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Investigating potential future changes in surface water flooding hazard and impact

Short title: Potential future changes in surface water flooding

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Abstract

Surface water flooding (SWF) is a recurrent hazard that affects lives and livelihoods. Climate change is projected to change the frequency of extreme rainfall events that can lead to SWF. Increasingly, data from Regional Climate Models (RCMs) are being used to investigate the potential water-related impacts of climate change; such assessments often focus on broad-scale fluvial flooding and the use of coarse resolution (>12km) RCMs. However, high-resolution (<4km) convection-permitting RCMs are now becoming available that allow impact assessments of more localised SWF to be made.

At the same time, there has been an increasing demand for more robust and timely real-time forecast and alert information on SWF. In the UK, a real-time SWF Hazard Impact Model framework has been developed. The system uses 1km gridded surface runoff estimates from a hydrological model to simulate the SWF hazard. These are linked to detailed inundation model outputs through an Impact Library to assess impacts on property, people, transport and infrastructure for four severity levels.

Here, a set of high-resolution (1.5km and 12km) RCM data has been used as input to a grid-based hydrological model over southern Britain to simulate Current (1996-2009) and Future (~2100s; RCP8.5) surface runoff. Counts of threshold-exceedance for surface runoff and precipitation (at 1-, 3- and 6-hour durations) are analysed. Results show that the percentage increases in surface runoff extremes, are less than those of precipitation extremes. The higher-resolution RCM simulates the largest percentage increases, which occur in winter, and the winter exceedance counts are greater than summer exceedance counts. For property impacts the largest percentage increases are also in winter however, it is the 12km RCM output that leads to the largest percentage increase in impacts. The added-value of high-resolution climate model data for hydrological modelling is from capturing the more intense convective storms in surface runoff estimates.

Keywords

Climate change, hazard, impact, modelling, pluvial flooding, surface water flooding.

1 Introduction

Surface water flooding (SWF), also known as pluvial flooding, is a global hazard. For example, parts of Europe (Germany, Bung et al. 2011; Italy, Di Salvo et al. 2017) and Asia (Japan, Bhattarai et al. 2016; India, Akilan et al. 2017) have all experienced SWF in recent years. SWF occurs when rainwater cannot drain away quickly enough through drainage systems or by soaking into the ground; instead water lies on or flows over the ground. This type of flooding tends to occur as a consequence of intense and localised rainfall often associated with convective events (e.g. thunderstorms), however it can be caused by prolonged 'moderate' rainfall (e.g. June 2007 flooding in Hull, Falconer et al. 2009) sometimes with embedded high-intensity rainfall cells, or by rapid melting of snow.

Like all flooding, SWF causes significant disruption to people's lives and livelihoods, damaging homes and businesses (Bhattarai et al. 2016), closing roads (DfT 2014), schools and hospitals and disrupting water and power supplies, and communications (Defra 2018). It can also cause environmental and human health impacts and even deaths (Burton et al. 2016, Milojevic 2015). Urban areas are particularly vulnerable due to the concentration of people, buildings, infrastructure, and associated impermeable surfaces, which results in overwhelmed drainage systems from increased surface runoff (Kaźmierczak & Cavan 2011). Rapid urbanisation (UN 2014) is likely to increase vulnerability in urban areas into the future (Houston et al. 2011, Miller & Hutchins 2017).

SWF threat is also likely to increase due to climate change (Miller & Hutchins 2017), with precipitation patterns predicted to shift towards more intense events in the future (IPCC 2013). Until recently, climate models have been too coarse to assess the impacts of sub-daily rainfall that is a key driver of SWF (Miller & Hutchins 2017), however high-resolution convection-permitting regional climate models (RCMs) are now becoming available (Pan et al. 2011, Kendon et al. 2014, Prein et al. 2015) that allow impact assessments of more localised SWF to be made.

