Synoptic climatology of cold air drainage in the Derwent Valley, Peak District, UK

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ABSTRACT: Cold air drainage is a characteristic of hilly or mountainous terrain and can have significant impact on agricultural or horticultural activities. This paper considers a range of synoptic and topographic factors that could affect the phenomenon of cold air drainage, through an exploration of its characteristics in the Peak District of central England, showing that cold air drainage events can occur at any time of the year, with summer events being even more frequent than those usually noticed in winter. The occurrence of such events is related to the local topography, and particularly the correspondence to hollows and local valleys on the scale of 0.5–1 km, rather than on the scale of the principal drainage routes in the region. In contrast to some previous studies, synoptic and local weather conditions were not found to be strong indicators of cold air drainage events. It is also shown that under suitable conditions cold air drainage can overcome the effects of the urban heat island. Copyright © 2012 Royal Meteorological Society

KEY WORDS cold air drainage; mountains; valley wind; frost

1. Introduction

Mountainous terrain is well known for the creation of local ‘frost hollows’ due to cold air drainage. The significant temperature anomalies experienced in such regions can have strong impacts on local native plant distributions, as well as horticulture and agriculture (Chung et al., 2006; Hubbart et al., 2007; Inouye, 2008). There is also an associated human cost in the quality of life, heating costs and building design. Short-distance variation in currently poorly predictable weather conditions due to local topographic effects on the kilometre to 10 km scale can also have a biasing effect on station data in climate data sets (Daly, 2006).

Relatively little research has been undertaken on the prevalence and causes of such cold air drainage. Typically, such flows have been observed to be limited in depth, sometimes being as thin as a few tens of metres (Goulden et al., 2006; Hubbart et al., 2007). They typically form in the first half of the night (Gustavsson et al., 1998) under clear-sky, and anticyclonic, conditions (Iijima and Shinoda, 2000; Mahrt et al., 2001; Whiteman et al., 2004; Chung et al., 2006). Inversions typically form at the top of this lower layer (Yoshino, 1984). In some cases, such as at the top of kilometre-sized limestone sinkholes (Clements et al., 2003), these can be extremely pronounced, and strong inversions can lead to considerable cold air drainage (Chung et al., 2006). In less extreme landscapes, the appearance of an inversion can cause the drainage to cease (Mahrt et al., 2001). Generally, however, the onset of the early-evening inversion reduces vertical mixing of the warm air above the boundary layer, and, in sheltered locations in particular (Gustavsson et al., 1998), allows cooling to progress quickly.

An important factor in controlling the severity and cessation of cold air drainage is the sky view (Whiteman et al., 2004). Thus, sheltered and pronounced local hollows, such as sinkholes or craters, encourage drainage (Clements et al., 2003; Whiteman et al., 2004; Yao and Zhong, 2009). Cooling ceases when the net radiative flux balances the sum of the ground, latent and sensible heat fluxes, although the last two are generally small in light wind situations. There is limited evidence for the annual cycle of cold air drainage, but longer nights would give the potential for more cooling, so for example, Iijima and Shinoda (2000) found that in the Yatsugatake range of central Japan cold air pooling in the summer was less pronounced than for autumn events. Nevertheless, Pyper et al. (2007) found more than 80% of summer nights in the afforested catchment in Oregon experienced cold air drainage.

The flowing cold air drains gravitationally down slope (Goulden et al., 2006), often at variance to the prevailing synoptic flow above (Mahrt et al., 2001), although the drainage will be enhanced if it lies in the same direction as the prevailing wind (Zängl, 2005). The drainage can be blocked by topography, causing ponding of the cold air (Zängl, 2005).

