Dealing with Complexity and Extreme Events Using a Bottom-up, Resource-based Vulnerability Perspective

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Abstract

We discuss the adoption of a bottom-up, resource–based vulnerability approach in evaluating the effect of climate and other environmental and societal threats to societally critical resources. This vulnerability concept requires the determination of the major threats to local and regional water, food, energy, human health, and ecosystem function resources from extreme events including climate, but also from other social and environmental issues. After these threats are identified for each resource, then the relative risks can be compared with other risks in order to adopt optimal preferred mitigation/adaptation strategies.

This is a more a inclusive way of assessing risks, including from climate variability and climate change than using the outcome vulnerability approach adopted by the IPCC. A contextual vulnerability assessment, using the bottom-up, resource-based framework is a more inclusive approach for policymakers to adopt effective mitigation and adaptation methodologies to deal with the complexity of the spectrum of social and environmental extreme events that will occur in the coming decades, as the range of threats are assessed, beyond just the focus on CO_2 and a few other greenhouse gases as emphasized in the IPCC assessments.

1. Introduction

"The Earth's climate system is highly nonlinear: inputs and outputs are not proportional, change is often episodic and abrupt, rather than slow and gradual, and multiple equilibria are the norm……. there is a relatively poor understanding of the different types of nonlinearities, how they manifest under various conditions, and whether they reflect a climate system driven by astronomical forcings, by internal feedbacks, or by a combination of both…… [We] suggest a robust alternative to prediction that is based on using integrated assessments within the framework of vulnerability studies ……. It is imperative that the Earth's climate system research community embraces this nonlinear paradigm if we are to move forward in the assessment of the human influence on climate" [*Rial et al.,* 2004].

The concept of spatio-temporal chaos introduced by *Milanovic* [2011] reinforces this view of the complexity of the climate system, and applies more generally to all components of society and the environment. He defines spatio-temporal chaos as dealing with the dynamics of spatial patterns**:**

> **"***Weather and climate are manifestations of spatio temporal chaos of staggering complexity because there is not only Navier Stokes equations, but there are many more coupled fields. ENSO is an example of a quasi standing wave of the system."*

The dominant scientific perspective is top-down and carbon-dioxide-centric. It focuses on multi-decadal global climate model predictions involving quasi-linear responses dominated by the increases in greenhouse gases which are downscaled to societal and environmental impacts (i.e., following the progression from the Working Group 1 [*Solomon et al.,* 2007] to the Working Group 2 reports [*Parry et al.,* 2007], which culminate in the Working Group 3 report [*Metz et al.,* 2007] of the IPCC). This narrow approach, however, has serious limitations in assessing risks of extreme events to key resources as is discussed below. An overview of these limitations, presented in Figure 1 reproduced from *Kabat et al.* [2004], includes the spatial averaging of climate predictions over relatively large areas, the focus on single stressors, and gradual, near-linear predictions of climate change.

An additional limitation of the top-down approach is that if the IPCC projections and actual climate trajectory differ significantly in coming decades, recognition of this error may occur too late for policymakers to realign the adaptation/mitigation strategy in order to respond to the actual state of climate at the local/regional scale. In contrast, if the adaptation strategy had considered more scenarios, then it could handle a larger margin of error than the constrained top-down approach.

This paper begins by overviewing the limitations of the top-down approach to assess risk from extreme events as well as the difficulty in detecting changes in the threat of extreme events over time. We then discuss a bottom-up resource-based approach which we conclude is a more robust tool to provide policymakers and the impacts community with a much better estimate of the threats faced by key resources in the future. We conclude the paper with examples illustrating why we need a bottom-up approach to assess the threats to water, food, energy, human health, and ecosystem function.

2. Use Of Top-Down Downscaling To Determine Risks From Extreme Events

IPCC climate change projections are at relatively coarser resolution [*Solomon et al.*, 2007], whereas the impacts and potential mitigation policies of interest to stakeholders are mostly at local to regional scales. For example, climate models may project increasing drought at a regional scale. The resilience to such increased occurrence as well as changes in the intensity of droughts is, however, dependent on the local-scale environmental conditions (such as moisture storage and convective rainfall), and farming approaches (access to irrigation, timing of rain or stress, etc). According to *Adger* [1996] an important issue for IPCC-like global reports is to assess whether the top-down approach can incorporate the "*aggregation of individual decision-making in a realistic way, so that results of the modelling are applicable and policy relevant.*"

There are also unresolved issues both for generating and applying IPCC-type model predictions to climate risk assessments for policymakers and other users [e.g., *Holman et al.*, 2005]. They are often presented as "projections" yet are actually forecasts (predictions) of the future climate based on different assumptions of greenhouse gas emissions. Such terminology has been debated before by *Pielke Sr.* [2002] and *MacCracken* [2002]. In this paper, we use the terms projection, prediction and forecast interchangeably [*Bray and von Storch*, 2009].

Multi-decadal IPCC-type forecasts, if used without consideration of regional and local vulnerabilities, can lead to misleading outcomes and actions for the impacts and adaptation community as well as for policymakers [*Patt et al.*, 2010; *Pielke Jr. et al.*, 2007].

There are several reasons why top-down IPCC-type multi-decadal climate global climate change model predictions are not skillful. First, as a necessary condition for skillful prediction, the multi-decadal global climate model simulations must include all first-order climate forcings and feedbacks. However, they do not [see for example: *NRC*, 2005; *Pielke et al.*, 2009]. Omission of these forcings can introduce large uncertainty in the local and regional estimates of impact on the atmospheric and oceanic circulations [e.g., *Myhre and Myhre* 2003, *Matsui and Pielke*, 2006, *Davin et al.* 2007].

