FOOD RESEARCH PARTNERSHIP: RESILIENCE OF THE UK FOOD SYSTEM SUBGROUP

Severe weather and UK food chain resilience

Detailed Appendix to Synthesis Report

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SEVERE WEATHER AND UK FOOD RESILIENCE

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I. DEFINITION AND SCOPE

Severe weather is taken to mean any weather event that can cause significant impact to the UK supply chain. This includes the impacts of severe weather on UK production. It also includes impacts of severe weather outside the UK as it impacts on our food supply chains (via fluctuation in global supply of food and feed and also on price).

There is an important distinction between "high impact weather" and "extreme weather". Extreme weather is rare weather occurring at the tails of the historical distribution of weather events. High impact weather is a weather event that has high impact even if it is not climatologically extreme. With climate change, the shape and location of distributions of weather events will change, so it is possible that what was historically extreme will in future become more common (and therefore not, by a strict definition extreme)[1]. Similarly, as society changes the same weather event can change in its impact (e.g. population expansion onto flood plains makes the impact of any flood greater). Thus, the impact of weather on food supplies is a combination of the weather itself, and the sensitivity of different parts of the food chain to those impacts. This sensitivity will itself vary over time and space. For example, an event, such as a drought, in one place may have a limited local impact, but if the same drought occurs at a time when there are floods in another place, the impact is amplified. To avoid terminological complexity, we therefore use the term "severe weather" as a term that means unusual weather that has an impact on the food system.

The complexity of interactions between the global food supply chain and global weather means that the impacts of a particular weather event will vary with the location, timing and the overall context. The evidence is not available properly to describe with any certainty how variable weather will impact on food production systems and worldwide trade, but our contention is that we need greater investigation of what they *could* be, with perhaps greater consideration being given to reasonable "worst case scenarios". The UK food system may well be relatively resilient to weather, but there may sometimes be combinations of events, clustered in time and over space, which will lead to significant impacts on food availability. The weather in 2012 (drought to floods in the UK, drought, heatwave, floods across the rest of the Northern Hemisphere) cautions us to consider fully that weather may simultaneously impact in different places separated widely in space, and that therefore there is potential for widespread impacts on food supply. Given that the frequency of weather extremes is increasing, the potential for large impacts, and unprecedented ones, is growing[2].

I. HOW DOES WEATHER IMPACT PRODUCTION?

Severe weather can impact the resilience of the food chain by affecting soil (e.g. erosion caused by heavy rainfall), growing conditions and yield, amount and quality (by affecting temperature and water availability), harvesting and planting conditions (via dryness, wetness or snow, or by lack of seed availability from a previous poor year[3]), storage and transport logistics and the collective impacts working on price through the market therefore affecting access to food (including animal feed) as well as availability. A range of potential routes to impact are summarised in Table 1.

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[1] A recent influential paper (Coumou & Rahmstorf, 2012,Nature Climate Change DOI 10.1038/NCLIMATE1452) is titled "a decade of extremes" highlighting that historical extremes are increasing in frequency (and if so, by definition, are no longer extreme).

[2] Hansen, J., M. Sato, R. Ruedy, 2012: Perceptions of climate change: The new climate dice. http://www.columbia.edu/~jeh1/mailings/2012/20120105_PerceptionsAndDice.pdf

[3] As is a current concern for 2012 planting, as expressed by the NFU

Table 1. Summary of potential impacts of weather on production.

Weather event	Mechanism of impact	Impact
Rainfall	Affects pollination Impedes access: • Delayed mechanised activity including applying fertiliser, and plant protection products • Reduced time livestock on land • Mechanised activity on wet ground increases compaction Increases disease risk Waterlogging reducing growth Lodging of crops	Delayed agricultural activity, reduced yields, reducing quality, increased costs (e.g. feed bills for livestock kept indoors, drying costs for damp grain etc) Land left unharvested Potential increase in waste food due to impact on consumer choice/behaviour Higher harvesting cost Land abandonment (due to reduction in field capacity days)
Flooding	Impedes access Erodes soil, washes away nitrogen and other inputs Removes plants, drowns plants, lodges plants Reduces growth Livestock loss	e.g. harvest Long term yield loss Loss of yield, replacement planting Yield/forage loss Lost yield
Heat/drought	Increased stress (see Table 3 for crops) Heat stress (e.g. pre-sheering in sheep) Reduction in forage requiring supplementary feeding	Lost yield and quality (see Table 3 for crops)
High wind	Lodging of crops Loss of leaves/blossom in fruit Closure of UK ports Impacts on farm buildings, fences, hedges	Lost yield Lost yield Interrupts UK supply chain Increased repair bills
Snow/frost/hail	Access to forage for livestock causing condition loss, abortion, death Frost damage (e.g. horticulture) Crop damage	Lost yield Yield loss
Weather impacting on pests/diseases	Wind aiding migration of insects from the Continent and transmitting e.g. Bluetongue Disease impacts due to particularly favourable conditions for pests e.g. fire blight affects apples during spring blossom period and risk of spread maximum above 27 degrees (Defra AC0310). For many insects a warm winter followed by a hot spring and summer would allow multiple generations of pests increasing impacts exponentially	Yield loss Yield loss
Weather/air quality interaction	Hot still weather interacting with air pollution causes increases in ground level ozone which pollutes plant metabolic activity (wheat is sensitive). (Refs in USGCRP 2009)	Loss of yield

Crop and livestock growth, as well as farmer behaviour, are very plastic in that poor periods can sometimes be compensated for by change in growth or management. The impacts of severe weather therefore crucially depend on their timing. Table 2 highlights some potentially vulnerable times for crops and livestock.

Table 2: Sensitivity of processes to weather After Defra AC0301.

Crop Type	Examples	Vulnerable Process
Annual seed crops	Cereals, oilseeds, peas	Planting, establishment, flowering, seed formation
Annual vegetable crops	Brassicas, potatoes	Planting, establishment, development, lifting or harvesting, stress impact on quality
Annual Protected crops	Tomatoes	Quality, yield
Perennial fruit crops	Apples	Bud break, flower initiation, flower development, fruit growth and quality
Perennial Biomass Crop	Miscanthus	Establishment
Sheep		Lambing, heat stress pre-sheering
Cattle		Calving, lactation, growth, time on land impacted by ground water

Heat stress as an exemplar.

Recent research, using fine scale temperature recording, indicates the way that temperature extremes can impact upon yields[4]. For three crops, cotton, soy and maize, there is evidence of sharp declines in yield above threshold temperatures of about 30 degrees, especially in the time around anthesis (flowering). For maize, each degree day above 30 degrees centigrade reduces yield by 1% when water is available or 1.7% when water is not. This indicates that the impacts of temperature and drought interact. Given that the climate is warming, without further adaptation, area-weighted average yields in the US for cotton, maize and soy are predicted to decline this century by 30-80% based on the impact of temperature alone (with the variation in estimates largely depending on the climate change scenario). Thirty degrees centigrade is, similarly, a critical threshold for wheat, above which most UK varieties suffer steep reductions in yield.

[4] Schleneker, W & M.J. Roberts (2009) Nonlinear temperature effects indicate severe damages to US crop yields under climate change. PNAS 106: 15594-15598; Lobell, B.D. *et al* (2011) Nonlinear heat effects on African maize as evidenced by historical yield trials. Nature Climate Change 1: 42-45

Table 3; High temperature effects on development of different crops. From Defra AC0301.

Extreme Weather	**Physiological impact**	**Crops affected**
High temperatures in summer	Reproductive (flower) development impaired	Cereals, oil seeds, peas, tomatoes, apples
	Flower bud formation– effects seen the following year	Apples
	Crop development and yield impaired	Vegetable brassicas, tomatoes
	Crop quality impaired	Oil seeds, cereals, tomatoes, apples, vegetable brassicas
High temperatures in winter	Cold hardiness limited	Winter cereals, winter oilseeds, apples
	Early bud break and frost susceptibility	Apples
	Delayed curd induction	Winter cauliflowers
	Impaired flower development	Apples, blackcurrants

The historical scale of weather impacts on UK farming

The scale of risk to our local production is exemplified by the severe drought/heatwave that affected production in France and Northern Italy in 2003. Battisti (2009)[5] claims that "Italy experienced a record drop in maize yields of 36% from a year earlier, whereas in France maize and fodder production fell by 30%, fruit harvests declined by 25%, and wheat harvests (which had nearly reached maturity by the time the heat set in) declined by 21%".

Collation of data by the NFU exemplifies the range and scale of impacts (Appendix 1). For example, flooding in 2007 affected c 42000 ha of farmland, costing each farmer, on average, £89.5k; drought in 1976 had a cost estimated at £500m in terms of crop losses (which were about 500,000 tonnes less than 1975). To illustrate the internationality of production systems, the 2011 US drought led to >30% increase in soya for pig feed, with a considerable proportion (up to 25%) of UK pig farmers indicating they may be leaving the industry in 2012. Recent data shows the European Union pig herd is declining at a significant rate in response to higher feed costs. In the 12 months to June 2012 herd have decreased in Denmark (-2.3%), Germany (-1.3%), Ireland (-6.6%), Spain (-2.8%), France (-3.2%), Italy (-13%), Hungary (-5%), the Netherlands (-3.6%), Austria (-2.8%), Poland (-9.6%) and Sweden (-7.2%)

Current early estimates, compiled by the BBC, of 2012's wet summer on UK production indicate economic losses in excess of £1bn[6]. Provisional statistics on harvest yields for 2012 show that overall yields for cereals in the UK have dropped from 7.0 tonnes per hectare in 2011 to 6.2 tonnes per hectare in 2012[7].

Thus, there is considerable evidence that weather *can* have considerable impact on local production systems, and sometimes does. As exemplified in Fig 1, where a time series of agricultural production

[5] Battisti, DS 2009 "Historical warnings of future food insecurity with unprecedented heat" Science 323, 240-244

[6] The Cost of our wet summer", BBC Countryfile, (broadcast 7th Sept 2012)

[7] Farming statistics, Provisional crop areas, yields and livestock populations at June 2012, UK http://www.defra.gov.uk/statistics/foodfarm/landuselivestock/farmstats/

show considerable year to year variability; it is noticeable, however, that the fluctuations are asymmetric: negative impacts of severe weather are large, positive impacts are smaller.

