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The Physical Science Basis

WG I

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important general point: even if a particular flood event may have been made more likely by human influence on climate, there is no certainty that all kinds of flood events in that location, country or region have been made more likely.

Rahmstorf and Coumou (2011) provide an example of an empirical approach to the estimation of attributable risk applied to the 2010 Russian heat wave. They fit a nonlinear trend to central Russian temperatures and show that the warming that has occurred in this region since the 1960s has increased the risk of a heat wave of the magnitude observed in 2010 by around a factor of 5, corresponding to an FAR of 0.8. They do not address what has caused the trend since 1960, although they note that other studies have attributed most of the large-scale warming over this period to the anthropogenic increase in GHG concentrations.

Dole et al. (2011) take a different approach to the 2010 Russian heat wave, focussing on attributable magnitude, analysing contributions from various external factors, and conclude that this event was 'mainly natural in origin'. First, observations show no evidence of a trend in occurrence frequency of hot Julys in western Russia, and despite the warming that has occurred since the 1960s, mean July temperatures in that region actually display a (statistically insignificant) cooling trend over the century as a whole, in contrast to the case for central and southern European summer temperatures (Stott et al., 2004). Members of the CMIP3 multi-model ensemble likewise show no evidence of a trend towards warming summers in central Russia. Second, Dole et al. (2011) note that the 2010 Russian event was associated with a strong blocking atmospheric flow anomaly, and even the complete 2010 boundary conditions are insufficient to increase the probability of a prolonged blocking event in this region, in contrast again to the situation in Europe in 2003. This anomaly in the large-scale atmospheric flow led to low-pressure systems being redirected around the blocking over Russia causing severe flooding in Pakistan which could so far not be attributed to anthropogenic causes (van Oldenborgh et al., 2012), highlighting that a global perspective is necessary to unravel the different factors influencing individual extreme events (Trenberth and Fasullo, 2012).

Otto et al. (2012) argue that it is possible to reconcile the results of Rahmstorf and Coumou (2011) with those of Dole et al. (2011) by relating the attributable risk and attributable magnitude approaches to framing the event attribution question. This is illustrated in Figure 10.18c, which shows return times of July temperatures in western Russia in a large ensemble of atmospheric model simulations for the 1960s (in green) and 2000s (in blue). The threshold exceeded in 2010 is shown by the solid horizontal line which is almost 6°C above 1960s mean July temperatures, shown by the dashed line. The difference between the green and blue lines could be characterized as a 1.5°C increase in the magnitude of a 30-year event (the vertical red arrow, which is substantially smaller than the size of the anomaly itself, supporting the assertion that the event was 'mainly natural' in terms of attributable magnitude. Alternatively, it could be characterized as a threefold increase in the risk of the 2010 threshold being exceeded, supporting the assertion that risk of the event occurring was mainly attributable to the external trend, consistent with Rahmstorf and Coumou (2011). Rupp et al. (2012) and Hoerling et al. (2013) reach

similar conclusions about the 2011 Texas heat wave, both noting the importance of La Niña conditions in the Pacific, with anthropogenic warming making a relatively small contribution to the magnitude of the event, but a more substantial contribution to the risk of temperatures exceeding a high threshold. This shows that the quantification of attributable risks and changes in magnitude are affected by modelling error (e.g., Visser and Petersen, 2012) as they depend on the atmospheric model's ability to simulate the observed anomalies in the general circulation (Chapter 9).

Because much of the magnitude of these two heat waves is attributable to atmospheric flow anomalies, any evidence of a causal link between rising GHGs and the occurrence or persistence of flow anomalies such as blocking would have a very substantial impact on attribution claims. Pall et al. (2011) argue that, although flow anomalies played a substantial role in the autumn 2000 floods in the UK, thermodynamic mechanisms were primarily responsible for the change in risk between their ensembles. Regardless of whether the statistics of flow regimes themselves have changed, observed temperatures in recent years in Europe are distinctly warmer than would be expected for analogous atmospheric flow regimes in the past, affecting both warm and cold extremes (Yiou et al., 2007; Cattiaux et al., 2010).

