



Detection and attribution of anthropogenic climate change impacts

Cynthia Rosenzweig^{1*} and Peter Neofotis^{2,3}

Human-influenced climate change is an observed phenomenon affecting physical and biological systems across the globe. The majority of observed impacts are related to temperature changes and are located in the northern high- and mid-latitudes. However, new evidence is emerging that demonstrates that impacts are related to precipitation changes as well as temperature, and that climate change is impacting systems and sectors beyond the Northern Hemisphere. In this paper, we highlight some of this new evidence—focusing on regions and sectors that the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) noted as under-represented—in the context of observed climate change impacts, direct and indirect drivers of change (including carbon dioxide itself), and methods of detection. We also present methods and studies attributing observed impacts to anthropogenic forcing. We argue that the expansion of methods of detection (in terms of a broader array of climate variables and data sources, inclusion of the major modes of climate variability, and incorporation of other drivers of change) is key to discerning the climate sensitivities of sectors and systems in regions where the impacts of climate change currently remain elusive. Attributing such changes to human forcing of the climate system, where possible, is important for development of effective mitigation and adaptation. Current challenges in documenting adaptation and the role of indigenous knowledge in detection and attribution are described.

© 2013 John Wiley & Sons, Ltd.

How to cite this article:

WIREs Clim Change 2013, 4:121–150. doi: 10.1002/wcc.209

INTRODUCTION

The Earth's climate is changing and observed climate changes are causing a wide array of impacts on systems and sectors around the globe (Figure 1). An observed climate change impact is a documented change in a physical, biological, or human system that is driven by a long-term climate trend (Box 1). Recent climate change detection and attribution reviews have focused primarily on the

climate itself.^{1,2} Here, we focus on climate change impacts—a topic of major concern—and the issues arising from the detection and attribution of these impacts. These issues include consideration of multiple drivers of change, new types of evidence that have emerged since the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4),³ and attribution of climate change impacts specifically to anthropogenic forcing.

This paper presents an overview of the detection and attribution of climate change impacts, including how climate variables and non-climate factors affect physical and biological systems, methods of detection of observed changes, and the attribution of changes to anthropogenic climate forcing. We then present a summary of observed impacts and new evidence with a focus on the tropics and marine systems, which have

*Correspondence to: cynthia.rosenzweig@nasa.gov

¹NASA Goddard Institute for Space Studies, Climate Impacts Group, New York, NY, USA

²Department of Biological Sciences, Brooklyn College, City University of New York, Brooklyn, NY, USA

³Graduate School and University Center, City University of New York, New York, NY, USA

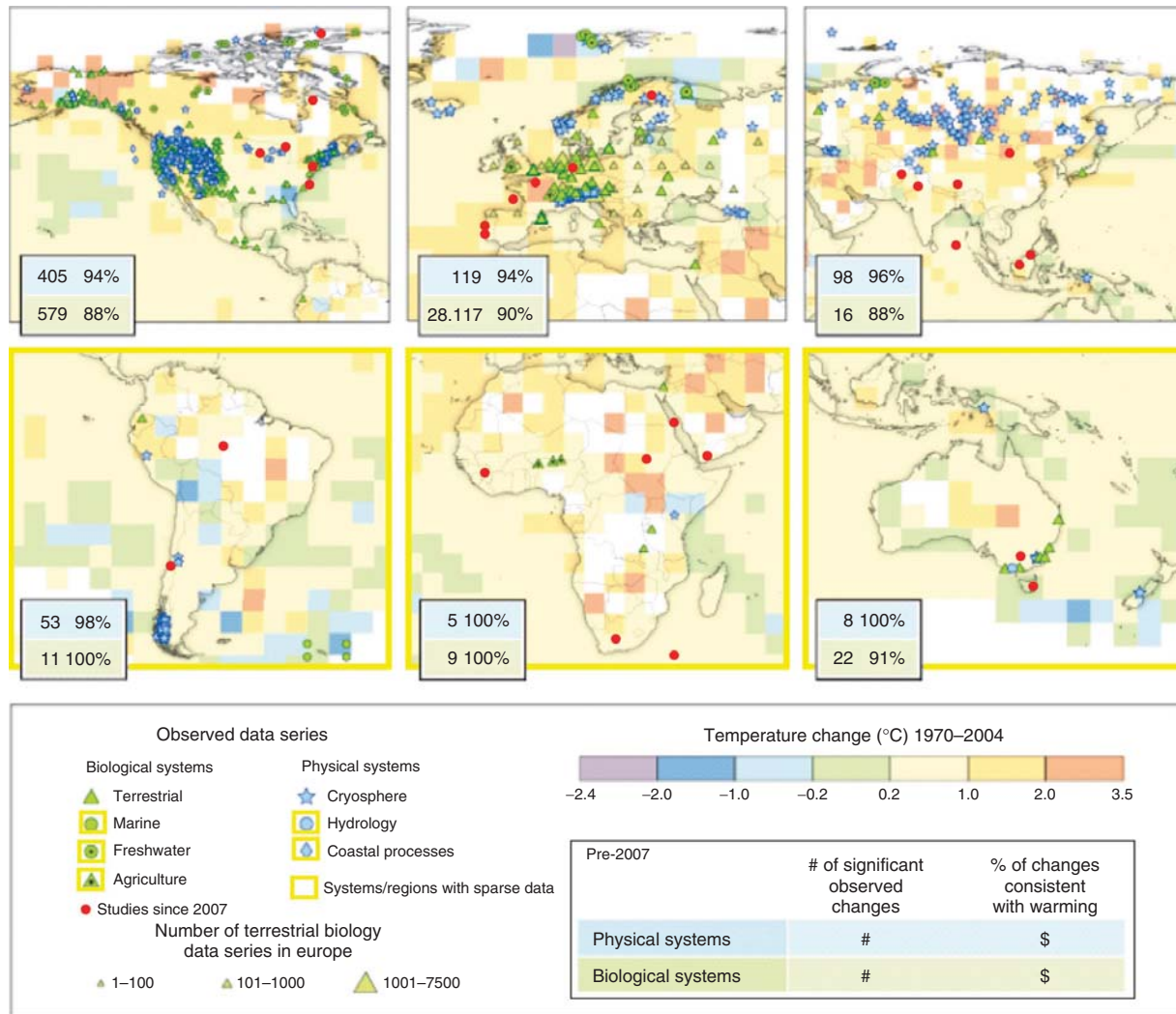


FIGURE 1 | Locations of significant changes in physical and biological systems shown with air temperature changes over the period 1970–2004 (HadCRUT3).⁴ The data series met the following criteria: (1) ending in 1990 or later; (2) spanning a period of at least 20 years; and (3) showing a significant change in either direction, as assessed by the individual studies. Red dots indicate locations of new studies since IPCC AR4.³ Yellow outlines refer to systems and regions where data remain comparatively sparse.

been underrepresented in previous reviews. Finally, we look at observed changes related to climate in human systems, challenges in documenting adaptation, and contributions from indigenous knowledge. The overall goal is to improve understanding of the complex effects of climate change on exposed systems and to synthesize directions for future research.

CLIMATE DRIVERS OF OBSERVED IMPACTS

Gaps in the knowledge of climate change impacts are related to understanding fully the drivers of change, i.e., the relevant climate variables and how they impact

systems at different spatial and temporal scales. Climate change impacts have been primarily associated with temperature, which can be seen as a primary driver in the high- to mid-latitudes—where most of the evidence has thus far been observed. However, analysis of the relationship between precipitation trends and observed ecosystem impacts is especially important in the tropics, because seasonal responses tend to be more precipitation-driven in those ecosystems. By understanding multiple climate drivers and linking them to anthropogenic forcing, we may glean a better picture of the global fingerprint of climate change.

Many aspects of the climate system influence characteristics and distributions of biological and physical systems. Here we focus on temperature,

BOX 1

KEY DEFINITIONS FOR CLIMATE CHANGE IMPACTS (ADAPTED FROM THE IPCC EXPERT WORKSHOP REPORT ON DETECTION AND ATTRIBUTION⁵)

Observed climate change impact. A change in a physical, biological, or socioeconomic system affected by climate that can be identified (e.g., by using statistical tests) as a change in the mean or the variability of its properties, and that persists for an extended period, typically decades or longer. Observed climate change impacts are related to at least one external climate driver, acting either directly or indirectly.

Detection. Detection is defined as the process of demonstrating that a system affected by climate has changed in some defined statistical sense without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%.⁵

Attribution. Attribution is broadly defined as the process of evaluating the relative contributions of multiple causal factors including climate to an impact with an assignment of statistical confidence. The process of attribution requires the detection of a change in the observed system. For observed impacts, the causal chain related to anthropogenic climate change starts with human-caused forcing of climate and leads to climate change impacts on physical and biological systems, which in turn can elicit adaptation responses.

For example, anthropogenic greenhouse gas emissions are causing temperatures to rise, rising temperatures are leading to glacial melting, which are in turn resulting in more glacial lake outflows (GLOFs) and adaptation responses involving enhanced flood-prevention measures by nearby communities.³ Attribution studies focus on assessing the strength of such causal relationships.

External forcing. A forcing factor outside the climate system that causes a change in the climate system. Volcanic eruptions, anthropogenic changes in atmospheric composition, and land use are examples of external forcings of the climate system.^{5,6}

External driver. Any external forcing factor, including climate change, outside the impact system of interest that causes a change in the system.⁵ For instance, a drying climate and

overgrazing due to increased human population pressure are external drivers that can lead to desertification of semiarid ecosystems.⁷

Climate change. Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, such as persistent anthropogenic changes in the composition of the atmosphere or in land use.⁶

Note that the Framework Convention on Climate Change (UNFCCC) defines climate change as that attributable to human activities altering the atmospheric composition.⁶

precipitation, and carbon dioxide (CO₂) as these are common variables for which there are readily available long-term instrumental data. Precipitation is often used as a proxy for water availability, which is a complex set of variables that influences many systems. Other climate variables such as humidity, radiation, windspeed, and frost are important in some systems, and could be included in future assessments. Some climate variables co-vary (e.g., increased temperatures are often correlated with drought).

Temperature

Temperature affects physical and biological systems in a variety of ways. For ecosystems in temperate regions, it strongly affects the abundance, distribution, migration, and patterns of plant and animal species,^{8,9} as well as the timing of spring and fall events.^{10–12} A recent study showed that during the period 1979–2009 European waterfowl have progressively delayed their migration to the northern Sahara desert.¹³

Temperature effects can be nonlinear, with exceedances of temperature thresholds leading to dramatic changes. US crop yields of corn and soybeans have been found to increase with temperature up to 29°C for corn, 30°C for soybeans, and 32°C for cotton.¹⁴ Temperatures above these are harmful, with the slope of the decline above the optimum significantly steeper than that of the incline below it.

Precipitation

A growing number of observed climate change impact studies are now considering whether and how effects are related to precipitation changes.

Although difficult, attribution of regional precipitation changes to increases in greenhouse gases may allow better understanding of how anthropogenic climate change is affecting certain physical and biological systems in ways other than the ‘warming fingerprint’, which was characterized by the first observed impact meta-analyses in the IPCC Third Assessment Report (TAR).^{8,10}

Researchers have found several ways to determine if precipitation trends could be a driving force of observed impacts. In Northern Victoria, Australia, a survey from 1995 to 2008 revealed that woodland bird species in the region have declined in occurrence and abundance. The authors concluded that these declines reflect the added stress of sharp reductions in rainfall in conjunction with increases in temperature in Northern Victoria, Australia.¹⁸ In another study, stepwise multiple regressions were used to determine the effects of both temperature and precipitation on the phenophase date of multiple plant and animal life cycles.¹⁷ At the global scale, a study of worldwide glacier retreat was able to attribute global wastage to increasing global temperature trends rather than to precipitation change, because the global-scale precipitation reductions that would be needed to explain the widespread loss of ice have not been observed.^{15,16}

Attention to precipitation changes may also allow better understanding of how climate change is being manifested in underrepresented regions. Studies have documented shifts in precipitation in Africa, the extreme south of Europe, and the Arabian Peninsula.¹⁹ From 1978 to 2002, the start of the wet season arrived later in the year for the majority of these regions as time progressed, likely affecting ecosystems and agriculture. Finally, giving a more complete picture of climate-related impacts in a region already known to be undergoing changes, Min et al.²⁰ found that human-induced Arctic moistening is consistent with observed increases in Arctic river discharge and freshening of Arctic water masses. This provides evidence that human activity has contributed to Arctic hydrological system changes.

Carbon Dioxide

Increasing atmospheric carbon dioxide concentration, in and of itself, causes direct physiological effects on terrestrial vegetation and indirect effects on marine ecosystems through ocean acidification. Thus, the role of CO₂ needs to be taken into account in observed impact studies where relevant. In plants, increasing CO₂ can increase carbohydrate formation by suppressing the photorespiration of RuBPCO (ribulose-1, 5-bisphosphate carboxylase/oxygenase)—which often

wastefully binds with oxygen rather than CO₂. The increase in CO₂ may also allow plants to maintain lower stomatal conductance, thereby reducing transpiration and increasing water-use efficiency. The integrated response can result in a stimulation of growth especially for C3 plants under hot and dry conditions.

