Ecological Complexity 20 (2014) 325–334

Contents lists available at ScienceDirect

Ecological Complexity

journal homepage: www.elsevier.com/locate/ecocom

Integrating *Homo sapiens* into ecological models: Imperatives of climate change

Andrew Long [a,*], Rebecca C. Tyson [b]

[a] Department of Mathematics and Statistics, Northern Kentucky University, Nunn Drive, Highland Heights, KY 41099, USA
[b] Mathematics & Statistics, IKBSAS 5 BLDG SCI, University of British Columbia Okanagan, 3333 University Way, Kelowna, BC V1V 1V7, Canada

ARTICLE INFO

Article history:
Received 2 December 2013
Received in revised form 1 May 2014
Accepted 12 May 2014
Available online 11 July 2014

Keywords:
Climate change
Mathematical model
Mathematical ecology
Human behaviour

ABSTRACT

In the opening lecture at a 2013 Banff International Research Station (BIRS) workshop on the impact of climate change on biological invasions and population distributions, Henri Berestycki (École des Hautes Études en Sciences Sociales) asked a crucial question: Can a species keep pace with a changing climate? "Species" in this context was generally understood to be all living things on Earth (except humans). But mounting scientific evidence suggests that it is time to pose the parallel question: Can *Homo sapiens* keep pace with a changing climate? Furthermore, should we merely "keep pace", or should we strive to get ahead and then do our utmost to stop any further climate change?

In this paper we document the very real potential for climate change to have devastating consequences before the end of this century. The urgency of the situation calls for concerted action by anyone who understands the problem, and mathematical ecologists are uniquely trained to contribute to such efforts. We ask modellers to deliberately incorporate the species *H. sapiens* into their modelling work, and offer suggestions as to how this might be done. Ultimately modellers must seek ways to provide guidance to citizens and policy-makers as we all wrestle with the most important existential threat of our time.

1. Introduction

The magnitude and pace of climate change have simultaneously reached a point where new modelling approaches are needed (Gilman et al., 2010; Warren, 2011). The 2013 BIRS workshop entitled "Impact of climate change on biological invasions and population distributions" (Berestycki et al., 2013) which inspired this special issue of Ecological Complexity, focussed on ecological models incorporating climate change. A common approach in nearly all of the workshop models was to assume particular changes in one or more climatic variables (temperature, climate variability, precipitation, etc.), and then explore the consequence of this change to (1) shifts in species range boundaries, (2) dynamics of invasive species, (3) multispecies interactions, and/or (4) shifting patterns of vegetation (Berestycki et al., 2013). The excellent work presented at the workshop documented a host of consequences for species persistence, biodiversity, genetic variability, etc. We were struck, however, by the relative scarcity of models incorporating any feedback to the human-related mechanisms of climate change. This omission is common in the ecological modelling literature: While there is an extensive and valuable body of work looking at the current and future impacts of climate change on a host of organisms, few models in ecology include the primary agent of all this climate trouble: *Homo sapiens* (Liu et al., 2007). In this paper, we argue that there is a strong need to include humans and human behaviour in ecological models addressing climate change.

There is a long history of mathematical models in ecology that treat humans as separate, possibly rooted in the notion, conscious or unconscious, that humans are somehow different or above the workings of ecological systems. Indeed, Judeo-Christian scripture puts us on this pedestal: "And God said, Let us make man in our image, after our likeness: and let them have dominion over the fish of the sea, and over the fowl of the air, and over the cattle, and over all the earth, and over every creeping thing that creepeth upon the earth."[1] The notion stuck in the western world, at least for awhile: We humans are different – we have dominion, and that may have never been so evident as it is today.

* Corresponding author. Tel.: +1 859 572 5794.
E-mail address: longa@nku.edu (A. Long).
URL: http://artscience.nku.edu/departments/math/people/mathematicsfaculty/long.html

[1] Genesis 1:26, King James version.

http://dx.doi.org/10.1016/j.ecocom.2014.05.008
1476-945X/

An additional reason to leave humans out of models incorporating climate change is the pervasive notion that there is not much that we can do about global warming. For example, a 2006 survey by the Pew Center found that 22% of Americans believed that there is nothing that humans can do to reduce the effects of global warming (Pew Research Center, 2006). The absence of human behaviour from ecological models suggests that many mathematical ecologists simply accept that climate change is happening, and seek to determine the consequences to ecological systems. This approach is fine as long as the anticipated change is not too drastic, and simply adapting to the altered climate is sufficient. Unfortunately, we have reached a point where catastrophic bifurcations are entirely possible (Boulton et al., 2013; Budzianowski, 2013; Di Paola et al., 2012; Ashwin et al., 2012; Kwadijk et al., 2010). A recent report (Schwartz and Randall, 2003; Shearer, 2005) examined threats to National U.S. Security posed by climate change through disruptions of food, water, or fuel: "[o]cean, land, and atmosphere scientists at some of the world's most prestigious organizations have uncovered new evidence over the past decade suggesting that the plausibility of severe and rapid climate change is higher than most of the scientific community and perhaps all of the political community is prepared for." Consider the consequences of having supply centres of essential commodities such as oil taken out by severe storms [already increasing in magnitude and geographic extent (Karl et al., 2009)], food supplies severely reduced or eliminated through the loss of pollinators [already experiencing significant decline (Potts et al., 2010; Vanbergen et al., 2013)] or through trophic mismatch (Harrington et al., 1999), and drastic reductions in the availability of clean water through disruption of the hydrologic cycle (Sachs, 2009). The trajectory of anthropogenic activity is predicted to lead to severe changes as soon as the year 2100, when children and grandchildren born today are only in their 80s (Mora et al., 2013; IPCC, 2013a). If we are lucky, the changes will be slow enough for humans to adapt gracefully to them, but it is not at all clear that our luck will hold. As mathematicians know, bifurcations can be dramatic. It is therefore not enough to simply accept that climate change will happen: We must do something about it.

It is important that we establish at this point that it is indeed human activity that is changing the Earth's climate. The evidence for this view continues to mount, and the latest report from the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2013a) states with high confidence that global warming is due largely to anthropogenic forcing. Given that it is anthropogenic activity that is almost surely the chief cause of global warming, it is clear that we humans can no longer be considered "separate" from the natural systems we inhabit, at least when it comes to climate change. Since humans are causing the climate problem, humans also hold the key to solving it.

In this paper, we present as a call to arms a brief primer on climate change and the implications thereof (Section 2), and then argue that there is a pressing need for mathematicians to engage in studies that consider the human factor as a dynamic element in our models (Section 3), and give some illustrative examples. Finally, we argue that we mathematical biologists need to speak broadly about our results (Section 4) so as to raise awareness of the situation with as many people as possible and, hopefully, inspire effective action. If we are fortunate, together with our neighbours we will influence those with the power to change our current and potentially disastrous trajectory.

2. Climate change as crisis

We begin by assembling here an easily communicated collection of some of the most accessible research regarding climate change. For many people, the issue remains a threat too large or too distant to really comprehend at a personal level. The assertion that an average increase of 2 °C is disastrous is difficult to reconcile with personal experience of annual and daily temperature swings considerably larger than 2 °C. The material gathered here helps to personify the problem and put climate change into perspective. Our goals are to clarify the urgency of the situation to you, the reader, and to arm you with information that can be used in discussions with friends and colleagues.

Our assertions of human responsibility for climate change are justified by the findings detailed in the 2013 fifth assessment report (AR5) of the IPCC[2]. One of the highly publicized findings is that, with 95% certainty, humans are the principal drivers of the rapid global warming we have experienced over the period since the beginnings of the industrial revolution, and that the culprits are the greenhouse gases that we have been emitting. Some people have puzzled over the use of "95%" certainty (up from 90% in the 2007 IPCC report). A recent AP news report puts that figure into better perspective: "Top scientists from a variety of fields say they are about as certain that global warming is a real, man-made threat as they are that cigarettes kill... They say they are more certain about climate change than they are that vitamins make you healthy or that dioxin in Superfund sites is dangerous" (Borenstein, 2014).

The inescapable scientific conclusion is that we humans are manipulating the composition of the atmosphere, using the skies as an enormous carbon dumping ground, and are thus altering our climate. There has been to this point no direct cost for doing so [the cost has been externalized (Nordhaus, 2013), "represent[ing] the biggest market failure the world has seen" (Stern, 2008)], and so this practice has continued up to the present in a global demonstration of the Tragedy of the Commons (Hardin, 1968).

