

# The International Journal of Meteorology

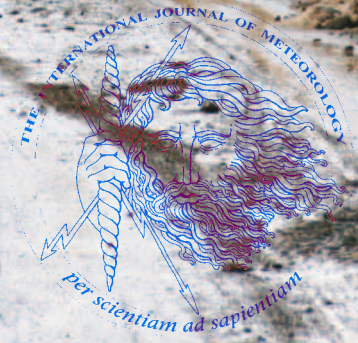
[www.ijmet.org](http://www.ijmet.org)

Volume 36, number 359

April/May 2011



Hailstorm Damage Survey Results, UK  
Solar Irradiation and Temperatures in Botswana  
TORRO Tornado and Thunderstorm Reports





# The International Journal of Meteorology

Editor-in-chief: SAMANTHA J. A. HALL (B. A. Hons)  
[sam@ijmet.org](mailto:sam@ijmet.org)

April/May 2011, Vol. 36, No. 359

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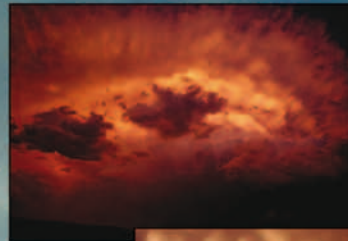
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## THE INTERNATIONAL JOURNAL OF METEOROLOGY

Published in association with The Tornado and Storm Research Organisation (TORRO)  
a privately supported research body, serving the international public interest



www.ijmet.org is sponsored by Simply Mail Solutions  
www.simplymailsolutions.com

Editor-in-chief: Samantha J. A. Hall, International Editorial Office, 20 Massey Avenue,  
Lymm, Cheshire, WA13 0PJ, United Kingdom  
sam@ijmet.org / editorial@ijmet.org

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Please note that for universal citation purposes the recommended abbreviation for **The Journal of Meteorology (ISSN 0307-5966)** was *J. Meteorology, UK*. The recommended abbreviation for **The International Journal of Meteorology (ISSN 1748-2992)** is *Int. J. Meteorology, UK*.

**The International Journal of Meteorology is a non-profit making research periodical. Donations and bequests are always gratefully welcomed and go towards expanding the publication and supporting valuable research and awards in the field of severe weather and climate.**

Published by Artetech Publishing Company, UK.

ISSN 1748-2992

## THE 'OTTERY ST MARY' HAILSTORM OF 30 OCTOBER 2008: DAMAGE SURVEY RESULTS AND EYEWITNESS ACCOUNTS

By MATTHEW R. CLARK

TORRO; IJMet Feature Writer, IJMet, 20 Massey Avenue, Lymm,  
Cheshire, WA13 0PJ, U.K.

([matthew@ijmet.org](mailto:matthew@ijmet.org))

**Incident:** Excessive Hailstorm

**Incident Location:** Ottery St Mary, UK

**Investigated by:** Matthew Clark

**Date of Incident:** 30-31 October 2008

**Date of Investigation:** 1 November 2008

**Abstract:** During the early morning of 30 October 2008 an intense local storm produced significant flash flooding and large accumulations of hail within a small part of East Devon. This damage was documented by way of several surveys undertaken between 12 hours and 10 days after the storm. Further information was available in the form of eyewitness accounts, which were kindly offered by local residents following an appeal for information. The worst flood damage occurred within a 5 km swathe along the lower western slopes of the Otter Valley between Fairmile in the north and Metcombe in the south, including western parts of the town of Ottery St Mary. Transportation and deposition of hail by floodwaters resulted in deep deposits of hail in places, most notably on the west side of Ottery St Mary. Some of these deposits exceeded 1 metre in depth and persisted for more than a week after the storm. Using a combination of eyewitness information and measurements of residual, un-drifted lying hail depths made during the damage surveys, a map of estimated maximum level hail depths over the worst affected area is constructed. Maximum level hail depths of 20 – 25 cm occurred within an area of less than 1 km<sup>2</sup>, centred on the west side of the Otter Valley between West Hill and Ottery St Mary. Hail depths of 2 – 5 cm or more occurred within a larger, though still narrow, southwest – northeast orientated swathe of maximum width ~5 km. The distribution of hail depths appears to correspond well to the spatial distribution of precipitation totals as inferred from radar data.

**Keywords:** hailstorm, flash flood, TORRO, damage survey, Devon.

## INTRODUCTION

Between 0000 and 0300 UTC on 30 October 2008 intense, localised thunderstorms occurred over a small part of East Devon. Flash flooding caused extensive damage to property, highways and farmland within a highly localised area centred close to the town of Ottery St Mary. Deep accumulations of hail occurred which apparently augmented flooding by preventing the free drainage of water. Around 200 mm of precipitation is estimated to have fallen within three hours (Grahame *et al.*, 2009). The meteorological factors leading to this exceptional storm have been investigated by Clark (2011). To summarise, the storm occurred along the rear edge of an occlusion which moved southeast and then became slow moving over southwest England. During this period an upper level cold pool approached the area, resulting in steepening lapse rates and increased instability. Convection initiated along the occlusion and then became focussed by strong low-level convergence associated with a deepening, mesoscale surface low pressure area. The mesolow became slow moving over East Devon, leading to intense rain- and hail-fall of exceptional duration within the worst affected area.

The purpose of this report is to present information which has been provided by eyewitness accounts of the storm. The collective findings of multiple damage surveys conducted between 12 hours and one week after the event are also presented, together with a selection of photos illustrating the damage. Figure 1 shows a map of the worst affected area, including locations of the towns, villages and hamlets mentioned in the main text.

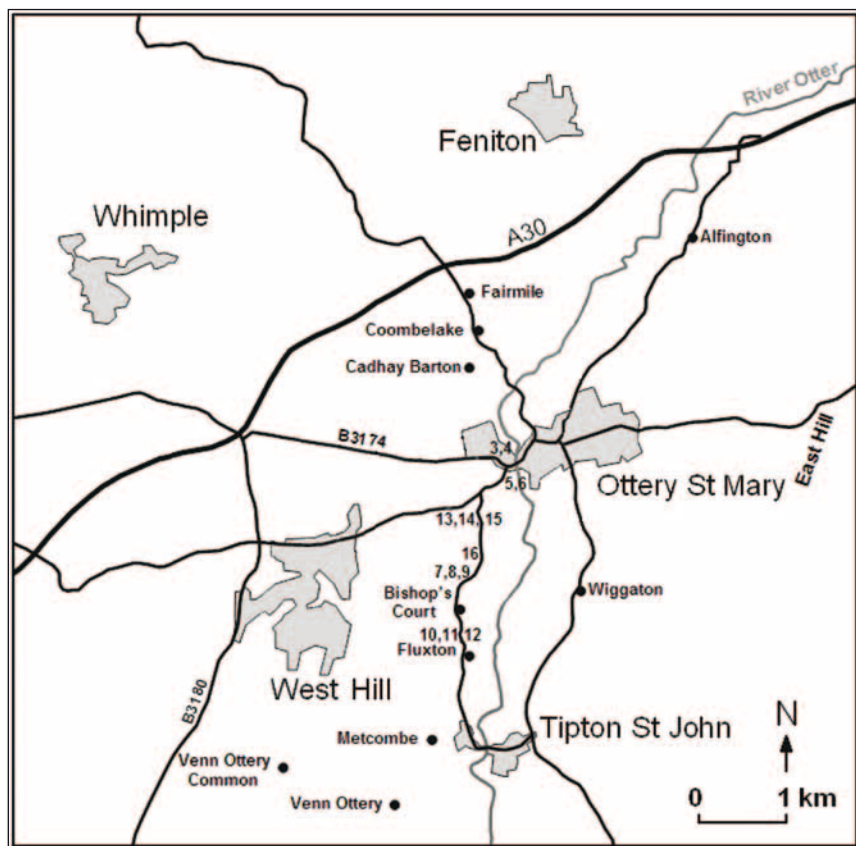


Figure 1. Map of Ottery St Mary and surrounds. Locations of towns, villages and hamlets mentioned in the main text are given. Locations at which the photographs comprising Figures 3 – 16 were taken are shown by the corresponding numbers.

#### EYEWITNESS ACCOUNTS

An appeal for information produced several detailed eyewitness accounts of the storm, from individuals located both within the worst affected areas and in surrounding areas. Witnesses were asked a standard set of questions, in order to highlight similarities and differences in observational accounts of the storm in different localities. Witnesses stated that rainfall occurred at times during the evening of the 29th October, some of which was heavy, though not unusually so. It is clear that the initial development of deep convection commenced in the late evening, between 2300 UTC on the 29th and 0000 UTC on the 30th. Most witnesses who were awake prior to the storm's arrival state that lightning was first observed around 2300 to 2345 UTC.

In the area around West Hill and Ottery St Mary, the heaviest rainfall appears to have commenced within approximately 30 to 60 minutes of the first observed lightning, generally between about 0000 and 0045 UTC. Hail appears to have commenced at a similar time to the very heavy rainfall. For example, in Ottery St Mary 'plenty' of hail was falling by 0030 UTC. In Feniton, hail commenced just after midnight, but was sporadic until about 0045 UTC. Over much of the affected area, the hail and rainfall appears to have reached a peak in intensity at around 0100 or 0130 UTC. Eyewitnesses unanimously stated that the hail was mixed with rain, and at no time did hail appear to fall without rain. In Feniton, continuous intense hail with rain fell for approximately 1.5 hours, ending 0215 UTC. A further 1 hour of torrential rainfall occurred after cessation of the hail. In Ottery St Mary, torrential rain and hail occurred for at least 1.5 hours (probably nearer 2 hours), ending at approximately 0200 UTC. Although no direct measurements were made by the eyewitnesses interviewed, the hail was thought to be of a 'normal' size, with no indication that unusually large hail had occurred. This is in agreement with the results of measurements of hailstone diameter conducted during damage surveys after the event (see below).

Available eyewitness accounts reveal that accumulated hail depths varied widely even within the small area affected by the worst flooding. For example, an observer in the north of Ottery St Mary estimated between 3 and 5 cm of hail accumulated on most open surfaces. Another observer in the western part of the town gave a maximum depth of 8 cm. In Wiggaton, located approximately 2 km south of Ottery St Mary, hail formed a thin covering on most objects, but did not accumulate to more than 1 cm depth at any time. Over eastern parts of Ottery St Mary, eyewitnesses suggested that no significant accumulation of hail occurred, though some hail fall was reported. Not more than 2 km further east, towards East Hill, no hail was observed throughout the duration of the event. Accumulated hail depths were difficult to estimate in Feniton, since much of the hail at the observer's location was carried away by water as soon as it fell. A separate report later received from a resident of West Hill suggested hail accumulations exceeded 20 cm at that location.

Another interesting feature of this storm was the lightning activity, which appears to have been unusually intense and long-lived given the time of year. Eyewitness accounts are very consistent in suggesting that the large majority of lightning discharges were intra-cloud. However, occasional cloud-to-ground discharges also occurred which may have contributed to the power outages experienced in some locations. More than one observer commented that many flashes were composed of several discharges, creating a flickering effect. All eyewitnesses in the worst affected areas described the thunder as being unusually loud, being sufficient to cause sensible vibrations in Ottery St Mary and Wiggaton. The vivid brightness of the lightning flashes was also remarked upon by observers in these locations, whilst an observer in Feniton remarked upon the apparent power of the cloud to ground strikes. Most of the above observations can be at least partly explained by the fact that the lightning was very close to the observer, though it should be noted that even overhead (i.e. <5 km distant) lightning discharges do not always produce such effects (particularly so in the case of intra-cloud lightning). In general the lightning frequency was estimated to have been between 0.5 and 2 discharges per minute. Frequency was observed to decline from about 0215 UTC in Feniton. However, in Wiggaton, the lightning activity appears to have reached a peak around 0200 UTC, with more than one extremely close ground strike around this time, and a frequency of around three discharges per minute. An observer near Fluxton, also towards the southern limit of the area worst affected, described the lightning as frequent for a time, with near continuous thunder at one point. In Wiggaton, the lightning was observed to approach from the south and recede to the north. Conversely, in Feniton, the first flash observed was more or less directly overhead, and there was no obvious movement of the storm or storm cells.