Traditionally SWF forecasts are based on the probability of forecast rainfall exceeding a given threshold for a set of durations. However, employing a hydrological model to estimate surface runoff has the potential to provide benefits beyond existing rainfall depth threshold approaches, because the hydrological model enables the dependence on land cover, soil type and antecedent soil moisture to be included (Cole et al. 2016b). Kaspersen et al. (2017) used runoff modelling to investigate the potential impacts of climate change on pluvial flooding in four European cities (Odense, Vienna, Strasbourg and Nice). They showed increases in total area affected by SWF events, which varied between the cities due to a range of factors including differences in soils and topography. However, they only used change factors for extreme hourly precipitation derived from an ensemble of Global Climate Models (GCMs) downscaled via a 50km resolution RCM, which may not represent sub-daily extremes well. Here, for the first time, a set of high-resolution (1.5km and 12km) RCM data has been used as input to a hydrological model to investigate the potential future changes in SWF over southern Britain. The aims of this paper are to

- Investigate potential future changes in SWF hazard and impact, using surface runoff.
- Investigate the effect of RCM resolution on projections of change in surface runoff.
- Compare results for different parts of the country and in different seasons.
- Compare results based on surface runoff to those based on precipitation.

Section 2 describes the study area, models, datasets and methods, Section 3 the results, and Sections 4 and 5 the discussion and conclusions.

2 Materials and Methods

2.1 Study area

In England SWF threatens more people and properties than any other form of flood risk; about 3 million properties are at risk of SWF but about 2.7 million are at risk from rivers and the sea (Bevan 2018). Recent SWF events such as those in Hull (2007; Coulthard & Frostick 2010), Newcastle (2012; Newcastle City Council 2013) and Birmingham (2016; Birmingham City Council 2017) led to widespread damage and disruption. This has led to an increasing demand for more robust and timely real-time forecast and alert information on SWF (Cabinet Office 2008).

Within the Natural Hazards Partnership (NHP; Hemingway & Gunawan 2018) a real-time Hazard Impact Model (HIM) framework has been developed that includes SWF as one of the hazards chosen for real-time pre-operational trials (Cole et al. 2013, 2016b, Speight et al. 2018). The SWF HIM system uses surface runoff estimates from the Grid-to-Grid (G2G) hydrological model (Moore et al. 2006, Bell et al. 2009) to estimate the SWF hazard, and links this to detailed inundation model outputs to assess impacts on property, people, transport and infrastructure using a pre-computed Impact Library (Aldridge et al. 2016). Here, a set of RCM data have been used to explore the potential future changes in SWF hazard, and property impacts, over the southern part of Britain (Figure 1) at climate timescales.

2.2 Regional climate models

In this study a set of nested high-resolution Met Office Hadley Centre RCM runs are used. The 1.5km model domain spans southern Britain (Figure 1) and is driven by a 12km RCM, which has a European domain and is in turn driven by a 60km GCM (HadGEM3, Walters et al. 2011). The 1.5km RCM is convection-permitting, meaning that it does not need to employ the convection parameterisation schemes required in coarser resolution

models. The model runs cover both Current and Future periods (Table 1) and use climatological aerosols. Further RCM details are provided by Kendon et al. (2012, 2014).

Analyses using runs of the nested RCMs driven at the boundaries by ERA-Interim reanalysis data showed than the 1.5km RCM better represents sub-daily precipitation in Britain than the 12km RCM, in terms of duration and spatial extent (Kendon et al. 2012) and summer extremes (Chan et al. 2014b), although improvements in daily precipitation are less clear (Chan et al. 2013). Analyses using runs of the nested RCMs driven by GCM boundary conditions showed future increases in summer heavy rainfall in the 1.5km RCM that were not seen in the 12km RCM (Kendon et al. 2014). Also, the 1.5km and 12km RCMs show different changes in summer precipitation extremes (Chan et al. 2014a), with the 1.5km RCM projecting increases of ~10% in hourly intensity across a range of return periods (but little change in daily intensity) but the 12km RCM projecting decreases in both hourly and daily intensity at short return periods (<5 years) and large increases at long return periods (>20 years). Increases in (hourly and daily) winter precipitation intensity are much larger than for summer, for both the 12km and 1.5km RCMs, and the increase in daily intensity is much higher for the 1.5km RCM than the 12km RCM.

Kay et al. (2015) show that the 1.5km RCM generally performs worse than the 12km RCM for simulating river flows in 32 example catchments, with a clear east/west pattern of bias consistent with patterns of mean bias shown in the RCM precipitation data. The results using GCM-driven RCM runs show in all seasons except summer, the 1.5km RCM tends towards larger increases in flood peaks than the 12km RCM, with differences most pronounced for spring and winter.

