Report No. 233

Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

WARNDIS Project Final Report: A Review of Climate Change-related Hazards and Natural Disaster Vulnerabilities and of Agencies Involved in Warning and Disaster Management

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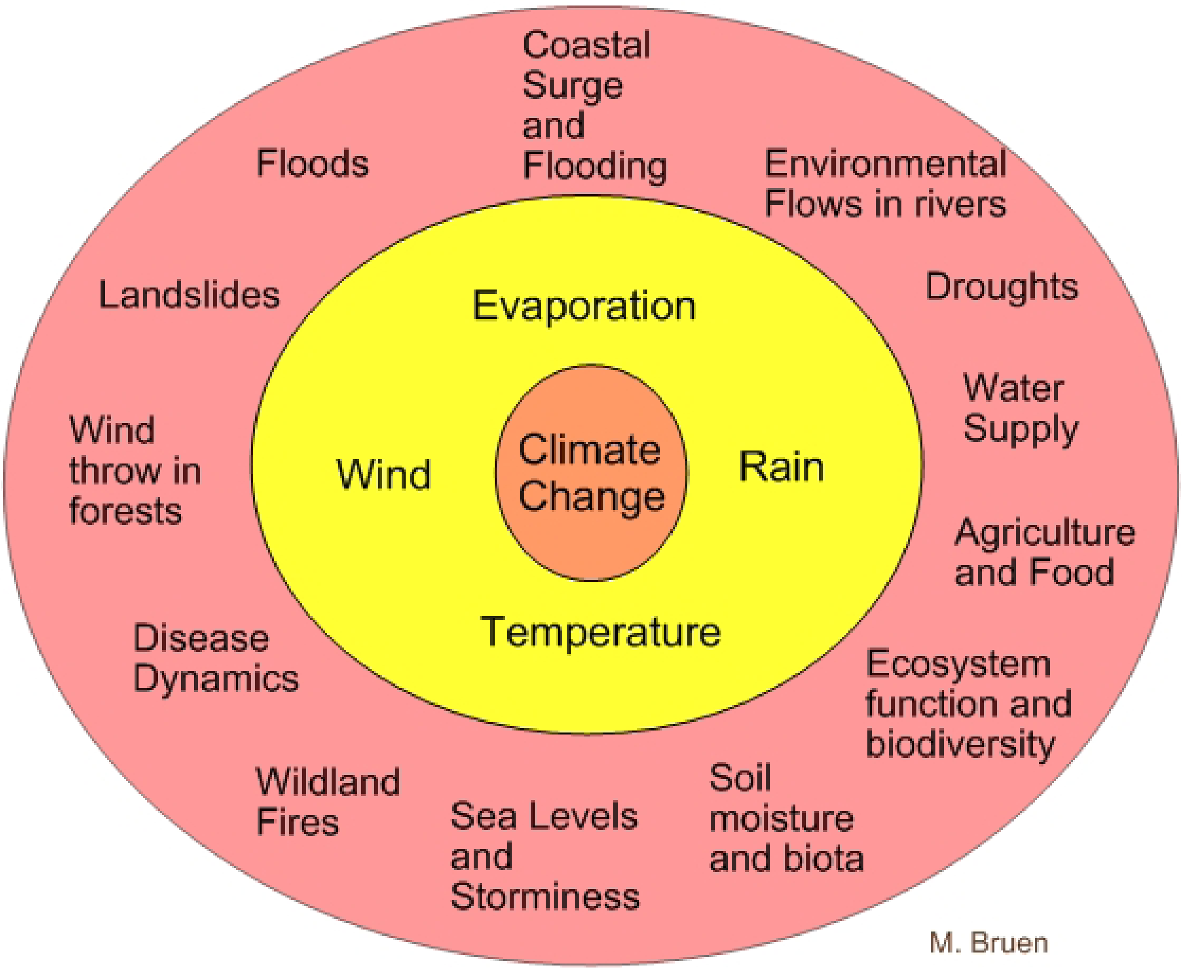

Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

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ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: *We implement effective regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

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Advocacy: *We work with others to advocate for a clean, productive and well protected environment and for sustainable environmental behaviour.*

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- large scale industrial activities (*e.g. pharmaceutical, cement manufacturing, power plants)*;
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- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
- sources of ionising radiation *(e.g. x-ray and radiotherapy equipment, industrial sources)*;
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- waste water discharges;
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- Promoting radon testing in homes and workplaces and encouraging remediation where necessary.

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The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2014–2020

WARNDIS Project Final Report: A Review of Climate Change-related Hazards and Natural Disaster Vulnerabilities and of Agencies Involved in Warning and Disaster Management

(2012-CCRP-DS.5)

EPA Research Report

Prepared for the Environmental Protection Agency

by

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

WARNDIS was a desk study project funded by the Environmental Protection Agency. The purpose was to (1) identify and review the main types of natural disasters that may be impacted by anticipated climate change and particularly those most relevant in Ireland; (2) identify the key agencies involved in providing warnings and information about the most relevant disaster types; (3) assess their roles and capabilities; and (4) identify existing and new potential data streams to assist with warning and disaster management. While mainly a desk study/literature review, the project team held a well-attended workshop to gauge the priorities of Irish personnel involved with disasters and visited and held discussions with two of the main service providers of warnings in Europe [European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, UK, and the European Commission's Joint Research Centre (JRC) in Ispra, Italy].

The main relevant natural hazards identified in the literature review were:

- extremes of precipitation (both increases and decreases in rainfall amounts and spatial and temporal patterns) and the implications for floods and droughts;
- extremes of temperatures (particularly heatwaves and wildfires);
- sea levels (increase in means and extremes);
- landslides.

The effect of these on human activities and natural ecosystems were investigated, as substantial changes to these could lead to challenges in relation to sustainability, food and health including consequences for:

- ecosystem function and biodiversity;
- agriculture and food;
- human health.

Once the main types of relevant disasters were identified, the WARNDIS project team identified the main researchers, policymakers and disaster response managers working in these areas and organised a workshop on natural hazards and climate change, to bring them together in a dialogue about research needs and results informing their activities. The workshop had presentations from invited speakers detailing the activities and research results of a number of key organisations in Ireland. It concluded with a session of small group discussions intended to feed into a statement on research needs, which may inform future policy. A wide range of concerns were raised, mainly about flooding impacts, particularly on pollution, aquaculture, human health and failure of infrastructure. The data sources considered necessary included (1) new data sources, such as data collection on human health impacts and remote sensing (satellite) data, and also related to (2) higher resolution and greater spatial coverage of existing data sources.

Disaster response in Ireland is coordinated at three levels: national coordination, regional coordination centres and local/on-site coordination. While there is a national committee with a coordinating role, almost all frontline work is devolved to local authorities and other first responders at the local level. This is appropriate, but more coordinated support is needed. There is no national warning system for specific hazards except for severe weather; however, a flood warning centre is being planned, supported by Met Éireann and the Office of Public Works. Some local flood warning systems are in place and are effective. For example, in triggering the deployment of defences such as demountable barriers, these warning systems have generally worked well to date. In a recent improvement, Ireland now receives flood warnings for specific catchments from the European Flood Awareness System (EFAS), which proved useful in the floods of December 2015.

For all of Europe, the ECMWF provides a critical climate and atmospheric modelling and forecasting service to European regional and national meteorological services. In the case of flooding, the EFAS flood forecasting system, operated by the JRC at Ispra, has proved effective for large catchments. Other model-based disaster support platforms for surge and drought monitoring, based on the Copernicus platform, and social media monitoring platforms have been shown to be useful. However,

a number of international warning platforms depend almost entirely on input from national organisations and the goodwill of a hosting agency, and this is not ideal.

Recommendations

1. A national flood warning service has been promised and this should be integrated, in real time, with emergency response systems (JBA Consulting, 2011). This will be primarily based on Met Éireann weather forecasts, which require global information from ECMWF, and on hydrological modelling. This should be integrated, in real time, with the official emergency response structures. Integration of such a national flood forecasting and warning service with European systems such as ECMWF, EFAS and Copernicus is essential, as well as integration and data sharing with higher resolution local systems to meet specific requirements, e.g. triggering deployment of demountable barriers.
2. Any future centralised warning service, be it only for floods or for all natural hazards, should incorporate an active research division linked to the relevant research centres in third-level institutions. This is essential to maintain an up-to-date, state-of-the art warning service.
3. Ireland benefits from its subscription to EFAS and, being a maritime nation, should also consider subscribing to the European surge prediction network and evaluate and/or integrate its own bespoke higher resolution local systems with more detailed bathymetry.
4. Ireland should also become more closely involved with a number of European disaster-related initiatives, e.g. relating to landslide risk and the use of media monitoring.
5. A broader range of methods is required to communicate warnings and disaster-related information to the public. Such information should be up to date (preferably real-time), should have specific components especially for vulnerable groups of the at-risk population, and should incorporate a large element of resilience and redundancy. A study of how and when to communicate effectively with the public (to both provide and receive information and to produce specific response actions, e.g. evacuations) would be particularly useful, with a focus on reaching the most vulnerable at-risk groups of society.
6. Mobilisation of pollution by floods has been highlighted as an issue with severe consequences across a range of areas, including human health, and safe food and water. Measures are required to reduce these risks, by removing or isolating their sources and minimising the risks of their mobilisation.
7. Risks to other infrastructure, particularly roads, power and communications systems from floods are important, and ensuring the resilience of such systems should be prioritised.
8. Regarding data needs, a wider range of data sources should be utilised and at greater resolution (temporal and spatial) where beneficial in specific areas. Greater use of remote sensing technologies, e.g. Earth observation and radar, should be considered in specific cases. Ireland should continue to participate in European initiatives to use satellite and other remotely sensed data (e.g. the Copernicus project), both during disasters and in post-event analyses.
9. The current reliance on the knowledge and commitment of specific individuals at the local flood response coalface (typically local authorities, An Garda Síochána, fire and health services) to identify vulnerable individuals for prioritisation is not ideal and a more formal systematic approach to identifying and addressing the needs of these groups is recommended.
10. The literature review strongly suggested that current research on climate change impacts on Ireland is overly fragmented and could benefit considerably from increased collaboration between climate change experts and experts in the specific areas of impacts. A tipping point has been reached in the need for a broad interdisciplinary approach to the analysis of impacts and the recognition and study of their inter-connectedness. Significant scientific progress, within Ireland, will depend on this. The establishment of a coordination centre to generate, manage and provide access to the large data sets involved and with a strong remit to foster a multi-disciplinary approach to evaluating impact would benefit Ireland.

1 Introduction

The purpose of this desk study was to (1) review the range of natural disasters that may be impacted on by climate change, (2) identify the key agencies involved in providing related information and warnings, (3) assess their roles and capabilities, and (4) identify existing and new potential data streams to assist with warning and disaster management. This report consolidates the outputs/deliverables from all of the above into a single document. Work started with a detailed literature review focusing on the individual hazards and potential climate change impacts (reported in Chapter 2). In parallel, the key agencies involved in generating relevant data streams and warnings were identified (Chapter 3 for international agencies and Chapter 4 for Irish agencies). Two agencies were quickly found to have central roles in Europe, namely the European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, UK, and the European Commission's Joint Research Centre (JRC) in Ispra, Italy. These were visited by the project researchers to get detailed information on their roles and responsibilities. Subsequently, a workshop was organised to bring together researchers, emergency responders and policymakers to consider the current situation in Ireland and discuss future warnings and data requirements (Chapter 5).

From the early 1960s to the mid-2000s, globally, the number of people affected annually by natural disasters climbed from below 10 million to over 200 million, but has declined to below 150 million in the past decade according to the Emergency Events Database (EM-DAT; http://www.emdat.be/). At the start of the 21st century, it was estimated that 1 in every 30 people suffer death, injury, displacement, disease or property damage related to a natural disaster such as a flood, earthquake, forest fire, hurricane, landslide, tornado or volcano. With increasing world population, and with many with vulnerability exacerbated by poverty, the reality of climate change, increased meteorological variability and more frequent extreme events must be addressed. Between 1993 and 2012, more than 530,000 people died as a direct result of extreme weather events; damage and losses cost more than US$2.5 trillion and 8 of the 10 countries most affected were developing countries (Kreft and Eckstein, 2013). Although there were far more deaths from geological disasters, mostly in the recent earthquake in Haiti and the tsunami in Japan, more than 90% of all disasters and 65% of associated economic damage were related to extreme weather events, including flooding, heatwaves, droughts, storms, extreme precipitation and wildfires (Huber and Gulledge, 2011). Of all the extreme weather events, flooding caused the highest number of fatalities and largest economic losses in the past decade (EM-DAT, http://www.emdat.be/). Such extreme weather-related disasters have become more frequent in the recent years (e.g. IPCC, 2012; Peterson *et al*., 2013b), and climate change is strongly implicated in many of them, particularly heatwaves and extreme precipitation (e.g. Donat *et al*., 2013; IPCC, 2013). The combination of observed trends, theoretical understanding of the climate system and numerical modelling demonstrates that global climate change is, indeed, increasing the risk, as described in Chapter 2.

2 Extreme Events, Natural Hazards and Disasters

2.1 Definitions and Background

The Intergovernmental Panel on Climate Change (IPCC) SREX (2012) report defines an extreme event as the occurrence of a value of a weather or climate variable above (or below) a specified threshold value (often the 10th or 90th percentile) near the upper (or lower) ends of the range of observed values of the variable. However, the word extreme is also used to describe the impact or some physical aspect of the event itself, which can lead to confusion. Natural hazards can be defined as natural processes or phenomena that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage (UNISDR, 2009). Disasters and natural hazards/extreme events are often associated with each other, but they are not the same. A disaster, which can be defined as a serious disruption of the functioning of a society or community, causing widespread human, material, economic or environmental losses that exceed the ability of the affected society or community to cope, using its own resources (UNISDR, 2009), is a result of the severity of a natural hazard, combined with exposure to the hazard, pre-existing vulnerability and an inability to adapt to or mitigate the impacts of the hazard (Figure 2.1). All of these are influenced by social, economic and governance factors.

The types of hazards associated with climate change and considered here include:

- increased magnitude and frequency of extreme temperatures;
- increased magnitude and frequency of extreme precipitation;
- increased magnitude, duration and frequency of droughts;
- increased magnitude and frequency of inland flooding;
- sea level rise and increased magnitude and frequency of storm surges and coastal flooding;
- increased risk of landslides and debris flows;
- increased risk of wildfires;
- disruption of ecosystem function;
- increasing food insecurity;
- increasing risk of a wider range of diseases and other impacts on human health.

Some of these extreme events, while increasing in frequency, are still relatively rare, so identifying long-term trends or making reliable projections for the

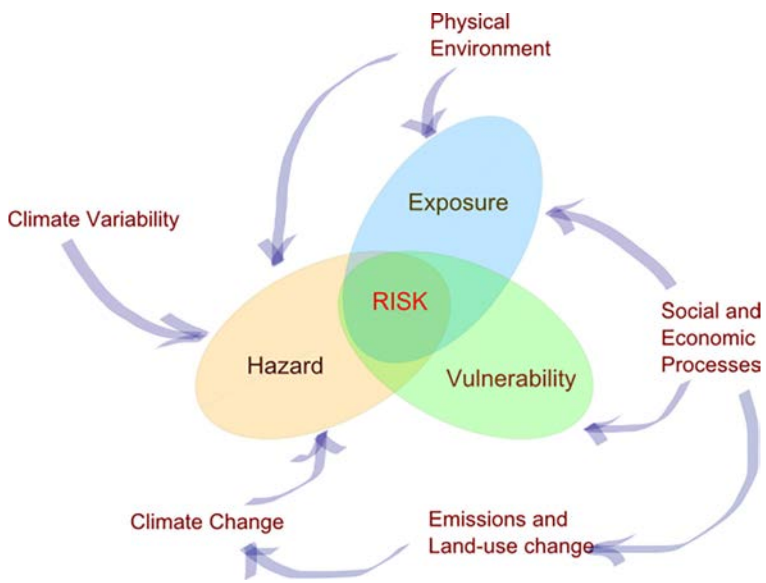


Figure 2.1. Relationship between the physical climate system, hazard, exposure and vulnerability producing risk. Developed from IPCC (2014).

future is complicated. However, most of these have been studied to some degree and past trends and future predictions have been established, although with varying degrees of confidence. For instance, confidence in future projections depends on factors such as the uncertainty inherent in climate simulations (a large proportion of which is epistemic, so-called knowable unknowns), the type of extreme event, the temporal and spatial scale of events, etc. (Kunkel *et al*., 2013a; Peterson *et al*., 2013a; Vose *et al*., 2014a,b; Wuebbles *et al*., 2014).

2.2 Extreme Precipitation

Extreme precipitation, defined as precipitation that substantially exceeds the long-term mean over a given range of time and space (Haerter, 2013), can lead to socio-economic, infrastructural and environmental impacts (Gobiet *et al*., 2013). Several observational records indicate substantial increases in heavy precipitation events in recent years at global to regional scales. For instance, Trenberth *et al*. (2007) considered it likely that there had been an increase in the number of heavy precipitation events (e.g. above the 95th percentile), including rare precipitation events (1 in a 50-year return period) in many land regions globally since about 1950, even in those regions where there had been a reduction in total precipitation amounts. This conclusion is well supported, e.g. by Schmidli and Frei (2005), Alexander *et al*. (2006), Kunkel *et al*. (2008), Donat *et al*. (2013), Hartmann *et al*. (2013) and Kunkel *et al*. (2013b). Patterns of recent decadal changes in several global precipitation indices are shown in Figure 2.2. The average change in number of heavy precipitation days (Figure 2.2a), the contribution from very wet days (Figure 2.2b) and the average intensity of daily precipitation (Figure 2.2d) increased, particularly over the eastern half of North America as well as over large parts of eastern Europe, Asia and South America. The number of consecutive dry days (Figure 2.2c) reduced over larger parts of North America, Europe and southern Asia. Although the number increased in the southernmost parts of Africa and South America, and the easternmost parts of China, decadal averages over the entire globe show a progression towards an overall wetter climate (Bokal *et al*., 2014).

The increased moisture-holding capacity of air warmed by climate change may be one factor contributing to the increase in precipitation extremes (Trenberth *et al*., 2007; Kunkel *et al*., 2013b) or perhaps it is the most important factor (Gobiet *et al*., 2013). The magnitude of the maximum water vapour changes are shown to follow temperature changes with an approximate Clausius–Clapeyron relationship (Kunkel *et al*., 2013b), which supports the causative link. Recent analyses obtained from a global data set of 8326 high-quality land-based observing stations with more than 30 years of records over the period from 1900 to 2009 (Westra *et al*., 2013) and empirical relationships between the wet-day mean temperature and 95th percentiles in 24-hour precipitation amounts (Benestad, 2013) affirmed this, having found statistically significant associations between precipitation extremes and the annual global mean near-surface temperature. Overall, the amount of extreme precipitation changed, from 1900 to 2009, in proportion to changes in global mean temperature at a rate of about 7% per degree warming (Trenberth, 2011; Westra *et al*., 2013; Zhang *et al*., 2013a).

The increases in precipitation are ascribed to climate warming, particularly in the Northern Hemisphere mid-latitudes and also in the Southern Hemisphere subtropics and deep tropics. Based on monthly precipitation observations over global land areas in two 20th century periods, 1925–1999 and 1950–1999, Zhang *et al*. (2007) concluded that anthropogenic forcing had a detectable influence on observed changes in average precipitation within these latitudinal bands of the Northern Hemisphere mid-latitudes, and also in the Southern Hemisphere subtropics and deep tropics, and that these changes could not be explained by internal climate variability or natural forcing. Similarly, by comparing observations with simulations from 22 coupled climate models, Min *et al*. (2008) showed that anthropogenic greenhouse gases and sulfate aerosols influenced the spatial and temporal pattern of precipitation change over high-latitude land areas during the second half of the 20th century. Further analyses of observational data along with several Coupled Model Intercomparison Project (CMIP) 3 model simulations (Noake *et al*., 2012) and CMIP5 model simulations (Polson *et al*., 2013; Kitoh and Endo, 2016) show clear global- and regional-scale changes associated with anthropogenic forcing. In the mid- and high-latitudes of the Southern Hemisphere, human influence was also found to have caused changes in austral summer precipitation,

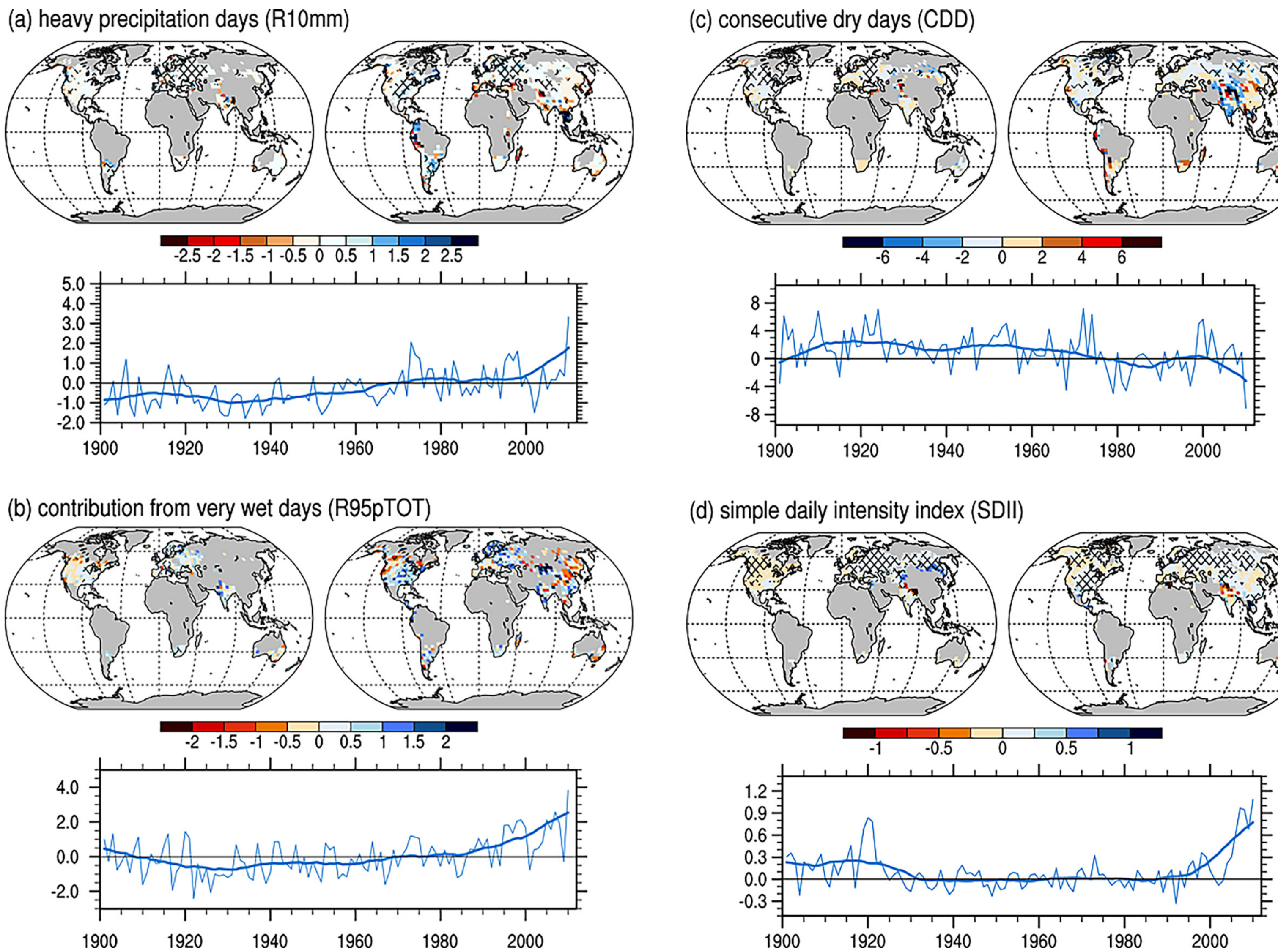


Figure 2.2. Decadal trends and global average time series for annual indices of (a) number of heavy precipitation days in days, (b) contribution from very wet days in percentage, (c) consecutive dry days in days, and (d) simple daily intensity index in mm per day. In each case, the left-hand globe shows changes in the period 1901–2010 and the right-hand globe shows changes in the period 1951–2010. Reproduced from Donat *et al*. (2013) with permission from Wiley.

where averaged zonal precipitation had declined in the latitudes around 45°S and increased in the latitudes around 60°S since 1957 (Fyfe *et al*., 2012). Nevertheless, over land areas, the observed changes were significantly larger than the model-simulated changes (Zhang *et al*. 2007; Min *et al*., 2008), although the difference between models and observations decreased if changes were expressed as a percentage of climatological precipitation (Noake *et al*., 2012; Polson *et al*., 2013).

However, some contrasting trends in extreme precipitation occurred at the regional scale. For instance, recent studies of European weather (Anagnostopoulou and Tolika, 2012; Burauskaite-Harju *et al*., 2012; Karagiannidis *et al*., 2012) report opposite trends in extreme precipitation in different regions. In 2012, the UK experienced its wettest summer since 1912, whereas Spain suffered drought and wildfires associated with the second lowest summer rainfall in the last 60 years (Dong *et al*., 2013). Similar contrasting trends were found for the western USA over the period 1970–2007, with increases in extreme precipitation in western Washington and coastal northern California, but decreases in Oregon and no significant trends in other areas (Dulière *et al*., 2013).