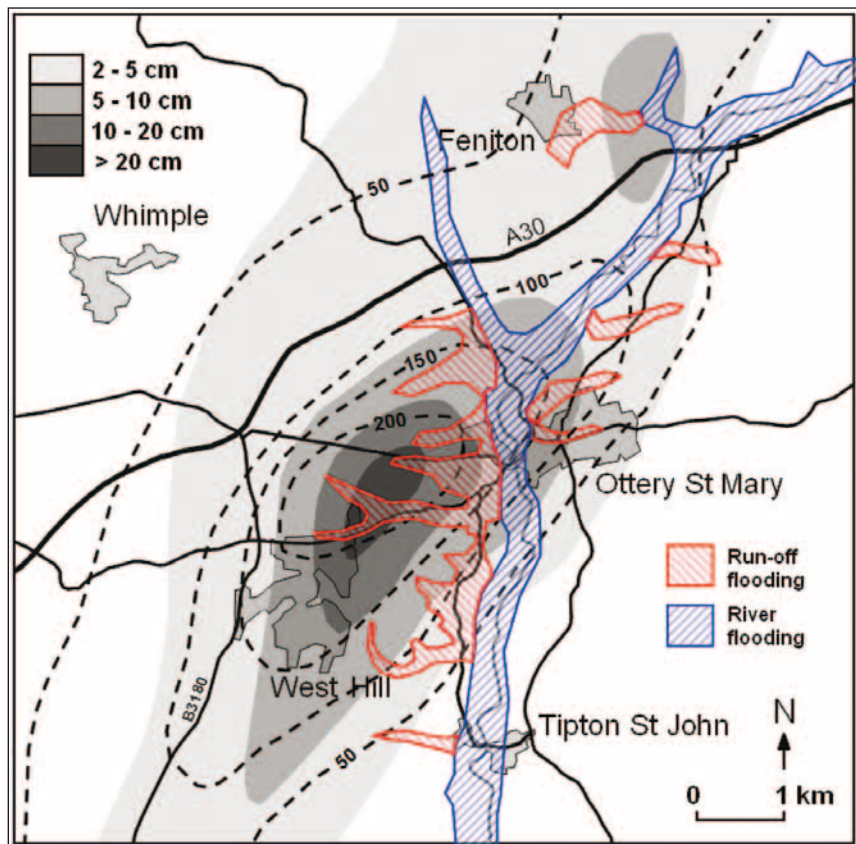


Figure 2. Map showing estimated distribution of maximum level hail depth over open ground (shading) and radar estimated rainfall accumulations in mm (dashed lines) within the Otter St Mary area. Note that the radar estimates are likely slightly higher than reality, owing to the strong returns associated with hail and assumptions made in the derivation of equivalent rainfall rates. Locations affected by the more extensive hail deposits, surface run-off and small stream flooding are shown by red hatching. Locations affected by river flooding are shown by blue hatching.

A number of other observations are worth noting. Firstly, rainfall amounts appear to have decreased rapidly to the east of Otter St Mary. Much flooding occurred in the middle to lower sections of the streams located on the east side of the Otter Valley near the town. However, at locations nearer to East Hill, signs that usually accompany particularly heavy rainfall events were noted by one observer to be absent, suggesting that the rainfall was not exceptional here. This agrees well with the distribution of radar observed rainfall totals (see Figure 2). The distribution of flood damage is discussed further in subsequent sections. Secondly, the majority of observers noted that almost calm conditions accompanied the heaviest hail and rainfall, with precipitation falling vertically. However, the eyewitness in Wiggaton, close to the southern edge of the worst affected area, commented that noticeably windy conditions accompanied the storm, with winds from an approximately southerly direction. Available wind data are largely consistent with these observations; for example at Feniton, southeasterly winds reached a peak of 11 knots around 0045 UTC.

Winds then backed towards northeasterly and declined to between 3 and 5 knots for the remainder of the duration of the storm, before increasing again after the storm dissipated. At stations to the south and east of the storm, the wind direction appears to have been more constant through the duration of the event, and from the southeast. At the Norman Lockyer Observatory in Sidmouth, located 8.5 km south-southeast of Otter St Mary, the mean speed remained between 8 and 11 knots from 2300 UTC to 0400 UTC, with gusts as high as 33 knots. These observations suggest a reasonably strong inflow to the storm, likely associated with the strong pressure gradients along the southeastern flank of the mesoscale area of low pressure within which the storm occurred (Clark, 2011).

#### DAMAGE SURVEYS

Several surveys of the area were undertaken between 12 hours and 10 days after the event. The first survey, which was undertaken between 1200 and 1300 UTC on the 30th October, included locations on the northern and western fringes of the worst affected area, including the B3180 running close to West Hill and locations near to the A30 between Whimble and Honiton. At this time, access to the worst affected areas was not possible due to road closures and the limited time available for surveying. The second survey was conducted from 0600 to 0900 UTC on the 31st October (i.e. 30 hours after the event). This was conducted on foot, since vehicular access to the worst affected areas was still not possible. A detailed survey of approximately 4 or 5 km<sup>2</sup> was conducted, predominantly on the west side of the Otter Valley, from Fairmile southwards to Fluxton, including western and central parts of Otter St Mary. All of the photos presented herein were taken during this survey. The third survey was conducted on the 1st November between 1300 and 1600 UTC. Remaining areas, including the eastern side of the Otter Valley, eastern Otter St Mary, West Hill, Tipton St John, Feniton and Newton Poppleford were surveyed at this time. Further smaller surveys were subsequently conducted, but the large majority of the evidence presented here was collected during the first three surveys.

#### Distribution of maximum level hail depths

Figure 2 shows the estimated distribution of maximum level hail depths over the affected area. This was constructed using a combination of eyewitness estimates of maximum level depths during and immediately after the storm (as discussed in the previous section), and surveys undertaken after the storm in which the remaining hail depth and its spatial distribution was documented. Comparison of the remaining hail depths at various times with the eyewitness reports, where both were available, allowed some approximate measure of melting over the intervening periods to be determined, from which the approximate distribution of maximum accumulations over the whole area could be reconstructed. Newspaper reports of hail depths were not found to be reliable, since the depth of waterborne hail drifts was often quoted as the level depth of hail fall. True level depths were significantly less than these values, though accumulations can nevertheless be described as exceptional in the worst affected areas. A number of assumptions have necessarily been made in the analysis of hail depth distribution. For example, it has been assumed that melting rates during and after the storm were nearly uniform throughout the area surveyed. In practice, several factors may lead to local variations in melting rates. For example, aspect could have a significant effect, though given the north-south orientation of the Otter Valley, differences across the area of interest should be minimised. Where possible, remaining hail depths were only measured over level, open grass surfaces. Altitude may also have had a small effect on post-storm melting rates, though altitude differences across the whole area surveyed do not amount to more than 120 metres.

Eyewitness estimates of level hail depths are also subject to potentially substantial errors. Nevertheless, the map (Figure 2) represents the best possible estimate of depths using the information available.



Figure 3. Looking east from the B3174 at the Finnimore Industrial Estate. Some clearing of the hail had taken place but the area in the foreground shows relatively undisturbed deposits, still considerably more than 30 cm deep, 30 hours after the storm occurred.

The evidence collated suggests that the greatest hail fall occurred within a small area stretching northeastwards from eastern parts of West Hill towards the western fringes of Ottery St Mary and points just to the west (Figure 2). Accumulations exceeding 20 cm occurred over an area of slightly less than 1 km<sup>2</sup>. Accumulations of over 10 ± 3 cm appear to have occurred over an area approximately 3 km<sup>2</sup> in size. Accumulations of 5 ± 2 cm occurred over an elongated oval approximately 15 km<sup>2</sup> in size, whose long axis was orientated approximately southwest to northeast. Smaller, though still notable, accumulations (i.e. 2 ± 1 cm or more) occurred over a larger swathe which was 5 km wide at its widest point. Some idea as to the quantity of hail which accumulated is given by the fact that partial to near-complete cover of hail remained in areas to the west and southwest of Ottery St Mary at the time of the second survey, 30 hours after the event. At locations close to the northeast edge of West Hill, a nearly complete cover remained even at the time of the third survey, 2.5 days after the event. Further afield, some hail fall was reported to have occurred as far northeast as Awliscombe and even Dunkeswell, but no significant accumulations are known to have occurred outside of the area delineated in Figure 2.

#### Hail characteristics

The persistence of extensive deposits of hail for several days after the event provided opportunity for analysis of the hail size and its distribution within the affected area. On the edges of the deposits hail tended to melt slowly, refreezing occasionally overnight, which led to the development of quite solid crusts. However, within the drifts, minimal melting and re-freezing occurred as evidenced by the fact that individual stones were not frozen together, and the deposits were quite un-compacted, even two to three days after the event. This is presumably a consequence of the insulating properties of the hail deposits.



Figure 4. Looking north along the B3174 at the Finnimore Industrial Estate.

The stones were placed in a straight-sided, flat bottomed container without compaction to a depth of 15 cm. The hail was then allowed to melt, resulting in a water depth of around 10 cm. This suggests a hail to water volumes ratio of 3:2. Applying this to the maximum level hail depth, which was likely to have been around 25 cm, suggests a precipitation total of 167 mm. In practice, this represents a minimum value, since the eyewitnesses all stated that hail was mixed with rain as it fell (though it should be noted that no observations from within the area of largest hail accumulations, where the hail may have comprised a larger fraction of the total precipitation, were available). Partial melting of hail during the storm as it accumulated may also have resulted in some underestimation. Nevertheless, this value agrees reasonably well with estimates derived from combinations of radar and rain gauge data (Graham *et al.*, 2009; Clark, 2011) which indicated a maximum storm total of around 200 mm (also see Figure 2).

#### Waterborne hail deposits

The most striking aspect of the aftermath of this storm, and that which probably attracted the most media attention, was the presence of deep and sometimes extensive deposits of hail which occurred in a remarkably localised area, including western parts of Ottery St Mary. The largest of these deposits evidently occurred in areas where floodwater had carried large quantities of hail in from surrounding higher ground, and in particular where the floodwater had subsequently pooled before subsiding.

Samples were taken at two locations: on the western edge of Ottery and St Mary, at the northeastern edge of West Hill. The distribution of sizes appeared remarkably constant in each of the two samples. The hail was generally small, at around 3 – 5 mm in diameter. However, widely scattered larger stones of up to 8 – 9 mm in diameter were also found. Allowing for the effects of some slight melting immediately after falling, the maximum diameter was probably around 10 mm. Therefore although copious quantities of hail fell, the hailstone size did not meet 'severe' criteria (i.e. diameter ≥ 20 mm). The hail was generally translucent or transparent, with an opaque core visible in some of the larger stones. The shape of stones was generally very nearly spherical. These characteristics suggest that the deposits were composed of 'true' hail, not graupel (sometimes called 'soft hail') though it is possible that graupel may have formed the opaque cores of some of the larger stones.