2.3 Hydrological model and driving data

The G2G is a distributed hydrological model that provides estimates of flow, surface runoff and soil moisture on a 1km^2 grid across Great Britain (Moore et al. 2006, Bell et al. 2009). An advantage of G2G is that it has one spatially consistent configuration and is able to model a wide variety of hydrological regimes due to use of spatial datasets (e.g. elevation, land cover and soil type) in the model construction. The effect of urban and suburban land cover on runoff and downstream flows is also included. The model addresses the ungauged hydrological forecasting problem and facilities forecasting ‘everywhere’ (Cole and Moore 2009) and is used within the Flood Forecasting Centre (England and Wales) and the Scottish Flood Forecasting Service for national-scale operational forecasting (Price et al. 2012, Maxey et al. 2012). Although the G2G has been used to assess the impact of climate change on river flooding (Bell et al. 2012, 2016) it has not, until now, been used to analyse the impact on SWF.

G2G requires input time series of precipitation and potential evaporation (PE). Hourly precipitation is directly available from the RCM runs, but needs to be converted from the RCM grid (rotated lat-long) to the 1km hydrological model grid (GB national grid). Conversion for the 1.5km RCM uses area-weighting, while for the 12km RCM the data are copied to each of the corresponding 1km grid boxes of the hydrological model grid. Hourly RCM precipitation is divided equally down to the 15-minute model time step.

Monthly PE is estimated from meteorological variables output by the RCMs, using the Penman-Monteith formula (Monteith 1965). PE is divided equally down to the 15-minute model time-step. A comparison of PE from the 1.5km and 12km RCMs shows they are very similar (Rudd & Kay 2015). Here, the PE from the 12km RCM runs is also used for the equivalent 1.5km RCM runs to ensure that any differences in surface runoff results are due only to differences in precipitation inputs. The estimation of PE for the Future period accounts for changes in stomatal resistance under higher atmospheric concentrations of CO_2, which results in much smaller increases in PE than if fixed stomatal resistance values are applied (Rudd & Kay 2015). This has been shown to influence simulated future changes in river flows (Kay et al. 2018), and could thus influence the simulated production of surface runoff.

2.4 Analysis of precipitation and surface runoff

Data from the 12km and 1.5km Current and Future RCM runs (Table 1) are used to drive G2G. The 1km grids of surface runoff simulated by G2G, and the RCM precipitation, are analysed relative to thresholds for 1-, 3- and 6-hour duration extremes. Thresholds are defined as the 99.9th percentiles from the Current RCM data, by ranking data from all pixels and all years (using the maxima of the *d*-hour values for each day) (Table 2). This provides model- and variable-dependent thresholds that allow for model biases. For each 1km pixel, a count is then made of the number of days when a threshold has been exceeded for at least one (over-lapping) *d*-hour period in the day (rather than counting the number of possibly over-lapping *d*-hour periods exceeding the threshold, which could count the same event multiple times).

As the 1.5km and 12km RCM runs show different precipitation changes in summer and winter (Chan et al. 2014a) the analysis is also separated for the four seasons; winter (DJF), spring (MAM), summer (JJA) and autumn (SON). The counts over the full (13 year) period are converted into average counts per season. To assess whether any individual years/events are unduly affecting the results, jack-knifing is applied. This involves leaving out one year at a time and repeating the above analysis of threshold exceedance, resulting in one set of counts using all of the data and 13 further sets of counts, leaving out one year in each case. The range shown by the 13 jack-knifed counts indicates the range of uncertainty introduced by individual years of data.

To analyse potential future changes in surface runoff and precipitation, percentage changes in exceedance counts for corresponding Current and Future runs are calculated. The analysis is carried out at a regional level because the change signals in sub-daily precipitation extremes at the grid-box scale are not robust or informative, due to the dominance of natural internal variability at small scales (Chan et al. 2014a). As the climatology of the British Isles is such that the west receives more precipitation than the east, the analyses are also split by region. The regions are based on an analysis of UK observed sub-daily extreme rainfall like that of Darwish et al. (2018). The analysis identified five regions (S. Blenkinsop, pers. comm.) and here the regions ‘Mid East’ and ‘North West’ have been amalgamated with the ‘South West’ region to form two regions for southern Britain; West and East (Figure 1).

