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Inland and coastal flooding: developments in prediction and prevention

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We review the scientific and engineering understanding of various types of inland and coastal flooding by considering the different causes and dynamic processes involved, especially in extreme events. Clear progress has been made in the accuracy of numerical modelling of meteorological causes of floods, hydraulics of flood water movement and coastal wind–wave-surge. Probabilistic estimates from ensemble predictions and the simultaneous use of several models are recent techniques in meteorological prediction that could be considered for hydraulic and oceanographic modelling. The contribution of remotely sensed data from aircraft and satellites is also considered. The need to compare and combine statistical and computational modelling methodologies for long range forecasts and extreme events is emphasized, because this has become possible with the aid of kilometre scale computations and network grid facilities to simulate and analyse time-series and extreme events. It is noted that despite the adverse effects of climatic trends on flooding, appropriate planning of rapidly growing urban areas could mitigate some of the worst effects. However, resources for flood prevention, including research, have to be considered in relation to those for other natural disasters. Policies have to be relevant to the differing geology, meteorology and cultures of the countries affected.

Keywords: flood prediction; weather forecasting; climate change; natural disasters

1. Introduction

Floods are the most serious type of natural disaster in most countries of the world, with an average of around 10 000 deaths per year (Rodda & Rodda 1999). It is likely that this number will increase as a result of global warming, increasing the severity and frequency of inland and coastal flooding. This trend is exacerbated by the majority of the world's population moving to large riparian and coastal conurbations, driven by two main economic factors, namely, the historical advantages of these locations for trade and the unstable tendency of large urban areas to grow at the expense of rural communities, which are becoming relatively depopulated (World Bank 2002).

Regrettably, the increasing number of natural disasters associated with flooding is likely to be exceeded in developed countries by the equally serious natural disaster of heat waves in urban areas, often associated with high levels of air pollution. Both flooding and heat waves will increase with the global

One contribution of 14 to a Theme 'The Big Flood: North Sea storm surge'.

environmental change caused by rising anthropogenic greenhouse gas emissions. Europe has been afflicted by serious flooding in the past 2 years (Hunt 2002; Wheater 2002), most notably in Germany in August 2002 when upwards of one hundred people drowned and there was considerable damage to property and infrastructure (Ulbrich *et al.* 2003). However, the recent heat waves in Europe and the USA had even greater catastrophic consequences, especially on elderly people, with in excess of approximately 20 000 deaths in Europe in the summer of 2003 and 1000 in USA in 1995 (Klinenberg 2003). Flooding events in other parts of the world, especially the effects of tropical cyclones and typhoons on coastal areas, are the main cause of the high number of flooding-related deaths worldwide. In the huge natural disaster in the Indian Ocean of 26 December 2004 drowning by flooding caused the deaths of nearly 150 000 people, following the impact of the Tsunami wave as it arrived at the coast and travelled inland (Hunt 2005).

It needs to be emphasized in the scientific community that governments have to focus on the most serious problems facing their nations, and that the prioritisation of serious problems can change rapidly. Therefore, it is advantageous to consider whether the scientific, engineering and organisational advances that deal with one kind of practical problem or natural disaster, such as flooding, can also be applied to other serious problems, such as the impact of heat-waves on communities (Tapsell *et al.* 2002). Also, the connections between types of disaster and environmental degradation need to be understood so that policies for reducing natural disasters are developed in relation to wider policies of sustainable development, such as those recently reviewed for coastal areas of Africa (ACOPS 2003). It is noted in this paper that the science and technology involved in the prediction of meteorologically related extremes and infrequent events is also being applied to natural disasters, including flooding and heat waves. Furthermore, many of the measures needed to warn and advise communities in advance of such disasters and to assist post-disaster relief are common to different types of disasters (Lee & Davis 1998), including those caused by human negligence or, even more typically, those caused deliberately. This 'joined-up' approach, which is advocated by social scientists (e.g. Parker 2004) who are studying these issues, is now increasingly adopted and understood by planning and environmental agencies as a means for improving their pre- and post-disaster arrangements. Of course there are particular technologies and practical arrangements, and, where appropriate, relating these to security arrangements (Home Office 2003) specific to each type of natural disaster, even those dominated by meteorological and hydrological phenomena, such as floods, droughts and heat waves. This brief paper reviews how advances in science and engineering are being applied to understand and reduce the damaging impacts of different types of flooding now and in the future, as climate change and population movement exacerbate these potential dangers. From estimates of the risks of different levels of damage, it is shown that forward planning decisions could be made by communities and government to mitigate climate change and its effects on flooding. Such decisions have had to be taken by communities in the past when threatened by changing environment or high risks of natural disaster. Whole towns had to be abandoned in the Middle Ages on England's east coast as the land sank below the sea. The Yorkshire coast where Henry Bolingbroke returned to depose Richard II '…upon the naked shore of Ravensburgh' (Henry IV, Pt I) no longer exists. This situation is predicted to recur during this century as the effective sea level rises by about 0.8 m (through global warming and geological subsidence), and higher wind generated waves combine to inundate coastal defences. The latest UK Government sponsored report (Evans *et al.* 2003) analyses such scenarios in some detail.