According to *Pielke et al.* [2009]:

> *"In addition to greenhouse gas emissions, other first-order human climate forcings are important to understanding the future behavior of Earth's climate. These forcings are spatially heterogeneous and include the effect of aerosols on clouds and associated precipitation [e.g., Rosenfeld et al., 2008], the influence of aerosol deposition (e.g., black carbon (soot) [Flanner et al. 2007] and reactive nitrogen [Galloway et al., 2004]), and the role of changes in land use/land cover [e.g., Takata et al., 2009]. Among their effects is their role in altering atmospheric and ocean circulation features away from what they would be in the natural climate system [NRC, 2005]. As with* CO_2*, the lengths of time that they affect the climate are estimated to be on multidecadal time scales and longer."*

Perhaps, at least partly for this reason, these global multi-decadal predictions are unable to skillfully simulate major atmospheric circulation features such the Pacific Decadal Oscillation [PDO], the North Atlantic Oscillation [NAO], El Niño and La Niña, and the South Asian monsoon [*Pielke Sr.*, 2010; *Annamalai et al.*, 2007]. However, these large-scale atmospheric/ocean climate features determine the particular weather pattern for a region [e.g., *Otterman et al.*, 2002; *Chase et al.*, 2006]. Proposed decadal prediction efforts seek to address some of these deficiencies but are still under development [*Hurrell et al.*, 2009].

Dynamic and statistical regional downscaling yield higher spatial resolution, however, the regional climate models are strongly dependent on the lateral boundary conditions and interior nudging by their parent global models [e.g., see *Rockel et al.*, 2008]. Large-scale climate errors in the global models are retained and could even be amplified by the higher spatial resolution regional models. Most downscaling methods also suffer from the inability to mimic second or higher order moments of the distribution on the regional and local scales and are typically conditioned to preserve the mean [*Salathe*, 2005]. In particular, the spatial gradient of precipitation may not be physically modeled well enough by downscaling methods to allow the accurate assessment of streamflow and other environmental features in regions of complex terrain [*Ferraris et al.*, 2003; *Salathe*, 2005; *Rahman et al*., 2009; *Yang et al.*, 2009].

Moreover, since as reported above, the global multi-decadal climate model predictions cannot accurately predict circulation features such as PDO, NAO, El Niño, and La Niña [*Compo et al.*, 2011] they cannot provide accurate lateral boundary conditions and interior nudging to the regional climate models. On the other hand, regional models themselves do not have the domain scale (or two-way interaction) to skillfully predict these larger-scale atmospheric features.

There is also only one-way interaction between regional and global models which is not physically consistent. If the regional model significantly alters the atmospheric and/or ocean circulations, there is no way for this information to alter the larger-scale circulation features which are being fed into the regional model through the lateral boundary conditions and nudging. Also while there is information added when higher spatial analyses of land use and other forcings are considered in the regional domain, the errors and uncertainty from the larger model still persists thus rendering the added complexity and details ineffective [*Ray et al.* 2010; *Mishra et al.* 2010].

In addition, lateral boundary conditions for input to regional downscaling require regional-scale information from a global forecast model. However the global model does not have this regional-scale information due to its limited spatial resolution. This is, however, a logical paradox since the regional model needs something that can only be acquired by a regional model (or regional observations). Therefore, the acquisition of lateral boundary conditions with the needed spatial resolution becomes logically impossible.

There is sometimes an incorrect assumption that although global climate models cannot predict future climate change as an initial value problem, they can predict future climate statistics as a boundary value problem [*Palmer et al.*, 2008]. With respect to weather patterns, for the downscaling regional (and global) models to add value over and beyond what is available from the historical, recent paleo-record, and worse case sequence of days, however, they must be able to skillfully predict the *changes* in the regional weather statistics. There is only value for predicting climate change *if* they could skillfully predict the *changes* in the statistics of the weather and other aspects of the climate system. There is no evidence, however, that the models can predict changes in these climate statistics even in hindcast. As highlighted in *Dessai et al.* [2009] the finer and time-space based downscaled information can be "misconstrued as accurate", but the ability to get this finer-scale information does not necessarily translate into increased confidence in the downscaled scenario [*Wilby*, 2010].

Statistical downscaling from the parent global model can be used as the benchmark (control) against which dynamic downscaling should improve [e.g., *Wilby et al.*, 1998; *Mearns et al.*, 1999]. If, however, the statistical relationship(s) between predictor(s) and predict and(s) changes in the future, the method will not provide the actual real world response. Under climate change, the statistical relationship between the climate and impacts would be expected to change [*Milly et al.*, 2008]. The same premise of stationarity also applies to the parameterized schemes within regional climate models.

There has also been a move towards higher spatial resolution and more complex global climate models. However, this added detail does not assure more skillful predictions of impacts to key resources decades from now. As concluded by *Landsea and Knaff* [2000], with respect to El Niño predictions, increase in model complexity can in fact compound the input errors and downgrade the model skill. They write

> *".....the use of more complex, physically realistic dynamical models does not automatically provide more reliable forecasts. Increased complexity can increase by orders of magnitude the sources for error, which can cause degradation in skill."*

Thus neither dynamic downscaling or statistical downscaling from multi-decadal global model projections add <u>proven</u> value to spatial or temporal accuracy that can assist the impacts community in ways beyond what is already available from historical, paleo- or analogue records [*Rajgopalan et al.*, 2009; *Parson et al.*, 2003]. The global and regional multi-decadal climate change models are providing a level of confidence in forecast skill of the coming decades that is not warranted.

