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ORIGINAL ARTICLE

Linking local impacts to changes in climate: a guide to attribution

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Abstract Assessing past impacts of observed climate change on natural, human and managed systems requires detailed knowledge about the effects of both climatic and other drivers of change, and their respective interaction. Resulting requirements with regard to system understanding and long-term observational data can be prohibitive for quantitative detection and attribution methods, especially in the case of human systems and in regions with poor monitoring records. To enable a structured examination of past impacts in such cases, we follow the logic of quantitative attribution assessments, however, allowing for qualitative methods and different types of evidence. We demonstrate how multiple lines of evidence can be integrated in support of attribution exercises for human and managed systems. Results show that careful analysis can allow for attribution statements without explicit end-to-end modeling of the whole climate-impact system. However, care must be taken not to overstate or generalize the results and to avoid bias when the analysis is motivated by and limited to observations considered consistent with climate change impacts.

Keywords Observed impacts of climate change · Impact detection · Attribution · Human and managed systems · Multiple drivers

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Introduction

Human interference with the climate system has been visible at global scales for some time and is increasingly becoming apparent at regional scales (Stott et al. 2010; Bindoff et al. 2013). Consequently, the rigorous attribution of changes in local environmental conditions to changes in climate, and specifically the detection of climate change impacts in human systems and sectors interlinked with them, is gaining importance and public attention. Recent assessments of historical responses to climate change have drawn upon large amounts of direct observational evidence, applying formalized procedures for the detection and attribution of observed impacts (Rosenzweig and Neofotis 2013; Cramer et al. 2014).

While impacts of recent climate change are now documented for all continents and across the oceans, geographical imbalances and gaps in the documentation of impacts for human and managed systems remain. Based on scientific knowledge about the sensitivity of many human and managed systems to weather and climate variability, it is plausible to expect that recent climate change will have had a role in locally observed changes. However, confident detection of local effects in historical data remains challenging due to naturally occurring variability in both climate and potentially impacted systems, and the influence of other important drivers of change, such as land use, pollution, economic development and autonomous or planned adaptation (Nicholls et al. 2009; Bouwer 2011; Hockey et al. 2011). Often, the specification of a numerical model representing the entire climate-impact system may not be feasible. In those cases, the careful examination of the individual steps of the causal chain linking climate to impacts can still provide insight into the role of recent climate change for the system in question. The goal of this paper is to provide guidance for such an approach to the detection and attribution of impacts of observed changes in climate.

Detection and attribution refer to the identification of responses to one or several drivers in historical observations, and a range of corresponding methods exists across research disciplines (Stone et al. 2013). In the context of climate change research, detection and attribution methodologies have been developed mostly in the field of physical climate science, where a substantial literature presents various model-based statistical approaches to the question how effects of anthropogenic forcing can be identified in historical climate data (see Barnett et al. 1999; Hegerl et al. 2007; Bindoff et al. 2013).

In contrast, efforts to develop overarching methods for the detection and attribution of observed impacts to climate change are limited (Stone et al. 2009; Hegerl et al. 2010; Stone et al. 2013). Studies that explicitly attribute individual observed impacts of climate change to anthropogenic forcing of the climate system are rare. They usually combine observational data and process or statistical models of the impact system with climate model simulations representing the historic, anthropogenically forced state of the climate system, and a hypothetical, natural state (Gillett 2004; Barnett et al. 2008; Christidis et al. 2010; Marzeion et al. 2014). In addition, methods have been developed to evaluate the role of anthropogenic forcing in large-scale patterns of multiple local impacts, mainly in ecology. These include the identification of so-called fingerprints of anthropogenic climate change in large sets of biological data (Parmesan and Yohe 2003; Root et al. 2003; Poloczanska et al. 2013), joint attribution (Root et al. 2005) and joint attribution combined with spatial pattern congruence testing (Rosenzweig et al. 2007, 2008). Generally, these approaches aim at the identification of a generic impact of anthropogenic climate change, which would emerge from analyzing a large number of cases in parallel, given that it is often not possible to confidently attribute changes in individual local records to anthropogenic forcing for technical reasons (Rosenzweig and Neofotis 2013; Parmesan et al. 2013).

The vast majority of impact studies are concerned with the identification of effects of regional changes in one or several climate variables in the context of multiple interacting drivers of change (Cramer et al. 2014). Methods for detecting and explaining change are a key part of many disciplines studying natural, human and managed systems, and can be applied in the context of attribution to climate change. For example, reliable process-based models have been developed and applied in climate attribution analysis for some species and crops (e.g., Battisti et al. 2005; Brisson et al. 2010; Gregory and Marshall 2012). Statistical models are increasingly being used to assess large-scale effects of recent climate change (e.g., Lobell et al. 2011b; Cheung et al. 2013). However, explicit numerical modeling of the climate-impact system is not always feasible (see also Sect. 2). Instead, conclusions about cause and effect are often inferred from a combination of multiple lines of evidence, such as process understanding, local knowledge, field and model experiments, observations from similar systems in other locations, or statistical analysis of observational data (see Sect. 3).

