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Floods in the IPCC TAR perspective ⋆

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Abstract. Recent floods have become more abundant and more destructive than ever in many regions of the globe. Destructive floods observed in the 1990s all over the world have led to record-high material damage, with total losses exceeding one billion US dollars in each of two dozen events. The immediate question emerges as to the extent to which a sensible rise in flood hazard and vulnerability can be linked to climate variability and change. Links between climate change and floods have found extensive coverage in the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC). Since the material on floods is scattered over many places of two large volumes of the TAR, the present contribution - a guided tour to floods in the IPCC TAR – may help a reader notice the different angles from which floods were considered in the IPCC report. As the water-holding capacity of the atmosphere grows with temperature, the potential for intensive precipitation also increases. Higher and more intense precipitation has been already observed and this trend is expected to increase in the future, warmer world. This is a sufficient condition for flood hazard to increase. Yet there are also other, non-climatic, factors exacerbating flood hazard. According to the IPCC TAR, the analysis of extreme events in both observations and coupled models is underdeveloped. It is interesting that the perception of floods in different parts of the TAR is largely different. Large uncertainty is emphasized in the parts dealing with the science of climate change, but in the impact chapters, referring to sectors and regions, growth in flood risk is taken for granted. Floods have been identified on short lists of key regional concerns.

Key words: extreme events, floods, flood hazard, perception of floods, vulnerability, climate change, climate change impacts, regional impacts, IPCC TAR

⋆ IPCC stands for Intergovernmental Panel on Climate Change and TAR for the Third Assessment Report on Climate Change. Professor Zbigniew W. Kundzewicz was involved in the IPCC TAR process in the capacities of: Co-ordinating Lead Author of Chapter 13 (Europe) of the IPCC Working Group II Report (Impacts, Adaptation and Vulnerability), contributor to the Technical Summary and Summary for Policymakers of the IPCC WG II TAR, and member of the Core Writing Team of the IPCC TAR Synthesis Report. Professor Hans-Joachim Schellnhuber was Co-ordinating Lead Author of Chapter 19 (Vulnerability to climate change and reasons for concern: A Synthesis) of the IPCC Working Group II Report, and contributor to the Technical Summary and Summary for Policymakers of the IPCC WG II TAR

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1. Introduction

Flooding, i.e., the destructive abundance of water (be it freshwater or sea water), has been a major concern of people populating the vicinity of rivers and water bodies since pre-historic times. Despite the fascinating developments in many areas of science and technology during the last decades, the hazard of flooding has not been eradicated. In fact, recent floods seem to be more abundant and destructive in many regions of the globe. According to the Red Cross (IFRCRCS, 1997), in 25 years (1971–1995), floods killed 318 thousand people worldwide and made over 81 million homeless, affecting in total more than 1.5 billion people. Berz (2001) examined inter-decadal variability of great flood disasters (understood as such events where the ability of the region to help itself is distinctly overtaxed, making international or inter-regional assistance necessary) in the period 1950–1998. Based on the data presented by him, one concludes that the number of great flood disasters worldwide has grown considerably over recent decades (six cases in the 1950s, seven in the 1960s, eight in the 1970s, 18 in the 1980s, and 26 in the 1990s). That is, the number of great flood disasters in the nine years 1990-1998 was higher than in the three-and-half decades 1950-1985, together (Kundzewicz, 2002).

Destructive floods observed in the 1990s all over the world have led to record-high material damage. In each of eight highly disastrous floods during the last decade of the twentieth century, the number of fatalities exceeded a thousand, and in each of two dozen events the total losses were in excess of one billion US dollars. The most fatal event was the storm surge in Bangladesh in April 1991, causing 140 000 fatalities (Munich Re, 1997), and the most costly were the floods in China in summer 1998 when material losses exceeded 30 billion dollars (Kundzewicz and Takeuchi, 1999). Catastrophic floods visit also areas, which have been free of major natural disasters for a long time, such as the catchment of the river Odra (Kundzewicz et al., 1999). In the last years of the 20th century, destructive deluges happened in many places, such as Mozambique, the Mekong drainage basin, Algeria, and several countries in Europe, to give just a few examples. This trend has continued in the 21st century, with extreme floods devastating large areas of China, Germany, Austria, Czech Republic, and other countries in summer 2002. The flood damage recorded in the European continent in 2002 is higher than in any single year before. A map in Figure 1 shows countries, where at least one destructive flood, including storm surge, has occurred since 1990. Figure 1 indicates that flood danger is indeed a serious problem in many countries of the world.