2. Different types of flooding events

Floods around the world can be seen to have two main causes, acting separately or in combination (a more detailed discussion of processes is given in §3):

(i) Inundation in fluvial inland areas results from such rapid precipitation in relation to the scale of the river basin or valley that the water cannot flow away, or from excess water flow that can be induced by melting, mudslides, or an unconstrained release of water from containing structures such as dams and river bands. The latter events are sometimes the result of structural collapse as a result of excess natural flow, for example, into a dam reservoir, or from non-hydrological causes, such as earthquakes, technological failure or sabotage. The relative likelihood of all these events has to be assessed carefully when considering the overall risks of flooding.

(ii) High winds combined with high tides raise the mean and fluctuating level of the sea (or lakes) so as to flood coastal (or lake shore) plains directly destroying coastal defences. These may be hard structures or ‘soft’ dunes and vegetated areas. Hard structures react with a brittle response either surviving the storm damage or being destroyed, whereas dunes and marshes respond more flexibly since their stores of sediment may be relocated and then returned to their former location provided engineering structures do not resist the process. However, in very severe storms, natural defences can be overwhelmed leading to substantial changes to coastlines even within one year, as occurred when tropical cyclones transformed the Outer Banks of North Carolina.

In principle, these two main types of flooding can occur at the same time or closely follow one another. If high precipitation over inland areas and rising river levels are followed by a coastal storm surge event then flooding in coastal areas could be twice as severe. Fortunately, in most extreme flooding events in temperate regions of the world, these two types of events have not occurred simultaneously. The meteorological conditions necessary for these two events very seldom coincide because the usual condition for inland flooding, namely intense precipitation over several hours to days in one region, is not usually associated with high winds. However, when inland flooding is caused by a heavy snowfall melting, high winds are more likely. The last time heavy snow melt caused flooding in England was 1946–1947 (Smith 1947). In the past 10 years, there have been huge inland floods in the USA in 1993 (which so saturated the ground that the weather was significantly affected), in Germany in 2002, in the UK in 1998 and 2001 and in Mozambique in 2001, with hundreds of people drowned and millions of dollars of damage (the floods in Mozambique had a substantial impact on the national economy), but the wind was quite low, so no storm surge occurred. A significant storm surge occurred on the coast of

Denmark in December 1999 but high winds were not accompanied by excessive precipitation. However, the east coast storm surge in 1953 did occur after several weeks of above average precipitation (see for example Baxter 2005) which weakened flood defences, raised water levels and made rescue work more difficult.

This is why predictions of flood risk require a good understanding of meteorological extremes and the probability of their joint occurrence. Traditionally, this has been a statistical exercise using past data, but in future, numerical weather prediction methods with increased resolution and computing capacity will be able to simulate the natural statistical distribution to integrate over long periods. Secondly, predictions of flood risk require computing the space–time pattern of floodwater from precipitation and wind distribution. Modern computer simulations are beginning to supplant empirical engineering rules, which more accurately reflect the land surface and river and coast forms (Fleming 2002; Falconer *et al.* 2002). Modelling is particularly valuable for predicting how water moves through and above the ground and in rivers, and for predicting how water breaks down dykes and river banks in extreme events. It is now possible to simulate these meteorological and hydrological processes to predict the effects of future climate change and flooding (see §3).

In the tropics, hurricanes, tropical cyclones or typhoons cause particular patterns of extreme flooding events along coasts and in adjoining inland areas. Typically, they are generated at latitudes less than 25° where the ocean temperatures are in excess of 26 °C. Strong typhoons can move as far north as Japan at 30–35°. First, as very high circulating winds of the order of 50 $\mathrm{m\,s^{-1}}$ or more move steadily over the ocean with the cyclone at speeds of the order of 5–10 $\mathrm{m\,s^{-1}}$ in a radius of 30–50 km, they generate substantial waves of 1–3 m ahead of the cyclone and then raise the water level along the coast in a surge of the order of 1 m. In large river deltas, such as those in Bangladesh, the surge can block the flow of the river and further add to the water level rise. As an intense tropical cyclone moves inland over a rougher surface the airflow converges and rises as it changes direction. Within 100 km of the coast the cyclones die out. Intense precipitation caused by this upward air motion can be so severe that inland flooding may occur over a large area, as happened in North Carolina in 2001. As Chan & Liang (2003) have recently pointed out, this precipitation builds up as the flow moves along the coast and can be a maximum where streamlines of the wind flow leave the coast.