Below, we will focus on impact detection and attribution in a multi-step analysis, based on a structured examination of multiple lines of evidence. In doing so, we follow the approach proposed by Stone et al. (2013) and applied in Cramer et al. (2014) and elsewhere in the WGII contribution to the fifth assessment report (IPCC 2014a, b). This approach is inspired by the framework laid out by the IPCC good practice guidelines for detection and attribution related to anthropogenic climate change (Hegerl et al. 2010), but introduces the important modification that impact detection "addresses the question of whether a system is changing beyond a specified baseline that characterizes its behavior in the absence of climate change" (see also IPCC 2014c).

Detection of change in the climate system is concerned with the identification of a signal or trend beyond the short-term variability caused by internal processes. However, the underlying assumption of a stable natural baseline state, with stochastic-like variability superimposed may not be valid or practical in the case of some impact systems, particularly those involving humans. Many impact systems are undergoing constant change due to internal dynamics as well as external drivers, which often interact and change over time. The observation of a trend in the overall behavior of such a system, or a lack thereof, may not, on its own, be informative for assessing whether a response to climate change or any other driver has been detected (see also Sect. 2). The main concern of impact detection is to identify the effect of climate change against that of other drivers of change. Therefore, the detection of a climate change impact must involve the explicit testing for confounding factors. In that sense, impact detection can not be entirely separated from attribution (see Stone et al. 2013).

In this paper, we discuss the major steps involved in a complete evaluation of the causal chain from recent changes in climate to locally observed impacts. Following this introduction, we outline the required steps for a comprehensive impact detection and attribution analysis in Sect. 2. We focus on distinguishing the effects of climate change from those of non-climate drivers, rather than evaluating the anthropogenic contribution to the observed change in climate. In Sect. 3, we apply the resulting procedure in an analysis of several examples from human and managed systems, based on available literature. Those cases illustrate some of the major challenges involved, including the treatment of systems undergoing change from multiple drivers, and the integration of different types of evidence. We further discuss those challenges and the limits and values of the detection and attribution of climate change impacts in Sect. 4, and provide brief conclusions in Sect. 5.

The five steps of an impact detection and attribution analysis

The logic of quantitative detection and attribution analysis—if not the methods—can also be applied to qualitative studies and those that combine various sources of evidence. That logical flow follows from a classical hypothesis test. Briefly, to test whether climate change has had an effect on a system, a suitable regression or other model reflecting the knowledge of the system is specified. This model includes a possible effect due to climate change as well as other potentially influential factors. The statistical test is then based on comparing the goodness of fit of the model with climate change to that of the model without climate change. In both cases, the model is fitted by optimizing a measure of the goodness of fit. If the correctly specified model that includes the effect of a changing climate provides a significantly superior fit than the model that does not, we conclude that the data are not consistent with the null hypothesis that climate change has not had an effect: In other words, we have detected a climate change impact. If we are also interested in the magnitude of the contributions of the various drivers, the fitted model provides a way of assessing these (e.g., based on the regression parameters).

The focus on impacts of recent climate change mostly restricts attention to cases in which the design involves a trend in climate (which may, in turn, be consistent with the effect of anthropogenic forcing). The identification of a trend over time in relevant climate variables is therefore part of the analysis. It is important to note that in order to avoid bias, the hypothesis taken as the starting point should not be formulated from the same data used to test it. Rather, it may be drawn from theory, e.g., model predictions, or independent data, such as observations in a similar system in a different location. It can also be helpful to differentiate between known external drivers of a system, which are explicitly accounted for in the specification of the baseline behavior, and confounding factors such as measurement errors, data bias, model uncertainty and influences from other potential drivers that are not explicitly considered in the study setup, but need to be controlled for (Hegerl et al. 2010).

Below, we outline the major steps involved in a comprehensive detection and attribution analysis in the context of climate change impacts (see Fig. 1).

1. Hypothesis formulation: identification of a potential climate change impact;
2. Observation of a climate trend in the relevant spatial and temporal domain;
3. Identification of the baseline behavior of the climate-sensitive system in the absence of climate change;
4. Demonstration that the observed change is consistent with the expected response to the climate trend and inconsistent with all plausible responses to non-climate drivers alone (impact detection);
5. Assessment of the magnitude of the climate change contribution to overall change, relative to contributions from other drivers (attribution).

Hypothesis

A common source of hypothesis is a prediction of an effect of expected anthropogenic climate change based on system understanding. For example, if an impact of future anthropogenic climate change has been predicted in an earlier analysis, one could test whether that effect is now detectable in accumulated observations. Another source might be the detection of impacts in similar systems in other locations, or observations from the recent past, or from paleo records. Naturally, studies will also be motivated by observations of change in the climate-sensitive system; while it is unrealistic to ignore that motivation, efforts need to then be made to minimize the effect of the resulting selection bias or to evaluate its importance (Menzel et al. 2006). A central part of this first step is the identification of metrics that characterize the expected response of the system to climate change.