Despite severe weather sometimes impacting in a significant way, historically, UK production has arguably been resilient. Whether this will continue to be the case depends on the way weather patterns change.

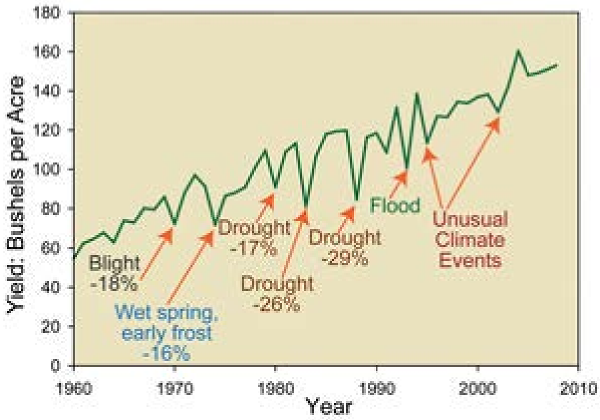
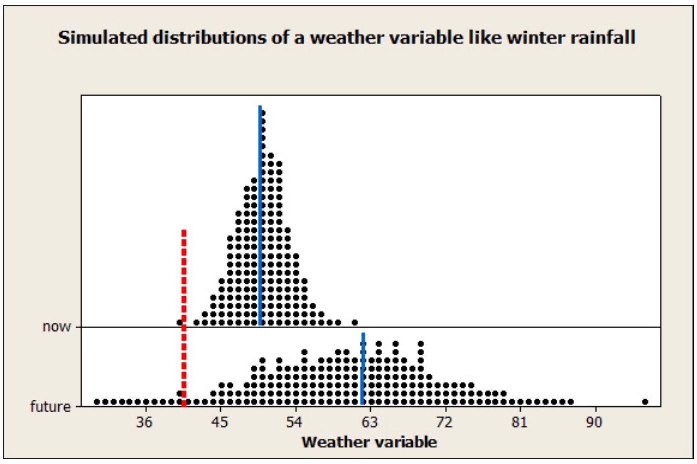


Fig. 1. Despite technological improvements that increase maize yields in the US, extreme weather events have caused significant yield reductions in some years. Source: USGCRP (2009) In the 1980s, 3 droughts occurred within a decade significantly reducing yields. Taken from http://www.epa.gov/climatechange/impacts-adaptation/agriculture.html July 13 2012

II. SEVERE WEATHER IS BECOMING MORE FREQUENT

There is considerable evidence that the climate is changing in both its average value and its variability (see Appendix 2 for a synthesis from the Met Office). As both averages and variances are changing, it implies that the shape of the distribution of weather events is changing[8]. In particular, there is now good evidence that extreme weather events are increasing in frequency at a considerable rate.[9]

As the shape of the distributions is changing, there are three crucial points that should be made:



1. It is quite common to make the first order assumption that extreme values will shift by the same amount as the average for a given variable, in the absence of any other guidance. However, there are plenty of reasons why this may not be a good assumption. For example, if, on average, winters are getting *wetter* it does not necessarily imply that dry winters may get *less* frequent and therefore a reduction in drought frequency. The figure to the right shows simulated data for the distribution of a weather variable, like winter rainfall, now and in the future. The future distribution is, on average, "wetter" (mean of 60 units compared with a mean of 50 units

[8] Hansen, J et al (2012) "Perception of climate change" PNAS www.pnas.orc/cgi/doi/10.1073/pnas.1205276109. The essence of this paper occurs in a range or preprints by the same authors e.g. See http://arxiv.org/ftp/arxiv/papers/1204/1204.1286.pdf

[9] See Hansen, above, and for a brief review Coumou, D. & S. Rahmstorf (2012) "A decade of weather extremes" Nature Climate Change DOI 10.1038/NCLIMATE1452 and IPCC (2012) A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA

now, indicated by the blue lines). However, if droughts occur when rainfall is less than, say, 40 units (the red dotted line) the future incidence of droughts will be >10x more common, even though winters on average will be wetter. Currently, there is insufficient evidence to understand how the shape (the variance and skew) of a distribution will change relative to the mean, so it is unwise to assume because a mean will change in a certain way then so will extreme values.

2. The impact of severe weather may be made worse by clustering in time. Extreme events are often described by their expected return time, which is expressed as a ratio (e.g. 1 in 20 years, that on average something will happen about every 20 years). The return time implies that extreme weather occurs randomly in time and that each year is equally unlikely to experience it. However, if weather is actually clustered in time then the impacts may be compounded (e.g. a single year of drought may have little impact, but two consecutive years of drought occur, the impact may be considerably worse). There are multi-year patterns in the weather driven by large scale oscillations (the Atlantic Multidecadal Oscillation, AMO, or the El Nino Southern Oscillation, ENSO) and some evidence to suggest temporal clustering of other variables (e.g. Mailier et al 2006)[10]. Although there is little knowledge of how temporal patterns will change, as well as extremes increasing (i.e. return time is decreasing) there are some indications that clustering is more common[11]. In other words, a 1 in 5 year return time may be realised as two consecutive "bad years" in a decade, rather than an event every five years. Furthermore, recent research indicates that changes in the Atlantic circulation may be responsible for the consecutive wet summers we have experienced in the last decade [12], and that this change may be a result of increasing anthropogenic aerosols in the atmosphere[13].
3. As with clustering in time, the way that weather plays out across space may compound the impact. Resilience will be high if weather impacting on one locality occurs when everywhere else is experience non-severe weather. However, if global weather patterns are such that many localities are affected in the same growing season, global food production can potentially be severely impacted. The obvious example of spatial correlation of weather events are the global impacts arising from ENSO. Thus, a local impact on production in the UK may be minor when everywhere else is "normal". However, if, like 2012, a bad year in the UK coincides with severe weather across the northern hemisphere, the situation is considerably worse. A recent paper highlights that during the baseline 1950s-1980s period, in any one year about 1% of the earth's surface experienced extreme heat (then defined as more than 3 standard deviations above the mean), now the figure is typically 10%[14]. Unprecedented extremes with values of >4-5 standard deviations now occur with appreciable frequency. To illustrate the issue: Defra internal analysis in March 2012 concluded that a UK drought may have marginal impact assuming that it affects UK production only. It also notes that if drought is more widespread across the EU there could be greater impacts, but does not consider the potential for impacts of bad weather at a greater spatial scale.

[10] Mailer, PJ et al (2006) Serial clustering of extratropical cyclones. Monthly Weather Review 134: 2224-2240
[11] E.g. Yang Ping (杨 萍) *et al* 2012 The characteristics of clusters of weather and extreme climate events in China during the past 50 years*Chinese Phys. B* **21** 019201

[12] Sutton, RT & B Dong (2012) Atlantic Ocean influence on a shift in European Climate in the 1990s. *Nature Geoscience* online 7th Oct 2012: DOI: 10.1038/NGEO1595
[13] Booth BBB et al (2012) Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature* 484, 228-232

[14] Hansen, J et al (2012) "Perception of climate change" PNAS www.pnas.orc/cgi/doi/10.1073/pnas.1205276109.

Much of our inference about future patterns comes from climate models, which may well contain a range of biases. For example, comparing data to model predictions of extreme rainfall, the authors of a recent paper [15] conclude: "Our results also show that the global climate models we used may have underestimated the observed trend, which implies that extreme precipitation events may strengthen more quickly in the future than projected and that they may have more severe impacts than estimated." In addition, for some climate phenomena (such as the way that large scale circulation patterns like the southern oscillation may change), inter-model comparison shows considerable variability[16]. Given that "it is difficult to rank models for their accuracy, ...any model integration can be considered equally valid, and those that indicate [worse] conditions imply a future potential risk"[17]. Thus, where there is currently no strong consensus from models does not indicate that there will be no change, and planning should consider the range of variation that different models predict.

Changes in UK weather that may impact upon production

As section II indicates, the potential for weather impacts on production systems is large. As climate is changing, so must our expectation of how farming may need to respond will change. Here we highlight some details of how UK extreme weather may change over future decades, although there are considerable uncertainties as to the extent (see Appendix 2, provided by the Met Office, for further details).

Extreme precipitation: There will be increases in extreme precipitation in winter, spring and autumn for most regions of the UK during the 21st century. Projections indicate a greater increase in short-duration extreme precipitation events rather than longer-duration events, and a greater proportion of the total precipitation from heavy rainfall days. There is however large variability between projections regarding the magnitude of changes in precipitation and especially the magnitude and return period of extreme precipitation events. During summer, there are large projection uncertainties (including the sign of the change, indicating potential for both increases and decreases in extremes) regarding changes in precipitation. IPCC (2012)[18] suggests that the return time of a 1-in-20 year rainfall event will decrease to approximately 1-in-10-to-12 years by mid-century for the UK (as part of C and N EU).

Floods: Whilst there is good agreement between models regarding projections of increased heavy precipitation events over the UK during winter, autumn and spring; the complexity of causation underlying flooding makes projections unreliable. The UK Climate Change Risk Assessment for Floods and Coastal Erosion Sector report[19] suggests an increase in heavy precipitation events in winter could result in larger volumes of runoff with potential negative impacts on flood risk; particularly as a result of the projected increases in winter (and to a lesser extent spring and autumn) rainfall. In addition, coastal flood risk will increase with sea-level rise over the 21st century.