The immediate question emerges as to the extent in which a sensible rise of flood hazard and vulnerability can be linked to climate variability and change. This thematic area has found extensive coverage in the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC, 2001, 2001a). The objective of the IPCC, a truly international body where developed countries, developing countries, and countries in transition are represented, is to assess the

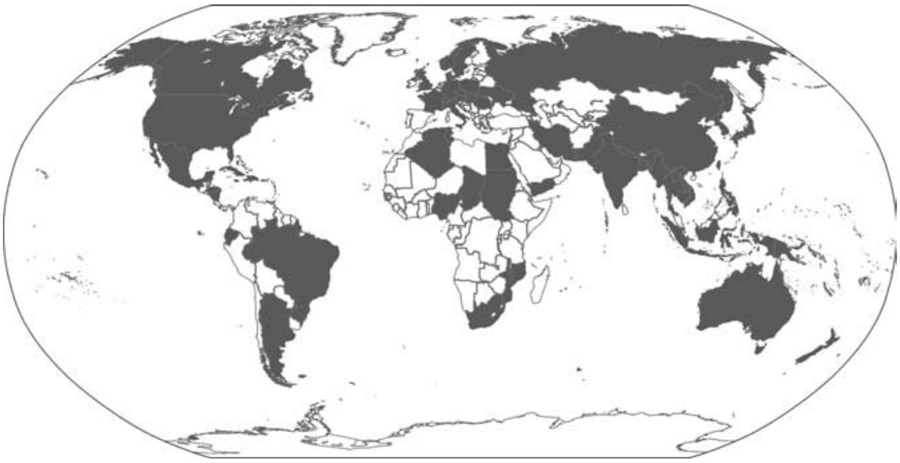

Figure 1. Countries where at least one destructive flood event (including storm surges) has occurred since 1990.

available information on climate change and its impacts. The two first volumes of the IPCC TAR refer to the scientific basis of the climate change (IPCC, 2001) and the impacts, adaptations and vulnerabilities (IPCC, 2001a). Since the material on floods is scattered throughout these two large volumes of the TAR (nearly two thousand pages together), the present contribution – a guided tour to floods in the IPCC TAR – may help a reader notice the different angles from which floods were considered in the IPCC report.

As the atmosphere's water holding capacity, and thus its absolute potential water content, increases with temperature, the possibility of intensive precipitation also increases. Higher and more intense precipitation has been already observed and this trend is expected to increase in a future, warmer world. This is a sufficient condition, *caeteris paribus*, for an increase in flood hazard. Yet there are also other, non-climatic, factors exacerbating flood hazard. Among them are land-use changes, leading to reduction in the storage volume and increase in the runoff coefficient, that is, to growth in amplitude and reduction of the time-to-peak of a flood triggered by a "typical" intense precipitation (as indicated earlier, the nature of a "typical" intense precipitation event has also changed due to climatic reasons, becoming more intense). Humans have been driven to occupy unsafe areas (e.g., informal settlements on flood plains around mega-cities in the developing world), thereby increasing the loss potential. Growing wealth has accumulated in flood-endangered areas. For instance, in Japan half the total population and about 70% of the total assets are located on flood plains, which cover only about 10% of the land surface. An important factor influencing the flood hazard is an unjustified belief in absolute safety of structural defenses. Even an over-dimensioned and perfectly maintained dike does not guarantee complete protection, as it can be overtopped when an extreme flood occurs. Further, a short memory syndrome can be observed – nations and decision makers gradually keep forgetting about the investments necessary for flood-preparedness systems, so that the solidarity and dedication, plentiful during a deluge and immediately after it, may already fade away a few years after a disaster.

2. Floods in a Holistic Perspective

Taking a holistic perspective on river and coastal floods, one can envisage the following scheme of inter-related blocks within the global super-system, whose characteristics can explain different aspects of floods:

(i) climate and atmospheric systems
(ii) terrestrial systems (hydrological systems and ecosystems)
(iii) economic and social systems.

IPCC TAR reports on flood-related changes in different variables pertinent to the items (i)–(iii) above. Some of the changes have already been observed and are expected to be more pronounced in the future. Other changes, which have not been observed yet, are expected to occur in the future. Among the variables and notions in question are changes in re (i):

- total precipitation;
- intense precipitation events;
- wind intensity;
- seasonal distribution and climate variability (e.g., ENSO);
- sea level;

re (ii):

- river discharge and stage (amplitude, frequency statistics, seasonality);
- water storage capacity (e.g., decrease caused by land-use change, e.g., deforestation, urbanization, elimination of flood plains and wetlands);
- runoff coefficient and infiltration capacity, portion of impervious area (e.g., changes caused by urbanization);
- impacts on ecosystems;

re (iii):

- anthropogenic pressure (population growth, urbanization, deforestation, channelization, and human occupation of non-safe areas, especially squatter settlements) causing changes listed in (ii);
- adaptive capacity;
- vulnerability;
- measures of flood losses (number of fatalities; number of evacuees; total material damage; insured losses; losses in cultural heritage; further specification of losses, e.g., destroyed infrastructure, buildings, industrial plants, railways, bridges, roads, dikes, etc.; inundated area; therein agricultural land, crop loss);
- risk perception.

It would be enlightening to study longer time series of records pertaining to the variables above. But this is possible only to a limited extent. Long time series are available only for a few of the variables from the list given above, and then only for a limited numbers of locations.

Studies of changes in flood data are of considerable theoretical and practical importance. They help us to understand the changes of the “natural” world. Flood protection systems have been designed and are operated on the basis of the assumption that hydrological processes relating to river stage or discharge are stationary. If this assumption is incorrect then the existing design procedures for embankments, dams, reservoirs, relief channels, polders, etc. will have to be revised. Without revision, the flood protection systems can be under- or over-designed and are either not serving their purpose adequately or are overly costly (e.g., with large safety margin).