Although the increases in extreme precipitation occur in all seasons (Figure 2.3), they tend to be more significant during winter and autumn in the Northern Hemisphere (Donat *et al*., 2013). In the Alps, climate warming seems to be associated with changes in the seasonality of precipitation and more intense precipitation extremes in the colder periods of the year (Gobiet *et al*., 2013). This is also evident in the USA, where a general increase in winter precipitation over the past 50 years was reported (Regonda *et al*., 2005). Moreover, in recent decades, more of the precipitation fell as rain rather than snow, which is consistent with a general global warming trend (Arnell, 1999; Regonda *et al*., 2005; Trenberth, 2011). In China, decreasing precipitation rates in spring and autumn and increasing rates in winter were observed for the period 1960–2000 (Zhang *et al*., 2012) and the period 1960–2005 (Zhang *et al*., 2013b), as well as in Australia (Aryal *et al*., 2009). A similar trend is found in the Netherlands where there has been an increasing trend in precipitation in spring and a decrease in

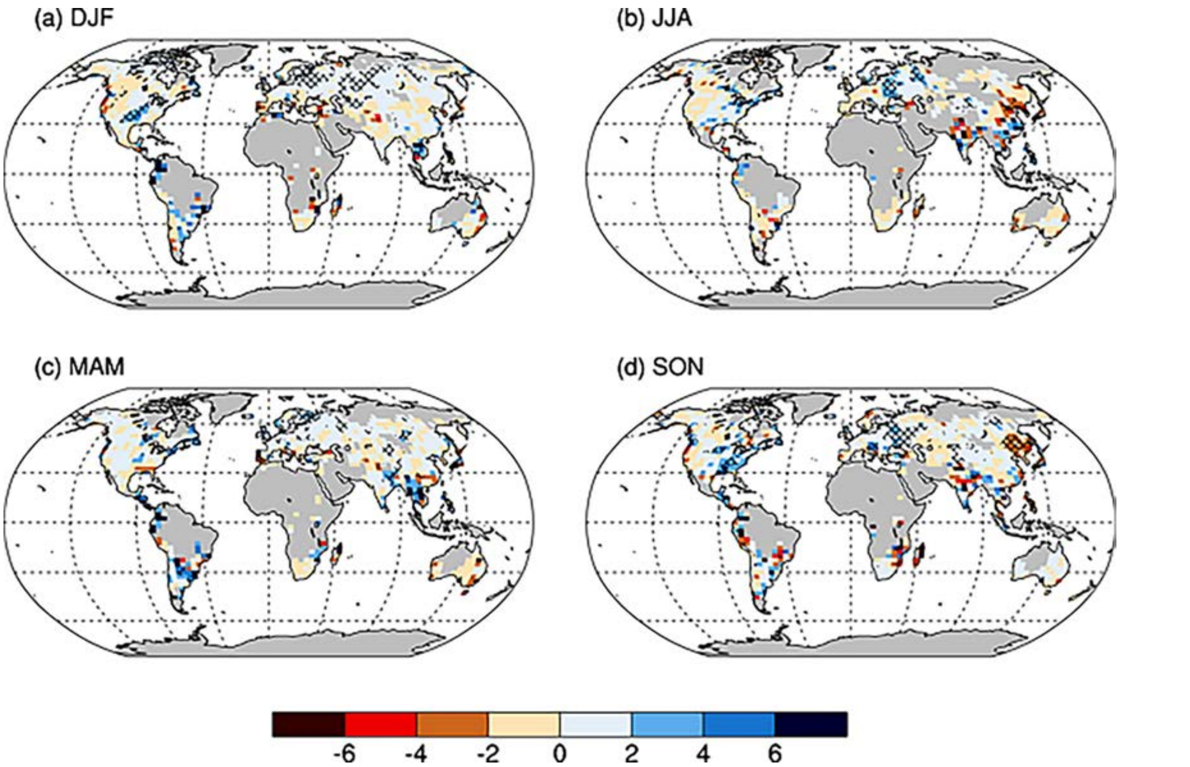


Figure 2.3. Global trends for seasonal series of maximum consecutive 5-day precipitation for the period 1951–2010 (mm/decade): (a) December to February, (b) June to August, (c) March to May, and (d) September to November. Reproduced from Donat *et al*. (2013) with permission from Wiley.

summer for the period 1951–2009 (Daniels *et al*., 2013). For the Mediterranean region, a 30% decrease in precipitation, especially in the warm season, was reported (Gao and Giorgi, 2008; Giorgi and Lionello, 2008). However, Tramblay *et al*. (2012) did not find any significant trends in extreme winter precipitation in the period 1961–2007 in Morocco.

In Europe, winter precipitation daily totals increased significantly along with their 90th, 95th and 98th percentiles over the period 1901–2000 (Moberg *et al*., 2006), as did winter extreme precipitation over the period 1950–2000 (Zolina *et al*., 2009). This regional trend of increasing winter precipitation has been confirmed by more detailed country-specific studies in Europe, e.g. for the UK (Osborn *et al*., 2000; Maraun *et al*., 2008), Germany (Zolina *et al*., 2008; Tölle *et al*., 2013), Switzerland (Widmann and Schar, 1997; Schmidli and Frei, 2005), Ireland (Gleeson *et al*., 2013a) and the Czech Republic (Kyselý, 2009), and in east-central Europe (Bartholy and Pongrácz, 2010). On the other hand, decreasing trends were found in other regions in Europe such as Italy (Pavan *et al*., 2008; Romano and Preziosi, 2013), Poland (Lupikasza, 2010) and some Mediterranean coastal sites (Toreti *et al*., 2010).

Projections of future precipitation patterns indicate an increasing likelihood of more frequent extreme precipitation events. A typical case in Europe was reported by Rajczak *et al*. (2013) and Jacob *et al*. (2014), in which a comparison between the present (1970–2000) and predicted future (2070–2100) conditions showed an increased risk of more frequent extreme precipitation. In the USA, probable maximum precipitation values are projected to increase by between 20% and 30% in the future (2071–2100) as a result of higher levels of atmospheric moisture (Kunkel *et al*., 2013b). Kyselý *et al*. (2012) projected increases in short-term (hourly) extremes to exceed those of daily and multi-day extremes over the western, central and parts of the eastern Mediterranean region for the late 21st century (2070–2099), even in regions and seasons in which mean precipitation was projected to decline. In many regions of the world, a decrease in the number of precipitation days is projected, but an increase in days with heavy rain from 2071 to 2100 is also projected (Hirabayashi *et al*., 2008). Caution in identifying precipitation increases in dry areas was urged by Sippel *et al*. (2016), who suggested that issues with data standardisation and choice of reference period can influence the conclusions.

2.3 Droughts

The definition of drought was clarified by Van Loon *et al*. (2016), who distinguish it clearly from the related, but different, terms water scarcity and water overexploitation, and argue for a multi-driver approach (including human influences) to link causes to droughts. Changes in drought conditions are primarily driven by altered precipitation and temperature regimes (Sheffield and Wood, 2008a; Briffa *et al*., 2009). Increases in temperature potentially increase direct evaporation from the soil and open water surfaces through increased atmospheric demand (although increased atmospheric CO_2 by itself tends to reduce actual transpiration from vegetation) (Kruijt *et al*., 2007; Steinthorsdottir *et al*., 2012). These influences need to be disentangled carefully from each other and from other factors such as nitrogen deposition (Sarhadi *et al*., 2016). In regions where the net result is an increase in moisture loss to the atmosphere and where this coincides with decreases in precipitation, the reduction in soil moisture is worse (Zhang *et al*., 2012). Seasonal shifts in precipitation, in response to changing climate, are implicated in triggering droughts in many areas across the world. Globally, there are estimates of a doubling in the area of very dry soils since 1970 (Trenberth *et al*., 2007). From an analysis of tree ring records, Cook *et al*. (2016) report that the recent 15-year drought in the Eastern Mediterranean was the worst in over 900 years (with 89% confidence) and was exceptional even considering the large natural variability. Large uncertainties and discrepancies arise in global assessments of past changes in droughts (Trenberth *et al*., 2014), mostly depending on the method of assessment. For example, Dai (2011) reported increases in drought-affected areas, based both on the Palmer Drought Severity Index (PDSI) for the period 1950–2008 and on soil moisture output from a land surface model for the period 1948–2004. In contrast, Sheffield and Wood (2008b) reported an overall small wetting trend over the period 1950–2000, but also a switch since the 1970s to a drying trend based on soil moisture simulations with an observation-driven land surface model. Many recent studies show contradictory global trends in drought since the middle of the 20th century. Dai (2013) reported an upwards trend in the observed global mean aridity from 1923 to 2010, whereas Donat *et al*. (2013) found that the annual maximum number of consecutive dry days had declined since the 1950s in more regions than it had increased. On the other hand, Trenberth *et al*. (2014) found a statistically significant drying trend in three out of four different precipitation data sets, including the recent CRU TS3.10 data set (Harris *et al*., 2013). Others found no strong case either for notable drying or moisture increase on a global scale over the periods 1901–2009 or 1950–2009 (Sheffield *et al*., 2012; van der Schrier *et al*., 2013). More significantly, Hartmann *et al*. (2013) suggested that the conclusions of Trenberth *et al*. (2007) regarding global increasing trends in drought since the 1970s were overstated. According to Trenberth *et al*. (2014), increased heating from global warming may not cause droughts directly, but when droughts occur they are likely to set in quicker and be more intense because of the warming.

Droughts can exhibit multi-year and even longer variability. Instrumental data show that the Dust Bowl of the 1930s and the 1950s droughts were the most widespread of the 20th century droughts in the USA, while tree ring data have indicated that the megadroughts in the USA in the 12th century exceeded anything in the 20th century in both spatial extent and duration (Andreadis *et al*., 2005; Peterson *et al*., 2013a). Recent analysis of long-term trends show strong regional variability, but increased drying was found across much of Africa, East and South Asia, eastern Australia, southern Europe, Alaska and northern Canada (Dai, 2011a,b). Based on monthly moisture variability for the period 1800–2003, van der Schrier *et al*. (2007) found that the late 1850s to the 1870s and the 1940s to the early 1950s stand out as persistent and exceptionally dry periods in the Alpine region. The driest summers on record, in terms of the amplitude of a simple drought index, averaged across the Alpine region, were 1865 and 2003. Europe has been affected by a number of droughts in recent decades, such as the catastrophic drought associated with the 2003 summer heatwave in central Europe and the 2005 drought in the Iberian Peninsula (EEA, 2012; WMO, 2013). In the Southern Hemisphere, Jiménez-Muñoz *et al*. (2016) associate extreme drought in the eastern Amazon rainforest (and a coincident severe wet period in western Amazonia) with the 2015–2016 El Niño event.

Using a relatively high spatial resolution coupled ocean–atmosphere–land General Circulation Model, Hirabayashi *et al*. (2008) projected increases in the frequency of droughts during the last 30 years of the 21st century to be significant globally. For Europe, projections suggest that droughts are to become more severe this century in many countries, including Ireland (Muñoz-Mas *et al*., 2016). In parts of Europe (and boreal Eurasia), there is an increasing risk of more frequent droughts (Garamvölgyi and Hufnagel, 2013) or an increasing duration of dry spells (Jacob *et al*., 2014) over the coming decades. However, this risk was found to be most prominent in central, eastern and southern Europe (Szinell *et al*., 1998; Lloyd-Hughes and Saunders, 2002; Bonaccorso *et al*., 2003; Dai *et al*., 2004; Lehner *et al*., 2006; Sheffield and Wood, 2008a; Briffa *et al*., 2009; Trnka *et al*., 2009; Dai, 2011a,b; Warren *et al*., 2012; Dai, 2013). Individual studies identify other specific regions in which drought is expected to increase, for instance in the Alps (Gobiet *et al*., 2013). Recognising the human dimension, recent drought mapping for Europe has been extended to include indices that combine both risk and vulnerability (e.g. Blauhut *et al*., 2015). In China, Zhang *et al*. (2013c) specifically projected increasing drought risk by the 2030s to range from 14% in the north-east to 28% in the south-west above the baseline climate for the period 1980–2008.

2.4 Extreme Temperatures

Global mean surface temperatures have increased since the late 19th century. Each of the past three decades has been significantly warmer than all the previous decades in the instrumental record (Figure 2.4), and the first decade of the 21st century has been warmer than the previous two decades (IPCC, 2013; WMO, 2013). The NASA Goddard Institute and the National Oceanic and Atmospheric Administration (NOAA) independently estimate that, globally, the average temperature for 2015 was the highest since 1888 (with 94% confidence) and that the average increase since then has been about 1°C per year (NASA GISTEAM, 2016), with most of the increase having occurred in the last 35 years. Earlier studies showed similar patterns. For instance, a World Meteorological Organization (WMO) analysis in 2013 indicated that the global combined land and ocean surface temperature for the previous three decades had increased by about 0.47°C above the long-term

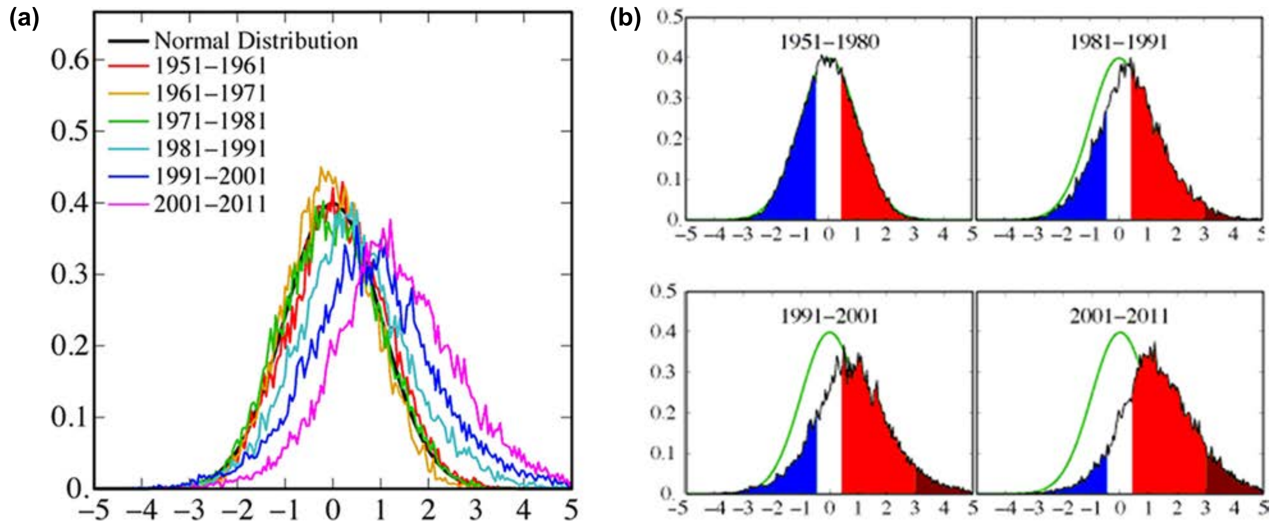


Figure 2.4. (a) Observed annual and decadal global mean surface temperature anomalies 1850–2012 with reference to the 1961–1990 base period and (b) shifting distributions of Northern Hemisphere land temperature anomalies (June to August) (base period 1951–1980 in green). Reproduced from Hansen *et al*. (2012) with permission from the National Academy of Sciences of the United States of America.

average value for 1961–1990. Hansen *et al*. (2012) demonstrated how the frequency distribution of local June to August temperature anomalies (relative to the 1951–1980 mean) for the Northern Hemisphere lands has shifted towards increased temperatures in the last decades (Figure 2.4a). The temperature anomalies in the period 1951–1980 match the normal distribution bell curve closely, shown in green (Figure 2.4b), which is used to define cold (blue), typical (white) and hot (red) seasons, each with a probability of 33.3%. The same cool summers now have a probability of 1 in 12, typical summers have a probability of 1 in 6, whereas the probability of warm summers is now 4 in 6, with a 1 in 12 probability of an extremely hot (red-brown) anomaly.

In addition, the numbers of both warm days or cold days due to climate warming have changed in many areas of the world, together with significant increases in the number of warm nights and a reduction in the number of cold nights (Trenberth *et al*., 2007; Donat *et al*., 2013). Many studies have noted that surface temperature extremes have probably been affected by anthropogenic forcing and also that this may have considerably increased the risk of extreme temperatures (Hegerl *et al*., 2007; Gutowski *et al*., 2008; Christidis *et al*., 2011; Zwiers *et al*., 2011; Christidis *et al*., 2012) on a global scale. In a recent study, Diffenbaugh and Scherer (2013) reported that heatwave events were four times more likely in the current forcing than in the pre-industrial forcing. Analysing hot spring temperatures in the year 2012 across eastern USA, Knutson *et al*. (2013) found that anthropogenic forcing contributed about 35% to late spring heat in that year.

In Europe, the heatwave across the western and central regions in the summer of 2003 was the hottest since comparable instrumental records began around 1780 and perhaps the hottest since at least 1500 (Luterbacher *et al*., 2004). It is also one example of an exceptional recent extreme (Beniston, 2004; Schär and Jendritzky, 2004). Furthermore, Barriopedro *et al*. (2011) noted that the historical evolution of the hottest summers in Europe (Figure 2.5) suggests that the last decade stands substantially above any other 10-year period since 1500, with at least two summers in this decade (2003 and 2010) having been most probably the warmest in the last 510 years in Europe. According to Stott *et al*. (2004), anthropogenic forcing has doubled (confidence >90%) the risk of European heatwaves exceeding the magnitude of the severe 2003 heatwave, which was the highest in the instrumental record until then, and exceeded other recent extremes such as in 2006 (Rebetez *et al*., 2009) and in 2007 in south-eastern Europe (Founda and Giannakopoulos, 2009), and was only exceeded by the 2010 heatwave in Russia (Barriopedro *et al*., 2011; WMO, 2013). Globally, Duan *et al*. (2013) noted that, even given the background of a warming global climate, regional climate responses may be different from place to place. In general, most studies indicate

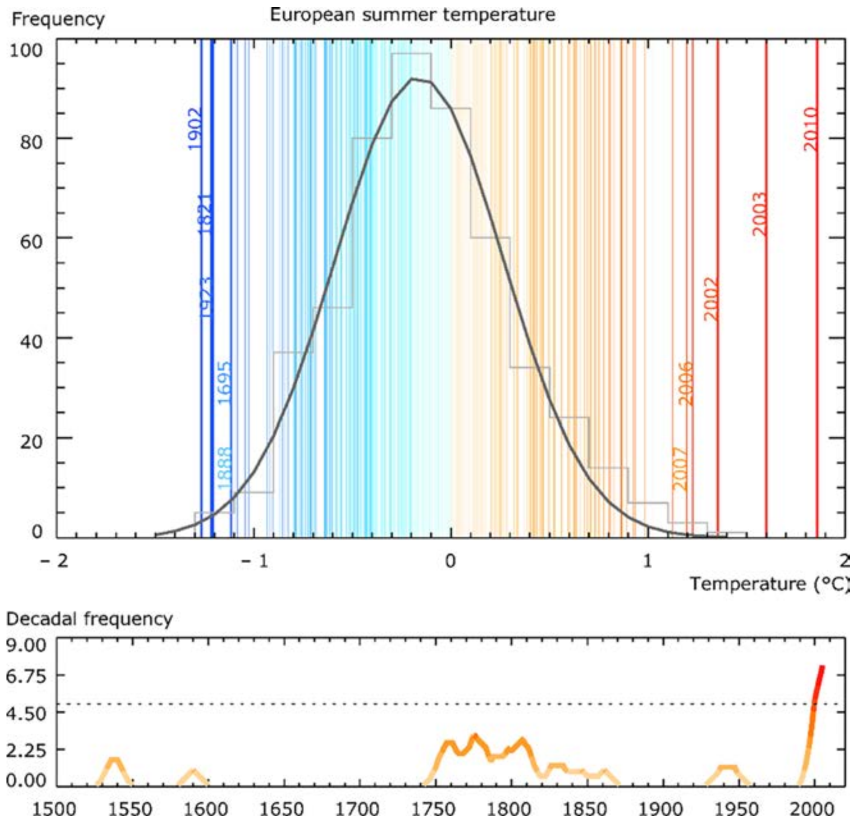


Figure 2.5. European summer temperatures for 1500–2010. The upper panel shows the statistical frequency distribution of best-guess reconstructed and instrument-based European (35°N, 70°N; 25°W, 40°E) summer land temperature anomalies (°C, relative to the 1970–1999 period) for the 1500–2010 period (vertical lines). The five warmest and coldest summers are highlighted. Grey bars represent the distribution for the 1500–2002 period, with a Gaussian fit in black. The lower panel shows the running decadal frequency of extreme summers, defined as those with temperature above the 95th percentile of the 1500–2002 distribution. A 10-year smoothing is applied. The dotted line shows the 95th percentile of the distribution of maximum decadal values that would be expected by random chance. Reproduced from Barriopedro *et al*. (2011) with permission from the American Association for the Advancement of Science.

a significant change, either an upwards trend in the duration and frequency of hot extremes (El Kenawy *et al*., 2011; Donat *et al*., 2013) or a trend towards reduced cold extremes. For example, an analysis of temperature trends in the mid- and high latitudes of the Northern Hemisphere by Alexander *et al*. (2006) showed a tendency towards a greater duration or frequency of warm spells in much of the region throughout the second half of the 20th century, with the exception of the south-eastern USA and eastern Canada. A positive shift in the distribution of daily minimum temperature throughout the world over the 1951–2003 period was also found. Cold temperature extremes had become less frequent across a significant proportion of the global land area during the second half of the 20th century (Frich *et al*., 2002). In the USA, some indices of cold extremes, such as the annual number of frost days or the percentage of cool nights, decreased with time over the period 1970–2007, whereas indices of hot extremes, such as the percentage of warm days or number of heatwaves, increased over the same period (Dulière *et al*., 2013).

Over the past few decades, heatwaves in the USA have generally increased in frequency (Peterson *et al*., 2013a) and magnitude (WMO, 2013), while cold waves have become less frequent in many areas, but not everywhere (Spinoni *et al*., 2015). However, decadal variations in the number of heat- and cold waves did not correlate that closely with the warming observed in each decade. For example, whereas the drought years of the 1930s had the most heatwaves in the USA, the 1980s had the highest number of cold waves (Peterson *et al*., 2013a). According to Kunkel *et al*. (2008), cold waves showed a decline in the first half of the 20th century, followed by an increased number of events during the mid-1980s, and then a decline. In a recent report, the year 2012 was found to be the warmest on record up until then in the USA (NOAA NCDC, 2013a), with temperatures of 3.2°F (1.8°C) above the 20th century average across much of central and eastern USA during spring and summer, and one of the most severe droughts on record (Hoerling *et al*., 2013). On a global scale, Knutson *et al*. (2013) reported that the year 2012 was characterised by a much greater occurrence of warm extremes than of cold extremes, where 15.3% of land areas recorded first, second or third warmest in the record for extreme annual means since 1851, compared with zero cold extremes. In the year 2013, the combined average temperature across global land and ocean surfaces for November was the record highest for the 134-year period on record, at 0.78°C above the 20th-century average (NOAA NCDC, 2013b). A recent global survey (WMO, 2013) indicated that a total of 56 countries (44%) reported that their highest absolute daily maximum temperature (from records covering the period 1961–2010) was observed in the decade 2001–2010 compared with 24% of countries reporting their maximum in 1991–2000, with the remaining 32% of countries spread over the earlier three decades. Conversely, 11% (14 out of 127) of the countries reported that their absolute daily minimum temperature record was observed in 2001–2010, compared with 32% in 1961–1970 and around 20% in each of the intermediate decades. In the eastern Mediterranean region, Kuglitsch *et al*. (2009) found an increase in heatwave intensity, number and length in summer over the period 1960–2006. Recent trends in daily temperature extremes over north-eastern Spain over the period 1960–2006 similarly indicated that changes were more prevalent in hot extremes than in cold extremes and that there was a significant increase in the frequency and intensity of most of the hot temperature extremes (El Kenawy *et al*., 2011). Furthermore, Ding *et al*. (2010) reported increasing numbers of heatwaves over most of China for the period 1961–2007. Ma *et al*. (2012), moreover, found that cold wave frequency had significantly reduced across China during the warm period (1978–2009) in comparison with that during the cold period (1957–1977).

Although unusually cold temperature events have become less common globally, winters with widespread patterns of unusually low temperatures have occurred in some areas in recent years. Duan *et al*. (2013) found that the frequency of extreme inter-annual decreases in cold-season temperature, in subtropical China, had increased since the 1930s. According to WMO (2013), perhaps the most significant extreme low-temperature and snowfall conditions, which were reported for the decade 2001–2010, was the extreme winter conditions across the Northern Hemisphere in the period from December 2009 to February 2010. At that time, strong negative temperature anomalies and prolonged snowfall events occurred across Europe, the Russian Federation, parts of North America, particularly the USA, and Asia. In Europe, the UK experienced its most prolonged spell of freezing temperatures and snowfall since the winter of 1981/1982, whereas Ireland and Scotland had their coldest winters since 1962/1963. Some 12 stations in the European part of the Russian Federation and Siberia registered new absolute temperature minima for that time of year.

2.5 Inland Flooding

Although many recent studies predict an increase in the number and frequency (rather than magnitude) of extreme floods (e.g. Alfieri*et al*., 2015; Muñoz-Mas *et al*., 2016; Olsson *et al*., 2016), to date there is no conclusive evidence of a strong climate change signal in the occurrence and severity of observed floods in Europe (Rojas *et al*., 2013; Hall *et al*., 2014). Detecting and attributing climate-driven trends from observations of river flow extremes is challenging as a result of the many confounding factors, including urbanisation, other land use changes, in-stream engineering and a large natural variability in flow extremes that complicate the analysis and interpretation of trends (Mudelsee *et al*., 2003; Yiou *et al*., 2006; Bormann *et al*., 2011; Murphy, 2013; Rojas *et al*., 2013). Because floods are, by definition, extreme in magnitude, they are difficult to measure, and because they are relatively rare events, it is difficult to determine their statistical properties from few events (Whitfield, 2012). Where model-based projections of future trends have been undertaken, the results may not be consistent with observed past trends (Kundzewicz *et al*., 2013). While the past data usually show no statistically significant general upwards trend in flood maxima, model projections do predict upwards changes, albeit not regionally coherent ones. The European Environment Agency (EEA) (2012) explained this disparity in the context of Europe by comparing observed trends reported by Stahl *et al*. (2010) with projections by Rojas *et al*. (2012). Over the period 1962–2004 (Figure 2.6a), increasing trends dominated in the wetter period from October to March, whereas decreasing trends dominated the drier period from April to September (Stahl *et al*., 2010). On the other hand, in projections for the summer and autumn of the period 2071–2100, Rojas *et al*. (2012) projected river flows to decrease, relative to the control period 1961–1990, in most of Europe, except for northern and north-eastern regions, where increases were projected (Figure 2.6b).

In other regions, Peterson *et al*. (2013a) reported decreasing trends in annual peak river flow in south-western USA, but increasing flood magnitudes in north-east and north-central USA. However, they noted that their analysis was confounded by multi-year and even multi-decadal variability, probably caused by both large-scale atmospheric circulation changes and basin-scale memory in the form of soil moisture. In Sweden, Lindström and Bergström (2004) analysed long-term variations in annual runoff volumes and the occurrence of floods (annual and seasonal peaks) for a total of 61 discharge series and demonstrated that both runoff volumes and flood magnitude increased substantially between 1970 and 2002, although similar conditions were experienced much earlier, in the 1920s. In Scotland, Werritty *et al*. (2002) noted that the more recent decades, since 1989, have produced new record peak flows in half of the largest river systems, particularly those draining the western part of the country. Across Scotland, the frequencies and mean flow magnitudes of floods exceeding modest thresholds varied considerably over the past eight decades. Flood frequencies were highest in parts of the 1980/1990s in many rivers across Scotland, but some longer records indicated that frequencies were higher, representing higher numbers of spates, around the 1950s, particularly in the north. Kundzewicz *et al*. (2013) and Hov *et al*. (2013) similarly indicated an increasing trend during a 25-year period (1985–2009) in the number of reported floods exceeding severity and magnitude thresholds of 2-year and 5-year return periods in Europe. In a recent review, Hall *et al*. (2013) summarised spatially the conclusions from numerous trend studies from many European countries (Figure 2.7). In these studies, different high-flow indicators were derived from observed discharge time series, some dating back to 150 years. Most of the decreasing trends are in eastern and northern or southern Europe and most of the increasing trends in western and central Europe, the last possibly influenced by rising sea surface temperatures in the Mediterranean (Volosciuk *et al*., 2016) and the frequency and tracks taken by cyclones (Pfahl and Wernli, 2012). The results provide insights into small-scale regional patterns of increasing, decreasing or non-detectable changes (at a specific significance level) in flood regimes.

Recent studies indicate that anthropogenic climate change could have increased the risk of rainfall-dominated floods in some river basins. For instance, Pall *et al*. (2011) used a physically based probabilistic event attribution method to indicate that the risk of an extreme flooding event in England and Wales had increased by over 20% (in 9 out of 10 simulations) as a result of the emission of anthropogenic greenhouse gases. In a UK-wide study, increasing high-flow trends since the 1960s were found to have parallels with observed changes in extreme rainfall and projections of increases in intense rainfall, in a future warmer world (Hannaford and Marsh, 2008).