In this paper some of these past synoptic and topographic findings and contradictions are explored through an investigation of the climatology and causal mechanisms of cold air pooling in the vicinity of Calver (Figure 1), a site just upstream of a blocking hill at a junction of tributaries in the Derwent Valley of the English Peak District. The Derwent Valley extends with a largely north–south orientation from the uninhabited moors of the High Peak of the Derbyshire/Yorkshire border through a set of restricted valleys to its junction with the River Trent near Derby. These valleys form a mix of moorland, agricultural, rural village, industrial and town-scapes. The high horizontal gradients from the tops of neighbouring hills 300–600 m in height to the Derwent Valley of around 100 m elevation leads to some extreme examples of the occurrence of frost hollows, as well
as a more widespread cold season temperature anomaly during episodes of cold air drainage. It will be shown that observations suggest temperature inversions between hill-top and valley floor exceeding 4°C are not uncommon; winter extreme minima on the valley floor approach or exceed −10°C in most years. This is therefore an ideal site to investigate some of the underlying causes for cold air drainage introduced in the earlier discussion.

2. Data description and methodology

2.1. Instrumental records

The region under investigation has a good network of daily observational stations (Figure 1). A valley bottom station is maintained by one of the authors (GRB) within the Derwent Valley at Calver (120 m amsl, U.K. National Grid Reference (NGR): SK 244745), near one of the first major topographic obstructions (Hare Knoll, at the junction of the Middleton and Derwent Valleys) in the Derwent Valley. It is a typical garden site, with some sheltering from surrounding buildings and high trees, but a good sky view to the north and west. A well exposed hilltop station at High Bradfield (390 m amsl; NGR: SK 277928), operated jointly by the Department of Geography, University of Sheffield and the Meteorological Office, provides a high temporal resolution upland control and enables calculation of effective inversion magnitudes. Nearby lowland controls within the City of Sheffield to the east of the Pennines are available at the Weston Park Museum site (131 m amsl; NGR: SK 340873), used as one of the Meteorological Office’s standard UK climatological stations, the exposed roof of the Department of Geography (125 m amsl; NGR: SK 341875) and the home of one of the other authors (EH; 100 m amsl; NGR: SK 361901). The latter station is a part of the Climatological Observers’ Link (COL; http://www.met.rdg.ac.uk/~brugge/col.html). Daily maxima and minima temperatures were available from Calver and Weston Park, while 15 min temperature and wind data were available from the other sites, from which the daily extremes were calculated. While the latter three stations potentially suffer from urban heat island bias, the impact of this was assessed from a comparison of the average temperature difference between the Calver and Sheffield sites, which are at similar altitudes. The investigation used daily data from the 1 January 2004 to 30 June 2006, although there were some breaks in the record due to equipment malfunction and observer holidays at one or other site. The longest two of these occurred in spring 2004 and 2006 respectively, although two thirds of the possible data for spring overall were available.

The first part of the investigation involved statistical analysis of the Weston Park, Calver and High Bradfield stations. The monthly mean and standard deviation of the daily maximum and minimum temperatures for each site were calculated. Days when Calver was more than one standard deviation colder than one, or both, of the other two sites are of particular interest as being possible candidates for the occurrence of cold air drainage within the upper Derwent Valley. This technique was used by analogy with various climate studies (e.g. El Niño; for an example see Kumar et al., 1999) where exceeding one standard deviation allows confidence in the anomalousness of conditions.

For days with a temperature difference of more than one standard deviation for Weston Park – Calver, the differences
between High Bradfield and Calver were calculated using the same method. This tests whether the cold conditions at Calver are likely to be due to: (1) an urban heat island effect in Sheffield, when the temperature difference between High Bradfield and Calver is normal or anomalously cold, or (2) cold air drainage, in instances when High Bradfield–Calver is anomalously warm.

To investigate whether prevailing wind velocity is an important factor in shaping the distribution of cold air drainage events (Zängl, 2005), seasonal wind roses were drawn, for both significant events and the overall distribution of each season, from the wind data of the High Bradfield site, and t-tests carried out. High Bradfield is representative of the larger-scale local atmospheric flow, and is often quoted by the Meteorological Office in news releases for this purpose during periods of high winds, e.g. most recently 93 mph on 5 January 2012 (Met Office website accessed on same date). To investigate the possible link between significant days of cold air drainage and synoptic conditions (Iijima and Shinoda, 2000; Chung et al., 2006), daily weather maps from http://www.wetterzentrale.de/topkarten/tkfaxbraar.htm for the British Isles sector (50°–60°N, 2°E to 10°W) were classified into Lamb weather types (Barry and Chorley, 2003) and statistically tested. Allied to this synoptic investigation, daily air pressure measurements from Weston Park were used to see whether air pressure in general, rather than a specific synoptic classification, is an influential factor on the initiation of cold air drainage.