An estimate of the water equivalent of the hail was made by taking a sample of loose, un-compacted stones from deep within a deposit located at the western edge of Ottery St Mary.



*Figure 5. Looking southeast at the western edge of the River Otter floodplain, immediately southwest of Ottery St Mary.*



*Figure 6. Accumulated hail confined to a track running across the River Otter floodplain, immediately southwest of Ottery St Mary.*



*Figure 7. Looking south along the unclassified north-south road, just north of Bishop's Court, close to the foot of the western slopes of the Otter Valley.*

As a result, these deposits could typically be found near small streams, especially where they approached and flowed out onto the flood plain of the River Otter, and immediately upstream of culverts and small bridges (e.g. where crossing under roads). Deep deposits also frequently occurred on the upslope sides of hedges and walls, even away from the courses of streams, and in any hollows on minor roads, particularly those adjacent to field gates and other openings in the hedges and banks bordering the fields.

Photographs of the deposits and other damage were taken during the second survey on the 31st October, a selection of which is presented in Figures 3 – 16. The location at which each photograph was taken is shown in Figure 1. The most extensive of the hail deposits occurred around the Finimore Industrial Estate and in the Thorne Farm Way neighbourhood, located in the western part of Ottery St Mary. This area appears to have been particularly afflicted since floodwaters flowed into the area from several sources. The area is situated on the floodplain to the west of the River Otter, and appears to have been inundated by at least 30 cm and possibly up to one metre of floodwater during the storm, primarily due to flooding of the River Otter itself. Some hail may have been transported in by this floodwater. Of significance, a small stream also runs through the middle of Thorne Farm Way (the street forms a closed loop). This stream rises on the upper slopes of the west side of the Otter Valley, approximately 1.5 km west of Thorne Farm Way, reaching the floodplain just below Thorne Farm, at the western edge of the neighbourhood. The stream then flows south along the floodplain after passing through Thorne Farm Way, and along the western and southern edges of Finimore Estate before reaching the River Otter. It is likely that a large volume of hail was transported into the area by this stream; the hail probably accumulated where the flow decreased as the swollen stream waters met the floodwaters of the River Otter. The B3174, which runs down the western slope of the Otter Valley for approximately 3 km, turns southeast on meeting the floodplain and also forms the western edge of the Finimore Estate. This road also carried a great deal of runoff during the storm. Along much of the final kilometre of its descent, the road is situated within a steep cutting, which must have augmented the volume of water and hail which collected and flowed downhill. Numerous small landslides occurred along the embankments situated along this stretch of the road. A significant amount of waterborne hail is likely to have been transported in by floodwaters following the road, again collecting where the fast flowing water met the more extensive floodwater on the floodplain, at the Finimore Estate. The final result appears to have been a rather stagnant, thick layer of hail which floated partially within and partially on top of the floodwater. When the floodwaters subsided, between 30 and 60 cm of somewhat compacted hail was left over much of the area (Figures 3 and 4).

Similar (though less extensive) deposits were observed at prone locations all along the lower slopes of the western side of the Otter Valley, primarily between Fairmile in the north, and Metcombe in the south. There are too many to describe individually.

*Figure 8. Looking northeast, across the unclassified north-south road just north of Bishop's Court.*



However, several of the deposits observed at other locations warrant special mention. Firstly, approximately 0.25 km south of the Finnimore Industrial Estate, a small track runs southeast from the unclassified road which runs southwest from Ottery St Mary towards West Hill. The entrance to this track is located at the base of the west slopes of the Otter Valley, and runs out along the floodplain. Hail deposits of between 30 and 60 cm depth were present along the entire length of this track, which is over 150 metres, starting at the roadside (Figure 5). It is likely that the hail had also accumulated on the road, but had been ploughed away prior to the time of the survey. The remaining hail was restricted almost entirely to the track (Figure 6), which strongly suggests that it had been carried by floodwater flowing along the track. The most likely source is runoff from the adjacent road and fields on the lower slopes of the valley (a gate leading from these fields is located across the road directly opposite the entrance of the track photographed).



*Figure 9. looking south over fields just north of Bishops Court. The debris on top of the gate show that the floodwaters must have been over 1.2 metres deep at their height. Note the large accumulations of hail on the upslope side of the hedges bordering the road, on the far left of the photo. The larger rocks exposed in the field were at least 30 cm long.*

Secondly, deep hail deposits occurred along the unclassified road which runs south towards Fluxton, at a location just north of Bishop's Court. A small gated track runs east-west through farmland to the west of the road, terminating on meeting the road. The track is situated in a small trough, but a stream does not normally occupy this. An enormous quantity of mud, silt and rocks had been washed down the track and out onto the road, where it extended along the road to the north and south (Figure 7).



*Figure 10. Looking south at the northern edge of Fluxton, showing extensive deposits of mud, sand, gravel and stones along the roadside.*

*Figure 11. looking northwest at the northern edge of Fluxton. Water has evidently flowed over the top of the hedge into the lane, whilst debris and hail have accumulated on the upslope side of the hedge.*



Additionally, a large volume of hail flanked the deposits of mud, particularly just to the north of the track entrance, extending for perhaps 50 metres along the road. Again, these deposits must have extended across the road, but had been ploughed out of the centre of the road before the survey was conducted. This had increased the depth of the deposits in places, though on the east side of the road to the north of the gate the deposits appeared largely undisturbed. Here they were up to one metre deep, being



*Figure 12. Looking southeast from the unclassified road just north of Fluxton. Note the section of hedge and supporting earth bank which has been removed by the floodwaters.*

level with the top of the hedge on the east side of the road (Figure 8). Within the field to the west of the road, which was at this time recently ploughed with little or no vegetation, further debris had accumulated, with scouring of the surface clearly visible. Within this area, many rocks of up to 20 – 30 cm diameter appear to have been exposed and transported by the floodwater (Figure 9).

Deep hail deposits were also present on the upslope side of the hedge bordering the road, some of which could still be seen ten days after the storm during one of the subsequent surveys. Similar deposits of mud, gravel and rocks could be observed at a location slightly less than 0.5 km to the south along the same road, just north of Fluxton (Figure 10). Here, water and debris had flowed over the hedge bordering the field to the west of the road, with large quantities of mud, gravel and rocks deposited and further deep deposits of hail just visible in the field to the west (Figure 11).

A small section of hedge on the opposite side of the road had been washed away; the accumulated water and debris had evidently burst through this gap and onto the floodplain below, to the east (Figure 12).

#### *Flood damage*

On the east side of the valley, very little evidence of similar hail deposits could be found, aside from some smaller drifts close to the courses of streams flowing just north of and through Ottery St Mary itself. Conversely, the effects of flooding were clearly apparent along the lower sections of streams on this side of the valley, from Ottery St Mary northwards. For example, floodwater had removed small sections of hedges near one or two streams crossing the B3177 between Ottery and Alington, and flooding of properties was reported to have occurred in Alington itself. On the whole however, the most severe flood damage was restricted to the west side of the valley. Here, severe flooding had occurred along the course of every stream between Fairmile to the north and Venn Ottery to the south. Thick deposits of mud were present along all roads in the vicinity of Coombelake, with properties having been flooded, though curiously there were no signs of hail deposits here at 0600 UTC on the 31st. Immediately north of Cadhay Barton, sand, gravel and rocks covered the road and hail deposits of between approximately 40 and 60 cm had accumulated at the bottom of fields on the upslope side of the earth and hedge boundaries. 0.8 km further south, the road was still flooded where it bridges a stream near Thorne Farm (just upstream of the Thorne Farm Way neighbourhood of Ottery St Mary where some of the most extensive hail deposits occurred) owing to a large build up of sand and silt which was preventing water draining away.



*Figure 13. Looking west towards West Hill, from the lower slopes of the Otter Valley, approximately 0.5 km south of Ottery St Mary. The normal stream course is marked by the boundary between the two fields, where the trees and hedges can be seen.*

*New channels have been cut by floodwaters in the field south of the original course of the stream.*

Arguably the worst flood damage (of that associated with run-off and small streams) was observed along the course of the neighbouring stream to the south. Two streams rise in the vicinity of West Hill, their confluence being just to the northeast of the village, and their valleys straddling the area of highest precipitation and hail accumulations. The single stream then flows east through a small, steep sided valley to join the River Otter approximately 1 km south of the centre of Ottery St Mary.

The damage was viewed from where the stream crosses the unclassified road which runs from Ottery St Mary south to Fluxton. Here, floodwater had engulfed fields on either side of the stream, leaving rocks, bricks and other debris strewn over the fields, and thick deposits of sand and mud, these being over 15 cm deep along the roadside (Figure 13). Residual floodwater flowed through new channels cut in the field, to the south of the original course of the stream, and the road was still flooded where the stream normally passes under, owing to the build up of silt and hail (Figure 14). Flanking this flood-swept area to the north and south, further hail deposits were observed, which were generally between 15 and 30 cm deep, though perhaps deeper than this to the north (Figure 15). Along the road to the north and south of the stream, sections of hedge had been washed away. A small brick wall on the east side of the road bridge had been dislodged and moved slightly downstream. Flooding of property also occurred close to this stream, for example, immediately to the east of the road bridge. Further flooding occurred along the streams which flow through Fluxton, Metcombe and Venn Ottery, with similar deposits of rocks, sand and silt along roads, over 30 cm deep in one or two places (as described previously), though in general the degree of damage appears to have decreased steadily from Fluxton southwards.



*Figure 14. Looking south along the unclassified road to Fluxton, about 0.5 km south of Ottery St Mary, where a small stream crosses under the road. Note the removal of the hedges on the west side of the road close to the course of the stream.*

In addition to flooding near to the courses of streams flowing down the valley side, significant run-off flooding appears to have occurred over larger swathes of land on the west side of the valley between Cadhay Barton and Fluxton. This was evident from the volume of mud and debris that had flowed out of fields onto adjacent roads. In places, water had flowed over the top of earth banks over 1.5 metres high and into adjacent lanes. Numerous small landslides and holes (the latter apparently caused by scouring from water and waterborne debris) were observed along roadsides in this area (Figure 16).

Although the flooding from small streams and that associated with direct run-off caused much of the observed damage, river flooding was responsible for a large portion of the total property damage. These effects extended well beyond the area directly affected by the hailstorm. The approximate area affected by river flooding in the immediate vicinity of the storm is shown by the blue shaded area in Figure 2. Severe flooding occurred along the entire length of the River Otter from Honiton to its mouth at Budleigh Salterton. The peak passed quickly near Honiton and Ottery St Mary. Flooding was much slower to subside at locations further downstream, for example, near Otterton and Budleigh Salterton. Tipton St John was particularly badly affected.



Figure 15. Hail deposits flanking the flood swept area within the valley of the small stream flowing from near West Hill towards the flood plain 0.5 km south of Ottery St Mary.



Figure 16. Damage caused by water flowing out of fields and over the earth banks lining the road running south towards Fluxton on the western side of the Otter Valley. Note the exposed utility pipe. The width of the hole is approximately two metres.

Widespread flooding also occurred along the River Tale which meets the River Otter about 1 km north of Ottery St Mary. Further west, the Rivers Clyst and Culm also flooded heavily, as floodwater drained south and west into areas where very little rainfall had occurred overnight. The West Coast mainline was closed due to flooding of the River Culm at Hele. To the north, some flooding occurred close to the courses of many other streams draining off the Blackdown Hills.