3. Detection Time of Extreme Events

Historically, changes in exposure and the value of capital at risk have been much more important drivers of economic losses from weather-related hazards than anthropogenic climate change [*Bouwer*, 2011]. Nonetheless, our ability to detect *future* changes in extreme events depends on several additional factors: the strength of the predicted trend (signal) relative to the sample variance (noise); the length of time over which the trend persists; the choice of extreme index; the power of the statistical test; and the level of confidence required in the outcome of that statistical test (Figure 2). Quantitative predictions of extremes by climate models are highly uncertainty due to: the choice of model(s); unknown future changes in radiative and other climate forcing (by anthropogenic emissions, land-surface modifications and natural (e.g., solar, volcanoes); and random, internal variability of climate.

When taking all of these factors into account it is hardly surprising that detection of robust anthropogenic signals in regional climate predictions is seldom possible within decision-making time scales of a few decades. For example, *Ziegler et al.* [2005] find that time-series of 50-350 years are required to detect plausible trends in annual precipitation, evaporation and discharge in the Missouri, Ohio, and Upper Mississippi River basins. Likewise, *Wilby* [2006] showed that, under widely assumed climate change scenarios, expected trends in UK summer river flows are seldom detectable within typical planning horizons (i.e., by the 2020s). Again, depending on the climate model and underlying uncertainty of the regional projections, emergence time scales for US tropical cyclone losses range between 120 and 550 years [*Crompton et al.,* 2011].

Hawkins and Sutton [2010] consider the extent to which the signal-to-noise (S/N) ratio in future temperature and precipitation might vary in space and time; as well as the scope for improving predictive power by decreasing climate model uncertainties. Using the CMIP3 ensemble they show that the tropics have the highest S/N for temperature but the lowest for precipitation (which is greatest at the poles). Even when model uncertainty is set to zero, the gains in S/N for regional precipitation are only modest, especially for predictions over the next few decades. However, other model experiments suggest that changes in indices of extreme precipitation may be stronger than corresponding changes in mean precipitation [*Hegerl et al.*, 2004]. This view is supported by *Fowler and Wilby* [2010] who found that significant changes in multi-day heavy rainfall accumulations could emerge in some parts of the UK within a decade or so (if the regional climate scenarios of the PRUDENCE ensemble are realized). Others assert that an attributable human fingerprint is already evident in the *risk* of flood occurrence at the scale of the UK [*Pall et al.*, 2011].

So what is the utility of top-down climate model prediction and detection of extreme events? Taken at face value, poorly discerned and attributed changes in extreme events imply either that adaptation decisions will have to be taken ahead of tangible evidence of the need to act, or that those anticipatory measures should simply be deferred [*Pielke et al.*, 2007]. The latter argument is sometimes supported by naïve mismatching of trends in historic weather extremes with regional climate model projections [see: *Wilby et al.*, 2008].

Rather than an excuse for inaction, long emergence time scales reinforce the need for bottom-up, vulnerability-based responses. Anthropogenic climate change trends may already be underway but statistically undetectable for many more decades. This does not exclude the possibility that the same trends could have much earlier *practical* significance. For example, a rise in maximum temperatures of just a few tenths of a degree coinciding with lower river flows, could result in abrupt changes in freshwater ecosystems that are already stressed by river regulation and pollution.

At least three steps can be taken to better detect complex, highly uncertain, and potentially dynamic patterns of extreme events. First, climate model outputs can be used to highlight potential “hotspots” of emerging risk (i.e., high S/N), thereby guiding a more targeted approach to environmental monitoring and assessment. For example, a strong signal is predicted for heavy rainfall in western England, particularly in the uplands. Early signs are that the expected trend may be emerging in the winter precipitation and streamflow record [*Dixon et al.*, 2006; *Fowler and Wilby*, 2010]. Of course, there is always a danger of making Type I errors in such cases (i.e., erroneous trend detection when there is none) but this risk diminishes as the trend remains and the record grows. We should, therefore, be safeguarding lengthy, homogeneous records, whilst being mindful of other factors that can confound trend analysis. These include changes in instrument, location, observing/ recording practice, site characteristics, and sampling regime [*Pielke et al.,* 2007].

Second, regions with relatively low certainty in predicted extremes should be the focus for intensive field campaigns to improve understanding of regional climate forcing and representation in models. For example, large model uncertainty exists with respect to the future behavior of the South Asian monsoon. Rigorous scrutiny of the global climate models (GCMs) underpinning the IPCC reports revealed that just six of the 18 models have a plausible representation of monsoon precipitation climatology [*Annamalai et al.,* 2007]. Of these six GCMs, only four exhibited a robust ENSO-monsoon correlation, including the well-known inverse relationship between ENSO and rainfall anomalies over India.

Another comprehensive assessment reviewed 79 GCMs simulations from 12 different climate models and 6 different emission scenarios to ascertain whether any consensus can be reached about predicted changes in the main features of ENSO and the monsoon climates of South Asia [*Paeth et al.,* 2008]. Although most models project La Nina-like anomalies – and thus an intensification of the summer monsoon precipitation in India by the end of the 21st century – the response is barely distinguishable from natural climate variability. Early detection is unlikely in this case.

Third, more judicious selection of indices could increase S/N, as in the case of long-duration precipitation extremes. We should also recognize that some types of extreme (such as droughts linked to persistent Atlantic blocking, or intense summer convective downpours and associated flash flooding) are not adequately resolved by the present generation of climate models, even under present conditions [e.g., *Fowler and Ekström*, 2009]. Nor is there any guarantee that higher resolution models will lead to reduced uncertainty, particularly if additional Earth System feedbacks are incorporated [*Hawkins and Sutton*, 2010]. However, by optimizing the choice of detection index, season and domain, it should be possible to identify a network of 'sentinel' regions for earliest detection. But these hazard indices should not be so sophisticated that they lose societal relevance.