In summary, increasing numbers of studies are finding that the probability of occurrence of events associated with extremely high temperatures has increased substantially due to the large-scale warming since the mid-20th century. Because most of this large-scale warming is *very likely* due to the increase in atmospheric GHG concentrations, it is possible to attribute, via a multi-step procedure, some of the increase in probability of these regional events to human influence on climate. Such an increase in probability is consistent with the implications of single-step attribution studies looking at the overall implications of increasing mean temperatures for the probabilities of exceeding temperature thresholds in some regions. We conclude that it is *likely* that human influence has substantially increased the probability of occurrence of heat waves in some locations. It is expected that attributable risks for extreme precipitation events are generally smaller and more uncertain, consistent with the findings in Kay et al. (2011a) and Pall et al. (2011). The science of event attribution is still confined to case studies, often using a single model, and typically focussing on high-impact events for which the issue of human influence has already arisen. **While the increasing risk of heat waves** measured as the occurrence of a previous temperature record being exceeded **can simply be explained by natural variability** superimposed by globally increasing temperature, conclusions for holistic events including general circulation patterns are specific to the events that have been considered so far and rely on the representation of relevant processes in the model.

Anthropogenic warming remains a relatively small contributor to the overall magnitude of any individual short-term event **because its magnitude is small relative to natural random weather variability on short time scales** (Dole et al., 2011; Hoerling et al., 2013). Because of this random variability, weather events continue to occur that have been made less likely by human influence on climate, such as extreme winter cold events (Massey et al., 2012), or whose probability of occurrence has not been significantly affected either way. Quantifying how different external factors contribute to current risks, and how risks are

Alles in allem kommen immer mehr Studien zu dem Ergebnis, dass die Wahrscheinlichkeit des Auftretens von Ereignissen im Zusammenhang mit extrem hohen Temperaturen substantiell zugenommen haben, und zwar infolge der Erwärmung in großem Maßstab seit Mitte des 20. Jahrhunderts. Weil der größte Teil dieser Erwärmung sehr wahrscheinlich der Zunahme atmosphärischer Treibhausgase geschuldet ist, kann man via eines multilateralen Prozesses Einiges dieser Zunahme der Wahrscheinlichkeit dieser regionalen Ereignisse dem menschlichen Einfluss auf das Klima zuordnen.

Diese Zunahme der Wahrscheinlichkeit ist konsistent mit den Implikationen mit Studien zum Thema Einzel-Zuordnung bestimmter Umstände, wenn man auf die Gesamt-Implikationen steigender Mitteltemperaturen schaut, die über die Temperatur-Bandbreiten in einigen Regionen hinausgehen. Wir folgern, dass es wahrscheinlich ist, dass menschlicher Einfluss die Wahrscheinlichkeit des Auftretens von Hitzewellen in manchen Gebieten deutlich erhöht hat.

Es wird erwartet, dass die Risiken für extreme Niederschlagsereignisse allgemein geringer und unsicherer bestimmten Attributen zuzuordnen sind, was konsistent ist mit den Ergebnissen von Kay et al. (2011a) und Pall et al. (2011). Die Wissenschaft der Zuordnung von Ereignissen beschränkt sich immer noch lediglich auf Fallstudien, wobei oftmals ein Einzel-Modell herangezogen wird. Sie konzentriert sich typischerweise auf Ereignisse mit starken Auswirkungen, für welche durch menschlichen Einfluss schon jetzt eine erhöhte Wahrscheinlichkeit besteht.

Während das zunehmende Risiko von Hitzewellen, festgemacht als das Auftreten des Überschreitens bisheriger Rekordwerte, leicht mit der natürlichen Variabilität erklärt werden kann, die sich der global steigenden Temperatur überlagert, sind Schlussfolgerungen für ganzheitliche (holistische) Ereignisse einschließlich des Zustands allgemeiner Zirkulationen spezifiziert auf die Ereignisse, die bisher in Betracht gezogen worden waren und die sich auf die Repräsentation relevanter Prozesse im dem Modell stützen.