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[15] Min, Seung-Ki et al (2011) Human contribution to more-intense precipitation extremes Nature 470, 378-381

[16] Guilyard, E et al (2012) A first look at ENSO in CMIP5 available at http://www.gfdl.noaa.gov/~atw/yr/2012/guilyardi_etal_2012_clivex.pdf

[17] P32 in Forster, P et al (2012) Food Security: near future projections of the impact of drought in Asia. Working Paper from the Centre for Low Carbon Futures. Available at http://www.lowcarbonfutures.org/

[18] Field, C.B., et al. (eds.) (2012). A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA

[19] Ramsbottom, D., Sayers, P. and Panzeri, M. 2012: Climate Change Risk Assessment for the Floods and Coastal Erosion Sector, http://www.defra.gov.uk/environment/climate/government/

Droughts: Due to natural variability and projection uncertainty it is not yet possible to robustly predict changes in UK meteorological droughts (based on cumulative monthly precipitation anomalies). There is general agreement between projections for there to be an increase in meteorological drought occurrence over the UK during the 21st century, however the strength of the trend, and in some cases even the sign of the change, can vary for changes in short- and long-term meteorological droughts with different model ensembles. The impact of any drought will depend on its duration and its severity. In addition, it will depend on temperature as droughts coupled with high temperatures have larger impacts on yields[20] as well as high temperatures influencing a range of social factors that impact upon water availability for agricultural purposes.

Temperature: In the UK there will be increases in the average and extreme temperatures during the 21st century. Projections indicate that cold temperature events will decrease in a future warmer climate and that heat waves (compared to the baseline period, 1961 - 1990) would be more intense, more frequent, and last longer. IPCC (2012) suggests that the return time for a 1-in-20 year hottest day will reduce to 1-in-2-to-5 by mid-century[21] . Although there is good agreement between model predictions regarding temperature changes over the UK, in the short term the natural variability dominates over the changes caused by anthropogenic influences.

Other weather: The IPCC's SREX Report highlights that there is general agreement between projections of an increase in extreme winds over northern Europe during the 21st century. Projections indicate only small changes in future synoptic scale systems, and their impact on mean climate conditions. The frequency and strength of extra-tropical storms as well as (blocking) anticyclones are projected to remain relatively stable. Although small changes in the position of the North Atlantic storm track are possible, Murphy *et al.* (2009)[22] found the projections to be inconsistent between different models and different model variants.

III. IMPACT OF THE CHANGING WEATHER ON UK FOOD CHAIN RESILIENCE

Potential impacts of severe weather on UK production

Previous work has concluded that changing weather patterns may not have high impacts. For example, Defra projects AC0301 (2008)[23] and AC0310 (2010) examined aspects of severe weather and its impacts on crop/livestock production under climate change. The general conclusion from AC0301 is that as drought and heatwaves become more common, phenological changes to the seasonal cycle mitigate the risk as anthesis will occur earlier in the year. In other words as the growing season is advancing, the peak of heat risk occurs increasingly after harvesting. This implies that inherent plasticity in the life cycle of the crops will act as a resilience mechanism, ensuring that production irons out a degree of likely changes in climate.

However, whilst this may be true "on average" (i.e. a July heatwave in 2050 won't have the same impact as a July heatwave today because harvesting may have happened), it is not necessarily the case. As discussed above, average weather and its variance may become decoupled. This means that extreme heat may be more likely in Spring than hitherto, or if temporal patterns change, a dry winter may be followed more often by a hot spring, exacerbating the impact of heat. Thus, if either

[20] Lobell, B.D. *et al* (2011) Nonlinear heat effects on African maize as evidenced by historical yield trials. Nature Climate Change 1: 42-45

[21] Field, C.B., et al. (eds.) (2012). A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109-230.

[22] Murphy, J. Et al. 2009: UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter. http://ukclimateprojections.defra.gov.uk.

[23] AC0301 at http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&completed=0&ProjectID=14424. AC0310 at http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=16590

or both of these assumptions are violated (and the extent to which they will hold is unknown), there is little real evidence to support the conclusions that plasticity in the biology will enable production systems to maintain their resilience against climate change. For any particular event, the impacts could be larger (e.g. extreme heat in May may not be as absolutely hot as it could be in July but it could still be sufficiently hot in future to prevent function).

The likelihood of severe weather impacting on UK production is probably increasing, with the potential for significant reductions in yields of up to up to 30%. As Hansen has written, the systematic shift in extreme temperatures occurring is akin to "loading the climate dice"[24]. To further his analogy: during the historical baseline period the climate distribution was divided into three areas: hot, cold and average, each being equally likely. This could be represented by a die with two blue, two red and two white faces. In any roll of the die, a hot, cold or average summer is equally likely. The analogous die now would have 4 red sides, not two, so the die is loaded towards extremes of heat.

Perhaps a UK drought coupled with a heat-wave gives the potential for greatest impact – as water is necessary for growth, plant development and plant cooling and the hotter it gets the more there are competing demands on water from society. Cumulative periods of rain, summing to extreme weather (as summer 2012)[25], also can markedly affect yields. UK agriculture is at risk from flooding, as 57% of Grade 1 agricultural land is below the 5m contour, although, whilst potentially severe in a locality, are arguably less likely to have a spatially extensive impact necessary to significantly reduce national production. Notwithstanding this, a widespread inundation of the Fens may create a significant impact given that 40% of the vegetables produced in England are produced there.

As 2012 has indicated by going from one of the driest periods on record to one of the wettest, as variability increases, uncertainty generally increases. This provides the biggest challenges to resilience as what *may* happen in a given year is increasingly uncertain, requiring planning for simultaneous excess and lack of water.

Potential impacts of severe weather on worldwide production

As exemplified by horticulture, the resilience of the UK food system does not inherently depend upon local production. Approximately 90% of all our fresh fruit is imported. Of indigenous fruit consumed, we produce about 40%. We import at least 75% of our vegetables with about 40% of the indigenous vegetables produced in the UK. We are more than self-sufficient in fresh potatoes but import processed potato products (generally frozen) because they are cheaper. The real issue for the UK food chain is therefore the impact of severe weather on other countries.

There have been a considerable number of studies around the world charting the potential impacts of climate change and extreme weather on local production. Many look ahead into mid-end century. An exception to this is Forster et al (2012)[26] who look at projections for the 2020s-2030 on the impact of climatological drought on production of wheat, maize and rice in Asia. Although the change in drought duration, frequency and severity over this timescale appears small, the potential impacts on production are large, with China, Pakistan, Mongolia and Afghanistan being the worst affected countries. As China is the largest producer of wheat and rice globally, and also the largest producer of maize in Asia, there is increasing potential, over the next decade, for drought to impact on the global market. Indeed, Forster's report highlights the need for drought adaptation measures to be developed with urgency.

[24] Hansen, J et al (2012) "Perception of climate change" PNAS www.pnas.orc/cgi/doi/10.1073/pnas.1205276109

[25] Summer 2012 has been the wettest for 100 years, and therefore is cumulatively has been "extreme" weather, even if the daily weather itself has not been extreme.

[26] Forster, P et al. (2012) *Food Security: Near future projections of the impact of drought in Asia* http://www.lowcarbonfutures.org/

The extent to which impacts on UK resilience occur will depend on the potential for substitution of sources or products on the global market. This potential will partly depend on the geographical spread of production, as well as the extent to which bad weather may be correlated across large spatial extents. In 2011, there were extreme weather events across the globe, all connected with the El Nino Southern Oscillation (ENSO) [27]. The impact of this on agricultural production was many billions of US dollars[28]. The situation both with respect to the extent of weather extremes across the northern hemisphere, and the impacts on production, in 2012 are, if anything, worse than 2011, though figures are not yet available. The FAO Cereal Supply and Demand Brief (Sept 2012)[29] summarises the situation:

> *Continued deterioration of cereal crop prospects over the past two months, due to unfavourable weather conditions in a number of major producing regions, has led to a sharp cut in FAO's world production forecast since the previous report in July. Based on the latest indications, global cereal production would not be sufficient to cover fully the expected utilization in the 2012/13 marketing season, pointing to a larger drawdown of global cereal stocks than earlier anticipated. Among the major cereals, maize and wheat were the most affected by the worsening of weather conditions.*

Non production impacts on food availability

Beyond the field, there is the potential for a range of weather-related impacts on food chain logistics (storage and transport). These include:

Higher ambient temperatures coupled with greater levels of humidity could potentially give rise to increased microbial loadings in susceptible foods particularly during their preparation, storage and distribution. This in turn may result in increased risks of foodborne disease from pathogens as well as possible natural chemical contamination from, for example, cereal mycotoxins or shellfish toxins. Improved and more rigorous temperature and humidity controls would therefore be required across those food chains that were affected.

Winter weather (snow, fog, port closure during bad weather), may be involved in interrupting food-chain logistics in impacted areas. The assessments are that extreme cold events will decrease in frequency not, as with rainfall, drought and hot temperatures, increase in frequency. Given the historical resilience to winter weather, the risk of this being an increasing problem, in the absence of an increase in winter blocking weather (as in the cold winter of 20010/11) is low.

The impact of any severe weather effect on supply may be amplified by consumer perception of supply shortfalls, leading to panic buying and siege shopping. However, this is likely to be localised in time and space (e.g. to short-term supply interruptions affecting transport logistics). The impact of most production shortfalls will be more gradual and felt through food price changes (see below).

Food Industry perspective on weather impacts on food production

With increasingly global markets for agricultural raw materials, extreme weather events around the world, such as droughts, floods and wildfires can have significant implications of the supply and cost of agricultural raw materials to the UK food industry as well as for food prices.

For example, the biggest factor affecting the supply of agricultural raw materials in 2010 and early 2011 was extreme weather conditions across the world which brought about poor harvests of food

[27] Trenberth, KE (2012) Framing the way to relate climate extremes to climate change. Climatic Change DOI 10.1007/s10584-012-0441-5

[28] Coumou, D. & S. Rahmstorf (2012) "A decade of weather extremes" Nature Climate Change DOI 10.1038/NCLIMATE1452

[29] http://www.fao.org/worldfoodsituation/wfs-home/csdb/en/

crops. Most of the poor yields of staple foods were due to extreme weather conditions linked to El Niño/ La Niña. Wildfires and drought in Russia, Kazakhstan and Ukraine led to a significant fall in the production of cereals. There was also significant unseasonal wet weather and flooding across parts of the world including Pakistan, Brazil, Australia, Sri Lanka, the Philippines and South Africa.