However, the very issue of detecting a climate change signature in river flow data is complex. Increasing concentrations of greenhouse gases in the atmosphere cause global temperature rise, and, in consequence, enhance evapotranspiration and precipitation in most areas, accelerating the hydrological cycle. Runoff is the difference between precipitation and evapotranspiration, so the net effect on their difference is not intuitively clear.

Apart from the inherent complexity of the issue of detecting a greenhouse component in flow records, there are serious problems with the data with which to work, and also with the methodology to detect changes. Data should consist of long time series of good quality records. They are not available in many areas. Due to financial constraints, several countries have been reducing their observation networks. Even if data are collected, they may not be readily available for international research studies. Because of strong climate variability, records of less than 30 years are almost certainly too short for detection of climate change. It is suggested that at least 50 years of records are necessary for climate change detection (Kundzewicz and Robson, 2000), but in the case of strong natural variability even this may not be sufficient (cf. Chiew and McMahon, 1993).

There are further problems related to the data, one of which is non-homogeneity: baseline conditions are rare, and human influence is typically strong (river regulation, deforestation, urbanization, dams and reservoirs). In order to detect a weak, if any, climate change component in the process of river flow, it is necessary to eliminate other influences and use data from pristine (baseline) river basins. Possible further sources of heterogeneity (e.g., due to changes in instruments, observation techniques, and rating curves, i.e., stage-discharge relationships) should also be identified and dealt with. A great deal of uncertainty results from the need for extrapolation of rating curves to high values, where no direct flow measurements exist. Missing values and gaps are further complicating factors.

But, even if the data are perfect, it is worthwhile to re-state a tautology: *extreme events are rare*. They do not happen frequently, so even where a very long time series of instrumental records exists, one still deals with a small sample of truly extreme floods, of most destructive power (cf. Kundzewicz and Robson, 2000).

This dilemma may only be resolved by deriving the correct probability density functions for disastrous events from first geophysical principles. The self-organized criticality approach may be helpful in this context (see, e.g., Andrade *et al.*, 1998).

The consequences of floods may be felt in many sectors. Therefore, the issue of floods pervades several chapters in the IPCC TAR, both chapters referring to sectors (e.g., devoted to climate, water, impacts on different sectors) and to regions. Impacts of floods tackled in the IPCC TAR refer to such diverse items as agriculture, ecosystems, water supply, health, transport, settlements, insurance and financial services, mountain areas, and coastal areas. The consequences of flooding are mostly adverse, with the exceptions of benefits to some riparian ecosystems and the recharging of aquifers.

3. What Changes have been Observed?

According to IPCC, the increase in global land precipitation over the 20th century (about 2%) was statistically significant (IPCC; 2001, p. 142), but neither spatially nor temporally uniform. Precipitation increase was of the order of 7–12% for the zones 30 °N to 85 °N and about 2% for zones 0 °S–55 °S. Precipitation has increased (2.4% per century) over tropical land areas (p. 103). Over the 20th century, statistically significant increases have been found at the national level, e.g., in the USA, Canada, and Argentina. Instrumental records of land-surface precipitation continue to show an increase of 0.5 to 1 % per decade in much of the Northern Hemisphere mid- and high latitudes. A marked increase in precipitation has been observed in the latter part of the 20th century over Northern Europe (IPCC, 2001, p. 143) and Western Russia. A general increase in precipitation in the Northern Hemisphere mid- and high latitudes is particularly pronounced in autumn and winter (IPCC, 2001a, p. 197).

It is very likely "that in regions where total precipitation has increased ... there have been even more pronounced increases in heavy and extreme precipitation events. The converse is also true". Moreover, increases in "heavy and extreme precipitation" have also been documented in some regions where the total precipitation has decreased or remained constant. That is, the number of days with precipitation may have decreased more strongly than the total precipitation volume. As stated in IPCC (2001, p. 104), changes in the frequency of heavy precipitation events can arise from several causes, e.g., changes in atmospheric moisture or circulation. Over the latter half of the 20th century it is likely that there has been a 2 to 4% increase in the frequency of heavy precipitation events reported by the available observing stations in the mid- and high latitudes of the Northern Hemisphere.

The area affected by most intense daily rainfall is increasing, and widely distributed parts of the mid- and high latitudes have locally significant increases in both the proportion of mean annual total precipitation in the upper five percentiles and in the annual maximum consecutive five-day precipitation total. The latter statistics increases significantly for the global data; in 1961–1990, a 4% increase in the annual maximum five-day precipitation total was noted (IPCC, 2001, p. 158). The number of stations reflecting a locally significant increase in the proportion of total annual precipitation occurring in the upper five percentiles of daily precipitation totals outweighs the number of stations with significantly decreasing trends by more than 3 to 1 (IPCC, 2001, p. 159).

There is evidence that the frequency of extreme rainfall has increased in the USA and in the UK (IPCC, 2001a, p. 197) and a greater proportion of precipitation is currently falling in large events than in earlier decades. As stated in IPCC (2001a, p. 596), Australian annual mean rainfall has increased by a marginally significant amount over the last century. However, increases in heavy rainfalls have been observed over many parts of Australia. There has been a 10 to 45% increase in heavy rainfall, as defined by the 99th percentile of daily totals, over many regions of Australia from 1910 to 1995, but few individual trends were statistically significant (IPCC, 2001, p. 158). In Siberia, for the summer season in the period 1936–1994, there was a statistically significant decrease in total precipitation of 1.3% per decade, but the number of wet days also decreased (more strongly), so in total an increase in the frequency of heavy rainfall (above 25 mm) of 1.9% per decade was noted. (IPCC, 2001, p. 158).