The above methodology, relying on Calver’s daily minimum temperature being more than one standard deviation below that of either High Bradfield or Weston Park, enabled us to select days of extreme cases of cold air drainage. The use of remote sensing MODErate resolution Imaging Spectroradiometer (MODIS) brightness temperatures was tested to see if this provided more detail in discerning the flow of cold air through the valleys. However, some candidate cold air drainage days were not covered by the satellite, and on others cloud cover obscured the local area. For the remaining examples, it was found that the resolution of these images at around 1 km was insufficient to provide us with significant insight into the mechanisms and detailed paths of cold air drainage. This will therefore not be expanded on further in the analysis, but these limitations are noted for future studies.

GIS techniques were also used to examine likely preferred routes for gravitationally-driven cold air drainage in the local area around Calver. These details are important in investigating causal mechanisms for the cold air drainage, and in 2009–2010 led to a series of vehicular transects through a range of terrains in the Sheffield and Derwent Valley areas, sampling drainage paths, the varying geology and the general landscape. The transects involved driving along the route shown in Figure 1, sampling temperature and humidity using a Kestrel 4500 sensor and position using a GlobalSat GPS, both logging at intervals down to 5 s. During the same period the Calver site was instrumented with a Tinytag temperature and humidity logger, set to 15 min logging, to provide in situ data during the time of the transects. These transects took place in the early morning around dawn (over an ~75 min period), when the special temperature logging record from Calver suggested there is a period of small temperature change (~1 °C) during such events. Earlier surveys had a reduced sampling interval (of approximately 1 min) and in Section 3.3 examples of both earlier coarser and later finer resolution are shown. The overall interpretation of the transects does not depend on this temporal resolution, but the finer ones were trials for a future study examining the physical dependence of cold air drainage routes on sub-kilometre scale topography. Both cold air drainage events and more normal days were sampled, and are discussed below.

2.2. GIS methodology

GIS is widely used in hydrological modelling and there is now a set of standard tools that are used to model the flow of water over a surface. In GIS, the topographic surface is stored in what is called a Digital Elevation Model, in which elevation is sampled on a regularly spaced grid across the area. In the present work, the PANORAMA DEM produced by the British Ordnance Survey was used, in which height is sampled at 50 m intervals.

Most hydrological analysis uses the approach described by Jenson and Domingue (1988) based on the work of O’Callaghan and Mark (1984) which begins by calculating the direction in which water will flow out of each cell. This is done by considering the vertical angle between the cell and each of its eight neighbours, and identifying the neighbour with the greatest downslope angle. The direction to this cell is stored using a code in which 1 is east, 2 southeast, 3 south and so on. In reality water can of course flow in any direction from a given point on the surface, but it has been found that this approximation to the nearest cardinal direction works well for predicting the location of the main drainage lines in an area (Quinn et al., 1991).

Once the flow direction has been calculated for each cell, the next stage is to calculate what is called the flow-accumulation: the number of cells which are ‘upstream’ of each cell in the DEM. Cells which are located on ridges will have very few ‘upstream’ cells, whereas those which lie in valleys will have far higher flow-accumulation values. By identifying cells with flow-accumulations over a chosen threshold it is possible to identify cells belonging to the drainage network.