In Europe, Benito *et al*. (2003) reported that climate changes in the Iberian Peninsula over the last millennium had induced a response in hydrological extremes (positive or negative), irrespective of the individual flood-producing mechanism. Tu *et al*. (2005) found significant increases in flood peaks in the Meuse River and also in antecedent precipitation amounts in its catchment since the early 1980s. A similar conclusion arose from a study of rivers in northern France (Renard *et al*., 2008). Further east, a study of data from 145 discharge gauges in Germany for the period 1951–2002 also found statistically significant (10% confidence level) upwards trends in floods for over one-quarter of the basins analysed and no significant trends for most of the remaining gauges and a few with significant downwards trends (Petrow and Merz, 2009). The increasing trends were mainly in the western side of Germany and the few significant decreasing trends were in the east of the country. Because of the spatial and seasonal coherence of the results across all spatial scales examined, they inferred that the changes were climate driven. In the

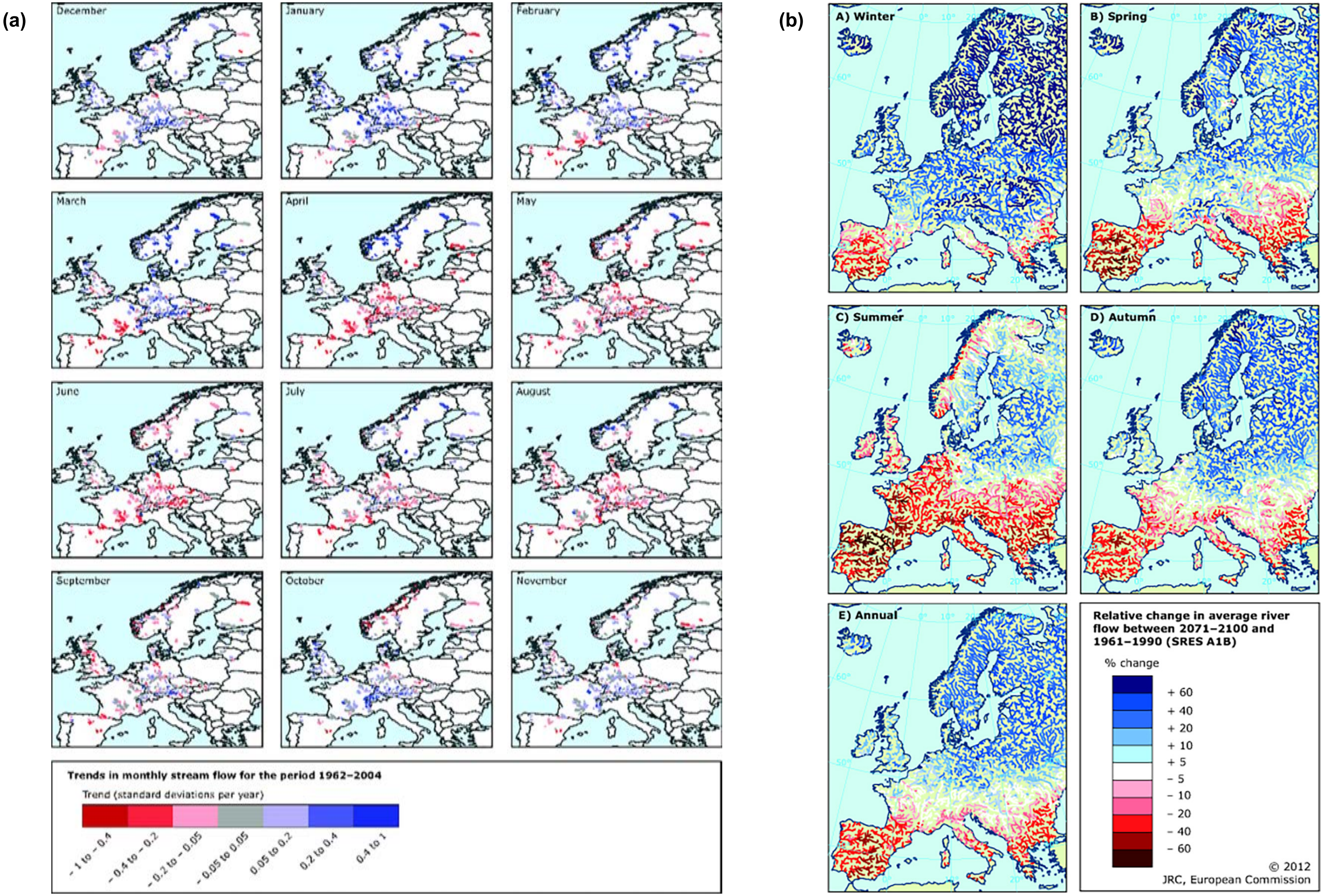


Figure 2.6. Observed and projected change in mean stream flow across Europe. (a) Observed trends for the period 1962–2004. Reproduced from Stahl *et al.* (2010) with permission from the European Geosciences Union. (b) projected trends for the period 2071–2100, relative to 1961–1990. Reproduced from Rojas *et al*. (2012) with permission from Wiley.

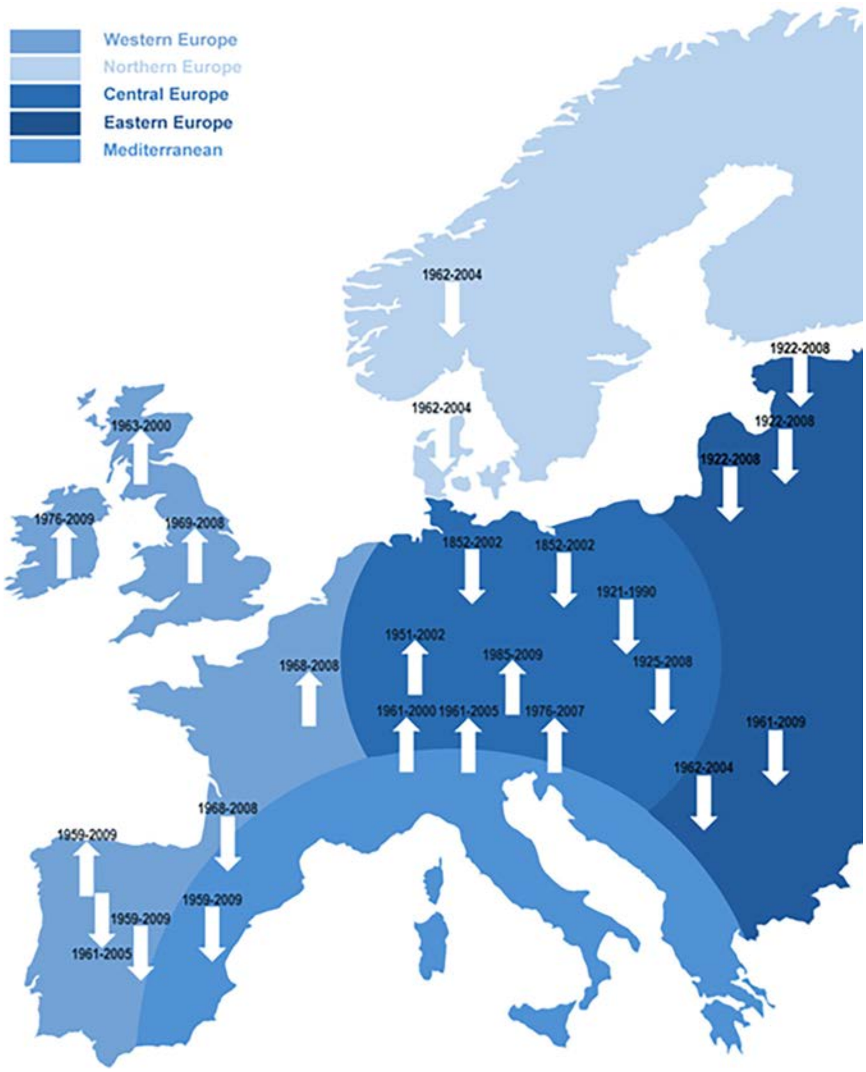


Figure 2.7. Schematic summary of observed flood changes in Europe derived from several studies using different, but not directly comparable, change analysis methods and time periods. Arrows in the schematic indicate the majority of trends including regions with weak and/or mixed change patterns. Areas with no/inconclusive studies owing to insufficient data (e.g. Italy) and inconclusive change signal (e.g. Sweden) are not shown. Reproduced from Hall *et al.* (2013) with permission from the European Geosciences Union.

USA, from analysis of daily streamflow data for 400 sites covering the period 1941–1999, McCabe and Wolock (2002) found a noticeable increase in annual minimum and median daily streamflow around 1970 and a less significant, mixed pattern of increases and decreases in annual maximum daily streamflow primarily in eastern USA. The streamflow increases seemed to occur as a step change rather than as a gradual trend, which coincided with an increase in precipitation, which they interpreted as a shift in the climate system to a new regime that was likely to remain relatively constant until a new shift or step change occurred.

In regions where floods often result from snowmelt, there is evidence that earlier spring melt, related to recent warming trends, has resulted in more rapid melt of the winter snow pack and higher peak flows. This was observed in the Alps (Renard *et al*., 2008), in north-east Europe (Dankers and Feyen, 2008), in Canada (Cunderlik and Burn, 2002; Cunderlik and Ouarda, 2009), in the USA (Regonda *et al*., 2005; Clow, 2009; Hidalgo *et al*., 2009; Elsner *et al*., 2010; Hamlet *et al*., 2013), in Peru (Mark and Seltzer, 2003), in northern Sweden (Graham *et al*., 2007), in Russia (Smith, 2000; Shiklomanov *et al*., 2007) and northern Britain (Kay and Crooks, 2014). Hidalgo *et* *al*. (2009) concluded that observed trends towards earlier "center" timing (i.e. the day in the water year on which 50% of the water yield for that year has been measured) of snowmelt-driven streamflows in the western USA since 1950 were different from natural variability (5% confidence level). This agrees with the results of Barnett *et al*. (2008), who showed that up to 60% of the climate-related trends of river flow, winter air temperature and snow pack between 1950 and 1999 were due to human-caused climate changes from greenhouse gases and aerosols. Cunderlik and Burn (2004) explained that the significant increases in spring air temperature had shifted the timing of the snowmelt process, resulting in a significant increase in early spring maximum flow. However, the magnitude of the spring flood depends on whether the preceding winter snow depths increased, producing a larger flood (Meehl *et al*., 2007) or decreased, which could result in a smaller flood (Hirabayashi *et al*., 2008; Dankers and Feyen, 2009).

However, despite temperature-induced increases in glacial melt throughout the 21st century, Crossman *et al*. (2013) found, from a study of an Alaskan glacier-fed river, that it was precipitation (both adding to the build-up of snow pack in winter and direct precipitation in spring) that predominantly affected most river discharges, rather than the increased melting due to temperature increases. Earlier, Lindström and Bergström (2004) had reported that runoff in Sweden at the beginning of the 19th century was even higher than in recent decades, although temperatures were lower. Consequently, the balance between rainfall- and snow-driven river floods in currently snow-dominated areas made projections of future flood hazard in these regions highly uncertain (Dankers and Feyen, 2009).

Many studies of data from the 20th century have not been able to conclusively attribute the observed trends in flood frequency and magnitude to changes in climate. For example, Shiklomanov *et al*. (2007) analysed daily discharge records from a data set of 139 Russian gauges in the Eurasian Arctic drainage basin with watershed areas from 16.1 to 50,000 km^2 for signs of change in maximum river discharge and did not find any widespread trends. Lindström and Bergström (2004) also analysed long-term variations in annual runoff volumes and the occurrence of floods (annual and seasonal peaks) in Sweden for a total of 61 discharge series, with emphasis on the period 1901–2002, and found no increased frequency of floods with a return period of 10 years or more. They stressed that it was difficult to conclude that flood-peak magnitudes were increasing. Other similar studies found no conclusive evidence of a direct link between climate and changes in the frequency or magnitude of floods in the USA during the 20th century (Lins and Slack, 1999; Douglas *et al*., 2000; McCabe and Wolock, 2002; Villarini *et al*., 2009), in Canada during the three decades from 1974 to 2003 (Cunderlik and Ouarda, 2009), in Scotland during the 20th century (Werritty *et al*., 2002) or in Africa during the 20th century (Di Baldassarre *et al*., 2010).

However, flooding trends were linked with indices of meteorological condition. For instance, in western areas of the UK, high-flow indicators correlated with the North Atlantic Oscillation Index (NAOI) (Hannaford and Marsh, 2008), and recent trends may reflect the influence of multi-decadal variability related to the NAOI. Camilloni and Barros (2003) report that two-thirds of the major discharges in the Paraná River at Corrientes in Argentina occurred during El Niño events. Over the period 1958–1999, Ward *et al*. (2013) found that the El Niño Southern Oscillation (ENSO) exerted a significant influence on annual floods in river basins covering over one-third of the world's land surface, and that the ENSO influence on floods is much greater than on average flows. Similarly, most of the major discharges from the upper and middle Paraguay basins occur during El Niño periods (Barros *et al*., 2004). In the USA, Regonda *et al*. (2005) speculate that an advance in the timing of peak spring season flows over the past 50 years was due to enhanced ENSO activity.

Overall, to date, while there is much speculation, no conclusive evidence of a climate signal in the occurrence and severity of riverine flooding has emerged in the literature. Detecting a possible trend has been hampered by the interaction between the climate-driven physical causes and socio-economic factors such as population changes, urban development, land use change and in-stream engineering activities (Mudelsee *et al*., 2003; Yiou *et al*., 2006; Bormann *et al*., 2011; Murphy, 2013; Tanoue*et al*., 2016). Nevertheless, there is some acknowledgement of the time-varying character of flood risk and a realisation that an adaptive approach to flood protection design is required (Sarhadi *et al*., 2016).

2.6 Sea Level Rise, Storm Surges and Coastal Flooding

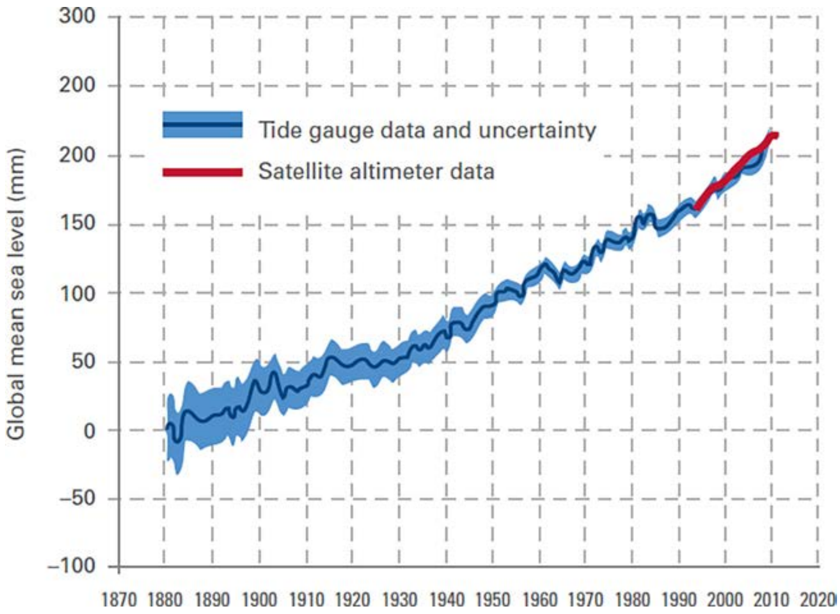
Coastal flooding in many areas across the world have been attributed mainly to storm surges during high or spring tides, which can be exacerbated by sea level rise (Werritty *et al*., 2002; Dawson *et al*., 2009). Opinions are divided on whether or not such storminess has increased under climate warming. On the one hand, a 40-year reconstruction (1955–1994) of the wave climate in the North Atlantic showed an increase of the annual maximum significant wave height of about 5–10 cm yr^{-1} for large parts of the North-east Atlantic (Günther *et al*., 1997), with increased risk of flooding of adjacent coastal areas, e.g. Scotland (Dawson *et al*., 2001). A more recent review by Feser *et al*. (2014) assessed storm studies across the North Atlantic and the north-western European landmass and found that a large number of proxy- and observation-based studies detected no storm trend at all (33 out of 75 articles), while 24 studies described a decrease and 18 studies reported an increase (Figure 2.8b). For the North Sea, the North-east Atlantic and the British Isles, most studies showed no trend at all. Across central Europe, most studies found a decrease in storminess. The Baltic Sea region gave inconsistent results, with as many articles returning increasing as decreasing storm numbers. Interestingly, when proxy studies of periods longer than the last 100 years are analysed, there are large variations but no overall trend, while when shorter series, e.g. the last four to six decades, are studied, an increase in storminess between the mid-1970s and mid-1990s is suggested (Günther *et al*., 1997; Alexandersson *et al*., 2000; Wang *et al*., 2009; Dangendorf *et al*., 2014; Feser *et al*., 2014). Part of the increased variability was related to the North Atlantic Oscillation (NAO). The main consensus is that there was relatively high storminess around 1900 and in the 1990s and that the 1960s and 1970s were periods of low storm activity (Bärring and von Storch, 2004; Bärring and Fortuniak, 2009; Wang *et al*., 2009). Similarly, in reviewing the evidence for storm activity across the North Atlantic region derived from instrumental records, together with much earlier archival evidence of storm impacts in the last 200 years, Clarke and Rendell (2009) found periods of increased storminess during the Little Ice Age (AD 1570–1990). On the other hand, there are no robust signs of any long-term trends in storminess since about 1780 (Bärring and von Storch, 2004; Bärring and Fortuniak, 2009). The present intensity of the storm and wave climate seems to be comparable with that at the end of the 19th century and beginning of the 20th century. The final two decades of the 20th century were found to have the same storminess as the 1900s. Bijl *et al*. (1999) specifically detected no significant increase in storminess across north-west Europe on the basis of a 100-year data set. On global scales, no significant increase in storminess has been demonstrated (Menéndez and Woodworth, 2010; Woodworth *et al*., 2011).

Widespread evidence from tide gauge data suggest that global sea levels have risen over the last 100 years (Werritty *et al*., 2002) and, indeed, that the rate of observed sea level rise increased from the 19th to the 20th century (Bindoff *et al*., 2007; Church and White, 2011; Woodworth *et al*., 2011). The global mean sea level reportedly rose at a rate of about 1.7 mm yr^{-1} over the 20th century (Church and White, 2006; Bindoff *et al*., 2007) and at the same rate over the last 110 years (Chambers *et al*., 2012). Sea levels have continued to rise into the 21st century (Church and White, 2011, Chambers *et al*., 2012; Baur *et al*., 2013). The observed rate of increase over the last decade (2001–2010) was circa 3 mm yr^{-1} (WMO, 2013), about double the observed 20th century trend. Global sea levels averaged over the decade were approximately 20 cm higher than those of 1880 (Figure 2.8).

In Europe, local relative sea level rise at most locations post-1900 ranges from –6.5 mm/year (Oulu, Finland, where isostatic uplift of the land contributes) to +6.8 mm yr^{-1} (Poti, Georgia), with many tide gauges recording 2 mm yr^{-1} of rise (Figure 2.8a). Tide gauges around the North Sea and southern Europe have the highest rate of relative sea level rise, partly due to land subsidence. Northern coasts experience low relative sea level rise, or even sea level fall as a result of isostatic uplift, which complicates the interpretation of relative changes.

In many cases, increases in sea level extremes generally followed the rise in sea level averages. However, increases in the extremes have been more pronounced since the 1970s (Woodworth and Blackman, 2004; Lowe *et al*., 2010; Menéndez and Woodworth, 2010; Woodworth *et al*., 2011). Linear trends in total sea level extremes, consistent with trends in mean sea level, were also found in a number

(a)



(b)

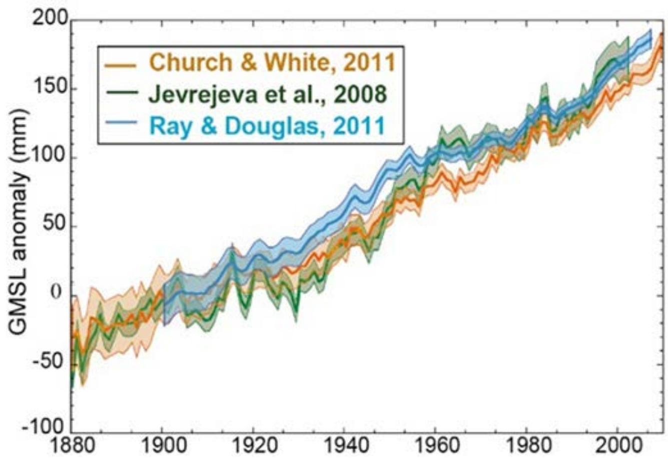


Figure 2.8. Evolution of global mean sea level (GMSL) anomalies from the different measuring systems. (a) Global time series of sea level anomalies from 1880 to 2011, using tide gauges and satellite altimetry. Source: WMO (2013). (b) Global mean sea level reconstructed from tide gauges (1900–2010) by three different approaches. Source: IPCC (2013).

of studies, including in southern Europe on the basis of 73 tide gauge records from 1940 (Marcos *et al*., 2009), in Marseille on the basis of hourly tide gauge records for the period 1885–2008 (Letetrel *et al*., 2010) and in the English Channel on the basis of 18 tide gauge records over the period 1900–2006 (Haigh *et al*., 2010). Similar trends were found in Buenos Aires (D'Onofrio *et al*., 2008) and Mar del Plata (Fiore *et al*., 2009). Other studies have found the extremes to have increased in magnitude at faster rates than the average. For example, on the basis of hourly tide data spanning the period 1979–1995, Ullmann *et al*. (2007) reported that maximum annual sea levels had risen twice as fast as mean sea level in the Camargue (Rhône Delta) region of southern France. At Prince Rupert in British Columbia, sea level extremes were similarly found to have risen at approximately 3.4 mm yr^{-1} since 1945, which was twice the rate for mean sea level in that period (Abeysirigunawardena and Walker, 2008).

A large part, if not all, of the observed sea level rise is caused by global warming (Shum *et al*., 2008; Willis *et al*., 2010; Church *et al*., 2011; Moore *et al*., 2011; Shum and Kuo, 2011). For example, Woodworth and Blackman (2004) found a general worldwide increase in extreme high-water levels since 1975, and noted that the variations in extremes in this period were closely related to changes in regional climate. Climate warming causes global sea levels to rise as a result of (1) thermal expansion of the oceans and (2) the loss of some land-based ice on account of increased melting (Bindoff *et al*., 2007; Bellard *et al*., 2013). Evidence that the contribution to sea level due to mass loss from Greenland and Antarctica is accelerating is well documented (Velicogna, 2009; Rignot *et al*., 2011; Sørensen *et al*., 2011; WMO, 2013). In a recent study, Clague (2013) pointed out that any substantial increase in ice losses from Greenland and Antarctica in the coming decades may raise the sea level by close to 1 m by the end of this century. Rignot *et al*. (2011), on the basis of a 20-year record of monthly ice sheet mass balances, estimated that the Greenland and Antarctic ice sheets experienced a combined mass loss equivalent to 1.3 (± 0.4) mm yr^{-1} sea level rise. A similar value was reported by Shepherd *et al*. (2012) on the basis of a reconciled estimate of ice sheet mass balance over the same period. This combined total acceleration in ice sheet loss was found to be three times larger than for mountain glaciers and ice caps. It was concluded that, if this trend continued, ice sheets would be the dominant contributor to sea level rise in the 21st century. The same conclusion was drawn by WMO (2013), which noted that the world's glaciers lost more mass in 2001–2010 than in any other decade since records began. Snow cover in the Northern Hemisphere (Figure 2.9) and Arctic sea ice extent similarly declined significantly. A specific study by Levermann *et al*. (2013) revealed that oceanic thermal expansion and the Antarctic ice sheets contributed quasi-linearly to sea level rise, with 0.4 m $°C^{-1}$ and 1.2 m $°C^{-1}$ of warming, respectively. They projected that, within the next 2000 years, sea level will rise approximately 2.3 m $°C^{-1}$.

Many recent studies point to the effect of atmospheric circulation on the extreme sea level trends, including, in particular, the ENSO and NAO. Ullmann *et al*. (2007) found that maximum annual sea levels in the Camargue region of southern France had risen twice as fast as mean sea level during the 20th century, largely because of changes in the wind field in recent decades. Further studies on the relationships between air pressure, winds and storm surges in the area, and, in particular, the link between large surges and the negative phase of the NAO is well documented (Ullmann and Moron, 2008; Ullmann *et al*., 2008; Ullmann and Moron, 2010; Tsimplis *et al*., 2013). The inter-annual and decadal variability of mean sea level and extremes in southern Europe correlate negatively with the winter NAOI (Marcos *et al*., 2009). At Prince Rupert in British Columbia, Abeysirigunawardena and Walker (2008) found a possible acceleration in sea level trends during the latter half of the 20th century and attributed this to both the effects of global warming as well as to cyclic climate patterns such as the strong positive Pacific Decadal Oscillation (PDO) phase that had been present since the mid-1970s. More particularly, ENSO forcing was found to exert significant influence on winter sea level fluctuations, while the PDO dominated summer sea level variability. At the Californian coast, Cayan *et al*. (2008) noted that during El Niño events, large-scale oceanic and atmospheric mechanisms often elevated sea level

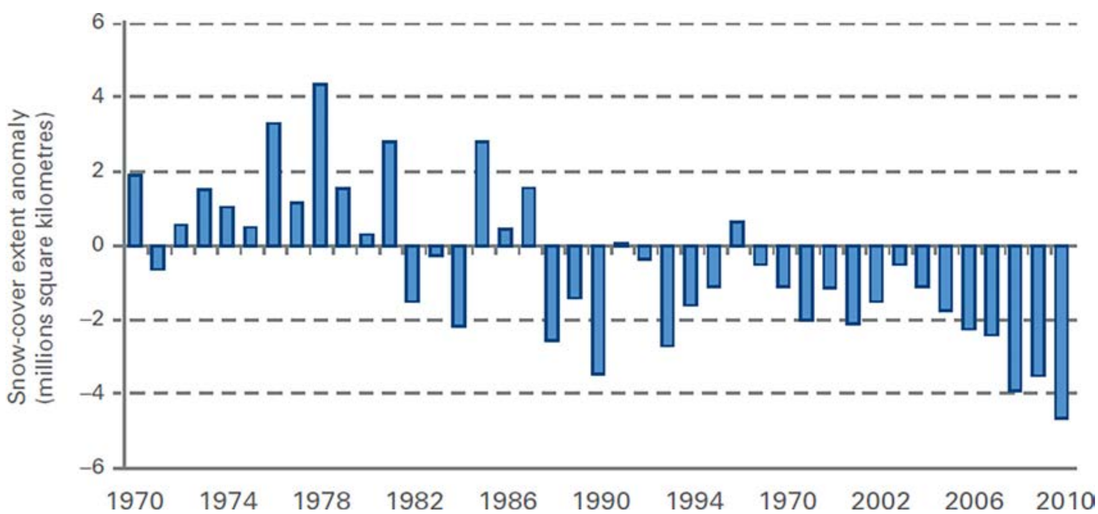


Figure 2.9. Northern Hemisphere snow cover anomaly for June 1970–2010. Source: WMO (2013).

along the West Coast, yielding non-tide sea level anomalies with amplitudes of 10–20 cm, which often persisted for several months. Based on sea level records since the 1970s, Menéndez and Woodworth (2010) found that ENSO had a large influence on inter-annual variations in extreme sea levels in the Pacific Ocean and the monsoon regions. At Mar del Plata, Fiore, Argentina, D'Onofrio *et al*. (2009) similarly found an increase in the number and duration of positive storm surges in the decade 1996–2005 compared with previous decades, which they attributed to a combination of mean sea level rise and changes in wind climatology resulting from a southward shift in the South Atlantic high.