Crop failures overseas resulting from extreme climatic conditions contribute to rising agricultural raw material prices and this is exacerbated by the use of export prohibitions and restrictions. For example, Ukraine and Russia imposed restrictions on exports of wheat after crop failures in 2010. This in turn triggered panic buying in the Middle East and North Africa which are reliant on wheat imports from Russia.

Supply shocks caused by adverse weather conditions can often be offset by the use of food stocks stored by suppliers, dampening the impact on price levels. Between 2007 and 2008, stock levels of many food commodities were at extremely low levels, particularly rice and wheat, which exacerbated price increases when the initial supply shocks hit. By 2010, stock levels for some commodities had recovered but not enough to compensate for further supply shocks.

Food producer prices tend to move slowly relative to the underlying raw material costs. The time lag which exists between food producer and commodity prices is often the result of fixed-term contracts with suppliers (forward buying) and futures contracts traded on commodity exchanges (hedging). Food manufacturers can lock in commodity prices up to 12-18 months, long enough to cover a season of bad weather but short enough for underlying demand changes to feed through.

Overview of Economic impacts of food prices and the relationship with food-for-biofuels

Price shocks are the most noticeable feature of extreme event by those not directly affected by them. Food consumers in the UK and EU are unlikely to experience food shortages *per* se, instead they are likely to experience short to medium term increases food prices. The impacts of which will be felt by food consumers and upstream food and agriculture. To some extent, the EU food consumer has been insulated from volatility in global food commodity markets through the operations of the CAP which kept prices artificially high. The increasingly open UK/EU trading system means however that the UK/EU is vulnerable to extreme events beyond the frontier and in a sense the reform of the CAP has substituted high but stable prices with lower more variable prices. Paradoxically therefore, the more open, and therefore resilient global system may increase exposure to price risk in the EU. It is important to recognise that whilst the CAP might have reduced the exposure to price risk in the EU, it is likely to have contributed to increased volatility on the global market. Similarly, the imposition of export bans by some countries during the 2008 price spike has been shown to have worsened the international situation.

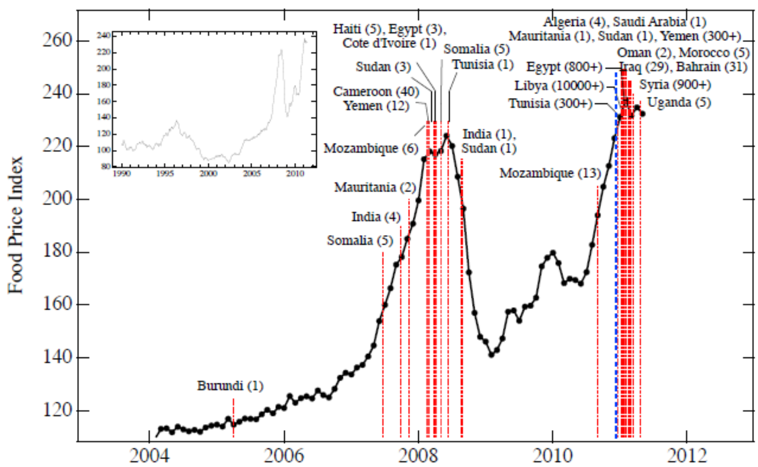
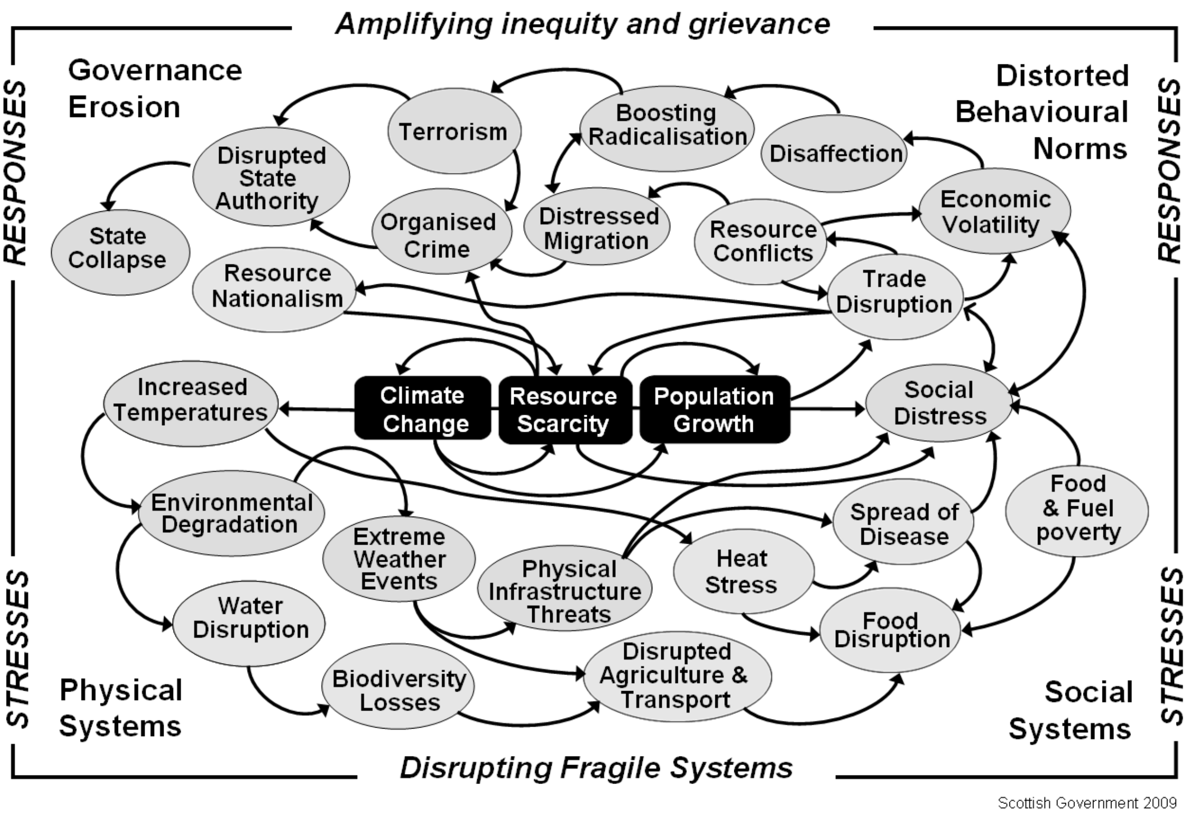


Fig 2. Food prices and social unrest in North Africa and the Middle East. From Lagi et al (2011). The black line indicates the FAO food price index, and the vertical redlines are where there was civil unrest in North Africa and the Middle East, with the numbers in brackets indicating estimated deaths.

Globally, food price volatility is an important cause of civil unrest (Fig 2)[30]. Therefore, any severe weather impact on the production of globally traded commodities is likely to increase food price inflation. That has the potential to exert a severe impact on the poorest people and in the worst cases destabilise society. The food price spike in 2007/8 and 2010/11 led to widespread social unrest. This in turn has the potential to further disrupt the global market, exacerbating the impact further.

Food price inflation and its potential to undermine civil society is less likely in the UK, but cannot be excluded. The diagram below, produced by the Scottish Government, highlights the threats to national security driven by a range of factors, including food/fuel poverty, resource scarcity and climate change.



Price volatility in agricultural commodity markets is not a new phenomenon; it is the result of inelastic demand and short term supply combined with supply that is variable dependent on the weather. Low elasticity of demand and supply means that any shock in supply (or demand) produces relatively large fluctuations in price, and this is exacerbated by the trend (from policy and the food chain) to reduce stocks. Recognition of the phenomenon of low elasticity lies behind much of the traditional intervention in agricultural markets in order to protect farmers against the downside risk of good harvest. Interestingly, in developed countries at least, there are few, if any, examples of a counterpart designed to protect consumers against the upside risk. One explanation for the tendency for foods to exhibit inelastic demand is the lack of close substitutes. Thus, increasing the diversity of the diet to make it more resilient would be expected to increase the elasticity of demand and thereby contribute to a reduction in price volatility. Equally in production the availability of substitutes is a major determinant of resilience. For example, a Defra study on soy

[30] Lagi, M., Bertrand, K. Z., & Bar-Yam, Y. (2011). The Food Crises and Political Instability in North Africa and the Middle East, accessed at http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1910031

for livestock feed[31] concluded that were there to be a catastrophic impact on soy production through the emergence of a new pest, severely curtailing US and S American production over a decade, substitution in space and type would be possible. However, it was unclear the extent to which substitution would impact on prices.

It is important to recognise that the impacts of price spikes are not even across people, sectors or crops. In considering the food consumer, food is a much larger portion of expenditure for low income families; therefore the impact of a price increase is correspondingly higher. Regarding the different agricultural sectors a given price increase may have quite different impacts across sectors. For example, whilst the arable sector may benefit from an increase in cereal prices, this would have an adverse impact on the livestock sector. Finally the degree of processing associated with a product will have an impact. Agricultural commodity value is a small proportion of retail price of most foods, therefore as we move down the food manufacturing chain the impacts of a food commodity price shock are likely to be reduced. Possible exceptions to this include fresh produce.

As has been argued above, state intervention in markets often risks exacerbating the problem of excess volatility. Intervention is justified however where circumstance prevent the efficient operation of a commodity market . A number of distortions may exist. For example, "thick" markets are generally more robust than "thin" markets. Isolating part of the market therefore reduces the capacity to absorb supply shocks in one part of the market. Examples of interventions which may increase volatility include restrictions on international trade and, as will be discussed below biofuel mandates. In this context the behavioural response of both consumers and policy makers to a shock can influence the resilience of the system as a whole. In general, what might be termed panic measures, such as export bans on the part of policy makers or hoarding on the part of consumers are likely to amplify the impacts of a shock on price.