#### HISTORICAL CONTEXT

The nature and severity of the flood damage revealed by the site investigations, the depth of accumulated hail, and the estimated precipitation totals all suggest that the 'Ottery St Mary' storm was an exceptional event. Although a number of other storms producing copious quantities of hail are known to have occurred in the UK, few if any of these appear to have produced level accumulations of comparable depth. Other notable events include the following:

- The storm of 23 May 1975 over mid-Devon, which produced up to 10 cm of un-drifted lying hail in the Chulmleigh area (J. D. C. Webb, *pers. comm.*).
- On 23 July 1972 a thunderstorm produced flash flooding with drifts of hail up to 90 cm deep in the Radford area of Nottingham (J. D. C. Webb, *pers. comm.*).
- On 8 June 1957 an intense storm at Camelford, Cornwall produced 138 mm of precipitation within 2.5 hours, with waterborne hail drifts almost knee deep accumulating in the vicinity (Bleasdale, 1957).
- The Tunbridge Wells storm of 6 August 1956 produced waterborne hail drifts of 0.9 – 1.2 metres in depth over lower lying parts of the town, with level accumulations of hail exceeding 5 cm locally (Booth, 1956).
- During early August 1938, severe thunderstorms produced large hail accumulations in several places, including a reported 10 cm of un-drifted hail at St Marychurch, near Torquay early on the 4th, and drifts to 60 cm depth at Wold Newton, Yorkshire, on the 12th (Douglas, 1938; Glasspoole, 1938).
- The storm of 9 June 1910 produced up to 7.5 cm of level hail at Waterstock, near Oxford. Drifts of 60 – 90 cm could still be seen four days after the event (Mill, 1910; Webb, 2011).
- An intense storm on 22 July 1907 produced drifts of up to 1.5 metres depth on the Monmouthshire – Herefordshire border, some of which could still be seen ten days after the event (Gant and Kennea, 1986).

The description of damage and eyewitness accounts presented by Gant and Kennea (1986) suggest that the storm of 22 July 1907 may have been comparable to the Ottery St Mary storm in terms of the sheer quantity of hail that fell, though maximum level hail depths are not known to allow a direct comparison. A number of other events which produced lesser, though still significant, accumulations of hail have also been documented more recently (e.g. Rodgers, 1980; Mortimore, 1982; Webb, 2009).

#### ACKNOWLEDGEMENTS

Thanks are due to all eyewitnesses who kindly provided information about the storm and meteorological data; in particular, to Chris Wilson and all members of the Norman Lockyer Observatory, Sidmouth, and to Nick Gardner of Feniton. Thanks are also due to TORRO's Jonathan Webb for providing details of other significant hailstorms in the UK.

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# STOCHASTIC CHARACTERISTICS OF SOLAR IRRADIATION AND TEMPERATURES IN BOTSWANA: ARIMA MODELS

J. PRAKASH <sup>1</sup>, E. M. LUNGU <sup>2</sup>, and P. K. JAIN <sup>3</sup>

<sup>1,2</sup> Department of Mathematics, and <sup>3</sup> Department of Physics  
University of Botswana, P Bag 0022, Gaborone, Botswana.

<sup>1</sup> (prakashj@mopipi.ub.bw); <sup>2</sup> (lunguem@mopipi.ub.bw); <sup>3</sup> (jainpk@mopipi.ub.bw).

**Abstract:** This paper presents bivariate models that relate solar irradiation to extreme temperatures for Sebele, Botswana. Autocorrelation analysis revealed that the solar irradiation series is stationary for  $d = 2$  and  $D = 0$ , and the extreme temperatures series are stationary for either  $d = 1$  and  $D = 1$ , or  $d = 0$  and  $D = 1, 2 \dots N$ . A lag of three months is found between the peaks of the differenced series of solar irradiation and maximum temperatures, whereas there is a lag of at most one month between the differenced series of solar irradiation and minimum temperatures. Analysis of the noise component revealed that the bivariate processes under consideration behaved either as ARIMA processes of order  $(0, 1, 1) \times (0, 1, 1)12$  or as MA processes of order  $(0, 1, 1)12$ . However, where non-seasonal influences are present, i.e., in the case of model  $(0, 1, 1) \times (0, 1, 1)12$ , these effects exhibit month to month memory only. The relationships found for Sebele can be applied to estimate extreme temperatures at other locations in the region, where similar climatic conditions prevail.

**Keywords:** solar irradiation, temperatures, arima models, bivariate models, Botswana.

## INTRODUCTION

Extreme temperatures influence our lives through thermal comfort or discomfort, through their influence on the agricultural and industrial sectors, water loss due to evapotranspiration, condensation, precipitation etc. In Botswana, water loss per annum due to evapotranspiration is estimated to vary from 1950 mm in the south to 2150 mm in the north, while the annual rainfall ranges from 250 mm in the south-west to 650 mm in the north-east (Balhotra (1987), SMEC (1987)). Planning for the reduction in water loss from evapotranspiration requires, among other things, a reliable database of extreme temperatures over a long period. In Botswana, it is mostly clear with very little cloud cover, very low humidity and insufficient rainfall, and the extreme temperatures appear to be related to solar irradiation. The object of this study is to derive relationships, if any, between solar irradiation and extreme temperatures for Botswana using autoregressive integrated moving average (ARIMA) modelling techniques (Box and Jenkins, 1970; Lungu and Sefe, 1991; Jain and Lungu, 2002) which could be applied for simulating extreme temperatures where measured data is not available for sufficiently long periods.

## METEOROLOGICAL DATA USED FOR THE STUDY

For this study we have used daily solar irradiation, and extreme temperatures data for Sebele (latitude:  $24^{\circ} 34' S$ ; longitude:  $25^{\circ} 57' E$ ; altitude 994 m), the oldest Agricultural Research Station in Botswana, 10 km north-east of the capital city Gaborone. Sebele is a good representative of climatic conditions in Southern Africa that include most parts of Botswana, northern part of South Africa, western Zambia, western Zimbabwe, and south-east Namibia. Mean monthly averages of solar irradiation for 17 years (1976 to 1992), and mean monthly averages of maximum and minimum temperatures for 25 years (1976 to 2000) are used to understand the characteristics of, and to fit univariate ARIMA models to these series.

However, to study bivariate relationships between solar irradiation and extreme temperatures, data series for an overlapping period of 17 years (1976 to 1992) are used. With less than 2 % missing data points, all data sets used are considered to be reliable.

**THEORETICAL FRAMEWORK**

The daily measured data of solar irradiation, and the maximum and the minimum temperatures are reduced to mean monthly series,  $Y_{\alpha t}$  where  $t = 1$  to 12 denotes January to December months, and  $\alpha = 1$  to N denotes the year. It is these series that are used for analysis and modelling.

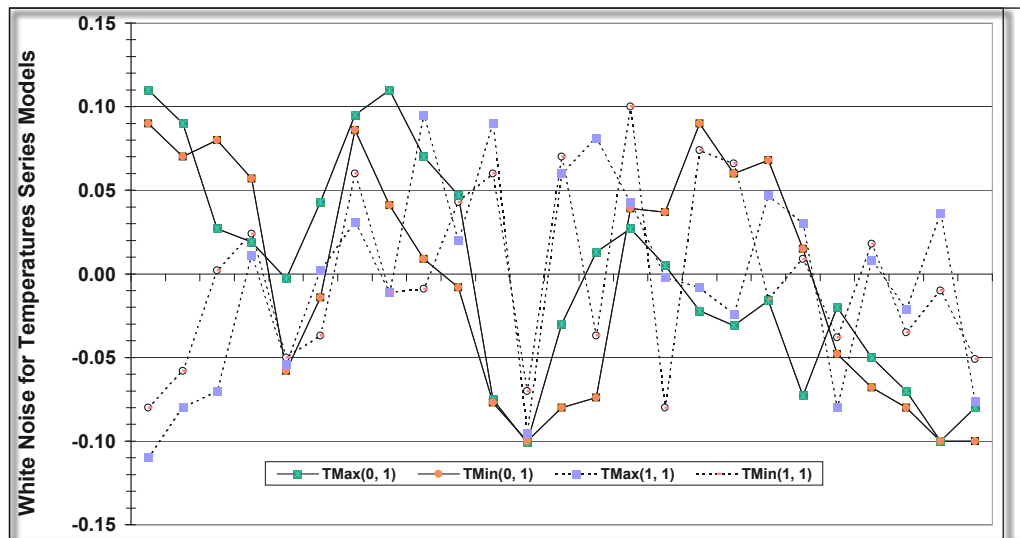


Figure 1. Autocorrelations of the white noise (residues) series for the extremum temperatures models.

**Harmonic Analysis and the Periodic Component**

Since meteorological phenomena are cyclic and stochastic in nature, we can decompose each of the mean monthly series,  $Y_{\alpha t}$ , into a deterministic periodic component  $M_t$  and a stochastic component  $e_i$  as:

$$Y_{\alpha,t} = M_t + e_i \tag{1}$$

where  $i = 1, 2, \dots, m (= 12 \times N)$  is the number of observations, and  $M_t$  are the average monthly values given by average over N years of the  $Y_{\alpha t}$ , series for  $t=1$  to 12 months. The stochastic component  $e_i$  has zero mean and variance  $\sigma e^2$ .

**The ARIMA Models**

The general non-seasonal ARIMA model is autoregressive to order p and moving-average to order q, and operates on the d th difference of  $Z_i$ , where  $\{Z_i\}$  are time series values for  $i = 1, 2, \dots, m$ , and m is the number of observations. The model can be written as:

$$\phi_p(B) \nabla^d Z_i = \theta_q(B) a_i \tag{2}$$

where  $\phi_p$  and  $\theta_q$  are polynomials in B of order p and q respectively, B is the backward shift operator,  $\nabla$  is the difference operator, and  $d = 0, 1, 2, \dots$ , such that  $B s Z_i = Z_{i-s}$ ;  $\nabla s = (1 - B s)$ ; and  $\nabla^d s = (1 - B s)^d$ . s is the period of the season (= 12 for the present case), and  $\{a_i\}$  are the residuals.

If an observation  $Z_i$  of a particular month has some relation with the observation made in the same month of the previous year, equation 2 can be modified (Box and Jenkins, 1970) to account for the seasonal dependence. The general multiplicative seasonal ARIMA model of the order  $(p, d, q) \times (P, D, Q)$  is given as:

$$\Phi_P(B^s) \phi_p(B) \nabla_s^D \nabla^d Z_i = \Theta_Q(B^s) \theta_q(B) a_i \tag{3}$$

where  $\Phi_P$  and  $\Theta_Q$  are the seasonal autoregressive and moving-average operators of order P and Q respectively.

**Bivariate Modelling**

**Correlation Analysis:** To establish the basis for bivariate modelling, the study begins by investigating the correlations between mean monthly solar irradiation (Slrd), maximum temperatures (TMax) and minimum temperatures (TMin). From the correlation matrix (Table 1), solar irradiation is seen to be highly correlated to both the maximum and the minimum temperatures, and it is the bivariate models between solar irradiation and maximum temperatures, and solar irradiation and minimum temperatures that are investigated. Extreme temperatures TMax and TMin are also highly correlated to each other, but their relationship is not investigated further.