Die anthropogene Erwärmung bleibt ein relativ geringer Beitragender zur Gesamt-Magnitude jedweder individueller kurzfristiger Ereignisse, weil deren Größenordnung klein ist im Vergleich zum natürlichen zufälligen Wetterablauf im Kurzfristbereich (Dole et al., 2011; Hoerling et al., 2013). Infolge dieser Zufalls-Variabilität wird es weiterhin zu Wetterereignissen kommen, die mit geringerer Wahrscheinlichkeit dem menschlichen Einfluss auf das Klima geschuldet sind wie etwa extreme winterliche Kältewellen (Massey et al. 2012), oder deren Wahrscheinlichkeit des Auftretens bisher in keiner Richtung signifikant beeinflusst worden ist. Die Quantifizierung, wie unterschiedliche externe Faktoren zu gegenwärtigen Risiken beitragen und wie diese Risiken sich ändern,

changing, is possible with much higher confidence than quantifying absolute risk. Biases in climate models, uncertainty in the probability distribution of the most extreme events and the ambiguity of paleoclimatic records for short-term events mean that it is not yet possible to quantify the absolute probability of occurrence of any observed weather event in a hypothetical pristine climate. **At present, therefore, the evidence does not support the claim that we are observing weather events that would, individually, have been extremely unlikely in the absence of human-induced climate change,** although observed trends in the concurrence of large numbers of events (see Section 10.6.1) may be more easily attributable to external factors. The most important development since AR4 is an emerging consensus that the role of external drivers of climate change in specific extreme weather events, including events that might have occurred in a pre-industrial climate, can be quantified using a probabilistic approach.

in the 17th century (Section 6.2.3, Figure 6.7), followed by increases in GHG concentrations with industrialization since the middle of the 18th century (middle of the 19th century for N_2O , Figure 6.11).

When interpreting reconstructions of past climate change with the help of climate models driven with estimates of past forcing, it helps that the uncertainties in reconstructions and forcing are independent from each other. Thus, uncertainties in forcing and reconstructions combined should lead to less, rather than more similarity between fingerprints of forced climate change and reconstructions, making it improbable that the response to external drivers is spuriously detected. However, this is the case only if all relevant forcings and their uncertainties are considered, reducing the risk of misattribution due to spurious correlations between external forcings, and if the data are homogeneous and statistical tests properly applied (e.g., Legras et al., 2010). Hence this section focuses on work that considers all relevant forcings simultaneously.

10.7 Multi-century to Millennia Perspective

Evaluating the causes of climate change before the 20th century is important to test and improve our understanding of the role of internal and forced natural climate variability for the recent past. This section draws on assessment of temperature reconstructions of climate change over the past millennium and their uncertainty in Chapter 5 (Table 5.A.1; Sections 5.3.5 and 5.5.1 for regional records), and on comparisons of models and data over the pre-instrumental period in Chapters 5 and 9 (Sections 5.3.5, 5.5.1 and 9.5.3), and focuses on the evidence for the contribution by radiatively forced climate change to reconstructions and early instrumental records. In addition, the residual variability that is not explained by forcing from palaeoclimatic records provides a useful comparison to estimates of climate model internal variability. The model dependence of estimates of internal variability is an important uncertainty in detection and attribution results.