However, positive responses to higher CO₂ have been shown to decrease in plants over periods of months to years.²¹ A number of process-based explanations have been hypothesized for this ‘down regulation’, which is highly variable across species, mineral availability, and duration of enrichment.²¹ Some causes may be related to limiting essential nutrients. For example, experiments where both CO₂ and N supplies were varied demonstrated a larger downward acclimation in low compared with high N environments.^{22,23}

Despite this observed down regulation, evidence may be emerging of terrestrial species’ longer-term responses to rising CO₂—such as has been documented in the increase in large woody vines, or lianas, in the Amazon.²⁴ Another study using a unique dataset of tree biomass collected over the past 22 years from 55 temperate forest plots in Edgewater, Maryland, USA, with known land-use histories—as well as known stand ages that ranged from 5 to 250 years—found that recent biomass accumulation greatly exceeded the expected growth caused by natural recovery.²⁵ Over 100 years of local weather measurements and 17 years of on-site atmospheric CO₂ measurements also show consistent increases, which are in line with the global patterns. However, another study called into question these results.²⁶ Finally, although many studies have predicted an increase in plant productivity and water-use efficiency with rising CO₂ (especially in crop species), others have shown that positive effects have been outweighed in some regions by rising temperatures and droughts in regard to tree growth.^{27,28}

Ocean acidification caused by rising CO₂ is perceived as a threat to marine organisms. Some calcifying marine organisms, such as sea urchins (*Strongylocentrotus purpuratus*), have demonstrated broad-scale decreases in major cellular processes in experiments that expose them to more acidic conditions.²⁹ Observational evidence has also shown that the processes of acidification, along with seasonal upwelling, are responsible for the thinning of shells of planktonic foraminifera such as *Globigerinoides ruber*.³⁰ Some tropical marine fish, on the other hand, appear to function adequately under the levels of increased CO₂ acidification likely to be experienced in the future.³¹ Elevated CO₂ with stable or increasing water temperatures actually seem to benefit some organisms

such as the sea star *Pisaster ochraceus*, leading to increased growth and feeding rates under experimental conditions.³² The effect of CO₂-driven ocean acidification on marine ecosystems needs to be explored further. A recent review found that the main threat to calcifying organism from ocean acidification may not be reduced calcification as often purported³³ but rather enhanced dissolution.³⁴

Major Modes of Climate Variability

While the IPCC has documented that the global climate system is changing and that changes are already causing impacts on physical and biological systems, large-scale modes of internal climate variability, such as the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO) continue to exert strong influence on both climate and impact systems (Box 2).³⁵ It is often difficult to determine whether an impact being observed is happening because of (1) a long-term change in climate via rising air or sea surface temperature or (2) internal variability associated with ENSO, NAO, or PDO cycles, or (3) a change in ENSO or other mode of climate variability associated with climate change.

This has implications for adaptation strategies and policies. If effects are related to a major mode of climate variability, they will be episodic. Policies, then, are needed that cope with such recurring effects. With long-term climate change, some impacts may become either more or less severe through time, and policies are needed to encourage interventions that respond to changing conditions through time.

Untangling the roles of long-term underlying trends and such oscillations requires decades of climate and impacts data, as temperature and precipitation are inter-related at multiyear and multiregion scales through the major modes of climate variability. Time series of observed impacts as long as possible are needed, especially in areas where such oscillations have a known strong effect. Although El Niño events occur on average about once every 2–7 years, the periodicity, duration, and intensity are all highly variable.³⁵ Long time series allow for observation of variation in both the climatic variability and the ecosystem responses. While satellite observations suggest that the intensity of El Niño events in the central equatorial Pacific has almost doubled in the past three decades; this appears to be unrelated to a general rise in background sea-surface temperatures (SSTs).³⁶ Thus, these changes in intensity have not yet definitely been associated with anthropogenic climate change.

BOX 2

IMPACTS OF ENSO, NAO, AND PDO ON PHYSICAL AND BIOLOGICAL SYSTEMS³⁵

ENSO. Off the Baja California peninsula in the Gulf of California Mexico, El Niño events tend to bring precipitation that dramatically transforms the ecosystems of the normally arid islands there.^{38,39} In the desert islands, plant cover—which usually ranges between 0 and 4% of available surface—rises between 55 and 90% during the rain-filled El Niño years. The resulting flush of vegetation transforms the island's ecosystems from a dependency on energy and nutrients derived from marine sources to a state influenced more by *in situ* terrestrial productivity.

During 1989–1999, a study conducted in Borneo showed that a sample of more than 50 dipterocarps species dispersed seed only within a 1- to 2-month period every 3–4 years during ENSO events.⁴⁰

NAO. In Europe, researchers have studied the role of the NAO, which has a widespread effect on ecological and physical processes across the continent.^{37,41–48} These authors in general have found that, while strong, the NAO influence is weaker than the long-term temperature trend.³⁷ This makes sense as NAO can be considered an index of the contribution of large-scale synoptic processes to local meteorology (including temperature) in Europe. Similarly, in a study of rapid changes in flowering time in British plants, the correlations with the Central England temperature record over five decades were stronger than with NAO data in all cases.⁴⁹

In the North Atlantic, a study of calanoid copepods (a zooplankton) from 1958 to 2005 found that they are responding quickly to SST rise by rapidly moving geographically northward at ~23 km/year. The analysis showed that nearly half (~46%) of the total variance in SST in the northeast Atlantic and adjacent seas is related to global temperature rise, while natural modes of atmospheric and oceanic circulation explain ~26% of the total variance in SST.⁵¹

PDO. A study of changes toward earlier timing of streamflow across western North America from 1948 to 2002 found that temperature changes are partly controlled by the decadal-scale Pacific climate mode PDO; a separate and significant part of the variance is associated with a springtime warming trend that spans the PDO phases.⁵⁰

LAND USE CHANGE AND OTHER DRIVERS

In addition to being affected directly by multiple climate drivers of change, physical and biological systems can also be affected by other drivers including geological processes, land-use change, management practices, pollution, and human demography shifts, either directly or indirectly through their own effects on the climate system. Land-use change, in particular, may directly affect certain ecosystem processes such as productivity and nutrient cycling in forested areas converted to agriculture.

Understanding of changes in ecological processes—such as earlier spring arrivals or shifts from cool-adapted to warm-adapted species—allows more direct linkage to climate drivers. Figure 2 shows schematically some direct and indirect (via climate) pathways from non-climate drivers to impacts on physical and biological systems.

The socioeconomic processes that drive land-use change include population growth, economic development, trade, and migration—all processes that are operating at local, regional, and global scales.⁵² Understanding how such driving forces influence physical and biological systems across these telescoping scales is crucial to improved understanding of the responses to climate that are the focus here.

Land-use change such as urbanization can stymie species' range shifts in response to climate change, leading to additional biodiversity losses.⁵³ Land-use changes related to both urbanization and agriculture

have been linked to deteriorating air quality and soil and water pollution, all of which affect biological functioning.^{54,55} Along with clearing of land for food production that releases carbon from standing and belowground biomass, they can affect greenhouse gas emissions through changes in local carbon cycles and temperature that affect plant primary productivity and evapotranspiration.^{56,57} Land-use change can modify local climate by altering albedo and the water cycle, and thus indirectly affect physical and biological systems. Land-use and land-cover changes can also strongly magnify the human health effects of extreme climate events (e.g., heat mortality, injuries/fatalities from storms, and ecologically mediated infectious diseases).⁵⁸

With regard to freshwater lakes, local processes such as eutrophication—along with climate change—can bring about phenological shifts.⁵⁹ A study examining patterns and drivers of change among four lakes in the English Lake District over a 58-year period (1945–2003) found that the soluble reactive phosphorous amounts—the local variability driver—had a more consistent effect upon phenology than climate.⁶⁰

Individual studies, as well as reviews and meta-analyses of observed climate change impacts, should consider the role of non-climate drivers that may influence the observed impacts.¹² Studies that take into account such considerations include those listed in Table 1. Methods for isolating the role of climate influences include conducting studies in remote undisturbed areas, searching for coherent patterns across large areas, and ruling out other

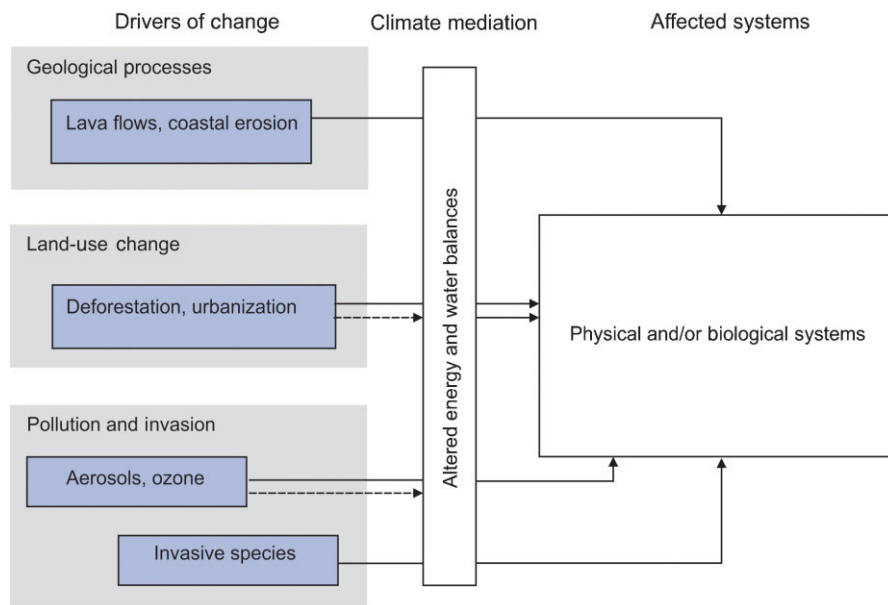


FIGURE 2 | Direct (solid line) and indirect (dashed line) effects of non-climate drivers of observed changes in physical and biological systems.

TABLE 1 | Observed impact studies and the likelihood/role of other drivers besides greenhouse-gas-forced temperature change directly affecting changes in physical and biological systems

Change	Likelihood of other drivers besides temperature affecting observed physical or biological change directly*	Explanation
Invertebrate species in California intertidal community. ⁶³	Very unlikely	Since 1917, site has been protected as an ecological reserve.
Migration timing of adult Atlantic salmon. ⁶⁴	Very unlikely	Coherent patterns of migration timing changes were observed in multiple systems.
Diatom assemblages in northern Canadian high elevation lakes. ⁶⁵	Exceptionally unlikely	Remote, pristine environment in northwest Canada.
Diatom assemblage composition in Canadian arctic lakes. ⁶⁶	Exceptionally unlikely	Acidification, nutrient enrichment, and contamination ruled out as possible causes for diatom changes.
Spring phenology of lake phytoplankton. ⁵⁹	Very likely	Changes linked to both nutrient enrichment and lake warming
Earlier flowering in agricultural varieties of white clover. ⁶⁷	Very unlikely	Other potential drivers ruled out

Likelihoods assigned according to IPCC AR4 definitions (IPCC 2007) based on statements by study authors and expert judgment.

*E.g., habitat disturbance, pollution, invasive species, over-fishing, acid deposition.

causes through functional understanding of their likely effects on ecosystems. Regional climate models can be used in combination with observed impact time-series data to determine if land-use change could indirectly be causing the changes, for example, by inducing warming through creation of an urban heat island effect or through local land clearing.^{61,62}

For recent climate trends on a global scale, the effect of land-use change on temperature has been found to be small in climate model studies that compare simulations with and without the documented historical conversion of natural ecosystems to agriculture.⁶⁸ These effects may result in warming in some areas and cooling in others, depending on the land conversion or region. Agricultural expansions tend to warm the Amazon by removing the shading effect of forest, and cool the mid- and high latitudes due to increased albedo of open agricultural land versus forested areas (especially in winter when snow cover is usually masked by trees).^{69,70} While land-use change is thus unlikely to explain coherent responses to long-term increasing temperature trends across a diverse range of systems at continental and global scales, it can still indirectly affect climate and thus physical and biological systems at regional scales.⁷¹

A study of South African birds could not find a consistent climate change fingerprint, as taxa were found to extend their ranges not only toward the south (toward cooler latitudes—consistent with climate change) but also the west (toward drier and warmer habitats—inconsistent with climate change).

The southward movers were mobile taxa, whereas the westward movers were associated with human-modified elements in the landscape such as croplands, plantations, and buildings.⁷² The results suggest that both land-use change and climate change are acting simultaneously on South African birds. However, separating the relative strength of each individual driver is challenging, especially in regions such as Africa that are undergoing rapid land-use change.⁷²

Questions that need continuing investigation in regard to non-climate and indirect climate drivers of observed impacts include ‘What is the spatial extent of localized deforestation and urban heat island effects on temperature and precipitation and their associated impacts?’ and ‘What are robust methodologies for separately determining effects of land-use change and climate change on physical and biological systems?’

DETECTION OF OBSERVED IMPACTS

Detection of observed impacts involves a measured change in a physical, biological, or human system and a related change in a climate variable. To assess whether a significant change of a biological or physical system is due to long-term changes in temperature or other climate variable, the observed impact is correlated with the climate variable over a period long enough to separate the effects of climate variability (sometimes referred to as ‘noise’) from the signal of long-term change. This establishes a correlation between climate trends (usually approximated

as linear) with a linear or low-frequency trend in the observed impact, with the slope serving as a measure of the responsiveness of the impact to the climate variable. Recent examples include studies on the effects of climate change on the phenology of butterflies in the northwest Mediterranean Basin⁷³ and on the phenology of both flora and fauna across Europe.⁷⁴

It is also critical to determine if the change in the system is the one that coincides with a functional understanding of how altered temperatures and/or other climate variables interact with the system under consideration.^{8,75} This can be done via process-level understanding, spatial or temporal sign-switching fingerprints, and/or simulation model studies.

Spatial sign switching is documented through studies that examine the entire range of a species on the regional scale, thereby testing for differential spatial impacts. Temporal sign switching is characterized through long-term studies that span periods of climate cooling as well as warming. If the distributions of species are indeed driven by climate trends, these species should show opposite responses to cooling and warming periods.⁸

One study based on process-level understanding was conducted between 1977 and 2007 along an elevational gradient in Southern California's Santa Rosa Mountains.⁷⁶ Average elevation of the dominant plant species rose by ~65 m between the surveys. Several considerations provided evidence that the observed vegetation redistributions could be linked to climate changes. Vegetation shifts were uniform across elevation, which precluded fire as a causal factor as the degree of fire regime perturbation varies with elevation. The vegetation shifts were also consistent with the predicted bioclimatic responses to observed climate shifts. These included responses to increased temperature, frost-free period, snow line elevation, and occurrence of severe drought, which would be expected to decrease a species' ability to survive in the drier, warmer, and lower parts of its range and to increase its competitive ability and tolerance in the wetter, cooler, and upper parts of its range.

