Met Office

Objective classification of storm environments associated with surface-water flooding in the UK

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November 2025

Introduction

- Surface water flooding (SWF) is the primary hazard associated with deep, moist convection in the UK. Work is ongoing at the Met Office to facilitate operational recognition of synoptic-scale, mesoscale and storm-scale environments associated with SWF-producing convection.
- A set of 103 SWF-producing storms has been identified over the period 2014 – 2021, using multiple sources of impact reports. Only storms producing substantial flooding impacts (e.g., disruption to critical infrastructure, internal flooding of multiple properties) are included.
- Previous work has shown that convective environments of these events are typically characterised by modest instability (median MUCAPE equal to 561 J kg^{-1}) and weak vertical wind shear (median effective bulk wind difference 6.6 m s^{-1}), but that there is substantial variation across the event set.
- In this work, we seek to objectively define different types of SWF-producing storm environments. We also explore how the radar-observed morphology of storms varies across the environmental types so defined.

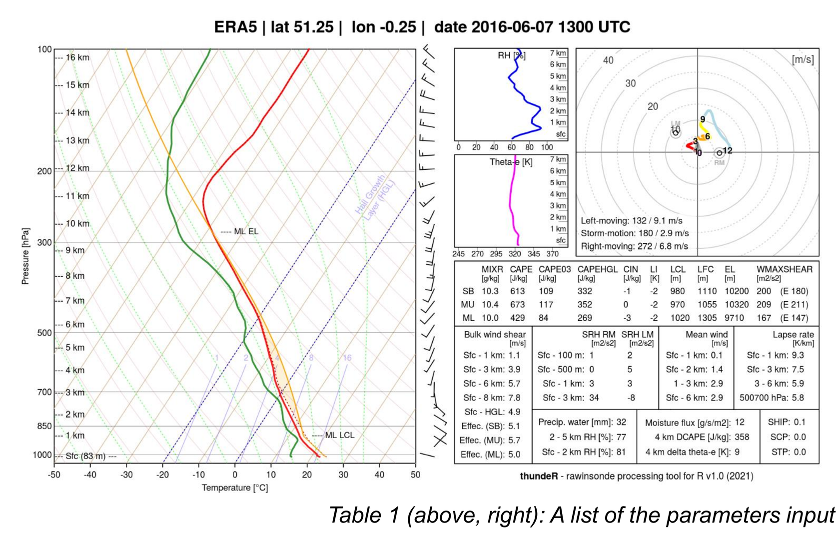


Figure 1 (right): Skew-t plot (main panel) for one of the SWF cases, showing vertical profile of temperature (red), dewpoint temperature (green) and winds (barbs) from ERA5. Also shown are a hodograph (top right) and table of selected convective diagnostics (bottom right). Generated using the thundeR software (available online at https://rawinsonde.com/ERA5_Europe).

	Parameter
1	LCL height (m)
2	LFC height (m)
3	EL height (m)
4	0 - 3 km bulk wind difference (m s^{-1})
5	0 - 6 km bulk wind difference (m s^{-1})
6	0 - 1 km vector mean windspeed (m s^{-1})
7	Magnitude of Corfidi upwind vector (m s^{-1})
8	Magnitude of Corfidi downwind vector (m s^{-1})
9	MUCAPE (J kg^{-1})
10	MU lifted index (deg C)
11	3 - 6 km lapse rate (K km^{-1})
12	Downdraft CAPE (J kg^{-1})
13	0 - 2 km relative humidity (%)
14	2 - 5 km relative humidity (%)
15	Precipitable water (mm)
16	MUCIN (J kg^{-1})
17	Convective layer depth (m)
18	Height difference between LCL and LFC (m)
19	Normalised CAPE (J kg^{-1} m^{-1})
20	Bulk wind difference between base and top of convective layer (m s^{-1})
21	Vector mean windspeed over convective layer (m s^{-1})
22	Maximum storm-relative windspeed in lowest 25% of convective layer (m s^{-1})
23	MUCAPE below the minus 10 deg C level (J kg^{-1})
24	Temperature of the equilibrium level (K)

Table 1 (above, right): A list of the parameters input to the clustering algorithms.