The dangerous effects of inland flooding in mountainous areas, which can be greatly exacerbated by mud slides in steeply sloping hillsides, led the Hong Kong government to introduce a prediction warning system at the same time as strengthening the foundations of its buildings in the dense housing developments on the mountain sides. By contrast, in central America in 1998, Hurricane Mitch caused such flooding damage on hillsides that approximately 50 000 people drowned in the floods and the economic losses were, proportionately, more severe than any previous flooding event. It was estimated that 80% of the Gross National Product was destroyed in some of the smaller states, which are heavily reliant on agriculture. Regrettably, in that instance, warnings were not heeded by the local population. Had the local people taken more notice of warnings, there would have been fewer lives lost but the economic damage would still have been severe. This shows the importance of combining high technical levels of forecasts and warnings with sufficient political and social arrangements to ensure both their effective dissemination and their credibility (Lee & Davis 1998).

3. Prediction and warning of flood events

(*a*) *Short range quasi-deterministic forecasts*

Most quasi-deterministic systems for forecasting inland floods up to a few days ahead are currently based on (i) meteorological and hydrological numerical models derived from fundamental physical 'laws' (especially those determining the conservation of matter and energy) and (ii) empirical relations (e.g. for resistance along complex river systems). Increasingly, modelling is being primarily based on the first of these approaches (Falconer *et al.* 2002).

The level of accuracy of flooding predictions varies greatly, depending on the meteorological condition and the type of flooding event. Where the flooding is initiated by precipitation in large scale weather systems over scales of 300–1000 km, such as 'frontal rain' or tropical cyclones, the accuracy of prediction is comparable to that for atmospheric pressure and surface wind speed as defined by the errors ahead for 24 h of approximately 1 to 2 mb or $\pm 2\ \mathrm{m\ s^{-1}}$. These average errors are steadily reducing all over the globe at the rate of approximately 3–5% per year. This striking improvement in accuracy is not found for forecast periods beyond approximately 6 days, though statistically significant and partially useful forecasts (usually in certain conditions known in advance) are now possible for up to 10 days (e.g. Meteorological Office 2001), especially for pressure and wind distributions. Deterministic precipitation forecasts, which are very sensitive to the temperature in clouds, are only accurate over shorter time periods. This is why long range forecasts for storm surges and coastal flooding are available further 'ahead' than for precipitation and inland flooding. The errors in the locations of a moving frontal system or tropical cyclones are found to grow approximately linearly with the forecast period, so that for 24 h ahead the error lies between 110 and 140 km (it was 220 km in 1992), while for 72 h it is 330–480 km (Chan & Liang 2003). Some reasons, based on fluid dynamics of interaction of atmospheric vortices and of errors in the numerical models, have been proposed by Hunt (1999) and Orrell (2002).

The reason why weather forecasts have become more reliable is because of (i) greater computing capability (leading to spatial resolution for global numerical models at 30 km and reducing by about 1 to 2 km per year on average); (ii) reduced errors resulting from better physical modelling (e.g. ground, hydrological and meteorological) and numerical methods; and (iii) more effective use (using data assimilation methods) of the increasing volume of measurement data, especially from satellites. Since meteorological data from geostationary and polar orbiting satellites cover the whole world (every few hours), weather and flood forecasting in the Southern Hemisphere has the same level of accuracy as for the Northern Hemisphere (Hunt & Coates 2002). Despite this general progress, there are intrinsic reasons why significant errors in deterministic predictions of certain types of meteorological and geographical situations are inevitable.

The least predictable of these situations occur whenever the average state of the atmosphere is sufficiently unstable that large convective clouds and associated local winds can develop rapidly over a few hours, usually from perturbations on the mesoscale over distances less than 10 km. The reason for the unpredictability, especially of precipitation, in these large 'systems' or structures is that they are determined by the interaction and merger of intermediate scale structures. Since these systems tend to break up or to move round each other, this merger process generally has a much smaller chance of success than the downscale process in which eddies on intermediate scales produce smaller ones by the cascade process (Hunt & Vassilicos 2000). Consequently, the forecasts of these large-scale events, such as thunderstorms, have to be probabilistic. In future, such forecasts could possibly be improved by being based on estimates of the likelihood of such interaction events, and by more localized weather measurement systems on the space and time-scales of these events (see below).

