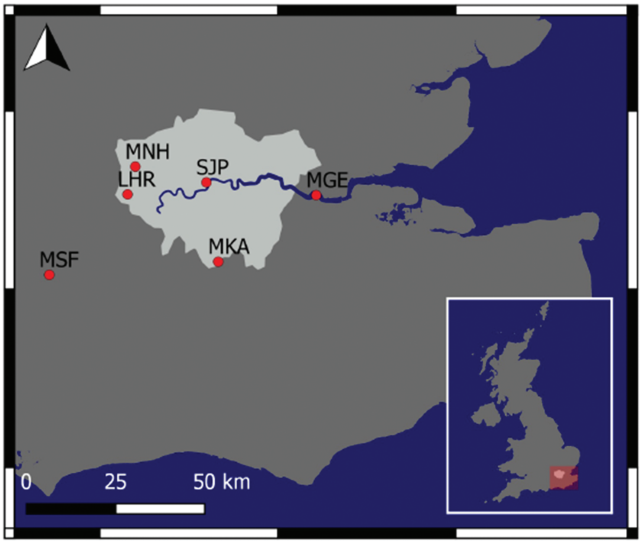

FIGURE 1 Map showing locations of measurement sites. LHR = Heathrow; MGE = Gravesend; MKA = Kenley; MNH = Northolt; MSF = Farnborough; SJP = St James' Park

3 | METHODOLOGY

The methodology is adapted from a fuzzy-logic approach employed by Huang and Mills (2006a; 2006b) for detecting wind change timing from single station observations. Huang and Mills (2006a) describe their method as objective because it provides automated algorithmic detection, as opposed to human inspection of time series and surface charts which is subjective and time-consuming. Here we present a simpler fuzzy-logic algorithm, supplemented by additional constraints to make the method applicable to the detection of sea breezes. The passage of a sea-breeze front is generally accompanied by a change in wind direction, an increase in wind speed, gustiness and (sometimes) relative humidity and a decrease in temperature (e.g., Plant and Keith, 2007). The basic idea is simple and consists of the following steps: (a) Combine computed rates of change in all or a subset of these quantities (depending on data availability) into a single suitably defined fuzzy function. (b) Detect maxima of this fuzzy function above a certain threshold to reveal the timing of strong correlated changes in these quantities.

A simple fuzzy function $y = f(x)$ is defined which takes a constant value y_1 when the independent variable x is below a threshold x_1, another constant value y_2 when x is above a higher threshold x_2, and a value linearly interpolated between y_1 and y_2 when x is between x_1 and x_2,

$$f(x) = \begin{cases} y_1, \; x \le x_1 \\ y_1 + \left(\dfrac{y_2 - y_1}{x_2 - x_1}\right)(x - x_1), \; x_1 < x < x_2 \\ y_2, \; x \ge x_2 \end{cases}.$$

In the following, the variable x will denote the rate of change of one of these five quantities: wind direction, wind speed, gust, relative humidity (optionally) and temperature.