2.7 Landslides

Landslides may constitute one of the biggest threats to many areas of the world arising from climate change, which increases the intensity of precipitation and the rate of melting of glacier ice and mountain permafrost (Liggins *et al*., 2010; McGuire, 2010; Huggel *et al*., 2012a,b; Liggins *et al*., 2013; McGuire, 2013). Warm extremes can trigger large landslides in temperature-sensitive high mountains by increasing the production of water by melting of snow and ice, and by rapid thawing (Huggel *et al*., 2010, 2013; Clague 2013). These drive load-pressure changes and increases in soil pore water pressures that, together, act to promote hazardous geomorphological and geological activity (McGuire, 2010, 2013).

Despite the difficulties of attributing specific causes to individual events with certainty, there is broad evidence of slope destabilisation by warming permafrost. For example, during the extremely hot and dry summer of 2003, many rockfall events in the European Alps originated from permafrost melting in steep bedrock (Gruber *et al*., 2004). These exceptional rockfalls are probably related to warming and a corresponding destabilisation of ice-filled discontinuities. Fischer *et al*. (2013) found strong coupling between steep glaciers and underlying bedrock in the Alps, with most bedrock instabilities located in areas where surface ice had disappeared recently. In British Columbia, Holm *et al*. (2004) found significant spatial associations between the occurrence of recent catastrophic failures, gravitational slope deformation and slopes that were oversteepened and then debuttressed by glacial erosion. According to Geertsema *et al*. (2006), recent melting of glaciers in British Columbia had debuttressed rock slopes adjacent to glaciers, causing deep-seated slope deformation and catastrophic failure. Similarly, in the Qinghai–Tibet Plateau, Niu *et al*. (2005) reported that permafrost in the thaw slumping area of south-facing slope processes was often degraded when landslides occurred and that saturation and the loss of soil strength induced by ground ice melting was the basic cause of the landslides. Further evidence at four failure sites in three mountain ranges (Alaska, Caucasus and European Alps) was provided by Huggel (2009), and in the central Southern Alps of New Zealand by Allen *et al*. (2011). It is clear here, then, that the hotter summers predicted by climate models for the coming decades will result in reduced stability of many alpine rock slopes, and landslides may be a direct and unexpectedly fast impact of climate warming (Gruber *et al*., 2004).

Many recent studies point to an apparent increase in the frequency of large rock slides during the past decades, and especially during the first years of the 21st century in the European Alps (Ravanel and Deline, 2011; Allen and Huggel, 2013; Fischer *et al*., 2013), in the French Alps (Saez *et al*., 2013), in the Southern Alps of New Zealand (Allen *et al*., 2011), in northern British Columbia (Geertsema *et al*., 2006) and in Sri Lanka (Rathnaweera *et al*., 2012) resulting from temperature increases, glacier shrinkage and permafrost degradation. Additionally, a number of longer time period studies, over the past decades and century, in the Alps and Himalayas, have found evidence of higher landslide (debris flows and large rock slides) frequency during warmer and wetter periods of the Holocene (Huggel *et al*., 2012a). More specifically, in an inventory of rockfall occurrences since the end of the Little Ice Age on the north side of the Aiguilles de Chamonix (Mont Blanc massif), Ravanel and Deline (2011) reported that over 70% of rockfalls after 1947 occurred during the last two decades, with a maximal frequency during warm summers, especially in 2003. It was noted that climate change-driven permafrost degradation had triggered many of the recent rockfalls in High-Alpine steep rock walls. Also, rock slope failures have increased over the past decades in the central European Alps and many such events, particularly those involving smaller volumes, are associated with extremely warm periods (Allen and Huggel, 2013). Fischer *et al*. (2013)

demonstrated that the start of intense mass movement activity in the European Alps coincided with strongly increased mean annual temperatures around 1990. Furthermore, an observed increase in snowmelt-driven landslide reactivations in the French Alps since the early 1990s (Saez *et al*., 2013) was reported to be quite clearly linked to the ever-increasing spring temperatures and the rapid melt of winter snow cover. A recent study in the central Southern Alps of New Zealand (Allen *et al*., 2011) similarly reported that in the period post-1949, many apparently spontaneous landslide and rockfall events were recorded, occurring most frequently from the east to south-east aspects of the hanging wall of the Main Divide Fault Zone. The occurrence of these recent failures was significantly greater in bedrock slopes located in close proximity to glaciers, where ice retreat may have been a relevant factor.

In contrast, there is much debate about the impacts of climate change on the frequency and magnitude of debris flow. While broad evidence exists that the current global warming and increase in the frequency of extreme precipitation events may have enhanced the occurrence of mass-movement processes, many recent studies assert that there is no such increase in debris-flow activity. For example, in the Swiss Alps, Rebetez *et al*. (1997) reported that the frequency of debris flows had increased in recent years, but in the analysis at a larger time scale (Bollschweiler and Stoffel, 2010) this trend was found to be no longer apparent. In fact, Bollschweiler and Stoffel (2010) found more debris-flow activity after the end of the Little Ice Age and in the period 1920–1929 than during the most recent part of the record (2000–2009). On the basis of 123 debris-flow events in the Swiss Alps since AD 1570, Stoffel and Beniston (2006) also found enhanced activity during the wet periods (1864–1895) following the last Little Ice Age glacier advance and in the early decades of the 20th century. In contrast, comparatively low activity has been observed since 1995, with only one event recorded. On the basis of periglacial debris flows and meteorological records dating back to 1864, Schneuwly-Bollschweiler and Stoffel (2012) showed that the debris-flow season at high-elevation sites (ranging from 2000 to 4545 m above sea level) in the Swiss Alps was now much longer (May to October) than it used to be in the late 19th century when activity was limited to between June and September. A similar trend was observed by Stoffel *et al*. (2011), who concluded that the Swiss Alps had experienced a cluster of debris flows in the early decades of the 20th century and a reduction in debris-flow activity since the mid-1990s. A recent study by Stoffel *et al*. (2005) reported that debris-flow activity at a local site in the Swiss Alps was higher during the 19th century than the present. Elsewhere in the French Alps, Jomelli *et al*. (2004) found no significant change in the debris-flow frequency since the 1980s in elevations above 2200 m. At lower altitudes of less than 2200 m, the number of debris flows and the frequency of debris flows less than 400 m in length has decreased significantly since the 1980s. In the Austrian Alps, Procter *et al*. (2011) reported less debris-flow activity in the early to mid-20th century and increased activity since 1948. In the period 1875–2003, Pelfini and Santilli (2008) reported that the debris-flow frequency in the upper Valle del Gallo (northern Italy) increased gradually, but the highest values occurred in the period 1974–1983, with a lessening of event frequency in the last few decades.

2.8 Wildfires

The current global climate warming may have a profound and immediate impact on wildfire activity through changes in fuel condition, fuel volume and ignitions (Hessl, 2011). Wildfire activity has already increased in many parts of the world as a result of climate change (Flannigan *et al*., 2013), mostly because, in these areas, climates have shifted to drier conditions and longer fire seasons (Attiwill and Binkley, 2013; Keywood *et al*., 2013). Recent exceptionally intense fire events, such as the Australian Black Saturday fires in 2009 and Russian fires in 2010, demonstrated the devastation that such fires can cause. Williams (2013) explains that, in many places, the rate of biomass accumulation has become far greater than the rate at which it is used, treated or otherwise decomposes. In the presence of drought and higher temperatures, more of these fuel accumulations become available to burn at ever-higher intensities, compounding wildfire risks. Evidence from north-east China equally indicates that the incidence of forest fires from 2003 to 2011 was closely linked to extreme conditions of climate warming and drought (Tao *et al*., 2013).

Climate change has had a detectable influence on the area burned by forest fires in Canada in recent decades (Gillett *et al*., 2004), while Westerling *et al*. (2006) reported that wildfire activity in the western USA increased substantially in the late 20th century. The latter is ascribed to higher temperatures and earlier snowmelt. The burn season in the western USA has increased by 2.5 months since the 1970s (Climate Central, 2012), starting earlier and finishing later in the year. In addition, there was a seven-fold increase in the number of fires greater than 10,000 acres (4000 ha) over this period. A summary of historical wildfire records from the national forests of the Southern Rockies Ecoregion, USA, from 1930 to 2006 revealed an order of magnitude increase in the annual number of fires recorded over the full period and in the number of large fires since 1970 (Litschert *et al*., 2012). Other studies have also documented changes in fire regimes (Pausas, 2004; Kasischke and Turetsky, 2006; Hu *et al*., 2010) and in other parts of the world, e.g. in the Iberian Peninsula (Pausas, 2004) and in Australia (Clarke *et al*., 2013)

Further increases in wildfire activity, in future decades, have been predicted by a large number of modelling studies. The fire season is projected to lengthen by 23 days in the warmer and drier US mid-west climate at mid-century (Yue *et al*., 2013). Recent projections using three general circulation models and three emission scenarios for mid-century (2041–2050) and late century (2091–2100), relative to the 1971–2000 baseline predicted significant increases in the global fire season severity for all models and scenarios (Flannigan *et al*. 2013). The models forecast three-fold increases in severity over the baseline for the Northern Hemisphere at the end of the century. Fire season length changes were predicted to be more pronounced at the end of the century and for northern high latitudes, where fire season lengths may increase by more than 20 days per year. In a comparative study, de Groot *et al*. (2013) simulated the impacts of climate change on 2091–2100 fire regimes in two large boreal areas in central Russia and western Canada using three global climate models and three climate change scenarios and found that the severity of future fire weather conditions increased in both areas, but was more extreme in the Canadian study area.

Despite very broad agreement on changes in wildfire activity in many areas, there is not universal agreement on the magnitude of the projected changes, and in some cases, the direction of the predicted change for all areas. In a review of the implications of changing climate for global wildfire, Flannigan *et al*. (2009) found many studies that suggested a general increase in area burned and fire occurrence, but there was a lot of spatial variability, with some areas of no change or even decreases in area burned and fire occurrence. Previous studies on the impact of future climate change on wildfire activity in North America show similar trends (Yue *et al*., 2013). In contrast, Fauria and Johnson (2008) noted that most studies on fire frequency in the boreal forest of North America identified a change towards longer frequencies during the mid-19th century, which has been attributed to climatic change. Thus, increasing evidence indicates an unclear relationship between warmer temperatures and increased area burned. Using stepwise regression to build empirical relationships between observed area burned and a suite of meteorological variables and fire indexes in Canada, and then applying these relationships to the outputs of two climate models, Flannigan *et al*. (2005) projected a two-fold increase in area burned by the end of this century. Using a comparable approach, but only one climate model, Balshi *et al*. (2009) similarly found that area burned across Alaska and western Canada would double by 2050 and increase by 3.5–5.5 times by the last decade of the 21st century. Another estimate, by Spracklen *et al*. (2009), predicted a smaller increase of only about 50% in the area burned over the western USA by the 2050s, relative to the present day. On the other hand, using fire scars and charcoal data to construct the fire history of the western USA, Marlon *et al*. (2012) revealed that there was a slight decline in burning over the past 3000 years, with the lowest levels attained during the 20th century and during the Little Ice Age.

In efforts to explain this diversity, Pausas and Ribeiro (2013) found evidence to suggest that climatic warming may affect fire activity differently depending on the biomass productivity of the region. Fire regimes in productive regions were vulnerable to warming (i.e. drought-driven fire regime changes), while, in low-biomass productivity regions, fire activity was more vulnerable to fuel changes (i.e. fuel-driven fire regime changes). In Mediterranean-type ecosystems, projections under a warmer–drier future suggested that large parts could experience substantial decreases in fire activity, even in the near term, whereas a warmer–wetter future may lead to more widespread increases in fire activity (Batllori *et al*., 2013). According to Matthews *et al*. (2012), a warming and drying climate produced lower fine fuel amounts but a greater susceptibility of this fuel to burning as a result of lower moisture contents. In supporting this assertion, King *et al*. (2013) explained how future fire regimes will be determined, in part, by the different ways in which moisture determines fire risk. Morton *et al*. (2013) pointed out that climate–fire relationships at national scales, based on the complexity and diversity of fire types, ecosystems and ignition sources and on changes in the seasonality or magnitude of climate anomalies, were unlikely to result in uniform changes in fire activity.

2.9 Ecosystem Function and Dynamic Shifts

The current climate change has had a large impact on individual organisms, populations, communities and terrestrial ecosystems by changing phenotypes, genotypes, growth, phenology, the distribution of organisms, their competitive ability, their ecological relationships, their risk of extinction (Garamvölgyi and Hufnagel, 2013; Peñuelas *et al*., 2013) and their size-structure (Brose *et al*., 2012; Lurgi *et al*., 2012; Woodworth-Jefcoats *et al*., 2013). This is mainly due to higher concentrations of CO_2; altered rainfall and temperature patterns; rising sea levels; increased sea temperatures and acidity; and more frequent extreme storms, floods and heatwaves (Department of the Environment, 2009; Garamvölgyi and Hufnagel, 2013; Gosling, 2013). In Switzerland, for example, there is an upwards elevation shift in species distributions, a wider distribution of thermophilous species, colonisation by new species from warmer areas and phenological shifts (Vittoz *et al*., 2013). In drier areas, worsening droughts affect vegetation survival, from grasses to trees. In lowland freshwaters, fish suffer from the effects of warmer temperatures (Root *et al*., 2003; Menzel *et al*., 2006; Fischlin *et al*., 2007; Donnelly *et al*., 2011; Wolkovich *et al*., 2012). A study of brown trout habitats in Spain under climate change scenarios predicted a reduction of the number of days with suitable habitat and the elimination of the trout from certain river reaches (Papadaki *et al*., 2016); a similar result was found for the Balkans (Garbe *et al*., 2016). A review of 19 studies for the IPCC Fourth Assessment (Fischlin *et al*., 2007) concluded that 20–30% of studied plant and animal species were at an increased risk of extinction if warming exceeded 2–3°C above the pre-industrial level. The subsequent IPCC Fifth Assessment confirmed the ecological risks with high confidence (Jiménez Cisneros *et al*., 2014).

One of the most noticeable responses of plants and animals to the current climate change is a shift in phenology (Peñuelas and Filella, 2001; Fitter and Fitter, 2002; Peñuelas *et al*., 2002; Cleland *et al*., 2007; Rosenzweig *et al*., 2007; Wolkovich *et al*., 2012; Donnelly *et al*., 2013; Peñuelas *et al*., 2013). Phenology is a widely used indicator of change (Menzel *et al*., 2006). Significant advances in the timing of leaf unfolding, flowering and fruiting, attributed to warming climate, have been reported in Mediterranean regions (Peñuelas *et al*., 2002; Llorens and Peñuelas, 2005; Gordo and Sanz, 2009, 2010), in other areas of Europe (Menzel and Fabian, 1999; Menzel, 2000; Huelber *et al*., 2006; Menzel *et al*., 2006), and in the USA (Sherry *et al*., 2007; Miller-Rushing and Primack, 2008; Morin *et al*., 2009; Rollinson and Kaye, 2012). These trends have been observed across a diverse range of plant taxa, including herbs and grasses as well as trees and shrubs (Richardson *et al*., 2013).

Spring blooming in some plants now occurs earlier than at any time during the previous 1200 years (Aono and Kazui, 2008; Primack *et al*., 2009). Rosenzweig *et al*. (2007) concluded that onset of spring blooming has advanced by about 2.3 to 5.2 days per decade in the last 30 years because of climate warming. Analysis of phenology data from around the world indicate that leaf-out was generally earlier in warmer years than in cooler years and that the onset of leaf-out had advanced in many locations (Polgar and Primack, 2011). Recent analyses in Ireland show that the timing of key phenological phases of trees (Donnelly *et al*., 2006; Donnelly *et al*., 2013; Gleeson *et al*., 2013b) has been affected by rising spring temperature. Long-term records of flowering by a range of herbaceous and woody forest species in the USA (Miller-Rushing and Primack, 2008) since the 1850s have recorded phenological advances of circa 3 days $°C^{-1}$ rise of air temperature. On the basis of a data set of more than 125,000 observational series of 542 plant species in 21 European countries over the period 1971–2000, Menzel *et al*. (2006) showed that leaf unfolding had advanced 2.5 days °C^{-1}, and leaf fall was delayed 1 day °C^{-1} of temperature increase. An average spring advancement of 2.5 days per decade (Menzel *et al*. 2006) or about 4 days °C^{-1} (Estrella *et al*., 2009; EEA, 2012) has been observed in Europe. The EEA (2012) reported a lengthening of the growing season by 11.4 days on average from 1992 to 2008 for a number of agricultural crops in Europe. The delay in the end of the growing season was more pronounced than the advancement of its start.

On the basis of more than 200,000 records for six phenological events of 29 perennial plant species monitored from 1943 to 2003 in the Mediterranean region, Gordo and Sanz (2010) demonstrated that warm and dry springs had advanced flowering (–6.47 days °C^{-1}) and leaf unfolding (–6.99 days °C^{-1}) dates. Fruiting dates and the growing season had also lengthened. In Hungary, a noticeable shift of dates, of approximately 3–8 days, towards earlier flowering was found for *Robinia pseudoacacia* L. (the locust tree) between the years 1851 and 1994 (Walkovszky, 1998). For 29 years of the 30-year period 1970–1999, Abu-Asab *et al*. (2001) found that the first flowering in 89 plant species in Washington, DC, had advanced 4.5 days in response to the local increase in minimum temperature. In the Mediterranean region, Peñuelas *et al*. (2002) showed that leaves unfolded on average 16 days earlier, and plants flowered on average 6 days earlier than in 1952. Additionally, fruiting occurred on average 9 days earlier than in 1974. For *Populus tremuloides* (quaking aspen), Beaubien and Freeland (2000) found a 26-day shift to earlier blooming over the last century in the area of Edmonton, Alberta. An 8-day trend to earlier flowering compared with the mean spring flowering indices for three Edmonton data sets, which together span the last six decades, were also found. Similarly, in the central parklands of Alberta, Canada, bloom dates for *P. tremuloides* and *Anemone patens* (prairie crocus) advanced by 2 weeks during the period 1936–2006 (Beaubien and Hamann, 2011). Leaf appearances in boreal Eurasia after 1990 were the earliest since 1958 at the continental scale, the earliest since 1936 in the Baltic region, and the earliest since 1920 in central Siberia (Delbart *et al*. 2008). The spring phenophases for 20 species of deciduous trees and conifers at four sites in different regions of southern Norway occurred 7 days earlier during the period 1971–2005 (Nordli *et al*., 2008). The advancement in the timing of the earliest phenophase, bud burst of *Betula pubescens* (downy birch), ranged from 0.7 days per year in southern boreal zone to 1.4 days per year in middle and northern boreal zones (Pudas *et al*., 2008). Observations covering 160 years of the leaf bud burst of two species and of the flowering of six species of native deciduous trees growing in Finland showed advancement ranging from 3.3 to 11.0 days per century (Linkosalo *et al*., 2009).

Changes in the timing of autumn phenology have also been detected, such as delays in leaf colouring and abscission (Richardson *et al*., 2013). The changing trends have typically been linked to increases in late summer or early autumn temperatures (Estrella and Menzel, 2006; Doi and Takahashi, 2008; Beltaos and Prowse, 2009). Over the period 1982–2008, Jeong *et al*. (2011) showed that the autumn senescence in Europe, East Asia and North America was delayed by approximately 3 days per decade. Similar trends were found in China for the period 1986–2005, where leaf fall was delayed significantly at a rate of 2.2 days per decade (Chen and Xu, 2012), and the period 1963–2011, where the leaf colouring date was delayed by 2.6 days per decade (Dai, 2013). In the Mediterranean region, Peñuelas *et al*. (2002) showed that leaves fell on average 13 days later in 2002 than in 1952. More recently, a modest trend towards delayed leaf abscission of 1.2 day per decade since the 1970s was also reported for the Mediterranean region (Gordo and Sanz, 2009). An experimental study in north-east Greenland showed that warming treatments delayed autumn senescence by 15 days (Marchand *et al*., 2004).

Climate change has also had significant direct effects on the phenology and behaviour of many animals (Parmesan and Yohe, 2003; Root *et al*., 2003; Menzel *et al*., 2006; McKellar *et al*., 2013). These effects include earlier breeding, changes in timing of migration, changes in breeding performance (egg size, nesting success), changes in population sizes and distributions, and changes in selection differentials between components of a population. Many bird species show earlier spring arrival and egg-laying dates in response to warmer spring temperatures (Crick, 2004; Gordo and Sanz, 2005; Sparks *et al*., 2005; Gordo, 2007; Donnelly *et al*., 2009; Fletcher *et al*., 2013). The annual variation in tropical precipitation and temperature, through their indirect effects on food availability, influence departure from non-breeding grounds and earlier arrival to breeding grounds in many migratory birds (Gordo *et al*., 2005; Studds and Marra, 2011; Stirnemann *et al*., 2012; Tøttrup *et al*., 2012; McKellar *et al*., 2013). The earlier appearance of insects is related to temperature increases (Roy and Sparks, 2000; Gordo and Sanz, 2005). In Ireland, the timing of key phenological phases of birds (Donnelly *et al*., 2009; Stirnemann *et al*., 2012) and insects (O'Neill *et al*., 2012) are affected by increased spring temperatures.

Over the past 30 years, a pattern of migratory birds arriving earlier in spring is apparent at various locations throughout the world. For instance, Lehikoinen *et al*. (2004) reported significant earlier arrivals for 39% of 983 data series of first arrival dates of migratory birds into 10 European countries. A recent review in Switzerland also reported earlier arrivals of 10 days for the short-distance migrant *Sylvia atricapilla* and of 8 days for the trans-Sahara migrant *Hirundo rustica* (Vittoz *et al*., 2013). Sparks *et al*. (2005) reported that, over the period 1959–2002, the total distribution of spring migration timing of willow warbler (*Phylloscopus trochilus*), chiffchaff (*Phylloscopus collybita*) and pied flycatcher (*Ficedula hypoleuca*) at locations in the UK, Germany, Russia and Finland were significantly earlier at each site. A long-term data set (1972–2008) of whooper swan (*Cygnus cygnus*) departure dates from a wintering site in Ireland (Stirnemann *et al*., 2012) indicated trends towards earlier departure for the date of the maximum rate of departure and for the date when 50% of the whooper swans had departed. In eastern Lithuania, arrival dates advanced by between 1 day for spotted flycatcher (*Muscicapa striata*) and 23 days for black redstart (*Phoenicurus ochruros*) and buzzard (*Buteo buteo*) during a 34-year period from 1971 to 2004 (Zalakevicius *et al*., 2006). The spring migration phenology of long-distance migratory birds whose wintering grounds were in sub-Saharan Africa to Oxfordshire, UK, has advanced by up to 8 days over the 30-year period from 1971 to 2000 (Cotton, 2003), regardless of whether their destination was the Mediterranean region (Gordo and Sanz, 2005; Jonzén *et al*., 2006) or eastern Ireland (Donnelly *et al*., 2009).

Not all species are equally responsive to climate warming. For example, in north-eastern Spain, Peñuelas *et al*. (2002) found that although butterflies appeared 11 days earlier, spring migratory birds arrived 15 days later in 2000 than in 1952. From data from England covering more than 200 years (1736–1947), Sparks and Carey (1995) found that while some migrant birds such as the barn swallow (*Hirundo rustica*) arrive later in response to climate warming, the cuckoo (*Cuculus canorus*) appeared earlier. Both and Visser (2001) examined how a long-distance migrant bird, the pied flycatcher, had responded to recent climate change, using data from a long-term study in the Hoge Veluwe, the Netherlands, by analysing data from 1980 to 2000 collected from a nest-box breeding population. They found that over the period, the birds had not advanced the spring arrival at their breeding grounds, but had advanced their mean laying date by about 10 days. In contrast, Both and te Marvelde (2007) found pied flycatchers had delayed their laying in northern Europe, but had advanced their laying in western and central Europe. Jonzén *et al*. (2006) reported that long-distance migrants advanced their spring arrival more than short-distance migrants in Scandinavia. However, in eastern Lithuania, Zalakevicius *et al*. (2006) found that the arrival dates were earlier for both short-/medium- and long-distance migrants.

Patterns of earlier arrivals of many insect species are reported in many locations throughout the world in response to a warming climate. According to Roy and Sparks (2000), climate warming of the order of 1°C advanced first and peak appearance of most butterflies by 2–10 days. However, on the basis of 155 moths and butterflies collected during the period 1866–1884 in Wiltshire, southern England, Sparks *et al*. (2006) demonstrated that species responded to increased temperature in the previous October by delayed appearance and to increased temperature in the current spring by advanced appearance. Gordo and Sanz (2006) examined the first adult appearance of two insect species, the honey bee (*Apis mellifera* L.) and the small white butterfly (*Pieris rapae* L.) between 1952 and 2004 in the Iberian Peninsula and reported that the first appearance was delayed until the mid-1970s and had advanced since that time. The appearance times for both species were negatively related to mean temperature between February and April, with both species appearing earlier in years with warmer springs. Similar trends were found for *A. mellifera*, *P. rapae* and the olive fruit fly (*Bactrocera oleae*) in the Mediterranean region (Gordo and Sanz, 2005). On the other hand, the Colorado potato beetle (*Leptinotarsa decemlineata*) has significantly advanced its emergence linearly over the last 50 years (Gordo and Sanz, 2005). Using data for 35 butterflies over a period of 1976–1998, Roy and Sparks (2000) found that first appearances of most British butterflies had advanced in the last two decades and was strongly related to earlier peak appearance and, for multi-brooded species, longer flight period. A more recent study by Diamond *et al*. (2011) found that most resident UK butterfly species had significantly advanced their dates of first appearance during the past 30 years. Peñuelas *et al*. (2002) found that butterflies appeared 11 days earlier in 2000 than in 1952 in the Mediterranean region. In boreal forest ecosystems in Manitoba, Canada, Westwood and Blair (2010) reported that flight period extensions increased by approximately 32 days over the period 1972–2004 for 13 butterfly species.

Changes in species' distribution and range shifts have occurred (Garamvölgyi and Hufnagel, 2013; Telwala *et al*., 2013), particularly for marine taxonomic groups (see Figure 2.10). The main trends found in terrestrial ecosystems included the advance of the tree line, reduction in the alpine vegetation belt, forest diebacks and a shift from coniferous forests to deciduous forests and invasion, among others. The spatial distributions of many bird species have undergone substantial range shifts (Maclean *et al*., 2008). Using counts of waders (Charadrii) collected from 3500 sites over 30 years and covering a major portion of western Europe, Maclean *et al*. (2008) demonstrated that the weighted centroids of populations of seven species of wader occurring in internationally important numbers had undergone spatial shifts of up to 115 km, generally in a north-easterly direction. The distributions of eight out of nine common species of waders overwintering on UK estuaries changed in association with recent climate change (Austin and Rehfisch, 2005). Warming-driven geographical range shifts were recorded in 87% of 124 endemic plant species studied in the alpine Sikkim Himalaya, resulting in increased species richness in the upper alpine zone, compared with the 19th century (Telwala *et al*., 2013). In boreal forest ecosystem, in Manitoba, Canada, Westwood and Blair (2010) demonstrated that two butterfly species, *Junonia coenia* and *Euphydryas phaeton*, increased their northerly ranges by ≈ 150 and 70 km, respectively, over the 33-year period of 1972–2004. A study by van Swaay *et al*. (2010) showed that the location of European butterfly communities has shifted northwards during the period 1990–2009 by approximately 75 km. In Ireland, despite insufficient data to draw firm conclusions, the speckled wood butterfly is thought to have expanded its range northward over the past 30 years (Regan, 2013).