Given that humans are indeed responsible for global warming, we now continue our story to its logical conclusion. The rest of the story is based on three critical information sources for climate change (one data set and two organizations): The Keeling data, the United States' National Academy of Sciences (NAS), and the Intergovernmental Panel on Climate Change. That the authority of these voices is being so widely disregarded or, even worse, dismissed is something of a mystery; that their tale is not at the forefront of discussions throughout the halls of academia is a cause for acute dismay. We acknowledge and thank those people giving impassioned and eloquent deliveries of this story (Annan, 2013; Vidal, 2012), but the message is not being taken seriously, by and large, as evidenced by the lack of concerted international action.

The story begins with the Keeling data (NOAA, 2014), called the most important environmental data set taken in the 20th century (Kennel and Keeling, 2011). Charles David Keeling demonstrated the rapid and inexorable increase in CO_2 that has occurred with steadily increasing industrialization worldwide (Fig. 1). In spite of the Kyoto Protocol (1997), a treaty with the stated purpose of reducing greenhouse gas emissions, the planet has shown no evidence of a slow-down in CO_2 pollution. In fact, it appears from the graph in Fig. 1 that the trend is actually accelerating (an acceleration attested to as well by the World Meteorological Organization in their 2013 Greenhouse Gas Bulletin (World Meteorological Organization, 2013)).

The increasing levels of CO_2 in the atmosphere are accompanied by increasing global temperatures (Fig. 2). Since the industrial revolution, global mean temperatures have increased by 0.8 °C, and current trends indicate that we could see an increase of anywhere between 1.8 and 4 °C by the end of the 21st century (Working Group I, 2007). On a daily basis however, humans regularly experience daily temperature swings of anywhere between 5 and 15 °C. Why, then, is an increase in global mean

[2] Working Group I's report on the physical state of climate (IPCC, 2013a).

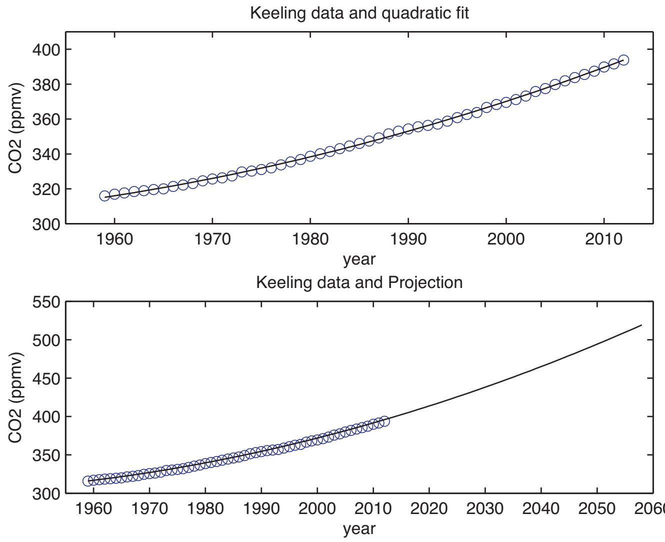

Fig. 1. The Keeling data, current as of July, 2013 (NOAA ESPL data, obtained from www.esrl.noaa.gov/gmd/ccgg/trends/). The Keeling data is plotted with a quadratic curve (1) obtained via least squares fitting. In the lower panel, the fitted curve is plotted forward in time, to suggest the time course of future increases in atmospheric CO_2 assuming no major changes in human behaviour.

temperature of just a few degrees so worrisome? It is difficult to put this number into perspective, but the key lies in understanding tipping points. As mathematicians, we are intimately familiar with the dramatic changes in behaviour that can occur when a bifurcation parameter changes by just a small amount: The smallness of the change in parameter value is irrelevant if a bifurcation point is crossed. Global mean temperature appears to be a bifurcation parameter, leading to "climatic tipping" of different phenomena at different values (e.g. dieback of the Amazon rainforest, or the end of the Atlantic thermohaline circulation) (Lenton et al., 2008).

We do not know exactly where the bifurcation value(s) lies, but scientists are becoming increasingly adept at modelling the physical processes connected with climate change (Mora et al., 2013), and mathematical biologists (and many others) are able to provide well-informed estimates of species survival under various scenarios (Gilman et al., 2010; Di Paola et al., 2012). At just 2 °C of warming, significant negative impacts are anticipated (Elkin et al., 2013) and some regions will likely experience an average warming of much more than 2 °C (Corlett, 2012). Given all of this research, a warming of 2 °C is regarded by the United Nations Framework Convention on Climate Change as an *upper-limit* of (relatively) safe warming, that is, a *lower-limit* on any bifurcation value of temperature which we must

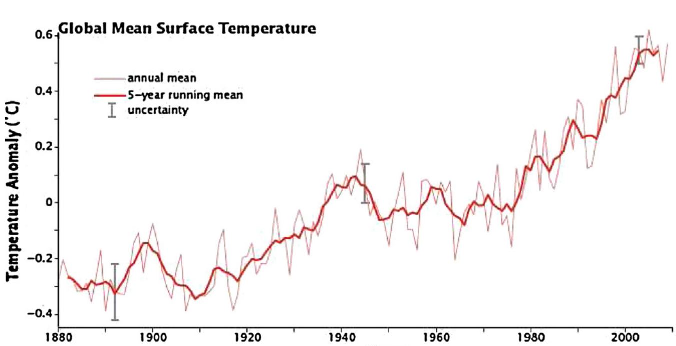

Fig. 2. Image from NASA's Earth Observatory website (http://earthobservatory.nasa.gov/).

not exceed (United, 2013). Nonetheless, all signs point to exceeding this lower-limit (Joshi et al., 2011), and so we risk exceeding a bifurcation value as well.

The National Academy of Sciences has issued its best estimates of the relationship between atmospheric CO_2 and increases in global mean temperature (CSTAGGC, 2011), shown in Table 1. An elementary analysis of this table and the Keeling data demonstrates why there is real urgency to the current situation. In order to estimate when we can expect the atmospheric carbon level to have increased by a given amount, we model Keeling's data with a simple non-linear regression model of the form[3]

$$CO_2(t) = A(t-1958)^2 + B(t-1958) + C. \quad (1)$$

Using (1), we arrive at a point estimate of 2026.67 for the year at which we achieve 430 ppmv (Fig. 1, lower panel). Note that at a point estimate of 430 ppmv of CO_2, the global average temperature will be expected to have warmed by 2° (Table 1). Thus, in a mere 13 years (from 2013) the model predicts that we will have locked in 2 °C of warming (provided we employ the best estimates of the National Academy of Sciences).

At around 600 ppmv the NAS predicts 3.5 °C of global warming, and at this level the IPCC projects that 40–70% of all species will be extinct or at significantly increased risk of extinction (IPCC, 2007). Increased CO_2 in the atmosphere will also increase already significant ocean acidification, posing extreme threats to the bottom of our food chain (Warren, 2011). The same model used above projects the arrival of 600 ppmv in 2080.91: Children born today will be just 67 years old. More sophisticated analyses (Betts et al., 2011), based on the A1FI scenario of the IPCC's AR4 (Working Group I, 2007), suggest that four degrees C of warming may come even earlier, in the 2070s.[4]

Our straightforward story may seem fantastic, impossible even; we point out, however, that since the creation of the IPCC, global warming has consistently exceeded the worst case predictions of the panel (PSMCRDS, 2009). Indeed, the IPCC's reports (and other consensus reports) have been overly conservative (Freudenburg and Muselli, 2010; Brysse et al., 2013; Rahmstorf et al., 2007; Scherer, 2012). "...[I]f anything, global climate disruption may prove to be significantly worse than has been suggested in scientific consensus estimates to date" (Freudenburg and Muselli, 2010). A recent article in Nature (Schiermeier, 2013), released just a few months before the IPCC Working Group III report (Working Group III, 2014), warned that the IPCC report would find that "...all realistic stabilization scenarios are decidedly at odds with current emissions trends." Our climate is destabilized, and destabilizing further.

A 2009 article in the New Scientist (Vince, 2009) paints a grim, even horrific, picture of life in the "4 °C world" (that is, the world to come if we continue on a "business as usual" trajectory and cause a 4 °C rise in global temperature). Life will have moved to the high latitudes near the poles (including an increasingly ice-free Antarctica), the human population reduced to under a billion, and a risk of runaway global warming taking down even our own species (among the many others that will have disappeared).