Since cold air drainage is driven by gravity in the same way as the flow of water, the standard hydrological tools should be useful for modelling cold air flow. However, there are two differences between the flows of air and water that complicate matters. Firstly, air flow is not only driven by gravity, as is water flow, but is partly driven by the background large-scale atmospheric pressure gradient, which means that the topographic surface is not the only factor controlling the local pressure gradient. In effect, this means that, depending on the strength of the prevailing wind, air can sometimes flow ‘upslope’. Secondly, air flows in much larger volumes relative to the topographic surface. Water, even in hillside gullies, flows in volumes that are small relative to the scale of the landscape, and hence topography is the major control on the flow. Air masses are generally much larger relative to the landscape. This can lead to rather different effects. When a shallow cold air flow is moving slowly or is strongly stratified, and so has a low Froude number (Zängl, 2003), defined as \( U/\sqrt{gD} \) with the Brunt–Väisälä frequency \( N \) the Brunt–Väisälä frequency and \( d \) the depth of the cold air layer, it can become trapped by topographic barriers that would not trap water. Conversely, when the cold air flow is rapid or has lower stratification, and so has a high Froude number, it can flow over barriers, rather than go around them (Drobinski et al., 2006), and so minimize friction. In other words, it is necessary to identify valleys as opposed to the stream channels that occupy those valleys, and in particular it is of interest to identify topographic hollows.
 Experimentation was carried out to investigate ways of incorporating the prevailing pressure gradient effect into the GIS analysis, by adding varying slopes to the DEM commensurate with wind flow from different directions, but it was found that it did not significantly change the interpretation of cold air drainage events. To disentangle the impact of the scale of airflow, experiments were carried out using different dimensions of landscape in the DEM to derive drainage basins so as to seek that which corresponded best to the authors’ sense of the scale of trapping of slow-moving air, as seen through observed fog features. This could possibly be done by using a coarser resolution DEM with a cell spacing of the order of 1 km. However, it was decided to use a piece of software called Landserf 2.3 that has been specifically written to consider the analysis of topography at multiple spatial scales (Wood, 1998; www.landserf.org). In standard GIS, terrain parameters, such as slope, aspect and flow-direction, are always calculated based on a 3 × 3 window of cells around a central cell. By fitting a polynomial surface to this group of nine cell values it is possible to estimate the curvature at that point on the landscape. However, this is considering the landscape on a very fine scale, and while an individual cell may have concave curvature locally, it may be part of an otherwise planar slope. Wood (1998) realized that if a larger window was used around the central cell it would be possible to estimate surface parameters over a wide range of scales. Wood (1998) also developed a method for identifying which landform class each pixel appeared to belong to, based on the pattern of slope and curvature around it, and this technique can classify each pixel into one of the following classes: peak, pit, valley, ridge, pass and plane. The hypothesised dependence of cold air drainage on topographic obstructions led to required knowledge of the valley classification, so Landserf 2.3 was used to identify valleys in the study area, on the scale of 0.5 km (Figure 2). In other words, the shaded areas in Figure 2 are those pixels that fall within features that at the 0.5 km scale can be considered as valleys. Note that the main Derwent valley, which...
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Figure 3. Histograms showing the frequency distribution of temperature difference, scaled by seasonal standard deviation, between Weston Park and Calver for (a) winter, (b) spring, (c) summer, (d) autumn.

runs north–south through the area, is not identified as a valley because it is too large, and so only the central area, around the channel, is identified as a valley at this scale. What the method does do, however, is identify the tributary valleys. Furthermore, the valleys that are identified do not form a connected network, as the stream channels did, because at this scale the valleys contain topographic barriers to flow. Figure 2 is therefore a map of areas of potential cold air accumulation when synoptic conditions mean that the prevailing wind is too weak to have an effect on air-flow.

3. Analysis

3.1. Climatology of temperature extrema differences between the Calver, Weston Park and High Bradfield sites

Over the two and a half years considered, Calver typically had a higher monthly average maximum temperature than Weston Park, although only in the spring is this difference persistent and statistically significant (0.9 ± 0.6 °C), but a higher frequency of lower monthly average minimum temperatures (−2.0 ± 0.9 °C below Weston Park on average). The latter is true for all seasons, but particularly autumn (−2.8 ± 0.9 °C) and summer (−2.2 ± 1.1 °C). On average, Calver has a larger standard deviation for both minimum and maximum temperatures. This reflects the fact that a combination of sheltering and cold-air drainage increases the range of temperatures within the valley bottom at the Calver site.

Histograms of the distribution of the temperature difference between Weston Park and Calver for both the daily maximum and minimum temperatures, and for each season, are shown in Figure 3. These show extremely different distributions for maximum and minimum temperature differences. Maximum temperature differences are smaller, and are roughly normally distributed about a mean. These latter distributions change with the seasons, but the mean remains close to zero. Minimum temperature differences, however, are skewed towards the right, showing much colder conditions at Calver in general. Interestingly, the most skewed season is the summer.