Within the context of biological systems, three main types of changes have been observed in temperate regions. The first type is a response to a change in growing season. For terrestrial ecosystems in temperate regions this usually translates into an advance in spring events, although it sometimes also coincides with a delay in fall events. For marine systems, there is often a shift in the dates of peak productivity observed in both the spring and fall.¹¹ The second type of biological system change relates

to range shifts, which have been shown for terrestrial species to be 6.1 km per decade and 16.9 km per decade depending on methods of meta-analysis and locations.^{8,77} Species often move poleward in latitude or higher in elevation in response to warming temperatures. Thirdly, studies document changes in species composition in response to warming temperatures—with warm-tolerant species out-competing cold-tolerant ones.⁷⁸

A key methodological issue in the accurate detection of biological responses is the handling of species that exhibit 'no change', i.e., those species that are not experiencing statistically significant changes and thereby do not appear in published studies because of a lack of a compelling result^{79,80} (Figure 3). On the other hand, system changes in both expected and unexpected directions are readily published. To account for these issues, phenological changes of butterflies in the northwest Mediterranean Basin were analyzed using a two-tailed binomial test to check for random distribution in the signs of regressions (whether significant or not), under the assumption that if there were no consistent changes in phenology with time an equal number of positive and negative regressions would be expected.⁷³ This is known as 'field significance';⁸¹ its primary importance is in determining if the individual significance signals collectively in a sample are truly representing a real signal or are simply the result of Type I errors in a large sampling, i.e., the 'flukes'.

In meta-analyses of biological responses, several methods have been employed regarding the consideration of those species exhibiting nonsignificant or 'no' change. One involves including all species in the meta-analysis found in the literature review, regardless as to whether significant changes have been observed.⁸ This approach, however, may not be based on random sampling and thus the changes reported may not reflect a particular ecosystem or region as whole. Also, it is fairly certain that a publishing bias exists for reporting of species that

		Climate	
		Change	No change
System	Change	Most likely to be published, especially when as expected	Likely to be published, explained by other drivers
	No change	Unlikely to be published, explained by counterbalancing factors or lack of sensitivity	Unlikely to be analyzed or reported

FIGURE 3 | Categories of system responses to observed changes and non-changes in climate and relation to publication biases.⁷⁴

exhibit change. If this method is used, this weakness can be at least partially overcome by including in the meta-analysis multiple species in a single location and single or multiple species in larger-scale studies, rather than single-species in single-location studies, as authors of multiple species and location studies may be less likely to focus only on those species showing change. The latter studies often include subregions with no change in either climate or biological system (e.g., no change in the number of frost days in the southeastern United States from 1951 to 2000,⁸² little or no change in spring onset in continental Eastern Europe from 1951 to 1998,^{83,84} or subgroups of North American birds species with no change^{85,86}).

Other studies seek to obviate the publication bias by excluding those physical and biological data series with nonsignificant change and by focusing on whether the changes reported are consistent with temperature change.^{10,12} While this creates a selected group of species, all showing change across geographical areas, the issue of nonrandom selection may still exist. Comparing the percentage of data series with significant changes in large network data can provide an indication of whether the database may represent an unbiased sample of observed changes.¹²

Studies that rely on network data where species information is collected continuously on a large number of species over long time periods from the same areas are the most comprehensive. For example, changes in spring green-up of a number of plants have been recorded in botanical gardens across Europe for decades and in some cases centuries.⁸⁷ However, such networks are rare outside Europe. Analysis of species that are changing and those that are not within such network data provides a check on the accuracy of the use of the indicator for global warming and the ability to check for 'false positives', i.e., changes observed where no significant temperature change is measured. The latter can help to elucidate the role of non-climate drivers in the observed changes. Larger observational networks also allow for comparisons between different types of organisms. A study of 36,000 phenological time series for Europe covering 1971–2000 confirmed differences in behavior between plant perennials and agricultural crops. The average temperature response of perennial plants⁸⁸ (leaf/needle unfolding of deciduous trees, fruit trees, and conifers; and flowering of fruit trees, deciduous trees, and wild shrubs/flowers) was significantly greater (-4.2 days °C⁻¹) than that of annual crops (leaf unfolding and growth stages of agricultural crops) (-3.0 days °C⁻¹).

ATTRIBUTION TO ANTHROPOGENIC CLIMATE FORCING

Attribution is defined broadly as the process of evaluating the relative contributions of multiple causal factors including climate to an impact with an assignment of statistical confidence (see Box 1). This broad definition includes the attribution of an observed change in a system to an observed change in climate conditions. Of particular interest, however, is whether the observed impacts may be attributed to anthropogenic climate forcing. Here, the underlying causal chain involves anthropogenic forcing of climate and related climate change impacts on physical and biological systems (attribution of changes in socioeconomic systems has been rarely attempted to date).

There are several methods that have been utilized to attribute observed changes in impact systems to anthropogenic forcing. These have been characterized as 'single step', 'multiple step', or 'associative pattern'⁵ (see Box 3). Methodological steps to be considered in climate change impact attribution studies include characterizing the relationships of internal variability and anthropogenic and non-anthropogenic forcings to the relevant climate change via climate models, and investigating the relationships of climate and other external drivers to the observed change in a physical or biological system via impact models (Figure 4). A combination of process-based climate and impact models and statistical analyses are used.

A growing body of studies has linked the observed responses in some physical and biological systems to global or regional-scale warming due to anthropogenic climate change in many regions of the world (Figure 5 and Table 2). Although limited in number, these anthropogenic climate change attribution studies cover physical and biological systems ranging across glacier retreat in Switzerland and Norway,⁹² observed patterns of changes in snowpack and streamflow,^{93–95} changes in the spring events of Northern Hemisphere wild plant and animal species⁹⁶; and forests burned in Canada over the last four decades.⁸⁹ Table 2 shows these and other studies, elucidating both their attribution conclusions and methods of detection and attribution.

Recent glacial retreat in Switzerland and Norway has been attributed to anthropogenic climate change using global climate model (GCM) output with internal forcing, statistical downscaling, a glacier mass balance model, a dynamic ice flow model for glacier length, and comparison to historical glacier fluctuations.⁹² The results showed that the recent glacial retreat is very likely to be caused by external climate forcing; this result could be strengthened by

BOX 3

METHODS OF ATTRIBUTION TO EXTERNAL FORCINGS (ADAPTED FROM THE IPCC EXPERT WORKSHOP REPORT ON DETECTION AND ATTRIBUTION⁵)

Single-step attribution to external forcings. This method attributes an observed change within a system to an external forcing based on explicitly modeling the response of the variable to external forcings and drivers. Modeling can involve a single comprehensive model or a sequence of models. The attribution step involves detection of a significant change in the variable of interest and comparison of observed changes in the variable of interest with expected changes due to external forcings and drivers (typically derived from modeling approaches).

An example of a single-step attribution to external forcings is a study that compared simulated temperatures based on anthropogenic forcing with interannual variations of forested area burned in Canada. The authors found that human-induced climate change has had a detectable influence on the area burned over recent decades.⁸⁹

Multistep attribution to external forcings. This method attributes an observed change in a variable of interest to a change in climate and/or environmental conditions, plus separate assessments that attribute the change in climate and/or environmental conditions to external drivers and external forcings.

In multistep attribution, observed changes in physical or biological systems are demonstrated to be associated with an observed regional climate change within a specified degree of confidence. Second, a measurable portion of the observed regional climate change, or the associated observed change in the system, is attributed to anthropogenic causes—by use of modeled data, with a similar degree of confidence. Confidence in attribution statements involving multistep climate change and observed impacts is lower than the confidence in either of the individual attribution steps alone due to the combination of two separate statistical assessments.

Some studies have linked declining marine calcification in coral reefs to SST stress and rising atmospheric carbon dioxide;^{5,33,90} however, these studies do not causally link SST rise directly to anthropogenic forcing factors via GCM simulations. By explicitly linking the coral studies to a separate analysis of global ocean

warming to anthropogenic forcing using a coupled GCM,⁹¹ multistep attribution could be achieved.

Associative pattern attribution to external forcings. This method uses a synthesis of large numbers of results (possibly across multiple systems), demonstrating the sensitivity of impacts to a change in climate conditions and other external drivers. The link between externally forced climate change and this ensemble of results is made using spatial and temporal measures of association.

In one example of associative pattern attribution, GCM simulations of current climate were compared to observed climate to determine the patterns of significant warming.⁶⁸ These patterns were found to be significantly related to patterns of observed impacts at global and continental scales. The climate attribution assessment presented in the IPCC AR4 was used to link the significant areas of warming to anthropogenic causes.

testing the attribution steps with GCM simulations with and without anthropogenic forcing.⁹²

Climate change effects on river flow in the western United States have been investigated using a high-resolution hydrological model forced by global climate models.⁹³ Sixteen hundred years of downscaled

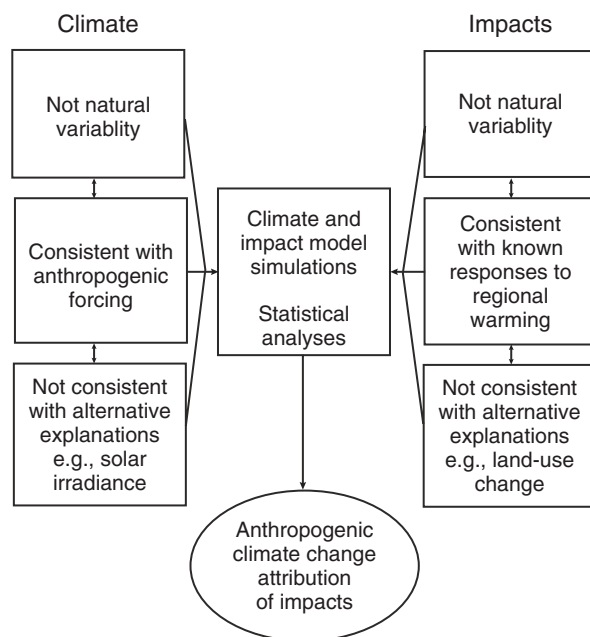
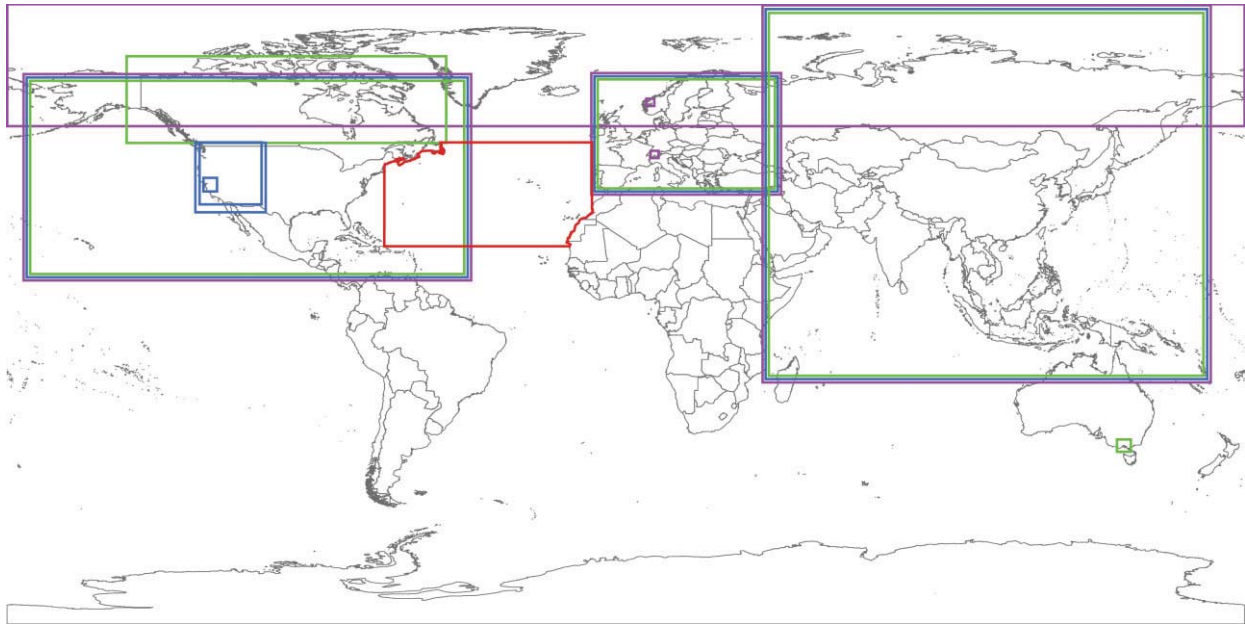


FIGURE 4 | Methodological elements in anthropogenic climate change attribution of impacts.¹²



- Cryosphere: Changes in snow, ice and frozen ground
- Hydrology: Changes in rivers and streams
- Biological systems: Changes in phenology, species ranges and assemblages, and forest fire regimes
- Ocean chemistry: Salinity changes

FIGURE 5 | Geographic areas and types of systems for which impact attribution studies have been published. Sectors include cryosphere,^{12,20,92} hydrology,^{12,93–95} ocean chemistry,⁹⁷ and biological systems.^{12,89,96,98} Regions are from study authors or designated by continent.^{99,100}

TABLE 2 | Observed changes in physical and biological systems with methods for attributing impacts to human influence on climate change

Observed change	Attribution methodology
Cryosphere	
Arctic sea ice decline ²⁰	Observed and simulated changes in Arctic sea ice extent using an optimal fingerprinting method with multiple GCMs
Glacier retreat ⁹²	Mass balance model of intermediate complexity, dynamic ice flow model, and GCM control experiments
Hydrology	
Trends in river flow and snow pack in western US ⁹³	High-resolution hydrological model forced by downscaled GCMs
Earlier snowmelt-driven streamflow in western US ⁹⁵	Observations, GCMs and hydrologic model
Snowpack reduction in western US ⁹⁴	Observations and GCMs
Ocean chemistry	
Salinity changes ⁹⁷	Observations compared to modeled spatial patterns in optimal detection analysis
Biological systems	
Changes in plant and animal traits ⁹⁶	Observed frequency distributions of correlation coefficients compared to GCMs with and without natural and anthropogenic forcing
Early emergence of butterfly in southeast Australia ⁹⁸	Physiological model of climatic influences on development and statistical analyses of climate data and GCM projections
Area burned by forest fires in Canada ⁸⁹	GCM with anthropogenic forcing and statistical analyses
Physical and biological systems	
Impacts on multiple physical and biological systems ¹²	Spatial pattern comparison of observations and GCMs

control run data were used to estimate the probability that the observed signal could be due to natural internal variability. The results show that up to 60% of the climate-related trends of river flow between 1950 and 1999 are human-induced. Also in the western United States, streamflow timing change has been detected and attributed to climate change.⁹⁵ Similar results have been found for snowpack in the region.⁹⁴

Analysis of observed and modeled oceanic processes shows that significant changes of salinity in the Northern Hemisphere Atlantic Ocean are beginning to emerge as a result of human influence.⁹⁷ The authors calculated spatial patterns of the expected changes (the 'fingerprints'), which were then regressed against the corresponding observed patterns.

