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Summer Floods in Central Europe – Climate Change Track?

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Abstract. In Central Europe, river flooding has been recently recognized as a major hazard, in particular after the 1997 Odra /Oder flood, the 2001 Vistula flood, and the most destructive 2002 deluge on the Labe/Elbe. Major recent floods in central Europe are put in perspective and their common elements are identified. Having observed that flood risk and vulnerability are likely to have grown in many areas, one is curious to understand the reasons for growth. These can be sought in socio-economic domain (humans encroaching into floodplain areas), terrestrial systems (land-cover changes – urbanization, deforestation, reduction of wetlands, river regulation), and climate system. The atmospheric capacity to absorb moisture, its potential water content, and thus potential for intense precipitation, are likely to increase in a warmer climate. The changes in intense precipitation and high flows are examined, based on observations and projections. Study of projected changes in intense precipitation, using climate models, for several areas of central Europe, and in particular, for drainage basins of the upper Labe/Elbe, Odra/Oder, and Vistula is reported. Significant changes have been identified between future projections and the reference period, of relevance to flood hazard in areas, which have experienced severe recent floodings.

Key words: flood hazard, flood risk, intense precipitation, river flow, climate change, climate change impact, central Europe

1. Introduction

According to the global data of the Red Cross for the time period 1971–1995, floods killed, in an average year, over 12,700 humans, affected 60 million people and rendered 3.2 million homeless. Berz (2001) examined temporal variability of great flood disasters (understood as events where international

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or inter-regional assistance is necessary). His data show that recently the number of great flood disasters worldwide has considerably grown. In the nine years 1990–1998 it was higher than in the three-and-half earlier decades 1950–1985, together (Kundzewicz, 2003). Since 1990, there have been over 30 floods worldwide, in each of which material losses exceeded one billion US$ and/or the number of fatalities was greater than one thousand. The highest material flood losses, of the order of 30 billion USD, were recorded in China in the summer of 1998, while the storm surge in Bangladesh during two days of April 1991 caused highest number of fatalities (140,000).

It is estimated that the material flood damage recorded in the European continent in 2002 has been higher than in any single year before. According to Munich Re (2003), the floods in August of 2002 alone caused damage at the level exceeding 15 billion Euro (therein 9.2 in Germany, and 3 each in Austria and in the Czech Republic). During severe storms and floods on 8–9 September 2002, 23 people were killed in southern France (Rhone valley), while the total damage went up to 1.2 billion USD. Several destructive flood events also occurred overseas in 2002. In July and August of 2002, floods and landslides in northeastern and eastern India, Nepal and Bangladesh killed 1200. A flood in central and western China in June caused 3.1 billion USD losses and killed 500, while another one, in central and southern China in August, caused 1.7 billion USD damage and killed 250.

In recent years, several catastrophic floods have occurred in large central European rivers: Elbe/Labe, Oder/Odra and Vistula. The present paper will put these destructive flood events in perspective.

2. Flood Risk on the Rise? In Search of Causal Mechanism

Having observed that flood risk and vulnerability is likely to have grown in many areas, one is curious to understand the reasons for growth. A review of possible mechanisms of changes (in terrestrial systems, in socio-economic systems, and in climate) is presented in Table I.

Flood risk may have grown due to a range of land-use changes, which induce land-cover changes, hence changes of hydrological systems. Deforestation, urbanization, and reduction of wetlands empoverish the available water storage capacity in a catchment. Urbanization has adversely influenced flood hazard in many watersheds by increase in the portion of impervious area (roofs, yards, roads, pavements, parking lots, etc) and increase of the runoff coefficient. In result, higher peaks of runoff responses to intensive precipitation have been observed and the time-to-peak has decreased. Timing of river conveyance may also have been considerably altered by river regulation measures (channel straightening and shortening, construction of embankments).

Flood risk has substantially grown due to considerable changes in socio-economic systems, corresponding to development of flood-prone areas.

Table I. Possible reasons for changes in flood risk and vulnerability in central Europe

- Changes in terrestrial systems (hydrological systems and ecosystems; land-cover change, river regulation – channel straightening, embankments, changes of conditions of transformation of precipitation into runoff leading to a higher peak and shorter time-to-peak).
- Changes in socio-economic systems (increasing exposure and damage potential – floodplain development, growing wealth in flood-prone areas, land-use change: urbanization, deforestation, elimination of natural inundation areas (wetlands, floodplains causing land-cover changes in terrestrial systems), changing risk perception).
- Changes in climate (holding capacity of the atmosphere, intense precipitation, seasonality, circulation patterns).

Shortage of land, attractiveness of floodplains, and unjustified belief in absolute safety of structural flood protection schemes (dikes, dams), cause the tendency of massive human encroaching into flood-prone areas, and investing in infrastructure there. Many wrong locational decisions have been taken, which cause the flood loss potential to increase. In the same time, much of the natural flood storage volume is lost, ecosystems are devastated and riparian wetlands destroyed.

In addition to the changes specified above, also changes in climate are likely to play an important role in changing flood risk and vulnerability.

According to IPCC (2001a), a statistically significant increase in global land precipitation over the 20th century has been noted. This refers to both mean values and extremes, but the extremes in precipitation are likely to change more than the mean. It results directly from physics (Clausius–Clapeyron law) that the atmosphere's capacity to absorb moisture (and its absolute potential water content, pool of precipitable water, and thus potential for intensive precipitation) increases with temperature. This is a sufficient condition, *caeteris paribus*, for an increase in flood hazard. Indeed, higher and more intense precipitation has been already observed in many areas of the mid- and high latitudes, e.g. in the USA and in the UK (IPCC, 2001a), and this trend is expected to strengthen in the future, warmer world.

It is very likely (IPCC, 2001a) "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, 2001a), 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 growing and significant increases have been observed in both the proportion of mean annual total precipitation in the upper five percentiles and in the annual maximum consecutive 5-day precipitation total. The latter statistic has increased for the global data in the period 1961–1990 by 4% (IPCC, 2001a). 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, 2001a).

Where data are available, changes in river flow usually relate well to changes in total precipitation (IPCC, 2001a). There are a number of studies reporting that high flows have become more frequent (cf. Kundzewicz, 2003). Many increases of annual maxima and peak-over-threshold (POT) variables have been found in a part of the river flow data in different areas, e.g. in the UK (particularly in Scotland and in southeastern England), and in the USA. However, this does not directly translate into general finding on changes in flood flows everywhere. No globally uniform increasing trend in maximum river flow has been detected. In some stations, a statistically significant decrease has been reported, while in many stations – no statistically significant change has been found.

The links between flood-risk growth and climate variability and change have found extensive coverage in the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC, 2001a, b; Kundzewicz and Schellnhuber, 2004). In (IPCC, 2001b), floods have been ubiquitously identified on short lists of key regional concerns.

The general conclusion drawn from the science of the climate change is as follows: the hydrological cycle is likely to accelerate in the warmer climate. Yet, there is a great deal of uncertainty in findings about future climate change impacts on water resources, and this refers particularly to extreme events. Part of the problems is due to a spatial and temporal scale mismatch between coarse-resolution climate models and hydrological (catchment) spatial scale and between monthly/daily data and daily/hourly dynamics of flood routing. Only in some, but not all, areas, the projected direction of change of hydrological processes is consistent across different scenarios (emissions of greenhouse gases, which drive climate models) and across different models.