Method

- Representative vertical profiles for each SWF event were obtained from thundeR, which computes and plots vertical profiles and a large set of convective diagnostics from ERA5 reanalysis data (see Figure 1 for an example).
- The timing and location of the vertical profile was selected manually in each case, with reference to network radar imagery, with the aim of sampling the near-storm environment on the inflow side of the storm, wherever this could be determined.
- A sub-set of environmental parameters were then selected for input to the clustering algorithms (see Table 1).
- The parameter values were first input to principal component analysis (PCA), with 10 principal components found to retain 95% of the variance in the data.
- Agglomerative clustering was then performed using the distribution of events within the reduced ten-dimensional principal component parameter space. Elbow plots and silhouette scores were used to ascertain the optimal number of clusters (five).
- The robustness/repeatability of the clusters obtained was tested by randomly removing 10% of the events and rerunning the PCA and clustering. This was repeated five times. Identified clusters were found to be at least reasonably consistent across the five instances.

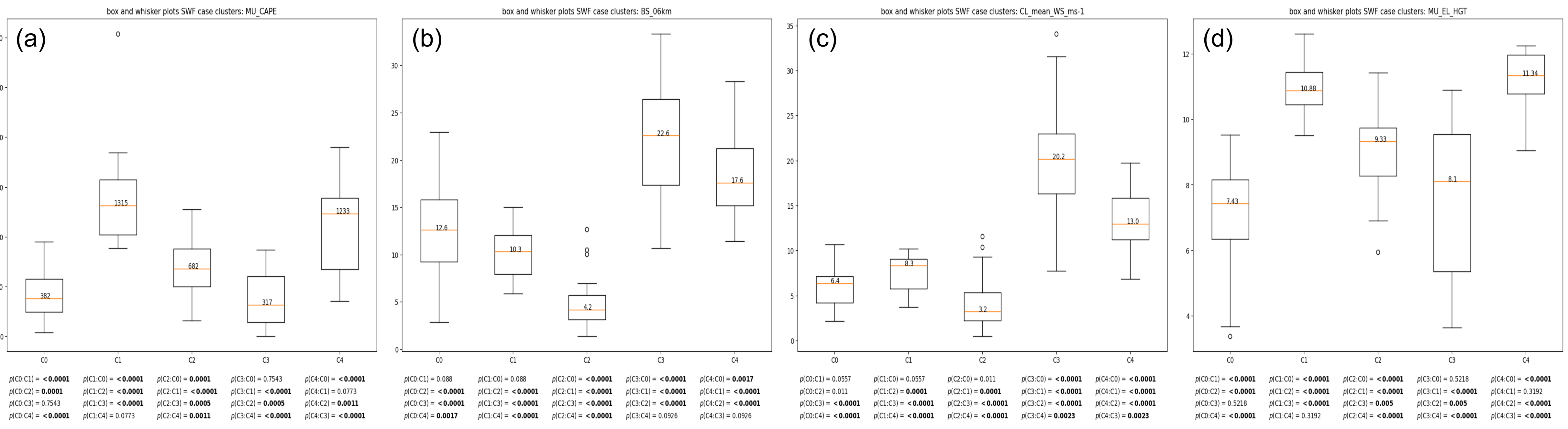


Figure 2: Box plots showing the distribution of key parameters over the set of cases within each cluster: (a) MUCAPE (J kg^{-1}); (b) 0 – 6 km AGL bulk wind difference (m s^{-1}); (c) vector mean windspeed over the convective layer (m s^{-1}); (d) MU equilibrium level height (km AGL). Boxes extend from the lower to the upper quartiles of the distribution, and tails to the 10th and 90th percentiles. Orange lines within each box and adjacent text indicates the median value in each cluster. Text underneath each panel indicates the p-value obtained from a t-test of the differences of the distributions between cluster pairs, as labelled. Bold font indicates differences that are statistically significant at the 99% level.