With regard to biological systems, the frequency distributions of the correlation coefficients for spring phenological data were examined for 145 Northern Hemisphere wild animal and plant species and temperature from GCM simulations with natural climate forcings alone, with greenhouse gas and aerosol forcings, and with combined natural and anthropogenic forcing.⁹⁶ As expected, there was strongest agreement between correlation coefficients using the simulated temperatures from combined natural and anthropogenic forcing.

The relationship of rates of change of climate variables and observed impacts is another key topic that affects attribution. For example, researchers have found that the mean emergence date for a butterfly *Heteronympha merope* in Melbourne, Australia, has shifted 1.6 days per decade over a 65-year period with a concurrent increase in local air temperatures of approximately 0.14°C per decade and have linked that shift to anthropogenic forcing.⁹⁸ Such studies contribute to an improved functional understanding of the responses of natural and managed systems to anthropogenic climate change.

SUMMARY OF OBSERVED IMPACTS AND NEW EVIDENCE

The IPCC Fourth Assessment found, with very high confidence,⁴ that physical and biological systems on all continents and most oceans are already being affected by recent climate changes, particularly regional temperature increases.³ Since the publication of the AR4, many new studies have brought forward further evidence of observed impacts and a more nuanced understanding of underlying processes (see Figure 1 and Table 3). These studies document new or more strongly observed impacts in physical systems (e.g., Himalayan glacial lakes and Antarctic ice shelves) and comparisons of rates of change among biological

species (e.g., birds and butterflies). Some impacts have been inferred from agricultural data (e.g., negative effects on positive trends in global crop production). New evidence is particularly important in tropical regions and marine systems, which the IPCC AR4 noted as underrepresented.³

Physical Systems

With regard to physical systems, climate change has been found to be strongly affecting many aspects of systems related to snow, ice, and frozen ground (including permafrost). Evidence continues to emerge in hydrological systems, water resources, coastal zones, and oceans. The global glacial wastage^{15,101–103} and declines of snow cover^{104,105} have coincided with the thawing of permafrost,¹⁰⁶ a shorter travel season for vehicles over frozen roads in the arctic¹⁰⁷ and the enlargement and increase of glacial lakes in mountain regions.¹⁰⁸ Spring discharge is also occurring earlier in rivers affected by snow melt.¹⁰⁵ And as a result of climate warming, there has been increased coastal erosion.^{3,109}

Recent data suggest a more complex picture of the effects of the continuing warming trend. In regard to permafrost in Russia, there has been substantial warming in the last 20–30 years, typically 0.5–2°C at depth zero annual amplitude (the distance from the ground surface downward to the level below which there is practically no annual fluctuation in ground temperature).¹¹⁰ This warming occurred predominantly between the 1970s and 1990s, and there was no significant observed warming in the 2000s in most areas. However, warming seems to have resumed in the last 2–3 years, particularly in coastal areas. In all, a northward displacement of the boundary between continuous and discontinuous permafrost zones of several tens of kilometers has been observed.

In North America, permafrost temperatures have almost all increased over the past two to three decades, but there has been a slowing in the rate of warming at many locations in the past decade.¹¹¹ In Northern Quebec and the eastern Arctic, however, warming did not begin until 1993 and has continued through the present.

There are contrasting patterns in size evolution of glacial lakes. In the Hindu Kush Himalaya mountain ranges, the East/West patterns of lake changes are in agreement with existing glacial measurements.¹¹² In the East (Nepal and Bhutan), glacial lakes are bigger and more numerous than in the West (Pakistan and Afghanistan), and grew continuously between 1990 and 2009, while in the

TABLE 3 | Examples of observed impacts published since IPCC AR4

Emerging detection of impact	Observed change	Region
Terrestrial biological systems		
Increasing global soil respiration	Global soil respiration has increased 0.1 Pg C/year between 1989 and 2008 in response to rising air temperatures. ¹¹⁵	Global
Extinction of cold-adapted species with low colonizing ability	European land leech near Graz, Austria, suffered extinctions coinciding with 3°C rise in average summer temperatures and reduction of soil moisture 1961–2004. ¹¹⁶	Europe
Upward elevation shifts in the tropics	On Mount Kinabalu, Borneo, six moth assemblages show that average altitudes of 102 montane Geometridea species increased by 67 m 1965–2007. ¹¹⁷	Tropical Southeast Asia
CO ₂ fertilization	Aspen growth increased 53% over past five decades, primarily in response to 19% rise in ambient CO ₂ levels. ¹¹⁸ Sampling biases may have over-estimated increase. ¹¹⁹	Wisconsin, USA
Differential advances in plant type	Average temperature response of perennial plants was significantly greater (−4.2 days °C ^{−1}) than that of annual agricultural crops (−3.0 days C ^{−1}). ⁸⁸	Europe
Range shifts in types of butterfly communities	Butterfly species in Finland demonstrated range shift exceeding previous records worldwide (from 1992–1996 to 2000–2004). Non-threatened butterflies expanded their ranges strongly northward (84.5 km), whereas distributions of threatened species were near stationary (−2.1 km). ¹²⁰	Europe
Plant and pollinator shifts	Bee phenology in northeastern North America advanced by 10.4 days over past 130 years. Bee emergence has kept pace with shifts in host-plant flowering. ¹²¹	North America
Marine biological systems		
Species range shifts related to ocean temperatures	Subantarctic seabirds range shift in Southern Ocean. ¹²³	Southern Indian Ocean
Coral growth	Skeletal growth of apparently healthy colonies of reef-building coral has declined by 30% since 1998. ¹²⁴	Red Sea
Regime shifts and migration of top predators	Albacore tuna arrived 8 days earlier than 40 years previously; bluefin tuna arrived 14 days earlier than 25 years previously. ¹²⁵	Bay of Biscal, Eastern Atlantic
Shifts in seaweed communities	Poleward shifts in distribution of several temperate species on Australian coasts, with ocean warming rearranging ecologically important species in subtidal communities and driving temperate species toward edge of continent. ¹²⁶	Australia
Biological changes related to changes in upwelling as result of warming	Weakening of coastal upwelling linked to decrease of zonal sea level pressure gradient and correlated with increase in SST and NAO caused reduction of sardine landings at local harbors and proliferation of harmful algal blooms. ¹²⁷	Iberian coast

West, the extent of the glacial lakes remained the same or decreased. Most glaciers in the Himalaya and Karakoram region have retreated and lost mass since the mid-19th century.¹¹³ Although the loss rates have probably accelerated in recent decades, the observed tendencies are not uniform.

There is also evidence that ice shelves have retreated in Antarctica over the past half century due to a combination of climatic and cryospheric conditions¹¹⁴.

Biological Systems

The IPCC AR4 found more evidence to confirm earlier findings from a wider range of species and communities in terrestrial ecosystems and substantial new evidence in marine and freshwater systems, showing that recent warming is strongly affecting natural biological systems.³ Keystone examples of these responses range from plants blooming earlier;¹²⁸ frogs calling earlier;¹²⁹ earlier breeding and migration of birds;^{85,130–132} cannibalism in

polar bears;¹³³ within-species genetic shifts toward more warm-adapted genotypes;¹³⁴ changes in diatom assemblages;⁶⁵ and shifts from cold- to warm-adapted marine communities.^{135,136}

Since the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), more evidence has emerged that species are responding to the warming, but as predicted in the IPCC TAR, some of the response time appears to be lagging behind the changes in climate, while some are nearly synchronous. Examples of emerging impacts are summarized in Table 3. Much of the new evidence provides a more complex picture of the biological changes occurring.

Rates of Change

Some studies have examined in detail *rates of change* among species. For example, using data from French breeding bird surveys conducted from 1989 to 2006, it was found that changes in community composition were insufficient to keep up with temperature increase: birds were lagging approximately 182 km behind climate warming based on changes in species range edges.¹³⁷ A study of butterflies found that of those species that fare well, the ability to adapt and migrate appears key to survival.¹²⁰ Thus, the need for protected landscapes and migration corridors is stronger than ever.¹³⁸ Another study in Europe showed that phenology responses may be nonlinear, becoming more marked with higher temperatures.¹³⁹

A meta-analysis of available studies of latitudinal (Europe, North America, and Chile) and elevational (Europe, North America, Malaysia, and Marion Island) range shifts for a range of taxonomic groups estimated that the distribution of species has recently shifted to higher elevations at a median rate of 11.0 m/decade, and to higher latitudes at a median rate of 16.9 km/decade.⁷⁷ These rates are, respectively, approximately two and three times faster than previously recorded. The studies used in the meta-analysis are from temperate zones and tropical mountains; different rates of change might be observed in moisture-limited systems. Other research looking at the first flowering date of 19 European species introduced into North America showed that equivalent phenological responses to temperature are occurring in North America and Europe. This result supports the conclusion that temperature is indeed a strong driving force of species' ranges—across certain environments—and verifies the reliability of species distribution models.¹⁴⁰

Another study analyzed 25,532 rates of phenological change for 726 UK terrestrial, freshwater, and marine taxa, and found that the majority of spring

and summer events have advanced more rapidly than previously documented.⁸⁰ The average rates were consistent with what would be expected for large-scale drivers and the observed warming trend. For the first time, the study also showed that there are broad-scale differences in phenological changes across environments and trophic levels, with advances in timing slowest for terrestrial secondary consumers (e.g., birds are secondary consumers of terrestrial invertebrate larvae)⁸⁰ (Figure 6).

Future work needs to investigate further how temporal and spatial patterns of observed impacts compare with impact model predictions. For example, the IPCC TAR predicted that climate change would lead to poleward movement of the boundaries of marine organism distributions, along with loss of habitat for cold- and cool-water fishes and gain in habitat for warm-water fishes (high confidence).¹⁴¹

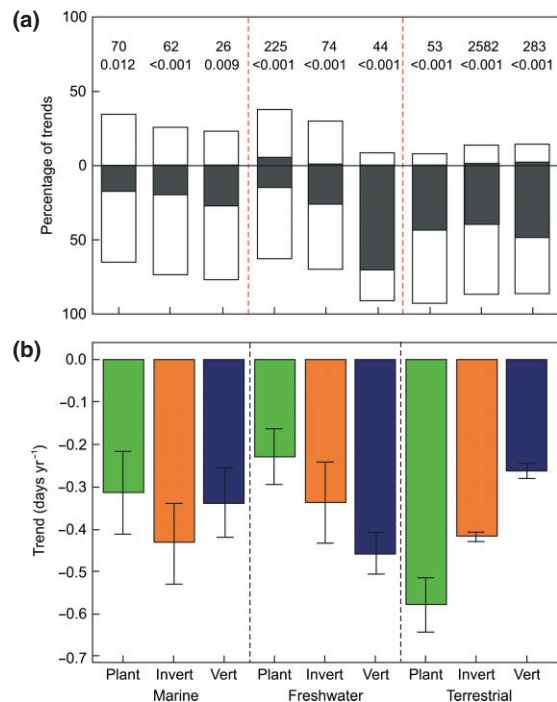


FIGURE 6 | Phenological change for 726 UK flora and fauna from 1976 to 2005. (a) Percentages of advancing (below horizontal) and delaying (above horizontal) trends for each taxon-environment combination. Statistically significant advancing and delaying trends are indicated by black shading. Nonsignificant trends are indicated by white shading. The number of trends analyzed for each taxon-environment combination (*n*) is given above each bar. Also shown is the significance level (*P*) of a two-tailed binomial test of the null hypothesis that negative and positive trends are equally likely. (b) Mean \pm SEM rates of change for plants/phytoplankton (plant; green bars), invertebrates (invert; orange bars) and vertebrates (vert; blue bars) in marine, freshwater, and terrestrial environments. All mean trends are negative, indicating an advance of phenological events.⁸⁰

This was subsequently observed and assessed in AR4, which documented long-term changes in the mean number of marine plankton species per association in the North Atlantic from 1960 to 1999, indicating a northward movement of southern shelf and temperate species and a dwindling of cold-temperate and subarctic species.^{136,142}

Spectrum of Species

A wider spectrum of species is now showing changes. For example, the Chinese alligator, *Alligator sinensis*, has been laying its eggs earlier over the period from 1991 to 2005 in conjunction with a warming trend in April;¹⁴³ and whole communities of small mammals are migrating.¹³⁸ In the northern US Great Lakes Region, changes in the small mammal population have substantially affected the composition and structure of forest communities.¹⁴⁴

Recent work has also concluded that over the past 130 years the phenology of 10 bee species from northeastern North America has advanced by a mean of 10.4 ± 1.3 days.¹²¹ Most of this advance has taken place since 1970, paralleling global warming

increases. The authors found that the directional changes found in bee phenology were likely due to recent climate warming because across all of the locations where bee specimens were collected there was a positive association between mean April temperature and year (Figure 7). When long-term bee phenology data were compared to shifts in 106 native plant species, they found that changes in bees have paralleled changes in the plants that they visit.