**Theory of Linear Transfer Functions:** Suppose there are m meteorological observations on two variables,  $X_t$  (independent variable) and  $Y_t$  (dependent variable) at equispaced intervals of time t (monthly averages in this case). One needs to find the impulse response function  $\{v_k\}$  of the system such that:

$$Y_t = v(B) X_{t-k} \tag{4}$$

where  $v(B) = v_0 - v_1 B - v_2 B^2 - \dots$  is called the transfer function, and  $k = 0, 1, \dots$ , is the delay parameter. In practice, however, the system is infected by disturbances or noise, whose net effect is to corrupt the output predicted by the transfer function model by an amount  $n_t$  so that the combined transfer function noise model (Box and Jenkins, 1970) may be written as:

$$y_t = v(B) x_{t-k} + n_t \tag{5}$$

where  $x_t$  and  $y_t$  are stationary input and output series for some value of differencing d. The Box and Jenkins (1970) pre-whitening procedure involves fitting an ARIMA model to the differenced input  $x_t$  series as a first step. The same transformation which transforms the  $x_t$  series to a uncorrelated white noise series  $a_t$  is applied to the differenced output series  $y_t$  to filter the corresponding white noise series  $\beta_t$ . Next the cross-covariance function of the  $a_t$  and  $\beta_t$  are calculated. The estimates of  $v_k$  so determined are found to be reliable (Box and Jenkins, 1970). Lastly, one identifies appropriate ARIMA models that describe the transformed noise series at the output.

**Harmonic Component of Solar Irradiation**

Harmonic analysis of the monthly averages series ( $M_t$ ) and the mean monthly series ( $Y_{\alpha, t}$ ) of solar irradiation revealed that: (i) For the  $M_t$  series, only the first harmonic is significant as it explains about 91 % of the variance of the series. (ii) For the  $Y_{\alpha, t}$  series the 17th harmonic is the most significant, as it explains about 40 % of the variance of the series (Table 2). Thus for the  $Y_{\alpha, t}$  series the stochastic component  $e_i$  is important as it explains about 60 % of the variance of the series.

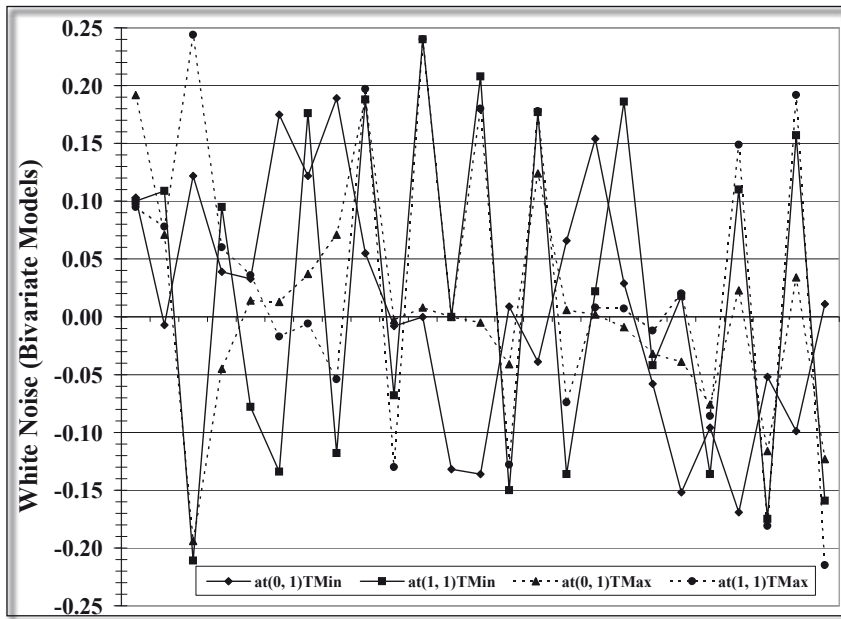


Figure 2. Autocorrelations of the white noise (residues) series for some of the bivariate models.

**Stochastic Component of Solar Irradiation**

Autocorrelation analysis of the stochastic component series,  $e_i$  shows that: (i) For the  $Y_{\alpha, t}$  series of solar irradiation, stationarity is achieved for  $d = 2$  and  $D = 0$ . The autocorrelation functions mimic the autoregressive behaviour. This is confirmed by the partial autocorrelation functions which display the behaviour of a moving average process. (ii) Compared with 95 % confidence limits, few of the partial autocorrelations are significant. (iii) The analysis suggests that  $e_i$  series follow the autoregressive process of order 2. Thus, we obtain:

$$e_i = (\phi_1 B + \phi_2 B^2) \nabla^2 e_i + a_i \tag{6}$$

The  $\phi_{\bullet, j}$  determined as in Box and Jenkins (1970), and given in Table 3 show a higher dependence on the first stochastic component ( $\phi_2$ ). This means that the month to month effects are more important than dependence on past events, i.e. two or more months ago.

The autocorrelation analysis of noise series  $a_i$  shows that: (i) the sequences are normally distributed, (ii) compared with 95 % confidence limits all the autocorrelations of the  $a_i$  series are insignificant, and (iii) the AR(2) model (equation 6) pass the portmanteau statistics test with the portmanteau statistics computed using the first 25 values of the autocorrelations.

Hence, the  $a_i$  series can be considered to be indistinguishable from a white noise sequence. On this basis, it is concluded that equation 6 can be considered to be a valid representation for the stochastic components  $e_i$  for the  $Y_{\alpha, t}$  series of solar irradiation.

**Harmonic Components of Extreme Temperatures**

Harmonic analysis of the monthly averages series ( $M_t$ ), and the mean monthly series ( $Y_{\alpha, t}$ ) of the extreme temperatures revealed that: (i) for both the  $M_t$  series the first two harmonics are the most significant as they explain about 91 % of the variance of the series. (ii) For the  $Y_{\alpha, t}$  series, the 25th and the 50th harmonics explain about 80% of the variance of maximum temperatures, whereas the minimum temperatures are more deterministic as two harmonics (25th and the 50th) explain 95 % of the variance (Table 2). Thus the maximum temperatures are in general more stochastic in nature as 20 % of the variance is explained by this component.

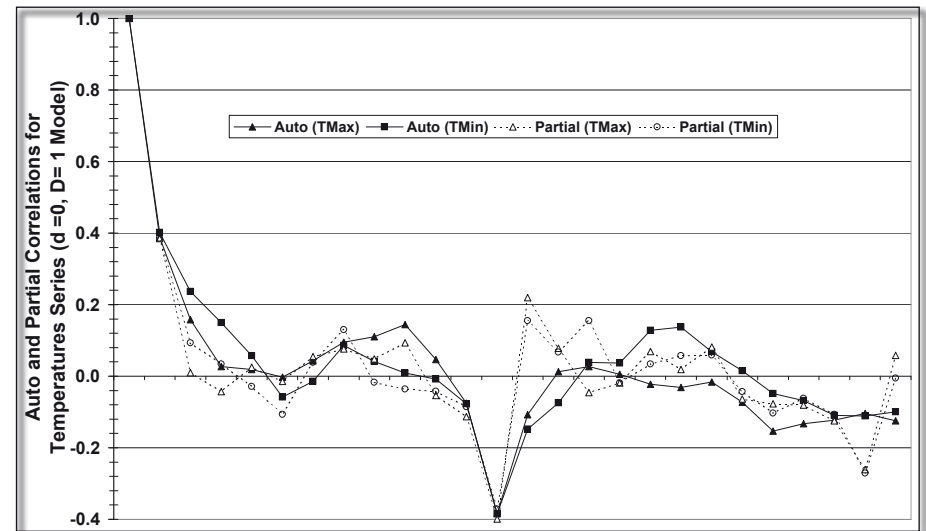


Figure 3. Auto and partial correlations of the mean monthly extremum temperatures series for  $d = 0$ , and  $D = 1$  model.

**Stochastic Components of Extreme Temperatures**

Several autocorrelations for extreme temperatures were calculated for differencing schemes  $d = 0, 1, 2$ , and  $D = 0, 1, 2$ . These autocorrelations suggested two possible schemes:  $d = 0$  and  $D = N$  (where  $N = 1, 2, \dots$ ) or  $d = 1$  and  $D = 1$  for further investigation..

The model  $d = 0$  and  $D = N$  is purely seasonal. A detailed discussion for  $d = 0, D = 1$  case follows. The autocorrelation functions display seasonality as evidenced by the large,  $r_{ij}$ , values at  $r_1, r_{11}, r_{12}, r_{13}$ . Compared to the 95 % confidence limits, most of the autocorrelations at other lags are insignificant. These autocorrelation functions mimic the behaviour of a moving average process. This is confirmed by the partial autocorrelations which mimic autoregressive behaviour. This behaviour of the time series is represented by the model (0, 1, 1)<sub>12</sub> given as:

$$\nabla_2 Z_t = (1 - \Theta_1 B^2) a_t \tag{7}$$

Table 1. Correlation matrix for the mean monthly solar irradiation (Slrd), maximum temperatures (TMax) and minimum temperatures (TMin) for Sebele.

	<b>Irradiation</b>	<b>TMax</b>	<b>TMin</b>
<b>Irradiation</b>	1	0.8413	0.7826
<b>TMax</b>		1	0.9175
<b>TMin</b>			1

The values of the parameter  $\Theta_1$  that minimize  $\Sigma at_2$  for the extreme temperature series are given in Table 3, and the residual autocorrelations are shown in Figure 1. Compared to 95 % confidence limits the residual functions are representative of a random series.

For  $d = 1$  and  $D = 1$  the autocorrelations are all insignificant except  $r_1, r_{1,1}, r_{1,2}, r_{1,3}$ . This is an indication of the presence of seasonal as well as non-seasonal effects since  $d = 1$ . The autocorrelations together with the partial autocorrelations indicate that a seasonal, non-seasonal multiplicative IMA (Integrated Moving Average) model of the form  $(0, 1, 1) \times (0, 1, 1)_{12}$  could be fitted to the extreme temperatures data. The proposed model is:

$$\nabla \nabla_{\alpha} Z_t = (1 - \theta_1 B)(1 - \Theta_1 B^2) a_t \tag{8}$$

The appropriate values of  $\theta_1$  and  $\Theta_1$  are those that minimize  $\Sigma at_2$ , and the admissible values must satisfy  $-1 < \theta_1 < 1$ , and  $-1 < \Theta_1 < 1$ . The minimization procedure is carried out by plotting the sum of the squares-surface for a range of values of  $\theta_1$  and  $\Theta_1$ . The surface is well behaved, having just one minimum for each case. Table 3 gives the values of the optimum parameters.

Table 2. Variance and significance of Slrd, TMax and TMin series explained by various harmonics.

Meteorological Data	Data Series	Significant Harmonics	Variance (%)	Significance (%)
Solar Irradiation (17 Years)	Monthly Series ( $M_t$ )	1 <sup>st</sup>	91	99
	Total Series ( $Y_{\alpha,t}$ )	17 <sup>th</sup>	40	82
Maximum Temperatures (25 Years)	Monthly Series ( $M_t$ )	1 <sup>st</sup> and 2 <sup>nd</sup>	91	100
	Total Series ( $Y_{\alpha,t}$ )	25 <sup>th</sup> and 50 <sup>th</sup>	80	80
Minimum Temperatures (25 Years)	Monthly Series ( $M_t$ )	1 <sup>st</sup> and 2 <sup>nd</sup>	92	100
	Total Series ( $Y_{\alpha,t}$ )	25 <sup>th</sup> and 50 <sup>th</sup>	95	95

The residual autocorrelations for the  $(0, 1, 1) \times (0, 1, 1)_{12}$  model of extreme temperatures are shown in Figure 1. These autocorrelations are typical of a random series. Note also that the seasonal effects in the residual autocorrelations have been nearly eliminated as the autocorrelations  $r_{11}, r_{1,2}, r_{1,3}, r_{1,4}, r_{1,5}$  are all close to zero. The  $a_t$  sequences pass the portmanteau statistics test with the portmanteau statistics computed using the first 25 values of the residual autocorrelations. Compared with the value of  $\chi^2$  at the 5% level with 23 degrees of freedom all the autocorrelations are insignificant, suggesting further that the residual series may be considered as random. The two models, namely the purely seasonal model  $(0, 1, 1)_{12}$ , and the IMA model  $(0, 1, 1) \times (0, 1, 1)_{12}$ , can be considered as suitable representatives of the given extreme temperatures series.