Climate trend

In order to detect an impact of observed climate change on a system, the climate must actually have changed and also

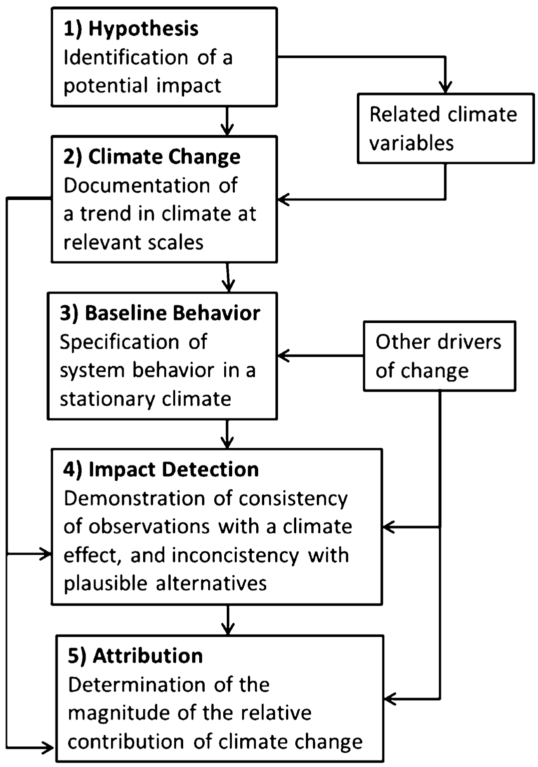

Fig. 1 Schematic of the five steps of detection and attribution of observed climate change impacts. Note that in practice the specification of the baseline behavior and the detection and attribution steps may be performed in parallel, given they all require explicit examination of all drivers of change in the system

have been observed to have changed for the relevant location and period. This condition distinguishes an impact study from a pure sensitivity analysis. Climate change is defined by the Intergovernmental Panel on Climate Change (IPCC) as "a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer" (IPCC 2014c). In that sense, we consider a change in climate any long-term (e.g., 20 years and more) trend in a climate variable that is substantial in relation to short time scale variability, regardless of the cause of that trend.

A local climate trend is not necessarily caused by anthropogenic climate change. While it is plausible to assume that a local temperature trend that is consistent with the temperature trend in the larger area, which in turn has been attributed to global climate change, may also be caused by anthropogenic forcing, this must not be taken as proven. In general, individual and local climate records show higher variability than aggregated or global measures (Bindoff et al. 2013). Local climate is influenced by topography and turbulence, but also by other local factors such as water management or land use change. As a result, local trends may run contrary to or enhance the global warming signal or may not emerge at all. Changes in atmospheric circulation patterns or multidecadal natural variability could also generate local trends that differ from global ones. The question of how one might determine whether an observed trend is anthropogenically forced is beyond the scope of this paper, but has been considered elsewhere (Stott et al. 2010).

Systems may be sensitive to aspects of the climate other than the average, such as temperature exceeding 30 °C during a certain period in plant development (e.g., Lobell et al. 2011a). The chosen metric needs to reflect this aspect of the expected climate change.

Baseline

For some situations, the identification of a deviation from baseline behavior is relatively straightforward: The metric shows a trend consistent in direction and magnitude with what one would expect under climate change and that trend is also inconsistent with what could be plausibly expected as the effect of one or a combination of other known drivers in a stationary climate, either because those drivers are of insufficient magnitude or they mutually cancel. However, in most human and managed systems, we expect the observed overall response to be consistent with the combined effect of climate change and other drivers, but not with that of climate change alone. The failure to account for all drivers in the baseline may lead to erroneous conclusions about the influence of climate change on a system, as illustrated in Fig. 2.

So, in order to evaluate whether a climate change effect has been observed the baseline behavior of the system *in the absence of climate change* has to be specified (Stone et al. 2013). For some systems, that behavior may be nonstationary even in the absence of all drivers.

As a world without climate change cannot be observed directly, the baseline must be constructed using statistical techniques, observations of analogous systems and/or system understanding expressed in the form of numerical or conceptual models. Specifying a reliable model is often hampered by lack of data, incomplete knowledge on processes and mechanisms involved in systems undergoing change from multiple stressors, limited understanding of causality within complex networks of social systems, and how climate drivers and their perception influence those. In addition, research in qualitative social sciences focuses on descriptive, non-numerical understanding of how systems behave and interact and is often site- or case specific. For a comprehensive assessment of impacts on humans systems, expectations of baseline behavior may have to be developed and adopted based on qualitative methods.