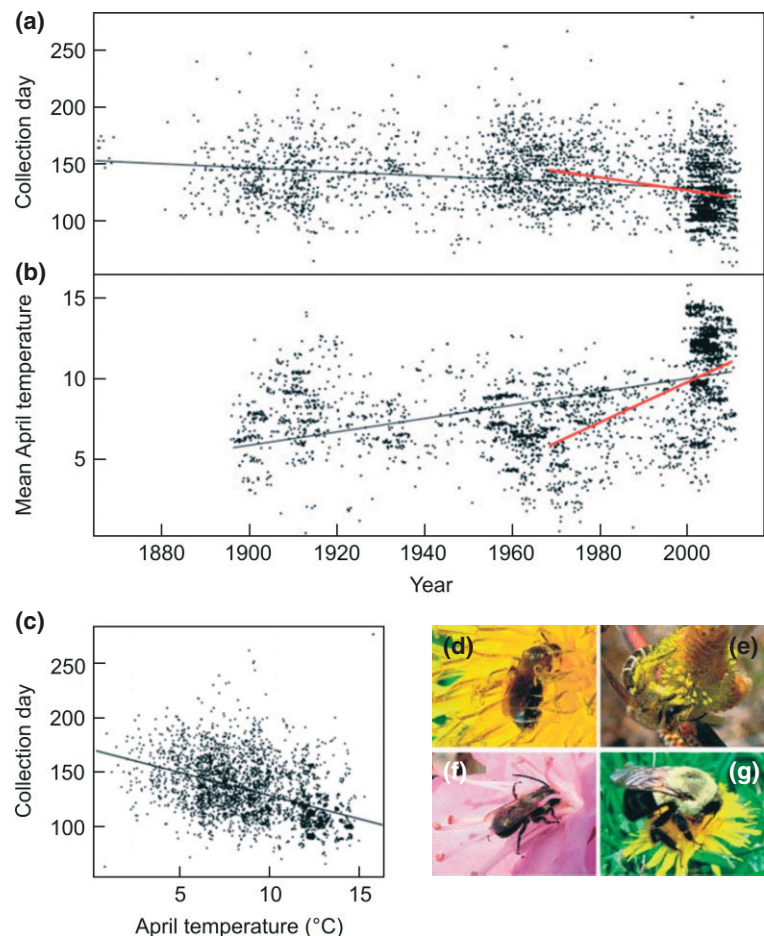
Community Shifts

Community shifts have been documented at regional scales. A northward migration of trees is underway in the eastern United States at rates of ~ 100 km/century for many species¹⁴⁵ and forest plant species on average are shifting upward in elevation at 29 m/decade in western Europe.¹⁴⁶ Comparable shifts are also being observed in tropical and marine systems, detailed in later sections.

Agriculture

The IPCC AR4 found a significant advance in phenology for agriculture and forestry in large parts

FIGURE 7 | Rates of change in bee phenology and temperature in northeastern North America over time. Each point represents a bee specimen used in the analysis. Raw data are shown without correcting for covariates. The collection day for each bee specimen, where January 1st is day 1 (a), and the mean temperature during the month of April (in °C) at the location where the specimen was collected (b). The overall trend (black lines) and the trend from 1970 to 2010 (red lines) are shown. (c) The correlation between bee collection day and temperature. The overall trend is shown (black line). Representative species for the genera in the analysis: (d) *Andrena miserabilis*, (e) *Coelophora inaequalis*, (f) *Osmia lingnaria* and (g) *Bombus impatiens* queen.¹²¹



of the Northern Hemisphere. Such changes included advances in the emergence of maize in Germany,¹⁴⁷ beginning of fruit tree flowering in France,¹⁴⁸ and observed increases in livestock production related to warming in summer and annual temperatures in Tibet.¹⁴⁹ Recent work has inferred declines in maize and wheat production from counter-factuals without warming trends from 1980 to 2008 in cropping regions and growing seasons of most countries, with the exception of the United States.¹⁵⁰ Remote sensing has been used to measure long-term changes in rice phenology in Punjab, India, where the rice growth pattern in terms of emergence and peak vegetative stage has advanced by 3–4 weeks.¹⁵¹

Some satellite instrumental records are now becoming long enough to detect phenological changes, which can be related to agricultural growing seasons. The Advanced Very High Resolution Radiometer (AVHRR) data from 1982 to the present show significant positive trends for the length of growing season and extension of the end of growing season documented for the Soudan and Guinean regions in Africa.¹⁵² Understanding the effects of climate trends on agriculture continues to be a priority.

New Evidence from the Tropics and Southern Hemisphere

Besides lack of data, research funding, and published studies, the dearth of observed impact studies in the tropics may also be due to the lack of knowledge of system sensitivity related to differing responses to climate variables, lag effects, and resilience. For instance, a hallmark of many observed impact studies in higher latitudes is an advance in spring phenology—yet even beginning to look for such a change is dubious in the lower latitudes that have less definite temperature seasons and more pronounced rainfall seasons.

While evidence of observed impacts is still predominantly found in Europe and North America, some new studies are emerging from Africa, Oceania, and Latin America.

In Africa, there are studies that document recent distributional changes of birds and forest biomes.¹⁵³ Seabird species in South Africa—such as Leach's storm petrel (*Oceanodroma leucorhoa*), crowned cormorant (*Phalacrocorax coronatus*), Hartlaub's gull (*Larus hartlaubii*), kelp gull (*Larus dominicanus*), African penguins (*Spheniscus demersus*), Cape gannets (*Morus capensis*), Cape weavers (*P. capensis*), bank cormorants (*P. neglectus*), and swift terns (*Sterna bergii*)—have been altering their ranges along the coast.¹⁵³ In North Africa, another study showed

that populations of common buzzards, *Buteo buteo*, that wintered formerly in North Africa are now wintering closer to their breeding grounds in Europe.¹⁵⁴ Another study found that Mount Kilimanjaro appears to be not only losing its ice caps, but also cloud forest because of changing precipitation patterns.¹⁵⁵

In Borneo, researchers repeated a historical altitudinal transect originally carried out in 1965 on Mount Kinabalu and found that the average altitude of individuals of 102 montane moth species, in the family Geometridae, increased by a mean of 67 m over the 42 years.¹¹⁷ In Southeastern Australia, lizards (*Bassiana duperreyi*, Scincidae) have adjusted both nest depth and seasonal timing of oviposition in response to rising temperatures.¹⁵⁶ They have been unable to compensate entirely for climate change, which has led to altered sex ratios related to warmer nest temperature that exceeded the thermal threshold directly affecting offspring sex. Also in Australia, a researcher found support for the hypothesis that at tropical latitudes frog declines were likely to occur following three consecutive years of unusually warm weather. However, the author acknowledges uncertainty in regard to associating these linkages with pathogens, but notes that these findings appear consistent with global warming predisposing some upland amphibians to dangerous organism.^{157–159}

In Latin America, north of Manaus, Brazil, widespread significant increases in tree mortality across plots were found between 1981 and 2003, with tree seedling recruitment also rising significantly over time but lagging behind mortality.¹⁶⁰ The increasing forest dynamics, growth, and basal area observed are broadly consistent with the CO₂ fertilization hypothesis. Although pronounced short-term variability in stand dynamics might be associated with climatic oscillations, mean temperatures and rainfall seasonality have both increased over time in central Amazonia, and are likely to have long-term effects on forest dynamics and carbon storage. Further north, at the fringe of a neotropical rainforest in French Guiana, a census of vascular plants across a 10-year interval (1995–2005) revealed that species richness decreased, with global warming the probable cause.¹⁶¹ However, the study's short time period and the presence of the major El Niño event of 1997–1998 in the record may confound this observed relationship.

Recent satellite studies show that there have been drought-induced reductions in global terrestrial net primary productivity from 2000 through 2009—primarily because of reductions in the Southern Hemisphere. This is a reverse of a trend in which carbon fixed as biomass increased from 1982 to 1999 in part because of increasing solar radiation as a result

of declines in cloud cover.¹⁶² As temperature patterns and precipitation have continued to change over the past 10 years, large-scale periodic regional droughts and a general drying have occurred over the Southern Hemisphere. Of the three major rainforests, only Africa's had an increasing trend in NPP.¹⁶³ However, there is disagreement on direction of change among different vegetation measures over this time period in Africa. Furthermore, this region has a sparse density of weather stations, so the confidence in gridded meteorology is relatively low.¹⁶⁴

Metabolic rate, which is a fundamental measure of physiological activity and ecological impact, has been estimated to have increased more quickly in the tropics than in polar regions.¹⁶⁵ The increase in metabolism in the tropics was large, despite the small increase in temperature there, likely because tropical warming is taking place in a climate already relatively warm.¹⁶⁵ Thus, large effects of recent warming on metabolism rates may be occurring for invertebrates, amphibians, and reptiles in equatorial West Africa, the Caribbean and Central America, Ecuador, eastern equatorial Brazil, and the Persian Gulf region. This work provides insight into new types of changes that can be studied in tropical ecosystems to determine if they are also undergoing alterations as a result of climate change—albeit by different measures.

New Evidence from Marine Systems

Marine ecosystems have also tended to be under-represented in impacts studies,¹⁶⁶ although rates of geochemical change in the oceans currently exceed anything recorded in the last 300 million years.¹⁶⁷

Both the rate and magnitude of environmental change pose challenges to seaweeds.¹⁶⁸ Changes in temperature extremes and patterns of variability can have profound biological consequences, as well as changes in means. For instance, for some seaweed species, reproduction may only occur if temperatures drop below a certain threshold for a sufficiently long period of time.¹⁶⁹

Some of the more readily detectable changes relate to distribution, either in terms of zonation of intertidal and subtidal seaweeds or distribution shifts across larger spatial scales. A study of macroalgae off the coast of Portugal analyzed from historical records from the 1950s and 1960s found that cold-water species, taken together, showed no particular trend but that warm-water species expanded their range northward.¹⁷⁰ The study also found that range retractions of certain species at low latitudes were offset by expansion into higher latitudes—as was the case for the warm-water species that expanded northward in Western Europe.

However, such expansions may not always be possible for species along coastlines with significant physical geomorphic barriers, such as those on the edge of continents.¹⁶⁸ For example, a recent study was conducted that interrogated >20,000 herbarium records of macroalgae collected in Australia since the 1940s, and poleward shifts in the distribution of several temperate species on both coasts were found (Figure 8).¹²⁶ On the east coast 85% of the species and on the west coast 56% of the species were only recorded farther poleward in the period 1990–2009 compared with 1940–1960. As some key species provide shelter and food for thousands of other flora and fauna, their shifts could have substantial impacts on local environments.

Comparing distribution records in the periods 1860–1950, 1980–1993, and 1994–2005, 2008, and 2010, the red-tide dinoflagellate, *Noctiluca scintillans*, was found to be expanding its range in the Southern Ocean, southward from Sydney Harbor. Isotherms of the East Australian Current (EAC) have moved >350 km southward over time,¹⁷¹ which in turn has been linked to changes in the South Pacific gyre in response to climate change.¹⁷² The range expansion of *Noctiluca* into the Southern Ocean then

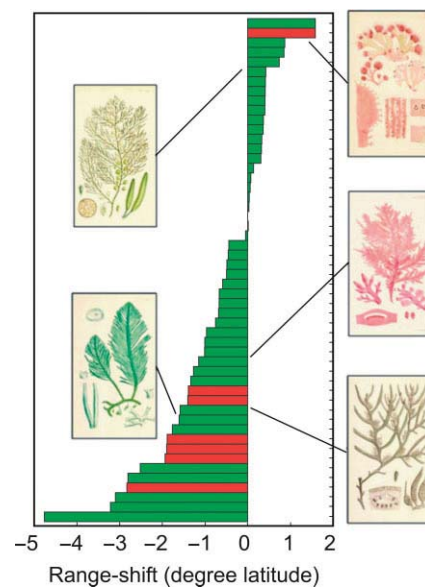


FIGURE 8 | Shift in northern range limits of temperate macroalgae in Australia between the periods 1940–1960 and 1990–2009 as determined from herbarium records. Negative degrees indicate southward shifts. Green bars represent samples from the west coast of Australia and red bars are from the east coast. Inserts: Color plates of selected algae from Henry Harvey's *Phycologia Australica* (1858–1863); from top left: *Caulocystis uvifera* and *Caulerpa flexilis* and from top right: *Martensia fragilis*, *Pterocladia lucida*, and *Scytothalia doryocarpa*.¹²⁶

is likely to be a consequence of the increased poleward penetration of the EAC and the subsequent increase in the frequency of warm core eddies traveling to Tasmania and beyond. The intensification of the East Australian Current has also caused the establishment of a new species of sea urchin, which is causing a fundamental shift in the structure and dynamics of Tasmanian rocky reef systems by the formation of sea urchin 'barrens' habitats.¹⁷³ These barrens represent an interaction between the effects of climate change and the reduction of large predatory rock lobster due to fishing.¹⁷³

Also near Australia in the Tasmanian Sea, there have been major changes in the distribution patterns of fishes, and these changes have corresponded with dramatic warming observed in the local marine environment.¹⁷⁴ Many warm temperate species have colonized the cool temperate Tasmanian region or substantially expanded their ranges, consistent with a strengthening Eastern Australian Current and associated rise in temperature. The lack of refugia south of Tasmania, the southernmost part of the Australian continental shelf, is a reason of concern—especially for coastal fish species.¹⁷⁴

Off the coast of Japan, a survey of mollusks from 1978 to 2006 on Pacific rocky shores showed that the dominance of southern species increased on 11 of the 15 shores in a southern, warming sea area but on only 1 of the 6 shores in a northern area with no warming trend. The results also agreed with studies from terrestrial plants that showed similar phenological responses to climate change among closely related species.¹⁷⁵

In the North Atlantic, a study analyzing tuna catches during their feeding migration to the Bay of Biscay showed that tuna now arrive earlier, with albacores arriving about 8 days earlier than 40 years ago and bluefins arriving 14 days earlier than 25 years ago.¹²⁵ Although other studies have identified regime shifts in the North Sea¹⁴² and reported that calanoid copepods are responding quickly to SST rise,⁵¹ tunas are the first documented top predators who have exhibited a similar regime shift in migration phenology and latitudinal distribution.¹²⁵

Despite slower ocean warming than on land, the velocity of climate change (in km/year calculated by the ratio of the long-term temperature trend in °C/year to the two-dimensional spatial gradient in temperature in °C/km, calculated over a 3° × 3° grid) and seasonal shifts in the ocean are as high as on land; direct effects of climate warming are therefore likely to be as great in the oceans as on land at comparable latitudes and even greater around the equator.¹⁷⁶

There are also some new data on changes in corals. One recent study has found that in the

Andaman Sea of South Thailand between 1984 and 2005 there was a significant decrease in annual growth increments (by 19.4–23.4%) and mass of coral calcification (by 23.5%), consistent with rising SSTs in the area.^{177,178} These corals appear to be subjected to temperatures beyond their thermal optimum. The relationship between coral bleaching and rising temperatures has been further documented in places such as the Caribbean.¹⁷⁹

It has also been shown that corals, as symbioses, might acclimatize or adapt to environmental changes by altering the physiology of the individual partners—the coral host (via, e.g., development of heat shock proteins or tissue expansion), the algal symbionts, and the microbial associates. They may also vary the identities and/or composition of the algal and microbial communities.¹⁸⁰ However, although there has been evidence that corals in some areas (e.g., Gulf of Chiriqui, Panama) can adapt to hosting more heat-resistant dinoflagellate symbionts,¹⁸¹ other studies have cautioned that such adaptations may be geographically limited and not possible in places such as the Great Barrier Reef.¹⁸² More study of coral reef evolution capacity is needed as model results show that coral reefs are likely to collapse within a few decades if genetic or community evolution does not occur.¹⁸³

Opportunities for Further Exploring New Data Sources

The strong evidence of observed impacts of recent climate change presented in the IPCC AR4 was nonetheless limited to the northern terrestrial ecosystems (see Figure 1). A notable lack of geographical balance continues to exist in the data and literature on observed changes in natural and managed systems, with a marked scarcity from developing countries. Evidence of terrestrial observed changes is especially sparse in Africa and Latin America, although it is growing in Australia and New Zealand. Evidence is lacking in South and Southeast Asia, as well as for marine systems in the Indian Ocean and regions in the Pacific.¹²

To enhance research capability on changes in physical, biological, and socioeconomic systems, particularly in regions with sparse data, observation networks and programs such as the Global Observing Information Center (COSIC) and Global Surface Network (GSN) (www.gosic.org) need to be surveyed and engaged to examine changes associated with alterations not only in temperature regimes but also in wet and dry seasons.