Results: Cluster Characteristics

Figure 2 shows the distribution of key environmental parameters for the five identified clusters. From these, the clusters may be described as follows:

- Cluster 0 (C0): Low CAPE, moderately weak wind shear (22 events)
- Cluster 1 (C1): High CAPE, weak shear (15 events)
- Cluster 2 (C2): Moderately low CAPE, very weak shear (35 events)
- Cluster 3 (C3): (Frontal): Low CAPE, very strong shear and mean flow (15 events)
- Cluster 4 (C4): (Elevated convection): High CAPE, moderately strong shear (16 events)

It is encouraging that the elevated cases (as identified manually from the ERA5 soundings) were mostly grouped into a single cluster, since the mode (elevated versus surface-based) was not included as an input to the clustering algorithms.

Whilst clusters 3 and 4 are clearly distinct, clusters 0 and 2, which together comprise 55% of the event set, are apparently similar. Both are characterised by modest CAPE and weak shear, though the CAPE is lower in cluster 0, whilst the wind shear and convective-layer-mean windspeed are particularly low in cluster 2.

Table 2 (right): Incidence of lightning in events belonging to the various identified clusters. Data are from the Met Office ATDNet lightning detection system. Detections are summed over a domain of 100 km squared, centred on the impacted location in each case, and over 1-hour periods for the duration of each event. The maximum hourly total for each event is then calculated.

	C0	C1	C2	C3	C4
Median hourly max flash rate	34	707	32	80	686
% of events without any lightning	9.1	0.0	11.4	33.3	0.0

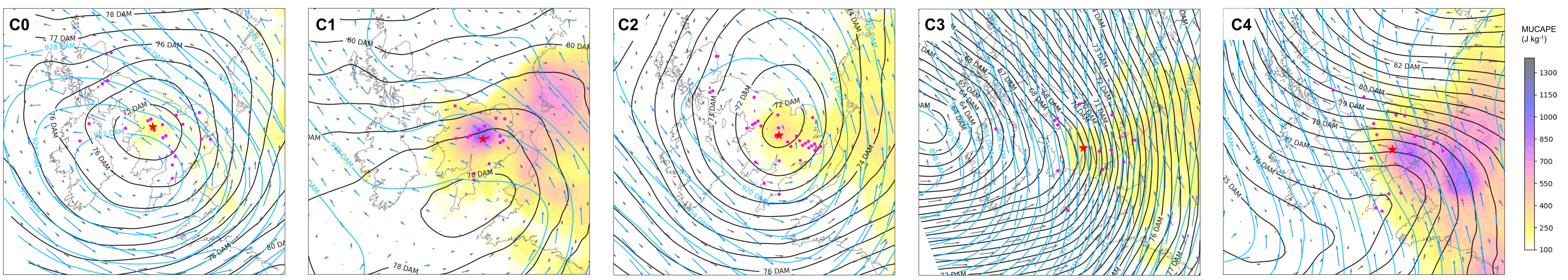


Figure 3: Composite ERA5 fields for the five clusters of event (as labelled). Geopotential height at 925 and 300 hPa are shown by the black and light blue contours, respectively. Winds at the same levels are shown by grey and blue vectors, respectively. Colour shading indicates MUCAPE (J kg^{-1}; see colour scale at right). Magenta dots denote the locations of individual SWF events within each cluster, whilst the red star symbols denote the mean event location in each cluster; fields for individual events have been translated horizontally according to the displacement between the event location and the cluster mean event location, prior to compositing.