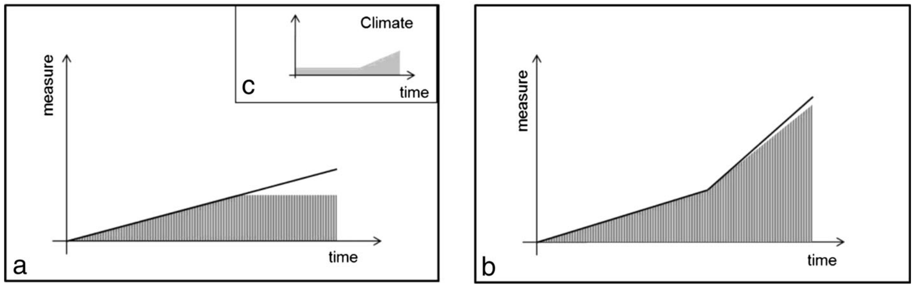

Fig. 2 Stylized examples of the time series of some measure representing a climate-sensitive system that is responding in time to multiple drivers, one of them climate change (the corresponding time series of the climate variable for both cases is shown in *panel c*). The *black line* depicts the overall behavior of the system, while the *dark, vertically striped area* represents the combined effect of non-climate drivers under stationary climatic conditions, and the *light area* represents the additional effect due to recent climate change. In *panel a*, the baseline condition (*dark area*) shows a clear change midway through the record (e.g., due to a policy measure), but this is compensated by the influence of climate change. However, the resulting overall measure does not show a deviation from its historical pre-climate change trend, thus masking the existing climate change effect (potential type I error). In *panel b*, the observed behavior shows a change that is consistent in direction with a predicted climate change impact; however, the majority of that change happens due to a change in the baseline arising from other factors. This situation could lead to erroneous detection (potential type II error) or an overstatement of the climate effect

Impact detection

For natural, human and managed systems, impact detection addresses the question whether a system is changing beyond a specified baseline that characterizes behavior in the absence of climate change (IPCC 2014c). In other words, impact detection requires the demonstration that an observed long-term change in a system cannot be fully accounted for by non-climate drivers. So, in order to detect an impact, it is not sufficient for climate change to be a plausible explanation, but it must also be shown that there is no (equally valid) alternative mechanism for the observed change (see also Fig. 2).

In well-observed systems, a common way to investigate the effect of a driver on an outcome in the presence of other drivers is multiple regression analysis. To detect a climate change impact, the null hypothesis that climate change has not affected the outcome has to be tested, controlling for the impact of other drivers and confounding factors, including autonomous and planned adaptation. If the null hypothesis is rejected using a correctly specified model, a climate change impact has been detected. Following this statistical approach, a detection statement is always binary: An impact has (or has not) been detected at a chosen level of significance.

However, in many systems of interest, quantitative models representing causal relationships will be either impossible to construct or incompatible with the type of data available. In these situations not amenable to statistical testing, a detailed discussion of the role of other drivers and potential confounding factors such as measurement errors or data bias may provide a thorough evaluation of the various hypotheses. Though not directly comparable to the results of a rigorous analysis of long-term data, a clear and comprehensive qualitative analysis represents a valid form of evidence that should not be dismissed.

Attribution

Attribution needs to examine all drivers of change that influence the system and evaluate their relative contribution to the detected change. Impact detection implies that climate change has had at least a minor role in the observed outcome. Assessing the magnitude of the contribution of climate change to an impact is a separate, but equally important matter in a detection and attribution exercise.

An attribution statement needs a qualifier describing the relative importance of climate change to an observed impact. This involves either simply an ordinal statement (e.g., climate is the main influence responsible for a change) or a cardinal statement, which of course requires estimation of the exact relative magnitude of the contribution of climate change in relation to other drivers (see also Stone et al. 2013). The descriptor relates to the size of the response to the climate driver relative to that to other drivers of change in the system, regardless of the direction of that change. While it may be relevant in other ways, the absolute size of the impact is not vital to the attribution statement.

A key challenge for all attribution exercises consists of accounting for non-additive effects of multiple drivers interacting on several temporal and spatial scales (see Parmesan et al. 2013; Oliver and Morecroft 2014). While of particular concern for human and managed systems, such effects have also been shown in analyses of large datasets of biological changes (Crain et al. 2008; Darling and Cote 2008).

Impact attribution assessments—examples from human and managed systems

In this section, we provide examples that illustrate the challenges of thorough assessments of climate change impacts. The examples were chosen to cover a range of different conditions in terms of quality and type of evidence, and clarity of climate trends and observations. In line with the focus of this paper, we selected examples from human and managed systems, and from world regions that are currently underrepresented in the literature. The assessments are based on available literature at the time of writing and provide a summary of the more complex considerations detailed in the underlying literature. As detection is a necessary condition for attribution, the attribution step is omitted in cases where a climate impact has not been detected.

Fisheries productivity on Lake Victoria

Hypothesis

The inland fisheries of the Great Lakes are an important food source for the human population of Eastern and Southern Africa, with Lake Victoria having the largest freshwater lake fishery in the world. An expected outcome of anthropogenic climate change is warming of the Great Lakes, with faster warming at the surface increasing stratification (Lehman et al. 1998; Verburg and Hecky 2009). Along with the direct effects of warming, increased stratification is expected to limit nutrient recycling, consequently leading to increased abundance of algae and hypoxic conditions detrimental for the large fish supporting the regional fishery industry (Lehman et al. 1998). Hence, the fishery catch per unit effort would be expected to have decreased on Lake Victoria.

Climate trends

Atmospheric warming has occurred in the Great Lakes region (Verburg and Hecky 2009; Ndebele-Murisa et al. 2011), and lake surface waters appear to have warmed, too (Sitoki et al. 2010; Loiselle et al. 2014). Analyses of sediment cores suggest that the surface waters of other large Great Lakes have warmed to temperatures unprecedented in at least the last 500 years (Tierney et al. 2010; Powers et al. 2011). A strengthening of the thermocline (and hence increase in stratification) has been observed before 2000, but appears to have weakened since, possibly due to variability in local wind regimes (Stager et al. 2009; Sitoki et al. 2010).