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) or North-Atlantic Oscillation (NAO) lead to interesting findings. The frequency and intensity of ENSO have been unusually high since the mid 1970s, as compared with the previous 100 years of instrumental records (IPCC, 2001a). This is likely to have direct consequences related to changes in flood hazard, since in some regions of South America, intensive precipitation and floods occur frequently in the El Niño phase (IPCC, 2001b).

Regional changes in timing of floods have already been observed in many areas, with increasing late autumn and winter floods (caused by rain and/or earlier snowmelt) but lower spring snowmelt flows and less ice-jam-related floods, e.g. in central Europe. This has been a robust result. Yet, intensive and long-lasting precipitation episodes happening in summer, especially those induced by the Vb cyclone (see Section 5), have led to disastrous recent flooding in Europe. Certainly, one should be very careful with attempts to attribute the responsibility for occurrence of a particular flood to global changes (e.g. of climate). A particular flood may have well manifested the natural variability of the river flow process – virtually any maximum flow rate, which was observed recently, had been exceeded some time in the (possibly remote) past. Yet, increased probability of intense summer precipitation and floods fits well into the general image of the changing (warming) globe with intensified, accelerated hydrological cycle.

Changes in future flood frequency are likely to be complex (Arnell and Liu, 2001). They depend on the flood-generation mechanism. Increasing flood magnitudes are likely to occur where floods result of heavy rainfall. Decreasing magnitudes are expected where floods are generated by spring snowmelt. All in all, climate change is likely to cause an increase of the risk of riverine flooding across much of Europe.

The climatic impact on water resources depends, in general, not only on changes in the characteristics of streamflow, but also on such system properties, as: pressure (stress) on the system, its management (also organizational and institutional aspects), and adaptive capacity. Climate change may challenge existing water resources management practices by contributing additional uncertainty, but in a particular place, non-climatic changes may have posed a greater impact.

3. Recent Floods in Central Europe in a Nutshell

In the basins of three large international rivers in central Europe: the Labe/Elbe (drainage basin in Czech Republic and Germany), the Odra/Oder (drainage basin in Czech Republic, Poland and Germany), and the Vistula (most of drainage basin in Poland, with basins of tributaries located also in Slovakia, Ukraine, and Belarus), cf. Figure 1, the water resources are rather scarce. However, even if the mean annual flow values are low, the hydrological variability is considerable, hence floods have not been uncommon. After the recent floods on three large rivers and their tributaries, floods have

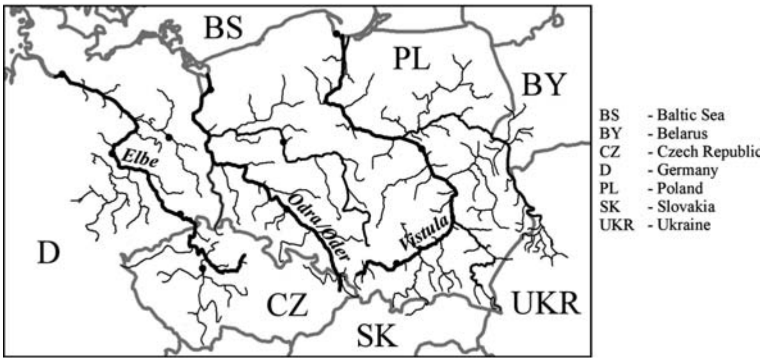

Figure 1. Location of the drainage basins of the rivers. Labe/Elbe, Odra/Oder, and Vistula.

been broadly recognized as a major hazard. The most destructive floods in central and eastern Europe, which occurred in 1997 in the basins of the Odra/Oder and the Vistula and 2002 in the basin of the Labe/Elbe, caused 114 and 36 fatalities, respectively, while the material damage reached 6.5 and 15.2 billion euro, respectively. The 2002 data include the flood on the Danube and its tributaries.

The three most recent floods; 1997 (Odra/Oder, Vistula, and their tributaries), 2001 (Vistula and its tributaries), and 2002 (Labe/Elbe and its tributaries) have several commonalities. All three flood events occurred in summer and were caused by similar atmospheric drivers – Vb atmospheric circulation type (cf. Figure 2). The floods were generated by intensive precipitation during a longer wet spell, which covered vast areas. Very fast, violent flash floods occurred in small and medium catchments of mountainous tributaries of large rivers and in the upper reaches of the main rivers. Huge masses of water propagated downstream the main rivers, causing dyke failures, and inundating urban areas, therein large towns. Since levees were broken and vast, mostly agricultural, areas were inundated, this was a relief to downstream areas. The flood wave flattened as part of it was trapped in a temporary storage. The return period of flood flow decreased downstreams; from very rare events in headwaters to more common events in lower (lowland) courses.

3.1. ODRA FLOOD OF 1997 – A POLISH PERSPECTIVE

In the second half of June 1997, abundant precipitation filled the natural storage and saturated the soil in a large part of the upper Odra/Oder catchment. From the 4th to the 10th of July, a quasi-stationary low-pressure trough developed, covering the catchment area of the upper Odra and its

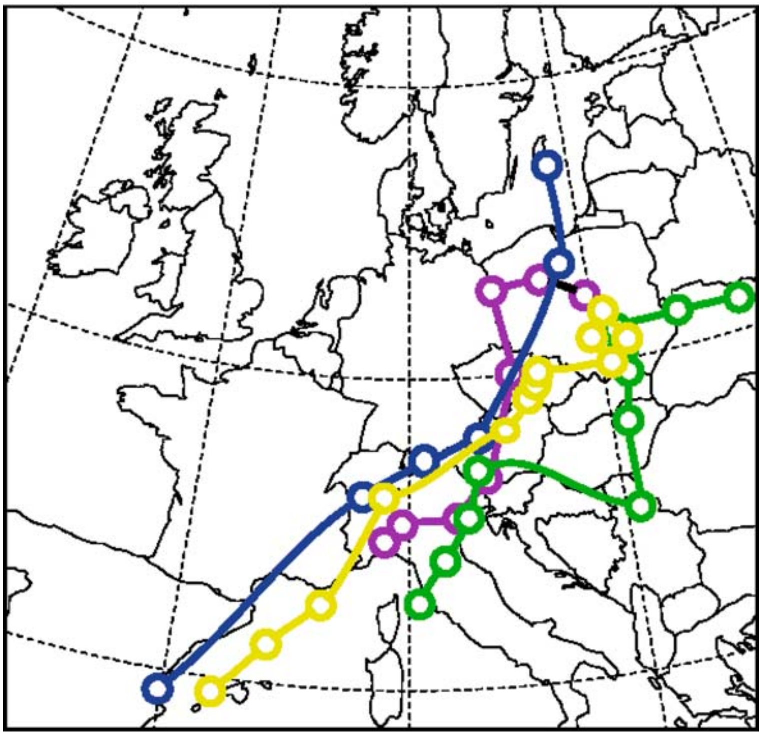

Figure 2. Cyclone track for 1997, 2001, and 2002 floods, with positions given in 12-hourly intervals. All lows shown have a north-eastward track. Green: low named "Xolska", 4 July 1997 00 UTC to 9 July 1997, 00 UTC; Yellow: low named Zoe, 16 July 1997 00 UTC to 21 July, 12 UTC; Blue: low named "Axel", 15 July 2001 00 UTC to 17 July 2001, 00 UTC. Pink: low named "Ilse", 10 August 2002, 00 UTC to 13 August 2002, 12 UTC. Results obtained within the MICE Project in the Institute for Geophysics and Meteorokogy, University of Cologne.

tributaries, with a front dividing humid air masses of largely different temperatures.