In summer months, intense locally produced convection is a regular feature of weather in the higher latitudes (when forecasts are statistically worse than in winter). But such features are a daily feature of the tropics which is one reason why rainfall prediction there is much more difficult. It is because of the lower predictability of convective precipitation that there has been intense effort to improve real time monitoring of these events and link these to real time meteorological and hydrological models to provide very short range forecasts over a few hours (Collier 2002; Soul *et al.* 2002). This is possible in developed countries with the use of weather radar but not in most developing countries, despite their greater need to monitor more intense and damaging precipitation systems. Disappointingly, a system for measuring lightning (or 'sferics') remotely, which could be available at much less cost than weather radar, is not used in most developing countries, despite their greater need to monitor intense and damaging precipitation systems in cloudy conditions where they cannot be monitored with satellite imagery. Such an arrival time detection system has been demonstrated by the UK Meteorological Office for monitoring the Northern Hemisphere and the Tropics (Hall *et al.* 1992).

As the theoretical concepts and the approximations involved in producing numerically based operational forecasts in different meteorological and hydrological conditions become better understood, the magnitudes of their errors can be more accurately estimated and then minimized. One technique for estimating meteorological forecast errors is to compare the forecasts of forecast centres where different models are used (Palmer & Raisonen 2002). This has led to combining different forecasts to produce the most likely ensemble forecast and an estimate of the ensemble error. In most cases, the average of this ensemble is an improvement on the forecast made at only one centre. This 'multi-model' approach is not yet used for inland or coastal flood prediction. This could be carried out quite readily in Europe where flood surge forecast models are routinely operated by meteorological and hydrological services, of which there are more than 20 in total. In the UK, computationally based forecasts for coastal flooding began following the 1953 floods. Forecasts of river floods have only been integrated into a joint system with the weather forecasts in the UK since 1999. The current accuracy is such that predicted errors in water level at tidal stations along the coast are less than about 0.15 m (Huthnance 2000). In the view of Professor Stelling of Delft (private communication 2003), assumptions and calculation of flood prediction methods are sufficiently different that significant differences between different computational centres are common, although they have never been studied systematically. This is why multi-centre and multi-model flood forecasts could provide greater accuracy and confidence in flood warnings. However, in some topographic or meteorological situations systematic errors are likely to occur in all models, such that even the multi-centre approach might not help much. In the floods on the west Danish coast following the windstorms across Europe in December 1999, the errors were, in all probability, a result of the wind speeds very near the coasts being under-predicted (Rogers *et al.* 1998; Hunt *et al.* 2004). Coastal flooding occurred that had not been forecast (E. Buch, private communication 2001).

Turning now to the hydrological and oceanographical element of flooding events, the understanding of, and prediction accuracy for most types of flooding events is similarly improving. As with weather forecasting, this is increasingly based on the computation of numerical models of fluid flows (Falconer *et al.* 2002). For inland or fluvial flooding, one of the greatest sources of error is calculating the movement of flood water after it has risen out of the main water courses, across fields and through areas of building. Quite small changes in land use (e.g. a few houses or embankments) make large differences to the slope and effective friction coefficient (which is usually averaged over a few kilometres) and to the other physical parameters that govern the water movement. Furthermore, these boundary conditions for the mathematical models can suddenly change during the flood event, as occurs when a river breaks its banks or dykes and other protective structures are breached. (By analogy, the accuracy of numerical weather prediction would suffer if similar uncertainties in boundary conditions occurred; these would correspond to a situation where the heights of mountains vary from one year to the next by an uncertain amount and where their slopes suddenly change in severe storms!) In modern computer models graphical display outputs are mapped onto geographical information systems. These display predictions for different flooding scenarios in such a way that planners, engineers and communities can readily comprehend them and, where possible, make necessary provisions for reducing future flooding damage. Improved observation of surface elevation is contributing to improved accuracy of flood movement predictions through regularly updated data of surface land form, obtained by remote sensing from aircraft and altimetry data from satellites of water levels in large rivers (up to a few days ahead for a large flood moving down a river catchment area). By comparison, there are no standardized national or international methods to monitor improvements in the accuracy of river flood forecasts in weather forecasts and extend the period for which forecasts are provided. Since both types of forecast are the responsibility of the World Meteorological Organization, one might expect greater uniformity in reviewing progress. Forecasts issued in the UK and Europe for floods moving along rivers are often provided from 3 to 5 days ahead, giving predicted levels to an accuracy of approximately 0.2 m.