Whilst the general principle of thick markets being more resilient holds a number of caveats apply. Thus, the increased capacity of integrated markets to absorb shocks is effectively a form of hedging and requires that risks affecting different parts of the market are uncorrelated. If risks are correlated however, increased integration can be counterproductive. For example during 2010 drought in Russia and floods in Pakistan were both attributable to the same climate phenomenon and therefore correlated. As a result, the adverse impacts on agricultural productivity on food prices arising from one event were reinforced by the other. One method to increase the thickness of markets is stockholding. This can therefore be effective in reducing volatility but it needs care, as there is some evidence to suggest that public stocks crowd-out private stocks.

The discussion serves to highlight the delicate balance which exists when considering interventions in agricultural commodity markets. Reductions in the levels of agricultural support potentially raise the levels of price volatility experienced by consumers to unacceptable levels. Equally, intervention in commodity markets, whether directly concerned with reducing volatility or with other objectives needs careful consideration in order to minimise secondary impacts on volatility elsewhere in the food system.

Finding ways for local markets to integrate better with global ones would expose some parts of the world to "foreign" shocks that they were previously insulated from (and avoid extreme local volatility), sending market signals to cause supply responses. This may generally be better as domestic production and thus market volatility is rising everywhere, so it ought to be better to be a part of world markets than not. This increase in the portfolio of production countries would shift the balance of export markets away from the very few big hitters. Relatedly, perhaps the biggest gain would be to depoliticise food in China so they start following market signals. It goes without saying that subsidies (even those decoupled from production) remove the impetus to respond to market

[31] Department of Environment, Food and Rural Affairs, Horizon Scanning and Futures – Supply Disruption Scenario for Soybean, October 2010.

signals. EU production, for example, showed a relatively small response to the 2007/8 food price spike, which may be a combination of the dampening impact of subsidies, coupled, for example, with agri-environmental scheme agreements reducing flexibility in local land use changes. It is also worth remarking here that the trend towards localisation that is favoured in some quarters may lead to a less resilient food system.

A further example of an intervention which effectively "thins" a market having an adverse impact on price volatility is the "biofuels' mandate". The mandate operates by compulsorily diverting a proportion of grain production to biofuels.

Sustainable biofuels can play a role in helping to meet demand for renewable energy supplies and in reducing greenhouse gas emissions. As this happens it places pressure on the food supplies and may lead to price increases. This may be acceptable if biofuels are a cost effective way of reducing GHG emissions however the large subsidies which exist at present suggest that this may not be the case. A distorted biofuel market may result in adverse impacts on both the level and variability of food prices. The position is further complicated by the range of raw materials and production methods currently in use and continuing uncertainties over the potential of new (second generation) technologies to address some of the sustainability challenges involved. The economic and social impacts of biofuel production also vary according to the relative prosperity and/or development needs of the countries concerned.

The G20 summit in June 2012 concluded that there was a need for further analysis of the relationship between biofuels production and the availability of food supplies, the response of agriculture to price increases and volatility and the factors contributing to environmental sustainability. A recent working paper from Defra[32] suggests that, by making the biofuels mandate more flexible, it can help to dampen price volatility:

"Grains and oilseeds produced for use in biofuels could be allowed to flow into animal feed or human food markets during temporary spikes in the price of agricultural commodities. Currently this is strongly discouraged from happening by legal requirements to blend biofuels with conventional transport fuel (often called biofuels mandates or blending obligations), but temporarily relaxing these requirements could allow agricultural markets to work more efficiently and reduce the size of a price spike. A system of flexible mandates would in effect create a 'virtual grain store'. Biofuels mandates have led to increased agricultural production relative to a state of the world where there are no biofuels mandates - this extra supply could follow market forces onto food or animal feed markets during a price spike, if the mandates allowed it."

The research shows that up to 15% of a hypothetical spike in the price of "coarse grains" could be avoided if the European Union removed its biofuels mandate at the same time as prices started to spike (coarse grains include maize, barley, oats etc.). The work also finds that similar action in the US could avoid over 40% of a hypothetical spike in coarse grain prices."

Government intervention is not the only method of reducing the exposure of key actors to price risk. Alternatively, commodity derivatives provide a market mechanism for reducing the impact of price shocks. Thus commodity futures are a mechanism for transferring risk to those that are willing to take it. Some argue that the increased involvement of non-food commodity traders (speculators) in the food commodity derivatives is a reason for increased volatility of commodity prices. One reason for the interest of non-food commodity traders in commodity futures is that food commodity prices are not well correlated with non-food and the food commodity derivatives provide an effective hedge against price risk in the non-food commodities. In a sense this is an extension of the thickening of real commodity markets by breaking down the barriers between markets, be they international boundaries of policy boundaries such as biofuel mandates. The involvement of non-food commodity traders should therefore reduce the impact of price shock but the reference point

[32] Durham, C et al 2012 http://www.defra.gov.uk/publications/2012/06/27/pb13786-biofuels-food-security/

should not be the commodity price on its own but the commodity price as modified by the use of a derivative contract.

IV. NEED FOR GOVERNMENT RESPONSES TO EXTREME WEATHER'S IMPACT ON UK FOOD RESILIENCE.

UK Production

The Government has well worked mechanisms for dealing with severe conditions. Perhaps the most relevant agriculturally impacting condition requiring government response to mitigate impacts occurs during drought. As a case study, we review the response to this year's drought, coordinated by Defra .

Broadly the drought started with the dry winter in 2010-11 and the dry and unseasonably warm spring in 2011 which led to low river flows and had an impact on the environment and agriculture. The second dry winter in 2011-12 meant that many farmers were unable to fill their winter storage reservoirs and rivers and groundwater supplies were low leading to pressure on the public water supply which led to some temporary use bans.

Government responded by holding drought summits to understand the impacts on different sectors, share information and ensure that actions were planned and co-ordinated across sectors. Environment Agency put in place flexible regulation to enable abstractors to take water when rainfall events led to higher flows and also extended licence periods to enable farmers to fill reservoirs beyond the usual end date for their abstractions. They worked with farmers and local abstractors groups on voluntary restrictions and to support initiatives to share water and make best use of what was available.

Following the second dry winter, Ministers set up a National Drought Group (NDG), chaired by the CEO of Environment Agency to co-ordinate the drought response and to plan ahead for the possibility for a third dry winter, ensuring early action was taken to mitigate any impacts. The NDG had a number of sub groups, of which land and agriculture was one. The sub groups were tasked with considering the actions they could take individually, as a sector and with support from Government or across sectors to manage an ongoing drought. The NDG will be considering the outputs of the sub groups, including recommendations for future actions to manage droughts and lessons learned from this drought.

The current year has emphasised that climate extremes are now common. It is therefore likely that we will continue to experience a range of varied weather, with lower expectation of historically "average" weather. This heterogeneity of risk is a challenge to recognise and adapt to – it may well be possible to have simultaneous droughts and flooding in different parts of the country in future. As the Forster report[33] indicates, climate change impacts are with us now and adaptation is urgently required to circumvent issues getting worse over this coming decade.

UK logistics

Severe weather can disrupt the logistics of UK food supply in a number of ways – heavy snow, floods or fog causing roads to close, high winds or coastal flooding closing sea ports which handle over 90% of imported food.

The UK food chain is inherently resilient due to the diversity of suppliers, retailers and sources of imported food. However, the just-in-time nature of the UK food chain does mean that severe weather may cause significant disruption, albeit this likely to be over a timescale of days, or at most a week or two in the case of severe weather.

[33] Forster, P et al. (2012) *Food Security: Near future projections of the impact of drought in Asia* http://www.lowcarbonfutures.org/

The Government has commissioned research on the resilience of UK ports, and on the energy dependency of the UK food chain. Both of these reports are due to report their findings in the autumn of 2012.

The Government and the UK food chain have contingency plans in place for disruptions to the supply chain. The impacts of severe weather can often affect other the food chain indirectly, such as through making staff unable to access the workplace, or disrupting the supply of fuel.

In May 2012 there was the potential for fuel tanker drivers taking industrial action and disrupting the supply of fuel within the UK. The result of this would have been very similar to a disruption caused by severe weather, and so the response of Government and industry is relevant.

The Government and industry worked closely together, primarily through the Food Chain Emergency Liaison Group, a standing group of industry and sectoral bodies set up to support planning and two-way communication between Government and the food chain during actual and prospective emergencies.

This method of communicating between Government and industry proved an effective method for preparing response to the disruption from potential industrial action. It also bears relevance to the response both Government and industry would have to any disruption caused by severe weather.

It is not just the physical disruption of the UK food chain that can cause problems. The perception of what may happen may be just as important in terms of impact. If consumers perceive there to be a risk of a lack of food it can result in panic buying.

This is when fear grips consumers and buying of basic commodities seems to spiral out of control. It leads to empty shelves (or forecourts), long queues, personal stress, social tensions and media hysteria. The term "panic buying" is rather loaded; indeed, its use by commentators can reinforce the phenomenon. Consumer stockpiling or speculative buying may be more objective terms.

An example of consumer stockpiling arose during the recent fuel dispute in April-May 2012. Although there was no dispute and no shortage of fuel, there was a perception of a risk of shortage. This caused a surge of consumers to fuel pumps, thus creating its own shortfall.

The media play a key role in this and the rise in social media shows the importance of clear and joined up messaging between both Government and industry very important. This is where networks between Government and industry, such as the Food Chain Emergency Liaison Group, can work well in ensuring the media and consumers get clear and reassuring factual information.

Government action to reduce the risk of panic buying has to be part of a coherent strategy to manage the overall situation; statements intended to allay public fears will be counter-productive unless the public can see that Government and the industry are working effectively together to avoid disruption, of to minimise and overcome it once started. Statements must also be evidence-based and capable of standing up to scrutiny from "independent experts" and the media.

Global trade and productivity

As described above, food price volatility can be increased by market interventions that de-risk farmers for poor harvests (at the expense of providing consumers with the consequent risk of price increases). Ensuring this producer vs consumer risk is optimised is a route to reducing volatility in prices.