[3] The model is motivated as a quadratic trend, tracing the increase in the average annual level of atmospheric CO_2. The monthly Keeling data (not shown) exhibits an annual sinusoidal oscillation corresponding to the seasonal photosynthetic activity of the northern forests. We do not wish to argue the virtues of this particular model, but simply use it as a practical starting point. Other simple models give virtually the same results. Our model fit has parameter values of $A = 0.0119$, $B = 0.8544$, and $C = 315.2$.

[4] Median simulation estimate of Betts et al. (2011): 2075; ironically, their minimum estimate – 2061 – would come on the 200th anniversary of John Tyndall's famous lecture "On the Absorption and Radiation of Heat by Gases and Vapours, and on the Physical Connexion of Radiation, Absorption, and Conduction", elucidating the role of carbon in creating the "greenhouse effect" (Tyndall, 1861).

Table 1
Estimates for the temperature increases expected due to an increase in our atmospheric CO_2 load. Values of CO_2 are given as parts per million by volume (ppmv). The range given is the 66% chance interval.

Min CO_2	Best estimate of CO_2	Max CO_2	Equilibrium global average warming (°C)
320	340	380	1
370	430	540	2
440	540	760	3
530	670	1060	4
620	840	1490	5

Source: The National Academy of Sciences (CSTAGGC, 2011).

"Alligators basking off the English coast; a vast Brazilian desert; the mythical lost cities of Saigon, New Orleans, Venice and Mumbai; and 90% of humanity vanished. Welcome to the world warmed by 4 °C" (Vince, 2009). While not all scientists predict such dire scenarios for a 4 °C world, these seemingly fantastic projections are entirely plausible. "In such a 4 °C world, the limits for human adaptation are likely to be exceeded in many parts of the world, while the limits for adaptation for natural systems would largely be exceeded throughout the world"(Warren, 2011).

Thus, we reach the conclusion of our story: it seems clear that we are on the verge (or in the midst) of a sixth mass extinction event (characterized by the loss of 75% or more of Earth's species (Barnosky et al., 2011)). While climate change is not the sole culprit (there are others, such as habitat fragmentation, human introduction of non-native species, etc.), it appears clear that human-caused climate change will be one of the largest contributors, should this loss of life come to pass.

From the discussion above, it is clear that humans and the climate form an enormous coupled dynamical system, and changes to one impact the other (Liu et al., 2007). Humans are not only *reacting* to changing climatic (and environmental) conditions, but are actually *responsible for setting them into motion*. We observe and model and predict the advance of malaria or Lyme disease or the mountain pine beetle, but it is we who set them to advancing. There is thus a strong need to include human behaviour – both the component responsible for effecting climate change and the component describing human response to the collateral effects of climate change – in ecological models.

3. New modelling approaches

Liu et al. (2007) recently coined the phrase "coupled human and natural systems" (CHANS) to describe models that include ecological processes and human behaviour. They established three aspects of CHANS models in general:

1. A focus on the patterns and processes that link human and natural systems.
2. Reciprocal interactions and feedbacks – effects of humans on the environment and effects of the environment on humans.
3. An understanding of within-scale and cross-scale interactions between human and natural components.

They assert that "...the science of CHANS promotes the integration of all these aspects. Such integration is needed to tackle the increased complexity and to help prevent the dreadful consequences that may occur due to the fundamentally new and rapid changes, because the magnitude, extent, and rate of changes in human–natural couplings have been unprecedented in the past several decades, and the accelerating human impacts on natural systems may lead to degradation and collapse of natural systems which in turn compromise the adaptive capacity of human systems" (Liu et al., 2007).

Mathematical modellers often focus on a species or two, or on a particular small part of the global ecosystem. This is a sensible approach: The resulting models are generally amenable to analysis, or thorough investigation through numerical techniques, and definitive conclusions can be reached. On the other hand, with the daunting prospect of a sixth mass extinction looming, one is compelled to ask if studying a small part of the ecosystem (based on the assumption that all else remains constant) even makes sense: It is clear, after all, that the rest of the world will not remain fixed in any meaningful sense of that word, especially if a tipping point is crossed. It is also clear that as the climate changes,[5] species will likely respond to the change at different rates and in different ways, and so dynamical considerations of whole ecological communities may lead to outcomes that differ from those predicted by study of just 1–3 species (Gilman et al., 2010).

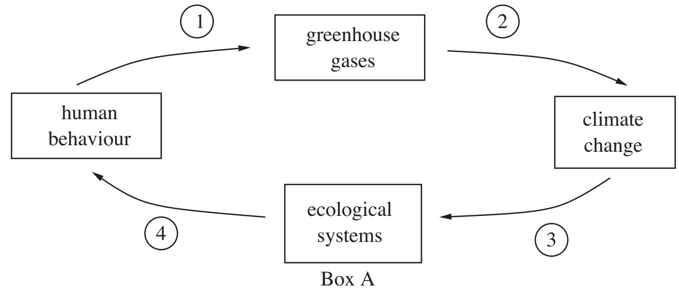

Fig. 3. Diagram illustrating the closed loop formed by human behaviour and climate. Theoretical ecologists have tended to focus on step 3, assuming changes in the climate and predicting the responses in Box A. Since this step exists within a closed loop however, and since changes in human behaviour are so critically needed to avert disaster (IPCC, 2013a), we argue that there is a strong need for theoretical ecologists to use their skills to model the entire loop. This is the focus of research in coupled human and natural systems (CHANS).

We illustrate the CHANS loop in Fig. 3. At the recent BIRS workshop (Berestycki et al., 2013), the majority of modelling work presented focussed on step 3. This important research predicts the effects that can be expected in Box A, and is an important part of the scientific evidence supporting the notion that the effects of climate change are of serious concern. At this point however, there is a desperate need for far more than concern: Significant changes to human behaviour are needed. While fear of disaster can change human behaviour, it can also induce a sense of fatalism justifying inaction. New models that address the full feedback loop provides humans an explicit demonstration of the connection between human behaviour and climate, and of the benefits that can be expected from changes in human behaviour. Theoretical ecologists are uniquely skilled in modelling natural systems, and so we suggest that, given the gravity of the situation with regard to climate change, mathematicians should begin adopting a CHANS-like approach as directly as possible.

There are several different aspects to the modelling process: model considerations and development, the creation of the model itself, the analysis of the model, and the communication of the results. In this section we suggest several ways in which *H. sapiens* can be integrated more directly into the entire modelling process, using a CHANS-like approach.

3.1. In our models: favour larger, more complex models

Large, complex models have generally been shunned by the mathematical community on the basis that they are too complex to be thoroughly understood, and therefore any real gain in knowledge will perforce be limited. Simple models seem better,

[5] We have been focussing on temperature, but the discussion is equally relevant for the myriad other aspects of climate change, such as precipitation, range shifts, flooding, etc.

because they are more tractable and may allow us to understand model behaviour better (if not completely). One then hopes that modellers can assemble their simple sub-systems together in some reasonable way to model more complex systems.

Unfortunately, it appears that the rapid pace of climate change will not give us the time to understand each and every simple building block in the entire complex system prior to putting them all together. We have at most 10–20 years before containing climate change within a peak warming of 2 °C becomes completely out of reach (Gillis, 2014; Stocker, 2013). Furthermore, mathematical studies of nonlinear systems have made it clear that such systems do not behave simply as the sum of their parts: Nonlinear interactions can lead to entirely new and unexpected behaviours under climate change (Gilman et al., 2010). "However, for the majority of species, the effects of climate change on such interactions have not been considered, and this is potentially significant in terms of unforeseen disruption to ecosystem functioning" (Warren, 2011). Given the urgency of the climate change problem, we suggest that modellers need to devote more time and energy to the study of large, complex CHANS. One goal might be to distill simpler yet reasonable models from these more complicated ones: since mathematical biologists are highly skilled at developing simple, insightful models of biological systems, any work we do on CHANS could very well lead to the development of novel and meaningful simplifications of the larger models.

3.2. In our models and discussion: use climate scenarios

Global Circulation (or Climate) Models (GCMs) use a variety of scenarios to predict the future global climate and the physical consequences thereof (IPCC, 2013b). The new aspect of scenario development in the fifth IPCC assessment report (AR5) is that the research community was asked to provide the scenarios to the IPCC (or at least guidance on them).[6]

This use of scenarios suggests an important new role for those incorporating climate change into their models: Results need to be presented in a way that can be easily used by policy-makers, and speaking the language of the IPCC scenarios is one way to accomplish this. For example, the conclusions of Mora et al. (2013) are presented based on IPCC's Representative Concentration Pathways (RCP) greenhouse gas concentration scenarios (Wayne, 2013): "Under RCP45, the projected near-surface air temperature of the average location on Earth will move beyond historical variability by 2069 (±18 years...) and two decades earlier under RCP85 (that is, 2047 (±14 years s.d.)...)". These scenario-based results can now be fed into future models, creating a body of research that provides scenario-specific climate change results within a context that is already understood by others.