Where data are available, changes in annual streamflow usually relate well to changes in total precipitation (IPCC, 2001, p. 103). This does not necessarily, and generally, translate to changes in flood flows. Published results of change detection in flood flows show no uniform and general greenhouse signature (Kundzewicz, 2002). In some areas (e.g., at many gauges in the Mississippi basin), large and significant increases have been observed, but in other areas no significant changes have been found. As stated in IPCC (2001a, p. 655): "[i]n more continental and upland areas, where snowfall makes up a large proportion of winter precipitation, a rise in temperature would mean that more precipitation falls as rain and therefore that winter runoff increases and spring snowmelt decreases. The timing of streamflow therefore alters significantly."

The risk from storm surge also appears to be changing. The global average sea level rose by 10 to 20 cm during the 20th century, partly due to the thermal expansion of ocean water (steric rise) and the widespread loss of land ice associated with the 20th century warming. The average rate of the sea level rise in the 20th century (1–2 mm per year) was about ten times larger than the average rate over the last 3000 years, i.e., 0.1–0.2 mm per year (IPCC, 2001, p. 31–32).

Studies of links between hydrological extremes and climatic variability (e.g., oscillations in the Ocean-Atmosphere system, such as the El Niño–Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO)) lead to interesting findings. The frequency and intensity of ENSO have been unusual since the mid 1970s, as compared with the previous 100 years of instrumental records. The warm phase of ENSO episodes has become relatively more frequent, persistent and intense than the opposite cool phase (IPCC, 2001, p. 32). This is likely to have direct consequences related to changes in flood frequency. In some regions, intensive precipitation (and floods) occur more frequently in the El Niño phase than in the La Niña phase (e.g., on the Atlantic side of Central America, in Northwest Peru, in the Central-Western and Pampas regions of Argentina, and in Chile; cf., IPCC 2001a, p. 722). In some other locations (e.g., Colombia, Northern Amazonia and Northeast Brazil, and also Australia, New Zealand and Southern Africa), it is the other way round. There seems to exist a link between the frequency of extreme flood events and the Southern Oscillation Index (SOI) anomalies, while no clear connections between the magnitude of extreme floods and the SOI anomalies have been detected.

4. Projections for the Changing Climate

A significant portion of the increase of flood hazard has been caused by human factors, including land-use change and the increase in population and wealth accumulated in endangered areas. These trends will continue to be active in the future.

However, there are also several climate change-related mechanisms, which may significantly influence future flood characteristics. Characteristics of extreme climatic phenomena influencing floods can change in the future climate, in the light of scenario analyses (cf. IPCC, 2001 and 2001a). Among climate-related impacts relevant to floods are: increased magnitude of precipitation events of high intensity in many locations, more frequent wet spells in mid/high latitude winters, more intense mid-latitude storms, and more El Niño-like mean states of ENSO. Some models show an increase in mean and peak intensity of precipitation and peak wind intensity of tropical cyclones (IPCC, 2001). No conclusive evidence as to the paths of depressions and storms has been established.

Based on global model simulations and for a wide range of scenarios, global average water vapour concentration and precipitation are projected to increase during the 21st century.

Precipitation extremes are projected to increase more than the mean and the intensity of precipitation events is projected to increase. The frequency of extreme precipitation events is projected to increase almost everywhere (IPCC, 2001, p. 72).

Changes in future flood frequency are complex, depending on the generating mechanism, e.g., increasing flood magnitudes where floods result from heavy rainfall and decreasing magnitudes where floods are generated by spring snowmelt (IPCC; 2001, p. 206). In some places, "[r]apid snowmelt from rain-on-snow events or warm periods in the middle of winter is a potential threat in a warmer world" (IPCC, 2001a, p. 395).

Projections for the future are based on mathematical models, which are validated for the past situation, so direct verification of future projections is not possible before modeling results and observed values can be directly compared. Yet, despite

Table I. Flood-related changes listed in WG I SPM (Scientific Basis) (IPCC, 2001, p. 15). Estimates of confidence in observed and projected changes in extreme weather and climate events are also given. Likelihood refers to judgmental estimates of confidence used by IPCC TAR WG I; very likely represents 90–99% chance, likely: 66–90% chance

Confidence in observed changes (latter half of the 20th century)	Changes in phenomenon	Confidence in projected changes (during the 21st century)
Likely, over many Northern Hemisphere mid- to high latitude land areas	More intense precipitation events	Very likely, over many areas
Not observed in the few analyses available	Increase in tropical cyclone peak wind intensity	Likely, over some areas
Insufficient data for assessment	Increase in tropical cyclone mean and peak precipitation intensities	Likely, over some areas

all the caveats and deficiencies, models may estimate frequency statistics for the future reasonably well.