For the calculation of coastal flooding caused by storm surge, there are similar uncertainties about changing surface boundary conditions and boundary processes. The movement of surge currents and waves are equally susceptible to changes in bottom elevation (i.e. bathymetry) and to resistance caused by bottom undulation, vegetation and human or natural structures such as wind energy platforms or coral reefs (Sheremet & Stone 2003). In fact, the highly variable responses of bottom sediments to waves and currents greatly affects the erosion of shorelines and, thence, the viability of natural defences, especially when the sediments are made up of very small particles which do not readily coalesce (Purnell, private communication 2000). Remote sensing is contributing to the monitoring of these coastal changes. However, as with inland surfaces, the satellite data (for example, microwave reflection and absorption) can only be used to derive the required subsurface properties of the ground or sea bottom with the aid of both refined data analysis and complex calculation of physical processes in the air, water and ground. In polar regions, the variation of ice thickness, which affects sea level and the amplitude of coastal waves, is derived from laser and radar measurements of the relative levels of ice and water, that is, 'satellite altimetry' (e.g. Laxon *et al.* 2003). In coastal waters, not only do the amplitudes of undulations of the sea bottom vary as much as 30% of the depth but these amplitudes have been observed to vary by as much as 20% per year. Microwave probing from satellites of the variation of small surface waves over the undulations provides a reliable method for detecting these changes in the sea bottom when depths are less than approximately 30 m (Argoss 2003). Further research into the structure of waves and currents over bottom undulations may well extend this technique to deeper water.

To improve the accuracy of the predictions for extreme coastal flooding events, especially in the future as conditions change, better models are needed for the combined effects of coastal waves and the tidal surge (Wolf *et al.* 1988). Both are driven by the wind and, therefore, their forecasts are sensitive to the accuracy of prediction of the sharp spatial variations of wind speed that occur in the coastal zone over 1–10 km. These are caused by the effects of Coriolis and buoyancy forces in the stably stratified atmosphere and by changes in the surface frictional drag as the boundary-layer flows over the changing roughness of the land and sea surfaces (Rogers *et al.* 1998). Because the limited resolution of mesoscale meteorological models used operationally is currently as large as 12 km, this can lead to errors in coastal winds of 15% (Capon 2003; Hunt *et al.* 2004; Orr *et al.* 2005). This could cause approximately 30% errors in predictions of wave heights (which vary approximately with the square of the wind speed). Despite these systematic errors, and some uncertainties in bottom and shoreline boundary conditions, the models for tidal surge and coastal currents (that also depend on Coriolis forces) are more accurate than wind forecasts for typical conditions, probably because they average the effects of both the wind stress and the changed boundary and bottom conditions over a wide area (Gill 1980).

Informal 'soundings' of modelling centres in the UK, Netherlands and Denmark indicate that there may not be much variation in the prediction of coastal wind-surge at different hydraulic modelling centres. However, greater errors and variability in predictions occur in extreme conditions when flooding occurs over flat coastal areas and coastal defences (Heiselink *et al.* 2003). Then, the flood water movement is sensitive to the wind stress distribution and vice versa. Here, the coupling of hydraulic and meteorological models within a few metres of the air–water surface needs close examination and further studies, especially in the presence of significant waves (greater than 1 m; Stelling, private communication 2003).

The forms and statistical distribution of coastal waves have not yet been systematically described or completely understood theoretically. Although the heights of waves increase as they move into shallow coastal waters, this mechanism is limited by complex nonlinear and dissipative dynamical interactions between the waves (Peregrine 1983). Their orientation is also changed by mean currents generated by coastal winds and nonlinear distortions of the waves. Wave energy can be directed towards focal points where large amplitude waves are most likely. Along with large currents and high water levels, large waves can break or even destroy flood defences, in which case the shoreline boundary conditions for the current and waves substantially changes. Recent research on nonlinear wave dynamics, including interactions with shorelines, was presented at the Isaac Newton Institute programme on Surface Waves in 2001 (Hunt 2002; Sajaadi & Hunt 2003). A striking conclusion was that although it is now feasible to compute nonlinear wave interactions directly in a 'numerical wave tank', the computational time is so large (even compared with that required for computing an equivalent number of modes in three-dimensional turbulence) that it is not possible in practice to use these direct numerical methods for coastal wave predictions. Instead, following Hasselmann (1962), computational models have been developed that provide a statistical approximate to the weakly nonlinear, dissipative and wind–wave generation processes. However, although these models have been adapted to apply to coasts (Battjes & Gerritsen 2002) they have deficiencies, especially in predicting extreme events involving large waves and storm surges.

Currently, the statistics of extreme values of coastal sea level caused by the combined action of storm-surge and high waves are derived empirically, rather than combining dynamical models of these two processes. This is a serious challenge to those who believe that, in a changing environment, rational methods should be preferred because they are more soundly based than statistical methods based on previous experiences.