Results: Storm Morphologies and Lightning

The variability of radar-observed morphological attributes of SWF-producing storms within each cluster has also been analysed. For example, in Figure 4 it is seen that the proportion of storms with quasi-linear structure, where the long axis of the line was closely aligned with the advection velocity, was highest in C3, and lowest in C1 and C2. Back-building storms were most common amongst the C1 and C2 events, and least common amongst the C3 and C4 events.

Table 2 shows that the incidence of lightning also varies substantially between clusters. For example, lightning activity is relatively weak in clusters C0, C2, and C3. A third of C3 cases had no lightning at all. In contrast, C1 and C4 cases tend to produce much more frequent lightning. These differences are consistent with the differences in CAPE and equilibrium level (*cf.* Figures 2(a) and (d)) with deeper storms and larger CAPE being associated with more lightning activity, as might be expected.

Finally, the distribution of events, and event clusters, in the two-dimensional parameter spaces defined by the various input parameters have also been analysed. Some of the results hint at possible differences in the underlying physical mechanisms; for example, Figure 5 shows that cases with larger downdraft CAPE (DCAPE) tend to have larger storm-relative flow in the low levels. One possible explanation is that larger storm-relative flow is required to balance the stronger tendency for cold pools to expand outwards away from existing storms where downdrafts are stronger/colder, which would otherwise tend to reduce the likelihood of multiple cells initiating in similar locations. Subjective analysis of the radar data shows that such repeated initiation of cells is observed near to the flood-impacted locations in many of the identified SWF cases.

Results: Composite Plots

Composite plots of selected ERA5 fields on pressure levels were produced for each cluster (Figure 3). Fields were translated so that the event location was the same in all cases within a cluster before averaging of the translated fields.

Cluster 0 and 2 events were both, on average, located in an area of weak near-surface winds close to the centre of a surface low pressure. However, in cluster 0, the low pressure was tilted south-westward with height, such that there was stronger southerly flow aloft, whereas in cluster 2, the low pressure was more vertically stacked, with weak winds at all levels. Convective-layer-mean windspeeds were therefore particularly low in cluster 2 cases, a situation that would be expected to favour very slow-moving cells.

Cluster 3 cases were associated with much stronger winds, with strong troughing in the low- to mid-level height fields centred close to the mean SWF event location. This reflects the fact that most of these events were associated with narrow cold-frontal rainbands. Cluster 4 events, which are mostly elevated convection cases, show strong warm advection in low- to mid-levels (not shown), and a strong CAPE gradient (larger CAPE upwind relative to the direction of the convective layer mean wind vector).