It can be seen that the perception of flood risk in TAR, and particularly assessments of uncertainty, differ among the different working groups of the IPCC, and also among different sectoral and regional chapters. The statements of the IPCC Working Group I (Scientific Basis of Climate Change) have been very cautious, adhering to the attitude that quantification of statistics of extreme events and attribution of causes is difficult and subject to high uncertainty. As stated in IPCC (2001, p. 54), "the analysis of and confidence in extreme events simulated within climate models are still emerging" and the analysis "in both observations and coupled models is underdeveloped". In the document of Working Group II, (IPCC, 2001a), evaluation of flood impacts takes a prominent role, and the overwhelming uncertainty of WG I is replaced by rather crisp observations that flood hazard will increase over many regions, with considerable impacts in several sectors. Perception of floods in the TAR is illustrated in a set of tables. The first two tables stem from the summaries for policymakers (SPMs) of the two IPCC working groups (WGs) responsible for the TAR, that is: WG I (Scientific Basis) and WG II (Impacts, Adaptation and Vulnerability). Table I (WG I SPM) is more cautious and less "wordy" than Table II (WG II SPM). In the latter table, the representative examples of projected impacts are also included.

4.1. REGIONAL PROJECTIONS

Distribution of likely adverse future changes in flood risk is shown in Figures 2 and 3. Figure 2 (including storm surge and coastal inundation risk) has been produced based on scattered information given in IPCC TAR. Figure 3, showing changes in

Table II. Flood-related changes listed in WG II SPM (Impacts, Adaptation and Vulnerability) (IPCC, 2001a, p. 7). Estimates of confidence (referring to WG I classification) are also given. The adverse impacts listed in Table II can be lessened by appropriate response measures. Likelihood refers to judgmental estimates of confidence used by IPCC TAR WG I; very likely represents 90–99% chance, likely: 66–90% chance

Projected changes during the 21st century in extreme climate phenomena and their likelihood	Representative examples of projected impacts (throughout: high confidence of occurrence in some areas)
Simple extremes	
More intense precipitation events (*very likely, over many areas*)	* Increased flood, landslide, avalanche, and mudslide damage * Increased soil erosion * Increased flood runoff could increase recharge of some floodplain aquifers [positive impact; though in limited number of locations; comment added] * Increased pressure on government and private flood insurance systems and disaster relief
Complex extremes	
Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities (likely, over some areas)	* Increased risk to human life, risk of infectious disease epidemics, and many other risks * Increased coastal erosion and damage to coastal buildings and infrastructure * Increased damage to coastal ecosystems, such as coral reefs and mangroves
Intensified … floods associated with El Niño events in many different regions (*likely*)	* Decreased agricultural and rangeland productivity in … flood-prone regions
Increased Asian summer monsoon precipitation variability (likely)	* Increased flood … magnitude and damages in temperate and tropical Asia
Increased intensity of mid-latitude storms (*little agreement between current models*)	* Increased risks to human life and health * Increased property and infrastructure losses * Increased damage to coastal ecosystems

a proxy for flood risk (magnitude of the 10-year return period maximum monthly runoff) stems from Arnell (1999). The message conveyed by Figures 2 and 3 is that the adverse changes in the flood risk are ubiquitous in the world. Moreover, comparison of Figures 2–3 and Figure 1 proves that adverse changes are likely also to occur in locations where the flood risk is already high at present. Table III, stemming from the WG II SPM (IPCC, 2001a, pp. 14–17) indicates that floods have been identified on a short list of key regional concerns.

Regional precipitation scenarios developed under the ACACIA project (Parry, 2000, IPCC, 2001a, p. 650) show a marked contrast between winter and summer precipitation change in Europe. Wetter winters are predicted throughout the continent, with the two regions of highest increase being the Northeast of the continent

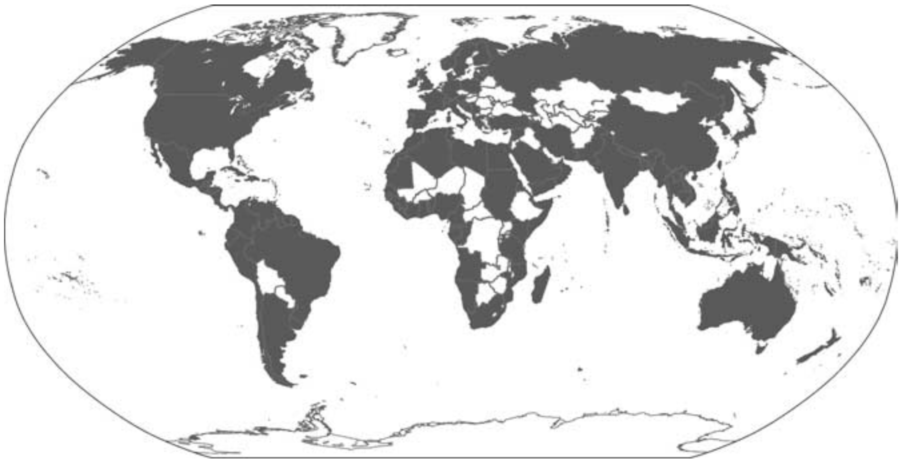

Figure 2. Regional distribution (at country level) of adverse changes in the risk of flood, storm surge, and coastal inundation, according to information contained within the IPCC TAR.