(*b*) *Prediction of flooding events over seasonal to climate time-scales*

Over periods greater than the natural time-scale of large scale weather systems, say 10 days in the temperate latitudes, any prediction of the occurrence of weather and flood variables can only be provided in statistical terms as a probability over a defined period (greater than 10 days). In other words, over such long periods, predictions cannot be time specific because the interactions of the atmospheric processes are too sensitive to calculate on which day or days, say one month ahead, the high winds or precipitation or flooding will occur in any given location. (There is a controversial minority view, for example, expressed by Dr Piers Corbyn, that these events are so strongly affected by the variability of emissions of particles from the sun, which have a much longer time-scale than the Earth's weather systems, that the timing of significant weather events is predictable. Although the influence of solar variability on climate over decades is recognized (Stott *et al.* 2000), there is no statistical evidence for its influence on these shorter time-scales on the order of weeks and months.)

There are three main methods for determining such probabilistic predictions: based on statistical analysis of previous and present data, based on computation of numerical weather and flood models initiated with present and previous data and computations of both approaches. Attempts have been made with limited success by stake-holder organisations, such as environmental agencies, research funding bodies and insurance research groups, to encourage researchers from the statistical and computational modelling 'communities' to compare, select or systematically combine the most appropriate methods for different types of prediction. The increasing availability of very large computers, many connected in grid networks, suggests that statistical concepts could be tested rigorously using the vastly increased data emerging from these simulations.

The power of statistical analyses lies in their use of methods that are general to many types of natural phenomena, including weather, climate and flood (Cox *et al.* 2002), thereby providing greater confidence in their application to new situations. The insights from these methods could, perhaps, be enriched by greater use of concepts that have been developed in statistical mechanics, such as those of chaos, self-organized systems and fractal distributions (Bak 1996). Although advances in theoretical and computational fluid dynamics have aided short-term weather and flood predictions, as discussed in §3*a*, the analysis of floods has generally been statistical. Indeed, the study of floods led to some of the basic statistical concepts of extreme events including that of the 'return period', the average time-interval between the recurrence of extreme events greater than a given magnitude. The statistical methodology led to the discovery of certain general relations valid for most river systems, giving rise to practical guidance for assessing risk and designing flood defences. This method has limitations, especially under variable conditions where the physical nature (e.g. built structures) of river systems and the climate are changing (Fleming 2002).

Furthermore, recent research on the statistics of extreme values (for physical and non-physical random variables including finance) has shown that significantly different estimates of the 'return period' or probability for extreme values are derived from the data, depending on the range of data used to construct the empirical probability distributions. In particular, by focusing mainly on the extreme value data, a more reliable (and often more alarming) estimate of further extreme events is derived. (For a thorough mathematical account see Embrechts *et al.* 1997; for an illustrative model problem see appendix A). Clearly, this changing approach to statistics of extreme value requires further testing before its widespread adoption in practice. For example, the predictions of the 3-month probability of extreme weather, including floods, drought and tropical cyclones, are provided for different parts of the world and different seasons using all these techniques. Such predictions are based on statistical correlations conditioned on current and previous data (e.g. of ocean temperatures; Colman 1997). These are now compared, or used simultaneously, with those derived from computations of numerical weather for climate prediction models, using current climate variables as inputs. In both types of prediction, confidence levels and probable levels of error are generally provided; in the former method by assessing the magnitude of the various statistical indicators and in the latter by undertaking an 'ensemble' of numerical predictions for a range of initial conditions, deliberately chosen to maximize the spread in the resulting predictions (Palmer 2001). When the two types of prediction coincide there is some confidence in the reliability of the result and, where appropriate, practical remedial measures can be taken. But when they differ, only one of the methods (for, say, one particular model) indicates the possibility of an extreme climate event. This information is (or should be) disseminated, and the responsible organization can then assess the possible high impact of the low probability event.

If the possible impact is serious enough, precautions need to be taken. Most recently, the extreme heat in northwest Europe in August 2003 was predicted by a statistical correlation method of Colman (1997) in June 2003 (ECMWF 2003*a*,*b*; Meteorological Office 2003), but it was not predicted over this period by the seasonal forecasts derived from numerical models. Finding systematic methods for dealing with such divergences in prediction is an urgent need in many fields of risk.

Different methods are taken around the world for predicting extreme weather events on the seasonal time-scale. For severe winter storms with possible inland and coastal flooding in northwest Europe, summer temperatures and (with much less confidence) precipitation in Europe, monsoon strength and timing in India (Kumar *et al.* 1995) and frequency and strength of tropical cyclones in the west Atlantic and northwest Pacific, statistical methods are widely disseminated (e.g. Colman 1997; Saunders & Qian 2002; Chan & Liang 2003) and are generally, at this time, more reliable than deterministic climate and seasonal models. However, in March 2004, the first tropical cyclone was observed in the South Atlantic (Meteorological Office 2004), which was consistent with the prediction of climate models that such events could occur in the future as a result of warmer oceans.