4. A Bottom-up, Resource-Based Vulnerability Perspective

4.1. Definitions of Vulnerability

In general, "vulnerability" may be defined as the concept of "threats" from potential hazards to the population, to key resources, and to the infrastructure. According to the IPCC Working Group 2 report [*Parry et al.*, 2007]

> "*Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity".*

Bravo de Guenni et al. [2004] provides a useful summary below of the concept of vulnerability. *Risk* is the "chance of disaster" [*Fairman et al.*, 1998], which, of course, is an extreme event. This is an event that can disrupt the human and/or the natural environment. A *hazard* is the combination of both the active physical exposure to a natural process and the vulnerability of the human and/or environmental system with which it is interacting. A hazard is commonly described as the "potential to do harm". The physical exposure is a function of both its intensity and duration. It has a magnitude and a probability of occurrence and takes place with respect to a particular resource at specified locations. The natural process becomes a hazard when it produces an event that exceeds a coping threshold; i.e., *an extreme value*. Hazard duration is determined by the length of time the threshold is exceeded. Resilience is the capacity of a system below which the thresholds of vulnerability are not exceeded [*Vogel*, 1998]. Figure 3 from *Bravo de Guenni et al.* [2004] schematically illustrates the relationship between threshold and duration under different scenarios of threat and how they can change over time.

4.2. Two Approaches to Assessing Vulnerability Approach

The IPCC Fourth Assessment Report Working Groups (2 and 3) discuss vulnerability [*Pielke and Niyogi,* 2010; *Schneider et al.,* 2007]. The IPCC identifies seven criteria for "key" vulnerabilities: magnitude of impacts; timing of impacts; persistence and reversibility of impacts; likelihood (estimates of uncertainty) of impacts and vulnerabilities and confidence in those estimates; potential for adaptation; distributional aspects of impacts and vulnerabilities; and the importance of the system(s) at risk.

The IPCC also refer to "outcome vulnerability" as illustrated in Figures 4 (left-side) and 5 from *O'Brien* [2007] and *Füssel* [2007]. This is clearly a top-down driven perspective. The "contextual vulnerability" is, however, the more inclusive approach to assess risks to key resources since, rather than limiting to subset of threats, the entire spectrum of risks are considered.

For policymakers to develop resilient strategies it is necessary to consider a multi-dimensional perspective as illustrated in Figures 6 [from *Hossain et al.,* 2011] and Figure 4 (right-side) [from *Füssel,* 2007]. *Klein et al.* [1999], for example, sought to determine whether the IPCC guidelines for assessing climate change impacts as well as adaptive strategies can be applied to the example of coastal adaptation. They recommend that a broader approach is needed which has more local-scale information and input for assessing as well as monitoring the options. The missing link between local-scale features with global-scale projections becomes obvious.

The expanded eight-step approach of *Schroter et al.* [2005], designed to assess vulnerability to climate change, highlights the need to consider multiple interacting stresses. They recognize that climate change can be a result of greenhouse gas changes which are coupled to socioeconomic developments, which in turn are coupled to land-use changes – and that all of these drivers are expected to interactively affect the human – environmental system (such as crop yields). *Metzger et al.* [2006] concluded that most existing assessment studies cannot provide needed information on regional vulnerability.

5. Examples Of Vulnerability Thresholds For Key Resources

There are five broad areas that we can use to define the need for contextual vulnerability assessments: *water, food, energy, human health,* and *ecosystem function*. Each sector is critical societal well-being. The vulnerability concept requires the determination of the major threats to these resources from extreme events including climate, but also from other social and environmental pressures. After these threats are identified for each resource, relative risks can be compared in order to shape the preferred mitigation/adaptation strategy.

The questions to be asked for each key resource are:

1. Why is this resource important? How is it used? To what stakeholders is it valuable?

2. What are the key environmental and social variables that influence this resource?
3. What is the sensitivity of this resource to changes in each of these key variables? (This may include but is not limited to, the sensitivity of the resource to climate variations and change on short (days); medium (seasons) and long (multi-decadal) time scales).
4. What changes (thresholds) in these key variables would have to occur to result in a negative (or positive) outcome for this resource?
5. What are the best estimates of the probabilities for these changes to occur? What tools are available to quantify the effect of these changes? Can these estimates be skillfully predicted?
6. What actions (adaptation/mitigation) can be undertaken in order to minimize or eliminate the negative consequences of these changes (or to optimize a positive response)?
7. What are specific recommendations for policymakers and other stakeholders?

Each of these concerns is explored in more detail in the following sections.

5.1. Water

To understand the vulnerability of water resources, we first need to recognize that the water that is usable can occur in various forms such as rainfall, surface water, rechargeable and fossil ground water, snow, natural lakes, artificial reservoirs, and through state compacts and international treaties. The threats to these water resources are many, such as through health and contamination, changes in precipitation extremes, population demand, industrial and agricultural demand, contamination, national water policies, and climate [see *Vörösmarty et al.*, 2010]. There may also be ‘competition’ between different applications (resource production). For example, most of today's agriculture and fossil fuel-based energy production is water intensive [*Jones*, 2008]. Population and industrialization have continued to increase over the last century which results in more competition for available water resources between direct consumption (for public and industrial water supply) and resource production (for crops and energy).