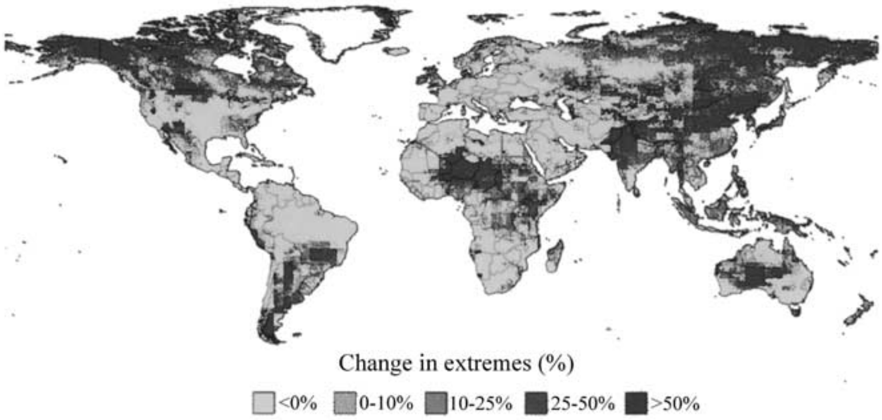

Figure 3. Changes in magnitude of the 10-year return period maximum monthly runoff by 2050s under HadCM3 (fragment of figure from Arnell, 1999).

and the Northwestern Mediterranean coast, including Northern Italy. In summer, there is a strong difference in precipitation change between Northern Europe and Southern Europe; the former getting wetter by 2% per decade, while the latter becoming drier by 5% per decade. However, there are large quantitative differences between scenarios and models.

Climate change is likely to cause the increase of the risk of riverine flooding across much of Europe. In some areas the time of greatest flood risk would shift from spring to winter. Winter flood hazard is likely to rise for many catchments under many scenarios. However, global warming may not necessarily reduce snowmelt flooding everywhere, as an increase in winter precipitation is expected, and snow cover may increase in areas where the temperature is still below 0 °C. Projected changes in the magnitude of peak flows in the Severn and Thames catchments (U.K.) by the 2050s show the increase of flood risk (IPCC, 2001a, p. 205).

According to IPCC (2001a, p. 750), "[p]ossible changes in runoff patterns, coupled with apparent recent trends in societal vulnerability to floods in parts of North America suggest that flood risks may increase as a result of anthropogenic climate change. Changes in snowpack accumulation and the timing of melt-off are likely to affect the seasonal distribution and characteristics of flood events in some areas." Winter and early spring flood events may become more frequent in mountainous western watersheds of the USA, while reduced winter and spring floods are possible in Southeastern Canada and Northeastern USA. However, Canadian rivers in northern areas may begin to experience winter ice break-ups and regional flooding.

The enhancement of the hydrological cycle and an increase in mean annual rainfall over much of Asia is expected, affecting Boreal Asia most (IPCC; 2001a, p. 548). The frequency and severity of floods is projected to increase in many areas of Asia. The intensity of extreme rainfall events is projected to be greater in a warmer atmosphere, suggesting thereby a decrease in the return period for extreme precipitation events and the possibility of more frequent flash floods in parts of India, Nepal and Bangladesh (IPCC, 2001a, p. 550).

Future seasonal precipitation extremes associated with an ENSO event are likely to be more intense in the tropical Indian Ocean region – anomalously wet areas could become even wetter (IPCC, 2001a, p. 550).

Although "drier conditions are anticipated for most of Australia over the 21st century", "an increase in heavy rainfall is also projected, even in regions with small decreases in mean rainfall. This is due to a shift in the frequency distribution of daily rainfall toward fewer light and moderate events and more heavy events. This could lead to … more floods" (IPCC, 2001a, p. 598).

Sea-level rise is perhaps the most important single climatic factor, which contributes to increasing (coastal) flood risk. In fact, a change in the mean level of the sea may exert significant impacts on the extremes (sea surges). Higher peak wind intensities could also contribute to the increasing severity of coastal flooding. It is likely that flood exposure and incidence for the coasts of Europe will increase considerably. Assuming no adaptation, the increase in flood incidence, measured as average number of people experiencing coastal flooding along the Mediterranean coast may grow from 1990 to 2080s by 260 to 120,000 % (IPCC, 2001a, p. 659). The quantitative assessments are very uncertain – the range of projections extends over three orders of magnitude, but all modelling results show a dramatic increase.

Needless to say, sea-level rise itself is a dangerous occurrence which jeopardizes low-lying coastal areas and which, after reaching a certain stage, may cause permanent inundations, resulting in massive relocation of people.

Global warming has the potential to trigger large-scale singular events, which could have important consequences for the risk of inundations. An example is the disintegration of the West Atlantic and Greenland Ice Sheets, in a time scale of

Table III. Flood-related issues referring to a regional adaptive capacity, vulnerability, and key regional concerns (excerpts from IPCC, 2001a, pp. 14–17). Confidence levels in Table III correspond to IPCC WG II classification (very high: 95% or greater, high: 67–95%, medium: 33–67%, etc.)