Table 3. Model parameters and statistics for mean monthly Slrd, and TMax, and TMin series.

Meteorological Data Series	Autoregressive Parameters					Model
	$\phi_{21}$	$\phi_{22}$	$\theta_1$	$\Theta_1$	$\Sigma a_t^2$	
<b>Slrd (2, 0)</b>	-1.30	-0.17	-	-	-	AR(2)
<b>TMax (0, 1)</b>	-	-	-	0.75	1012	$(0, 1, 1)_{12}$
<b>TMax (1, 1)</b>	-	-	0.85	0.85	834	$(0, 1, 1) \times (0, 1, 1)_{12}$
<b>TMin (0, 1)</b>	-	-	-	0.70	510	$(0, 1, 1)_{12}$
<b>TMin (1, 1)</b>	-	-	0.75	0.80	409	$(0, 1, 1) \times (0, 1, 1)_{12}$

BIVARIATE MODELS FOR SOLAR IRRADIATION AND EXTREME TEMPERATURES

The authors sought to determine bivariate models with solar irradiation series as input and either maximum or minimum average temperatures series as output. The order of monthly differencing  $d$ , the order of seasonal differencing  $D$ , the order of autoregressive operator  $\phi(B)$  and the order of the moving average operator  $\theta(B)$  (equation 3) are determined by autocorrelation and partial autocorrelation analysis. The values of  $d$  and  $D$  for which the input and output series are stationary are given in Table 4. It can be shown that the differenced input series  $x_t$  can be transformed into a purely random process represented by the residual series  $\alpha_t$  for values of the autoregressive parameters  $\phi_{21}$  and  $\phi_{22}$  given in Table 3. The autoregressive parameters obtained for the input series were applied to the output series  $y_t$  (Table 4) to obtain the corresponding residual series  $\beta_t$ . Then the cross-correlation function  $\nu_k$  between the  $\alpha_t$  and  $\beta_t$  series were calculated and compared with their approximate standard errors. These are given in Table 5 for lag  $k = 0$  to 4.

Table 4. Degrees of differencing  $d$  and  $D$  for which the input and output series are stationary.

INPUT $X_t$	(d, D)	OUTPUT $Y_t$	(d, D)
Solar irradiation (Slrd)	(2, 0) (2, 0) (2, 0)	Maximum temperature (TMax)	(0, 1) (0, 2) (1, 1)
Solar irradiation (Slrd)	(2, 0) (2, 0) (2, 0)	Minimum temperature (TMin)	(0, 1) (0, 2) (1, 1)

It is evident from Table 5 that there is a delay of three months between the peaks of differenced solar irradiation and maximum temperatures, and that there is either no delay or a delay of one month between the peaks of the differenced series of solar irradiation and minimum temperatures.

Next attention is given to identifying, estimating and fitting a model to the nt series (equation 5). It is assumed that the nt series can be represented by a seasonal ARIMA model of the type:

$$\Phi_p(B^s)\phi_p(B)\nabla_s^D\nabla^d n_t = \Theta_q(B^s)\theta_q(B)a_t \tag{9}$$

where the various terms have been defined with equation 3. Values for the parameters in equation 9 were determined by autocorrelation and partial-autocorrelation analysis. The nt series was found to be stationary either for d = 0 and D = N, where N = 1, 2... Or for d = 1, and D = 1. Furthermore, it was found that the nt series behaved as a moving average (MA) process of order (0, 1, 1)12 (eq. 7) or as an autoregressive moving average process of order (0, 1, 1) × (0, 1, 1)12 (equation 8). The autoregressive and moving average parameters for the nt series for some of the models identified are given in the Table 6.

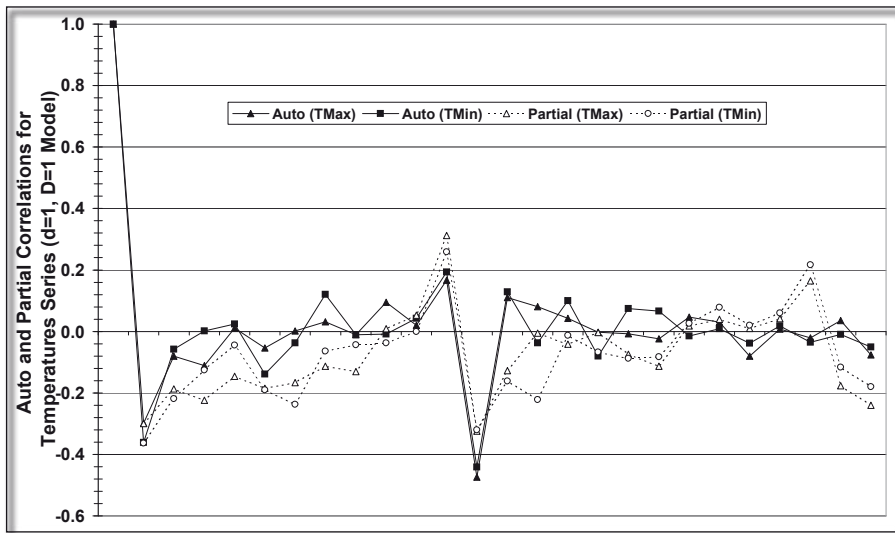


Figure 4. Autocorrelations of the white noise (residues) series for the extremum temperatures models.

The  $\alpha_t$  series were examined for cross-correlation with the nt series, and the cross-correlation was found to be weak. This suggests that the  $\alpha_t$  and nt series are independent. Moreover, examination of the autocorrelation function for solar irradiation shows that the  $\alpha_t$  series is a pure random process.

Figure 6, which is typical of the other sequences of the bivariate models, shows that the  $\alpha_t$  sequences are random sequences. The values of the ARIMA parameters indicate a persistent pattern with a memory of one month only with respect to non-seasonal effects. Seasonal effects are important as values of  $\Theta$  are found to be quite significant (Table 6).

Table 5. Cross correlation weights for the bivariate models.

QUANTITY (d, D)	$v_k$ for lag (k), k = 0 to 4				
	0	1	2	3	4
SIRD(2,0)/TMax(0,1)	-0.068	-0.686	-0.030	-0.110	0.004
SIRD(2,0)/TMax(0,2)	0.068	0.418	0.015	0.129	-0.138
SIRD(2,0)/TMax(1,1)	0.072	-0.011	-0.063	0.251	0.042
SIRD(2,0)/TMin(0,1)	-0.005	0.916	0.099	-0.122	-0.125
SIRD(2,0)/TMin(0,2)	0.010	-0.743	-0.060	0.075	0.067
SIRD(2,0)/TMin(1,1)	-0.213	0.477	0.109	0.159	0.002

DISCUSSION AND CONCLUSIONS

A good understanding of the meteorological phenomena may be achieved through examination of the impulse response weights  $v_k$ . The results show that there is lag of three months between the peaks of differenced solar irradiation and maximum temperatures, but there is only a delay of at most one month between the peaks of the differenced solar irradiation and differenced minimum temperature. The noise series follow either an ARIMA process of order (0, 1, 1) × (0, 1, 1)12 or a moving average process of order (0, 1, 1)12.

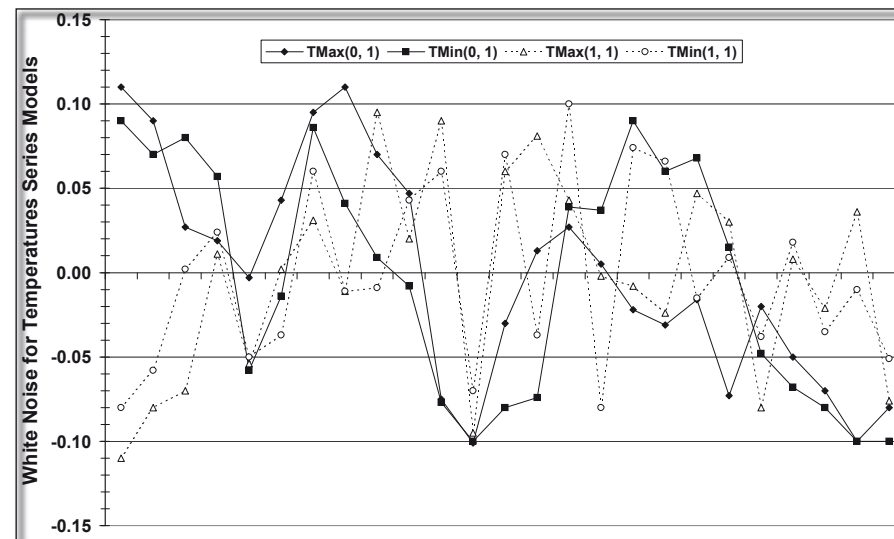


Figure 5. Auto and partial correlations of the mean monthly extremum temperatures series for d = 1, and D = 1 model.

The autoregressive parameters of the ARIMA model indicate that the non-seasonal effects are weak while the moving average parameters show strong seasonal effects. Note that the order of ARIMA models determined for the extreme temperatures series (Table 3) agree with the orders determined from the bivariate model (Table 6). Further validity of our model is provided by the fact that the linear transfer function model (equation 4) reproduces the characteristics of the extreme temperatures series. For instance, the first harmonic explains 90.5 % of the variance of the Mt series of either maximum or minimum temperatures. This compares very well with the corresponding results for the original temperatures series for which the variance explained by the first harmonic is 91 % to 92 %.

Table 5. Cross correlation weights for the bivariate models.

QUANTITY (d, D)	$v_k$ for lag (k), k = 0 to 4				
	0	1	2	3	4
Slrd(2,0)/TMax(0,1)	-0.068	-0.686	-0.030	-0.110	0.004
Slrd(2,0)/TMax(0,2)	0.068	0.418	0.015	0.129	-0.138
Slrd(2,0)/TMax(1,1)	0.072	-0.011	-0.063	0.251	0.042
Slrd(2,0)/TMin(0,1)	-0.005	0.916	0.099	-0.122	-0.125
Slrd(2,0)/TMin(0,2)	0.010	-0.743	-0.060	0.075	0.067
Slrd(2,0)/TMin(1,1)	-0.213	0.477	0.109	0.159	0.002

Table 6. Autoregressive and moving average parameters for the models identified for the  $n_t$  series.