Elevation shifts of species distributions towards mountain summits, spread of thermophilous species and colonisation by new species from warmer areas were particularly evident for many taxonomic groups in central Europe. A detailed review by Vittoz *et al*. (2013) demonstrated that many thermophilous aquatic species including the Mediterranean mayfly *Habrophlebia eldae*, the dragonfly *Crocothemis erythraea* and the stonefly *Leuctra geniculata*, which were previously limited to the warm, large lowland rivers, were now taking advantage of the warmer temperatures to expand their distribution. Moreover, some species that were only sporadically observed at the beginning of the 20th century were found to now be colonising Switzerland (e.g. the dragonflies *Aeshna affinis* and *Sympetrum meridionale*). In contrast, the warming of rivers decreases the potential distribution of fish species indirectly, with populations of *Salmo trutta fario* and others such as *Thymallus thymallus* declining. Additionally, many thermophilous insects such as *Cupido alcetas*, *Cupido argiades*, *Pieris mannii* and *Brenthis daphne* were observed to have recently colonised new regions with the warmer climate, whereas two lowland montane butterflies (*Spialia sertorius* and *Thymelicus lineola*) and one subalpine butterfly (*Erebia alberganus*) were found to have colonised sites 300–500 m above their previous distributional limit (compared with 1920–1941). In a recent study of the concurrent effect of climate change and invasive species on long-term changes in species composition and community function by comparing 3-year data sets, separated by 23 years (1979–1981 and 2003–2005) that cover pre- and post-invasion periods in Newcastle, Dijkstra *et al*. (2011) indicated concurrent shifts in both climate-related factors and in the groups of dominant organisms. The 1979–1981 community was dominated by perennial species (mussels and barnacles), whereas the 2003–2005 community was dominated by annual native and invasive tunicates (sea-squirts). On a global scale, a recent study found that the leading edge or front line of marine species distributions was moving towards the poles at an average of 72 km per decade, considerably faster than for terrestrial species, which were moving poleward at an average of 6 km per decade (Poloczanska *et al.*, 2013). The fastest leading-edge expansions were found in highly mobile or dispersive pelagic organisms: phytoplankton [469.9 (± 115.3) km per decade], bony fish [277.5 (± 76.9) km per decade] and invertebrate zooplankton [142.1 (± 27.8) km per decade]. See Figure 2.10 (Poloczanska *et al.*, 2013).

A biome-scale relationship between sea ice decline and increases in terrestrial primary productivity was clearly demonstrated for pan-Arctic tundra, which has increased in association with declining arctic sea ice extent over the past years (Post *et al.*, 2013). Using over 30 years (1982–2011) of remote sensing data (Bhatt *et al.*, 2010, 2013), the decline in sea ice extent is shown to correspond to land surface warming and increased vegetation cover. Thus, as sea ice area declined, the summer warmth index (sum of the monthly-mean temperatures above freezing) for low-elevation tundra along the Arctic Ocean increased, with an increase in vegetation production.

2.10 Agriculture and Food Security

There are many uncertainties in the underlying science and economics of climate change impacts on food and there is little direct evidence of the effects of climate change impacts on food access, utilisation and stability dimensions (Wheeler and von Braun, 2013). Agriculture is vulnerable to changes in temperature, precipitation, atmospheric CO_2 and ozone concentrations (Iglesias *et al.*, 2007), although temperature changes have a much stronger impact (Lobell and Burke, 2008; Thornton *et al.*, 2009; Schlenker and Lobell, 2010), at least at national and regional scales. Higher temperatures ultimately reduce yields and tend to encourage weed and pest proliferation (Kiselev *et al.*, 2013). Whereas greater variation in precipitation patterns increases the likelihood of short-run crop failures and long-run production declines (Mendelsohn, 2007; Kiselev *et al.*, 2013), increasing temperatures exacerbate the effects of water and rainfall reductions during the drier periods and can partially remove any advantage that occurs as a result of increased precipitation in wetter

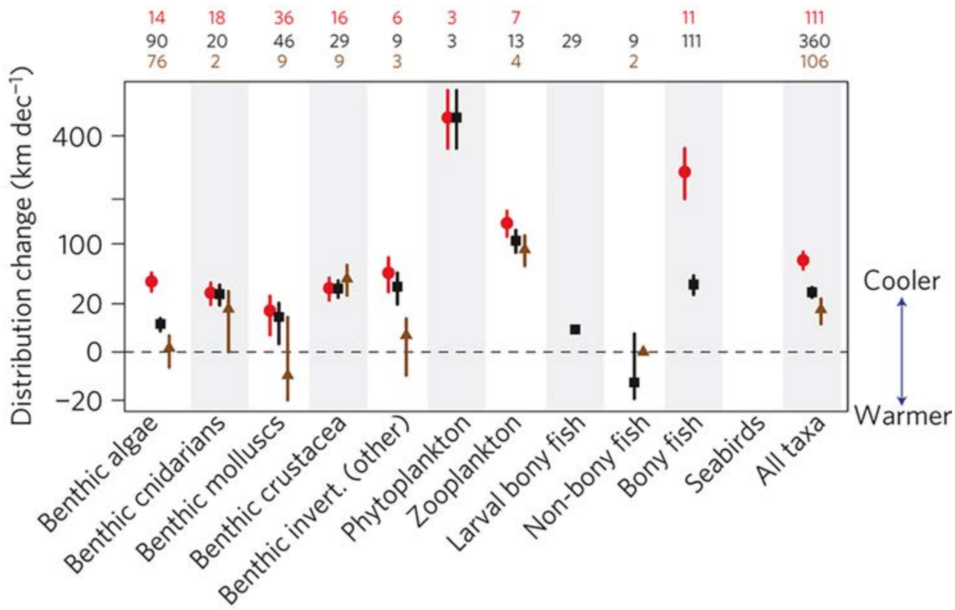


Figure 2.10. Rates of change in distribution of marine taxonomic groups at the leading edges (red circles), trailing edges (brown triangles) and from all data regardless of range location (black squares) over 1900–2010. Distribution rates have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward). Means ± standard error are shown, along with number of observations. Reproduced from Poloczanska *et al.* (2013) with permission from Nature Publishing Group.

periods (Thornton *et al*., 2009a; Muller *et al*., 2011). Many crops were found to be especially sensitive to extreme temperatures occurring just prior to or during the critical pollination phase (Hatfield *et al*., 2011). Water stress can exacerbate such temperature effects (Wheeler *et al*., 2000; Barnabas *et al*., 2008; Hatfield *et al*., 2008). Overall, although there might be gains in some crops in some regions of the world, the overall impacts of climate change on agriculture are expected to be negative, threatening global food security (Ejaz Qureshi *et al*., 2013; Kiselev *et al*., 2013; Wheeler and von Braun, 2013).

Although relatively little is known about the likely impacts of climate change on animal production and livestock systems, impacts from feed quantity and quality, heat stress, water availability, livestock diseases and disease vectors, biodiversity, systems and livelihoods are expected, together with other indirect impacts (Thornton *et al*., 2009b, 2013; Skuras and Psaltopoulos, 2012). Extreme temperatures impair production (animal growth, meat and milk yield and quality, egg yield, weight, and quality) and reproductive performance, metabolic and health status, and immune system response (Nardone *et al*., 2010). Mixed agricultural systems and industrial or landless livestock systems are at risk from variability of grain availability and cost, and low adaptability of animal genotypes. An additional threat from a warming climate is an increase in losses of soil organic carbon requiring an increasing amount of carbon replacement if its productivity is to be maintained (Wiesmeier *et al*., 2016).

A recent global-scale analysis by Lobell *et al*. (2011) indicated that the current warming trend had already negatively impacted agriculture production in many areas. The majority of these impacts are driven by changes in temperature rather than precipitation. Global net loss was estimated at about 6% relative to what would have been achieved without the climate trends in 1980–2008 (Figure 2.11). Previous studies at the global scale indicate that recent warming trends have depressed yields of rice, wheat, maize and barley (Peng *et al*., 2004; Lobell and Field, 2007). It was estimated that warming since 1981 had resulted in annual combined losses of wheat, maize and barley representing approximately 40 Mt or US$5 billion per year, as of 2002 (Lobell and Field, 2007). For rice, yields declined by 10% for each 1°C increase in growing season minimum temperature in the dry season (Peng *et al*., 2004). The significant negative impacts of increasing minimum daily temperature on rice yields is mirrored in recent studies of rice in Asia (Welch *et al*., 2010) and the USA (Mohammed and Tarpley, 2009). Plants grown under high night-time temperature (32°C) showed a 90% decrease in yield compared with plants grown under ambient night-time temperature (27°C). In the specific case of tropical and subtropical regions, major crops in these regions showed direct yield losses in the range of 2.5% to 16% for every 1°C increase in seasonal temperature (Peng *et al*., 2004; Lobell *et al*., 2008; Hatfield *et al*., 2011). The effects of increasing maximum temperature on yields are complex and non-linear, with increased yields in some regions (Welch *et al*., 2010) and insignificant effects in others (Peng *et al*., 2004). The effects of increasing diurnal temperature range are similar to those of maximum temperature in several rice- and maize-growing regions (Lobell and Field, 2007).

More specific studies of individual countries and at regional scales have suggested that climate change is a factor in the deceleration or decline of cereal yields in the course of the 20th century (Calderini and Slafer, 1998; Thornton *et al*., 2009a; Brisson *et al*., 2010). Among the largest country-specific reductions was wheat in Russia at nearly 15% (Figure 2.11; Lobell *et al*., 2011; Kiselev *et al*., 2013). In the wake of the extraordinarily severe heatwave over large parts of the European continent in the summer of 2003, a record drop in crop yield of 36% occurred in Italy for maize grown in the Po valley, which had extremely high temperatures (Ciais *et al*., 2005). In contrast, positive effects of climate warming have been reported for other regions, where the limits of crop cultivation shifted polewards, such as maize in the USA (Hatfield *et al*., 2011), maize in China (Meng *et al*., 2013), rice in China (Liu *et al*., 2013), and potato and wheat in Russia (Kiselev *et al*., 2013), resulting in net yield gains. A warming climate has been beneficial for most of the crops commonly grown in the Czech Republic, such as cereals, rape, sugar beet and legumes, with higher yields in warmer years (of the period 1920–2000) that had more hours of sunshine (Chloupek *et al*., 2004).

Climate extremes also influenced the quality of the grain. Variations in rainfall and high temperature

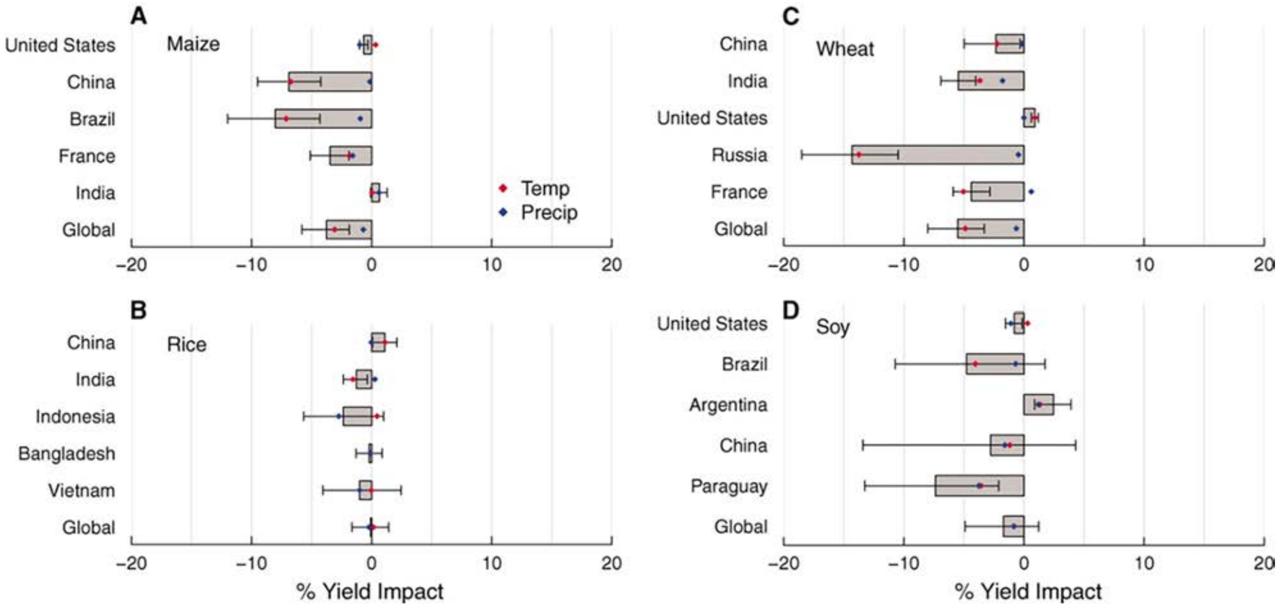


Figure 2.11. Estimated net impact of climate trends for 1980–2008 on crop yields for major producers and for global production. Values are expressed as a percentage of average yield. Grey bars show median estimate; error bars show 5% to 95% confidence interval from bootstrap resampling with 500 replicates. Red and blue dots show median estimate of the impact for temperature trend and precipitation trend, respectively. Reproduced from Lobell *et al*. (2011) with permission from the American Association for the Advancement of Science.

events during grain-filling of wheat altered its protein content, yield and flour quality (Kettlewell *et al*., 1999; Skylas *et al*., 2002; Hurkman *et al*., 2009). Perhaps more important is the effect of CO_2 enrichment on grain quality and the elemental composition of agricultural crops. Erbs *et al*. (2010) reported that increasing CO_2 reduced crude protein in wheat by 4–13% and in barley by 11–13%, but increased starch by 4%. For soybean, Hao *et al*. (2014) reported that total protein concentration in seeds was significantly reduced by 3.3% under CO_2 enrichment, but oil concentration increased by 2.8%. Additionally, CO_2 enrichment affected amino acid composition and the concentrations of macro- and micro-elements (Högy and Fangmeier, 2008; Fernando *et al*., 2014; Hao *et al*., 2014). Thus, flour from cereal grains grown under elevated CO_2 has a diminished nutritional and processing quality and an altered elemental composition. Several meta-analyses (Pleijel and Uddling, 2012; Myers *et al*., 2014) and the first field-scale test (Bloom *et al*., 2014) have indicated that CO_2 inhibition of nitrate assimilation is the explanation most consistent with the observations. For wheat, both uptake and assimilation of nitrate were inhibited under elevated CO_2 concentrations (Lekshmy *et al*., 2013).

With temperatures in the growing season by the end of the 21st century showing a high probability (>90%) of exceeding the most extreme temperatures observed from 1900 to 2006 for both tropical and subtropical regions (Battisti and Naylor, 2009), and free-air CO_2 levels showing no signs of decline (IPCC, 2013), food systems will most probably suffer net negative impacts, threatening food security around the world, shown in Figure 2.12. Projected changes in temperature trends and expected increases in the probability of extremes during the growing season in Africa (Muller *et al*., 2011), Australia (Ejaz Qureshi *et al*., 2013), central Eurasia (Lioubimtseva and Henebry, 2012; Lioubimtseva *et al*., 2013), China (Ju *et al*., 2013), the Mediterranean (Skuras and Psaltopoulos, 2012), the USA (Schlenker and Roberts, 2009; Lobell *et al*., 2013) and at a global scale (Deryng *et al*., 2014) provide ample evidence to indicate this further negative impacts on crop yields in the coming decades. A summary of such changes is provided in Figure 2.12. However, some recent analyses suggest that climate change in the first half of the 21st century may not be a short-term threat to food security in some regions as a result of the availability of adaptation strategies (Takle *et al*., 2013).

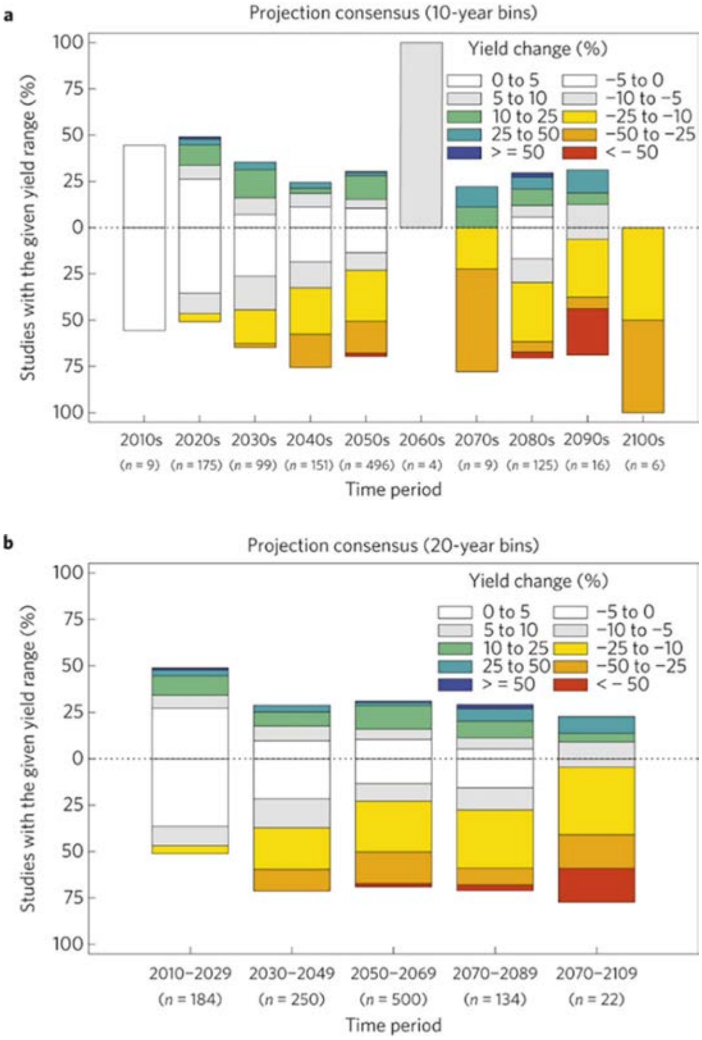


Figure 2.12. Projected changes in crop yield as a function of time for all crops and regions. *n*=1090 from 42 studies. The vertical axis indicates degree of consensus and the colours denote percentage change in crop yield. Data are plotted according to decade (a) or 20-year periods (b) in which the centre point of a study's projection period falls. The IPCC (2013) scenarios used include A1B, A1F1, A2, B1, B2 and IS92. Reproduced from Challinor *et al*. (2014) with permission from Nature Publishing Group.

2.11 Disease and Human Health

The effects of climate change on human health are complicated and wide ranging (Markandya and Chiabai, 2009; McMichael, 2013) and are thus often difficult to assess or predict (Snodgrass, 2013). This has led Costello *et al*. (2009) to describe climate change as the biggest global health threat of the 21st century, although the health impacts of climate change are not fully understood (Hambleton and Dobson, 2013). Recent studies indicate that climate change can have both direct and indirect effects on human health (Markandya and Chiabai, 2009; Griffiths, 2013; Kjellstrom and McMichael, 2013). Some health risks, such as the effect of rising temperature on the risk of heat stress are clear and direct, while others are less well defined, occurring via indirect pathways and through interactions with a range of other factors that are themselves affected by climate change (Thomas *et al*., 2012). The main direct effects are from exposure to altered frequencies and intensities of extreme weather events, together with sea level rise (Figure 2.13 and Table 2.1), which cause significant short-term increases in morbidity, mortality and the occurrence of various infectious diseases (de'Donato and Michelozzi, 2014). On the other hand, indirect health impacts from extreme weather events may include exposure to pathogens or toxic agents after an extreme event, such as weather- or flood-related natural disasters (Ivers and Ryan, 2006; Brown and

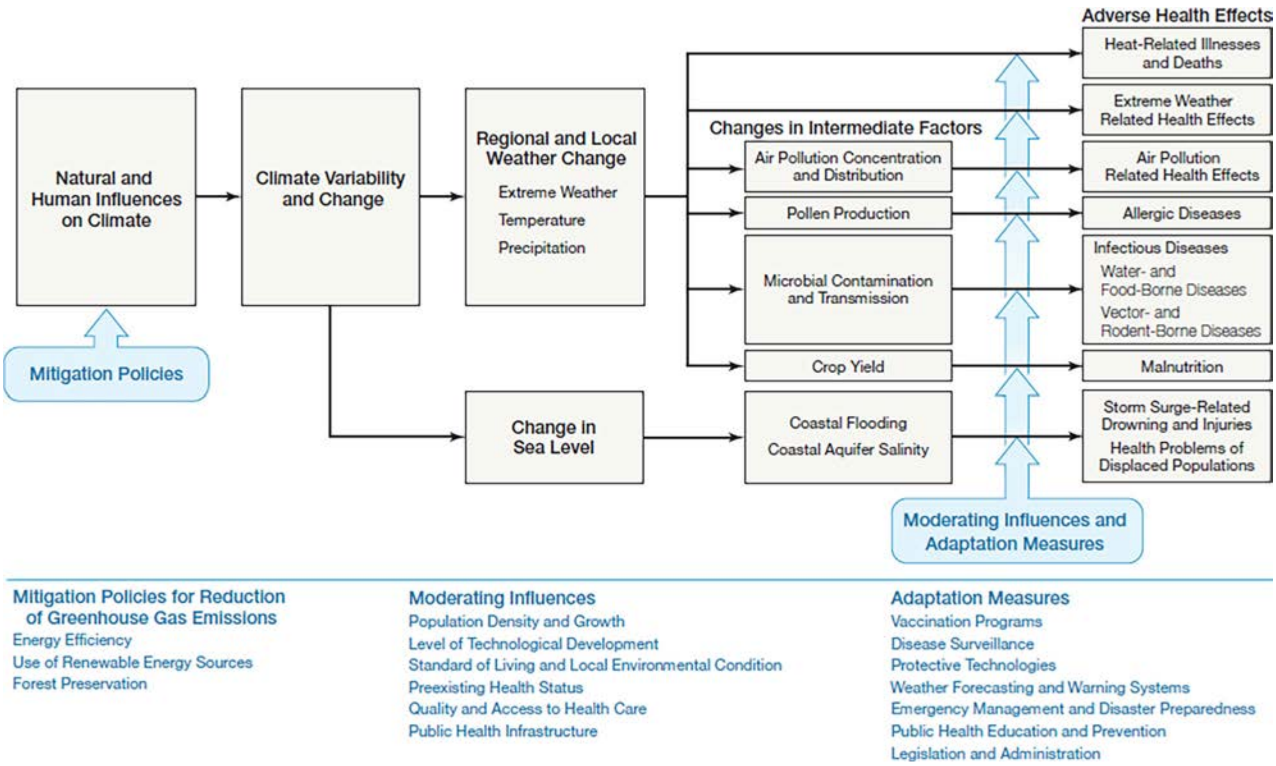


Figure 2.13. Potential health effects of climate variability and change. Reproduced from Relman *et al.* (2008) with permission from the National Academy of Sciences of the United States of America.

Table 2.1. Summary of the impact of climate change on health

Health impact	Potential impact pathway
Heat- and cold-related mortality and morbidity	Increase in heat stroke deaths during heatwaves
	Worsening of health conditions during heatwaves in patients with pre-existing chronic disease
	Decline in cold-related deaths
Deaths and injury	Increase in injuries and deaths related to extreme events (floods, wildfires)
Allergic rhinitis	Increase in asthma and rhinitis due to change in the distribution, seasonality and production of aeroallergens under climate change scenarios
Cardiovascular and respiratory disease	Increase in high temperatures and air pollutant concentrations increase cardiorespiratory disease
Infectious disease	Floods provide breeding ground for mosquito vectors and lead to disease outbreaks
Mental disorders	Floods may increase post-traumatic stress disorders
Mosquito-, tick- and rodent-borne diseases (malaria, dengue fever, tick-borne encephalitis and Lyme disease)	Higher temperatures shorten the development time of pathogens in vectors and increase the potential transmission to humans
	Climate conditions determine the necessary conditions to maintain transmission of each vector specie
Water-borne and food-borne disease	Climate conditions affect water availability and quality
	Temperature influences the survival rate of disease-causing organisms
	Extreme rainfall episodes affect the transport of specific organisms causing disease to enter the water supply
Malnutrition	Climate change will decrease food supplies and access to food

Source: de'Donato and Michelozzi (2014).

Murray, 2013). In any individual disaster, the risk is often dependent on a number of factors, including the endemicity of specific pathogens in the affected region before the disaster, the impact of the disaster on water and sanitation systems, the availability of shelter, the assembly of displaced persons, the functionality of the surviving public health infrastructure, the availability of healthcare services, and the rapidity, extent and sustainability of the response after the disaster (Ivers and Ryan, 2006).

The risks of infectious disease transmission and outbreaks are also related to substantial population displacement and exacerbated synergic risk factors after disaster events (Watson *et al*., 2007; Kouadio *et al*., 2012). Thus, health impacts may arise from stress, anxiety and mental illness (Fritze *et al*., 2008), and from increased vulnerability to infection (Alderman *et al*., 2012) after evacuation or geographical displacement, and disruption of socioeconomic structures and food production (Haines *et al*., 2006; McMichael *et al*., 2006), as shown in Figure 2.14. Other potential consequences include the influence of changing temperature and precipitation on infectious diseases (including the possible emergence of new pathogens), the increased distribution and abundance of agricultural pests and pathogens, and the increased production of photochemical air pollutants, spores and pollens (McMichael *et al*., 2004). Many of the health effects of climate change come about from interactions between the biophysical changes to the natural environment, demographic trends and human adaptations (Myers and Bernstein, 2011; McMichael, 2013; Myers *et al*., 2013).

A growing number of studies show the effects of observed climate change on the transmission of some vector-borne and other infectious diseases, either using field and laboratory experiments (Roy *et al*., 2004; Paull *et al*., 2012; Ben-Horin *et al*., 2013; Elderd and Reilly, 2013) or theoretically and empirically based models (Dobson, 2009; Molnar *et al*., 2013; Mordecai *et al*., 2013; Schijven *et al*., 2013; Thompson *et al*., 2013). However, conclusively detecting a climate signal effect on human vector-borne diseases remains difficult, in part, because of existing control measures, such as vector control, antimicrobial treatments, and infrastructural changes, which can dampen or mask climate effects (Altizer *et al*., 2013). On the other hand, wildlife and plant diseases are generally less influenced by these control measures, making the climate signal easier to detect (Chakraborty, 2013). Some of the unresolved issues include identifying the conditions under which climate warming causes either range expansions or contractions, understanding the impact of increasing variability of precipitation, and determining the additional economic costs associated with increased disease risk caused by warming.