In order to enhance studies of precipitation trends and impacts in the tropics, both precipitation and impacts need to be better observed.

Recently, advances have been made in developing high-resolution satellite-derived precipitation datasets for climate studies.¹⁸⁴ NASA missions have facilitated the production of high-resolution precipitation datasets, such as those produced by the Tropical Rainfall Measuring Mission (TRMM), Global Precipitation Climatology Project (GPCP), CPC Morphing technique (CMORPH) (Figure 9), and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN), which can be used for comparison to trends in observed impacts, as well as climate model validation (for hindcast simulations) and calibration (for future simulations).

Data for studying trends in cryosphere systems include satellite images and geo-hazard assessments;¹⁰⁸ snow depth (HS) and new snow (HN) data from agencies such as the Swiss Meteorological Institute (SMA; now known as MeteoSwiss), and the Swiss Federal Institute for Snow and Avalanche Research (SFISAR).¹⁸⁷ For hydrological systems, these include observations of discharge, stream water temperature, river-ice thickness, dates of river freeze-up and break-up, which are relatively uncontaminated by land-use changes and human-made structures. They are conducted and quality-controlled by

such agencies as the Russian Hydrometeorological Services¹⁸⁸ or the USGS Hydro-Climatic Data Network (HCDN).¹⁰⁵ For coastal processes and zones, data are available through such sources as the US NOAA's National Ocean Service, aerial photographs, and kinematic GPS surveys.^{189,190} Soil sampling has been done through nature reserves, such as the Everglades National Park and the US Geological Survey.¹⁹¹ The exploration of more data sources, particularly in the tropics, is strongly encouraged.

ADAPTATION AND INDIGENOUS KNOWLEDGE

Responses to climate changes in human systems are difficult to identify because of multiple non-climate driving forces and the presence of adaptation.³ Furthermore, many climate change assessments often do not include or include only minimally indigenous knowledge narratives, in part because peer-reviewed studies rarely document oral narratives or changes observed by indigenous groups as evidence. New work is beginning to address these challenges.

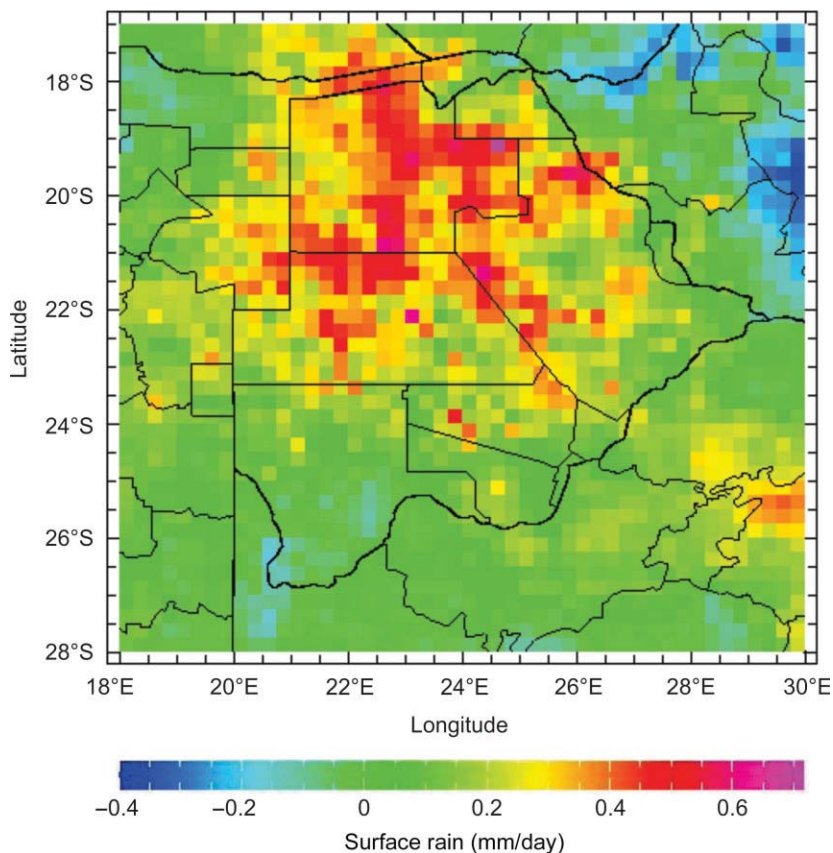


FIGURE 9 | Linear trend of monthly-average TRMM precipitation data for March values 2001–2009 over the Okavango Delta in Botswana, an example of satellite data that could be used in detection of precipitation-related impacts.^{185,186} Created using IRI Data Map Room (<http://iridl.ldeo.columbia.edu/maproom/>).

Observed Adaptation

Systematic assessment of adaptations related to the physical and biological changes brought forward by detection studies are especially important. Examples include drainage of glacial lakes in response to increasing outflow floods in Himalayan communities;¹⁰⁸ enhanced monitoring efforts to document long and short-term Arctic system changes related to indigenous livelihoods;¹⁹² and farmers in Europe adjusting their sowing dates to earlier spring onset.¹⁹³

The IPCC WGII AR4 documented some limited examples of *autonomous adaptation*^b to observed changes in socioeconomic systems and sectors such as energy demand and tourism.³ In some areas of the developing world, farmers have demonstrated autonomous adaptation and incorporated new crops to compensate for the negative impacts of climate change.¹²² Other studies have found that farmers in the tropics appear vulnerable to climate change due to lack of adaptation capacity and access to hydrological forecasts.¹⁹⁴ Also at issue in developing regions is that agriculture often represents a large part of national GDP and that markets tend to be fairly closed.

Researchers have developed and applied a systematic mixed-methods literature review methodology to identify and characterize climate change adaptation¹⁹⁵ (Figure 10). Using publications as proxies for observations of adaptation, they find limited

evidence of adaptation action in developed countries. Where interventions are being implemented and reported on, they are typically in sectors that are sensitive to climate impacts, are institutional in nature, and are carried out at the municipal level with facilitation by higher-level government policies and programs. There is negligible description of adaptation taking place with respect to vulnerable groups, and reporting is highly unequal by region and sector. This proxy methodology can be used for monitoring progress in adaptation over time.

Essential for documenting adaptation is availability of approaches and tools for better understanding and mapping climate change effects. For instance, web-based climate information resources that have been created for malaria prediction and control in Africa can be used to analyze impacts and adaptation trends over time.¹⁹⁶ Similarly, agricultural maps of changes in growing seasons are now being made available in developing areas such as sub-Saharan Africa.¹⁹⁷ Climate impact information systems disseminated through centers such as the NOAA Regional Integrated Sciences and Assessments (RISA) programs (www.climate.noaa.gov/cpo_pa/risa) in the United States and the United Kingdom Climate Impacts Programme (UKCIP) (www.ukcip.org.uk) play an important role in observing as well as facilitating adaptation.

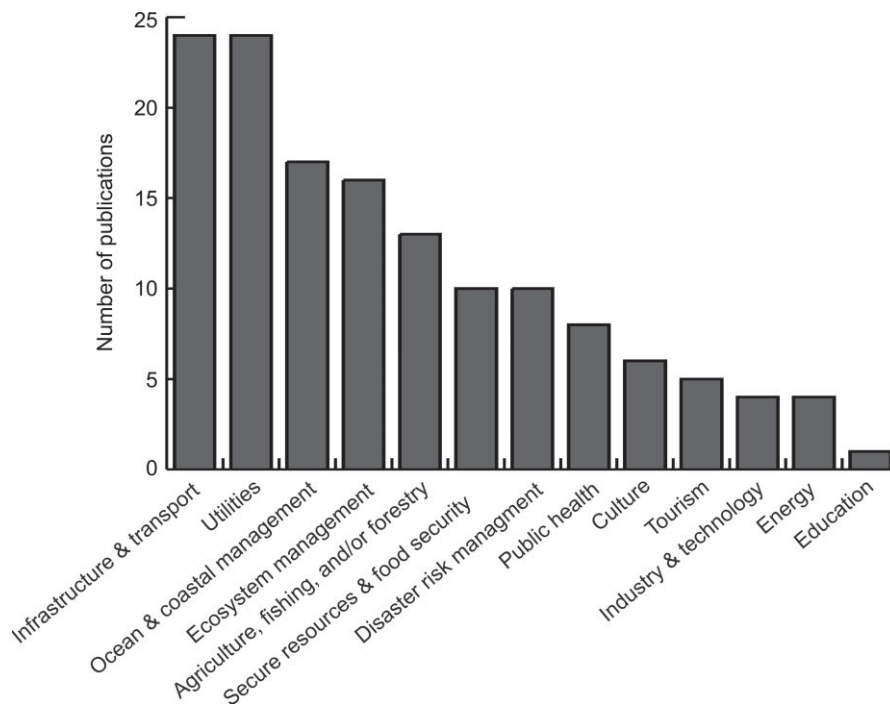


FIGURE 10 | Number of publications reviewed that addressed observed adaptation in developed countries, by sector (used as a proxy for observations of adaptation). The review included publication up to July 1, 2009.¹⁹⁵

Indigenous Knowledge of Observed Impacts and Adaptation

In remote areas, indigenous knowledge, often presented in the form of narratives,^c can significantly enhance understanding of the impacts of climate change on physical and biological systems and human responses to these impacts. These impacts are being experienced by many indigenous communities, especially in the northern high latitudes, and include changes in hunting patterns and therefore food supply,^{71,198} losses and disturbances in culture and threats to homes and ancestral settlements.^{199,200} For example, persistent flooding and erosion associated with sea level rise are affecting the perception of spatial distribution of human and supernatural beings by Inuit people in Alaska.¹⁹⁹

The evidence given by local people can provide a rich source of information about climate change and enhance science assessments that contribute to public policy. Indigenous narratives provide intergenerational observations regarding local climate change, its impacts on physical, biological, and social systems, as well as adaptation and mitigation. Efforts such as the Stories of the Raven,²⁰¹ and the Arctic Climate Impact Assessment,¹⁰⁷ include many examples whereby local traditional knowledge of Inuit, Sami, Athabaskans, Gwich'in, Aleut, and other Arctic indigenous people documented observed impacts of climate change, often in otherwise understudied areas.²⁰²

Indigenous knowledge can provide a form of proxy data of physical and biological changes, as well as show examples of human adaptation to climate change. However, characterizing the potential for documenting such observations of physical, biological, and human responses in systematic ways remains a challenge because of differences in the knowledge systems of indigenous people and scientists. This type of information might be brought into assessments through collations of indigenous narratives in parallel with scientific data and peer-reviewed studies to ensure mutually respectful power relationships.²⁰² This involves bringing together indigenous narratives 'side-by-side' with instrumental records of observed temperature and other climate variables and peer-reviewed studies of observed impacts (Figure 11). In remote areas with sparse temperature records, indigenous knowledge narratives can serve as proxy data. On the other hand, point data and/or remote sensing measurements may aid in explaining local phenomena that may be difficult to observe through tactile or visual means (e.g., ocean current strength/direction changes, atmospheric oscillations, ocean temperature, air temperature, wind strength/direction, and long-term trends).

Inclusion of indigenous knowledge in climate change assessments may be guided by the Convention on Biological Diversity (CBD), which is currently developing a code of ethical conduct for the inclusion of indigenous knowledge.²⁰³ The CBD articles and related provisions recognize the need to maintain the integrity of traditional knowledge, be concerned about the impacts of climate change on indigenous communities, and be mindful of cultural diversity. The IPCC could similarly provide guidance to include traditional knowledge in its assessments. Such a process of inclusion would enhance the IPCC Fifth Assessment (AR5) process, now underway.²⁰²

CONCLUSIONS

Currently, the evidence of climate change impacts remains strongest in the Northern Hemisphere, particularly with regard to attribution of impacts to anthropogenic forcing. However, studies documenting impacts in underrepresented sectors and regions are emerging, particularly in marine systems and the tropics. Work in Australia and New Zealand is also progressing. Moving forward, we believe that it is critical for more observed impact studies to be carried out, particularly in marine systems, the tropics, and the Southern Hemisphere, and that studies in all locations examine climate drivers beyond temperature as well as non-climate drivers of change to gain a fuller understanding of the wide range of influences on physical and biological systems. Continuous remote sensing and ground-based monitoring are needed to provide extended timeseries of data in the coming decades.