PROCESS Input/ Output	$n_t$ Series Parameters		ARIMA Parameters		$\Sigma(at)^2$
	d	D	$\theta_1$	$\Theta_1$	
Slrd(2,0)/ TMax(1,1)	0	1	-	0.01	28943355
Slrd(2,0)/ TMax(1,1)	1	1	0.05	0.20	
Slrd(2,0)/ TMin(1,1)	0	1	-	0.55	386 263
Slrd(2,0)/ TMin(1,1)	1	1	0.65	0.75	

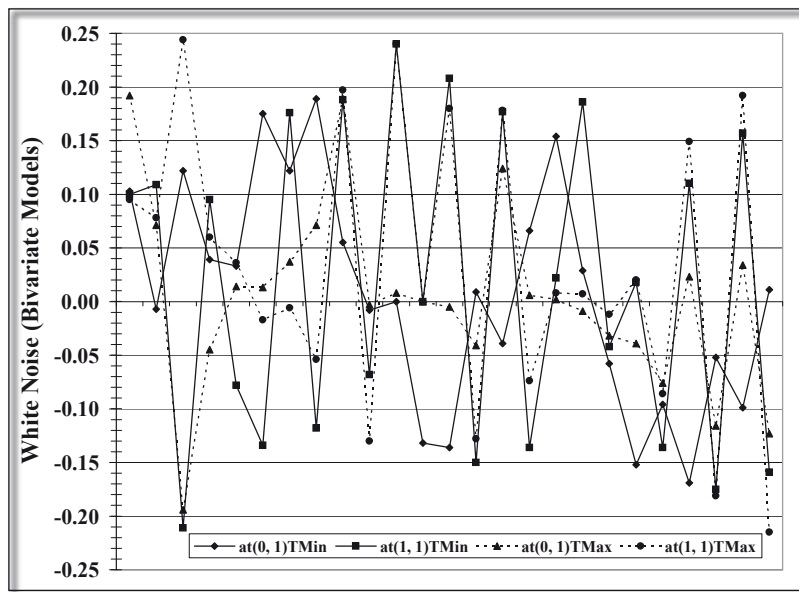


Figure 6. Autocorrelations of the white noise (residues) series for some of the bivariate models.

In the case of the total estimated temperatures series, we found that it is the 17th harmonic which is the most significant. This result is again in agreement with the anticipated results because 17 years of irradiation data is used to generate temperatures series.

Lastly, it is interesting to note that the behaviour of the deterministic component of the meteorological time series is analogous to the case of a vibrating string fixed at both ends. For a time series consisting of N years of data, it is the Nth harmonic which is the most significant in explaining the variance of the series. Although the results obtained in this study reproduce some important characteristics for the simulated temperatures series, it must be pointed out that to generate accurate temperature data a non-linear transfer function would be more appropriate.

ACKNOWLEDGMENTS

The Department of Agricultural Research, Sebele, for providing the daily solar radiation and extreme temperatures data used in the present analysis is gratefully acknowledged.

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**TORRO TORNADO DIVISION REPORT: June 2010**

By PAUL R. BROWN and G. TERENCE MEADEN



High pressure dominated the weather in the south during June 2010, where there was a good deal of dry, and sometimes warm, weather, but the north was more changeable, with unsettled conditions at times, and all parts had a cyclonic spell in the second week. There were three known tornadoes this month (all definite), and 11 reports of funnel clouds; land devils were reported almost daily in the last 10 days.

fc2010Jun06/I *Great Witley, Worcestershire (52° 17' N 2° 22' W, SO 7565)*

The *Worcester News* of the 8th June published a photograph taken by Mr Grant Hinton showing what appeared to be a disintegrating (or incipient) funnel cloud. The time was about 1340 GMT, and he described it thus: "There was a huge clap of thunder, and then I noticed what looked like legs on the clouds right above us. They started to turn faster and faster and form a small tornado. Unfortunately, it only lasted five minutes".

At 1200 GMT England and Wales were under a slow-moving shallow low, 1010 mb, with one centre over the Low Countries and the other over Norfolk. Many parts had showers, thundery in central and eastern areas, while northern England had longer spells of rain.

fc2010Jun06/II *Near Wallheath, Kingswinford, Staffordshire (c 52° 30' N 2° 11' W, SO 8889)*

Mr Richard Swain submitted a report of a funnel cloud, which he estimated to have been three miles (5 km) away from his position at Brookside Way (direction not stated). The time was 1335 GMT, so this may have been another sighting of the Great Witley funnel cloud (allowing for the normal underestimation of distances by observers).

TN2010Jun06/I *Marshland St James, near Wisbech, Norfolk (52° 40' N 0° 15' E, TF 522096)*

This tornado was reported in the *Eastern Daily Press* of the 8th June. Mr Ken Adams of Smeeth Road had his summer house lifted out of the garden and deposited in a field, while his neighbours, Mr Derek Barker and Mrs Jean Barker, had their garden severely damaged and a few roof tiles removed; several other houses also suffered minor roof damage. Mr Adams said: "I heard a loud roar ... I then looked outside and my summer house was gone ... the strange thing is the summer house had lots of windows and none of them were broken". The time was about 1300 GMT. Force T1.

TN2010Jun06/II *Stradsett, Norfolk (c 52° 37' N 0° 28' E, TF 668053)*

The *Lynn News* (8th June) published details of this tornado, as well as describing the Marshland St James one. It occurred about 1400 GMT, and was seen by Mr Max Stuart coming across a field, looking like "something out of the film *Twister*". It ripped the roof off a garden shed and carried it into a tree 100 metres away, and lifted a child's trampoline up onto an electricity line, causing a power cut. Mr David Wilson, who had been driving through the village, had to stop because the drivers in front had stopped to watch "a tornado-like cloud disappearing off". Force T0.

FC2010Jun06/III *Long Stratton, Norfolk (52° 29' N 1° 13' E, TM 1992)*

The *Eastern Daily Press* (*loc. cit.*) said that "Later funnel clouds ... were sighted around Watton and Long Stratton"; and film was received showing a rather short thick funnel over the latter village at about 1530 GMT (information from Chris Bell of TORRO). Watton is at TF 9100, so it is unclear whether this would have been a separate sighting.

FC/TN2010Jun07 *Wigton, Cumbria (54° 49' N 3° 09' W, NY 2647)*

The *News & Star* of the 9th June reported this under the headline 'Shock as tornado hits Wigton', and published photographs taken from the Highmoor part of the town by Ms Sophie Jackson and an anonymous correspondent. But while they show a well-formed funnel cloud reaching at least halfway to the ground, there is no confirmation that it reached the surface. The time was only given as 'afternoon', and it lasted about five minutes. At 1200 GMT a slack pressure pattern covered most of Britain ahead of a low, 1000 mb, moving into southwest Ireland; a shower trough lay northwest to southeast across Cumbria. Periods of rain moved into southwestern areas, while showers and isolated thunderstorms developed in the east and north.

FC2010Jun08/I *Broughton Green, near Droitwich, Worcestershire (52° 15' N 2° 05' W, SO 9461)*

The *Droitwich Advertiser* of the 10th June reported that 'tornado-type clouds' were spotted over Droitwich at about 1720 GMT. A photograph was added to the report at a later date, showing a well-developed funnel reaching about halfway to the ground, taken by Mr Jan Jenkinson at Upper Goosehill Farm, Broughton Green (about 5 km east of Droitwich).

At 1200 GMT the previous day's low, 999 mb, was slow-moving near the south coast of Ireland, and a variety of fronts and troughs were circulating round it. Central and southern parts of England and Wales had showers, many of which turned thundery in the east, while longer spells of rain occurred further north.

FC2010Jun08/II *West of Northampton, Northamptonshire (c 52° 15' N 0° 58' W, SP 7062)*

Mr Andy Ball of the Royal Meteorological Society photographed a funnel cloud reaching about a third of the way to the ground looking west from Northampton at about 1730 GMT (information from Peter Kirk of TORRO); it lasted about three minutes and was said to have been a few miles away.

TN2010Jun08 *Near Desborough, Northamptonshire (c 52° 26' N 0° 51' W, SP 7883)*

The *Lutterworth Mail* (8th June) published photographs of a funnel cloud seen from Market Harborough: one was taken by Mr Richard Nichols, who said it appeared to be beyond Clack Hill (i.e. towards Desborough); another was from Mr James Voyce, who saw it in the distance as he approached the town from the northwest. Film of the funnel was also recorded by a couple of scally lads driving along a main road, although it is not clear exactly where they were. None of these reports indicates more than a funnel cloud, but Ms Carolyn Sherratt contacted us to say she had seen it while driving over the hills into Desborough from Harrington. She stopped and watched it with several other people, one of whom saw it reach the ground; Ms Sherratt's ground view was obscured by foliage, but she did see swirling debris in the funnel, which seems to confirm that it was a tornado. She estimated that it was no more than two miles away across the valley. Most reports indicated a time of about 1500 GMT.

FC/TN2010Jun08/III *King's Lynn, Norfolk (c 52° 45' N 0° 24' E, TF 6220)*

Chris Bell of TORRO received two pictures of funnel clouds this day, one from Rothwell at 1500 GMT, which would have been the one here recorded under the *Desborough* heading, the other from King's Lynn at about 1530 GMT. Both appeared to be close to the ground.

FC2010Jun09/I *North of St Buryan, Cornwall (c 50° 06' N 5° 40' W, SW 3828)*

Mr Graham Easterling of the uk.sci.weather weather group saw a clear funnel cloud near Chapel Carn Brea, two miles north of St Buryan.

Time approximately 1445 GMT (information from Jonathan Webb of TORRO).

At 1200 GMT the previous day's low had become absorbed by a new low, 997 mb, over northwest Spain, from where a broad trough extended north to Cornwall; an easterly airflow covered much of Britain, and a shower trough lay across Wales and the Midlands. Scattered showers and local thunderstorms developed over many parts of England and Wales.

FC2010Jun09/II *East of Bude, Cornwall (c 50° 54' N 4° 23' W, SS 3214)*

John Pask of TORRO saw a long, thin, funnel cloud to the east from near Bude at 1148 GMT; he estimated its position as near the village of Bradworthy. It was visible for about one minute, and reached two-thirds of the way from the cloudbase to the ground.

FC/TN/WSJun13/I *Near Blyth?, Northumberland (c 55° 10' N 1° 25' W, NZ 38?)*

Mr Tony Sales, a correspondent to the UKWeatherworld forum, submitted a photograph (of poor quality) taken by a friend of his showing a large funnel cloud near the horizon, but very little detail was forthcoming. It was said to have been off the Northumberland coast, perhaps near Blyth; the picture, however, shows only land, the base of the funnel disappearing below the horizon; so if it reached the surface it could have been either a tornado or a waterspout. No time of day was given. (Nick Coles of TORRO alerted us to this and the following report.)

At 1200 GMT a low, 1010 mb, was moving southeast across Scotland, and its cold front was crossing the Irish Sea. There were outbreaks of rain on the front, and showers ahead of it over eastern England (where a few thunderstorms developed in the evening).

FC2010Jun13/II *Whittlesey, Cambridgeshire (52° 33' N 0° 08' W, TL 2797)*

An anonymous correspondent to the UKWeatherworld forum photographed a very slender funnel cloud at 1840 GMT. It appears to reach about a quarter of the way to the ground.

LD2010Jun20 *Apperley, Gloucestershire (51° 57' N 2° 12' W, SO 864279)*

Mr John Gerner of Willow Hill Farm, Apperley, submitted this report of a land devil seen at 1242 GMT. It travelled southeast across a field of mown grass, lifting some of it up to 30 metres in the air, rocked a caravan, and blew over two chairs. The weather was fine with light wind and temperature about 19 °C. At 1200 GMT an anticyclonic northwesterly airflow covered the British Isles associated with a high, 1026 mb, near western Ireland. England and Wales were dry with long sunny periods (but not particularly warm).

LD2010Jun21 *Bicester, Oxfordshire (51° 54' N 1° 09' W, SP 581233)*

Mr A. Greening of Almond Road, Bicester, submitted a report of a whirlwind which occurred at 1320 GMT. On a fine sunny day, temperature 23 °C, the tree and bushes at the end of his garden were suddenly subjected to a very high wind, and a parasol was lifted about a metre out of its base and damaged on landing; small branches in leaf were scattered on the patio. It only lasted a few seconds, and no other neighbouring trees were affected. At 1200 GMT the previous day's high, 1025 mb, was centred off southwest England, and a ridge covered most of the country. The weather was dry and warm, but coasts were cooler with sea breezes.