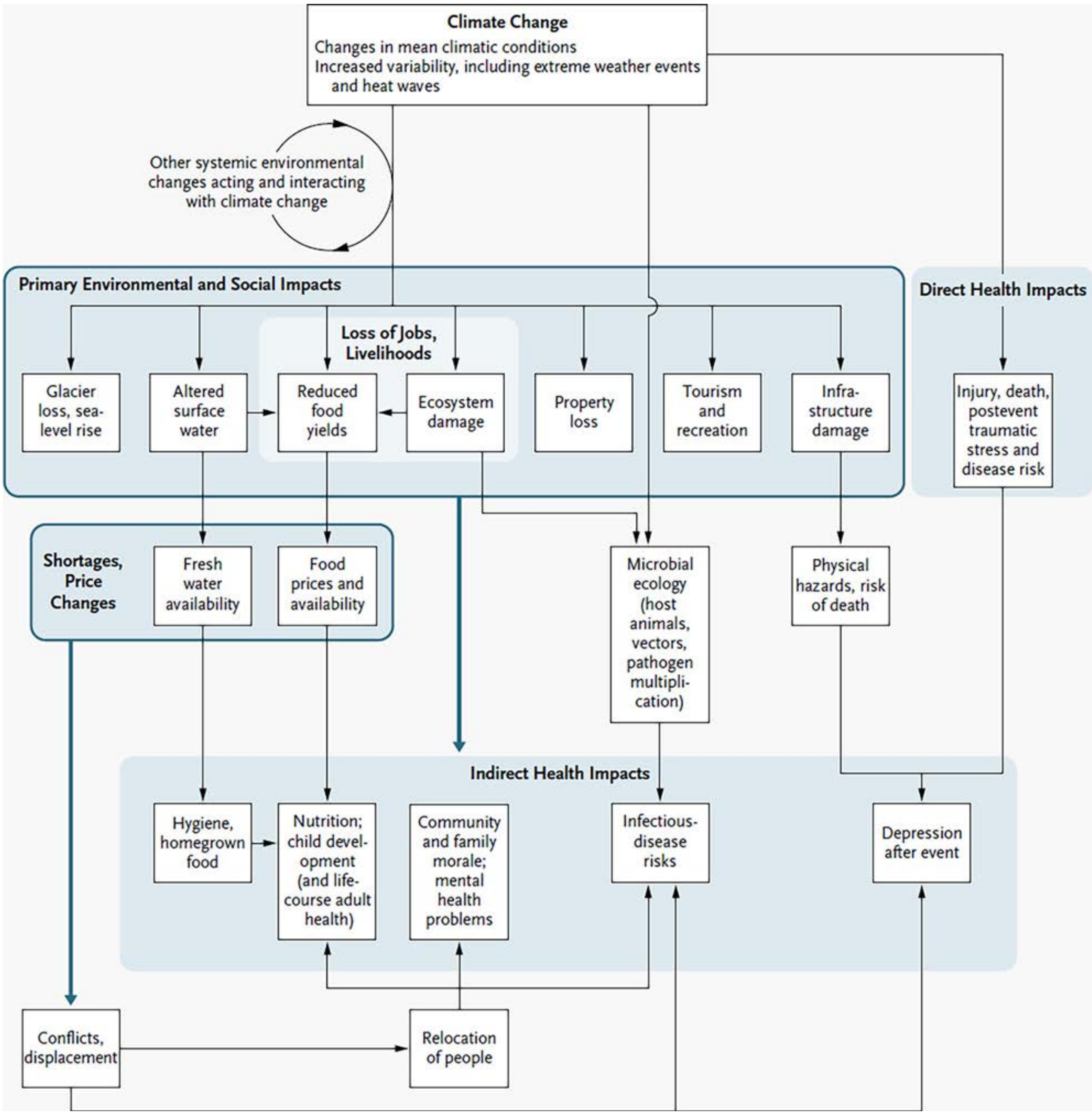


Figure 2.14. Processes and pathways through which climate change influences human health. The direct health impacts of climate change are shown in the upper right part of the figure, most of them due to amplified extreme weather events. All the other, less direct, health impacts, shown in the lower part of the figure, are mediated by the primary environmental and social impacts of climate change. These include the five categories of indirect health impacts and the tertiary effects on health and survival that arise from more diffuse disruptions, dislocations, and conflicts, which are likely to increase in future decades and are indicated by upwards-pointing arrows. Reproduced from McMichael (2013) with permission from Massachussetts Medical Society.

3 Warning Agencies – International

3.1 European Centre for Medium-Range Weather Forecasts

The ECMWF (www.ecmwf.int) is an intergovernmental organisation, founded in 1975, which undertakes research on weather, climate simulation and data assimilation methods. It provides weather predictions (medium range, monthly and seasonal) for the 34 states that support it and for sale to other interested organisations. Its predictions are based on a numerical model of the Earth's atmosphere, which includes hydrological and ocean circulation components, run on its own double Cray XC30 supercomputer systems, based on Intel Xeon multi-core processors. It does air quality calculations and can simulate the movement of dust and pollutants in the atmosphere. It maintains an archive of weather data. It is a partner in the EC-Earth collaboration (http://ecearth.knmi.nl), which is building improved Earth system models for weather forecasting, based on the ECMWF's own systems.

3.1.1 The provisions of the ECMWF

Ensemble-based global numerical weather predictions

The ECMWF operational forecasting system consists of:

- high-resolution deterministic forecasts – twice daily (16 km, 91 levels, up to 10 days);
- ensemble forecasts – twice daily (51 members, 30/60 km, 62 levels, up to 15 days);
- monthly ensemble forecasts – twice weekly (51 members, 30/60 km, 62 levels, up to 1 month);
- seasonal forecasts – once per month, coupled with ocean model (51 members, 80 km, 91 levels, up to 7 months).

Observation data (40 million observations daily from geo-stationary, polar-orbiting and GPS satellites, aircraft-, ship- and land-based observation stations, ocean buoys, dropsondes, and atmospheric profilers/radar) are analysed to produce initial conditions for the model and are assimilated into the simulations.

The ECMWF forecasting system consists of an atmospheric general circulation model, an ocean wave model, a land surface hydrological model, an ocean general circulation model, and perturbation models to represent uncertainty in the initial conditions and modelled processes. For these medium-range forecasts, an ensemble of 52 members is created twice daily. One member (HRES) is at a higher spatial resolution than the others and it uses the best estimate of the initial state and the model physics. Another member of the ensemble is at a lower spatial resolution, but it also uses the best estimate of the initial conditions and the best description of the model physics. The other 50 ensemble members are also at the lower resolution, but their initial states and model physics have been perturbed to explore the effects on the forecasts of uncertainty in the observations and the model physics. All of these simulate a 10-day period.

Air quality predictions

The ECMWF collects data on the chemical and particulate composition of the atmosphere and predicts how it will change (up to a few days ahead) on a global scale. It coordinates the project Monitoring Atmospheric Composition and Climate (MACC-II; http://www.copernicus-atmosphere.eu), which, together with the European Earth observation organisation Copernicus (http://www.copernicus.eu), provides information on European air quality, global atmospheric composition, climate forcing, monitoring of the ozone layer, ultraviolet (UV) radiation levels, solar energy, and surface emissions and fluxes.

Climate monitoring: reanalysis of past atmospheric, ocean and land surface observations

From its stored data, the ECMWF can describe the past history of the atmosphere, land surface and oceans, which is useful for monitoring climate change and for research and education. These re-analyses have performed well in validation studies when compared with observed data (Decker *et al.*, 2012).

Severe weather predictions

Of particular interest to WARNDIS, the ECMWF provides early (medium-range up to 2 days) warnings of weather-related extreme events such as storms, heatwaves, floods, droughts, fires and severe wind, with generally good results, e.g. for important hazard-related variables such as snow (Dutra *et al*., 2010), soil moisture (Albergel *et al*., 2015), drought (Lavaysse *et al*., 2015) and solar radiation (Troccoli and Morcrette, 2014). In particular, the quality of its tropical cyclone track forecasts has been confirmed by observations (e.g. Majumdar and Finocchio, 2010; Hamill *et al*., 2011), but has not yet reached its predictability limits (Plu, 2011). Regardless, predicting the genesis of a cyclone is still challenging (Halperin *et al*., 2013; Tory *et al*., 2013).

3.1.2 Relevant ECMWF medium-range forecast products

Probabilities from ensembles

Forecast probabilities are computed from ensembles (ENS) for different parameters and relevant thresholds, for example the probability of more than 1, 5, 10 or 20 mm precipitation in a 24-hour period. In addition, individual ensemble members can be shown and, where a number of them show similar behaviour, they are clustered to produce weather scenarios.

Extreme forecast index and charts

ECMWF calculates two important indices that relate to extreme events: (1) the Extreme Forecast Index (EFI); and (2) the Shift of Tails (SOT) index. The EFI "highlight[s] occasions when there is a significant shift in the current ENS towards the extreme of the model climate. The EFI is produced for a number of important weather parameters: 2 metre minimum, maximum and mean temperatures, total precipitation, snowfall, wind gust and mean wind speed, and for maximum significant wave height. The complementary Shift of Tails (SOT) provides information about how extreme an event might be. Positive values of the SOT indicate that at least 10% of the ensemble members are above the 99th percentile of the model climate. The higher the SOT value is, the further this top 10% of the ensemble forecast is beyond the model climate" (www.ecmwf.int).

Meteograms

Meteograms of forecasts for a single place are available at http://www.ecmwf.int/en/forecasts/charts/medium/ens-meteograms and allow users to choose a place for the forecast and to see information on how it is created.

3.1.3 Relevence of ECMWF for Ireland

ECMWF is an essential component of Europe's capacity for forecasts, predictions and research on weather-related natural hazards. It provides information and forecasts that are used and disseminated mainly by national meteorological and other agencies, including in Ireland.

3.2 EUMETNET – OPERA

EUMETNET is a network of European meteorological services. It provides the meteoalarm service (www.meteoalarm.eu), which integrates information from EU national weather services on the possibility of extreme weather events and associated hazards, and presents a Europe-wide perspective on, for instance, (1) heavy rain and/or thunderstorms, (2) high winds, (3) extreme temperatures (high and low), e.g. heatwaves, (4) forest fires, (5) fog, (6) exceptional snow falls or ice, (7) avalanches and (8) exceptionally high tides. It provides links to the national service of the country concerned for more detail.

The EUMETNET programme OPERA provides a platform for the exchange of knowledge and expertise of operational weather radar and uses this to generate an operational Europe-wide radar composite (Figure 3.1).

OPERA has also developed and maintains the ODYSSEY data hub, which receives and distributes, after some quality control, radar volume data. It has also developed its own OPERA data information model (ODIM) and software for handling formats such as Hierarchical Data Format 5 (HDF5) and the Binary Universal Form for the Representation of meteorological data (BUFR) for data exchange.

3.2.1 Meteoalarm project

Meteoalarm is a project, run by EUMETNET with the support of WMO, which provides a pan-European

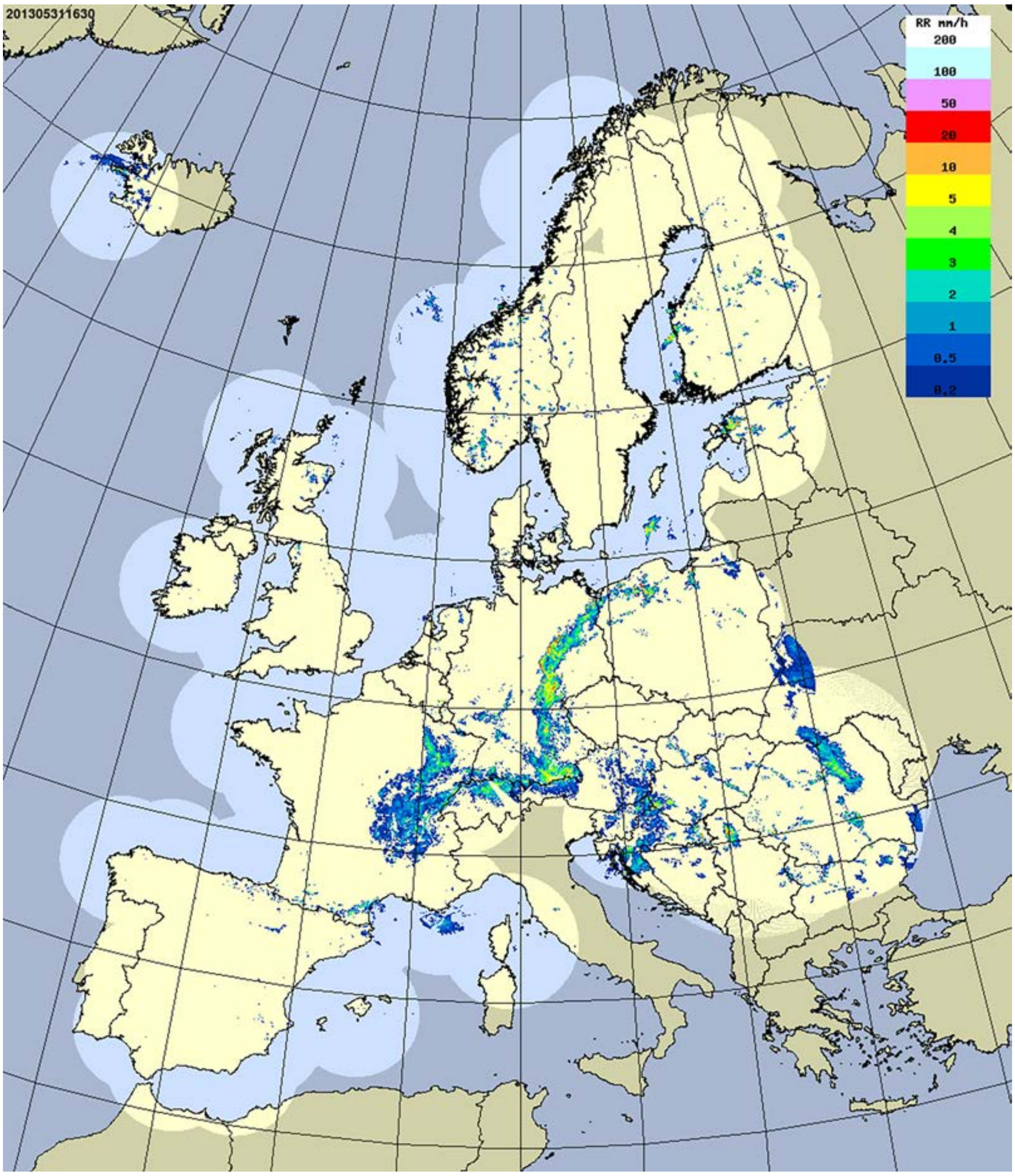


Figure 3.1. Example of OPERA European weather radar composite. Source: OPERA.

warning system for severe weather, e.g. heavy rain, gale force winds, heatwaves, forest fires, cold spells, fog, avalanches or very high tides, based on inputs from individual national weather services. The information is distributed in the form of a colour-coded map, with green, yellow, orange and red colours indicating none to high degrees of hazard (Figure 3.2), with an associated list of individual hazards forecasted for each country (Figure 3.3), with links to each national weather service.

3.2.2 The HAREN project

Hazard Assessment based on Rainfall European Nowcasts (HAREN) is a completed European project, funded by the European Commission Directorate-General for European Civil Protection and Humanitarian Aid Operations (DG ECHO), which sought to measure and predict, at high spatial resolution, precipitation in Europe. It uses information from the individual national radar networks in Europe through the EUMETNET programme OPERA (Matthews *et al*., 2011). OPERA generates a European precipitation field every 15 minutes on a 2 km square grid. The value of and improvements gained by such large coverage have been demonstrated (for US radars) by Germann *et al*., 2006. Improvements in nowcasting techniques were provided by completed European Commission projects under the Sixth and Seventh Framework

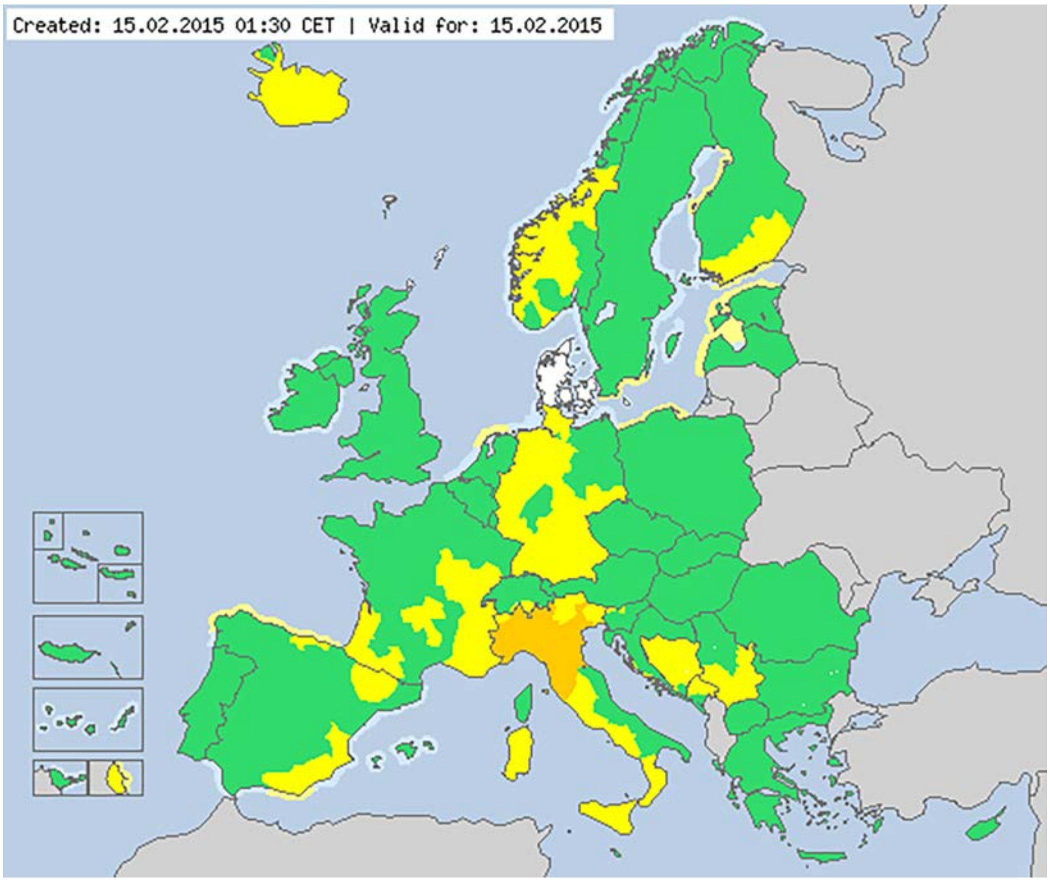


Figure 3.2. Screenshot of Meteoalarm's home page. Source: EUMETNET.

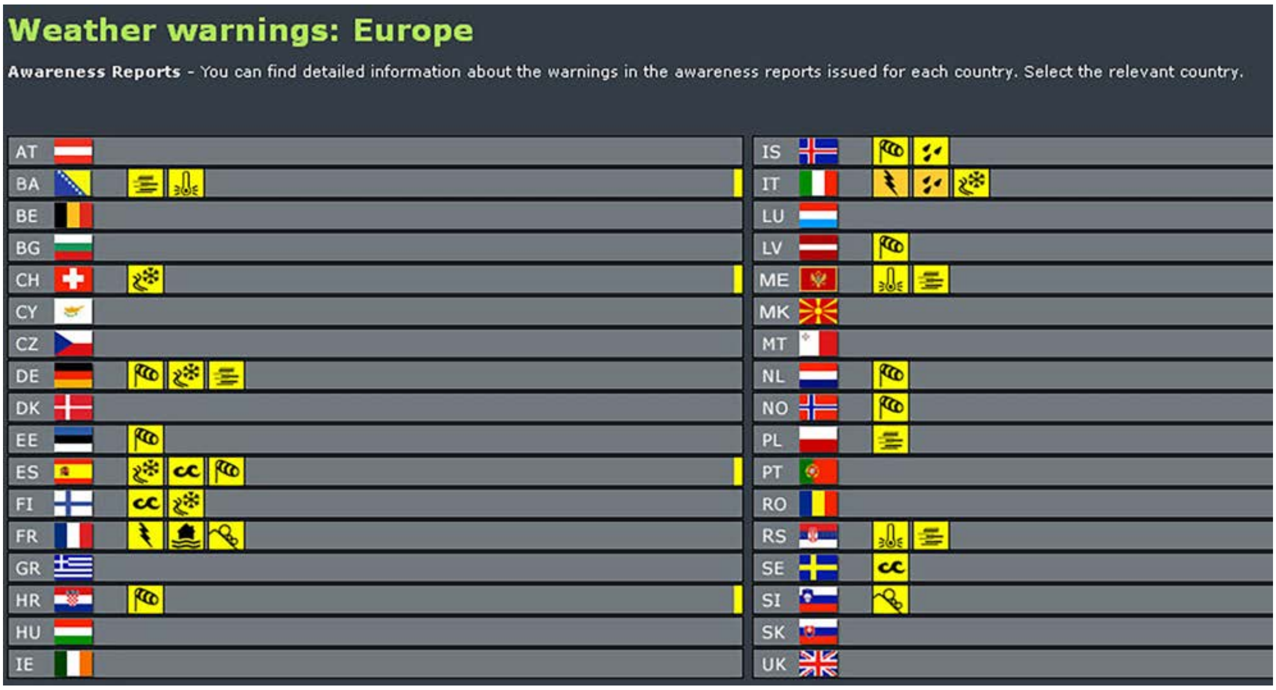


Figure 3.3. Meteoalarm individual country warnings. Source: EUMETNET.

Programmes (FP6 and FP7) [among others FLOODSITE, HYDRATE and IMPRINTS (http://www.crahi.upc.edu/imprints/)].

The HAREN project also assessed the uncertainties and performance of the system, e.g. Berenguer and Sempere-Torres (2013) reported that its best performance was in areas with the most severe precipitation, i.e. where it is most required.

3.2.3 EDHIT project

EDHIT (European Demonstration of an enhanced rainfall and lightning-induced Hazard Identification nowcasting Tool) (http://edhit.eu/) is a research project that produced a nowcasting (short lead time < 6 hours) tool for extreme rainfall and lightning. It involved both national meteorological services (through EUMETNET OPERA) and national civil defence organisations. It has adopted a multi-sensor approach, including the use of satellite information in real time and has demonstrated the added value of such information (particularly OPERA's European radar composite for short lead time forecasts), complementary to the forecasts of the European Flood Awareness System (EFAS) system.

3.2.4 Relevance of EUMETNET for Ireland

Ireland is a member of EUMETNET, and OPERA's composite radar precipitation product is used by Met Éireann in public weather forecasts but not for quantitative flood forecasting. There is potential benefit in developing the latter for use in larger catchments with longer lead times.

3.3 World Meteorological Organization

The WMO is a United Nations (UN) scientific organisation focused on the Earth's atmosphere, its weather and climate, and its interactions with the oceans and terrestrial water resources. It currently has 191 members, including Ireland. It promotes the international exchange of information, meteorological and hydrological education and training and has a specific concern for the safety and security of society and its protection from weather-related hazards.

3.3.1 World Weather Information Service

The Hong Kong Observatory runs (for WMO) the World Weather Information Service (WWIS) (http://www.worldweather.org/en/home.html), which provides forecasts and some climatological (mean monthly temperature and precipitation) information for over 1719 cities throughout the world. The information for each location is provided by the local weather service and its forecasters, so WWIS is essentially a clearing house for this information. It has a geographic information system (GIS)-based web interface for selecting the location of interest (Figure 3.4).

3.3.2 Severe Weather Information Centre

The Hong Kong Observatory also runs (for WMO) the Severe Weather Information Centre (SWIC) (http://severe.worldweather.org/), which also acts as a clearing house for severe weather warnings from the world's meteorological services and tropical cyclone warning centres. It provides information on observations and warnings related to tropical cyclones, heavy rain and snow, thunderstorms, gales and fog (Figure 3.5). SWIC supplies a widget that can be installed on a user's computer to monitor the site and alert the user when warnings are produced for selected regions in Asia. This type of service may, in the future, become available for other regions of the world.

3.3.3 Relevance of WWIS and SWIC for Ireland

As both WWIS and SWIC depend on information received from national weather services, they do not contribute additional information and therefore are of limited use for Ireland. At a continental scale they do show the progression of large-scale events. They are dependent on the support of a few individual WMO member countries and therefore cannot be considered as integral long-term services.

3.4 European Commission Joint Research Centre (Ispra, Italy)

3.4.1 General

The JRC is the European Commission's in-house advisor on scientific and technical matters (https://

Figure 3.4. Screenshot of WWIS's home page. Source: WWIS.

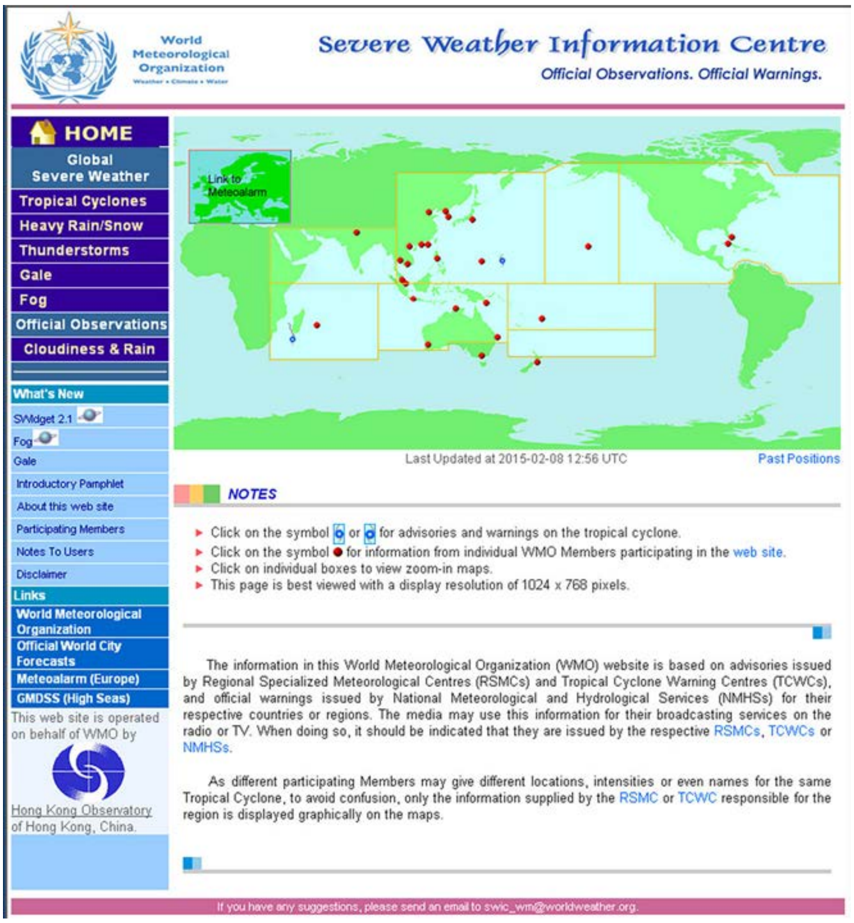


Figure 3.5. Screenshot of SWIC' s home page. Source: SWIC.

ec.europa.eu/jrc/en/about) and consists of seven institutes in six different locations. One of these, the Institute for the Protection and Security of the Citizen (IPSC) (https://ec.europa.eu/jrc/en/institutes/ipsc), located in Ispra in Italy, provides scientific and technological advice in relation to the safety and security of EU citizens and the stability of their surroundings and infrastructure. Its brief includes both natural hazards and the consequences of climate change. For natural hazards, the main focus is on Earth observation and warning, while, for overall safety and security, the focus is on disaster prevention and management. The IPSC's activities thus cover the evaluation of risks and impacts, monitoring, adaptation, mitigation and the sustainability of climate policies.

3.4.2 European Flood Awareness System

The JRC has developed and runs the EFAS (www.efas.eu), an EU initiative that is also supported by individual countries and is aimed at improving readiness to respond to riverine floods in large European river basins. Developed and tested from 2005 to 2011 (Bartholmes *et al*., 2009; Thielen *et al*., 2009), it became fully operational in 2012 and is now part of Copernicus support for civil protection in Europe (Figure 3.6). Ireland has subscribed to the EFAS system and receives the warnings it generates.

EFAS has a number of different components, each provided by a separate European organisation. For instance, ECMWF (see section 3.1) provides the meteorological forecasts and hosts the data platform. The Swedish (SMHI), Dutch (Rijkswaterstaat) and Slovak (HMI) hydrometric organisations undertake daily analyses and distribute the information to EFAS partners and the European Emergency Response Coordination Centre (ERCC). Spanish organisations (REDIAM and ELIMCO) are responsible for the collection of discharge and water-level data from the national agencies across Europe, while the JRC itself is responsible for collection of national meteorological data. EFAS uses the probabilistic information generated from ECMWF's ensemble forecasting system. Of particular concern is how best to communicate such uncertain information so that disaster managers can make optimum use of it (Bruen *et al*., 2010; Pappenberger *et al*., 2013).