The Government actively monitors food prices and the drivers behind changes in commodity prices. Research into this area has shown that the key drivers behind changes in food prices are global agricultural commodity prices, exchange rates, and fluctuating oil prices.

The Government is working nationally and internationally to promote open global markets and boost trade, which help keep food prices at affordable levels for households in the UK. The Government works with G20 partners to improve market information through the Agricultural Market Information System and discourage inappropriate reactions to market events, such as the use of export bans, through the Rapid Response Forum. In general, what might be termed panic measures, such as export bans on the part of policy makers or hoarding on the part of consumers are likely to amplify the impacts of a shock on price.

In the event of reductions in supply, portfolio theory implies that where substitutability is high, volatility will be reduced. This implies the need for an encouragement of both dietary breadth amongst consumers, and a food manufacturing system that does not overly rely on a small number of difficult-to-substitute ingredients. Issues of substitutability have been discussed (e.g. Defra Green Food Project) but with an angle of reducing environmental impacts. Considerable work is on-going on issues of consumer behaviour and dietary choice.

For example, the Green Food Project recommended that a the steering group should facilitate a wider, more sophisticated debate across the whole of the food chain about the role diet and consumption play in the sustainability of the food system. The Department of Environment, Food and Rural Affairs will play a key role in this debate. In addition, the Global Food Security Programme is developing a significant investment in research in this area.

A system of flexible biofuels mandates would in effect create a 'virtual grain store'. International concerns regarding the distortionary impacts of biofuel mandates are increasing. In this context, the European Commission and Member States should bring forward their planned review of the impact of the implementation of the existing binding renewable transport fuel target on the availability of foodstuffs at affordable prices and to increase investment in researching both current impacts and the scope for advanced technologies to promote a more sustainable balance between food and energy security in future.

Farming and Food industry requirements

The biggest threat is to ignore that climate variability is increasing, and not fully appreciate the risks this entails. In highly stochastic systems, long term persistence (the flipside of resilience) comes about by trading off the mean returns in favour of reducing the variability in performance. This need is summed up by Deirdre Mahon, the CFO of Diageo: "It is insufficient, and even irresponsible, to consider only short term payback when making...decisions. This is entirely consistent with embedding a business model that is genuinely long-term and sustainable"[34].

This equally applies to farmers. Recognition that the future is more uncertain than the past may mean more complex planning is needed to ensure resilience. This may require increasing investment in farm water storage, and irrigation technology for example. It may also require managing soils in a different way, by increasing the organic content and the water-storage capacity. It may require changing drainage patterns to cope with more variable rainfall and so on.

Adaptation of the UK farming system will require increased flexibility in farmer behaviour, increased transmission of knowledge about the risks and how to manage them, from academia, government and other knowledge suppliers. It will require increased innovation. It may also require some regulatory flexibility (in terms of management of water, for example, or planning for local farm-scale reservoirs).

[34] Quoted in: Carbon Disclosure Project (2012) Business resilience in an uncertain, resource-constrained world. Available at http:/www.ukmediacentre.pwc.com

V. WHAT IS THE INFORMATION REQUIRED TO ASSESS THE EFFECTIVENESS OF THE UK FOOD CHAIN IN RESPONSE TO WEATHER

World supplies, and UK production, will always fluctuate with natural weather variability. However, we highlight here the need to consider that variability is increasing, and that the extremes may well perturb local production to an increasing extent (making “bad” years much worse than “good years”, as per Fig 1). Given that agricultural production exhibits trends over time, in one sense the resilience to weather can be assessed by the magnitude of the deviation of any given year from the trend. A similar view can be taken for food prices.

Adaptation to increasingly stochastic production systems requires, planning, diversification and investment. For farmers, there is also a need for information and advice. Given the actors in the food chain are private sector organisations, there is a need to encourage development of adaptation strategies, which may, in turn, require cultural changes in the private sector. As the quote above from Diedre Mahon indicates, resilient, sustainable industries increasingly need to performance on a longer-term than hitherto. Although the food industry is increasingly aware of the need to plan for resilience, there is a need to provide information and the tools to increase agricultural resilience. The information includes decadal scale weather forecasting, but also information on managing increasing uncertainty. Encouragement and help to plan adaptation strategies (e.g. for soil and water management) will be necessary. Without action, UK production is likely to become more variable.

VI. FINAL GAPS, RECOMMENDATIONS FOR FUTURE WORK

We conclude with some recommendations for further work.

The major message from this report is that we are potentially at considerable risk from increasing weather extremes, locally for UK production, and globally for UK food prices. Therefore our vulnerability is increasing and resilience decreasing. However, the evidence-base for exactly how the risk will change is not strong, but the potential worst case scenario could be extreme impacts on our local production simultaneous with a squeeze on global production and thus price rises. Ignoring the potential for the worst case scenario to occur because the evidence base is weak is unwise, given the indications that the “climate dice” are getting increasingly loaded. Our principal recommendation is to encourage more work, and planning, to cope with extremes. Previous work has concentrated either on longer-term planning, or planning on average conditions, and we now urge a fuller consideration of planning for the extremes, as this is where the impacts of climate change will most likely be felt. This planning could be:

- Further research on forecasting extremes, especially on a decadal scale; and with a greater emphasis on understanding how the shape of the weather distribution changes, and less emphasis solely on how the mean changes. For example, Hansen et al [22] show, in their Fig 4, that the right hand tail of the distribution of temperature anomalies is changing 2 to 2.5x faster than the mean is moving. This further implies that the average of any given period will be less important than the shorter term variation: in 2012 the annual rainfall may be close to average, but the average comprises both the driest period and the wettest periods in many years, and it is this variability that has had the impact, not the average.
- Using climate projections in the near term to assess the potential impacts, and use this information to develop adaptation strategies[35]
- Scenario planning for (a) managing simultaneous impacts (e.g. concurrent drought and excess rainfall in UK production), (b) informing farmer adaptation strategies, (c) challenging

[35] E.g. Forster, P et al. (2012) *Food Security: Near future projections of the impact of drought in Asia* http://www.lowcarbonfutures.org/

the food industry with how to manage the widespread impacts to global production from a year like 2012 but worse, (d) modelling the economic impacts of widespread disruption to a range of commodities simultaneously, in order to generate adaptation strategies.

- Developing an adaptation in agriculture strategy using the "potential pathways based approaches" to adaptation[36]. This approach (see Figure below, from Ranger et al.) is a process which fully articulates the context, risks, objectives, constraints and options for decisions on adaptation. By this, decision makers can identify appropriate adaptation strategies. This approach is a conceptual framework for adaptation planning, developed for, and contributing to, the theoretical framework of the UK's Committee on Climate Change Adaptation Sub-Committee's work on assessing the preparedness of the UK to meet the risks and opportunities arising from climate change.

[36] E.g. Ranger, N et al (2011) "Adaptation in the UK: a decision-making process" http://personal.lse.ac.uk/RANGERN/PB-adaptationUK-rangeretal.pdf

Appendix 1. NFU collated reports of the impact of weather on UK production prior to 2012

weather	date	sector	location	impact + cost	ref
drought	2011	Dairy	Shropshire farm	20% drop in yield in 3 weeks, whole-crop barley half-used supplemented with 1t/d of stock-feed potatoes at £30/t and ~£20/d of molassed protein product	FG Aug11
drought	2011	Dairy and sheep	Kent	Grass silage ~1/3rd of predicted, 1/3rd maize struggling to germinate, replacement forage likely >£30k, cull cows to market earlier and getting rid of spring stores.	FW Jun11
flooding	2007	various		estimated 42,000 ha of farmland across England. On average, insurance and charitable donations amounted to £4720/farm compared with losses of £89,415/farm, although most farmers received nothing.	Posthumous (2009)
flooding	2007	various		Cost to industry £66m	EA (FW,2010)
flooding	2009	various	Cumbria	£15k for removing gravel +£5k for cultivations + reseeding. £6.8k from RDPE	FW, 2010
drought	1976			Estimated £500 million in failed crops	Met Office
drought	1976			The total cereal crop about 0.5 million tonnes less than in 1975. Early potato crop yield in 1976 was above that for 1975 the main crop was severely affected by the drought, yields were lower than in 1975 and prices for potatoes rose considerably. Soft fruit yields were about 80% of normal and grassland production was severely restricted.	Rodda, J. and Marsh, TJ. 2011. The 1975-76 Drought - a contemporary and retrospective review.CEH.
frost	1997, 1999	fruit		Unseasonal frost devastated fruit crops in 1997 (Grower, 1997) and 1999 (Grower, 1999a)	Grower (1997, 1999)
flooding	2005	various	Cumbria	Flooding and storm winds also lead to severe damage and loss of livestock in Cumbria. Total cost to Cumbria over £400 million	CC0361
wet autumn	2000/ 2001	various		£603m	CC0372
flooding	2012	livestock	Somerset levels	2,500 acres of grazing land has been put out of use for up to a year 400ha under water for 9-10 weeks	Western Daily Press (2012) FG Aug12
high temp	2006	strawberry		Everbearer yields were around 30 per cent below average	EMR, 2011
disease	2010	livestock	south + east	BTV	
drought	2012	livestock		US drought led to increase in price of soya to ~£400/t up from £295 at end 2011. Estimates of up to 25% of UK farmers leaving pig industry by end of 2012.	FW Aug12
drought	2012	livestock		Dairy feed might increase by up to £50/t in autumn	FG Aug12
drought	2012		EU	Re-sowing combinable crops estimated at £165m	COPA-COGECA (FG Apr12)