The maximum and minimum temperature differences between High Bradfield and Calver show similar trends (Figure 4). As expected, High Bradfield’s daily maximum temperature tends to be lower than at Calver: it is almost 300 m higher in elevation and is much more exposed. However, despite this altitude difference and the occurrence of days when the expected lapse rate of around −6.5 °C km−1 is seen, the daily minimum temperature can be significantly higher than at Calver. All seasons show these low valley minima, with the summer having the most spread-out normal distribution. The winter has nights where High Bradfield–Calver minima differences most match those expected from pure lapse rate hilltop cooling. The implication of the combined results shown in Figures 3 and 4 is that the frequent cool anomalies at Calver are not a reflection of a night time urban heat island over Sheffield, but strongly suggestive of cold air drainage.

This conclusion is confirmed by examining the relationship between Weston Park–Calver and High Bradfield–Calver temperature differences. Table 1 shows the correlation for both minima and maxima for each season, and Figure 5 depicts this graphically for the summer season. In all cases the correlations are statistically significant to better than the 0.1% level, except for summer minima, where the scatter (Figure 5) is larger, and statistical significance is reduced to the 1% level. Note that, for the minima differences, most of the data points lie in the top right quadrant, as in the summer example illustrated (Figure 5). This suggests that cold air drainage...
Figure 4. Histograms showing the frequency distribution of temperature difference, scaled by seasonal standard deviation, between High Bradfield and Calver for (a) winter, (b) spring, (c) summer, (d) autumn.

Table 1. Table of correlations between Bradfield–Calver and Weston Park–Calver temperatures.

<table>
<thead>
<tr>
<th>Season</th>
<th>Maxima</th>
<th>Minima</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>0.87</td>
<td>0.59</td>
</tr>
<tr>
<td>Spring</td>
<td>0.88</td>
<td>0.55</td>
</tr>
<tr>
<td>Summer</td>
<td>0.82</td>
<td>0.54</td>
</tr>
<tr>
<td>Autumn</td>
<td>0.58</td>
<td>0.53</td>
</tr>
</tbody>
</table>

The raw data are in terms of the seasonal standard deviation.

A number of papers expect calm, clear, anticyclonic conditions to be necessary (Iijima and Shinoda, 2000; Mahrt et al., 2001; Whiteman et al., 2004; Chung et al., 2006), so this is the starting hypothesis.

For an overview of synoptic conditions, each day was classified according to its Lamb weather type (Barry and Chorley, 2003), using synoptic maps from midnight. The moor-top winds at High Bradfield were compared with the Lamb classification, to evaluate the local relevance of this UK-scale classification. The Lamb type directions, (N, NE, E, SE, S, SW, W, NW) were converted to degrees and plotted against the High Bradfield average hourly wind direction data for midnight on the significant extreme cold air drainage days (that is, days when the Weston Park – Calver minimum temperature difference was more than one standard deviation above zero).

In all seasons, there was a statistically significant correlation, supporting the use of the Lamb classification to represent prevailing wind conditions in the local free troposphere.

For each season, the relative frequency of Lamb classifications during significant extreme cold air drainage days was compared to that for all days using a $\chi^2$ test. For no season was there a statistically significant difference between the Lamb classification sets (Table 2). Thus, unlike some previous studies, in the upper Derwent Valley there is no clear subset of synoptic conditions associated with cold air drainage events.

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Wind strength, or the lack of wind, was another indicator in previous literature for cold air drainage (Clements et al., 2003). A $t$-test was carried out to compare the mean wind speed at Weston Park for each season against the mean wind speed for just the significant extreme days in that season. In each season, there was no statistically significant difference in the means (Table 3). In this location, therefore, there is no...
tendency for cold air drainage to occur preferentially on calm nights, although the sheltered nature of the site tends to reduce wind speeds locally on most occasions. Note that Gustavsson et al. (1998) showed that sheltering in complex terrain encouraged faster rates of cooling. Similarly, t-tests for each season, for differences in mean total cloud cover (from the ECMWF