Region	Adaptive capacity, vulnerability and key concerns
Africa	* Adaptive capacity of human systems in Africa is low due to lack of economic resources and technology, and vulnerability high as a result of … frequent … floods … * Increases in … floods … would add to stresses on water resources, food security, human health, and infrastructures, and would constrain development in Africa (*high confidence*) * Coastal settlements in, for example, the Gulf of Guinea, Senegal. Gambia, Egypt, and along the East-Southern African coast would be adversely impacted by sea-level rise through inundation and coastal erosion (*high confidence*)
Asia	* Extreme events have increased in temperate and tropical Asia, including floods … (*high confidence*) * Decreases in agricultural productivity and aquaculture due to … floods … would diminish food security in many countries of arid, tropical, and temperate Asia (*medium confidence*) * Runoff … may … increase in northern Asia (*medium confidence*) * Sea-level rise and an increase in the intensity of tropical cyclones would displace tens of millions of people in low-lying coastal areas of temperate and tropical Asia; increased intensity of rainfall would increase flood risks in temperate and tropical Asia (*high confidence*) * Sea-level rise would put ecological security at risk, including mangroves and coral reefs (*high confidence*)
Australia and New Zealand	* Increases in the intensity of heavy rains and tropical cyclones (*medium confidence*), and region-specific changes in the frequency of tropical cyclones, would alter the risks to life, property, and ecosystems from flooding, storm surges.
Europe	* [I]ncreases [of runoff, *comment added*] are likely in winter in the north and south (*high confidence*) * River flood hazard will increase across much of Europe (*medium to high confidence*); in coastal areas, the risk of flooding, erosion, and wetland loss will increase substantially with implications for human settlement, industry, tourism, agriculture, and coastal natural habitats
Latin America	* Floods … would become more frequent with … increasing sediment loads and degrade water quality in some areas (*high confidence*) * Increases in intensity of tropical cyclones would alter the risks to life, property, and ecosystems from heavy rain, flooding, storm surges … (*high confidence*) * Coastal human settlements, productive activities, infrastructure, and mangrove ecosystems would be negatively affected by sea-level rise (*medium confidence*)

Table III. Continued

Region	Adaptive capacity, vulnerability and key concerns
North America	* Snowmelt-dominated watersheds in western North America will experience earlier spring peak floods (*high confidence*) * Sea-level rise would result in enhanced coastal erosion, coastal flooding, loss of coastal wetlands, and increased risk from storm surges, particularly in Florida and much of the U.S. Atlantic coast (*high confidence*) * Weather-related insured losses and public sector disaster relief payments in North America have been increasing: insurance sector planning has not yet systematically included climate change information, so there is potential for surprise (*high confidence*)
Small Island States	* The projected sea-level rise of 5 mm yr^{-1} for the next 100 years would cause enhanced coastal erosion, loss of land and property, dislocation of people, increased risk from storm surges, reduced resilience of coastal ecosystems, saltwater intrusion into freshwater resources, and high resource costs to respond to and adapt to these changes (*high confidence*) * [M]angrove, sea grass bed, and other coastal ecosystems and the associated biodiversity would be adversely affected by ... accelerated sea-level rise (*medium confidence*) [This would adversely impact fisheries and tourism, among other sectors, *comment added*]

multiple centuries, which would cause a significant sea-level rise (of the order of meters), leading to a permanent inundation of large, now densely populated areas. The probability of such developments in the near future is low, but should not be ignored given the severity of their consequences. As summarized in IPCC (2001, p. 54), loss of grounded ice of the West Antarctic leading to substantial sea-level rise from this source is now widely agreed to be very unlikely (1–10% chance) during the 21st century, although its dynamics are still inadequately understood, especially for projections on longer time scales (IPCC, 2001, p. 16).

4.2. SECTORAL PROJECTIONS

Although Table II contains a sample of sectoral and regional impacts of floods, it seems worthwhile to illustrate these impacts in more detail. In the following, a roster of sectoral flood-related concerns is offered.

- *Financial services and insurance*. The finding in IPCC (2001a, p. 422) is that the costs of catastrophic weather events have exhibited a rapid upward trend in recent decades and yearly economic losses from large events increased over 10-fold between the 1950s and the 1990s (in inflation-adjusted dollars). The insured portion of these losses has grown even stronger. Other natural disasters (e.g., earthquakes) have increased more slowly than weather-related losses. There is good evidence that the intensity and frequency of flood-related extreme events is increasing in the USA (p. 423). The relative contribution of human and climatic factors to the changing patterns of loss varies, depending on the place and type of event. Part of the observed upward trend in weather disaster losses is linked to demographic and socio-economic factors, such as increase of concentration of population and property, but these factors alone cannot explain the observed growth in global losses. As stated in IPCC (2001a, p. 423), a part of the losses is linked to climatic factors, such as the observed changes in precipitation and flooding events.