disease	2012	potatoes	UK	5589 cumulative Smith Period events to July 11, 2012 cf 1034 by the same date last year Estimates that yield down 900,000t	FG Jul12 FG Aug12
"weather"	2012	Ornamental and garden centres	UK	2012 sales 9.4% down with sales of outdoor plants 19% lower	Horticulture Week Jun12
"weather"	2012	asparagus	UK	shortage with crop selling for £10/kg up from £6.kg	FG May12
flooding	2012	sugarbeet	Yorkshire	Field of sugarbeet under 8 feet of water	FG Jul12
"weather"	2012	dairy		Wet weather and higher feed costs mean the average farmer is already £3600 a month worse off than in April. Defra stats show cattle feed production rose 23% in May whilst compound feed prices increased 15-20% since May. Grass quality also poor.	FW Jul12
"weather"	2012	cereals	UK	Initial yield estimates show that total UK cereal yields have gone from 7.0 tonnes per hectare in 2011 to 6.2 tonnes per hectare in 2012	
rainfall	2012	livestock	Lancashire	Cows back indoors on full winter rations whilst 100 acres of grazing under water	FW Jul12
rainfall	2012	peas		Forecast of 40% drop in harvest with potential reduction in retail sales of up to £80m	
drought	2012	horticulture	Suffolk	Potato, onion and carrots (high value crops) cut by 80ha and replaced by OSR and maize. ~£70-80k in lost profit	FW Mar12
rainfall	2012	horticulture		lack of demand for soft fruit and poor prices resulting in fruit being discarded	G 2012
rainfall	2012	onions	Warks	Acres of overwintered onions ploughed in as it was too wet to harvest	FW Jun12
drought	2010	livestock		Reduction in silage yields of 25-40%, concerns about quantity and quality of second cut. Hay reduced by up to 50%. One Kent farmer forced to sell two-thirds of his herd because of lack of feed for winter	FG Jul10; FW Jul10
drought	2011	livestock		Store cattle sales in Herefordshire increased 20% as winter feed stocks low	FW Oct11
drought	2011	livestock	Somerset	50% increase in bought-in feeds, adding 2ppl to costs and knock £200,000 off the bottom line	FW Jun11
drought	2011			Earlier in the year losses estimated at £400m.	
low temperatures	2010	sugarbeet		£52m through crop losses. £15m in East Midlands alone as 10,000ha written off	
drought	2011	horticulture	Yorkshire	Three fruit and veg growers facing losses in excess of £1.2m; some salad growers close to losing £1m	FW Jul11

snow	2010	buildings		Snow and ice caused more than £15m of damage. More than 100 farm buildings collapsed in Scotland and 65 in the north of England due to weight of snow	
drought		malting barley		Spring barley quality badly affected by low rainfall. Extreme weather makes it difficult to achieve consistent N levels.	FW Apr12
drought	2003	OSR		32% of WOSR re-sown across 50,000ha because of dry conditions	NFU 2003
temperatur e	2006	soft fruit	Northumber land	Still picking raspberries, strawberries and blueberries in December	Times 2006
drought	2011	hops		20% lower yield	pers.comm.
drought	2011	dessert fruit and cider apples		small fruit led to poor grade outs and lower yields. A drop in yield of about 10-15%	pers.comm.
drought	2012	amenity nursery		projects which have been postponed until the autumn have valued £85,000 to date. Additional problem of how and where to keep the plants. The potential cost for replacement plant material, extra labour and materials and the emergency bed space needed estimated at £40,000. Sales also 16% down on budget since the beginning of the bans - an estimated £68,000 on sales budgets for April and May	

Appendix 2

Summary of short Term UK Climate Projection Extremes for Severe weather and UK Food Resilience report

30th August 2012

Written by:
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Authorised for release by:
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Introduction

This information has been prepared for the Severe Weather and UK Food Resilience report and summarises the current climate projections for different parameters and extremes for UK over the short term time period.

All values relate to projections using the IPCC's Special Report on Emissions Scenarios (SRES, Nakicenovic and Swart, 2000) A1B scenario unless otherwise stated. When available the central estimate (median) is provided followed by the 10% (projected to be exceeded), and 90% (projected to not likely be exceeded) probability levels in brackets. The reference period is 1961-1990 unless otherwise stated.

Extreme climate projections

Important Information
Adapted from The Met Office (2012) – Annex A

The weather and climate vary naturally; in the timescale of years to decades the average temperature and precipitation can fluctuate by large amounts. The climate risks of the next 2-3 decades are therefore very strongly dependent on the characteristics of natural variability.

Natural variability forms the main uncertainty in the short term UK climate projections; the year-to-year fluctuations are larger than the relatively gradual trend in long-term average conditions due to the build-up of greenhouse gases.

The presented climate projections should be treated as preliminary indications of the potential range of climate changes in the UK; planning should remain flexible to revised advice as climate science continues to develop. The projections are not based on individual extreme years or seasons, but multi-year averages; **weather events not in line with the projected average climate change can still be expected to occur**.

Please note that the provided 10% and 90% probability levels **do not** represent the upper and lower limits of possible change, but provide a guide as to the more plausible range of future outcomes. The 50% probability level (central estimate, median) **does not** represent the "most likely" scenario but should be treated as a projected intermediate level of change, for applications when a single representative scenario may be useful.

Summary

Precipitation

- There is good agreement between models and ensemble projections that there will be increases in extreme precipitation in winter, spring and autumn for most regions of the UK during the 21^{st} century. Projections indicate a greater increase in short-duration extreme precipitation events rather than longer-duration events, and a greater proportion of the total precipitation from heavy rainfall days (Fowler and Ekström, 2009, Boberg *et al.,* 2009, Murphy *et al.*, 2009).
- There is however large variability between projections regarding the magnitude of changes in precipitation and especially the magnitude and return period of extreme precipitation events; this is evidenced by the relatively large model projection ranges (IPCC, 2007, Seneviratne et *al.*, 2012).
- During summer, there are large projection uncertainties (including the sign of the change, indicating potential for both increases and decreases in extremes) regarding changes in precipitation; Fowler and Elkstrom (2009) note that regional climate models (RCMs) cannot adequately simulate summer precipitation extremes.

Floods

- Whilst there is good agreement between models regarding projections of increased heavy precipitation events over the UK during winter, autumn and spring; projected flooding events depend on changes in several variables (not just precipitation) and especially over the short term timescales, natural variability makes projections unreliable.
- The UK Climate Change Risk Assessment for Floods and Coastal Erosion Sector report (CCRA, Ramsbottom *et al.*, 2012), suggests an increase in heavy precipitation events in winter could result in larger volumes of runoff with potential negative impacts on flood risk.
- A large component of surface water and fluvial flooding is heavy rainfall; projections indicate that surface water flooding could increase, particularly as a result of the projected increases in winter (and to a lesser extent spring and autumn) rainfall.
- There is good agreement between model projections indicating a rise in sea level during the 21^{st} century; although the projected range of the sea level rise is large – a central median of 36.9cm (+13.1cm to +60.7cm, 5^{th} and 95^{th} percentile values respectively) not including land movement (Murphy et al 2009) - this is another factor which could put coastal and estuarine regions at a risk of flood.

Droughts

- Due to natural variability and projection uncertainty it is not yet possible to robustly predict changes in UK meteorological droughts (based on cumulative monthly precipitation anomalies) during the 21^{st} century (Burke *et al.,* 2010).
- There is general agreement between projections towards an increase in meteorological drought occurrence over the UK during the 21^{st} century, however the strength of the trend (Blenkinsop and Fowler, 2007, Burke *et al.*, 2010), and in some cases even the sign of the change (Blenkinsop and Fowler, 2007), can vary for changes in short- and long-term meteorological droughts with different model ensembles.

Temperature

- There is good agreement between model projections that the UK will show increases in the average and extreme temperatures during the 21st century (Murphy *et al.*, 2009, Kharin *et al.*, 2007, Christensen *et al.*, 2007).
- Projections carried out for the IPCC's 4th Assessment Review (Christensen *et al.*, 2007) and the Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation Report (SREX, Seneviratne et *al.*, 2012), indicate that cold temperature events will decrease in a future warmer climate and that heat waves (compared to the baseline period, 1961 - 1990) would be more intense, more frequent, and last longer.
- Simulations carried out for UKCP09 (Murphy *et al.*, 2009) project all areas of the UK to experience warming. The projections also indicate increases in mean summer temperatures, the mean daily maximum temperatures, the warmest day of summer (99th percentile of the daily maximum temperature) and the mean daily minimum temperature throughout the year.
- Although there is good agreement between model predictions regarding temperature changes over the UK, in the short term the natural variability dominates over the changes caused by anthropengic influences.

Synoptic Scale

- Projections indicate future changes in synoptic scale systems, and their impact on mean climate conditions, are small; the frequency and strength of extra-tropical storms as well as (blocking) anticyclones are projected to remain relatively stable (Murphy *et al.,* 2009).
- Although small changes in the position of the North Atlantic storm track are possible, Murphy *et al.* (2009) found the projections to be inconsistent between different models and different model variants and note that at the smaller UK regional scale the natural variability and sampling uncertainty dominates over any climate change signal.
- The IPCC's SREX Report (Seneviratne *et al.,* 2012) highlights that there is general agreement between projections of an increase in extreme winds over northern Europe during the 21st century (approximately 4% in the 98th percentile daily maximum wind speeds over UK by 2100 (Donat *et al.*, 2011)); however, there is concern the coarsely resolved stratosphere may present systematic biases (Scaife *et al.*, 2011).

Detailed Information

Precipitation

Climate projections carried out for the IPCC's Fourth Assessment Report (IPCC, 2007), and further discussed in SREX (Seneviratne *et al.,* 2012), indicate an increase in the proportion of total precipitation from heavy precipitation over most regions of the globe during the 21st century. Further to this, the projections indicate a possible increase in heavy daily precipitation events, including over some regions in which the total precipitation was projected to decrease.

Fowler and Ekström (2009) - using 13 Regional Climate Model (RCM) integrations from the PRUDENCE ensemble (Christensen *et al.*, 2007), located over the UK, and with a spatial scale of approximately 50 km and the A2 SRES scenario (Nakicenovic and Swart, 2000) - project an increase of between +15 to +30% in magnitude for the 1-day 5-year rainfall event across the UK during winter by the end of the 21st Century (above the baseline period 1961-1990); similar increases are projected, although with larger uncertainty for the higher 1-day 25-year return period.