Possible research questions for any modeller include:

1. Given the results of my study, what impacts are locked in without humans, and which aspects are under (or subject to) human control, and so "scenario dependent"?
2. What are the consequences of my species's movement or distribution on human beings (e.g. Lyme disease)? How should humans behave in order to avoid negative impacts, or facilitate positive ones (i.e. how should scenarios be tuned)?
3. What other facets of the environment (e.g. ecosystem services such as precipitation) am I assuming will remain constant throughout my study? Will they remain constant across climate change scenarios?

One potential consequence of this "scenario-based reflection" is that it may "flesh out" the RCP scenarios, thus making their implications clearer to policy-makers. "Collaboration is necessary, not just among scientific disciplines or between scientists..., but also with decision-makers, to better understand what they require and how scientific results are factored with other considerations to produce decision outcomes" (Anon, 2014).

3.3. In our model development and discussion: incorporate human responses to climate change

The complexity of human behaviour presents a daunting challenge to the mathematical modeller. It is in addressing such challenges however, that scientists make advances in human knowledge. In particular, we can make efforts to address the problematic notion that individuals can do little to combat climate change. Consider the following modelling questions:

1. What is the effect of specific changes in human behaviour on the species we study? Do we need every human on earth to reduce his or her carbon footprint by a given amount, or would it be enough to have 30% of humanity make such a change?
2. What targets could humans get excited about? We know that polar bears are at grave risk of extinction, but can modelling work be harnessed to show what portion of polar bear populations might be saved by certain measurable changes in human behaviour? Is it enough to ask humans to drive less and eat local, or are more extensive changes needed? Place your specie's issues into a human context.
3. Science does not operate within a vacuum: what are the political and economic tipping points that will finally align good governance with science? Do your models have economic or political ramifications that would facilitate this alignment?

Including human behaviour in a meaningful way, and presenting the results in a compelling way, may require that we collaborate with psychologists, philosophers and social scientists versed in the literature of human behaviour and how it is, or is not, changed by ideas.

Interesting studies provide insights into how humans approach the problem of climate change. For example, Jacquet et al. (2013) present evidence that "intergenerational discounting" is working against a solution to the crisis because "[t]he present generation bears the costs of cooperation, whereas future generations accrue the benefits if present cooperation succeeds, or suffer if present cooperation fails." An alternative interpretation of this "intergenerational selfishness" is that the present generation is causing the problem that successive generations will have to deal with. Climate scientist James Hansen expressed this well in the title of his heart-breaking book *Storms of My Grandchildren* (Hansen, 2009). Any way you express it, it's a clear violation of that fundamental rule that we were all supposed to learn in Kindergarten: When you make a mess, you should clean it up (Fulghum, 2004).

In another study, Stoll-Kleemann et al. (2001) found that even though their focus group members were "alarmed" about climate change, the members of the group found even more daunting the behavioural changes necessary to mitigate climate change. And so they erected denial mechanisms, which "...heightened the costs of shifting away from comfortable lifestyles, set blame on the inaction of others, including governments, and emphasized doubts regarding the immediacy of personal action when the effects of climate change seemed uncertain and far away." For those wishing to sow doubt in the population in order to forestall any action in the fight against climate change, the preceding quote suggests an ideal strategy: Emphasize the cost and impacts on citizens' preferred lifestyles (e.g. loss of jobs), while denigrating the value

[6] See the IPCC Data Distribution Centre website (IPCC, 2013c) for how scenarios have been developed for AR5. The process is described in more detail in Moss et al. (2010).

of any actions (e.g. why should we act, when China won't?). We're currently experiencing the fruits of that strategy.

These human thought processes, actions, and reactions should be incorporated into any ecological models, and pursued further. The world requires that we present an honest and realistic model of what is likely to occur if we continue on our current path. However, if societies ultimately fail to act on our advice, the implications of that failure must be made clear.

3.4. In our communications: actively encourage nonlinear thinking

One specific example of a popular "pattern and process" notion that works against climate action is "linear thinking", that is, the idea that small changes in inputs lead to small changes in outputs. This mode of thinking is so deeply ingrained that even mathematicians intimately familiar with dynamical systems and bifurcation points will ask "why is an increase of 2 °C such a big deal?"

We may encourage the citizenry in this unrealistic linearity by the way we present the findings of our work. Consider, for example, a recent publication of Levermann et al. (2013) in the Proceedings of the National Academy of Sciences: The major result, as presented in the public sphere, is epitomized by headlines such as "Each degree of warming raises sea levels 2.3 m in the long run, says study", or the line "for every degree Celsius the temperature increases, sea levels will rise about 7 ft"[7] Indeed the authors of the study do project that, to first order, sea level will rise 2.3 m for each degree of warming beyond pre-industrial times. Mathematicians know full well that the linear version of this result is incorrect, albeit a handy first approximation: The actual response will be nonlinear. "Linear thinking" misleads the public into imagining that small changes will *necessarily* have small effects: If we raise the temperature 0.5°, then we will have 1.15 m of rise; if we raise the temperature 2°, then we will have 4.6 m of sea level rise. This effectively buries the notion of tipping points, which are so crucial in the discussions of climate change, especially because they can occur without warning (Hastings and Wysham, 2010). It may well be that at 6 °C of warming, we have sea level rise of far more than 6 times 2.3 m, because of feedbacks in albedo, methane clathrates, etc. Non-linearities abound in climate, and yet we lure the public into linear thinking. We must lead them into a better understanding of non-linearities and tipping points instead.

In our modelling work therefore, we should be constantly aware of the real-world consequences of the tipping points we find, and emphasize this behaviour in our writing. We should also ask ourselves where we might expect tipping points, and what human behaviours would have either an exacerbating or mitigating effect. What community interactions are subject to tipping points as the climate warms? What tipping points might concern the public enough to result in changes in behaviour? If changes in behaviour are made, what behaviour can be expected from the system as the key parameter is carried back across the initial bifurcation value?

3.5. A simple example

Consider how one might modify a simple model in the interest of providing insight into the human element driving that system. Gilman et al. give an example of a host–pathogen interaction,

$$\frac{dI}{dt} = \beta SI - LI = \lambda I \tag{2}$$

where S and I are the susceptible and infected host densities, β the transmission coefficient, and L the loss rate from mortality and recovery (Gilman et al., 2010). They suggest introducing climate through parameter dependence on abiotic variables, such as temperature. For example, the parameter λ might depend on temperature in the following way,

$$\lambda(T) = \beta(T)K(T) - L(T) \tag{3}$$

where $S = K(0)$ is the initial carrying capacity. This is a step in the right direction, but does not contain direct human influence on temperature.

We encourage modellers to take this idea a step further: Rather than making the parameters *temperature*-dependent, one might make them *emissions*-dependent (hence directly related to human activity and behaviour). While it is indeed temperature that directly impacts the host-pathogen interaction, it is humans who have their hands on the thermostat via the concentration of greenhouse gases (e.g. CO_2 as evidenced by the Keeling data). By focussing on the variable under human control, we hope to make it clear to humans that we are both impacting other species, and also have some say in precisely what impact we have.