The heavy and long-lasting rains in the beginning of July, covering large areas, caused destructive flooding in Czech Republic and Poland. Yet, a few days later, another train of intensive rains occurred with up to 300 mm precipitation recorded from 17 to 22 July. A third wet spell, in the third decade of July 1997, occurred basically in the drainage basin of the river Vistula. Figure 3 presents the spatial distribution of precipitation over central and eastern Europe in July 1997 in relation to long-term July averages based on the 1961–1990 data.

One could distinguish three stages of the 1997 Odra flood in Poland. In the first stage, after the intensive rainfall in the catchments of the upper Odra and its headwater tributaries, river flows increased very fast. The flood was very

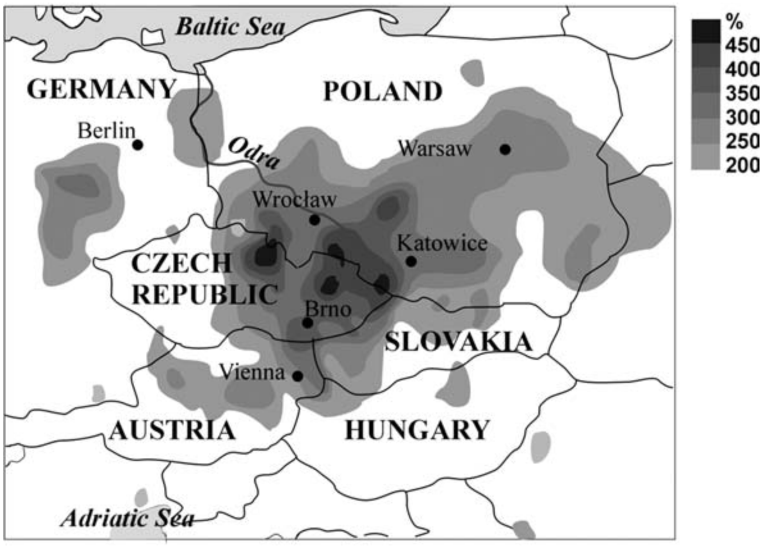

Figure 3. Precipitation in July 1997, compared to a mean monthly value (by courtesy of Dr Bruno Rudolf, Global Precipitation Climatology Centre (GPCC), German Weather Service, Offenbach).

destructive and dynamic – it virtually ruined the town of Kłodzko (31,000 inhabitants) located at the river Nysa Kłodzka, tributary to the Odra. It also destroyed several staff gauges, including the one in Racibórz-Miedonia, where all-time record was observed on 9 July before the records discontinued, as illustrated in Figure 4. In Racibórz-Miedonia, the former record stage of 838 cm and the record discharge of 1630 $m^3 s^{-1}$ of 1985 were marked out by the much higher values of 1045 cm and 3260 $m^3 s^{-1}$, respectively, in July 1997. The flow rate of the exceedance probability of 1% (100-year-flood) estimated in this cross-section, based on seven decades of records, reads 1680 $m^3 s^{-1}$.

In the second stage, a huge flood wave, which was already in the river channel of the Odra, propagated downstream and inundated towns located upon the river. Due to the huge size of the wave it was not possible to avoid urban flooding, yet, thanks to the time lag, some preparation could be made. The flood devastated large riparian towns located on the Odra, such as Racibórz (65,000 inhabitants), Opole (131,000) and Wrocław (700,000). In Opole, water level outstripped the absolute historic maximum by 173 cm (777 cm in 1997, as compared to 604 cm in 1813 and 584 cm in 1985) and the peak flow reached 3500 $m^3 s^{-1}$. The flood protection system of Wrocław was designed for a flow rate of 2400 $m^3 s^{-1}$, and was generally perceived as

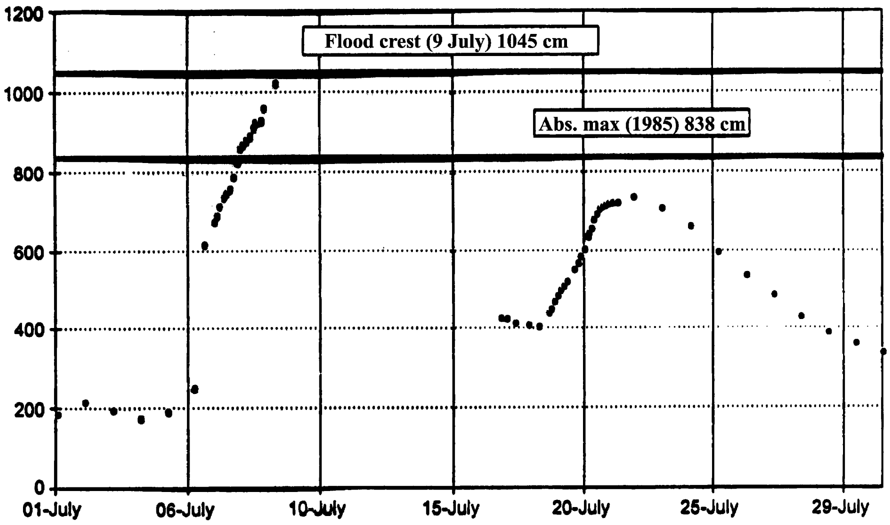

Figure 4. Stage hydrograph for the river Odra, gauge Racibórz-Miedonia in July 1997. (Source: Kundzewicz *et al.*, 1999, based on IMGW data.)

adequate. However, the peak flow rate in July 1997 was higher nearly by half than the design value, and large parts of the city were inundated. Due to dike failures and massive inundations, the flood wave in the Odra lost part of its impetus. The peak flow of the flood wave decreased while travelling downstream, so that the return period of the maximum discharge, being of the order of at least several hundreds up to thousands years in the headwaters (Grünewald, 1998), was far more common downstreams.

Finally, in the third stage of the flood, high water reached the boundary stretch (state border between Poland and Germany) and the lower Odra. There was more time for preparation – heightening and strengthening of embankments. The fight to save the dikes was largely successful on the Polish side. On the German side, several dike breaches occurred and significant material losses were recorded.

In Poland, the nation-wide toll for both the Odra and the Vistula floods of summer 1997 was an all-time high as far as the economic damages are concerned. The number of flooded towns and villages was 2592, the number of evacuees was 162,000, and around 665,000 ha of land were flooded, of which agricultural fields constitute over 450,000 ha. More detailed information can be found in Kundzewicz *et al.* (1999).