Baseline

The Great Lakes region has experienced a number of major environmental changes over the past few decades. The Nile Perch, a large predatory fish, and the Nile Tilapia were introduced in 1954–1964, and both species now comprise the bulk of the catch on Lake Victoria (Hecky et al. 2010). A fundamental and rapid change in the fish community occurred in the early 1980s, and fishing effort has increased in recent decades (Kolding et al. 2008). The invasive spread of the water hyacinth had disrupted lake access and transport on Lake Victoria in the 1990s until the more recent introduction of the weevil (Hecky et al. 2010).

Much of the land surrounding Lake Victoria has been converted to agriculture, leading to increased runoff of nutrients (Stager et al. 2009; Hecky et al. 2010). Like warming, this would be expected to contribute to increased eutrophication, increased thermal stratification (by increasing algal abundance), and a shift in species composition and decreased species diversity.

Impact detection

The dramatic rise in both absolute fish catch and catch per unit effort observed on Lake Victoria during the 1980s coincided with the large-scale establishment of the introduced Nile Perch. Altered predation dynamics due to a change in the light regime caused by the increased abundance of algae facilitated the success of the Nile perch (Kolding et al. 2008; Hecky et al. 2010). Another marked rise in catch of a native species in the 2000s is temporally linked to improved lake access after the establishment of efficient control of the water hyacinth (Hecky et al. 2010). That rise is not reflected in other species, and the relation to catch per unit effort is not documented; the Nile perch catch has been stable since the 1980s despite increased effort.

These catch changes are linked to other changes in the ecology of the lake, which indicate the possible ultimate causes. Increases in primary productivity and algal abundance were documented in the decades before 2000, though both may have decreased since (Stager et al. 2009; Hecky et al. 2010; Sitoki et al. 2010; Loiselle et al. 2014). Increases are consistent with warming, increased nutrient supply from agricultural development, and decreased abundance of planktivorous fish species caused by the introduced predators (Hecky et al. 2010); the possible recent decrease in algal biomass could be indicative of a decreased catch per unit effort, as decreases in abundance of large predators allow populations of smaller fish species to recover. While the expected effects of species introductions can be distinguished from the expected response to warming, the responses to increased agricultural runoff and increasing fishing effort are harder to differentiate. Thus, while current evidence may suggest a response to warming beyond the responses to other drivers, considerable uncertainties remain.

Attribution

While anthropogenic climate change may become the dominant driver of the biology and productivity of the Great Lakes in future decades, current evidence is unable to distinguish whether the influence of warming has already been comparable to or much smaller than that of other drivers of environmental change in the region.

Crop production in Southeast South America

Hypothesis

In Southeast South America, significant increases in summer crop productivity and the expansion of agricultural areas have been observed over the last decades. Given that agricultural activity in the region is often constrained by the amount of rainfall, wetter conditions are expected to have contributed to these trends.

Climate trends

Southeast South America refers to the South American area south of 20°S and east of the Andes, excluding Patagonia, and includes the important agricultural production center of the Argentinean Pampas, South-Eastern Brazil, Paraguay and Uruguay. Past precipitation and temperature trends are well-documented over the area (Giorgi 2002; Barros 2010; Magrin et al. 2014). The region has warmed by roughly 1 °C since the mid-1970s, and the frequency of warm nights has increased. Over the same period, there has been a reduction in the number of overall dry days (Rivera et al. 2013) and dry months in the warm season (Vargas et al. 2010), and increases in precipitation led to a westward shift of the 600 and 800 mm isohyetal lines (Barros 2010; Doyle et al. 2011).

Baseline

Across the region, socioeconomic factors such as policy incentives, market conditions, population growth and agronomic developments have positively affected cultivated area and agricultural productivity. The introduction of short-cycle soy varieties, no-till cropping systems and a general intensification of agriculture following macroeconomic development contributed to the expansion of agricultural activities into formally marginal land (Baldi and Paruelo 2008; Asseng et al. 2012; Hoyos et al. 2013).

Impact detection

Agricultural activity in the region is predominantly rain fed. The wetter and partly warmer conditions observed since the 1970s are consistent with varying, but substantial increases in yields observed in particular in those areas of Argentina, Uruguay and Southern Brazil where precipitation was the limiting factor in the first half of the century (Magrin et al. 2005, 2007). In the semi-arid and sub-humid areas at the western and northern fringe of the Argentinean Pampas, increases in precipitation enabled a shift of the "agricultural frontier" of about 100 km to the West into formally semi-arid land (Barros 2010).