Observed changes should also be used to test and improve the methods and models that project future impacts. The rate of change in observed impacts related to the trajectory of anthropogenic climate change is a critical component of the 'Reasons for Concern' described in the AR4 Synthesis Report.⁷¹

To examine a wider array of impacts driven by changing climate, the incorporation of satellite data as well as the mining of previously untapped data sources, such as archives in nature reserves and long-term ecological research stations, photographs, and museum collections should be encouraged.

Observed changes in socioeconomic systems are even more complex and should be studied rigorously as well. Evidence of climate-related changes in human systems such as agriculture or tourism is difficult to document because of the range of other driving forces (e.g., technology improvements, globalization) that also play a role. There is now a growing focus on

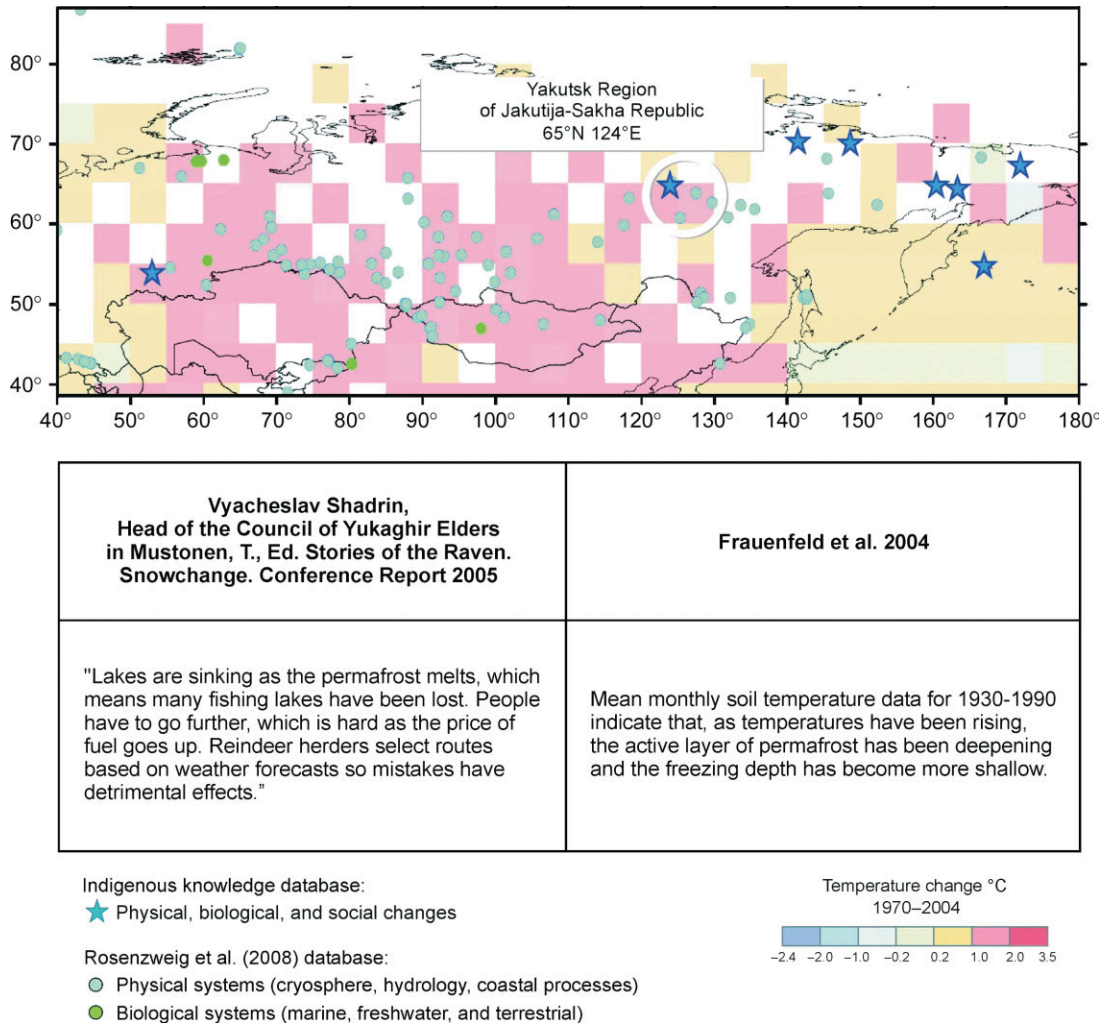


FIGURE 11 | Observed climate change impacts in the Yakutsk region of Russia, where indigenous knowledge narratives are located within 250 km of observations from the peer-reviewed scientific literature.²⁰² Latitude and longitude indicate the central location of the indigenous knowledge narrative overlaid on global HadCRUT3 temperature trends.⁴ Circles represent locations of statistically significant trends in changes in either direction in systems related to temperature or to other climate change variables, and that contain data from at least 20 years between 1970 and 2004.¹² Stars represent approximate locations of indigenous knowledge narratives related to climate change.

adaptation as an essential response to the growing risks of climate change. Collection of timeseries data on adaptation responses, such as timing of spring planting or harvest in more geographically diverse cropping systems, should be included as part of those efforts. Human responses to climate change, including adaptation to observed impacts, are beginning to be documented more widely, with indigenous groups playing a vital role.

Finally, it has been posited that chained attribution assessments—for example, from anthropogenic greenhouse gas emissions to climate change to biological change—are largely inappropriate, principally because understanding of the biological impacts of climate change cannot aspire to the level of certainty

achieved in physical climate science because of the presence of confounding drivers of change.^{204–206} Complexity in biological response does make attribution difficult. However, studies of attribution of observed impacts to anthropogenic forcings, albeit complex, are essential for the science-based development of both mitigation and adaptation policies. International policymakers need to know the extent of human-caused impacts as they develop global agreements to limit greenhouse gas emissions that cause climate change. Furthermore, human-caused impacts imply the need for long-term adaptation strategies for management of ecosystems, water resources, and agriculture—indeed for all systems—under changing climate trajectories.

We show that climate-related impacts have been attributed to anthropogenic causes in the Arctic, North America, the North Atlantic, Europe, Asia, and the southern tip of Australia. Linking climate change impacts to human causes in Africa and South America is an ongoing challenge, despite strong trends in warming and hydrological indicators. However, we find that documented evidence is growing and that attribution studies may soon prove that anthropogenic climate change is a driver of impacts throughout the world.

NOTES

^aAt least 9 out of 10 chance of being correct.⁶

^bAdaptation that does not constitute a conscious response to climate stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems, also referred to as spontaneous adaptation.

^cWe use the term ‘narrative’ to denote a set of observations by an indigenous person or group, transmitted in a mutually agreed manner.

ACKNOWLEDGMENTS

We gratefully acknowledge Dr. Marta Vicarelli for spatial analysis, Soyee Chiu for research assistance, Tommy J Moorman for scientific illustration, and José Mendoza for graphics. We thank the editors, especially Dr. Timothy R. Carter, and anonymous reviewers for their astute comments and suggestions on this manuscript. Support was provided by the NASA Earth Science Division through the office of Dr. Jack A. Kaye.

REFERENCES

1. Stott PA, Gillett NP, Hegerl GC, Karoly DJ, Stone DA, Zhang XB, Zwiers F. Detection and attribution of climate change: a regional perspective. *WIREs: Clim Change* 2010, 1:192–211.
2. Stone DA, Allen MR, Stott PA, Pall P, Min SK, Nozawa T, Yukimoto S. The detection and attribution of human influence on climate. *Annu Rev Environ Resour* 2009, 34:1–16.
3. Rosenzweig C, Casassa G, Karoly DJ, Imeson A, Liu C, Menzel A, Rawlins S, Root TL, Seguin B, Tryjanowski P. Assessment of observed changes and responses in natural and managed systems. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; 2007, 79–131.
4. Brohan P, Kennedy JJ, Harris I, Tett SFB, Jones PD. Uncertainty estimates in regional and global observed temperature changes: a new data set from 1850. *J Geophys Res-Atmosph* 2006, 111:D12106.
5. Hegerl G, Hoegh-Guldberg O, Casassa G, Hoerling MP, Kovats RS, Parmesan C, Pierce DW, Stott PA. Good practice guidance paper on detection and attribution related to anthropogenic climate change. In: Stocker TF, Field CB, Qin D, Barros V, Plattner G-K, Tignor M, Midgley PM, Ebi KL, eds. *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Detection and Attribution of Anthropogenic Climate Change*. Bern, Switzerland: University of Bern, Bern, Switzerland Working Group I Technical Support Unit; 2009.
6. IPCC. Summary for policymakers. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, eds. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press; 2007.
7. Hillel D, Rosenzweig C. Desertification in relation to climate variability and change. *Adv Agron* 2002, 77:1–38.
8. Parmesan C, Yohe G. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 2003, 421:37–42.
9. Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, Erasmus BFN, de Siqueira MF, Grainger A, Hannah L, et al. Extinction risk from climate change. *Nature* 2004, 427:145.
10. Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA. Fingerprints of global warming on wild animals and plants. *Nature* 2003, 421:57–60.
11. Edwards M, Richardson AJ. Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature* 2004, 430:881–884.
12. Rosenzweig C, Karoly D, Vicarelli M, Neofotis P, Wu QG, Casassa G, Menzel A, Root TL, Estrella N, Seguin B, et al. Attributing physical and biological impacts to anthropogenic climate change. *Nature* 2008, 453:353–357.
13. Lehikoinen A, Jaatinen K. Delayed autumn migration in northern European waterfowl. *J Ornithol* 2011, 153:563–570. doi:10.1007/s10336-011-0777-z.
14. Schlenker W, Roberts MJ. Nonlinear temperature effects indicate severe damages to US crop yields under

- climate change. *Proc Natl Acad Sci U S A* 2009, 106:15594–15598.
15. Oerlemans J. Extracting a climate signal from 169 glacier records. *Science* 2005, 308:675–677.
 16. IPCC, ed. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the International Panel on Climate Change*. Cambridge, UK and New York: Cambridge University Press; 2001, 881.
 17. Penuelas J, Filella I, Comas P. Changed plant and animal life cycles from 1952 to 2000 in the Mediterranean Region. *Glob Change Biol* 2002, 8:531.
 18. Mac Nally R, Bennett AF, Thomson JR, Radford JQ, Unmack G, Horrocks G, Vesk PA. Collapse of an avifauna: Climate change appears to exacerbate habitat loss and degradation. *Divers Distrib* 2009, 15:720–730.
 19. Kniveton DR, Layberry R, Williams CJR, Peck M. Trends in the start of the wet season over Africa. *Int J Climatol* 2009, 29:1216–1225.
 20. Min SK, Zhang X, Zweirs F. Human-induced Arctic moistening. *Science* 2008; 518–520.
 21. Urban O. Physiological impacts of elevated CO₂ concentration ranging from molecular to whole plant response. *Photosynthetica* 2003, 41:9–20.
 22. Peterson AG, Ball JT, Luo YQ, Field CB, Reich PB, Curtis PS, Griffin KL, Gunderson CA, Norby RJ, Tissue DT, et al. The photosynthesis leaf nitrogen relationship at ambient and elevated atmospheric carbon dioxide: a meta-analysis. *Glob Change Biol* 1999, 5:331–346.
 23. Dyckmans J, Flessa H, Polle A, Beese F. The effect of elevated [CO₂] on uptake and allocation of C-13 and N-15 in beech (*Fagus sylvatica* L.) during leafing. *Plant Biol* 2000, 2:113–120.
 24. Phillips OL, Martinez RV, Arroyo L, Baker TR, Killeen T, Lewis SL, Malhi Y, Mendoza AM, Neill D, Vargas PN, et al. Increasing dominance of large lianas in Amazonian forests. *Nature* 2002, 418:770–774.
 25. McMahon SM, Parker GG, Miller DR. Evidence for a recent increase in forest growth. *Proc Natl Acad Sci U S A* 2010, 107:3611–3615.
 26. Foster JR, Burton JJ, Forrester JA, Liu F, Muss JD, Sabatini FM, Scheller RM, Mladenoff DJ. Evidence for a recent increase in forest growth is questionable. *Proc Natl Acad Sci U S A* 2010, 107:E86–E87.
 27. Penuelas J, Canadell JG, Ogaya R. Increased water-use efficiency during the 20th century did not translate into enhanced tree growth. *Glob Ecol Biogeogr* 2011, 20:597–608.
 28. Linares JC, Delgado-Huertas A, Camarero JJ, Merino J, Carreira JA. Competition and drought limit the response of water-use efficiency to rising atmospheric carbon dioxide in the Mediterranean fir *Abies pinsapo*. *Oecologia* 2009, 161:611–624.
 29. Todgham AE, Hofmann GE. Transcriptomic response of sea urchin larvae *Strongylocentrotus purpuratus* to CO₂-driven seawater acidification. *J Exp Biol* 2009, 212:2579–2594.
 30. de Moel H, Ganssen GM, Peeters FJC, Jung SJA, Kroon D, Brummer GJA, Zeebe RE. Planktic foraminiferal shell thinning in the Arabian Sea due to anthropogenic ocean acidification? *Biogeosciences* 2009, 6:1917–1925.
 31. Munday PL, Donelson JM, Dixson DL, Endo GGK. Effects of ocean acidification on the early life history of a tropical marine fish. *Proc R Soc B Biol Sci* 2009, 276:3275–3283.
 32. Gooding RA, Harley CDG, Tang E. Elevated water temperature and carbon dioxide concentration increase the growth of a keystone echinoderm. *Proc Natl Acad Sci U S A* 2009, 106:9316–9321.
 33. Kleypas JA, Buddemeier RW, Archer D, Gattuso JP, Langdon C, Opdyke BN. Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science* 1999, 284:118–120.
 34. Roleda MY, Boyd PW, Hurd CL. Before ocean acidification: calcifier chemistry lessons *J Phycol* 2012, 48:840–843.
 35. Rosenzweig C, Hillel D. *Climate Variability and the Global Harvest*. New York: Oxford University Press; 2008.
 36. Lee T, McPhaden MJ. Increasing intensity of El Niño in the central-equatorial Pacific. *Geophys Res Lett* 2010, 37:1–5.
 37. Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin JM, Hoegh-Guldberg O, Bairlein F. Ecological responses to recent climate change. *Nature* 2002, 416:389–395.
 38. Polis GA, Hurd SD, Jackson CT, Pinero FS. El Niño effects on the dynamics and control of an island ecosystem in the Gulf of California. *Ecology* 1997, 78:1884–1897.
 39. Stapp P, Polls GA, Pinero FS. Stable isotopes reveal strong marine and El Niño effects on island food webs. *Nature* 1999, 401:467–469.
 40. Curran LM, Caniago I, Paoli GD, Astianti D, Kusneti M, Leighton M, Nirarita CE, Haeruman H. Impact of El Niño and logging on canopy tree recruitment in Borneo. *Science* 1999, 286:2184–2188.
 41. Chmielewski FM, Rotzer T. Response of tree phenology to climate change across Europe. *Agric For Meteorol* 2001, 108:101–112.
 42. Scheffinger H, Menzel A, Koch E, Peter C, Ahas R. Atmospheric mechanisms governing the spatial and temporal variability of phenological phases in central Europe. *Int J Climatol* 2002, 22:1739.
 43. Menzel A. Plant phenological anomalies in Germany and their relation to air temperature and NAO. *Clim Change* 2003, 57:243.