Figure 3.6. EFAS map browser. Source: EFAS.

Performance of EFAS in Ireland

Ireland has recently joined EFAS and its Office of Public Works (OPW) receives EFAS forecasts. Since the EFAS system is designed for large basins, the Shannon is the only Irish river sufficiently large to meet EFAS stated size limitation. However, EFAS forecasts proved useful during the December 2015 flood period, even for smaller basins. It provided warnings between 1 and 4 days in advance for catchments throughout the country such as the Shannon, Erne, Moy, Clare, Suir, Barrow and Slaney, clearly demonstrating its value for catchments of this size. In only one case, in a catchment with considerable storage, it did not provide any advance warning of the peak. While the performance in most catchments is valuable, it should be possible to improve on a 4-day forecast lead time for the large Shannon catchment, which, in its lower reaches, has a very slow (greater than a week, depending on location) response time to precipitation.

3.4.3 Global Disaster Alert Coordination Centre

The Global Disaster Alert Coordination Centre (GDACS) (http://www.gdacs.org/) operates a real-time coordination platform VirtualOSOCC (https://vosocc.unocha.org), which provides early and real-time information on a range of disasters, focusing on earthquakes, tsunamis, floods, volcanic activity and cyclones. It is run by the JRC on behalf of the UN, the European Commission and other international disaster-managing organisations. It also undertakes post-disaster impact assessments and provides a forum for scientific discussion on both technical and social aspects of disasters, for instance on topics such as (1) crisis response and management technology, (2) geospatial infrastructure and modelling, and (3) social media for crisis management.

GDACS cooperates with and receives and integrates information from a variety of sources:

- Flood disaster information is provided by the Dartmouth Flood Observatory (global, space-based observation of floods, based at Colorado State University; http://floodobservatory.colorado.edu/) and is integrated automatically into GDACS alerts and impact estimations.
- GDACS coordinates the creation and dissemination of disaster maps and satellite images. This service is facilitated by the UN Institute for Training and Research (UNITAR) Operational Satellite Applications Programme (UNOSAT). Relevant maps are integrated automatically into VirtualOSOCC disaster discussions.
- Detailed weather forecasts are provided by SARWeather (semi-commercial high-resolution weather forecasts for specific areas, suitable for search and rescue operations; https://www.sarweather.com/) and integrated into its VirtualOSOCC disaster discussions.
- JRC has developed a wave propagation model for simulating the movement of tsunamis (Figure 3.7), and this has been integrated into GDACS.
- GDACS uses a stable finite volume hydrodynamic model, HyFLUX2, of inundation of chemical and other factories during floods (Paul *et al*. 2015). It has also worked at linking together finite element models of structures with finite volume models of fluids to simulate their interactions (Franchello and Krausmann, 2008; Zhang *et al*. 2015).
- JRC now has a surge model (in collaboration with ECMWF) for the North Atlantic, but, to date, there has been no cooperation with Ireland for receiving and improving its forecasts. Such links should be established.

3.4.4 European Drought Observatory

As part of the European Climate Adaptation Platform (http://climate-adapt.eea.europa.eu/), the JRC has developed a European Drought Observatory (http://edo.jrc.ec.europa.eu), which is a web-based information integration and dissemination system for forecasting, monitoring and assessing droughts, at different scales, based on terrestrial and satellite measurements and soil moisture modelling. It provides a map viewer (Figure 3.8) to indicate the location of extreme values of its drought indices, rainfall deficits, soil moisture deficits and vegetation stress and also allows users to download and analyse its data. Studies of the ability to forecast drought at long lead times (e.g. more than months in advance) through precipitation forecasts currently indicate the difficulties involved (e.g. Singleton, 2012) and hence emphasise the importance of real-time monitoring and assessment activities.

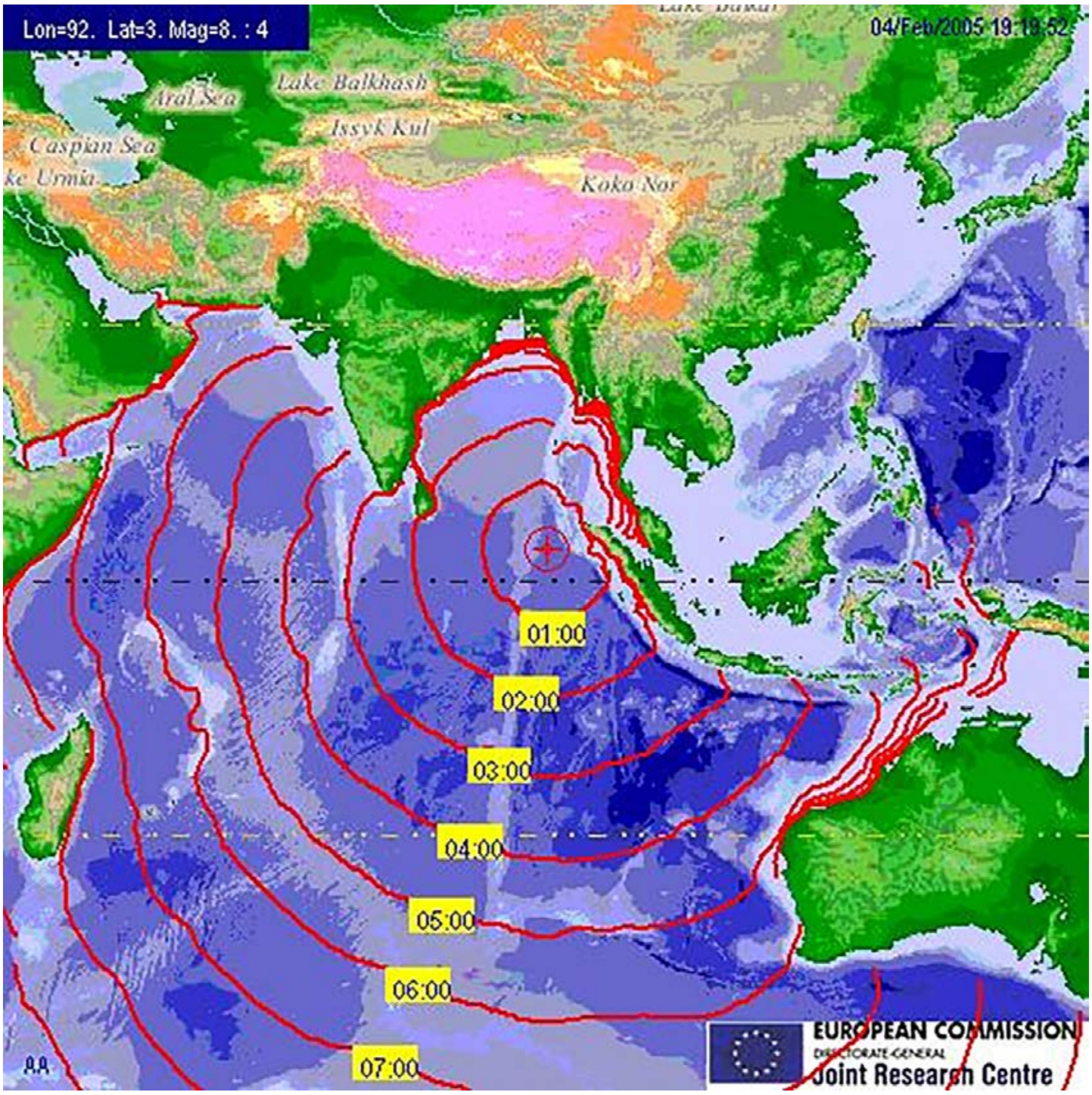


Figure 3.7. The JRC tsunami model. Source: GDACS.

3.4.5 European media monitoring

The JRC developed a software system that automatically gathers news reports from media sites from all over the world, classifies and analyses them, extracts the information content and provides reports, either as live breaking news reports (NewsBrief) or as daily news summaries (NewsExplorer). The system monitors over 10,000 RSS feeds and web pages in more than 60 languages. Although this covers a wide variety of topics, when natural disasters occur, local reports and news feeds will be picked up quickly and displayed.

The NewsBrief (emm.newsbrief.eu) site is updated every 10 minutes and shows the topics most discussed on electronic media, covering over 60 languages, over the past hour or so. The news is divided into over 100 subject categories (Figure 3.9).

The NewsExplorer is produced each day and summarises the people, organisations and places mentioned most in the news for that day (Figure 3.10). A map shows their locations and timelines show the temporal development of the subject and links with occurrences on previous days.

A special focus is given to the health area, and a real-time analysis of health topics is used to provide early warning alerts (Figure 3.11), based on selected key words (http://medisys.newsbrief.eu/medisys/homeedition/en/home.html).

Future plans are for the systematic monitoring of social media for indications of a range of disasters as they happen (Latonero and Shklovski, 2011; Akhgar *et al.*, 2013; Chan, 2013). Such possibilities for Europe have been explored, e.g. in Manso and Manso (2012), who described a possible platform for such interaction and

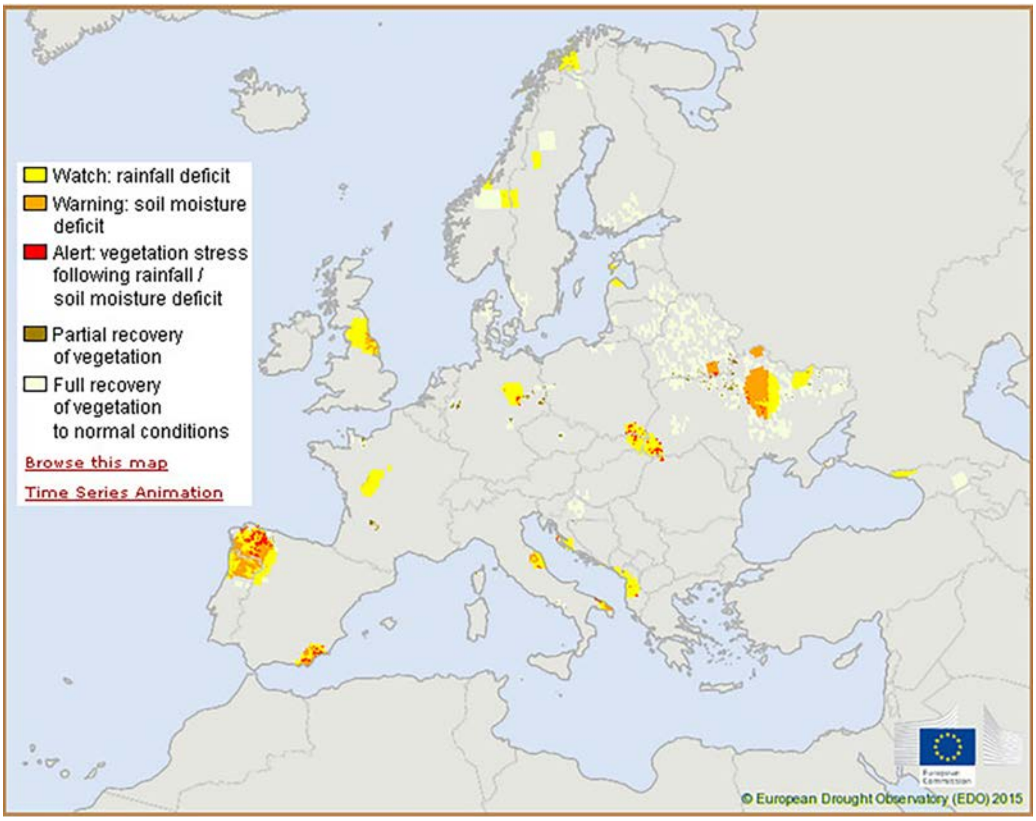


Figure 3.8. Drought indices for Europe. Source: European Drought Observatory.

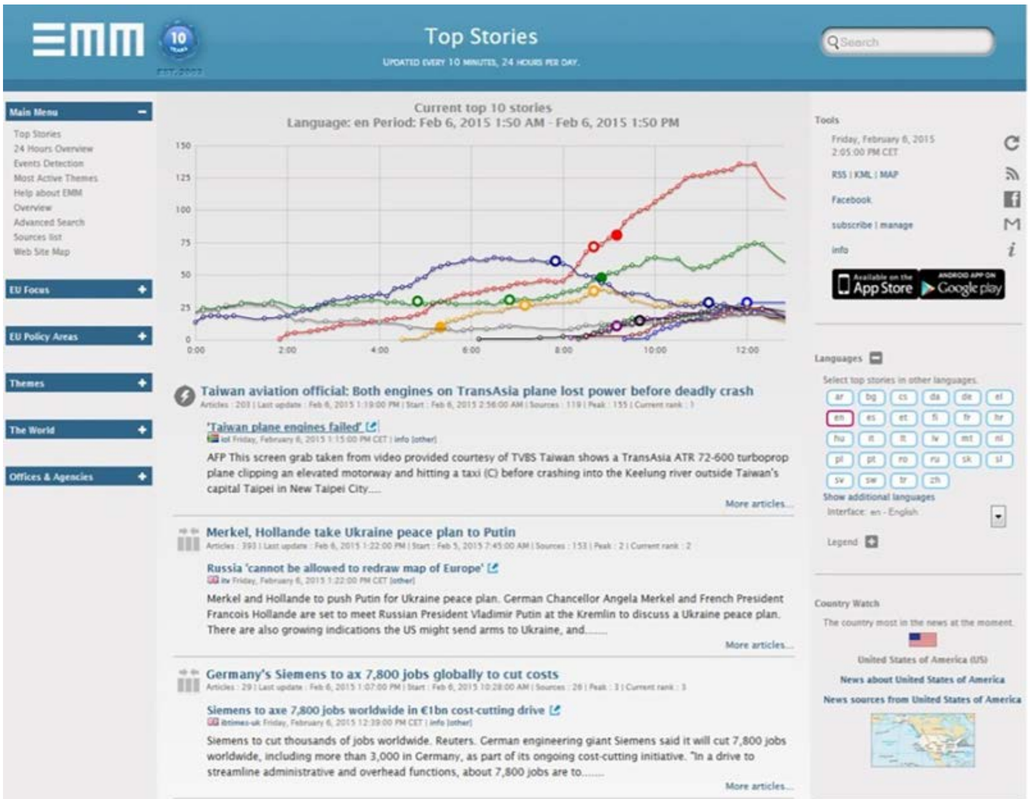


Figure 3.9. Screenshot of NewsBrief's "Top Stories" page. Source: JRC.

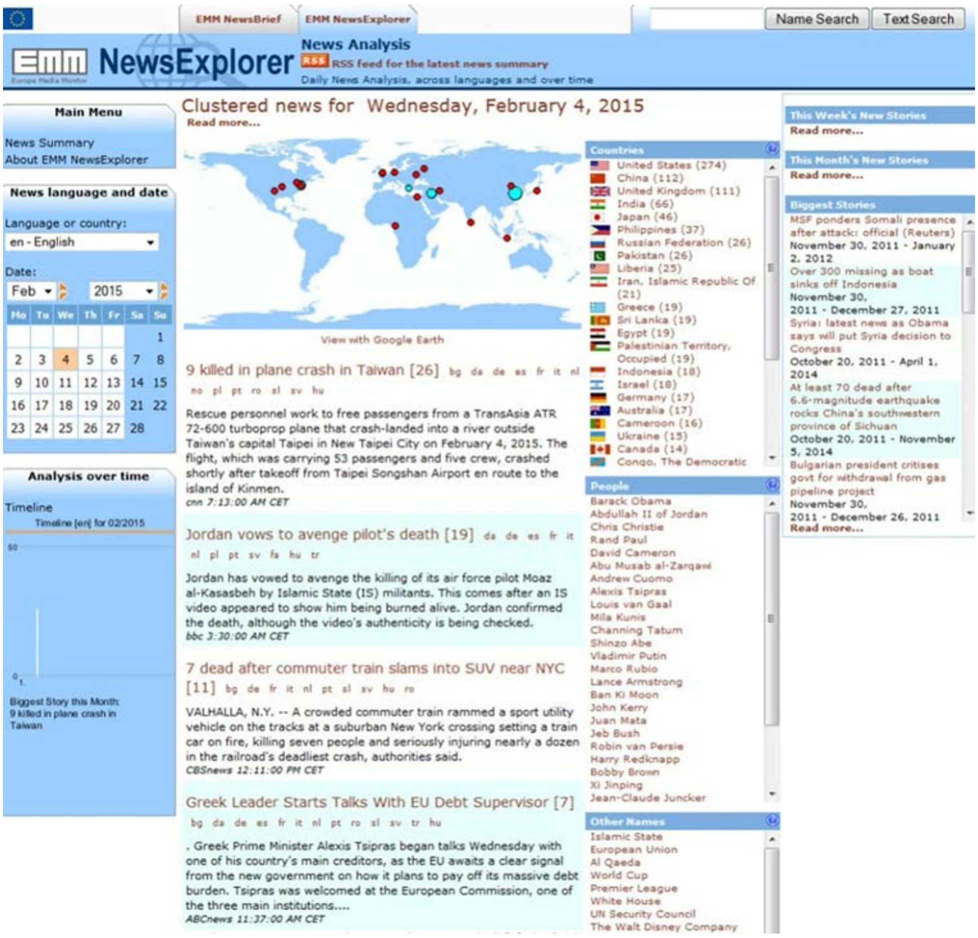


Figure 3.10. Screenshot of NewsExplorer's news page. Source: JRC.

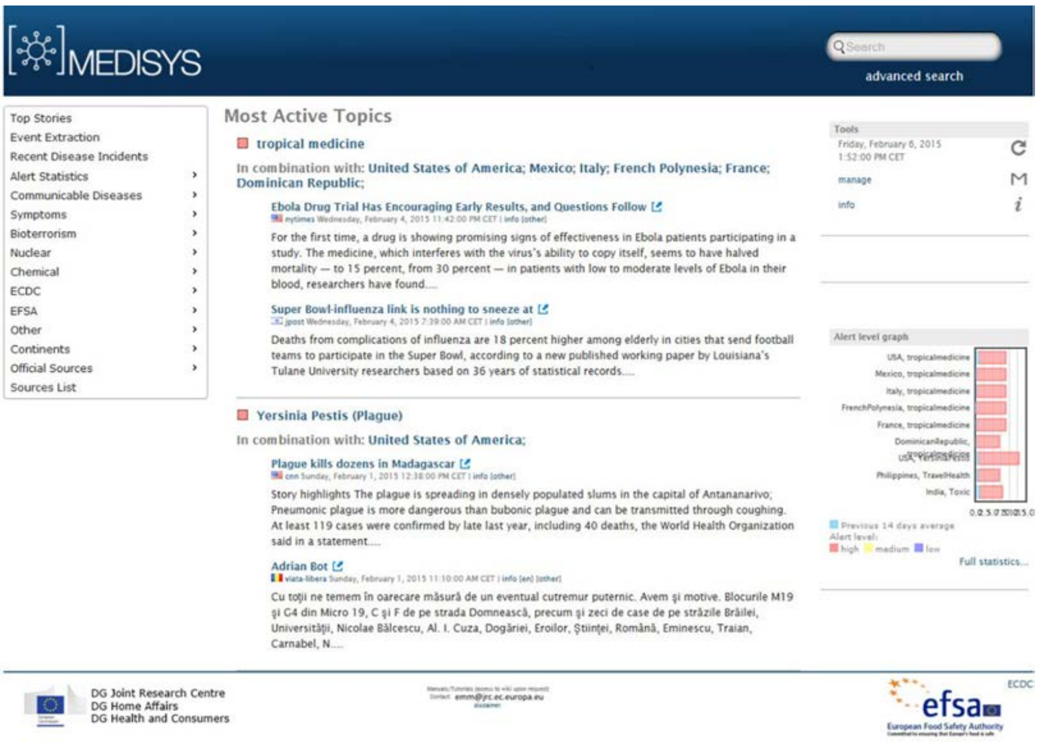


Figure 3.11. Screenshot of MediSys's site. Source: JRC.

listed potential existing tools. The associated research needs have been discussed by Li and Goodchild (2010) and include not just technological issues and visualisation platforms, but also legal, privacy, equity and social behaviour aspects.

3.4.6 European Response and Coordination Centre

The European Commission has a DG ECHO (http://ec.europa.eu/echo/), which is involved in disaster risk reduction (Casadei and Leconte, 2010). Its ERCC, based at JRC Ispra (http://ec.europa.eu/echo/en/what/civil-protection/emergency-response-coordination-centre-ercc), promotes a coordinated and quicker response to disasters both inside and outside Europe. However, its main activity appears to be dissemination of information and the development of frameworks for disaster response, rather than taking an active part in individual situations. It relies on input from all European countries and some others that are part of the European Union Civil Protection Mechanism (http://ec.europa.eu/echo/node/524). For instance, it can link to the Ensemble Tropical Rainfall Potential (eTRaP), precipitation forecasts of tropical precipitation using microwave data from polar-orbiting satellites, provided by NOAA (Kusselson *et al*., 2010; Ebert *et al*., 2011). ERCC is a coordination hub designed to reduce duplication of disaster response efforts. It also contributes to awareness raising and organises practical exercises simulating emergency response scenarios.

JRC institutes become involved in joint projects with external research centres to undertake research on topics of mutual interest. An example is the CASSANDRA (Centre for Advanced Simulation Studies AND Researches on Agroecological modelling) group at the University of Milan, modelling agro-ecological impacts of climate change, e.g. http://www.diprove.unimi.it/groups/agro_rg2.htm. Some of these projects have global linkages, e.g. with the World Bank.

3.4.7 Effectiveness of JRC Ispra regarding disaster information

JRC Ispra's EFAS flood flow forecasting system is widely used in Europe, particularly for the larger rivers. Ireland has recently subscribed to its service and it was useful in the December 2015 floods (see section 3.4.2). JRC Ispra's efforts at providing a coordination centre for information on global disaster information and on droughts in Europe, while useful, depend on information from external sources, typically national agencies. Ireland would benefit from being part of its surge forecasting network.

3.5 Copernicus Emergency Management Service

Copernicus Emergency Management Service (EMS) is an EU programme that uses satellite and terrestrial data to monitor the state of the environment with a specific objective of supporting (1) climate change mitigation and adaptation strategies, and (2) the efficient management of emergency situations. It provides a mapping platform to show the extent of disasters and their impacts at a useful resolution and an early warning system (based on the JRC's EFAS system; see section 3.4.2). The mapping platform was utilised by Ireland during the December 2015 floods to identify their scale and extent, and it continues to be used in the post-event analysis (see http://emergency.copernicus.eu/mapping/list-of-components/EMSR149).

3.6 UN Office for the Coordination of Humanitarian Affairs

The UN Office for the Coordination of Humanitarian Affairs (OCHA) (http://www.unocha.org/) is charged with, among other things, coordinating the response to emergencies/crises of any kind, including those related to natural hazards. Its role involves data management and the development of effective leadership. While most of its activities relate to the response to emergencies rather than warnings of them, it does have a preparedness remit and it thus runs the Environmental Emergency Centre (http://www.eecentre.org/), which is a source of information, tools and training related to emergency response. This centre supported the development of the Flash Environmental Assessment Tool (FEAT) by the Dutch National Institute for Public Health and the Environment (RIVM). This tool (van Dijk *et al*., 2009) is intended to facilitate the quick evaluation of risks to humans immediately following environmental disasters. While it concentrates on likely releases of hazardous and/or environmentally persistent chemicals, it also deals with physical impacts such as soil erosion and salt water intrusion (Miller-Rushing and Primack, 2008). It has been used in developing countries for both disaster response and hazard identification (Dulière *et al*., 2013).

In relation to hazards associated with climate change, OCHA focuses particularly on the human settlement and displacement consequences (van Dijk *et al.*, 2009) and especially in collaboration with the UN High Commission for Refugees (Nijenhuis and Wahlstrom, 2014).

3.7 UN Office for Disaster Risk Reduction

The UN Office for Disaster Risk Reduction (http://www.unisdr.org/) was created to implement its UN International Strategy for Disaster Reduction (UNISDR). This strategy was based on an earlier document, the Yokohama Strategy (1994), which was strongly based on the point that disaster prevention was far better (and more cost-effective) than disaster response and set out 10 principles to guide the UN's efforts. The fifth of these stated that early warnings of impending disasters and their effective dissemination using telecommunications, including broadcast services, are key factors for successful disaster prevention and preparedness. Its implementation called for improved risk assessment, broader monitoring and communication of forecasts and warnings. UNISDR has a number of roles, relating to coordinating the efforts of other UN agencies working in this area, as a catalyst by campaigning and advocating and as an information provider. One of its advocating topics is climate change adaptation and it established, in 2004, a working group on disaster risk reduction and climate change, which has published a number of briefing notes giving some general guidelines and practical examples on this topic. Closely associated is the Hyogo implementation framework, which, among other things, has produced a review of European disaster reduction platforms (Weerasinghe *et al*., 2014). Although Ireland is not included in the survey, there is a similarity between the approach in Ireland and in Europe in that disaster reduction response is predominantly (93%) run by a governmental organisation. However, a major difference with the Irish situation is the formal involvement in Europe of non-governmental organisations (NGOs) (78%) and academic or research organisations (74%). Interestingly, about 33% of platforms have a media involvement and about 44% have some involvement of private companies. UNISDR has also been involved in a worldwide survey of disaster response platforms (Türk *et al*., 2014), which echoed the high degree of top-down control (i.e. at national level) and the low level of participation of the media and private organisations in national disaster platforms. It recommends (1) better arrangements for financial investment and risk sharing, (2) development of better links between national platforms and international programmes, and (3) increased assessment of the effectiveness of communications strategies. The final report also suggests that a collaborative approach between disaster risk reduction and climate change adaptation is recommended as a good practice towards effective climate vulnerability reduction (Turk *et al*., 2014).

4 Warning Agencies – Ireland

4.1 General Framework

There is no single agency directly responsible for all aspects of peacetime disaster management in Ireland. Instead, the relevant government ministries and public authorities have some statutory responsibilities for specific aspects of disaster management, and coordination between them is overseen by the Government Task Force on Emergency Planning, chaired by the Minister for Defence, which provides political leadership and government oversight. Disaster planning activity at the national scale is supported by the Office of Emergency Planning (OEP), which supports coordination, communications and the production of a national framework for emergency management. These groups meet in a bespoke National Emergency Coordination Centre (NECC). However, the response to individual emergencies is generally at a local level; each of the county and city councils functions as a principal response agency (PRA) and, together with other agencies mentioned below, each is expected to have a major disaster response plan.

The OEP chairs the Inter-departmental Working Group on Emergency Planning (IDWG), which comprises officials representing government ministries and public authorities with lead or principal support roles in government emergency management. The National Steering Group develops, implements and updates the Framework for Major Emergency Management (the Framework MEM). This group comprises representatives of the PRAs and their parent ministries, the defence forces and the Department of Defence.

In the event of a major disaster, three levels of coordination centres are involved: (1) on site, (2) locally, and (3) nationally (Figure 4.1). The Framework recognises that coordination is a specific function in emergency management, and the coordination task is assigned to the lead agency in the local and regional response and the lead government ministry at national level. For local and regional response, the determination of the lead agency is set out in the Framework and is based on the incident type. For most of the types of incidents described in this report, e.g. involving severe weather, flooding, coastal erosion, landslides, fire, environmental pollution, and also hazardous materials and radioactive contamination, the lead is taken by the Department of Housing, Planning and Local Government, and for incidents involving epidemics, the lead is taken by the Department of Health.