2.5 Analysis of property impacts

To analyse the potential impacts of SWF on property into the future, the analysis (Section 2.4) is repeated with spatially varying surface runoff thresholds from the Impact Library (Figure 2) that utilise the updated Flood Map for Surface Water dataset (uFMfSW; EA 2013). The uFMfSW contains design flood maps from an inundation model for nine rainfall scenarios using combinations of three return periods (30, 100 and 1000 years) and three durations (1, 3 and 6 hours). The "effective rainfall" used as input to the inundation modelling accounts for rural runoff processes and losses to urban drainage. The Impact Library provides the severity level (minimal, minor, significant and severe) of property impact for each scenario, based on counts of properties at risk in each 1km pixel (Table 2 of Aldridge et al. 2016). Within this study the three 1 hour impact maps are used to identify the minimum 1 hour "effective rainfall" thresholds required to generate minimal, minor, significant and severe impacts. If a pixel crosses the 'significant' severity level it is implicit that it has already crossed the 'minimal' and 'minor' severity thresholds. Figure 2 shows that 'severe' and 'significant' property impacts can only occur in dense urban areas (e.g. London and Birmingham) and for relatively high threshold events, with lower threshold events causing lesser impacts ('minimal' or 'minor') in these areas. In more rural areas, higher threshold events can be needed to cause even 'minimal' or 'minor' impacts, and in some rural pixels there are too few/no properties to give any impacts. The G2G surface runoff estimates can reasonably be equated to the "effective rainfall" estimates (Warren et al. 2016), as done in the SWF HIM (Cole et al. 2016a), therefore the effective rainfall grids can be used as spatially varying thresholds in the impact analysis. Due to the significant spatial differences in the thresholds, especially for higher severity levels, southern Britain is considered as a whole.

3 Results

3.1 Precipitation and surface runoff

Figure 3 shows maps of the 12km and 1.5km RCM exceedance counts of precipitation and surface runoff for the annual and seasonal time-scales (winter and summer) for the Current and Future time-slices. The spatial patterns of topography are clearly visible for both precipitation and surface runoff, additionally urban areas stand out in the maps of surface runoff. For both precipitation and surface runoff the exceedance counts are generally higher in the Future time-slice than the Current. The 12km and 1.5km RCMs simulate similar patterns on an annual timescale, but the 12km exceedance counts are higher than the 1.5km exceedance counts in the Future in winter, especially over the mountainous region of Wales.

The grids of exceedance counts are averaged over two regions, to the West and East of southern

Britain (

Figure 1). These regional averages, and the percentage changes between the Current and Future time-slices, are plotted in Figure 4 for the 1-hour thresholds of precipitation and surface runoff (Table 2). Equivalent figures for the 3- and 6-hour exceedance counts are in the Supplementary Material (Figures S1 and S2).

The percentage change in precipitation exceedance counts are all positive, higher in the Future time-slice than the Current time-slice, except for the 12km simulation in the East in spring (~10% decrease). The largest percentage increases in precipitation exceedance counts are in winter and for the 1.5km, but the exceedance counts in the Current period are very small in these cases. The smallest percentage increases in precipitation exceedance counts are in summer (1.5km: ~10% and 12km: ~50%). The percentage increases in precipitation exceedance counts in the West are higher than in the East, except in summer for the 12km simulation. In winter and summer the increases in precipitation exceedance counts in the 1.5km simulation are larger than for the 12km.

The percentage changes in surface runoff exceedance counts are smaller than for precipitation, in all seasons and in both the West and East. The percentage changes in surface runoff are positive, except for the 12km in summer (West and East) and spring (East). The largest increases in surface runoff exceedance counts are in winter and for the 1.5km simulation (~400% in the West and 500% in the East). Decreases in surface runoff exceedance counts in summer are larger for the 12km simulation than the 1.5km. Percentage changes in surface runoff exceedance counts generally decrease slightly across the durations (Figure S2). The uncertainty from individual years (as estimated by jack-knifing) is relatively small (Figure 4a and Figure S1), especially for surface runoff.

3.2 Property impacts

Figure 5 shows the 1-hour exceedance counts (totals for southern Britain averaged per year), and the percentage changes in those exceedance counts, for the four levels of property impact severity (Section 2.5). The exceedance counts for the 1.5km simulation are higher than those for the 12km simulation (Figure 5a) and summer counts show the greatest absolute difference between resolutions. The percentage changes in exceedance counts (Figure 5b) are positive, and increase with increasing severity, except for the 12km simulation in winter (not monotonic) and the 12km simulation in spring where the percentage changes decrease with increasing severity and become negative for 'Severe' impacts. In summer and autumn, across all severity levels, the 12km percentage increases are higher than for the 1.5km RCM, whereas in spring the percentage increases for the 1.5km RCM are higher than for the 12km RCM (especially for the 'significant' and 'severe' impact levels), and in winter the percentage increases for the 1.5km and 12km RCMs are more similar to each other. The winter shows the largest percentage increases, and also the lowest absolute exceedance counts, particularly for 'severe' impacts.