For example, we might make use of a model proposed by Bowerman et al. (2011), of temperature as a function of time featuring a three-component atmosphere-ocean carbon cycle based on emissions. Their model can be used to transform ecological models based on global temperature to CHANS-like models based on *emissions*. Their model for the change in temperature T is a function of atmospheric carbon, C, which is itself a function of emissions E:

$$a_1 \frac{dT}{dt} = a_3 \ln\left(\frac{C(E_a(t), t)}{C_0}\right) - a_0 T - a_2 \int_0^t \frac{dT(t')}{dt'} \frac{dt'}{\sqrt{t - t'}}, \tag{4}$$

where t is time, the a_i are measurable constants, and C_0 is the pre-industrial level of atmospheric CO_2. The variable E_a represents anthropogenic carbon emissions. The functional dependence of atmospheric carbon on emissions and time is nontrivial; the reader is referred to the original paper (Bowerman et al., 2011) for details. Here we simply write $C = C(E_a(t), t)$ to emphasize the role of anthropogenic emissions in determining carbon levels. It is this last variable, E_a, that is key to our discussion here. The time-evolution of emissions depends on a host of factors including population growth, destruction of carbon sinks, and human action to curb emissions. If we let h represent whatever human responses the modeller might wish to explore, then anthropogenic carbon emissions is itself a function that we can write as

$$E_a = E_a(t, T, h(T, t)). \tag{5}$$

It is chiefly through exploration of different theoretical predictions for the function (5) that modellers can begin to explore the feedback between human behaviour, with respect to emissions, and ecological systems. A possible explicit functional form for (5), inspired by the model used by Bowerman et al., is

$$E_a = \begin{cases} a_1 e^{b_1 t} & 0 \le t_0 \le t < t_1, \\ a_2 e^{b_2 t^2 + c_2 t} & t_1 \le t < t_2, \\ a_3 e^{b_3 t} & t \ge t_2, \end{cases} \tag{6}$$

where t_0, t_1 and t_2 are critical times at which emissions behaviour is assumed to change, which might be temperature dependent. Other authors (e.g. Anderson and Bows, 2011) suggest reasonable emission scenarios based on human-desired targets. If these changes are modelled as responses to the outcomes in Box A (Fig. 3), then step 4 is being addressed and the full CHANS loop is closed in this model.

[7] The first from The Carbon Brief blog at http://www.carbonbrief.org/blog/2013/07/each-degree-of-warming-raises-sea-levels-23-metres-in-the-long-run,-says-study; the second is from the introduction to a Living on Earth interview with Anders Levermann – http://www.loe.org/shows/segments.html?programID=13-P13-00029&segmentID=3.

By combining Eqs. (2)–(5), the original host-pathogen system becomes one where the link to human behaviour, through emissions and then temperature, is directly included. There a wide range of plausible choices for E_a as a function of human behaviour. It is through the exploration of the effect of E_a on traditional ecological models such as (2) that ecologists may begin to make significant novel contributions to our understanding of the impact of *humans* on ecosystems via climate change. In this example we have switched the focus to the impact of *humans*, through their carbon emissions on the species under consideration, rather than *temperature* (which is a secondary effect). If we then consider changes to our emissions in response to the resulting impacts, then we will have closed the loop between human behaviour, climate, and natural systems.

There are other examples of models that include the full loop from human behaviour to the system being studied and then back to human behaviour again. These models can be used as inspiration for the type of work we are calling for here. In the field of epidemiology, it is well-known that human attitudes towards vaccination have a strong effect on disease dynamics, and vice versa. This full loop has recently been studied using evolutionary game theory as a modelling tool (Bauch and Bhattacharyya, 2012). Another recent paper uses a simple ordinary differential equation model to suggest that the collapse of our industrial society is highly likely (Motesharrei et al., 2014): "The scenarios most closely reflecting the reality of our world today are [those]... where we introduced economic stratification. Under such conditions, we find that collapse is difficult to avoid." By incorporating inequality among humans into their predator/prey equations, they encountered "collapse" dynamics which modelled real collapses throughout history. Their dynamical system, incorporating two types of humans (elites and commoners), a variable representing nature, and one representing wealth, provides a simple demonstration that our world can fail (from the human perspective) simply as a result of the unsustainable and inequitable use of resources. Mightn't we close the loop by generating changes in our behaviour?

3.6. Final thoughts, moving forward

Every obstacle (e.g. linear thinking, denial mechanisms) that prevents humans from understanding and acting on climate change is important, and must be swept aside. How do we incorporate into mathematical models the response time lag created by the climate change denial-sphere? Is that a pattern and process? At what scales does it operate? Perhaps denialism could be considered a reciprocal interaction and feedback – when the climate doesn't warm as much as we thought it might over the last decade, denialists make inroads; when Typhoon Haiyan slams into the Philippines, denialists take a hit. Each publication by another major scientific body should be breaking down the denial-sphere – such as recent publications by the IPCC (IPCC, 2013a), the American Association for the Advancement of Science (The AAAS Climate Science Panel, 2014), and the National Academy of Sciences and the Royal Society (Wolff et al., 2014), each of which has emphasized both the reality of climate change, and the root cause – human beings. One would think that humans would be beyond the denial stage. But when powerful economic interests stand to lose much by any relaxation of our fossil fuel addiction, those interests will naturally attempt to derail any political or societal will to change (Brulle et al., 2012).

By incorporating human behaviour into models, as we did by basing climate change in a model on human emissions rather than temperature in the Gilman/Bowerman example above, we change the focus of the discussion to the root cause, and we are on our way to suggesting changes in *human* behaviour that will have the best possible impact on the species under consideration. It would not be easy to incorporate human emotional and cognitive behaviour – both individual and collective – into mathematical models (Cook et al., 1995), either explicitly or as a feed-forward into policy, but we must keep the goal of doing so at the forefront. The problem is so gravely important – perhaps the most important of our time.

4. Conclusions

In 1824 the French mathematician and physicist Jean-Baptiste Joseph Fourier observed (Fourier, 2004) that it is the atmosphere that keeps the Earth warm (and cool) – that keeps temperatures suitable for life. Without an atmosphere, the Earth would be like the moon: Searingly hot during the day, frigidly cold at night. In 1861 the Englishman John Tyndall published his experiments (Tyndall, 1861) demonstrating that carbon gases trap infrared energy, meaning that carbon in the atmosphere prevents the Earth from shedding its heat. In 1896 Swedish scientist Svante Arrhenius insightfully estimated the temperature impact ("global warming") due to a doubling of atmospheric CO_2 (Arrhenius, 1896). In sum: we have known the implications of discharging carbon into our atmosphere for over one hundred years; but knowledge is not wisdom, and so we have continued to dump more and more carbon there.

Climate change is already driving significant changes in ecosystems around the globe (Rosenzweig et al., 2008), and truly significant changes in ambient climate will be observed within the next 50 years (Mora et al., 2013). In spite of this, we expect that many well-meaning and intelligent people have been under the illusion that if humans could just commute by bike instead of by car, and both buy less and buy local whenever possible (food especially, but other materials as well), the global carbon levels would equilibrate at an acceptable steady state level that would see most of us enjoying reasonably functional ecosystems and our current standard of living. Indeed, we shared that same illusion not so many years ago. Unfortunately, the yearly pollution from all of the cars in the world only add up to the yearly pollution of 16 of the world's largest ocean-going ships (Pearce, 2009). Reducing one's personal carbon footprint, while important, is simply not enough.

Sadly, there is still a great deal of denial and/or passivity surrounding the threat of climate change (Gleick et al., 2010; Folger, 2013), and people at all levels from individuals to governments find it easier to carry on with the *status quo*, or even reverse "green" policies (Borello, 2013), possibly in the vague hope that there will be a technological solution, or that the effects of global warming on matters of human relevance will be gradual enough for adaptation alone to be sufficient (Pew Research Center, 2006; Stoll-Kleemann et al., 2001). There is also a significant fraction of the population that simply finds the climate change problem too frightening and overwhelming to deal with, and so retreats into denial (Fig. 4). A 2010 survey of Republican candidates for the U.S. Senate found that "nearly all dispute the scientific consensus that the United States must act to fight global warming pollution" (Johnson, 2010). Even in some areas where humans are concerned enough about climate change to take drastic action, proactive behaviour is stalled by outdated regulations (Broenana and Chapin, 2013).

Given the severity of the climate change problem, and in the absence of meaningful leadership, it is crucial that everyone who understands what is at stake begin engaging, as much as possible, in activities that might lead to solutions. The magnitude and pace of change have simultaneously reached the point where new modelling approaches are needed (Gilman et al., 2010). Mathematical biologists have a unique ability to construct meaningful, simplified models of ecological systems, and decipher the real-world meaning of model solutions. Indeed, mathematical biologists

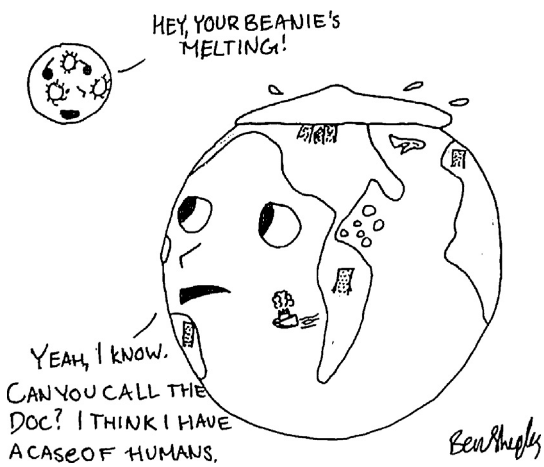

Fig. 4. While the scientific predictions surrounding climate change are a cause for enormous concern, fear often generates denial and inaction. In such cases, positive action can more often be generated by casting the problem in a humourous light.

have produced an excellent body of work documenting the negative effects of climate change for a host of different species and scenarios, as attested by the papers in this special issue and many others, a few examples include (Pounds et al., 1999; Hoye et al., 2007; Loarie et al., 2009; Visser and Both, 2005; Post and Forchhammer, 2008; Sala et al., 2000). We can use this skill set to develop models that include human behaviour, and look for ways in which we can begin addressing, not simply adapting to, the problem of climate change. Beyond that, we must make every effort to communicate the results of our work more broadly, to help drum up support for climate *action*.