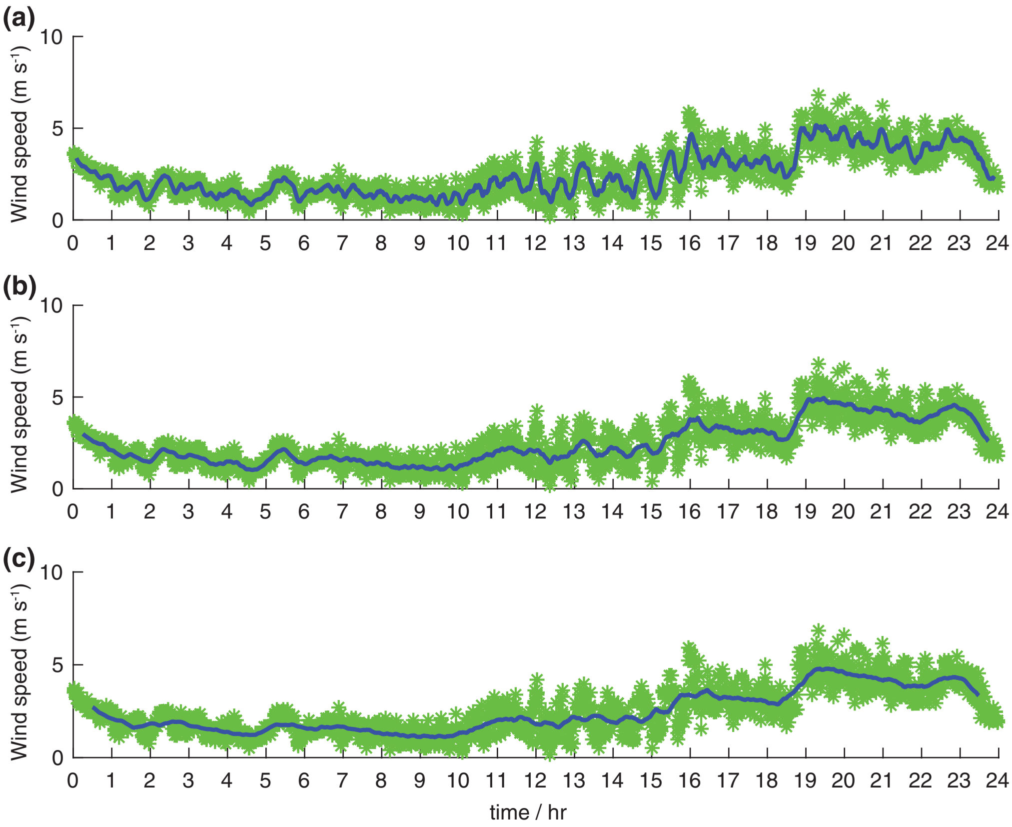

FIGURE 2 Wind speed at Heathrow station on July 25, 2012 at 1-min resolution (stars) and running average (solid line) over (a) 10, (b) 30 and (c) 60 min

The values of x_1, x_2, y_1 and y_2 need to be chosen for each quantity and in principle many choices are possible. It is desirable to set these values in such a way that the method is generic and not tailored to site-specific or variable-specific characteristics. With this in mind, the constant values are set to $y_1 = 0$ and $y_2 = 1$ for all quantities, so that values of $f(x)$ are confined to the range [0, 1]. The thresholds for the rate of change in quantity x are based on minimum ($x_{\min}$) and maximum ($x_{\max}$) values across all stations over the total time interval considered. For wind direction thresholds are chosen to be $x_1 = x_{\min} + (x_{\max} - x_{\min})/3$, $x_2 = x_{\max} - (x_{\max} - x_{\min})/3$, so that the range of observed wind directions is split into three equal segments, with the lower and upper thresholds being a third above the minimum and a third below the maximum, respectively. For the other meteorological variables (rates of change of wind speed, gust and humidity and the negative rate of change of temperature) $x_1 = 0$, $x_2 = x_{\max}/2$, because only a positive value for these quantities corresponds to a non-zero likelihood of a sea breeze. The precise values of x_1 and x_2 do not matter. The method works by capturing a large correlated change in the variables through an increase in the value of the fuzzy function; again, the absolute value of the fuzzy variable is not important.

At each time step at 1-min resolution the function $f(x)$ is computed for each quantity after performing a 30-min running average (section 2). The rate of change of each quantity is calculated over a specified time interval, chosen to be 10 min here. The precise choice of the time interval is not crucial because it is only required to detect a large correlated change in the variables and the absolute value of the fuzzy variable is largely immaterial; other time intervals have been tested which revealed this setting not to have a major impact. The values of $f(x)$ for the different variables can then be combined into a single average value, for example, using a weighted mean. Here, equal weights are chosen for each quantity simply because we do not posit any a priori reason to give any variable more weighting than another. The resulting time series of this mean fuzzy function contains a lot of fluctuations; however, simultaneously large rates of change for several quantities result in well-defined "spikes." To reduce the effect of background fluctuations the time series of the fuzzy function may in turn be smoothed using a moving average (this is not performed here). As these spikes mark clear outliers, they can be isolated from background fluctuations using a simple threshold. Here, a value of 0.7 was found appropriate. This value may need to be adjusted, depending on the sites considered and the local meteorology, to optimize the detection efficiency. As the fuzzy function often exceeds the set threshold for several consecutive time intervals, the maximum of the fuzzy function was used to determine the time of frontal passage. If more than one spike exceeded the threshold within an hour, then the detections were taken to correspond to a single event (given that the data was averaged over 30 min) and only the first peak of the fuzzy function was used.