4 Discussion

The analysis in this study showed that the percentage changes in threshold exceedance counts for precipitation and surface runoff are dependent on resolution, location and season. For seasons and regions when the 1.5km simulation shows larger percentage increases in threshold exceedance counts, e.g. in winter for precipitation and surface runoff, studies that consider only lower-resolution RCM simulations could be underestimating the range of potential future changes. This work shows that higher-resolution simulations are needed to understand the likely range of changes in precipitation and surface runoff.

Percentage increases in surface runoff are less than those of precipitation. This is likely due to the complex interaction of land cover (permeability) with surface runoff rates, and soil wetness will have an impact on how precipitation changes affect surface runoff changes. This interaction with the ground is what will ultimately control whether there is surface water flooding, rather than the rainfall depth per se. Using the surface runoff approach outlined here therefore adds value over a purely rainfall threshold based method. G2G is a process-based model that uses spatial data to characterise heterogeneity in the runoff response and simulates greater runoff in urban areas, but differences between results for precipitation and surface runoff will depend on the way the hydrological model conceptualises/characterises runoff-production processes; results for other hydrological models may be different.

This study also showed that the largest percentage increases in both precipitation and surface runoff are in winter rather than summer, consistent with Chan et al. (2014a), suggesting a shifting seasonal balance of surface water flood risk. For property impacts the largest percentage increases are also in winter; this follows-on from the largest increases in surface runoff. However, for property impacts it is the 12km RCM that shows the largest percentage increase, especially for the 'minimal' and 'minor' severity levels. This may be related to scale as the 12km surface runoff simulation may cover a wider area (i.e. more 1km^2 impact cells) than the 1.5km, which could affect the 'minimal' and 'minor' severity levels more due to there being more property impact cells at those levels than for 'significant' and 'severe' (Figure 2). Increased vulnerability for a particular season could affect the ability to respond and recover from such events. It should be noted that some of the exceedance counts for the Current time-slice are very small, so percentages changes can be very large; precise values are not meaningful in these cases, but it's the sign of the change that is important.

Only a single realisation of each time-slice was available due to the computational expense of running high-resolution RCMs. This could lead to a strong influence of natural internal variability in spatial results. Therefore, where appropriate, spatial averaging was applied to obtain more robust change signals. However, use of spatial averaging risks hiding local differences in response related to heterogeneity in landscape properties. This is particularly the case for surface runoff, which is affected by highly spatially variable factors like soil type and urban land cover, although precipitation will also be affected to some extent, via topographic controls. The UKCP18 project (Lowe et al. 2018) will provide an opportunity to extend the analysis using an ensemble of twelve realisations at 2.2km resolution covering the whole of the UK. In this case the 2.2km ensemble will sample uncertainty due to internal climate variability and parametric uncertainty in the driving model physics, but not uncertainty in the convection-permitting model physics itself.

5 Conclusions

This study produced the first estimates of future changes in surface water flood hazard and impact for southern Britain using a national-scale gridded hydrological model and high-resolution RCM data. The approach analysed potential changes in the frequency of surface water flooding using percentile-based precipitation and surface runoff thresholds, as well as spatially varying surface runoff thresholds for property impacts. It was found that the largest percentage increases are for precipitation rather than surface runoff, in winter rather than in summer and projected by the 1.5km RCM rather than the 12km RCM. The largest percentage increases in property impacts are projected to be in winter. Future surface runoff estimates such as these could be used to supplement rainfall estimates used for sewer/drainage design (Dale et al. 2017).

It is important to recognise that surface water flooding can happen anywhere, and is not always associated with urban areas and concrete. For example, there has been a dramatic rise in maize production to feed anaerobic digestion plants, and harvesting maize in late autumn (when the ground is often wet) can compact the soil meaning that rainwater is less easily absorbed and so more likely to produce surface water runoff and localised flooding (Bevan 2018). Such changes would not be simulated by the hydrological modelling applied here, but changes in land-cover, including urbanisation, could be accounted for in future work. Kaspersen et al. (2017) found that the relative influence of potential future climate change and recent historical urban development on pluvial flooding varied considerably between the four European cities they studied, so it would be interesting to investigate this balance in Britain. The inclusion of future urbanisation could be particularly important for flood damage assessments; Poelmans et al. (2011) suggest that future fluvial flood risk could be influenced more by urban expansion than climate change for a small sub-urban catchment in Belgium. The Impact Library applied here is based on a static set of receptor grids, but future work could allow for urban development.