In order to examine the role of different drivers in the expansion of agricultural land, Zak et al. (2008) and Hoyos et al. (2013) study the conversion of Chaco forest into crop- and rangelands in an area at the Northern fringes of the Argentinean Pampas. They show that conversion rates in the Western part of their study region, which did not experience increases in precipitation, are considerably lower than those in the Eastern part, where they document upward trends in precipitation. As both regions exhibit otherwise very similar conditions, they conclude that climate change is an important enabling factor of the observed agricultural expansion, synergistically with technological changes and socioeconomic drivers. The case is less clear for the La Plata basin, where no such natural comparative area has been identified and studied, and the pattern of land types converted does not allow for a clear distinction of the role of the climate trends (Baldi and Paruelo 2008) as opposed to other factors.

Magrin et al. (2005) use crop models to study the relative effects of observed changes in temperature and precipitation on yields in the Argentinean Pampas. They examine observed yields of four main crops (sunflower, wheat, maize and soy) in nine representative zones across the region. They conclude that climate change had non-negligible favorable effects beyond technological changes. In a similar exercise for six zones that extended to locations in Uruguay and Brazil, Magrin et al. (2007) found substantial positive climate change effects on yields in particular for summer crops. Effects were strongest in the originally drier regions.

Attribution

Recognizing what Zak et al. (2008) call "synergistic consequences of climatic, socioeconomic, and technological factors", climate change is estimated to be a major driver of the observed increases in summer crop yields and of the expansion of agricultural land into the formally semi-arid regions of South Eastern South America, while the magnitude of its role for other areas and crops is less clear.

Agroforestry systems in the Sahel

Hypothesis

Drought and heat-induced tree mortality is increasingly reported from many locations worldwide (Allen et al. 2010).

The pronounced drought over the western Sahel for much of the second half of the twentieth century would be expected to result in negative impacts on agroforestry systems.

Climate trends

Rainfall decreased markedly over the western Sahel in the few decades after 1950, resulting in extremely dry conditions during the 1970s and 1980s; there has been some recovery of the rains since 1990 but totals remain well below the mid-twentieth century values (Greene et al. 2009; Lebel and Ali 2009; Biasutti 2013). Like many regions of the world, the western Sahel has also warmed on the order of 1 °C during that time (Niang et al. 2014), promoting drought conditions.

Baseline

With a growing population, there has been a large increase in agricultural area in the western Sahel at the expense of wooded vegetation (Brink and Eva 2009; Ruelland et al. 2011). The growing population may also be harvesting a larger amount of firewood. The basic structure of the agroforestry system and its management by local farmers have been reported to be fairly stable over the period covered here (Maranz 2009).

Impact detection

Over the past half century, there has been a decrease in tree density in the western Sahel noted through field survey as well as aerial and satellite imagery (Vincke et al. 2010; Ruelland et al. 2011; Gonzalez et al. 2012), and by local populations (Wezel and Lykke 2006). Because of their sensitivity to moisture deficits, trees would be expected to become less densely spaced during long-term soil-moisture drought. Tree mortality has been more pronounced for introduced or managed fruit-bearing trees, which may be less adapted to decadal-scale drought conditions that appear typical of the western Sahel than the native vegetation (Wezel and Lykke 2006; Maranz 2009).

The patterns of tree cover changes remain correlated with the combined effects of the warming and drying trends after accounting for the effects of other factors (Gonzalez et al. 2012). Moreover, the enhanced mortality among introduced species in relation to indigenous species is more consistent with the effect of climate change than with that of the other drivers listed above (Wezel and Lykke 2006; Maranz 2009).

Attribution

The harvesting of firewood does not appear to have played a substantial role in the decrease in tree density (Gonzalez et al. 2012). The shift from wooded to agricultural areas is substantial (Brink and Eva 2009; Ruelland et al. 2011), and the decreases in tree density are correlated with proximity to human presence (Vincke et al. 2010). However, both the warming and decreased rainfall trends appear to have played at least as large a role in the overall decrease in tree density (Gonzalez et al. 2012), though this has not been examined specifically for fruit-bearing trees.

Wildfire in Australia

Hypothesis

Many high-impact fires occurred over the last decade, among them the 2009 "Black Saturday" Bushfires, which were reported as one of the worst natural disasters in the history of Australia, with 173 lives lost, and around 2,300 homes plus other structures destroyed (Crompton et al. 2010). Bushfires occur naturally in Australia, and many of the influencing parameters are directly (temperature, precipitation and windiness) or indirectly (available fuel, land use and cover, fire history) susceptible to climate change (Williams et al. 2009), with fire risk expected to increase under climate change (Reisinger et al. 2014, Box 25-6). Hence a possible increase in fire hazard due to recent climate change may have translated into increased damages from wildfire.

Climate trend

Increases in aggregate climate indices such as average temperature, maximum temperatures and the length of hot-spells have been detected on continental scale, albeit with strong seasonal and regional variations (Alexander and Arblaster 2009; Trewin and Vermont 2010). Composite indices such as the McArthur Forest Fire Danger Index (FFDI) have been developed to capture the combined influence of relevant meteorological variables such as temperature, relative humidity, wind speed and direction and antecedent precipitation for the assessment of fire risk. A trend in the FFDI toward increasing danger has been observed since 1970 over large parts of Australia, especially in the South and South East, with a clear signature of annual and decadal climate modes such as the El Niño/Southern Oscillation and the positive phase of the Indian Ocean Dipole (Mills et al. 2008; Clarke et al. 2013).