A report of a 'twister' in the skies over Sale (Cheshire) in the evening (*Messenger* newspaper, 22nd June) was discounted as improbable.

LD2010Jun22 *Queensferry, Flintshire (53° 12' N 3° 02' W, SJ 3168)*

Mr Tom Gibbons reported that he witnessed a 'mini-twister' picking up debris and hurling it in the air at his workplace at Queensferry. Time uncertain, but probably mid-afternoon. At 1200 GMT the previous day's high, 1026 mb, was centred in the English Channel. England and Wales were again fine and warm with sea breezes developing.

LD2010Jun23 *Pilton, Somerset (51° 09' N 2° 35' W, ST 5940)*

Mr Paul Simons, *The Times* meteorologist, wrote on the 2nd July that on the opening day of the Glastonbury Music Festival (at Worthy Farm, Pilton) a tent was seen to suddenly shoot up in the air together with a swirling mass of paper, etc. At 1200 GMT the previous day's high, 1025 mb, was still centred in the Channel, within a ridge from the Azores High to the Baltic. The south was again fine and warm with prolonged sunshine (15 hours at several places).

LD2010Jun25 *Slough, Buckinghamshire (51° 32' N 0° 37' W, c SU 956821)*

Mr Mark Fryer submitted a report of a dust devil that was seen at 1600 GMT in Northborough Road, Slough; it lasted about 30 seconds, and the weather was described as 'hot, sunny, humid'. At 1200 GMT a very slack pressure pattern covered the British Isles between a low, 997 mb, in mid-Atlantic, and a small high, 1019 mb, in the North Sea; by 1800 GMT a heat low of 1015 mb had formed over the Home Counties. The weather was fine and warm with coastal sea breezes.

LD2010Jun26 *Banstead, Surrey (51° 20' N 0° 12' W, TQ 256602)*

This was brought to our attention by Matt Clark of TORRO, and was later reported in the *Reigate Mirror* (8th July). It occurred in the morning, probably between 0900 and 0930 GMT, on an allotment in Lambert Road, where a shed full of gardening equipment was lifted at least 10 feet off the ground (the original report said 20-30 feet) before falling back down and collapsing some 20 feet from where it started. There was clear blue sky at the time. A witness, Mr Alan Dorrill, said: "I heard a noise and looked around and saw this shed 10 ft up in the air and then splatter on the floor. Nothing around it was touched. The weird thing was there was hardly any wind". At 1200 GMT a ridge of high pressure covered England and Wales between the Azores High and a small high, 1021 mb, in the North Sea. The weather was fine and very warm with sea breezes developing.

LD2010Jun27 *Wheathampstead, Hertfordshire (c 51° 48' N 0° 18' W, TL 1713)*

Ms Heather Waterfield contacted us to say that at 1230 GMT a whirlwind uprooted her gazebo and momentarily lifted her trampoline (which takes four strong men to move it) up in the air. At 1200 GMT the synoptic pattern was similar to that of the previous day, with a ridge from the Azores High across England and Wales. The day was fine and hot in the south (30 °C in the Home Counties).

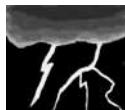
*Whirlwind in the Irish Republic*

FC2010Jun05 *Southwest of Fermoy, County Cork (c 52° 05' N 8° 20' W, W79)*

Mr Michael Fay saw a funnel cloud some distance away to the southwest of Fermoy (after having his attention drawn to it by his children). The time was about 1700 GMT, and it was said to have lasted about 30 minutes. At 1800 GMT a very slack pressure pattern covered Ireland between a shallow low, 1015 mb, over England and other lows far out over the Atlantic; an occlusion lay near the west coast. The weather over Ireland was rather cloudy with a few light showers.

## TORRO THUNDERSTORM REPORT FOR THE BRITISH ISLES: JULY 2010

By BOB PRICHARD



After a six-month absence, southwesterly winds returned with a vengeance this month (July has been the most 'southwesterly' of all the months throughout this decade). A relentless stream of depressions passed close to northwest Britain, and sometimes over the country, leading to a very wet month in the north and west, but giving mostly very little rain to the south. And still there was not very much thunder. In a few instances, after the weak fronts had left the southeast thundery outbreaks developed along them on the near Continent on the boundary of much hotter weather; some of the rain, but little of the thunder, from these occasionally clipped the extreme southeast. Only on the showery days of the 14th and 22nd was thunder at all widespread. Scattered districts over central and northern England had thunder on three days – whilst a few localities in southern England had still not had any at all so far in 2010.

On the 2nd, a shower that developed over the northern Highlands in the late morning turned thundery as it drifted north off the coast of central north Scotland and passed just to the west of Orkney. On the 4<sup>th</sup>, a vigorous depression tracked northeast close to northwest Scotland, and heavy, squally showers broke out just behind the frontal rain over Scotland in the afternoon; they turned thundery over parts of central, eastern and northern Scotland and, more especially, as they moved out over the North Sea.

The next reports are for the 10<sup>th</sup>, when there was thunder in Galway Bay in the early afternoon as a depression moved northeast across the area. In the warm southerly airflow ahead of the depression, isolated thunder appeared in showers over south Cheshire and near Newcastle-upon-Tyne in the evening. Thunder affected the northern isles briefly as the depression moved over them around midday on the 11th, when there was also a thundery shower near Dublin in the early evening. Hot air receded eastwards from the British Isles on the 12th, when there was a good deal of thundery activity over the near continent; parts of east Kent were briefly affected during the early hours by an outbreak that developed over the eastern Channel, and there was also a report of thunder from Sheffield around midday as a rain area from a trough, linked to the waving cold front to the east, crossed the Pennines. There were also some thundery showers over central Scotland during the afternoon, and the 13th saw one or two more of these in the afternoon in a southeasterly airflow over northern Scotland.

During the 14th, a depression moved northeast into Ireland and its associated cold front, followed by showery troughs, crossed the country. Thunderstorms developed quite widely during the afternoon and evening over England (except in parts of the south and East Anglia), Wales and western Ireland, with a drift north into parts of southern Scotland. Some of the storms were quite severe with very heavy rain, especially over the north Midlands: 48 cloud-to-cloud flashes were counted in a 35-min storm at Newcastle-under-Lyme (north Staffordshire) in the early evening, whilst at Desford, near Leicester, there were six to ten flashes of lightning a minute over a 40-min period with large hail covering the roads and visibility reduced to a few metres. A tornado was reported at Martley (Worcestershire), ripping off roof tiles and uprooting a large willow tree. The roof of a house at Haynes, near Bedford, was set on fire after a lightning strike, and after a similar incident at Cresswell, near Dumfries, houses were filled with thick smoke. A house was also struck at Ashford (Kent) in the evening. There were more thundery showers on the 15th over central regions, with

very heavy rain over parts of Northern Ireland. Then in the evening, as another depression moved northeast close to the coast of southeast Ireland, thunderstorms broke out near it; a lively storm affected Ashford (County Wicklow) for two hours around midnight. Isolated thunder reappeared near the depression track as it crossed Scotland during the 16th. In the brisk showery southwest to westerly airflow to the south of it, there was thunder in some of the showers from Somerset across the Midlands to Lincolnshire during the afternoon and early evening. Thunder also occurred in the Bristol area around dawn and near the Suffolk coast late next morning before a weak ridge of high pressure brought stabilisation from the west.

Yet another depression approached from the west during the 19th, when there was a little thunder over Ireland in the morning and in northern Scotland in the afternoon on the rear edge of a waving cold front. Areas of very heavy rain near this front over north Wales and northern England on the 20th were for the most part not accompanied by thunder, though there was some in localised areas during the afternoon and evening. There were also a few thundery showers behind the front late in the day over Ireland and Scotland, whilst on the 21<sup>st</sup> there were numerous thundery showers over eastern Ireland, and more scattered ones over Wales and northern England, during the afternoon and evening; a house was struck by lightning at Oldham. A 30-min period with nearly continuous thunder was reported from Ashford (County Wicklow).

A small depression and upper-air cold pool drifted southeast across England during the 22nd – but still could not induce thunder over most of the southeast. The main activity was across south Wales, the West Country, the Midlands and East Anglia during the afternoon and early evening. At Coton-in-the-Elms, near Burton-on-Trent, a violent thunderstorm produced 45 mm of rain in 40 min, with large hail, leading to flash flooding which damaged many properties. Lightning felled a tree at Salisbury and was believed responsible for a power failure affecting 8000 properties in the Reading area. It also damaged railway equipment in the Bristol area, with the resulting disruption of train services. Heavy hail destroyed 2000 acres of oilseed rape crop in the Bourne area (south Lincolnshire), whilst hailstones of 10 mm diameter were reported from Wokingham.

During the 27th, thunder broke out as a previously weak cold front crossed East Anglia from the west in the afternoon; 37 mm of rain was reported from Felixstowe, and 18 mm fell in 33 min at Brinkley (Cambs). The 28th brought a brief thundery shower in the Belfast area in the afternoon in a northwesterly airflow, and there was isolated thunder on a cold front over southwest Ireland on the afternoon of the 30th and in the early evening over northern England.



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## BOOK REVIEW

By PETER ROGERS

**WHY WE DISAGREE ABOUT CLIMATE CHANGE Understanding Controversy, Inaction and Opportunity by Mike Hulme ISBN 9780-521-89869-0 (hb) and 978-0-521-72732-7 (pb) CUP 2009 pp 392 pb £15.99.**

There have been an increasing number of books about climate change as a result of the mounting recent interest in this topic particularly in the period before the Copenhagen Summit. They are, perhaps inevitably, of variable quality but this volume seems to me to stand head and shoulders above most others. It is scholarly, candid and intensely thought provoking written by a member of the School of Environmental Studies at the University of East Anglia, who for seven years led the influential Tyndall Centre and reflects a lifetime's research into the subject.

The Chapter Headings of the ten chapters into which the book is divided give a very good indication of its contents: *The Social Meanings of Climate; The Discovery of Climate Change; The Performance of Science; The Endowment of Value; The Things We Believe; The Things we Fear; The Communication of Risk; The Challenge of Development; The Way we Govern, and Beyond Climate Change.*

What is so different about this book is that the author not only tells the story of climate change, from its origins up to the middle of 2008, but also reflects his own personal beliefs in a way that is very rare. He would not I think like to be classified as sceptic, but he tries to put the "threat" of climate change into context. The penultimate paragraph of the book spells this out very well:

*"The world's climates will keep on changing, with human influences on these physical properties of climate now inextricably entangled with those of Nature. Global climate is simply one new domain which reveals our embeddedness in Nature. But so too will the idea of climate change keep changing as we find new ways of using it to meet our needs. We will continue to create and tell new stories about climate change and mobilise those stories in support our projects. Whereas a modernist reading of climate may once have regarded it as merely a physical boundary condition for human action, we must now come to terms with climate change operating as an overlaying, but more fluid, imaginative condition of human existence"*

Each chapter is split into sections with a summary and list of relevant reading at the end, and a comprehensive Bibliography and Index at the end. There are Boxes, diagrams and graphs, and CUP has done this important volume full justice in the typeface, and printing on non-glossy paper.

The paperback edition of this book is well within the financial reach of most if not all readers of this Journal, and I urge you all to buy, read, digest and ponder this valuable book. It will be a long time before it will be rivalled for its breadth and depth of coverage of this vitally important subject.





“An international magazine for everyone interested in weather and climate,  
and in their influence on the human and physical environment.”