The resilience to known threats to water availability can be region-specific and vary due to a multiplicity of factors. The factors affecting availability of water in most parts of the world are many and at least more than a few key issues are involved [*Vörösmarty et al*., 2010]. The assessment of vulnerability of water resources requires an inherent recognition of these multiple threats (including from climate change and variability) to prioritize high-risk threats and plan adaptation strategies based on such multiple high risk scenarios.

For example, let us consider for a country that the 50 year water availability is dictated overwhelmingly by rapid population growth and accompanying environmental degradation of water quality when compared to climate change (IPCC) based projections [e.g., see *Vörösmarty et al.,* 2000]. A 50-year effective adaptation strategy that incorporates the 50-year population growth and expected water quality crises must therefore be resilient to any reasonably possible climate change.. This is the inherent strength of a bottom-up approach versus the limited top-down counterpart.

5.2 Food

Agriculture – crop based as well as animal driven – is a risk prone entity. For example, assuming a global model projection for a future climate is accurate for a particular region, one could ascribe a range of climatic changes. These could include higher temperatures, greater propensity for more intense rainfalls, and higher CO_2 levels. Each of these can positively affect the crop yield by promoting enhanced photosynthesis rates [*Curtis et al.* 2003, *Jablonski et al.*, 2002], taller and more robust crop and forest growth. Conversely, depending on the local conditions, the same changes could translate into increasing pest risk, higher ozone-related damages, increasing soil erosion risk, hail and frost damage, and reduced work days suitable for farm activities.

To extract the significance of the individual versus multiple climatic stressors on crop yields, *Mera et al.* [2006] developed a crop modeling study with over 25 different input scenarios of temperature, rainfall, and radiation changes at a farm scale for both C3 and C4 crops (e.g., soybean and maize). As seen in many crop yield studies, the results suggested that yields were most sensitive to the amount of effective precipitation (estimated as rainfall minus physical evaporation/transpiration loss from the land surface). Changes in radiation had a nonlinear effect with crops showing an increased productivity for some reduction in the radiation as a result of cloudiness and increased diffuse radiation and a decline in yield with further reduction in radiation amounts. The impact of temperature changes, which has been at the heart of many climate projections, however, was quite limited, particularly if the soils did not have moisture stress. The analysis from the multiple climate change settings do not agree with those from individual changes, making a case for multivariable, ensemble approaches to identify the vulnerability and feedbacks when estimating climate-related impacts [cf. *Turner et al.,* 2003].

A big unknown in food security, however, are the so-called non-climatic risks. This could include agricultural policies such as those permitting genetic versus organic farming standards for the region as practiced in some European Union countries, or the ethanol blending mandated in the Midwest USA. Even when considering the climatic factors alone, a large number of if-then probable scenarios can be developed that can have positive or negative impacts on crop yield and agricultural sustainability.

Niyogi and Mishra [2011] assess a number of stresses including a temperature increase – which can lead to increased yield for an initial period and can affect fertility, graining, and future generations; and the timing of the temperature and rainfall, both of which would be a significant source of uncertainties. For example, reduced rainfall during the two-week sowing period can translate into reduced yield even if the rainfall were adequate for the entire growing season. The stress on the plants particularly from heavy rain and even frost during the young stage would be much higher than during the mature period when the roots would be much deeper. The uncertainties also include pathogen and weed stress due to increased humidity and temperature interactions. Weeds are expected to be at significant advantage and not currently considered in conventional crop yield impact studies. From an adaptation perspective, if the farmers have information about possible droughts and sowed the seed deeper into the soil, which requires extra energy and time investment, the negative impacts could be alleviated.

Assessing the adaptation and mitigation approaches therefore requires a much broader view on the production processes and the life cycle of the entity than CO_2-driven global model predictions can provide. Current crop impact studies adopt a typical approach in which the global climate model scenario – often one or two extreme members instead of the ensemble – as input to simple process-based or statistical crop models. The bottom-up perspective provides a wider range of scenarios for the adaptive and mitigative strategies that individual growers, regional economies, and policymakers need to be able to respond to.

5.3. Energy

Two large categories of energy resources, namely nuclear and renewable, are considered as unlimited but this is practically untrue. The metals and other basic components used for producing the energy converters (e.g., nuclear reactors, solar cells, wind/wave generators, farming of plants for biomass production) are limited and therefore vulnerable to human intervention. A more characteristic case is the growing need of materials with unique characteristics (rare metals). Climatic variability can influence all these energy resources on many ways. The increase of energy consumption require intense mining of fossil fuels, increases the areas covered by on/offshore renewable energy parks and platforms with a resultant substantial influence of local climate (e.g., due to changes in local wind and/or wave conditions from the physical presence of these structures).

Renewable energy is potentially vulnerable to climate variability and longer-term change. For example, biomass production involving land use change can alter the regional climate. *Costa et al.* [2007] found a significant reduction in rainfall when the land was converted to soybeans as contrasted with a conversion to grassland as a consequence of the larger albedo of the soybean fields. Wind turbines and solar panels are obviously strongly influenced by weather and if they cover a large enough area, it has been stated that they alter regional and even larger-scale climate patterns [see for example, *Wang and Prinn*, 2009]. Hydropower, with its dependence on precipitation is obviously significantly affected by climate.

5.4. Human Health

The link between environmental conditions and human health is well established. Changes in weather and climate conditions on times scales ranging from days to decades can directly impact the conditions allowing certain diseases to flourish on the one hand while also affecting the exposure of human populations to disease on the other.

For example, ranges and pathogen incubation periods of various vector borne and waterborne diseases are directly linked to changes in climatic conditions [as is the case for malaria, see: *Githeko*, 2009]. Similarly, heat-related morbidity and mortality associated with hot and cold waves are well documented [e.g., *Keatinge et al.*, 2000]. Changes in the precipitation regimes, length of growing seasons and increased dust from drought all contribute to respiratory allergies, asthma, and airway diseases in vulnerable populations. The challenge of addressing the effects of climate on human health is very complex because local or regional cultural, political, and economic factors can exacerbate environmental stressors and the decisions that people make also influence health.