For seasonal weather predictions over northeast Brazil and the Sahel in Africa, the two methods now have comparable accuracy whereas until about 1997 statistical methods were clearly superior. In a review of the predictions of the very strong El Niño event in 1998, *Science* magazine concluded (Kerr 1998) that, for the first time, the global scale numerical climate and weather models were more accurate than any statistical or simpler models in predicting the timing and magnitude of this event, which had a global impact on weather in a way that previous weaker events had not. However, there are other regularly occurring cycles in the ocean-atmosphere system that are well observed experimentally but are still not predicted or simulated in complex global climate numerical models; for example, the North Atlantic Oscillation affects storm winds in the northeast Atlantic region on a biennial to decadal time-scale, while the Quasi-Biennial and other oscillations in the lower stratosphere (Baldwin & Dunderton 2001) couples ozone variability, depth of the tropopause and precipitation patterns on similar time-scales, especially in East Asia. Although mathematical models have been developed with specific features that simulate these oscillations, the general objective is that they should be accurately modelled by global circulation models. It has been suggested that this requires the smaller scale resolution new numerical method and massive computer resources now being developed on the Japanese Earth Simulator (Nikiforekis 2005).

Despite these limitations, international research has made great progress in the numerical simulation and prediction of climate change, especially the broad spatial and temporal trends of temperature. For example, the non-monotonic observed increase in global average temperature over the past 150 years followed by the marked rate of increase in the past 50 years, have been well simulated once the effects of volcanic eruptions and solar variability were included (Stott *et al.* 2002). The predicted spatial variations are also well verified with much greater relative warming in polar regions. The predicted increase in average winter rainfall and more intermittent but intense summer rainfall in the UK has been verified to some extent by observation (Osborn & Hulme 2002; Senior *et al.* 2002). However, data on extreme floods in central Europe in a major river system does not indicate the long-term trend that would be expected from climate change prediction (Mudelsee *et al.* 2003).

There are strong physical reasons for expecting this trend to be established as the troposphere warms and deepens as the stratosphere is cooled (because outgoing radiation is trapped by greenhouse gases). This would be consistent with the East Asian seasonal correlation of precipitation with the height of the tropopause. The predicted spatial variability in the trend of rainfall in the UK has not been so consistent (with the east–west trend of increased rain being the reverse of that predicted). It is likely that, as the vertical and horizontal resolution of climate models improves with growing computer capacity, the crucial mixing and condensation processes in clouds and surface and subsurface fluxes will be more accurately simulated.

Since climate models are primarily designed for average, rather than extreme, conditions, prediction of how climate change will affect flooding requires a focus on extreme events. One way is simply to undertake numerical simulations (Flather & Smith 1998); the other is to assume that the relation between extremes and average conditions is similar to that in the present climate, for example, the number and distribution of tropical cyclones or wave-surge height in relation to average values. There is some evidence that the waves are increasing more rapidly in height than average or peak wind speeds. The other way is to examine such extreme events in more detail in a changed climate, for example, if the oceans are warmer and coastal waters are deeper. This may affect the currents and the movement of bottom sediment in coastal water, with marked effects on coastal flooding. Although the primary climate change predictions are the estimates for anthropogenically induced increases in greenhouse gases from industry, transport, housing and agriculture, an equally crucial element in predicting long-term trends in flooding over the next 10–100 years is the large changes to the land form and urban areas that will take place. It is predicted that over 70% of the world's population will be living in urban areas by 2100 (United Nations 2002). As these areas grow in size they will greatly affect the climate, surface run off and the effects of coasts on currents and waves (Hunt 2004).

Although the former change is now almost inevitable, the latter changes depend more on the type of economic and political development of the developing countries where the largest changes will occur. Will these urban areas be densely populated as in Japan and Europe, or with much lower population densities and greater use of automobiles as in North America? Their environmental impact, including energy use and greenhouse gas emissions, will be much less in the former case, therefore reducing the potential impact on the global climate, climate change or flooding. Perhaps future climate change predictions should, as their confidence levels rise, focus not only on the greater dangers of flooding but also demonstrate how these dangers could be reduced with intelligent planning and administration of the world's burgeoning urban areas. Although these connections are becoming clearer to politicians, further scientific and engineering studies are needed to enable politicians and communities to establish sustainable policies for the future.

4. Technological and administrative developments

It is also essential that technology and administrative arrangements are directed towards reducing, as well as predicting, the impact of flooding, as indeed the Office of Science & Technology in the UK have recognized in their Foresight Project (Evans *et al.* 2003).