The PRAs, i.e. An Garda Síochána, the Health Service Executive (HSE) and the local authorities (including the fire service), are the agencies that respond to major emergencies on the ground. There are eight regions for civil protection purposes and each has an inter-agency Regional Steering Group (RSG) for MEM, comprising senior personnel from the PRAs within that region. Each region also has Regional Working Groups (RWGs) to support the RSG in its tasks, such as the preparation of emergency response plans, severe weather plans and the organisation of training.

Many volunteer organisations assist with emergency response in local areas, including Civil Defence, Irish Red Cross, the Order of Malta, The St John Ambulance Brigade of Ireland, Irish Mountain Rescue Association (IMRA), cave, river and inshore rescue units, Royal National Lifeboat Institution (RNLI), and sub-aqua organisations. At regional level, sub-groups of the RWGs have been formed to engage with these voluntary organisations along with smaller local volunteer groups.

A National Steering Group for MEM (www.mem.ie) has set out a framework for the preparation of a coordinated response from all agencies involved in an emergency and, in particular, An Garda Síochána and the HSE. While this includes man-made hazards such as transport accidents and incidents involving hazardous substances, it also includes climate-related emergencies due to severe weather and fires.

Note that the structure envisages most communication with the public to be through the media. While this is and should be an important channel of communication, it should not be the only one and the MEM should make provision for alternative methods of communication, including adequate redundancy and special provision for supplying information to

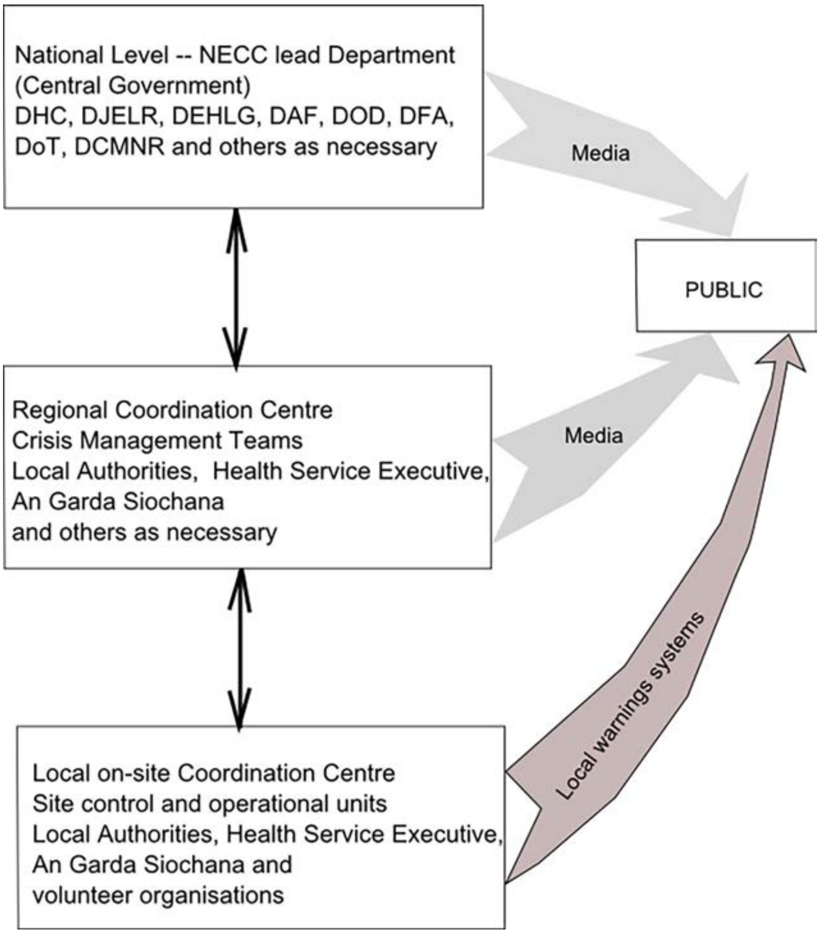


Figure 4.1. Organisational structure for disaster management in Ireland.

vulnerable population groups. A method of receiving useful information from the public is also desirable, including the monitoring of social media, see section 3.4.5. The Framework MEM does advise that the local coordination group may establish a sub-group for this purpose and use all available channels to make concise and accurate information available. This may include the use of dedicated 'help-lines', web pages, RTÉ Aertel and automatic text messaging, as well as through liaison with the media. However, this does mean that whether communication with and dissemination of information to the public occurs, how it occurs and when it occurs will vary locally, with no uniform approach or guidance. Communication with vulnerable at-risk sectors should be made a priority through national guidelines and should not be left to local discretion.

Individual reports from local areas for the flood event of December 2015 indicated that the specific knowledge of individual local authority personnel of vulnerable people in their locality was essential in ensuring that these people's needs during the emergency were prioritised. While this is commendable, the dependency on the knowledge and commitment of specific individuals is not ideal and a more formal systematic approach is recommended.

4.2 Met Éireann

Met Éireann is the Irish national meteorological organisation with a remit to obtain and analyse information about Irish weather and climate and to forecast their future states. It has links with a number of international meteorological organisations with which it shares data and forecasts.

Its mission statement includes remits relevant to natural hazard warnings, i.e. to:

- contribute to the protection and safety of life and property when threatened by meteorological hazards;
- contribute to the development of the science of meteorology;

- contribute to effective monitoring and good management of the natural environment;
- maintain a high-quality and cost-effective meteorological infrastructure.

It operates the national meteorological data collection network, which includes ground stations and radar and receives weather satellite information. From these, it produces a number of general and specialised forecasts, including:

- national and regional weather forecasts for (a) the entire country, (b) five major regions (Connaught, Dublin, Leinster, Munster and Ulster) and (c) each county and a number of inland lakes (Loughs Derg, Ree, Corrib, Mask, Key and Allen);
- specialised sea area forecasts for marine craft;
- synoptic charts showing the current weather situation in the Atlantic Ocean and western Europe and forecasts of how it is expected to change over 2 days;
- short-range detailed forecasts up to 12 hours ahead of precipitation, temperature, pressure, wind speed and direction derived from regional climate model predictions and information from Met Éireann's own data collection network, radar and satellite; it also provides a detailed forecast for 3 hours ahead and a 5-day ahead forecast of these variables, the latter based on information from ECMWF, together with forecasted significant wave heights.

Met Éireann provides forecast information and warnings to the public via television and radio and prints a monthly weather bulletin, technical reports and books, and its staff and collaborators publish research results in academic journals and conference proceedings. It maintains a database of historical weather data (http://www.met.ie/climate-request/).

4.3 Office of Public Works

The Irish OPW (www.opw.ie) is a government organisation with responsibility for estates management, building and heritage conservation and management, arterial drainage, and flood risk management. It is the main official organisation responsible for flood risk management and the implementation in Ireland of the EU Floods Directive (2007/60/EC). Under the Arterial Drainage Acts of 1945 and 1995 it has drained agricultural land to improve its productivity. It designs and commissions flood defence schemes for urban areas, and in 2009 it was given responsibility for all coastal protection (flooding and coastal erosion), including the maintenance of existing protection schemes. As part of implementing the EU Floods Directive, it has managed studies (1) to identify areas at risk and then (2) to produce flood risk management plans for those areas at highest risk. It undertook a study of the design of flood estimation methods (Flood Studies Update) to replace the original Flood Studies Report (NERC, 1973) with an internet- and GIS-based system that can be accessed at opw.hydronet.com. It has established and operates a network of approximately 380 flow-gauging stations on most major Irish rivers and lakes, and on some tidal locations in estuaries. Real-time data from many of these are made available to the public online (www.waterlevel.ie). The OPW undertakes flow gauging to acquire the data necessary to develop rating information from which flows are calculated from measurements of water levels. These and a number of useful derived products (e.g. annual maxima series and flow duration information) are available from its National Hydrometric Archive (http://waterlevel.ie/hydro-data/home.html). The OPW operates a number of rain gauges in areas subject to severe flooding. It leads the development of local flood warning systems for areas provided with demountable flood defences. Note that the Environmental Protection Agency (EPA), local authorities, the Electricity Supply Board (ESB) and Waterways Ireland also collect hydrometric data relevant to flows and flooding (see http://www.gov.ie/services/access-hydrometric-data/).

The OPW coordinated the production of the Flood Policy Review report of 2004, which recommended a variety of essential elements of a risk management strategy, including flood risk mapping and the development of a warning system based on hydrological modelling. Among other things the report provided an economic justification for these recommendations.

The OPW participated in the Flood Emergency Response Planning Project, between 2006 and 2007, to guide local authorities in the development and implementation of effective flood emergency response and recovery plans (FERPs) that specify what is to be done and by whom, before, during and after a flood event. It lists the personnel who should be involved (local authorities, emergency and support services and at-risk communities) and specifies the appropriate methods of communication between them. The project produced a state-of-the-art review, undertook pilot projects for the towns for which protection schemes were being planned, i.e. Clonmel, Fermoy and Mallow, and, building on these schemes, produced guidance documentation (a template for flood response plans and a protocol specification of roles and responsibilities).

The OPW commissioned a report on options for a flood forecasting and warning centre for Ireland (JBA Consulting, 2011), which recommended a single national centre supplying flood forecasts to four regional flood warning centres that would inform emergency responders, the media and the public. This has not yet been implemented and even the first step, a national flood forecasting centre, is required urgently and is currently being planned.

4.4 Health Service Executive

The Irish HSE is involved in emergency response (http://www.hse.ie/eng/services/list/3/emergencymanangement/) and in the development of major emergency plans. These include dealing with climate-related emergencies, particularly flooding and cold. The HSE has set up a National Crisis Management Team (NCMT), which collaborates with the National Public Health Emergency Team (NPHET) to assess each situation and determine the resources required. In cases of national emergencies they have special budgetary arrangements for quickly procuring appropriate services. In addition to the national level, the HSE has established emergency management arrangements at regional and local levels, and the need for adequate communication with all relevant stakeholders has been acknowledged.

5 WARNDIS Workshop

The WARNDIS project organised a workshop on "Natural Hazards and Climate Change" in the Newstead Building of University College Dublin (UCD), Belfield, on 7 May 2014. Its purpose was to bring together researchers, policymakers and disaster response managers in a dialogue about research results informing their activities and to give them an opportunity to explain their pressing research questions and needs. It started with presentations from invited speakers detailing the activities and research results of a number of organisations already active in this area. It ended with a session of small group discussion intended to feed into a statement on research needs that may inform future policy.

Participation was free. The programme is shown in Table 5.1 and invited speakers were from UCD, OPW, NUI Maynooth and Coastal and Marine Resources Centre – University College Cork (CMRC-UCC) and NUI Galway.

Forty-five people, from a wide range of backgrounds – academic, consulting engineers, government organsations and NGOs – attended. In the final period of the workshop, participants were divided into a number of small groups with 8 to 10 participants in each group and were asked for their input on a number of prepared questions. Participants were asked to write each suggestion on a card and the group could discuss each suggestion. At the end of each session, the cards were collected and the suggestions received from the participants are described below.

5.1 Question 1: What Impacts, Other Than Those Described in the Presentations, Should Be of Concern?

The concerns of the participants have been analysed and organised into categories as follows:

5.1.1 Mobilisation of pollution

- Soil pollution (food and health). Flood waters mobilise chemical and biological pollution, e.g. from industrial areas, sewage treatment works, slurry tanks, etc. While the flood provides some dilution, the amounts and range of pollutants mobilised can be large. The risk to human health, from both direct contact and through the food chain, should be evaluated.

Table 5.1. Workshop programme

Time	Speaker	Topic
9:55–10:00	Michel Bruen, UCD	Welcome
10:00–10:30	Oliver Nicholson, OPW	Flood risk management initiatives, information and data to support disaster planning and management
10:30–11:00	Conor Murphy, NUI Maynooth	Climate change research at ICARUS
11:00–11:30	Conor Sweeney, EI, UCD	Probabilistic forecasting of weather extremes
11:30–11:45	Short break	
11:45–12:15	Barry O'Dwyer, CMRC-UCC	Developing decision support tools for climate change adaptation
12:15–12:45	Mike Long, UCD	Landslide risk
12:45–14:00	Lunch	Light lunch provided
14:00–14:30	Michael Bruen and Dzakpasu Mawuli, UCD, CWRR and EI	Overview of climate change risks and WARNDIS project review and real-time information sources
14:30–15:00	J.J. O'Sullivan, CWRR, EI, UCD	Social vulnerability and risk communication in Europe – CRUE ERA-NET project
15:00–15:30	Kevin Lynch, NUI Galway	Decision-making and coastal risks
15:30–16:30	All – with facilitator – Margaret Desmond, EPA	Small-group workshop discussions with coffee and biscuits

EI, UCD Earth Institute.

- Waste management (sewerage). The siting of sewerage discharge pipelines on floodplains can reduce the conveyance capacity of the floodplain and increase the flooding risk upstream.
- Aquaculture. This is an important, specialised component of Ireland's food industry, consisting of the farming of finfish and shellfish in marine estuaries and sheltered bays around the coast. Shellfish are vulnerable to a number of flood-borne substances, particularly sediment and pathogens, particularly *Escherichia coli*, which are listed in Annex 1 of the EU Directive (2006/113/EC) on the quality of shellfish waters (subsumed into the Water Framework Directive in 2013). The risk of such contamination from flood-borne *E. coli* should be quantified and the potential benefits from early warning should be assessed.
- Risk to bathing water quality and human health. An important component of Blue Flag status for beaches is that the microbial quality of the water and testing is specified by the revised EU Directive on Bathing Waters (2006/7/EC). These make special provision for cases of microbial contamination mobilised by floods that are predictable, i.e. when a warning can be provided, see for example. the SmartCoasts INTERREG project (http://www.irelandwales.ie/projects/priority_1_theme_1/smart_coasts).
- Groundwater and spring contamination from pollutants mobilised by the flood waters and especially in karst areas.

5.1.2 Special flooding cases

- Turloughs. Where important infrastructure is at risk from turlough flooding, warnings are possible, but structural measures may be more appropriate.
- Tidal flooding, including storm surges. Tidal and coastal surge flooding can be forecast and warnings can be issued. There are a number of individual systems already in place, e.g. the OPW's Irish Storm Surge Forecasting Service (http://www.rpsgroup.com/Ireland/Services/C/Coastal-Engineering/Irish-Storm-Surge-Forecasting-Service.aspx) and Dublin City Council's coastal early warning forecast system for Dublin Bay. Ireland should request access to the EU storm surge forecast system and evaluate it for Irish conditions, which should include the possibility of wave overtopping of defence structures.
- Sewer flooding. Sewers flood when their capacity is exceeded, particularly during intense, short-duration rainfall in urban areas. The greater extremes of rainfall expected with climate change will increase the probability and magnitude of flooding of existing sewers. Appropriate control measures (with warning systems) should be implemented where appropriate. Because of the type of rainfall involved (short duration and high intensity), warning lead times are limited and, unless online storage capacity is provided, real-time management options are limited.

5.1.3 Risks to infrastructure

- Risk to critical infrastructure. Roads, rail, communications and electrical power systems may be affected by flooding, impeding the work of emergency response services, the deployment of demountable barriers and the operation of pumping systems, etc. These would benefit from timely warnings.

5.1.4 Emergency management structures

- Public information bank. There is a need to carefully consider how to make relevant up-to-date information available to the public in a directly accessible way (no specific suggestions made by participants; however, websites and on-site real-time displays of warnings and risk would seem appropriate).
- Real-time forecasting used to plan and update emergency services access, egress and evacuation routes.
- One participant observed that there is a tendency to depend on the actions of others and that an attitude change to more self-reliance or local community reliance would be desirable and could influence the design of emergency response plans.

5.1.5 Other risks

- Subsidence and landslide hazards and their relationship with rainfall intensity–duration thresholds (as triggers) should be studied.
- Climate change impacts on natural resources should be considered, as there are risks of shifts in ecosystems that could have disastrous consequences.

5.2 Question 2: What Other Information/Data Sources Exist or Should Be Acquired That Would be Useful for Emergency Response?

The responses are listed below and cover a wide range of potential data sources, many of which are very specific to individual hazards/applications. The need is seen for both additional data sources and higher resolution of existing data sources.

1. Compile data on pollution sources, which, when mobilised during disasters, could contaminate rivers, seas and oceans.
2. Better information is needed on water quality in bathing waters and its relationship with flood events.
3. More seabed bathymetry data and improved/more sea level and tidal current data of longer duration and greater spatial coverage are needed. There are relatively few gauges with a sufficient record for scientific study.
4. High-resolution (short-duration) rainfall data are needed. [Although the comment did not elaborate, this requires radar systems for urban areas and/or telemetering raingauges for small flashy rural catchments that can threaten population centres (e.g. Nire Valley/Clonmel and Dinan/Kilkenny).]
5. More routine use of Earth observations [no detail given, but could be used to map flood extent (see Copernicus project in section 4.5); however, a limitation is the frequency of coverage of low Earth orbit satellites with sufficient resolution and the high percentage of cloud cover impeding the view of many sensors]. A specific suggestion was more frequent airborne and satellite coastal imagery and to this could be added an assessment of the potential of drones as a real-time information source.
6. Make better use of old surveys in e.g. the OPW, Department of Agriculture, Food and the Marine, Teagasc, Brown Commission 1939. This is to establish pre-existing conditions (pre-development).
7. More data are required on the public health impacts of disasters, e.g. hospital data, but could also include numbers of general practitioner (GP) visits.
8. More data are required on infrastructure sustainability and vulnerability (including to seismic activity).

6 Conclusions

- The climate is a dynamic system and variation over many time scales is to be expected. However, we are currently in a phase of global warming to which humans have contributed and which seems set to continue for a considerable period into the future.
- The impact of global warming has been detected in many different categories of natural hazards, but not in all.
- Intensification of the hydrological cycle due to the warming climate has led to increased annual average amounts of precipitation in many areas. Even in those areas that have experienced a decrease in annual averages, there was often an increase in the intensity of extreme events.
- The projected impact of warming on flooding in Europe is that the central and western areas, including Ireland, will have more frequent flooding (rather than a substantial increase in the magnitude of the extremes), whereas the eastern and northern areas will see a decline in flooding. However, this pattern has not yet been reliably identified or associated with climate change in past measured flows. There are many other factors, unrelated to climate, such as urbanisation, river channel modifications and land use change that confound the signal.
- The absence of clear evidence of a climate change signal in past flood records, despite a clear change in precipitation characteristics is a cause for concern, as it indicates the highly non-linear nature of the hydrological response and raises the possibility of tipping points or thresholds, which, when crossed, may lead to much more rapid and severe response.
- Sea levels are rising as a result of global warming, at different rates in different places on account of local influences (e.g. isostatic uplift in Scandinavia). However, there is no consensus on whether storminess and wave heights are increasing.
- Climate warming has increased the incidences of landslides. The main mechanism is slope destabilisation due to melting of permafrost, so the impact is mainly in mountainous regions. Perhaps surprisingly, there does not seem to have been a corresponding increase in debris flows in downstream valleys.
- In many areas, the incidence and severity of wildfire events has increased as a result of global warming and the length of the wildfire risk period has lengthened. However, in some areas the incidence of wildfires has decreased and this appears to be because of a reduction in available biomass to burn.
- Climate change has influenced the range limits and phenology of many species, including plants, birds and animals, changing the timing of bud-burst and migration, changing patterns of migration and influencing mating success and the sizes of eggs and individuals.
- Whereas the local effects of climate change on agriculture and food may be positive in the short term in some regions, most global studies suggest that the impact on global food supplies will be negative, attributed more to increased climate variability, particularly in temperatures, rather than in precipitation.
- The health effects of climate change on humans are both direct, in terms of exposure to the risk of more frequent natural disasters and extremes of temperatures, but also indirect, in terms of the increased ranges of diseases and disease vectors.
- There are three very important organisations in Europe vital to understanding and responding to the threats of climate change; ECMWF, JRC Ispra and EUMETNET (their roles and contributions are described in detail in Chapter 3). Much of the primary data are provided by these organisations, and a number of Europe-wide hazard information dissemination platforms are either run by these organisations or depend on their support.
- In particular, the EFAS provided by JRC Ispra has continually improved its forecasting performance and, as the OPW subscribes to the service, it did forecast the severe floods in Ireland in December 2015/January 2016. However, there are good reasons to believe that its forecast lead time

for those floods on the River Shannon could be increased, perhaps to 8 to 10 days.

- A number of other warning dissemination services undertaken for international organisations are, in reality, funded or hosted by individual national organisations (or by the EU) [e.g. WMO's SWIC is run by the Hong Kong observatory and the UN's Global Disaster Alert and Coordination Service is run by the JRC (Ispra)]. While this reflects funding realities, it is hardly a sustainable situation and reinforces the importance of the European organisations, ECMWF, JRC and EUMETNET and of strengthening cooperation and collaboration with them.
- There are two main organisations in Ireland active in the area of hazard forecasting and warning, Met Éireann (severe weather) and the OPW (floods).
- While there is a centralised organisation structure in Ireland to coordinate the response to emergencies, there is not a comprehensive warning centre.
- Following the severe flooding of the River Shannon of December 2015/January 2016, a centralised warning service (a cooperation between Met Éireann and the OPW) is being planned. This should be a priority.
- The workshop discussions confirmed (independently – as the workshop participants did not have access to this review) the range of concerns about the range of impacts reviewed in this report and added two more that are not analysed here: (i) sewer flooding (out of scope) and (ii) turloughs (not considered here because of their small scale).

7 Recommendations

Climate change, as described in the review at the beginning of this report, is changing the nature and magnitude of disaster risks faced by the population. Incorporating the dynamic nature of these risks into (1) planning the location of infrastructure and (2) behaviour before, during and after emergencies is a challenge that has not yet been adequately addressed. Some specific aspects identified in the review and at the WARNDIS workshop are as follows:

1. A national flood warning service has been promised and this should be integrated, in real time, with the emergency response (JBA Consulting, 2011). This will be primarily based on Met Éireann weather forecasts, which require global information from ECMWF. This should be integrated, in real time, with the official emergency response structures. Integration of such a national flood forecasting and warning service with European systems such as ECMWF, EFAS and Copernicus is essential, as well as integration and data sharing with higher resolution local systems to meet specific requirements, e.g. triggering deployment of demountable barriers.
2. Any future centralised warning service, be it only for floods or for all natural hazards, should incorporate an active research division linked to the relevant research centres in third-level institutions. This is essential to maintain an up-to-date, state-of-the art warning service.
3. Ireland benefits from its subscription to the EFAS and, being a maritime nation, should also consider subscribing to the European surge prediction network and evaluate and/or integrate its own bespoke higher resolution local systems with more detailed bathymetry.
4. Ireland should also become more closely involved with a number of European disaster-related initiatives, e.g. relating to landslide risk and media monitoring.
5. A broader range of methods is required to communicate warnings and disaster-related information to the public. Such information should be up to date (preferably real-time), should have specific components especially for vulnerable groups of the at-risk population, and should incorporate a large element of resilience and redundancy. A study of how and when to communicate effectively with the public (to both provide and receive information and to produce specific response actions, e.g. evacuations) would be particularly useful, with a focus on reaching the most vulnerable at-risk groups of society.
6. Mobilisation of pollution by floods has been highlighted as an issue with severe consequences across a range of areas, including human health, safe food and water. Measures are required to reduce these risks, by removing or isolating their sources and minimising the risks of their mobilisation.
7. Risks to other infrastructure, particularly roads, power and communications systems from floods are important and ensuring the resilience of such systems should be prioritised.
8. Regarding data needs, a wider range of data sources should be utilised and at greater resolution (temporal and spatial), where beneficial in specific areas. Greater use of remote sensing technologies, e.g. Earth observation and radar, should be considered in specific cases. Ireland should continue to participate in European initiatives to use satellite and other remotely sensed data (e.g. the Copernicus project), both during disasters and in post-event analyses.
9. The current reliance on the knowledge and commitment of specific individuals at the local flood response coalface (typically local authorities, An Garda Síochána, fire and health service) to identify vulnerable individuals for prioritisation is not ideal and a more formal systematic approach to identifying and addressing the needs of these groups is recommended.
10. The literature review strongly suggested that current research on climate change impacts on Ireland is overly fragmented and could benefit considerably from increased collaboration between climate change experts and experts in the specific

areas of impacts. A tipping point has been reached in the need for a broad interdisciplinary approach to the analysis of impacts and the recognition and study of their inter-connectedness. Significant scientific progress, within Ireland, will depend on this. The establishment of a coordination centre to generate, manage and provide access to the large data sets involved and with a strong remit to foster a multi-disciplinary approach to evaluating impact would benefit Ireland.

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Abbreviations

CMRC	Coastal and Marine Resources Centre
DG ECHO	Directorate-General for European Civil Protection and Humanitarian Aid Operations
ECMWF	European Centre for Medium-Range Weather Forecasting
EEA	European Environment Agency
EFAS	European Flood Awareness System
EFI	Extreme Forecast Index
EM-DAT	Emergency Events Database
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
ERCC	European Emergency Response Coordination Centre
EU	European Union
Framework MEM	Framework for Major Emergency Management
GDACS	Global Disaster Alert Coordination Centre
HAREN	Hazard Assessment based on Rainfall European Nowcasts
HSE	Health Services Executive
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
MEM	Major Emergency Management
NAO	North Atlantic Oscillation
NAOI	North Atlantic Oscillation Index
NGO	Non-governmental organisation
NOAA	National Oceanic and Atmospheric Administration
OCHA	Office for the Coordination of Humanitarian Affairs
OEP	Office of Emergency Planning
OPW	Office of Public Works
PDO	Pacific Decadal Oscillation
PRA	Principal Response Agency
RSG	Regional Steering Group
RWG	Regional Working Group
SOT	Shift of Tails (index)
SWIC	Severe Weather Information Centre
UCC	University College Cork
UCD	University College Dublin
UN	United Nations
UNISDR	United Nations International Strategy for Disaster Reduction
WMO	World Meteorological Organization
WWIS	World Weather Information Service

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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WARNDIS Project Final Report: A Review of Climate Change-related Hazards and Natural Disaster Vulnerabilities and of Agencies Involved in Warning and Disaster Management

Authors: Michael Bruen and Mawuli Dzakpasu

Identifying Pressures

Climate change brings new threats and uncertainties but also opportunities. It challenges us to both mitigate the threats and gain from the opportunities. This project looked specifically at the threats from natural hazards. A large number of these, such as floods, droughts, landslides and wildfires will be more intense and more frequent in many areas as will the threats from disease and ecosystems changes. Planning to mitigate their impacts requires a good understanding of the vulnerabilities and the public perception of the risks in order to develop effective strategies. Warning systems are key elements of such strategies. This desk study assesses the information available on climate induced change in all these areas. It also held a workshop to which were invited representatives of the agencies involved in hazard warning, disaster preparedness and relief. One of questions asked of the participants was to identify other areas of natural hazards so that as wide a range of such pressures as possible could be considered.

Informing Policy

The project reviewed the warning systems already in place at Global, European and National levels. It pointed to some International warning and information systems that can readily be used in Ireland and gave examples of their outputs. In addition, at the project workshop, the participants were asked to suggest new sources of information that could be useful in emergency response. The suggestions are listed in the report and are a useful checklist to inform future policy in enhancing the systems dealing with natural hazard impacts. The suggestions included making better use of existing information but also included suggestions for new or enhanced (e.g. resolution) data sources.

Developing Solutions

The project identified the main types of natural hazards and summarised the international literature on the possible impacts of each and the projections of how climate change may influence these impacts. The project brought together representatives of many of the agencies involved in warning and disaster management in Ireland. This in itself should help in making each aware of the capabilities, roles and responsibilities of the others, and especially the role played by local authorities. The project identified sources of tools and information from European and International agencies that can readily be used in Ireland and it identified ways of enhancing the quality and use of data and information collected within Ireland and useful new data sources.

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