- *Settlements*. "The most widespread serious potential impact of climate change on human settlements is believed to be flooding" (IPCC, 2001a, p. 395). A variety of settlements in different regions may be affected, although specific evidence is still very limited. Further, "riverine and coastal settlements are believed to be particularly at risk, but urban flooding could be a problem anywhere. ... Urbanization itself explains much of the increase in runoff relative to precipitation in settled areas ... and contributes to flood-prone situations" (IPCC, 2001a, p. 395). Permanent glaciers shrink and glacial runoff increases in Asia and this leads to a rise in frequency of mudflows and avalanches affecting human settlements (IPCC, 2001a, p. 543). In Africa (IPCC, 2001a, p. 46), "[a]n increase in the frequency of damaging floods ... could degrade the integrity of critical infrastructures at rates the economies may not be able to tolerate, leading to a serious deterioration of social, health, and economic services delivery systems." Floods will also adversely affect transportation systems (IPCC, 2001a, p. 401) and could create water quality problems" (p. 384).
- *Human health*. Increasing floods pose danger to human health. Health effects can be either immediate (drowning, being swept against hard objects), medium (increases in communicable diseases such as those caused by ingestion of or contact with contaminated water, or respiratory diseases in overcrowded shelters), and long-term (moulds, fungi, malnutrition), cf. IPCC (2001a, p. 459). Furthermore, concerns include psychological or behavioural disorders and mental health.
- *Ecosystems*. Forest ecosystems in boreal Asia could suffer from floods and increased volume of runoff (IPCC, 2001a, p. 551). Heavy precipitation may leach nitrogen and other non-point source pollutants from agricultural lands and the resulting nutrient pulse may severely stretch ... ecosystems (IPCC, 2001a, p. 749). Also sewage entrained by floods is a reason of concern.

5. Post-TAR Results

Since the publication of the IPCC TAR, several important articles on floods have been published in *Nature* (Palmer and Räissänen, 2002, Milly *et al.*, 2002, Schnur, 2002), evidencing our increase in confidence in observed and projected changes in extreme rainfall and flooding.

Milly *et al*. (2002) demonstrated changes in the risk of great floods (exceeding 100-year levels). They admitted that detection of anthropogenically forced changes in flooding is difficult, because of the substantial natural variability, and that the models perform poorly for low latitudes. Their finding was that the frequency of large floods has increased substantially during the 20th century. For all (but one) large basins (over 200,000 km^2) analyzed, the control 100-year flood is exceeded more frequently as a result of CO_2 quadrupling. In some areas, what is given as a 100-year flood in the control run, is projected to become much more frequent, even occurring as often as every 2 to 5 years. Particularly strong increases are projected in Northern Asia. Milly *et al*. (2002) found that the likelihood that these changes are due to natural climate variability is small.

Palmer and Räissänen (2002) analyzed the modelled differences between the control run with 20th century levels of carbon dioxide and an ensemble with transient increase in CO_2 and calculated around the time of CO_2 doubling (61–80 years from present). They found a considerable increase of the risk of a very wet winter in Europe and a very wet monsoon season in Asian monsoon region. The modelling results indicate that the probability of total boreal winter precipitation exceeding two standard deviations above normal will increase by a factor of five to seven, or more, over large areas of Europe. For example, an over five-fold increase is projected over Scotland and the island of Ireland and much of the Baltic Sea basin. An over seven-fold increase was projected for parts of Russia.

Neither a single simulation nor an ensemble (consensus) average of model results are appropriate in extreme event studies. As stated by Schnur (2002), the ensemble (consensus) average of several models would lead to underestimation of extreme precipitation and flooding. Studying frequency distributions of extreme events among a large multi-model ensembles is likely to produce more trustworthy results (Palmer and Räissänen, 2002). Schnur (2002) expressed the opinion that multi-model ensembles should be produced "for a more complete picture of the factors contributing to climate change, such as other greenhouse gases and sulphate aerosols".

Findings reported in these recent publications agree with and corroborate the conclusions of the IPCC TAR.

6. Concluding Remarks

The IPCC TAR is a comprehensive account and material on floods is scattered over many places in nearly 2,000 pages of the first two volumes. Through the present study, a guided tour to floods in the TAR, the authors – insiders of the IPCC TAR process – try to provide some service to the community.

Recent studies show that the flood hazard is likely to rise in the future and that plausible climate change scenarios indicate the possibility of increases in both amplitude and frequency of flooding events. Yet there has been no conclusive and general proof as to how climate change affects flood behaviour, in the light of data observed so far. The general statement that severe floods are becoming more frequent is supported by several studies, while other publications report contradictory evidence, where a non-stationary behaviour of flood series could not be detected.

Regional changes in timing of floods have been observed in many areas, with increasing late autumn and winter floods (caused by rain) and less ice-jam-related floods, e.g., in Europe. This has been a robust result. Yet intensive and long-lasting precipitation episodes happening in summer have also led to disastrous recent flooding in Europe, e.g., the Odra/Oder deluge in 1997 (cf. Kundzewicz *et al.* (1999) and Kundzewicz (2001)), and the 2002 flooding, among others on the Elbe and its tributaries, the Danube, and other rivers.

Quantification of flood statistics is subject to high uncertainty. It is difficult to disentangle the climatic component from the strong natural variability and direct, man-made, environmental changes. There is a large difference between results obtained by using different scenarios and different models.

There is no doubt that the future changes of flood hazard due to climate forcing will be complex. In many places flood risk is likely to grow, due to a combination of anthropogenic and climatic factors. Vulnerability to floods can be regarded as a function of exposure and adaptive capacity (cf., IPCC, 2001a), and all three entities have been increasing in many areas, where exposure grows faster than the adaptive capacity.

It is a robust statement that, in general, today's climate models are not good at producing local climate extremes due to, *inter alia*, inadequate (coarse) resolution. There is hope that, with improving resolution, models will be able to grasp details of extreme events in a more accurate and reliable way. With a well-designed research programme we are in a position to drastically reduce uncertainties in assessments. It can be expected that a considerable improvement of understanding will take place in a near future and will be reflected in the Fourth Assessment Report of the IPCC.

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