The 1997 Odra flood was a surprise to many, since there have been no disastrous floods on the Odra for several decades before the recent deluge. However, many destructive events were recorded earlier in historic times; both winter floods, related to snowmelt and ice-jams, and summer rain-caused floods (typically in June and July). For example, in July 1310, a large flood hit Kłodzko, inundating suburbs and killing between 1500 and 2000 people. Floods usually occurred either on the upper and middle Odra (e.g. 1813, 1854, 1903, 1977 and 1985) or on the Lower Odra (e.g. 1855, 1940). Floods covering the whole length of the river have been more rare and usually very dramatic. The flood in the summer of 1997 was an extreme one in this category.

The flood of 1997 lasted long. The wave travelled slowly downstream and, at several gauging stations, the alarm levels were exceeded uninterruptedly during several weeks. The exceedance of the historic absolute maximum water levels lasted from 4 to 7 days at the upper Odra to about 16 days in Połęcko.

The existing flood protection system in the drainage basin, consisting of dikes, reservoirs (including dry flood protection reservoirs) and relief channels at the Odra and its tributaries, and a system of polders, could not accommodate such a gigantic flood wave as the one occurring in 1997. The structural flood defences, for several larger towns upon the Odra and its tributaries and for vast areas of agricultural land, proved to be dramatically inadequate for such a rare flood. No wonder, indeed, flood defences, are designed to withstand smaller, more common floods (of the order of tens to 100-year return interval), and fail when exposed to a much higher pressure of an extraordinarily high flood. Indeed, if a flood record is doubled and the flood recurrence interval gets into the range of several hundreds or thousands of years, i. e. very much higher than the design value (Grünewald, 1998), there is no way to avoid high material losses. One notable exception is the Dutch regulation, whereby major river dikes have been designed to withstand a very rare flood.

The event made the broad public aware of how dangerous and destructive a flood can be. It also unveiled the weaker points of the existing flood defence system and helped identify the most pressing needs for improvements. Indeed, every link in the chain of the operational flood management was found to be in need of considerable strengthening.

The flood of 1997 was the most extreme event on record, both in hydrological terms (peak stage, flow, inundated area) and in economic terms (material losses). It was an effect of exceptionally intensive and persistent precipitation covering a large area. This very rare hydrological event was superimposed on a complex, and dynamically changing, socio-economic system of Poland – a country with economy in transition from centralized to market-based system.

3.2. ELBE FLOOD OF 2002 IN PERSPECTIVE

The meteorological mechanism responsible for occurrence of heavy precipitation included composite events: two low-pressure systems (Hanne and Ilse), commencing near Ireland four days after each other, and then moving southeast over the Mediterranean, and further towards Northeast, meeting colder air masses. The Vb cyclone brought moisture from the Mediterranean area to central Europe (cf. Ulbrich *et al.*, 2003a, b). Intense, long-lasting precipitation was recorded, which covered large areas. Monthly precipitation in August 2002 is presented in Figure 5.

According to Czech data (Kubát *et al.,* 2003), for over a week since 6 August, every day, intensive precipitation was measured in one or several Czech raingauges. For instance, in Staré Hute (altitude 792 m, county Ceské Budejovice), there were three days, with daily precipitation in excess of 100 mm each (101.4 mm on 6 August, 152.9 on 7 August during the first train of intense precipitation and 107.4 on 12 August, during the second train of intense precipitation). In Knajpa (county Jablonec n. Nisou), precipitation observed on 12 August and 13 August was 75.6 mm and 278 mm, respectively. Extremely high precipitation of 312 mm was measured at the station Cínovec (county Teplice) on 12 August, but rainfall observed there in adjacent days was also high (68 mm on 11 August and 26 mm on 13 August).

Two waves of intense precipitation: 6–7 and 11–12 August (first one largely filling the storage capacity in the catchments) turned out to be fatal for

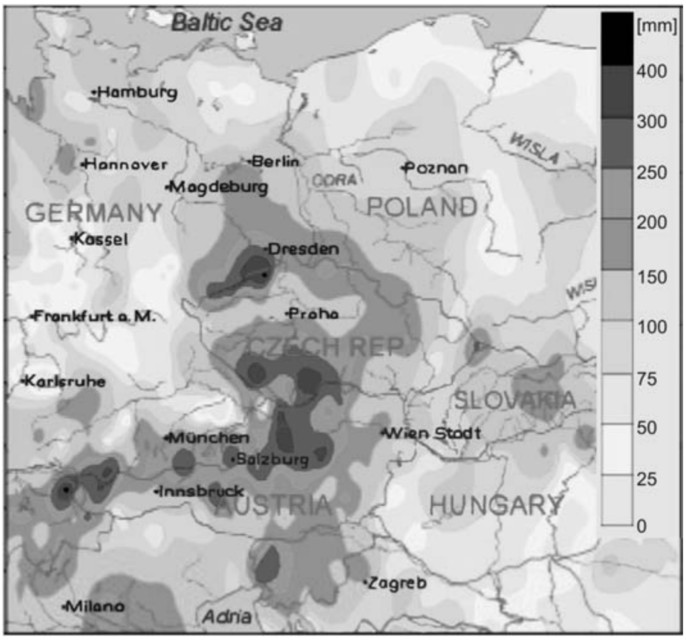

Figure 5. Precipitation in August 2002 (from: Rudolf and Rapp, 2003).

the Czech capital, Prague, jeopardized by the main river, Vltava (Moldau) and its tributaries (Sazava and Berounka). Upstream reservoirs in the Vltava basin (mostly multi-purpose, with hydropower as the main task, and corresponding operation rules) were filled during the first flood wave and could not accommodate high inflows during the second flood wave. The 2002 flood peak level in Prague exceeded all the events recorded in the last 175 years (Kubát *et al.*, 2003). This is the only instance when the flow rate of 5000 m^3/s^{-1} was exceeded. Between 1941 and 2001 Vltava flow never reached 2500 m^3/s^{-1}. Three exceedences of the $Q_{100} = 3700\ m^3/s^{-1}$ were observed within five decades of the 19th century (1845, 1862, 1890).

In four precipitation observing stations, the 24-hour precipitation in August 2002 has qualified into the ten highest observations ever recorded in the Czech Republic (Cinovec 312 mm in the Ore Mountains, Knajpa, 278 mm, Smedavská hora, 271.1 mm, and Jizerská 247.8 mm – all three stations in Jizerské mountains). Also in the category of two-day precipitation, the 2002 record at Cinovec (380 mm) was the highest in the history of observation record. However, in the category of three-day event, the Cinovec mark (406 mm) did not reach the top. It ranked ninth on record, while the top six three-day rainfalls, on the list of national records, stem from July 1997 (Kubát *et al.*, 2003).

The 24-hr precipitation of 312 mm was also recorded in Germany, beating the all-time national record. In Zinnwald-Georgenfeld (Saxony), 312 mm of precipitation was recorded from 12 August 2002, 6 a.m. UTC to 13 August 2002, 6 a.m. UTC (usual time interval for measuring one-day precipitation). However, since hourly values are available, it has been found that maximum 24-hour precipitation recorded from 12 August 2002, 5 a.m. UTC to 13 August 2002, 5 a.m. UTC was even higher and reached 352.7 mm (Rudolf and Rapp, 2003). The maximum 24-hr and 72-hr precipitations recorded in Zinnwald-Georgenfeld in August 2002 are expected to occur less frequently than once in a hundred years. High precipitation in Zinnwald and vicinities caused a catastrophic flood of the river Müglitz (Figure 6), which destroyed the village Weesenstein (south of Dresden).