Optional additional criteria can also be applied to remove false positives not associated with sea breezes, for example, if the wind direction is outside a certain sector, or if the events occur outside of a certain time interval (e.g., at night), or if it was raining at the given site at the given time. In the analysis reported in the next section, days during which widespread rain was recorded were excluded. An additional constraint was to restrict the search to between the hours of 1200 and 2000 UTC, because no sea breezes are expected in London outside of that time interval.

4 | RESULTS

The algorithm was applied to observations from all sites around Greater London (section 2) between March and October 2012 inclusive. To exclude potential false positives due to local variability, only days on which a detection took place at Gravesend before 1600 were selected. The reasoning for this constraint is that if a sea breeze reaches the inland stations (even from the south) then it must have occurred all around the coast. Hence, one should be detected at Gravesend too. After applying this constraint, events were detected during around a dozen days for Greater London in 2012, corresponding to 16 detected in Gravesend. In 30% of cases a detection was made at one or more of the other stations but not at Gravesend. Only six events were detected at Farnborough, with five corresponding to a southerly wind direction and one (on March 22, 2012) corresponding to a westerly.

The times corresponding to the maximum of the fuzzy function for the events detected at each station are shown in Table 1. It should be noted that the method worked well even for St James' Park, where only two meteorological variables (temperature and relative humidity) were available to compute the fuzzy function—a similar number of days resulted as for the other London stations. The dates on which events were detected did not always coincide across all stations. On 3 days there were detections at fewer than three stations. Discarding those gives a total of 13 days. There were several cases where events were detected twice or three times at the same station on the same day. This could be due to a sea-breeze front propagating west, followed by a later one propagating north.

If the detections correspond to the passage of a sea-breeze front, this should be reflected in their time-ordering. In general, one would expect a detection to be made at Gravesend well before the other stations. Kenley should be next, followed by either St James' Park or Heathrow, depending on the direction of the sea-breeze front. One would also expect times of detections at Heathrow and Northolt to be fairly close to each other. The rural station at Farnborough should be last for an easterly front propagation;

indeed, it might not register a detection at all given that it is so far inland and downwind of London. On the other hand, we might expect a detection at Farnborough around the same time as at Kenley for a southerly front propagation. Several of the candidate days broadly satisfy these expectations. The detection algorithm therefore gives a plausible shortlist of possible sea breeze candidates, which can then be investigated in more detail on a case-by-case basis.

As an example, on July 25, 2012 detections occur at Kenley, Northolt and Heathrow in an order consistent with the easterly propagation of a sea-breeze front. The fuzzy function is illustrated for that day, together with time series of five variables observed at Heathrow (Figure 3). The fuzzy function exceeds the threshold of 0.7 between approximately 1830–1900 (Figure 3f) when the temperature is decreasing (Figure 3a) while relative humidity (Figure 3b), wind speed (Figure 3c) and gustiness (Figure 3e) show a marked increase. In this case, the change in wind direction is small, of the order of a few degrees (Figure 3d); a larger increase occurs about half-an-hour later.

Based on an easterly wind direction (as recorded at Gravesend) the average speed of propagation from Gravesend to Heathrow is found to be approximately 3.4 m/s, which is consistent with textbook values for the speed of sea-breeze fronts (Simpson, 1994). Inspection of hourly spatial plots produced in simulations using the UK Met Office Unified Model over the UK at 1.5 km resolution reveal temperature and wind vector patterns consistent with a sea breeze around the southeastern coast of England (not shown).

5 | SUMMARY AND CONCLUSIONS

An algorithm for the detection of sea-breeze fronts based on commonly available meteorological surface observations is proposed. Combining the temporal rate of change of multiple variables such as air temperature, relative humidity, wind speed, wind direction and gustiness, a fuzzy function is computed that enables the identification of front passage based on one single threshold. The simplicity of the algorithm allows its applicability to data collected at different study areas.

The proposed method was applied to detect sea-breeze events in and around Greater London, UK, in 2012 based on six measurement stations. About a dozen potential sea breeze dates were identified at the inland sites, corresponding to 16 detected at a coastal reference site (Gravesend).