The inputs for detection and attribution studies for periods covered by indirect, or proxy, data are affected by more uncertainty than those from the instrumental period (see Chapter 5), owing to the sparse data coverage, particularly further back in time, and uncertainty in the link between proxy data and, for example, temperature. Records of past radiative influences on climate are also uncertain (Section 5.2; see Schmidt et al., 2011; Schmidt et al., 2012). For the preindustrial part of the last millennium changes in solar, volcanic, GHG forcing, and land use change, along with a small orbital forcing are potentially important external drivers of climate change. Estimates of solar forcing (Figure 5.1a; Box 10.2) are uncertain, particularly in their amplitude, as well as in modelling, for example, of the influence of solar forcing on atmospheric circulation involving stratospheric dynamics (see Box 10.2; Gray et al., 2010). Estimates of past volcanism are reasonably well established in their timing, but the magnitude of the RF of individual eruptions is uncertain (Figure 5.1a). It is possible that large eruptions had a more moderated climate effect than simulated by many climate models due to faster fallout associated with larger particle size (Timmreck et al., 2009), or increased amounts of injected water vapour (Joshi and Jones, 2009). Reconstructed changes in land cover and its effect on climate are also uncertain (Kaplan et al., 2009; Pongratz et al., 2009). Forcing of WMGHGs shows only very subtle variations over the last millennium up to 1750. This includes a small drop and partial recovery

10.7.1 Causes of Change in Large-Scale Temperature over the Past Millennium

Despite the uncertainties in reconstructions of past NH mean temperatures, there are well-defined climatic episodes in the last millennium that can be robustly identified (Chapter 5, see also Figure 10.19). Chapter 5 concludes that in response to solar, volcanic and anthropogenic RFs, climate models simulate temperature changes in the NH which are generally consistent in magnitude and timing with reconstructions, within their broad uncertainty ranges (Section 5.3.5).

10.7.1.1 Role of External Forcing in the Last Millennium

The AR4 concluded that 'A substantial fraction of the reconstructed NH inter-decadal temperature variability of the seven centuries prior to 1950 is *very likely* attributable to natural external forcing'. The literature since the AR4, and the availability of more simulations of the last millennium with more complete forcing (see Schmidt et al., 2012), including solar, volcanic and GHG influences, and generally also land use change and orbital forcing) and more sophisticated models, to a much larger extent coupled climate or coupled ESMs (Chapter 9), some of them with interactive carbon cycle, strengthens these conclusions.

Most reconstructions show correlations with external forcing that are similar to those found between pre-Paleoclimate Modelling Intercomparison Project Phase 3 (PMIP3) simulations of the last millennium and forcing, suggesting an influence by external forcing (Fernández-Donado et al., 2013). From a global scale average of new regional reconstructions, Past Global Changes 2k (PAGES 2k) Consortium (2013) find that periods with strong volcanic and solar forcing combined occurring over the last millennium show significantly cooler conditions than randomly selected periods from the last two millennia. Detection analyses based on PMIP3 and CMIP5 model simulations for the years from 850 to 1950 and also from 850 to 1850 find that the fingerprint of external forcing is detectable in all reconstructions of NH mean temperature considered (Schurer et al., 2013; see Figure 10.19), but only in about half the cases considered does detection also occur prior to 1400. The authors find a smaller response to forcing in reconstructions than simulated, but this discrepancy is consistent with

ist mit viel höherem Vertrauen möglich als die Quantifizierung des absoluten Risikos. Verzerrungen (Biases) in den Klimamodellen, Unsicherheiten bei der Wahrscheinlichkeits-Verteilung der extremsten Ereignisse und die Vieldeutigkeit paläoklimatischer Aufzeichnungen bzgl. kurzfristiger Ereignisse bedeuten, dass es bis jetzt noch nicht möglich ist, die absolute Wahrscheinlichkeit des Auftretens jedweder beobachteter Wetterereignisse in einem hypothetischen unverfälschten Klima zu quantifizieren. Daher stützen bisher die Beweise nicht die Behauptung, dass wir Wetterereignisse erleben, die individuell extrem unwahrscheinlich gewesen wären beim Fehlen von menschlichen Einflüssen auf das Klima, obwohl beobachtete Trends des Auftretens einer großen Anzahl von Ereignissen leichter externen Faktoren zugeordnet werden können. Die wichtigste Entwicklung seit AR4 ist ein aufkeimender Konsens, dass die Rolle externer Treiber des Klimawandels bei spezifischen Extremwetter-Ereignissen – einschließlich von Ereignissen, die auch in einem vorindustriellen Klima hätten auftreten können – mittels eines probabilistischen Verfahrens quantifiziert werden kann.