The return periods of some flood flows in August 2002 in Czech Republic and Germany were of the order of several hundred years.

The water level of the Elbe in the profile Dresden on 17 August 2002, i.e. 940 cm, has considerably (by 63 cm) exceeded the former highest mark, while records are available since 1275. The second highest water level, 877 cm, dating back to 31 March 1845, was related to snowmelt and ice-jam flood. In the past, stages in excess of 800 cm were observed in Dresden five times during less than a century – from 1785 to 1879 (four out of five times – in February or March), but this level has never been reached more recently in the over 120-year time period after 1880, until the 2002 flood. However, such a long period of lower annual maxima has not been uncommon in the

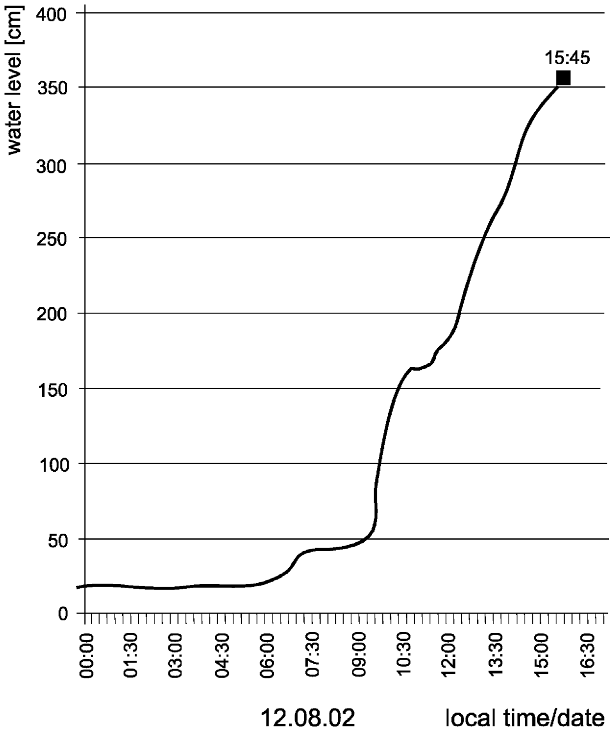

Figure 6. Stage hydrograph for the river Müglitz, gauge Dohna on 12 August 2002. Data were provided by Dr Höhne, Saxonian State Office for Environment and Geology (Sächsisches Landesamt für Umwelt und Geologie).

historical data. For instance, between 1502 and 1783, i.e. 281 years, the level of 800 cm was exceeded only once.

Figure 7 illustrates the spatial-temporal changes of flow of the river Elbe, for different cross-sections. It results from Figure 7 that the tributaries of particular importance during this event were: the Mulde (increase of flow in the Elbe due to strikingly high inflow) and the Havel (decrease of flow in the Elbe due to massive polder inundation).

Greatest devastation was caused by flooding on tributaries to the Elbe. Some rivers rose by up to 4 m, as the river Mulde (adjacent to the river Müglitz) in Grimma. The Dresden Central Station was inundated to the depth of 1.5 m by the river Weißeritz, which during the 2002 flood turned back to the old bed. Evacuation of people and wealth was necessary, including most valuable cultural treasures (e.g. musea in Dresden and Semper Opera house).

The breakdown of 2002 flood damage in Germany (the Elbe, the Danube, and their tributaries) amounting to 9.2 billion euro, after Munich Re (2003), reads: private households 2.1 billion euro, infrastructure belonging to state

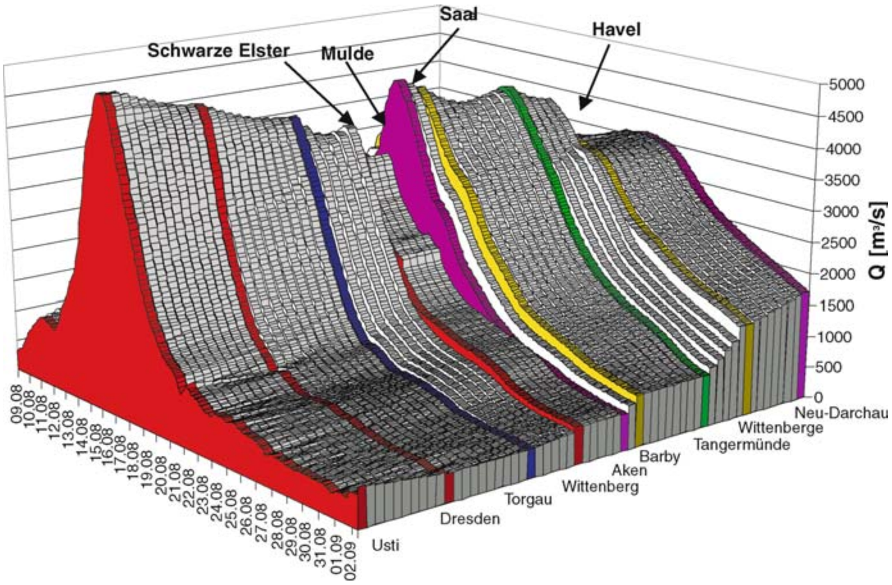

Figure 7. Spatial-temporal diagram of flow of the river Elbe. Courtesy of Dr Engel, Bundesanstalt für Gewässerkunde, Koblenz, Germany.

and local authorities 1.8, trade and industry 1.7, federal infrastructure 1.6, agriculture 0.29, other losses 1.7.

The 2002 deluge resembled historic events from remote past. For example, on 21 July 1342, a St. Magdalene's flood, caused by intensive rain, devastated large areas of Europe, causing thousands fatalities and immense destruction. Yet, apart from the record set in Dresden, the all-times historic flood records on the river Mulde in Döbeln (1897) and Grimma (1573) were exceeded in August 2002 by 126 cm, and 136 cm, respectively (Becker and Grünewald, 2003). The two types of disastrous floods occurring in the past were: summer floods in June–July–August, caused by intense precipitation, and winter floods caused by snowmelt, ice-advances and ice-blocking.

From the viewpoint of spatial extent of precipitation, its intensity and duration (a wave of two wet spells), hence – precipitation totals, the August 2002 event was exceptional.

During the 2002 flood, the structural defences – important element of the flood preparedness system – occurred to be insufficient. Dikes were found to be in need of heightening and strengthening. However, since the building of dikes has taken most of natural inundation areas, a strong opinion was voiced for a need "to give rivers their floodplains back". Sealing of land surface reduced retention and accelerated runoff. Careless development of areas exposed to flooding has amplified the impact. Most riparians have not been aware that indeed no technical protection gives a perfect safety, and that there exist no measure preventing inundations during really extreme floods, which are rare, but not impossible. So, in case of a rare flood, even an optimal flood protection system, composed of both structural and non-structural measures, can only minimize the damage, rather than guarantee a complete protection.