Because of the variations in geology, meteorology, hydrology and culture in different localities and different countries, quite different concepts, policies and practical arrangements are being tested to deal with increasing changes of fluvial and coastal flooding. In the Netherlands, the state passed a law that no land would be lost as a result of sea level rises, whereas in the UK, pragmatic decisions have had to made in which some areas are 'defended' and others are allowed to erode or be submerged. This marked divergence in policy is based on both cultural and scientific factors. It is possible to defend Dutch beaches by dredging the offshore and raising dykes—'replenishment'—but this is not possible along the low lying eastern shore of England because of the low cohesiveness of the muddy sediment (R. Purnell, private communication 2000). Hard defences or managed retreat appear to be the only options. One could say that on England's eastern coast we have the 'wrong sort of mud'—a result of the ice sheets which 8000 yrs bcp reached southern England, but not the continent (Hawkes 1959).

Since so many buildings in all countries of the world are located in areas prone to flooding and coastal inundation, it is necessary to apply and develop engineering solutions that can protect certain buildings and communities, or at least mitigate the effects of floodwater passing through buildings. Temporary water barriers, well known on the continent of Europe, are now being used along rivers in the UK. There is plenty of scope for ingenious designs to assist individual properties but their widespread use has to be carefully considered because they greatly affect the movement of flood water and may adversely affect other areas. This is why 'privatized' or individual solutions will not be generally acceptable. Predictive flood modelling is useful here too. The structure of housing or of refuges in these areas has to allow for flooding. In some riparian villages in China, where the ground floor is regularly flooded, the buildings are suitably constructed and there are well-established procedures for moving people and their possessions upstairs (as I observed on a visit to Guanzhou in 1996). A more extreme solution for exceptional floods is to construct refuges for whole communities where they will be above the flood water level. In Bangladesh these are regularly used following tropical cyclones. In Canvey Island, Essex, the elevated refuge constructed following the loss of life in the 1953 coastal floods has never had to be used. However, their local government representatives reminded the Royal Society meeting in May 2003 that this refuge is well maintained and, just as importantly, everyone knows about it. The use of refuges illustrates a critical point for all natural disasters: information should be of the highest quality and always based on the latest techniques. Technology, and the wide involvement of society, are both necessary for planning and warning over days to decades to reduce the vulnerability of communities and to ensure the most effective rescue and remedial measures following any flood event (Parker 2004).

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Appendix A

Here is a simple explanation of the new approach for improved estimations of the probability distribution of extremes by focusing on the extreme data only. I believe this simple example of flooding from rain illustrates the point.

Consider the volume of rain falling per unit area per unit time ($r \times m\,\mathrm{s}^{-1}$) as a result of a large rain cell containing a volume of water Q whose height is h and width is w. The cell empties itself over a time T (typically h/V_T, ca. 3 h, where V_T is the fall speed of droplets) while travelling at wind speed U.

Then,

$$r = Q/UT^2w = k/U, \tag{A 1}$$

where k is a coefficient that does not vary greatly with U.

Therefore, the probability distribution of r is related to the PDF of U by

$$p_r(r) = P_u(U(r))\left|\frac{\mathrm{d}U}{\mathrm{d}r}\right|. \tag{A 2}$$

Suppose U is Gaussian (a reasonable approximation for hourly wind speeds), i.e.

$$p_u(U) = \frac{\mathrm{e}^{-(U-\bar{U})^2/2\sigma_u^2}}{\lambda\sigma_u}, \quad U > 0, \tag{A 3}$$

where λ is a normalizing coefficient.

Since from (A 1) $\mathrm{d}U/\mathrm{d}r = -k/r^2$, then from (A 2), (A 3)

$$p_r(r) = \frac{\mathrm{e}^{-(k/r-\bar{U})^2/2\sigma_u^2}}{\lambda\sigma_u}\frac{k}{r^2}, \quad r > 0.$$

This shows that:

- (i) $p_r(r)$ has two quite different forms. For large r (or small U) $p_r(r) \propto 1/r^2$, while for typical values $p_r(r)$ has the same Gaussian form as $p_u(U)$ and,
- (ii) If data was used to estimate $p_r(r)$ it would be essential to use large values of r to derive the correct form over the extreme range where $p_r \propto r^{-2}$. Using data that is based over the whole distribution might well lead to an estimate of a Gaussian type distribution for $P_r(r)$.

In general, this model shows how, in complex nonlinear systems, an assumed (e.g. Gaussian) input (here U) can tend to a quite different (e.g. non-Gaussian) output (here r), and that the PDF of the extremes may be dominated as much by the differential relation between the variables ($\mathrm{d}U/\mathrm{d}r$ in this case) as by the extremes of the PDF of the input. This is a strong ‘deterministic’ argument for (i) looking at the extreme data and (ii) attempting to understand how the PDF of extremes of a variable might be caused by some deterministic connection between the variable and some other random forcing function. (A similar argument applies to the PDF of insurance costs, for example, of major windstorm storms on an urban area. This deterministic approach could help the search for the best fit to the data.)

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