Baseline

Damages from wildfire have increased over the course of the century, consistent with the observed climate trends, but also with the effects of an increased number of exposed assets (such as settlements built in or close to fire prone bush land), and increases in population. Better fire management and improved forecasting may counteract these trends; however, their influence has not been quantified (Crompton et al. 2011; Nicholls 2011).

Impact detection

No detectable trend has been found in building damages or losses of life normalized against trends in population and number of dwellings over the last century or decades (Crompton and McAneney 2008; McAneney et al. 2009; Crompton et al. 2010). The normalization process does not account for all factors that influence vulnerability, e.g., human behavior such as precautionary measures of individual home owners, or collective measures of changing spatial planning in order to reduce risk. Several of these factors have been explored in the literature, often with a focus on specific regions or events. Examples include the role of the "prepare, leave early or stay and defend" policy in New South Wales, or the reduction of community vulnerability through improved risk management (Haynes et al. 2010; O'Neill and Handmer 2012; Whittaker et al. 2013). Damage from extreme fires is mainly controlled by exposure, as structures built in close proximity to or within bush land are virtually impossible to defend during extreme fire conditions (Chen and McAneney 2004). In the Greater Melbourne area, encroachment of suburban dwellings into bush land has led to an increase in the number of exposed dwellings (Butt and Buxton 2009; Buxton et al. 2011).

Crompton et al. (2011) in a reply to Nicholls (2011) discusses and dismisses several factors (including improved fire management, forecasting, individual home owners defence measures) that could be masking a trend consistent with a climate signal in the overall loss statistics. They conclude that an influence of anthropogenic climate change "is not ruled out by our analysis, but, if it does exist, it is clearly dwarfed by the magnitude of the societal change and the large year-to-year variation in impacts." In summary, an impact of climate change on observed damages from bushfires in Australia has not been detected.

Urban coastal erosion and flooding in West Africa

Hypothesis

Anthropogenic warming of the climate system is expected to cause widespread rises in sea level. West Africa has a number of low-lying urban areas particularly exposed to sea level rise, with increases in coastal erosion and flooding expected (Dossou and Glehouenou-Dossou 2007; Douglas et al. 2008; Adelekan 2010).

Climate trends

There has been a lack of sustained tide gauge monitoring in West Africa over the past few decades (Church and White 2011; Fashae and Onafeso 2011). While satellite monitoring suggests rising total sea levels in the Gulf of Guinea, actual relative sea level changes at specific locations along the coast will depend on additional factors, such as human-induced subsidence, or natural variations in ocean currents (Stammer et al. 2013).

Baseline

The construction of ports has diverted coastal sediment transport around Cotonou, Benin, while marine sand quarries have already reduced the supply of sand to the city (Dossou and Glehouenou-Dossou 2007). Other plausible drivers of increased erosion have also been posited and include subsidence due to oil exploration for Lagos, Nigeria, and sediment trapping in reservoirs for most of the West African Coast (Ericson et al. 2006; Douglas et al. 2008).

Impact Detection

Based on photographic evidence and comparison with satellite imagery, coastlines in some urban areas in the Gulf of Guinea seem to have been retreating over the past few decades (Dossou and Glehouenou-Dossou 2007; Fashae and Onafeso 2011). Ericson et al. (2006) found that sediment trapping is the dominant cause of contemporary effective sea level rise for the Niger delta, with contributions from land subsidence due to oil exploration. Also, the construction of reservoirs on the Volta has led to a sharp decrease in sediments moving across the West African coast, passing cities such as Cotonou and Lagos. Given the lack of long-term monitoring of local sea level, coastal erosion and the various possible drivers of coastal erosion, it is currently not possible to examine whether an anthropogenic climate change signal has been detected.

Discussion

This paper was motivated by an apparent inconsistency between the accepted view that climate change is already impacting a number of vulnerable human and managed systems, and the relative lack of documented evidence of observed impacts of climate change for those vulnerable systems. There is a large literature concerning the sensitivity of such systems to climate and to future climate change, but there is comparatively little documentation of observed impacts of climate change (Cramer et al. 2014).

A major factor explaining this gap consists in the lack of calibrated long-term monitoring across sensitive systems and regions, which would provide the observational basis that underpins detection and attribution analysis. Under the United Nations Framework Convention on Climate Change (UNFCCC), nations are obligated to monitor their respective contributions to anthropogenic forcing through standardized national greenhouse gas inventories, but no such inventory scheme or standard exists for impacts of climate change.

Detection and attribution studies are virtually impossible for impacts in some regions due to the absence of an observational basis. For example, to determine how sea level rise might be affecting urban coastal areas in West Africa (see Sect. 3.5), the current ambiguity over whether relative sea level has actually risen along the urban coastlines is a hindrance. Innovate methods exist to fill in such gaps, for instance, through analysis of archival footage or consulting local and indigenous knowledge, and can provide valuable tools in some cases (Rosenzweig and Neofotis 2013).