A host of factors such as biological susceptibility, socioeconomic status, cultural norms, and the quality of infrastructure often come into play in determining the vulnerability to climate related disease conditions. Effective response strategies have to necessarily be region-specific and these must include defining environmental risk factors, identifying vulnerable populations, and developing effective risk communication and prevention strategies [*Portier et al.*, 2010].

5.5 Ecosystem Function

Feedbacks from human-activities have become directional drivers of change in both human and non-human dominated ecosystems. These factors may be independent of climate change forcing, amplify or attenuate the climate effects. For example, the fertilization of plants from enhanced atmospheric CO_2, the positive and negative effects of non-greenhouse forms of inorganic nitrogen in the atmosphere, and the 'wild card' effect of human-facilitated species introductions and extirpations are potentially changing local and regional landscapes as fast, or faster, than climate drivers [e.g., *Vitousek et al.*, 1997, *Hobbs et al.*, 2009]. Land use change can 'trump' all of the above.

Thus, in considering how ecosystems will respond and interact in the 21st century, two points need to be emphasized. First, ecosystem function is vulnerable to human activities that are tangential to the climate drivers. Human activities have induced local and regional 'tipping points' such has lake eutrophication [*Carpenter and Lathrop,* 2008] and desertification of rangelands [*Schlesinger et al.*, 1990]. These events are occurring due to factors independent of climate forcings. Clear evidence of climate variations and longer term change is also occurring in many areas; thus scenario planning, mitigation and adaptation requires that we understand how these different facets of global environmental change interact with the climate system. How do these other anthropogenic activities alter outcomes; how will they influence the vulnerability of these systems to change?

The above questions lead to the second point. The response functions of ecosystems to the climate drivers are determined by the net effect of past drivers on the current structure of the ecosystem. Ecosystems can respond to climate forcings by exhibiting resilience, a phenomenon well exemplified by the relatively benign response of the Great Plains grasslands to the drought of the 1930s. Conversely, the same areas can experience transformation, i.e., the dust storms and destruction of millions of hectares of agricultural lands caused by the same 1930s drought. Clearly, climate alone was not the causal mechanism for the dust bowl, and we know now that the subsequent feedbacks to the regional climate from either a vegetated or barren landscape were substantial [e.g., *Cook*, 2009]. Resiliency and adaptive capacity is often associated with healthy diverse ecosystems; restoring ecosystem function of degraded ecosystems can convey resilience to future climate [*McAlpine et al.*, 2010]. Thus, current decisions about land management will affect the ecosystem response functions that influence subsequent global climate change drivers.

6. Conclusions

The adoption of a vulnerability assessment approach to evaluate the effect of climate and other environmental and societal threats to key resources is an inclusive way of assessing risks, including from climate variability and longer term climate change. In contrast to the *outcome vulnerability* adopted by the IPCC, the *contextual vulnerability* discussed in *Füssel* [2009] are more inclusive and provide a more robust framework for policymakers to adopt mitigation and adaptation methodologies to deal with the spectrum of social and environmental issues in the coming decades.

The concept of contextual vulnerability enables the determination of major threats to water, food, energy, human health and ecosystem function from extreme events including those arising from climate, but also other social and environmental pressures [as in *Pielke Jr.*, 2010; *Wallace*, 2010; *Carmichael*, 2009; *Webster and Hoyas*, 2010; *Curry and Webster,* 2010]. After these threats are identified for each resource, then relative risks can be determined in order to prioritize individual response measures and to shape the preferred mitigation/adaptation strategy.