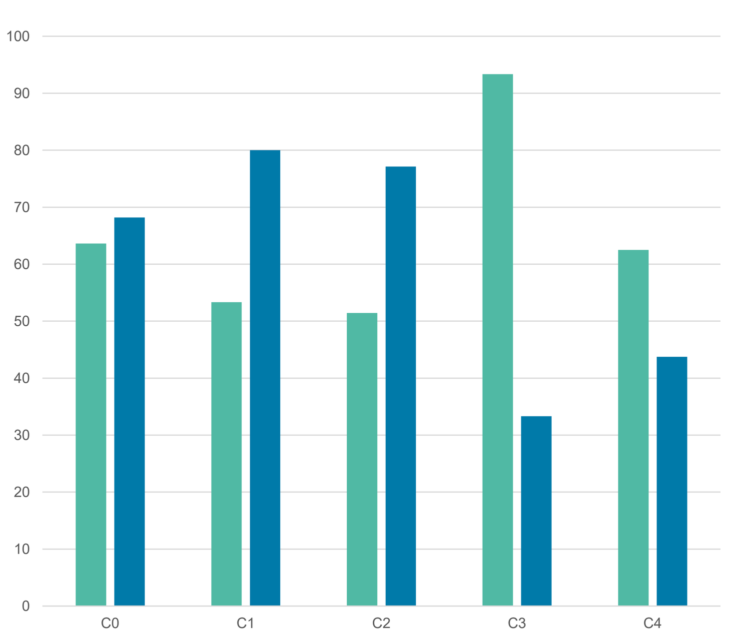
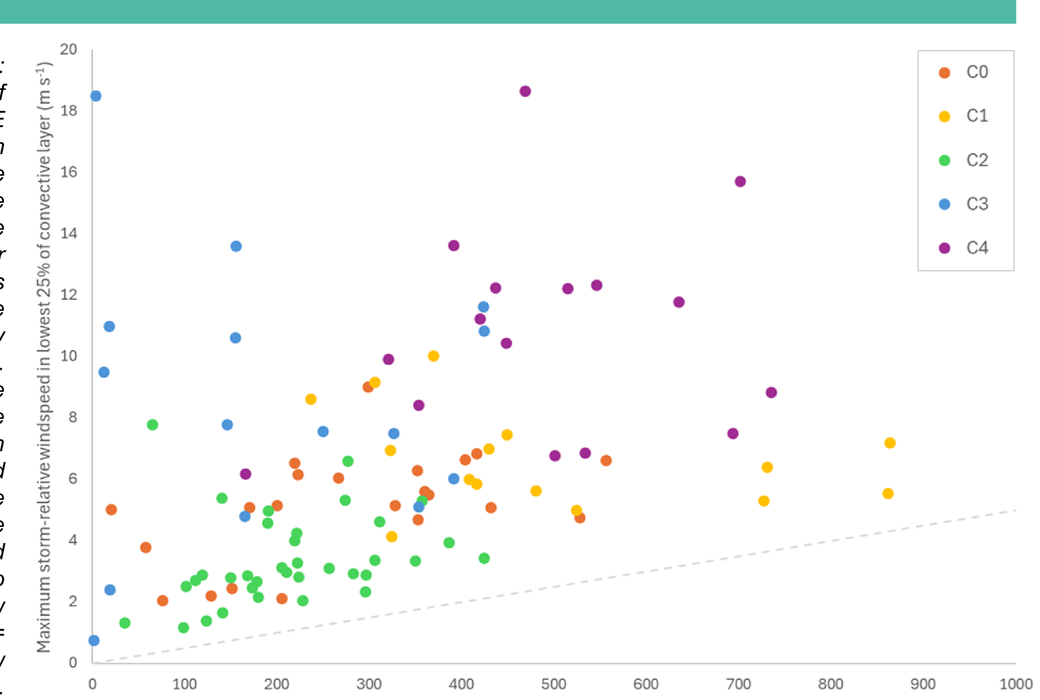


Figure 4 (left): Percentage of events in each cluster exhibiting: (i) quasi-linear morphology, in which the long axis of the system was closely aligned with the advection velocity (green bars) and (ii) back-building behaviour (blue bars), as analysed subjectively using network radar imagery.

Conclusions

- Clustering analysis applied to a set of 103 SWF cases has identified several different types of environment associated with SWF-producing convection in the UK.
- The two largest clusters were both characterised by relatively modest MUCAPE and weak vertical wind shear, though with some differences in detail (for example, stronger near-anvil-level flow in cluster 0 cases).
- Composite analyses show the clusters to be associated with different synoptic-scale situations, which may be useful as an aid to operational recognition of SWF environments. However, it is acknowledged that substantial variability exists in the mesoscale and synoptic-scale situations between cases *within* each cluster, and therefore the composite fields may mask details that are important in individual cases.
- Early results suggest that there are systematic differences between clusters in terms of the convection morphology and, possibly, underlying physical mechanisms. Future work will focus on these aspects, including more in-depth analysis of representative cases from each cluster.

Figure 5 (right): Scatterplot of downdraft CAPE versus the maximum storm-relative windspeed in the lowest 25% of the convective layer (LLSR flow), as assessed from the ERA5 proximity sounding data. Colours indicate the event clusters. Note the lack of events in the bottom right-hand corner of the parameter space (large DCAPE and small LLSR flow); no events occur below the line DCAPE = 200 x LLSR flow (dashed grey line).



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