Interim Analysis at 0600 UTC daily during this period for the nearest gridpoint to Calver) for days with extreme cold air drainage showed no link between low cloud cover and cold air drainage (not shown). This is in contrast to Steinacker et al.’s (2007) experiments in a high altitude limestone sinkhole in the Alps.
3.3. Transects and GIS analysis

A series of transects was driven over the path shown in Figure 1 during the summers and autumns of 2009 and 2010. The altitude change along these transects is shown in Figure 2(b). Detailed description of the links between individual hollows and cold air drainage will be the subject of a later paper, but here three examples of the broad scale patterns that typify different regimes that were encountered are presented. These are a pure cold air drainage event (Case a), a transect showing a mix of weak cold air drainage in rural areas with an urban heat island in Sheffield (Case b), and a third pattern where little change is seen apart from the expected altitude effects and a slight urban heat island in central Sheffield (Case c). The temperature transects for these three cases are shown schematically in Figure 6(a–c) respectively, and summaries of the weather and synoptic situations in Table 4. All data in these figures show a temperature relative to the outward transect’s
It has been seen here that cold air drainage is an ubiquitous feature of the microclimate of the Peak District of central England, with sometimes quite strong cooling, exceeding 5 °C, observed throughout the year. The summer–autumn half of the year shows the most frequent and pronounced examples of this phenomenon. This cooling can, on occasion, be sufficient to overcome the Sheffield urban heat island effect in the valleys of western Sheffield, which drain off the high moorland landscapes of the Peak.

It has been shown that, in this area, the occurrence of cold air drainage is not statistically related to any particular characteristic of the large-scale flow, whether synoptic condition, winds or early morning cloudiness are considered, although there are clear indicative differences between synoptic conditions at the times of the spatial transect case studies presented in Section 3.3. However, clear skies for some period of the night must be needed for hilltop cooling to occur and cold air to drain into the relatively deep valleys of the area. It has not been possible to test this hypothesis, although it is shown here that the early morning is not the key time of the night for clear skies leading to cold air drainage.

The central point of this study, Calver, is surrounded by plateaux and hills of similar height, but also complex valley structures reflecting the contrasting geology of the area. The western side of the Derwent valley in this area is basically limestone, while the eastern side is much less porous sandstone. Erosional features, vegetation and soil moisture levels are therefore rather different across the local area. However, the dominant characteristic determining the degree and extent of cold air drainage appears to be the presence of hollows in the landscape, on the scale of a kilometre or so, with adequate highland drainage. Figure 6(a) shows this well, and was one of a number of transects with very similar results. Work is underway to explore the links of both occurrence and relative severity of cooling to these hollows, in order to better understand the physics of these events, and ultimately improve models that will be of use for adaptation to local climate change.

Acknowledgements

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4. Discussion and conclusions

It has been seen here that cold air drainage is an ubiquitous feature of the microclimate of the Peak District of central England, with sometimes quite strong cooling, exceeding 5 °C, observed throughout the year. The summer–autumn half of the year shows the most frequent and pronounced examples of this phenomenon. This cooling can, on occasion, be sufficient to overcome the Sheffield urban heat island effect in the valleys of western Sheffield, which drain off the high moorland landscapes of the Peak.

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Table 4. Weather and synoptic data for cases shown in Figure 6.

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>Lamb weather type</th>
<th>Calver minimum (°C)</th>
<th>Weston Park minimum (°C)</th>
<th>Bradfield minimum (°C)</th>
<th>Bradfield wind speed (kn)</th>
<th>ECMWF 0600 cloudiness (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>4 September 2010</td>
<td>Anticyclonic</td>
<td>9.0</td>
<td>8.9</td>
<td>NA</td>
<td>5</td>
<td>60</td>
</tr>
<tr>
<td>b</td>
<td>13 August 2009</td>
<td>Anticyclonic</td>
<td>9.9</td>
<td>11.7</td>
<td>9.5</td>
<td>7</td>
<td>70</td>
</tr>
<tr>
<td>c</td>
<td>17 August 2009</td>
<td>Westerly</td>
<td>9.4</td>
<td>14.5</td>
<td>11.8</td>
<td>16</td>
<td>50</td>
</tr>
</tbody>
</table>

High Bradfield temperature data was not available for part of 2010, due to facility repair.

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