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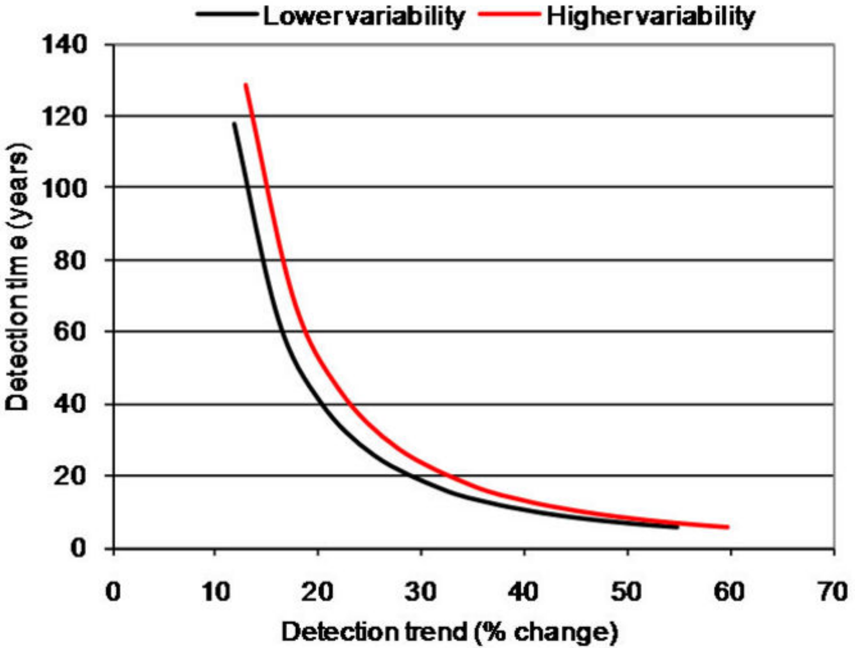
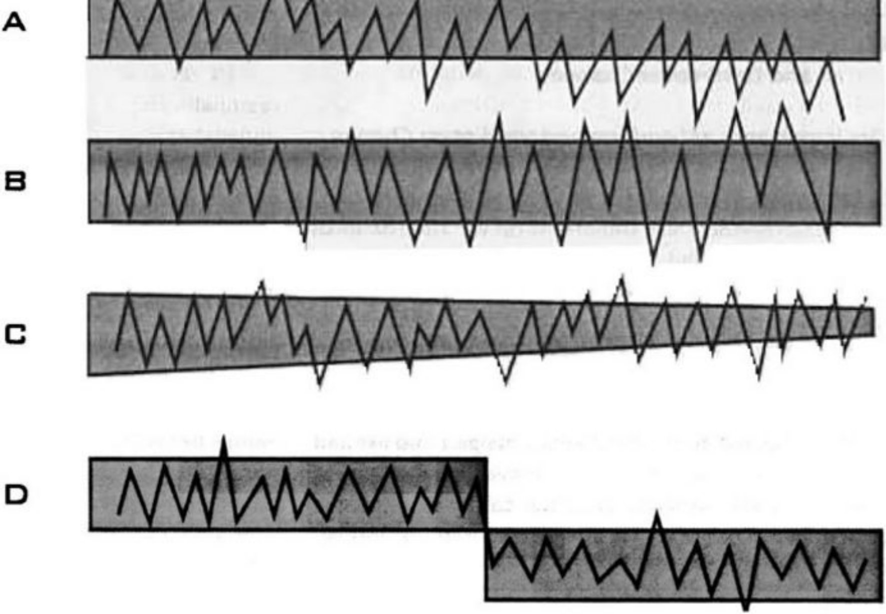
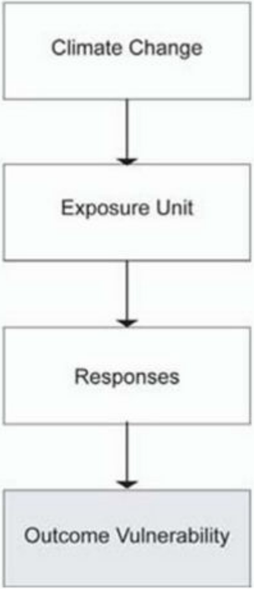
Approach	**Scenario**	**Vulnerability**
Assumed dominant stress	Climate, recent greenhouse gas emissions to the atmosphere, ocean temperatures, aerosols, etc .	Multiple Stresses: Climate (historical climate variability, land use and water use, altered disturbance regimes invasive species, contaminants/pollutants, habitat loss, etc.
Usual timeframe of concern	Long-term, doubled CO_2 30 to 100 years in the future.	Short-term (0-30 years) and long-term research.
Usual scale of concern	Global,sometimes regional. Local scale needs downscaling techniques. However, there is little evidence to suggest that present models provide realistic, accurate, or precise climate scenarios at local or regional scales.	Local, regional, national, and global scales.
Major parameters of concern	Spatially averaged changes in mean temperatures and precipitation in fairly large grid cells with some regional scenarios for drought.	Potential extreme values in multiple parameters (temperature, precipitations, frost-free days) and additional focus on extreme events (floods, fires, droughts, etc.) measures of uncertainty.
Major limitations for developing coping strategies	Focus on single stress limits preparedness for other stresses. Results often show gradual ramping of climate change-limiting preparedness for extreme events. Results represent only a limited subset of all likely future outcomes – usually unidirectional trends. Results are accepted by many scientists, the media, and the public as actual “predictions”. Lost in the translation of results is that all models of the distant future have unstated (presently unknowable) levels of certainty or probability.	Approach requires detailed data on multiple stresses and their interactions at local, regional, national, and global scales – and many areas lack adequate information. Emphasis on short-term issues may limit preparedness for abrupt “threshold” changes in climate sometime in the short or long term. Requires preparedness for a far greater variation of possible futures, including abrupt changes in any direction – this is probably more realistic, yet difficult.

Figure 1: Contrast between a top-down versus bottom-up assessment of the vulnerability of resources to climate variability and change [from *Kabat et al.*, 2004].


Lowervariability
Highervariability
Detection tim e (years)
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
Detection trend (% change)