3.3. HAS THERE BEEN A TREND?

Mudelsee *et al.* (2003) found no upward long-term trends in the occurrence of extreme floods in central Europe. In their considerations, they included such factors as reservoirs and deforestation, and found that they have had minor effect on flood frequency. The instrumental database used in their study was extended by concatenation of the historical database, of a largely different (lower) accuracy. In the instrumental dataset, decrease in winter flood occurrence over the last century was observed, with fewer events of strong freezing. For 1920–2002, and for 1852–2002, decreasing numbers of winter floods were observed for the Oder and the Elbe, respectively. Indeed, winter floods, which were so frequent in the past, have become quite rare now. For instance, the last ice flood on the Elbe and the Oder took place in 1947. Mudelsee *et al.* (2003) found trends for major summer flood events (classes 2–3) at significance level of 90% neither on the Elbe nor on the Oder, except for an upward trend for all flood events (including minor ones) and with correction for reservoirs. In their analysis of extreme precipitation events during the 20th century, Mudelsee *et al.* (2003) found increasing trend (90% level) for gridded monthly precipitation values at 50° N and 15° E (containing nearly the entire catchment of the Elbe at Dresden and part of the catchment area of the Oder at Eisenhüttenstadt) and no significant trend at 50° N and 18.75° E (containing eastern and southern parts of the Oder catchment plus large areas beyond the basin). Historical precipitation data consisted of homogeneized monthly estimates for grid boxes of the size of 2.5° latitude × and 3.75° longitude. Even if Elbe and Oder are large rivers, yet monthly interval is not adequate temporal resolution for studying intense precipitation and floods.

However, it is important to note that climate is just one of several important factors controlling the process of river flow. Figure 8 illustrates changes in annual maximum river flow of the river Warta (large right-hand tributary to the Odra) at the Poznań gauge. There has been a clearly decreasing long-term tendency in annual maximum flow, which is difficult to explain by climatic impacts. The tendency can be explained by direct human interference (changes in storage, land use, and melioration).

4. Intense Precipitation – What Changes are Expected in Central Europe?

Based on results of climate models, it is projected that changes of mean precipitation will significantly differ from changes of the potential future

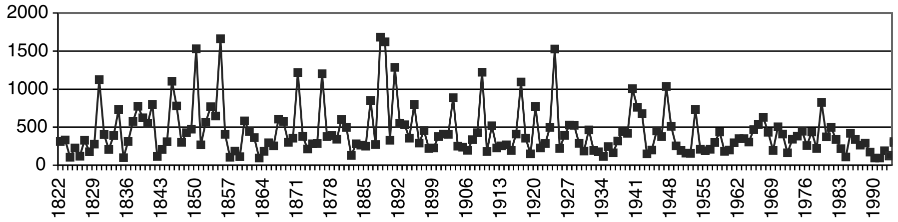

Figure 8. Maximum annual flow of the river Warta, gauge Poznań. (Source: Graczyk *et al*., 2002.)

occurrence of extreme precipitation events in central Europe, which are likely to become more intense and more frequent. For example, Christensen and Christensen (2003) used the regional climate model HIRHAM4 (Christensen *et al*., 1998), arriving at the conclusion that the amount of summer precipitation exceeding the 95th percentile is very likely to increase in many areas of Europe, even if the mean summer precipitation may decrease over a substantial part of the European continent. However, climate models are not overall consistent with respect to the direction of change on mean summer precipitation over central Europe (IPCC, 2001a). But, up to recent results, it seems likely that for broad parts of the investigation area the mean summer precipitation will decrease, corroborating the general projection of enhanced summer drying over continental interiors, while the amount of precipitation related to extreme events will increase.

The regional climate model considered here is the Hadley Centre (Bracknell, UK) model HadRM3. It is driven by the global atmospheric model HadAM3, following the dynamical downscaling technique. Details about the model physics and used parametrizations of the Hadley Centre model family can be found e.g. in Pope *et al*. (2000), Gordon *et al*. (2000) or Collins *et al*. (2001). In order to study a climate change signal, two 30-year time periods are compared. For present-day climate conditions the period 1961–1990 is assumed as representative, whereas a possible future scenario is represented by the period 2070–2099. The climate model experiments were based on the IPCC SRES (Special Report on Emission Scenarios) marker scenario A2 (cf. Nakicenovic *et al*., 2000).

One index used for the quantification of intense precipitation events is defined via the number of days with 24-h precipitation, exceeding an arbitrarily selected threshold of 10 mm. For Europe, the climate change signal for 2070–2099 (Figure 9) reveals a reduction in the number of intense rainfall events in the southern Europe and an increase over northern Europe.

Understanding of intense precipitation can be enhanced, when the daily precipitation produced by the model is separated into different intensity classes. The lower percentiles of daily precipitation over the upper part of the

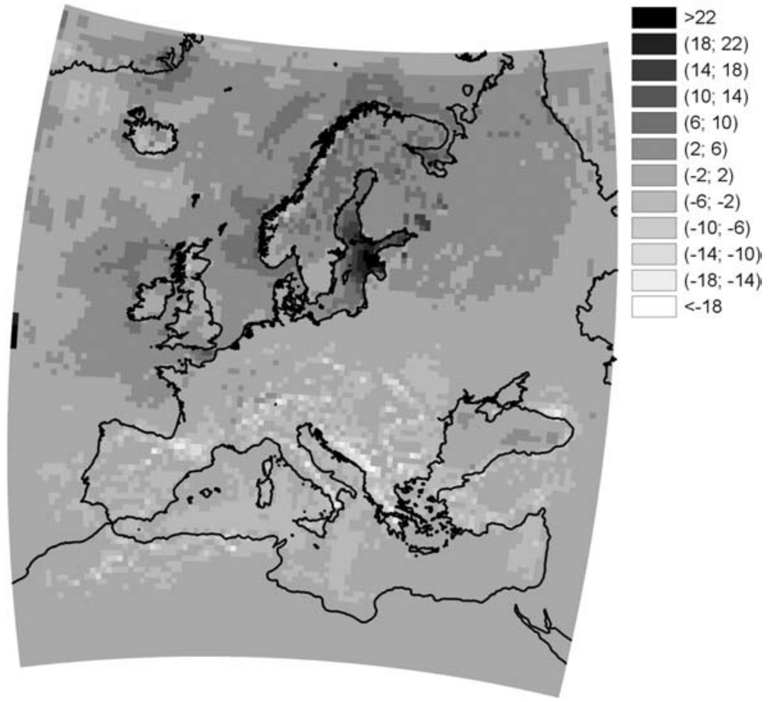

Figure 9. Number of days with 24 h precipitation, exceeding a threshold of 10 mm. Comparison of climate change signal simulated by HadRM3-P for the control period in the 20th century (1961–1990) and the future horizon of interest (2070–2099). The climate model experiment was run for SRES scenario A2a. Results obtained in the Research Centre of Agricultural and Forest Environment, Polish Academy of Sciences within the MICE Project.

Odra/Oder river basin are projected to decrease slightly, while the higher ones are likely to increase considerably (Figure 10). Looking at the drainage basins of all three large rivers of central Europe – Elbe (Labe), Odra (Oder), and Vistula, where dramatic flooding have occurred recently, one can note an increase in heavy precipitation (Figure 11) in projections for future maximum daily precipitation, likely to have important, and adverse, consequences for flood risk.