In spite of our political and cultural differences, we are responding as a species to climate change, and our actions will dictate the values of all those other parameters that are traditionally included in ecological models (such as temperature, precipitation, and length of seasons). If we include humans as an important additional species in the model, both driving and reacting to climate change, we will be better positioned to comment on the full process – its development, its consequences, and what mitigation options are available. What human behaviours will result in a particular species invading? What human behaviours will result in a species going extinct? What is the value of a non-human species to human life? However repugnant it may be to cast every question in terms of human values, it may be the only way to wake ourselves – *H. sapiens* – to the consequences of our actions, and to the dangers inherent in continuing to behave as if we are not all somehow responsible for (and vulnerable to) the potentially devastating consequences of climate change.

Acknowledgements

The authors are indebted to BIRS and the organizers of the BIRS workshop 13w5095 (Henri Berestycki, Alan Hastings, Mark Lewis, and Péter Molnár) for fostering important discussions leading to this article. The authors also thank many colleagues for insightful discussions and for pointing us towards key references, especially Lael Parrot, Adriana Dawes, Elissa Schwartz and Christina Cobbold (RT) and Mary Lou Zeeman (RT, AL). This work was supported by the NSERC Discovery Grants program (RCT) and a Northern Kentucky University Faculty Benefits Project Grant and Sabbatical (AL). Many thanks are also due to Ben Shipley who, at 13 years of age, is already an accomplished comic artist. He produced the illustration in Fig. 4.

References

Anderson, K., Bows, A., 2011. Beyond 'dangerous' climate change: emission scenarios for a new world. Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci. 369 (1934) 20–44, http://dx.doi.org/10.1098/rsta.2010.0290. arXiv:http://rsta.royalsocietypublishing.org/content/369/1934/20.full.pdf+html, http://rsta.royalsocietypublishing.org/content/369/1934/20.abstract.

Annan, K., 2013. Climate Crisis: Who Will Act? The New York Times, Opinion Pages, New York.

Anon, 2014. The Arctic in the Anthropocene: Emerging Research Questions. The National Academies Press, Washington, D.C.. , In: http://www.nap.edu/openbook.php?record_id=18726.

Arrhenius, S., 1896. On the influence of carbonic acid in the air upon the temperature of the ground. Lond. Edinb. Dublin Philos. Mag. J. Sci. 4 (251) 237–276.

Ashwin, P., Wieczorek, S., Vitolo, R., Cox, P., 2012. Tipping points in open systems: bifurcation noise-induced and rate-dependent examples in the climate system. Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci. 370 (1962) 1166–1184.

Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O.U., Swartz, B., Quental, T.B., Marshall, C., McGuire, J.L., Lindsey, E.L., Maguire, K.C., Mersey, B., Ferrer, E.A., 2011. Has the Earth's sixth mass extinction already arrived? Nature 471 (7336) 51–57.

Bauch, C., Bhattacharyya, S., 2012. Evolutionary game theory and social learning can determine how vaccine scares unfold. PLoS Comput. Biol. 8 , http://dx.doi.org/10.1371/journal.pcbi.1002452.

Berestycki, H., Hastings, A., Lewis, P.M. (Organizers). Impact of climate change on biological invasions and population distributions (13w5095). Banff International Research Station Workshop. http://www.birs.ca/events/2013/5-day-workshops/13w5095.

Berestycki, H., Hastings, A., Lewis, M., Molnár, P., 2013. Impact of climate change on biological invasions and population distributions. Tech. Rep. Banff International Research Station, In: http://www.birs.ca/workshops/2013/13w5095/report13w5095.pdf.

Betts, R., Collins, M., Hemming, D., Jones, C., Lowe, J., Sanderson, M., 2011. When could global warming reach 4 °C? Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci. 369 (1934) 67–84.

Borello, E. Tony Abbott may have enough crossbench support to repeal carbon tax in new senate. ABC News, http://www.abc.net.au/news/2013-10-05/government-pushes-for-carbon-tax-repeal-by-july/5000692.

Borenstein, S. What 95% certainty of warming means to scientists. San Jose Mercury News, http://www.mercurynews.com/california/ci_24163728/what-95-certainty-warming-means-scientists.

Boulton, C., Good, P., Lenton, T., 2013. Early warning signals of simulated Amazon rainforest dieback. Theor. Ecol. 6 (3) 373–384.

Bowerman, N.H.A., Frame, D.J., Huntingford, C., Lowe, J.A., Allen, M.R., 2011. Cumulative carbon emissions floors and short-term rates of warming: implications for policy. Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci. 369 (1934) 45–66.

Broenana, R., Chapin, F., 2013. Adaptive governance and institutional strategies for climate-induced community relocations in Alaska. Proc. Natl. Acad. Sci. 110 (23) 9320–9325.

Brulle, R.J., Carmichael, J., Jenkins, J.C., 2012. Shifting public opinion on climate change: an empirical assessment of factors influencing concern over climate change in the U.S., 2002–2010. Clim. Change, http://dx.doi.org/10.1007/s10584-012-0403-y.

Brysse, K., Oreskes, N., O'Reilly, J., Oppenheimer, M., 2013. Climate change prediction: erring on the side of least drama? Global Environ. Chang. 23 (1) 327–337.

Budzianowski, W., 2013. Tetra-stable bifurcation structure of the climate system of Earth: mechanisms triggering potential transition to the greenhouse steady state. Int. J. Glob. Warm. 5 (2) 152–178.

Cook, J., Tyson, R., White, J., Rushe, R., Gottman, J., Murray, J., 1995. Mathematics of marital conflict: qualitative dynamic mathematical modeling of marital interaction. J. Family Psychol. 9 (2) 110–130.

Corlett, R., 2012. Climate change in the tropics: the end of the world as we know it? Biol. Conserv. 151 (1) 22–25.

Committee on Stabilization Targets for Atmospheric Greenhouse Gas Concentrations, 2011. Climate stabilization targets: emissions, concentrations, and impacts over decades to millennia. Tech. Rep. National Academy of Sciences, In: http://www.nap.edu/openbook.php?record_id=12877.

Di Paola, A., Valentini, R., Paparella, F., 2012. Climate change threatens coexistence within communities of Mediterranean forested wetlands. PLoS ONE 7 (10) , http://dx.doi.org/10.1371/journal.pone.0044727.

Elkin, C., Gutierrez, A., Leuzinger, S., Manushc, C., Temperli, C., Rasche, L., Bugmann, H., 2013. A 2 °C warmer world is not safe for ecosystem services in the European Alps. Glob. Change Biol. 19 (6) 1827–1840.

Folger, T. New York's sea-level plan: will it play in Miami? National Geographic News, http://news.nationalgeographic.com/news/2013/06/130612-sea-level-rise-new-york-bloomberg-sandy-climate-change-science/.

Fourier, J.-B.J., 2004. On the temperatures of the terrestrial sphere and interplanetary space. Mém. Acad. R. Sci. Inst. France 7 (1827) , Translation by R.T. Pierrehumbert.

Freudenburg, W.R., Muselli, V., 2010. Global warming estimates, media expectations, and the asymmetry of scientific challenge. Global Environ. Chang. 20 (3) 483–491.

Fulghum, R., 2004. All I Really Need to Know I Learned in Kindergarten. Ballantine Books, New York.

Gillis, J. Climate Efforts Falling Short. U.N. Panel Says. The New York Times, http://www.nytimes.com/2014/04/14/science/earth/un-climate-panel-warns-speedier-action-is-needed-to-avert-disaster.html?_r=0.