In summer, model projections of precipitation over the UK span the zero percent change line; there is low confidence in these projections due to poor model performance in this season (Fowler and Ekström, 2009). For longer duration extremes, where the projection distributions are narrower indicating greater confidence, the projections show increases in magnitude for spring, autumn and winter.

Using daily statistics from an ensemble of seven RCMs from the ENSEMBLES project (Hewitt, 2005) located over Europe, and a grid spatial scale of approximately 25km, Boberg *et al.* (2009) projected an increase in the contribution to total precipitation from more intense events together with a decrease in the number of days with light precipitation (below 10mm) for the UK and most European subregions.

Results from the UKCP09 project (Murphy *et al.*, 2009) – an ensemble of eleven of the Met Office Hadley Centre's HADCM3 RCMs downscaled to an approximate spatial resolution of 25 km, located over the UK – project that the number of days with heavy rain (>25 mm) over most of the lowland UK to increase by a factor of between 2 and 3.5 in winter, and 1 to 2 in summer, by the 2080s. Projected changes in the wettest day of the winter range from a median value of zero (range, –12 to +13%) in parts of Scotland to median value of +25% (range, +7 to +56%) in parts of England. Projections show the biggest changes in precipitation in winter on the western side of the UK, with a central median increase up to +33% (+9 to +70%, 10th and 90th percentile ranges respectively). Conversely parts of the Scottish Highlands show decreases of a few percent (–11 to +7%, 10th and 90th percentile ranges respectively).

There is good agreement between models and ensemble projections that there will be increases in extreme precipitation for most regions of the UK in winter, spring and autumn during the 21st century. Projections also indicate a greater increase in short-duration extreme precipitation events rather than longer-duration events, as well as a greater proportion of the total precipitation from heavy rainfall days; even in regions where the total precipitation is projected to decrease (Fowler and Ekström, 2009, Boberg *et al.,* 2009, Murphy *et al.*, 2009). There is however large variability between projections regarding changes in precipitation and especially the magnitude and return period of extreme precipitation events; this is evidenced by the relatively large model projection ranges. The largest projection uncertainties (including the sign of the change) relate to precipitation during summer. Fowler and Elkstrom (2009) note that regional climate models cannot adequately simulate summer precipitation extremes and therefore there is little confidence in their projections; for a number of regions the ensembles span the zero change line indicating potential for both increases and decreases in extremes.

Floods

The IPCC's SREX report (Seneviratne *et al.,* 2012) highlights that literature regarding projections of flood changes at the catchment/river-basin scale are scarce, although several studies have been undertaken for UK catchments (Kay *et al.*, 2009; Prudhomme and Davies, 2009, Ramsbottom *et al.*, 2012). Although there is good agreement between models regarding projections of increased heavy precipitation events over the UK, projected flooding events depend on changes in several variables (e.g., precipitation totals, frequency, and intensity, snow cover and snowmelt, wind speed, soil moisture, sea level, land use and geography), and especially over the short term timescales, natural variability makes projections unreliable.

Kay *et al.* (2009) investigated the different sources of uncertainty for long term projections of flooding over two UK river catchment areas; the projections indicated that the uncertainty from global climate modelling is generally larger than that from other sources (e.g. future greenhouse gas emissions; downscaling from Global Climate Models (GCMs); hydrological model structure; hydrological model parameters and the internal variability of the climate system). Projections of flooding events also depend on the catchment orography; longer duration heavy precipitation events have a greater effect on larger, flatter catchment areas, than on more responsive (small, steep) catchment areas. In contrast, increases on the intensity of shorter duration rainfall would have a relatively greater effect on more responsive catchments.

The UK CCRA (Ramsbottom *et al.*, 2012), based on projections from UKCP09 (Murphy *et al.*, 2009) and Kay *et al.* (2010), suggests an increase in heavy precipitation events in winter could result in larger volumes of runoff with potential negative impacts on flood risk and sewer overflows in urban environments.

One of the main findings of the projections carried out in Ramsbottom *et al.* (2012) is the relatively large increase in flood risk for relatively small increases in river flows and sea level. A main component of surface water flooding is storm rainfall; the UKCP09 (Murphy *et al.*, 2009) projections indicate that surface water flooding could increase, particularly as a result of the projected increases in winter rainfall. The UKCP09 (Murphy *et al.*, 2009) projections, not including land movement, also show a rise in sea level during the 21st century with a central median rise of 36.9cm (13.1cm to 60.7cm, 5th and 95th percentile range respectively); although the projected range of the sea level rise is large, this is another factor which could put coastal and estuarine regions at a risk of flood.

Ramsbottom *et al.* (2012) note that the more complex aspects related to spatial and temporal variation of major floods are still active research areas; in the context of climate change modelling, projections of extreme rainfall and future flooding are one of the most challenging areas of climate change science and the spread of possible outcomes is large.

Drought

Burke et al (2010) describe that drought can be defined in three main ways: (1) meteorological drought which can be defined as a drying relative to the mean state; (2) agricultural drought which results in a reduced supply of moisture for crops; and (3) hydrological drought associated with a deficit in the supply of surface and subsurface water (Tallaksen and van Lanen, 2004). For this summary, only meteorological droughts are assessed.

Projections carried out for the IPCC's 4th Assessment Report (Christensen *et al.*, 2007) indicated a possible increase in meteorological droughts (based on cumulative monthly precipitation anomalies), in particular in subtropical and mid-latitude areas. The projections indicated little change over northern Europe but an increase in length and frequency of droughts over the Mediterranean region.

The IPCC's SREX report (Seneviratne *et al.,* 2012) notes however that insufficient knowledge regarding the physical causes of meteorological droughts, and links to the large-scale atmospheric and ocean circulation, is still a source of uncertainty in meteorological drought simulations and projections. For example, over the UK, the strength of the trend (Blenkinsop and Fowler, 2007, Burke *et al.*, 2010), and even the sign of the change (Blenkinsop and Fowler, 2007), can vary for changes in short- and long-term meteorological droughts with different RCM ensembles.

Burke *et al.* (2010) – using an eleven member ensemble of the Met Office Hadley Centre's HadRM3 model located over the UK, with 25 km resolution – projected an overall increase in meteorological drought occurrence (based on cumulative monthly precipitation rates) over the UK during the 21st century, however there was poor agreement between the ensemble projections indicating large uncertainty. This corresponds with Blenkinsop and Fowler (2007) and Vidal and Wade (2009) which also have large uncertainties and projected an increase in short duration meteorological droughts (The Met Office Hadley Centre, 2011).

Due to natural variability and projection uncertainty it is not yet possible to robustly predict changes in UK meteorological droughts during the 21st century Burke *et al.* (2010).

Temperature

There is good agreement between model projections that the UK will show increases in the average and extreme temperatures during the 21st century (Murphy *et al.*, 2009, Kharin *et al.*, 2007, Christensen *et al.*, 2007).

Projections carried out for the IPCC's 4th Assessment Review (Christensen *et al.*, 2007) indicate that cold temperature events will decrease in both frequency and magnitude in a future warmer climate and an increase in the frequency, intensity and duration of heat waves (compared to the baseline period, 1961-1990). The IPCC's SREX Report (Seneviratne *et al.,* 2012) highlights that more recent studies utilizing larger model ensembles (Kharin et al., 2007; Orlowsky and Seneviratne, 2011) generally agree with these projections.

Simulations carried out for UKCP09 (Murphy *et al.*, 2009) – an ensemble of eleven of the Met Office Hadley Centre's HADCM3 RCMs downscaled to an approximate spatial resolution of 25 km, located over the UK - project all areas of the UK to experience warming; with greater warming in the summer than in winter. The projections also indicate an increase in mean summer temperatures in parts of southern England up to 4.2 °C (2.2 °C to 6.8 °C) during the 21st century as well as increases in the mean daily maximum temperature and the warmest day of summer (99th percentile of the daily maximum temperature) from +2.4 °C (–2.4 °C to +6.8 °C) to +4.8 °C (+0.2 °C to +12.3 °C), depending on location, but with no simple geographical pattern. In addition, the projections indicate increases in the mean daily minimum temperature throughout the year; resulting in a decrease in the number of frost events.

It should be noted that although there is general agreement between model predictions that the UK will see an increase in mean and extreme temperatures during the 21st century, in the short term the natural variability dominates over the changes caused by anthropengic influences.

Synoptic scale

Murphy *et al.* (2009) examined projections of synoptic scale variability using an ensemble of 17 different HadCM3 (Met Office Hadley Centre model) experiments and a multi-model ensemble consisting of 20 alternative coupled models. The analysis of the projections indicate only small changes in future synoptic scale systems, and their impact on mean climate conditions. The frequency and strength of extra-tropical storms as well as (blocking) anticyclones are projected to remain relatively stable. Although small changes in the position of the North Atlantic storm track are possible, Murphy *et al.* (2009) found the projections to be inconsistent between different models and different model variants.

Projections carried out for the IPCC's 4th Assessment Review (Christensen *et al.*, 2007) show general agreement in a poleward shift of storm tracks, with some indication of fewer, more intense, depressions. Murphy *et al.* (2009) note however that this can only be inferred when looking at the hemispheric scale; at the smaller UK regional scale the natural variability and sampling uncertainty dominates over any climate change signal.

The IPCC's SREX Report (Seneviratne *et al.,* 2012) highlights that increases in winter wind storm risk over Europe are projected by a number of different studies such as Pinto *et al.* (2007), Leckebusch *et al.* (2008) and Donat *et al.* (2011). There is general agreement between projections indicating an increasing trend in extreme winds over northern Europe during the 21st century; for example projections carried out in Donat *et al.* (2011) indicate an increase of approximately 4% in the 98th percentile of daily maximum wind speeds over UK by 2100. It should be noted however, that there is concern the coarsely resolved stratosphere (present in many of the models used for IPCC's 4th Assessment Report) may present systematic biases in the Atlantic storm track response to increased anthropogenic forcing (Scaife *et al.*, 2011).

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