The five examples discussed in Sect. 3 draw on disparate studies across disciplines for a comprehensive analysis of the role of observed climate change in the changes that various systems have experienced during recent decades. However, they also illustrate some of the challenges involved in the detection and attribution of impacts of climate change. For example, the ecosystem of Lake Victoria faced the introduction of large predatory species, and subsequently a regime shift occurred. Predicting the ecosystem response to such major unprecedented change would be challenging even if the underlying ecosystem dynamics were well-understood. While it is plausible to assume that increased precipitation will have contributed to increases in agricultural productivity in Southeast South America, it is very difficult to disentangle the influence of the climate trend from that of technological development and socioeconomic conditions for parts of the region. Similarly, complex factors related to exposure preclude the detection of a climate-related signal in damages from bushfire in Australia. In the case of West Africa, the monitoring of all drivers contributing to coastal erosion and flooding, as well as the documentation of the actual changes, remains insufficient.

In some cases, though, the examples also point to ways forward. Local knowledge has been valuable in assessing the role of rainfall decreases in the thinning of western Sahelian forests, similar to what has long been documented for Inuit observations of change in the Arctic (e.g., Nichols et al. 2004; Krupnik and Ray 2007; Weatherhead et al. 2010). Sediment cores provide proxy evidence that the current warming of the African Great Lakes is, essentially, unprecedented. Examination of historical aerial and satellite photography provided important insights about the baseline in several of the case studies. The roles of some potential drivers for Australian bushfire damage were elucidated by comparative analyses across fire events, regions and other dimensions.

Several examples point to the synergistic effects of changes in climate and other drivers, e.g., the enabling role of the precipitation increases for extension of agricultural activity (3.2), or the role of warming and weakening winds in triggering the ecosystem shift in Lake Victoria (3.1). To adequately capture the role of climate change in light of other factors that may act as additional stressors, provide resilience or create synergistic effects different from the effect of any individual driver remains a central challenge for impact attribution.

A fundamental issue we have only touched upon briefly concerns the end point of attribution studies. For large parts of the community studying climate change and its impacts, as well as many stakeholders, “attribution” is used as a synonym for “attribution to anthropogenic forcing.” As one of the key motivations for detection and attribution research is to inform the UNFCCC, this end point has often been considered the main goal (Zwiers and Hegerl 2008). It is important in the context of potential litigation for adverse impacts of climate change (Grossman 2003) and may become relevant for the recently established “Warsaw International Mechanism for Loss and Damage” under the UNFCCC (James et al. 2014). To assess the relative role of anthropogenic versus natural forcing in observations provides a means to estimate whether recent and current impacts might be expected to persist, and to calibrate predictions of future impacts made with other methods. However, as we have shown, it is often very difficult to detect climate change effects in observed records and to disentangle the impacts of climate change from those of other drivers of change. Clearly, attribution of observed impacts to anthropogenic climate change adds another layer of complexity to an already challenging exercise.

Impact attribution research improves the understanding of vulnerabilities to long-term climatic trends, including interactions and non-additive effects of multiple drivers, for which identification of the underlying driver of the observed climate change may not be relevant (Parmesan et al. 2011, 2013). Impact detection and attribution provides important insights from “real-world” conditions as compared to experimental conditions or idealized models. Such knowledge is essential to identify the most adequate adaptation strategies and resilient pathways. Given the increasing rate of climate change and possible threshold behavior in impacted systems, as well as ongoing adaptation and general development, caution must be applied when inferring conclusions about future climate change impacts from observations.

It is also essential to be clear about the difference between the estimation of sensitivity to weather and the observation of an impact of climate change. This applies especially with regard to the perception of manifestations of climate variability, such as severe drought or storms. For many human and managed systems, impacts of extreme weather or climate shocks are the rare occasion where a clear climate-related signal can be detected. However, while the impact of a particular extreme can be an important indicator of sensitivity to climate, it does not by itself constitute a climate change impact (Allen et al. 2007; Stott et al. 2013; Hulme 2014).

Conclusions

Detection and attribution of climate change impacts provides the most complete and consistent analysis possible of the cause–effect chain, combining all possible sources of information in a coherent evaluation. While setting a high bar, the distinction between impacts that have been observed in data and linked to climate change with confidence, and those that are predicted to occur but cannot be detected and attributed by science (as yet) has proven useful. However, caution must be applied both ways when interpreting results. The lack of documented impacts attributable to climate change should not be misread as evidence for the absence of such impacts. On the other hand, it is true that for many historic impacts on human systems, non-climate-related drivers are equally or more important than recent climate change and must be accounted for.

There may be cases where data are insufficient to detect an impact, while given climate trends and known sensitivity strongly suggest that climate change will have affected the system. While we support the use of different types of evidence, and the application of interdisciplinary methods to establish causality, the fact remains that observational evidence demonstrating a long-term effect is needed for impact attribution. Or to put it another way—you can not attribute something you have not detected.

Detection and attribution analysis can be a powerful tool in understanding how and why our world is changing, albeit its cost is the need to possess the necessary observations and understanding, which remains poor in many areas. To identify those gaps, to determine whether they can be filled, and if so to prioritize research to address them, will lead to a more comprehensive and inclusive understanding of the impacts of climate change.

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