Gilman, S., Urban, M., Tewksbury, J., Gilchrist, G., Holt, R., 2010. A framework for community interactions under climate change. Trends Ecol. Evol. 25 (6) 325–331.
Gleick, P.H., Adams, R.M., Amasino, R.M., Anders, E., Anderson, D.J., Anderson, W.W., Anselin, L.E., Arroyo, M.K., Asfaw, B., Ayala, F.J., Bax, A., Bebbington, A.J., Bell, G., Bennett, M.V.L., Bennetzen, J.L., Berenbaum, M.R., Berlin, O.B., Bjorkman, P.J., Blackburn, E., Blamont, J.E., Botchan, M.R., Boyer, J.S., Boyle, E.A., Branton, D., Briggs, S.P., Briggs, W.R., Brill, W.J., Britten, R.J., Broecker, W.S., Brown, J.H., Brown, P.O., Brunger, A.T., Cairns, J., Canfield, D.E., Carpenter, S.R., Carrington, J.C., Cashmore, A.R., Castilla, J.C., Cazenave, A., Chapin, F.S., Ciechanover, A.J., Clapham, D.E., Clark, W.C., Clayton, R.N., Coe, M.D., Conwell, E.M., Cowling, E.B., Cowling, R.M., Cox, C.S., Croteau, R.B., Crothers, D.M., Crutzen, P.J., Daily, G.C., Dalrymple, G.B., Dangl, J.L., Darst, S.A., Davies, D.R., Davis, M.B., de Camilli, P.V., Dean, C., Defries, R.S., Deisenhofer, J., Delmer, D.P., Delong, E.F., Derosier, D.J., Diener, T.O., Dirzo, R., Dixon, J.E., Donoghue, M.J., Doolittle, R.F., Dunne, T., Ehrlich, P.R., Eisenstadt, S.N., Eisner, T., Emanuel, K.A., Englander, S.W., Ernst, W.G., Falkowski, P.G., Feher, G., Ferejohn, J.A., Fersht, A., Fischer, E.H., Fischer, R., Flannery, K.V., Frank, J., Frey, P.A., Fridovich, I., Frieden, C., Futuyma, D.J., Gardner, W.R., Garrett, C.J.R., Gilbert, W., Goldberg, R.B., Goodenough, W.H., Goodman, C.S., Goodman, M., Greengard, P., Hake, S., Hammel, G., Hanson, S., Harrison, S.C., Hart, S.R., Hartl, D.L., Haselkorn, R., Hawkes, K., Hayes, J.M., Hille, B., Hkfelt, T., House, J.S., Hout, M., Hunten, D.M., Izquierdo, I.A., Jagendorf, A.T., Janzen, D.H., Jeanloz, R., Jencks, C.S., Jury, W.A., Kaback, H.R., Kailath, T., Kay, P., Kay, S.A., Kennedy, D., Kerr, A., Kessler, R.C., Khush, G.S., Kieffer, S.W., Kirch, P.V., Kirk, K., Kivelson, M.G., Klinman, J.P., Klug, A., Knopoff, L., Kornberg, H., Kutzbach, J.E., Lagarias, J.C., Lambeck, K., Landy, A., Langmuir, C.H., Larkins, B.A., Le Pichon, X.T., Lenski, R.E., Leopold, E.B., Levin, S.A., Levitt, M., Likens, G.E., Lippincott-Schwartz, J., Lorand, L., Lovejoy, C.O., Lynch, M., Mabogunje, A.L., Malone, T.F., Manabe, S., Marcus, J., Massey, D.S., McWilliams, J.C., Medina, E., Melosh, H.J., Meltzer, D.J., Michener, C.D., Miles, E.L., Mooney, H.A., Moore, P.B., Morel, F.M.M., Mosley-Thompson, E.S., Moss, B., Munk, W.H., Myers, N., Nair, G.B., Nathans, J., Nester, E.W., Nicoll, R.A., Novick, R.P., O'Connell, J.F., Olsen, P.E., Opdyke, N.D., Oster, G.F., Ostrom, E., Pace, N.R., Paine, R.T., Palmiter, R.D., Pedlosky, J., Petsko, G.A., Pettengill, G.H., Philander, S.G., Piperno, D.R., Pollard, T.D., Price, P.B., Reichard, P.A., Reskin, B.F., Ricklefs, R.E., Rivest, R.L., Roberts, J.D., Romney, A.K., Rossmann, M.G., Russell, D.W., Rutter, W.J., Sabloff, J.A., Sagdeev, R.Z., Sahlins, M.D., Salmond, A., Sanes, J.R., Schekman, R., Schellnhuber, J., Schindler, D.W., Schmitt, J., Schneider, S.H., Schramm, V.L., Sederoff, R.R., Shatz, C.J., Sherman, F., Sidman, R.L., Sieh, K., Simons, E.L., Singer, B.H., Singer, M.F., Skyrms, B., Sleep, N.H., Smith, B.D., Snyder, S.H., Sokal, R.R., Spencer, C.S., Steitz, T.A., Strier, K.B., Sdhof, T.C., Taylor, S.S., Terborgh, J., Thomas, D.H., Thompson, L.G., Tjian, R.T., Turner, M.G., Uyeda, S., Valentine, J.W., Valentine, J.S., van Etten, J.L., van Holde, K.E., Vaughan, M., Verba, S., von Hippel, P.H., Wake, D.B., Walker, A., Walker, J.E., Watson, E.B., Watson, P.J., Weigel, D., Wessler, S.R., West-Eberhard, M.J., White, T.D., Wilson, W.J., Wolfenden, R.V., Wood, J.A., Woodwell, G.M., Wright, H.E., Wu, C., Wunsch, C., Zoback, M.L., 2010. Climate change and the integrity of science. Science 328 (5979) 689–690.
Hansen, J., 2009. Storms of My Grandchildren. Bloomsbury, New York/Berlin/London.
Hardin, G., 1968. The tragedy of the commons. Science 162, 1243–1248.
Harrington, R., Woiwod, I., Sparks, T., 1999. Climate change and trophic interactions. Trends Ecol. Evol. 14 (4) 146–150.
Hastings, A., Wysham, D., 2010. Regime shifts in ecological systems can occur with no warning. Ecol. Lett. 13, 464–472.
Hoye, T.T., Post, E., Meltofte, H., Schmidt, N.M., Forchhammer, M.C., 2007. Rapid advancement of spring in the high arctic. Curr. Biol. 17 (12) 449–451.
Intergovernmental Panel on Climate Change (IPCC). Projected Climate Change and its Impacts, Climate Change 2007: Synthesis Report, http://www.ipcc.ch/publications_and_data/ar4/syr/en/spms3.html.
IPCC, Climate Change 2013: The Physical Science Basis, IPCC Fifth Assessment Report (AR5), http://www.ipcc.ch/report/ar5/wg1/.
IPCC, 2013b. Projections of future changes in climate. IPCC Publications and Data, In: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/spmsspm-projections-of.html.
IPCC Data Distribution Centre, 2013c. Scenario Process for AR5, In: http://sedac.ipcc-data.org/ddc/ar5_scenario_process/.
Jacquet, J., Hagel, K., Hauert, C., Marotzke, J., Rohl, T., Milinski, M., 2013. Intra- and intergenerational discounting in the climate game. Nat. Clim. Change, http://dx.doi.org/10.1038/nclimate2024.
Johnson, B.. Amid Army of GOP Deniers Vying for Senate Seats. Only Mike Castle Supports Climate Action, Think Progress (website), http://thinkprogress.org/climate/2010/09/13/174788/gop-senate-deniers/.
Joshi, M., Hawkins, E., Sutton, R., Lowe, J., Frame, D., 2011. Projections of when temperature change will exceed 2 °C above pre-industrial levels. Nat. Clim. Change 1 (8) 407–412.
Karl, T.R., Melillo, J.M., Peterson, T.C. (Eds.), 2009. Global Climate Change Impacts in the United States. Cambridge University Press, U.S. Global Change Research Program.
Kennel, C., Keeling, C.D., 2011. The Charles David Keeling Lecture Series. Department of Chemistry at the University of Illinois, In: http://www.chemistry.illinois.edu/events/lectures/keeling/keeling_bio.html.
Kwadijk, J., Haasnoot, M., Mulder, J., Hoogvliet, M., Jeuken, A., van der Krogt, R., van Oostrom, N., Schelfhout, H., van Velzen, E., van Waveren, H., de Wit, M., 2010. Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. Wiley Interdiscip. Rev. – Clim. Change 1 (5) 729–740.
Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H.J., 2008. Tipping elements in the earth's climate system. Proc. Natl. Acad. Sci. 105 (6) 1786–1793, http://dx.doi.org/10.1073/pnas.0705414105. arXiv:http://www.pnas.org/content/105/6/1786.full.pdf+html, http://www.pnas.org/content/105/6/1786.abstract.
Levermann, A., Clark, P.U., Marzeion, B., Milne, G.A., Pollard, D., Radic, V., Robinson, A., 2013. The multimillennial sea-level commitment of global warming. Proc. Natl. Acad. Sci., http://dx.doi.org/10.1073/pnas.1219414110.
Liu, J., Dietz, T., Carpenter, S.R., Folke, C., Alberti, M., Redman, C.L., Schneider, S.H., Ostrom, E., Pell, A.N., Lubchenco, J., Taylor, W.W., Ouyang, Z., Deadman, P., Kratz, T., Provencher, W., 2007. Coupled human and natural systems. AMBIO: J. Hum. Environ. 36 (8) 639–649.
Loarie, S.R., Duffy, P.B., Hamilton, H., Asner, G.P., Field, C.B., Ackerly, D.D., 2009. The velocity of climate change. Nature 462 (7276) 1052–1055.
Mora, C., Frazier, A., Longman, R., Dacks, R., Walton, M., Tong, E., Sanchez, J., Kaiser, L., Stender, Y., Anderson, J., Ambrosino, C., Fernandez-Silva, I., Giuseffi, L., Ciambelluca, T., 2013. The projected timing of climate departure from recent variability. Nature 502, 183–187.
Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature 463 (7282) 747–756.
Motesharrei, S., Rivas, J., Kalnay, E., 2014. Human and nature dynamics (HANDY): modeling inequality and use of resources in the collapse or sustainability of societies. Ecol. Econ. 101 (0) 90–102, http://dx.doi.org/10.1016/j.ecolecon.2014.02.014, ISSN 0921-8009.
NOAA. Scripps (Keeling) and NOAA CO_2 trend data, NOAA Earth System Research Laboratory (website), ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_mm_mlo.txt.
Nordhaus, W., 2013. The Climate Casino: Risk, Uncertainty, and Economics for a Warming World. Yale University Press, New Haven/London.
Pearce, F. How 16 ships create as much pollution as all the cars in the world. Daily Mail (online), http://www.dailymail.co.uk/sciencetech/article-1229857/How-16-ships-create-pollution-cars-world.html.
Pew Research Center, 2006. Little consensus on global warming, In: http://www.people-press.org/2006/07/12/little-consensus-on-global-warming/.
Post, E., Forchhammer, M.C., 2008. Climate change reduces reproductive success of an arctic herbivore through trophic mismatch. Philos. Trans. R. Soc. B: Biol. Sci. 363 (1501) 2367–2373.
Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O., Kunin, W.E., 2010. Global pollinator declines: trends impacts and drivers. Trends Ecol. Evol. 25 (6) 345–353.
Pounds, J.A., Fogden, M.P.L., Campbell, J.H., 1999. Biological response to climate change on a tropical mountain. Nature 398 (6728) 611–615.
Panel on Strategies and Methods for Climate-Related Decision Support, 2009. National Research Council, Informing Decisions in a Changing Climate. The National Academies Press, In: http://www.nap.edu/openbook.php?record_id=12626.
Rahmstorf, S., Cazenave, A., Church, J.A., Hansen, J.E., Keeling, R.F., Parker, D.E., Somerville, R.C.J., 2007. Recent climate observations compared to projections. Science 316 (5825) 709.
Rosenzweig, C., Karoly, D., Vicarelli, M., Neofotis, P., Wu, Q., Casassa, G., Menzel, A., Root, T.L., Estrella, N., Seguin, B., Tryjanowski, P., Liu, C., Rawlins, S., Imeson, A., 2008. Attributing physical and biological impacts to anthropogenic climate change. Nature 453, 353–358.
Sachs, J., 2009. Water Wars, The Globe and Mail.
Sala, O.E., Stuart Chapin III, F., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M., Wall, D.H., 2000. Global biodiversity scenarios for the year 2100. Science 287 (5459) 1770–1774.
Scherer, G. Climate science predictions prove too conservative. Scientific American (Online), http://www.scientificamerican.com/article/climate-science-predictions-prove-too-conservative/.
Schiermeier, Q. IPCC: The Climate Chairman, Nature News, http://www.nature.com/news/ipcc-the-climate-chairman-1.13755.
Schwartz, P., Randall, D., 2003. An abrupt climate change scenario and its implications for United States National Security. Tech. Rep. Jet Propulsion Laboratory, Pasadena, CA., In: http://www.environmentaldefense.org/documents/3566_AbruptClimateChange.pdf.
Shearer, A., 2005. Whether the weather: comments on 'an abrupt climate change scenario and its implications for United States National Security'. Futures 37 (6) 445–463.
Stern, N., 2008. The economics of climate change. Am. Econ. Rev. Pap. Proc. 98 (2) 1–37.
Stocker, T., 2013. The closing door of climate targets. Science 339, 280–282.
Stoll-Kleemann, S., O'Riordan, T., Jaeger, C.C., 2001. The psychology of denial concerning climate mitigation measures: evidence from Swiss focus groups. Global Environ. Change 11 (2) 107–117.
The AAAS Climate Science Panel, 2014. What we know: the reality, risks and response to climate change. Tech. rep. American Association for the Advancement of Science, In: http://whatweknow.aaas.org/wp-content/uploads/2014/03/AAAS-What-We-Know.pdf.
Tyndall, J., 1861. On the absorption and radiation of heat by gases and vapours and on the physical connexion of radiation absorption and conduction. Philos. Trans. R. Soc. Lond. 151 (136) 1–37.