A corroborating result is produced when different global climate models are considered. The global models ECHAM4/OPYC3 (cf. Roeckner *et al.*, 1992, 1996) and HadCM3, both representing state-of-the-art coupled climate models, have been selected for analysis. The validation of global simulation (ECHAM4/OPYC3 and HadCM3) precipitation data has proved that the general characteristics of summer and winter half-year precipitation compare well to the station data for areas in central Europe, reproducing trends existing in the observations in the last 40 years (decrease in summer and

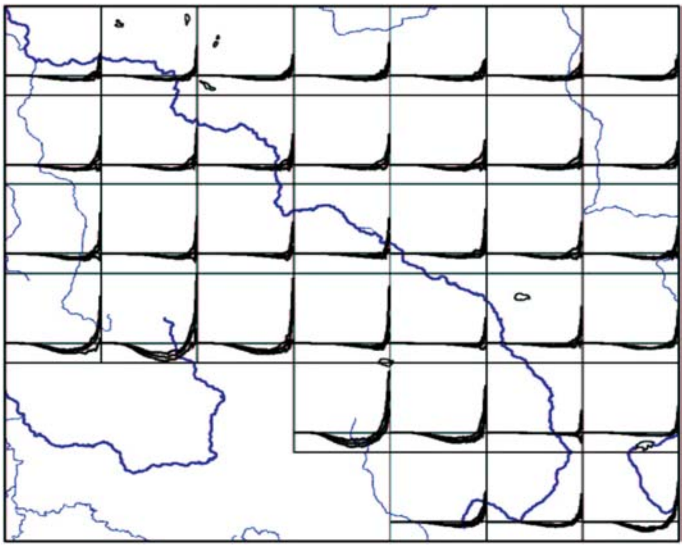

Figure 10. Climate change signal for different intensity classes of daily precipitation for the Odra basin (HadRM3 grid cells). Comparison of 1961–1990 and 2070–2099. For every grid cell considered, there is a diagram of changes of precipitation in different intensity classes. The x and y axes represent, respectively, precipitation intensity and change in precipitation of a particular intensity. Diagrams presented in individual grids show a decrease in low-intensity precipitation and an increase in high-intensity precipitation. Results were obtained in the Research Centre of Agricultural and Forest Environment, Polish Academy of Sciences within the MICE Project.

increase in winter), cf. Krüger (2002). For the Dresden area, changes of the daily precipitation amount per intensity class are shown in Figure 12 for summer (June, July, August) and for time intervals 2060–2089 *versus* 1930–1959. For ECHAM4/OPYC3 (a spectral model with a horizontal resolution of T42) the grid box area centred around 51.6257° N and 14.06257° E was selected, for HadCM3 four grid cells were chosen, for the regional model (HadRM3), nine grid cells have been selected. This was done in order to achieve a higher level of representativeness, as especially in the regional model the analysis of one grid cell is insufficient. The classification was done separately for each grid cell, and afterwards accumulated to one signal. From analysis of the climate model outputs it becomes clear that in HadCM3 and ECHAM4/OPYC3 simulations, the amount of precipitation related to events with daily precipitation less than 16 mm per day are reduced, whereas the amount related to intense precipitation events (>16 mm) will increase under climate change conditions. For HadRM3 simulations, the increase of intense precipitation event under climate change is projected only for the most extreme events (>32 mm).

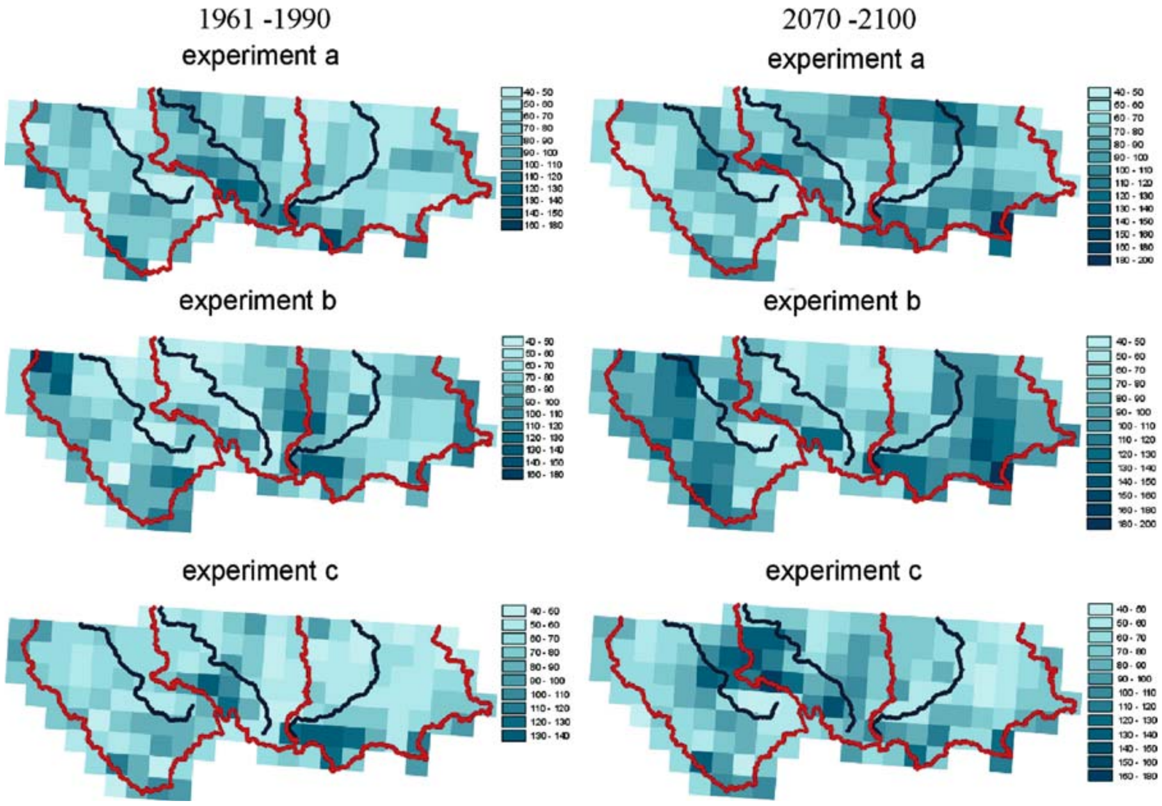

Figure 11. Maximum daily precipitation – comparison of projections for 2070–2099 *versus* the control period 1961–1990, based on HadRM3, for three model runs (a, b, c) for the upper parts of the catchments of the rivers Elbe (Labe), Odra (Oder) and Vistula. Results obtained in the Research Centre of Agricultural and Forest Environment, Polish Academy of Sciences within the MICE Project.