Data availability statement

The impact library data that support the findings of this study are available from the Environment Agency, and from the Ordnance Survey through the Public Sector Mapping Agreement. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors with the permission of the Environment Agency and the Ordnance Survey.

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Tables

Table 1 Summary of the available RCM runs, including the Met Office's RCM run names (five characters starting with 'a').

Run number	Description	Run name	Time period
1	Current 12km	alqtj	Dec 1996-Nov 2009 (+run-in period from Apr)
2	Future 12km	alqtk	As above but for 13-year period in ~2100 with RCP8.5 emissions
3	Current 1.5km	alxmc	Dec 1996-Nov 2009 (+run-in period from May)
4	Future 1.5km	alxme	As above but for 13-year period in ~2100 with RCP8.5 emissions

Table 2 Extreme precipitation and surface runoff thresholds applied. The thresholds are the 99.9th percentile (1 day in 1000 days) of the precipitation and surface runoff calculated from the 13 years of Current time-slice (1996-2009) RCM data.

Duration (hours)	Thresholds (mm)			
	Precipitation		Surface runoff	
	12km	1.5km	12km	1.5km
1	8.6	14.6	3.2	5.7
3	18.1	25.9	6.5	9.8
6	26.2	34.6	9.0	12.4

Figure 1 The area of southern Britain covered by the G2G runs. Also shown is the division of the area into two regions, West and East (dark and light grey respectively), used for analysis of results (Section 2.4).

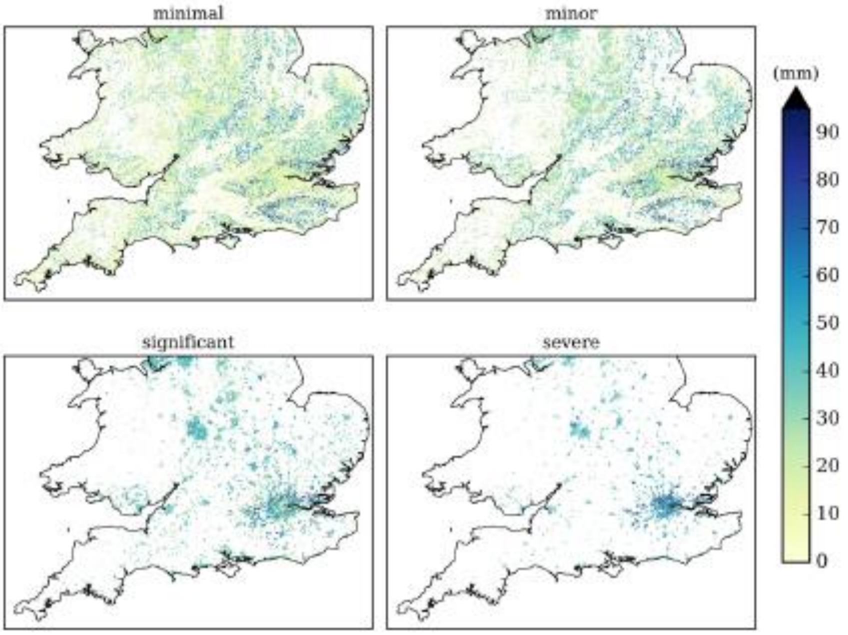

Figure 2 Spatially varying, 1 hour, effective rainfall thresholds for four different severities of property impact.