A
B
C
D

1a **Outcome Vulnerability**



1b **Contextual Vulnerability**

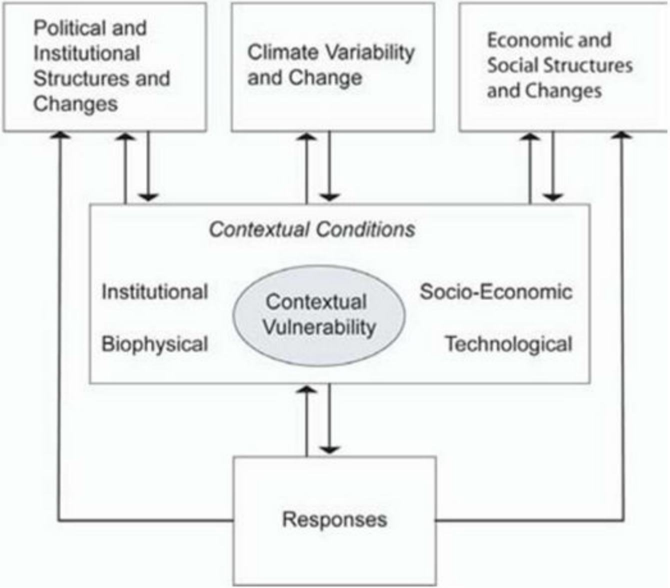
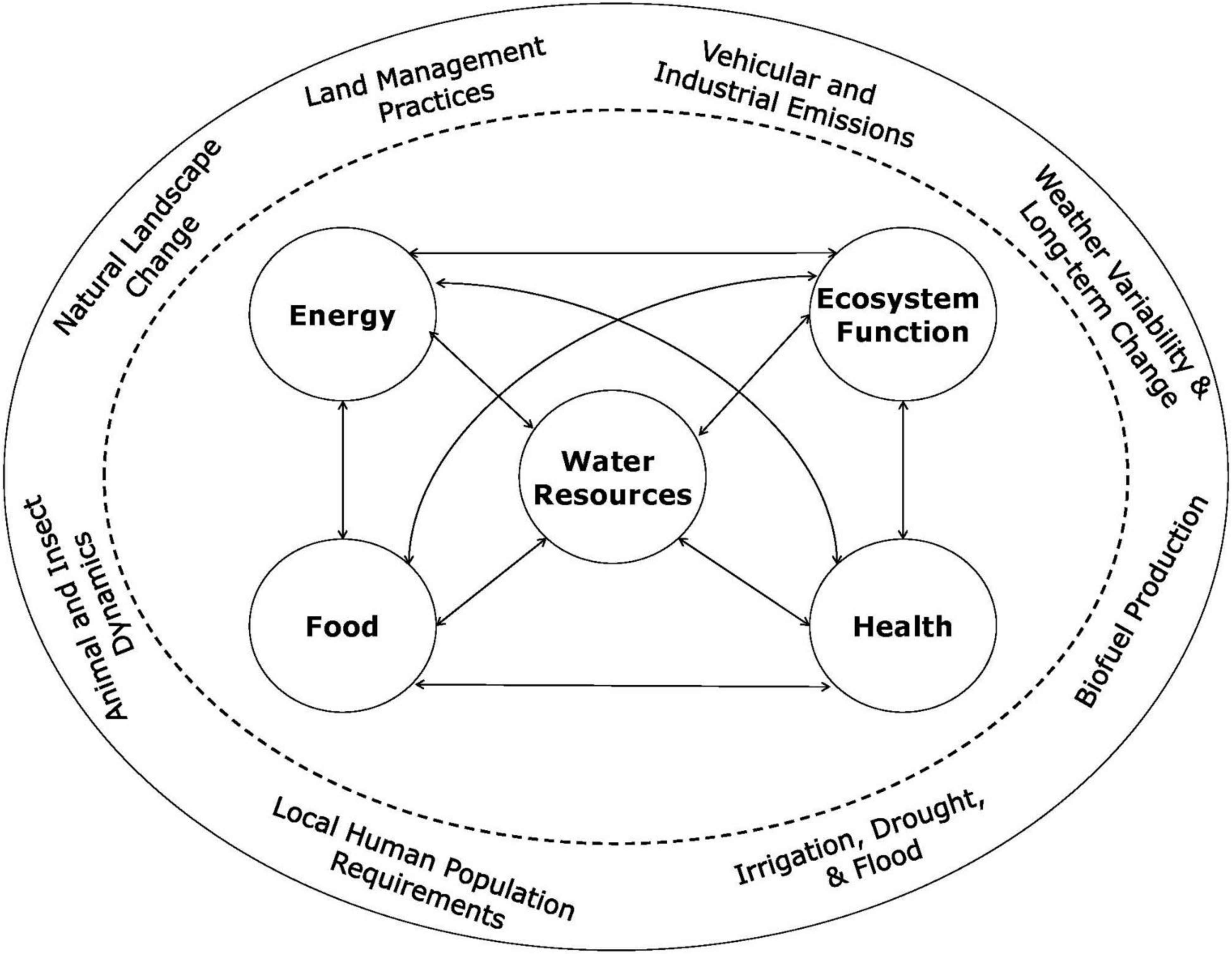


Figure 5 Two interpretations of vulnerability in climate change research from *Füssel* [2007].

	End-Point Interpretation	**Starting-Point Interpretation**
Root problem	Climate change	Social vulnerability
Policy context	Climate change mitigation, compensation, technical adaptation	Social adaptation, sustainable development
Illustrative policy question	What are the benefits of climate change mitigation?	How can the vulnerability of societies to climatic hazards be reduced?
Illustrative research question	What are the expected net impacts of climate change indifferent regions?	Why are some groups more affected by climatic hazards than others?
Vulnerability and adaptive capacity	Adaptive capacity determines vulnerability	Vulnerability determines adaptive capacity
Reference for adaptive capacity	Adaptation to future climate change	Adaptation to current climate variability
Starting point of analysis	Scenarios of future climate hazards	Current vulnerability to climate stimuli
Analytical function	Descriptive, positivist	Explanatory, normative
Main discipline	Natural sciences	Social sciences
Meaning of “vulnerability”	Expected net damage for a given level of global climate change	Susceptibility to climate change and variability as determined by socioeconomic factors
Qualification according to the terminology from Section 2	Dynamic cross-scale integrated vulnerability [of a particular system] to a global climate change	Current internal socioeconomic vulnerability [of a particular social unit] to all climatic stressors
Vulnerability approach	Integrated, risk-hazard	Political economy
Reference	*McCarthy et al.* [2001]	*Adger* [1999]


Land Management Practices
Vehicular and Industrial Emissions
Natural Landscape Change
Weather Variability & Long-term Change
Energy
Ecosystem Function
Water Resources
Food
Health
Animal and Insect Dynamics
Biofuel Production
Local Human Population Requirements
Irrigation, Drought, & Flood