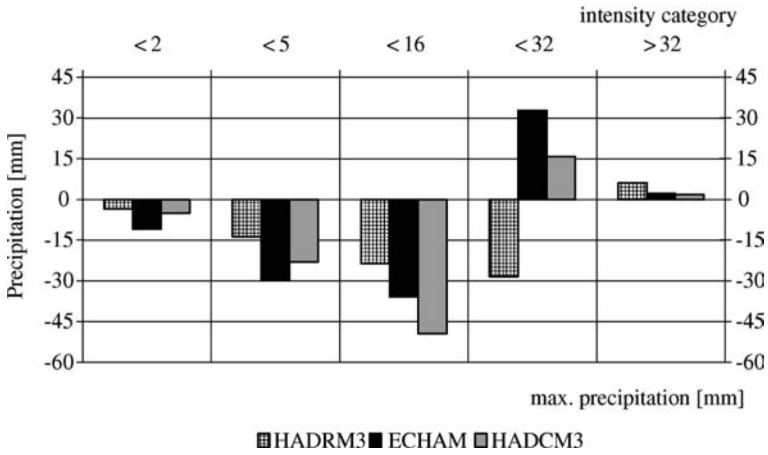

Figure 12. Changes in the daily summer (June, July, August) precipitation in different intensity classes for ECHAM4/OPYC3, HadCM3, and HadRM3, for grid box areas surrounding the city of Dresden for time intervals: 2060–2089 and 1930–1959. Result obtained in the Institute for Geophysics and Meteorology, University of Cologne.

Thus, summarizing the results presented so far, under future climate conditions (SRES A2 scenario) a tendency to a higher amount of extreme daily precipitation for summer rainfall can be diagnosed for the investigation area. This increase in intense precipitation, which is likely to increase the flood risk, is of significant concern for water management in these regions.

However, not all studies agree as to the direction of future changes in intense precipitation and flood frequency in selected catchments in central Europe. The mountainous area at the Czech-German border of the Elbe catchment, where floods along the Elbe and its tributaries frequently originate, has been investigated in terms of future flood development. In a first step, the rainfall-runoff model HBV-D (Bergström and Forsman, 1973; Menzel and Bürger, 2002) has been applied with observed climate data to reproduce historical discharge conditions, and found to perform well in the sense of mean values, showing reduction of mean discharge conditions over the scenario period. Subsequently, climate scenarios have been delivered from the stochastic method STAR (Werner and Gerstengarbe, 1997) which combines large-scale temperature change projections and locally measured, long-term time series of temperature and related climate parameters. Regional climate scenarios agree in their projections of a general mean precipitation decrease in the investigated regions and show a tendency of increasing precipitation intensities both in summer and winter, although not in a consistent way (statistically significant increases for some stations only). However, results of river flow simulations indicate reduced flood risk in the scenario period for the catchment in question. This is in contrast to clear increase in flood risk found, using the same methodology, for another examined catchment in western part of Germany. There are indeed large uncertainties resulting from the discrepancies between climatic models, problems with hydrological models (which are still not capable to reproduce small-scale, intense floods, especially when they occur during summer), and problems with the fit of the Gumbel distribution, used in flood frequency studies. Hence, further investigations are needed to confirm (or disprove) these results.

5. Possible Synoptic Causes and their Relation to Climate Change

The existence of a so called "Vb-track" situation in summer has accompanied recent occurrences of extreme precipitation events over Central Europe (cf. Ulbrich *et al.*, 2003a, b). The name "Vb-track" originates from a work of van Bebber (1891), who classified tracks of European lows. A Vb-track situation is characterized by a cyclone system travelling from the Gulf of Genoa northeastwards to central Europe. Occurrence of such situations in summer and comparison of the role of these cyclone tracks for extreme rainfall under present-day and future climate conditions are investigated. In order to detect changes of weather regimes connected with the occurrence of Vb-tracks, a specific analysis of Vb-tracks under climate change conditions, as well as an objective classification method of weather situations (Grosswetterlagen, GWL) were applied.

For the vegetation season (April to September), an algorithm from Murray and Simmonds (1991) was used for the identification and tracking of cyclone cores over the North Atlantic and European sector. This investigation was done using simulation data of the Global Climate Model ECHAM4/OPYC3, for the climatology of 1861–1930 as well as for enhanced greenhouse gas concentrations. A validation of the results with respect to NCEP-re-analysis data reveals a systematical underestimation of the number of tracks due to the model time and spatial resolution, whereas the distribution pattern (e.g. of the track density) is well reproduced (Pinto, 2002). From these identified systems only those following the pathway of typical Vb-tracks were considered. For historical climatology, the track density reaches a maximum above the Gulf of Genoa with up to 5 systems per summer, reducing to 2 or 1 system over the investigation area. The climate change signal of Vb-tracks reveals an overall reduction of the track density of the order of 20 to 30%. Thus, under changed climate, a tendency to a reduced number of Vb-track situations in summer is identified. However, the amount of rainfall related to extreme precipitation events increases. Thus, additionally an analysis of *Groswetterlagen* connected with heavy rainfall events (cf. Hess and Brezowsky, 1977; Gerstengarbe and Werner, 1993; Gerstengarbe *et al.*, 1999) was applied. Details of the applied objective classification method can be found in Krüger (2002) and Krüger and Ulbrich (submitted). Thirty different GWLs are distinguished, whereof mainly the GWL Trough Central Europe (TCE) is connected with the occurrence of Vb-track situations. In ECHAM4/OPYC3, for all days during the vegetation season, a reduction of the frequency of the TCE GWL is simulated, consistent with the reduced Vb track density. If only the days with precipitation above the 90th percentile (intensive rainfall) are considered, both models simulate an increase of the TCE GWL in summer (June to August). Thus, for days with intense rainfall events, Vb-track related circulation pattern become more important under enhanced greenhouse gas concentrations than for the present-day climate. While there are less Vb situations under enhanced GHG forcing, these situations are likely to lead to extreme rainfall more frequently than under present conditions. This increased risk is of considerable importance for flood preparedness systems.

6. Concluding Remarks

Even if the mean precipitation over catchments of large rivers in Central Europe is low, the rainfall variability is high and intense precipitation may occur, in particular in the headwaters area. After the 1997 Odra /Oder flood, the 2001 Vistula flood, and the most destructive 2002 deluge on the Labe/Elbe, river flooding has been recently recognized as a major hazard in the region.

Having observed that flood risk and vulnerability are likely to have grown in many areas, one is curious to understand the reasons for growth. These can be sought in socio-economic domain (humans encroaching into floodplain areas, land-use change), terrestrial systems (land-cover change resulting from land-use change, river regulation), and climate system. The atmosphere's capacity to absorb moisture, its potential water content, and thus potential for intense precipitation, increase in a warmer climate. General acceleration of hydrological cycle in the warming world, observed already to some extent and projected in the future to a larger extent, leads to the conclusion that intense summer precipitation events could be on the rise.

Projections show more intense precipitation events in the warming climate also for central and eastern Europe. Significant changes have been identified for the catchments of the large rivers in central Europe, between future projections and the reference period. They are of direct relevance to increase of flood hazard in areas, which have experienced severe recent floodings.

It is an open question, whether or not the Vb circulation track, responsible for major flooding has become more frequent. This type of circulation occurred several times in the year 2002. Also the search for eventual changes in cyclone tracks, subject to ongoing research, has not led to conclusive results yet.

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