United Nations Framework Convention on Climate Change, 2013. Background on the UNFCCC: The International Response to Climate Change, In: http://unfccc.int/essential_background/items/6031.php.

Vanbergen, A.J., Baude, M., Biesmeijer, J.C., Britton, N.F., Brown, M.J.F., Brown, M., Bryden, J., Budge, G.E., Bull, J.C., Carvel, C., Challinor, A.J., Connolly, C.N., Evans, D.J., Feil, E.J., Garratt, M.P., Greco, M.K., Heard, M.S., Jansen, V.A.A., Keeling, M.J., Kunis, W.E., Marris, G.C., Memmott, J., Murray, J.T., Nicolson, S.W., Osborne, J.L., Paxton, R.J., Pirk, C.W.W., Polce, C., Potts, S.G., Priest, N.K., Raine, N.E., Roberts, S., Ryabov, E.V., Shafir, S., Shirley, M.D.F., Simpson, S.J., Stevenson, P.C., Stone, G.N., Termansen, M., Wright, G.A., Initiative, I.P., 2013. Threats to an ecosystem service: pressures on pollinators. Front. Ecol. Environ. 11 (5) 251–259.

Vidal, J. Will Philippines negotiator's tears change our course on climate change? The Guardian.

Vince, G., 2009. How to survive the century. N. Sci. 201 (2697) 28–33.

Visser, M.E., Both, C., 2005. Shifts in phenology due to global climate change: the need for a yardstick. Philos. Trans. R. Soc. B 272, 2561–2569.

Warren, R., 2011. The role of interactions in a world implementing adaptation and mitigation solutions to climate change. Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci. 369 (1934) 217–241.

Wayne, G.P. The beginner's guide to representative concentration pathways. Skeptical Science (Online), http://www.skepticalscience.com/rcp.php.

Wolff, E., Fung, I., Hoskins, B., Mitchell, J., Palmer, T., Santer, B., Shepherd, J., Shine, K., Solomon, S., Trenberth, K., Walsh, J., Wuebbles, D., 2014. Climate change: evidence and causes. Tech. Rep. The U.S. National Academy of Sciences and The Royal Society, In: http://dels.nas.edu/resources/static-assets/exec-office-other/climate-change-full.pdf.

Working Group I, 2007. Climate Change 2007: the physical science basis. Summary for policymakers. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change. Tech. Rep. Intergovernmental Panel on Climate Change (IPCC), In: http://www.ipcc.ch.

Working Group III, 2014. Climate Change 2014: mitigation of climate change contribution of Working Group III to the 5th assessment report. Tech. Rep. Intergovernmental Panel on Climate Change (IPCC), In: mitigation 2014.org.

World Meteorological Organization, 2013. Greenhouse gas bulletin: the state of greenhouse gases in the atmosphere based on global observations through 2012. Tech. Rep. World Meteorological Organization, In: http://www.wmo.int/pages/prog/arep/gaw/ghg/GHGbulletin.html.