Automated, rapid detection of sea-breeze events is considered beneficial for the analysis of air quality measurements in urban areas located at or close to coastlines such as

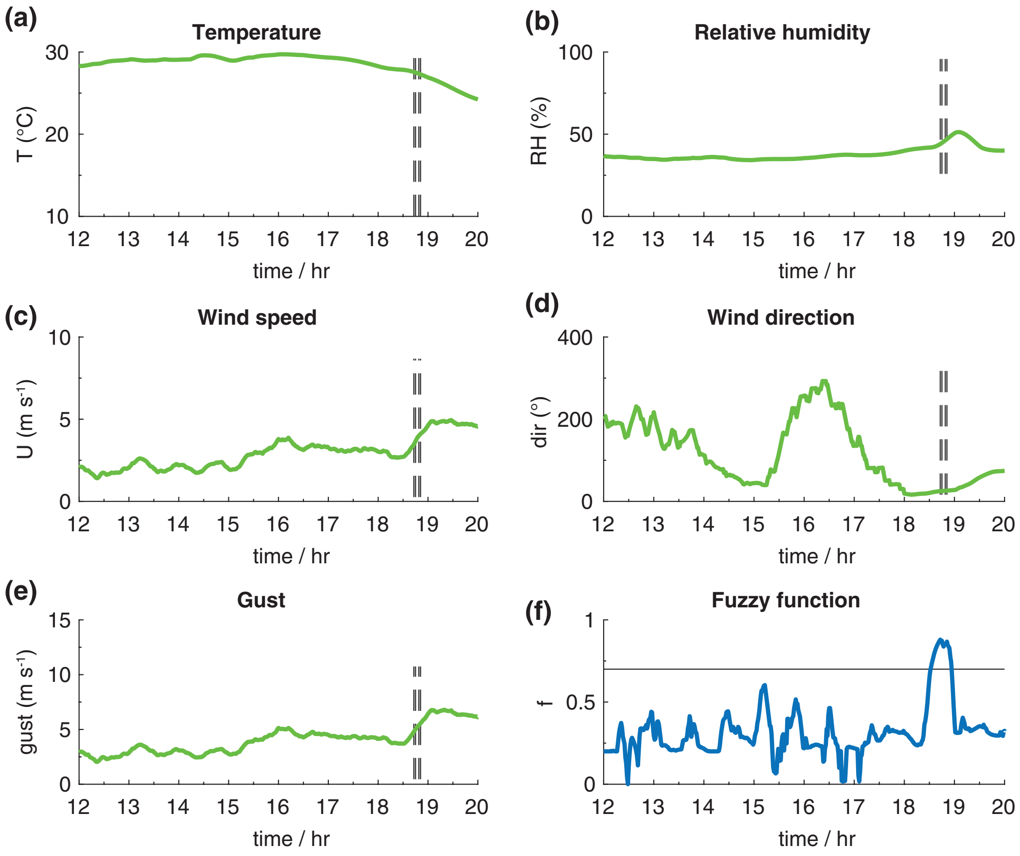

FIGURE 3 (a) Air temperature, (b) relative humidity, (c) wind speed, (d) wind direction and (e) gustiness observed at Heathrow on July 25, 2012; (f) fuzzy function *f* combining rates of change of all meteorological variables. Time of peak fuzzy function exceeding a threshold of 0.7 marked by horizontal line in (f) is indicated in (a–e) by vertical dashed lines

the case study area of London used here. Knowing about these fronts passing over the city and the associated change in air mass helps to interpret both observations and modelling fields and might assist the selection of case studies for more detailed investigations (Bohnenstengel *et al*., 2015).

The main advantages of the fuzzy-logic method are: its simplicity; the use of readily available time series data; it does not rely on prescribed empirical thresholds for different variables; it can be applied uniformly at multiple stations, even when there are different availabilities of data. Disadvantages include: additional constraints need to be imposed to apply the method to the detection of sea breezes; there is some ambiguity in how thresholds are fixed; this includes the thresholding of the fuzzy variable upon which a detection depends.

This method could be adapted to detect wind changes due to other types of meteorological phenomena too. Hence, it might prove useful for example in wind energy applications, where improved knowledge of causes of power production variability helps to increase confidence in potentially costly anticipatory decisions.

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