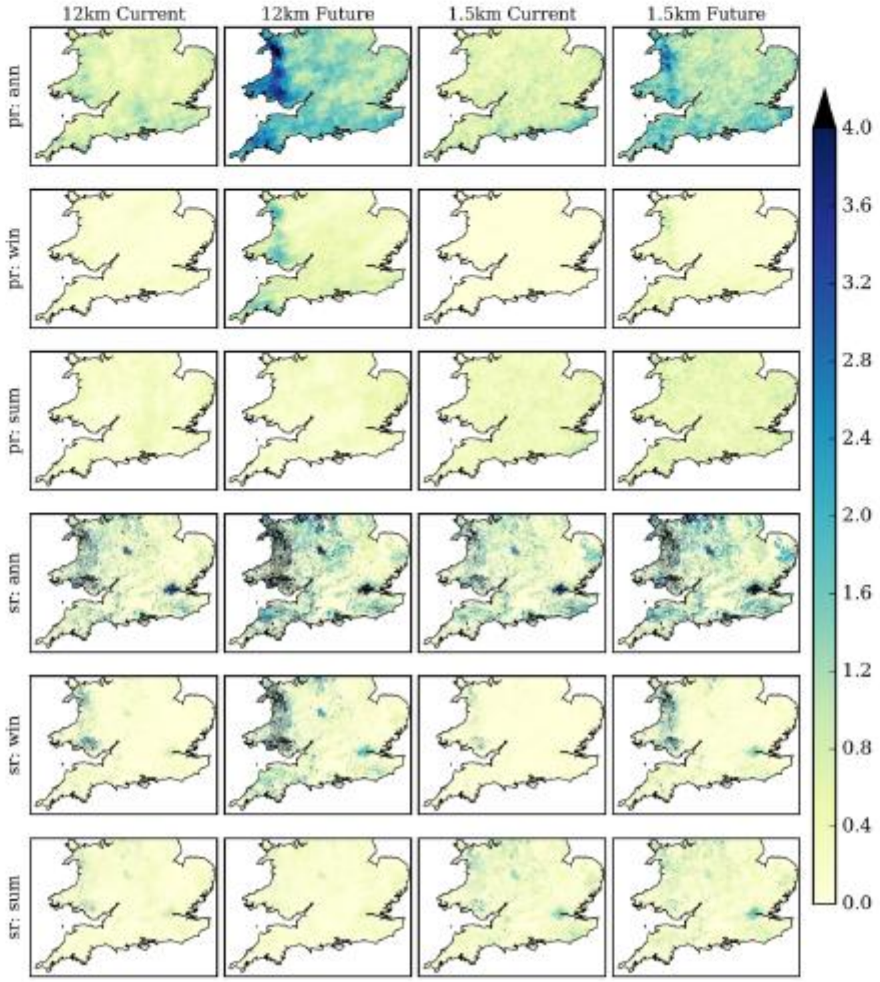

Figure 3 Annual, winter and summer exceedance counts of precipitation (top) and surface runoff (bottom) for 1-hour duration thresholds, for the four RCM simulations.

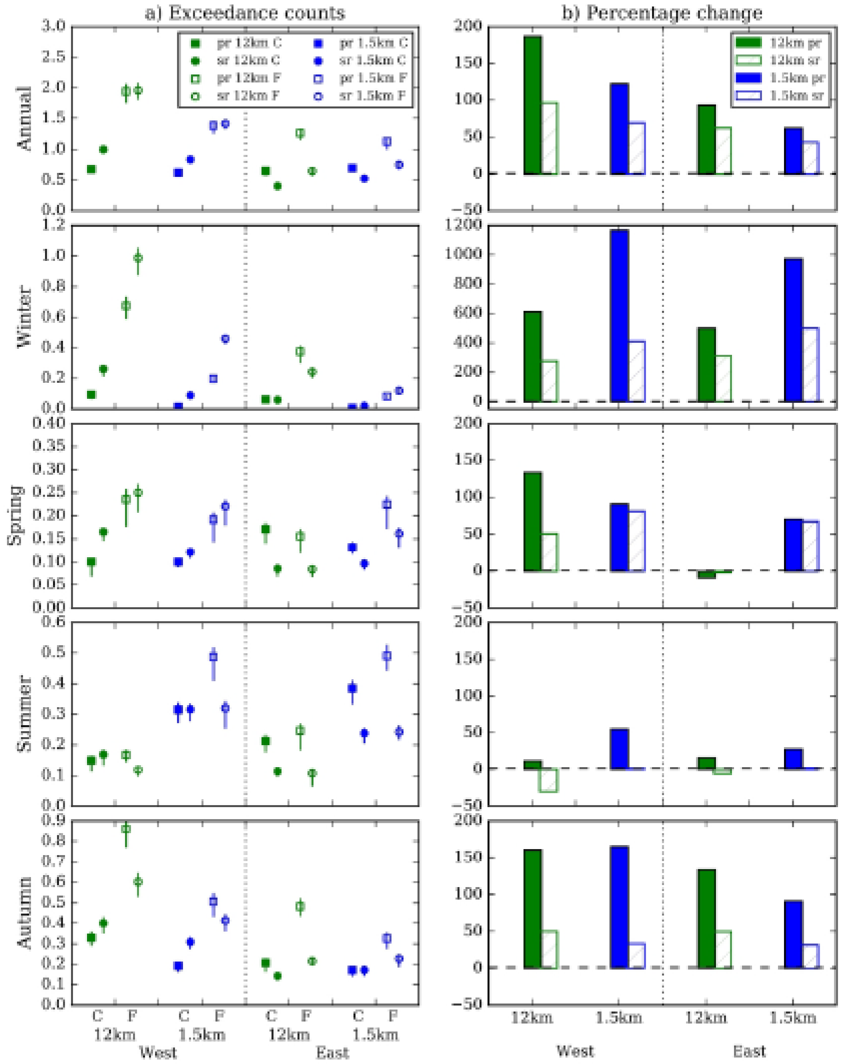

Figure 4 a) Regional average annual and seasonal exceedance counts of 1-hour precipitation (pr: squares) and surface runoff (sr: circles), for the 12km and 1.5km RCMs (green and blue) for the Current (C) and Future (F) time-slices (filled and open). The vertical lines show the range of counts given by jack-knifing. b) Percentage changes in exceedance counts (solid: precipitation, hatched: surface runoff).

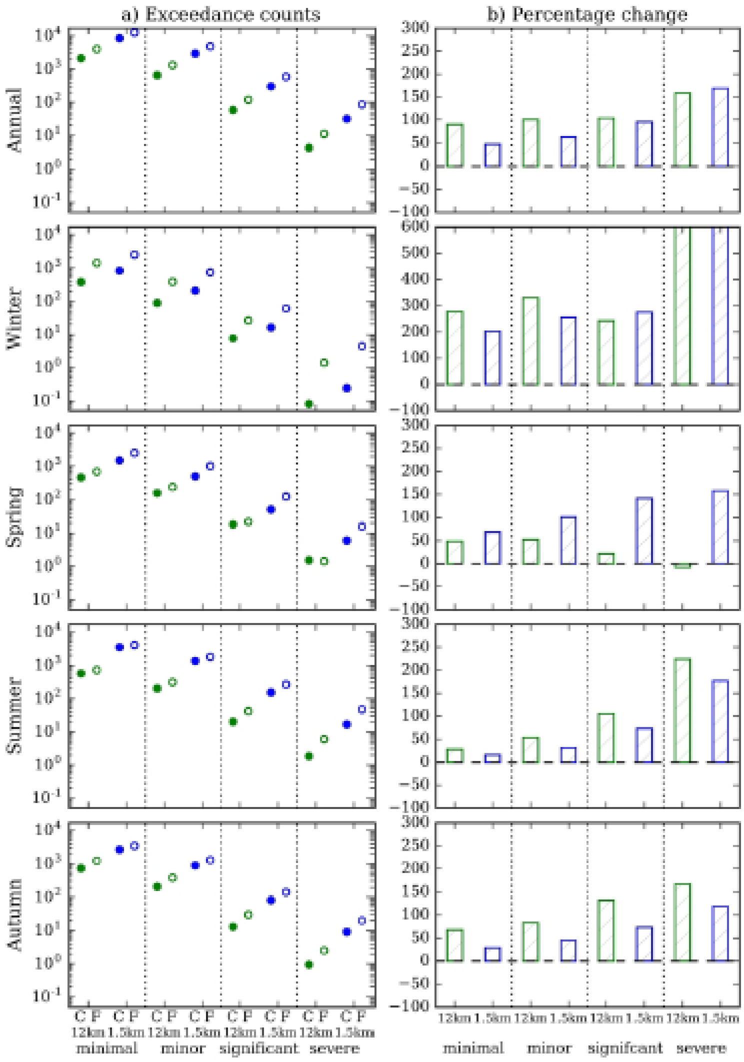

Figure 5 a) Annual and seasonal total (per year) exceedance of 1-hour surface runoff for the 12km and 1.5km RCMs (green and blue) for the Current (C) and Future (F) time-slices (filled and open) for four property impact severity thresholds. b) Percentage changes in exceedance counts. Note that the bars go off the scale for severe impacts in winter. The totals are for southern Britain.