44. Hubalek Z. Spring migration of birds in relation to North Atlantic Oscillation. *Folia Zool* 2003, 52:287–298.
45. Huppopp O, Huppopp K. North Atlantic Oscillation and timing of spring migration in birds. *Proc R Soc Lond B Biol Sci* 2003, 270:233–240.
46. Sanz JJ. Large-scale effects of climate change on breeding parameters of pied flycatchers in western Europe. *Ecography* 2003, 26:45–50.
47. Kanuscak P, Hromada M, Tryjanowski P, Sparks T. Does climate at different scales influence the phenology and phenotype of the river warbler *Locustella fluviatilis*? *Oecologia* 2004, 141:158.
48. Menzel A, Sparks TH, Estrella N, Eckhardt S. 'SSW to NNE' - North Atlantic Oscillation affects the progress of seasons across Europe. *Glob Change Biol* 2005, 11:909.
49. Fitter AH, Fitter RSR. Rapid changes in flowering time in British plants. *Science* 2002, 296:1689.
50. Stewart IT, Cayan DR, Dettinger MD. Changes toward earlier streamflow timing across western North America. *J Clim* 2005, 18:1136–1155.
51. Beaugrand G, Luczak C, Edwards M. Rapid biogeographical plankton shifts in the North Atlantic Ocean. *Glob Change Biol* 2009, 15:1790–1803.
52. Goklany IM. Factors affecting environmental impacts: the effects of technology on long-term trends in cropland, air pollution and water-related diseases. *Ambio* 1996, 25:497–503.
53. Opdam P, Wascher D. Climate change meets habitat fragmentation: Linking landscape and biogeographical scale levels in research and conservation. *Biol Conserv* 2004, 117:285–297.
54. Knowlton K, Rosenzweig C, Goldberg R, Lynn B, Gaffin S, Hogrefe C, Civerolo K, Ku JY, Solecki W, Small C, et al. Evaluating global climate change impacts on local health across a diverse urban region. *Epidemiology* 2004, 15:S100–S100.
55. Hogrefe C, Lynn B, Civerolo K, Ku JY, Rosenthal J, Rosenzweig C, Goldberg R, Gaffin S, Knowlton K, Kinney PL. Simulating changes in regional air pollution over the eastern United States due to changes in global and regional climate and emissions. *J Geophys Res-Atmos* 2004, 109:1–13.
56. Kalnay E, Cai M. Impact of urbanization and land-use change on climate. *Nature* 2003, 423:528–531.
57. Pielke RA Sr, Marland G, Butts RA, Chase TN, Eastman JL, Niles JO, Niyogi DDS, Running SW. The influence of land-use change and landscape dynamics on the climate system: relevance to climate-change policy beyond the radiative effect of greenhouse gases. *Philos Transact A Math Phys Eng Sci* 2002, 360:1705–1719.
58. Patz JA, Campbell-Lendrum D, Holloway T, Foley JA. Impact of regional climate change on human health. *Nature* 2005, 438:310–317.
59. Thackeray SJ, Jones ID, Maberly SC. Long-term change in the phenology of spring phytoplankton: species-specific responses to nutrient enrichment and climatic change. *J Ecol* 2008, 96:523–535.
60. Feuchtmayr H, Thackeray SJ, Jones ID, De Ville M, Fletcher J, James B, Kelly J. Spring phytoplankton phenology—are patterns and drivers of change consistent among lakes in the same climatological region? *Freshw Biol* 2012, 57:331–344.
61. Solecki WD, Oliveri C. Downscaling climate change scenarios in an urban land use change model. *J Environ Manage* 2004, 72:105–115.
62. Rosenzweig C, Solecki WD, Parshall L, Lynn B, Cox J, Goldberg R, Hodges S, Gaffin S, Slosberg RB, Savio P, et al. Mitigating New York City's heat island integrating stakeholder perspectives and scientific evaluation. *Bull Amer Met Soc* 2009, 90:1297–1312.
63. Barry JP, Baxter CH, Sagarin RD, Gilman SE. Climate-related, long-term faunal changes in a California rocky intertidal community. *Science* 1995, 267:672–675.
64. Juanes F, Gephard S, Beland K. Long-term changes in migration timing of adult Atlantic Salmon (*Salmo salar*) at the southern edge of the species distribution. *Can J Fish Aquat Sci* 2004, 61:2392–2400.
65. Karst-Riddoch TL, Pisarcic MFJ, Smol JP. Diatom responses to 20th century climate-related environmental changes in high-elevation mountain lakes of the northern Canadian cordillera. *J Paleolimnol* 2005, 33:265–282.
66. Ruhland K, Presnitz A, Smol JP. Paleolimnological evidence from diatoms for recent environmental changes in 50 lakes across Canadian Arctic treeline. *Arctic Antarc Alp Res*, 2003, 35:110–123.
67. Williams TA, Abberton MT. Earlier flowering between 1962 and 2002 in agricultural varieties of white clover. *Oecologia* 2004, 138:122–126.
68. Hegerl G, Zwiers FW, Braconnot P, Gillett NP, Luo Y, Marengo Orsini JA, Nicholls N, Penner JE, Stott PA. *Understanding and Attributing Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York: Cambridge University Press; 2007.
69. Feddema J, Oleson K, Bonan G, Mearns L, Washington W, Meehl G, Nychka D. A comparison of a GCM response to historical anthropogenic land cover change and model sensitivity to uncertainty in present-day land cover representations. *Clim Dyn* 2005, 25:581–609.
70. Bounoua L, DeFries R, Collatz GJ, Sellers P, Khan H. Effects of land cover conversion on surface climate. *Clim Change* 2002, 52:29–64.

71. IPCC. Summary for policymakers. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, eds. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press; 2007, 7–22.
72. Hockey PAR, Sirami C, Ridley AR, Midgley GF, Babiker HA. Interrogating recent range changes in South African birds: confounding signals from land use and climate change present a challenge for attribution. *Divers Distrib* 2011, 17:254–261.
73. Stefanescu C, Penuelas J, Filella I. Effects of climatic change on the phenology of butterflies in the north-west Mediterranean Basin. *Glob Change Biol* 2003, 9:1494.
74. Menzel A, Sparks TH, Estrella N, Koch E, Aasa A, Ahas R, Alm-Kubler K, Bissolli P, Braslavská O, Briede A, et al. European phenological response to climate change matches the warming pattern. *Glob Change Biol* 2006, 12:1969–1976.
75. Thomas JA, Telfer MG, Roy DB, Preston CD, Greenwood JJD, Asher J, Fox R, Clarke RT, Lawton JH. Comparative losses of British butterflies, birds, and plants and the global extinction crisis. *Science* 2004, 303:1876–1881.
76. Kelly AE, Goulden ML. Rapid shifts in plant distribution with recent climate change. *Proc Natl Acad Sci U S A* 2008, 105:11826–11826.
77. Chen IC, Hill JK, Ohlemüller R, Roy DB, Thomas CD. Rapid range shifts of species associated with high levels of climate warming. *Science* 2011, 333:1024–1026.
78. Beaugrand G, Brander KM, Lindley JA, Souissi S, Reid PC. Plankton effect on cod recruitment in the North Sea. *Nature* 2003, 426:661–664.
79. Menzel A, Estrella N, Heitland W, Susnik A, A. D. Species-specific effects on the lengthening of the growing season in two European countries. *Proc R Soc London B*, Submitted for publication.
80. Thackeray SJ, Sparks TH, Frederiksen M, Burthe S, Bacon PJ, Bell JR, Botham MS, Brereton TM, Bright PW, Carvalho L, et al. Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Glob Change Biol* 2010, 16:3304–3313.
81. Wilks DS. On “field significance” and the false discovery rate. *J Appl Meteorol Climatol* 2006, 45: 1181–1189.
82. Feng S, Hu Q. Changes in agro-meteorological indicators in the contiguous United States: 1951–2000. *Theo Appl Climatol* 2004, 78:247–264.
83. Ahas R, Aasa A, Menzel A, Fedotova VG, Scheifinger H. Changes in European spring phenology. *Int J Climatol* 2002, 22:1727–1738.
84. Schleip SC, Menzel A, Estrella N, Dose V. The use of Bayesian analysis to detect recent changes in phenological events throughout the year. *Agric For Meteorol* 2006, 141:179–191.
85. Butler CJ. The disproportionate effect of global warming on the arrival dates of short-distance migratory birds in North America. *Ibis* 2003, 145:484.
86. Strode PK. Implications of climate change for North American wood warblers (*parulidae*). *Glob Change Biol* 2003, 9:1137.
87. Menzel A, Fabian P. Growing season extended in Europe. *Nature* 1999, 397:659–659.
88. Estrella N, Sparks TH, Menzel A. Effects of temperature, phase type and timing, location, and human density on plant phenological responses in Europe. *Clim Res* 2009, 39:235–248.
89. Gillett NP, Weaver AJ, Zwiers FW, Flannigan MD. Detecting the effect of climate change on Canadian forest fires. *Geophys Res Lett* 2004, 31:L18211.
90. De'ath G, Lough JM, Fabricius KE. Declining coral calcification on the Great Barrier Reef. *Science* 2009, 323:116–119.
91. Reichert BK, Schnur R, Bengtsson L. Global ocean warming tied to anthropogenic forcing. *Geophys Res Lett* 2002, 29:1525.
92. Reichert BK, Bengtsson L, Oerlemans J. Recent glacier retreat exceeds internal variability. *J Clim* 2002, 15:3069–3081.
93. Barnett TP, Pierce DW, Hidalgo HG, Bonfils C, Santer BD, Das T, Bala G, Wood AW, Nozawa T, Mirin AA, et al. Human-induced changes in the hydrology of the western United States. *Science* 2008, 319:1080–1083.
94. Pierce DW, Barnett TP, Hidalgo HG, Das T, Bonfils C, Santer BD, Bala G, Dettinger MD, Cayan DR, Mirin A, et al. Attribution of declining western US snowpack to human effects. *J Clim* 2008, 21: 6425–6444.
95. Hidalgo HG, Das T, Dettinger MD, Cayan DR, Pierce DW, Barnett TP, Bala G, Mirin A, Wood AW, Bonfils C, et al. Detection and attribution of streamflow timing changes to climate change in the western United States. *J Clim* 2009, 22:3838–3855.
96. Root TL, MacMynowski DP, Mastrandrea MD, Schneider SH. Human-modified temperatures induce species changes: joint attribution. *Proc Natl Acad Sci U S A* 2005, 102:7465–7469.
97. Stott PA, Sutton RT, Smith DM. Detection and attribution of Atlantic salinity changes. *Geophys Res Lett* 2008, 35:L21702.
98. Kearney MR, Briscoe NJ, Karoly D, Porter WP, Norgate M, Sunnecks P. Early emergence in a butterfly causally linked to anthropogenic warming. *Biol Lett* 2010, 6:674–677. doi:10.1098/rsbl.2010.0053. Available at: <http://rsbl.royalsocietypublishing.org/content/6/5/674.short>.

99. Giorgi F. Variability and trends of sub-continental scale surface climate in the 20th century. Part I: observations. *Clim Dyn* 2002, 18:675–691.
100. Stott PA. Attribution of regional-scale temperature changes to anthropogenic and natural causes. *Geophys Res Lett* 2003, 30.
101. Dyurgerov MB, Meier MF. Glaciers and the changing earth system: a 2004 snapshot. *Occasional Paper No. 58*, 2005.
102. Arendt AA, Echelmeyer KA, Harrison WD, Lingle CS, Valentine VB. Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science* 2002, 297:382–386.
103. Casassa G, Rivera A, Acuna C, Brecher H, Lange H. Elevation change and ice flow at Horseshoe Valley, Patriot Hills, West Antarctica. *Ann Glaciol* 2004, 39:20–28.
104. Casassa G, Rivera A, Escobar F, Acuña C, Carrasco J, Quintana J. Snow line rise in Central Chile in recent decades and its correlation with climate. *EGS - AGU - EUG Joint Assembly, Abstracts from the Meeting Held in Nice, France*, 6–11 2003.
105. Cayan DR, Kammerdiener SA, Dettinger MD, Caprio JM, Peterson DH. Changes in the onset of spring in the western United States. *Bull Amer Met Soc* 2001, 82:399.
106. Frauenfeld OW, Zhang T, Barry RG, Gilichinsky D. Interdecadal changes in seasonal freeze and thaw depths in Russia. *J Geophys Res* 2004, 109:1–12.
107. ACIA. *Arctic Climate Impact Assessment, Scientific Report*. Cambridge: Cambridge University Press; 2005.
108. Richardson SD, Reynolds JM. An overview of glacial hazards in the Himalayas. *Quat Int* 2000, 65/66:31–47
109. Lantuit H, Pollard WH. Remotely sensed evidence of enhanced erosion during the 20th century on Herschel Island, Yukon Territory. *Berichte zur Polar- und Meeresforschung* 2003, 443:54–59.
110. Romanovsky VE, Drozdov DS, Oberman NG, Malkova GV, Kholodov AL, Marchenko SS, Moskalenko NG, Sergeev DO, Ukraintseva NG, Abramov AA, et al. Thermal state of permafrost in Russia. *Permafrost Periglac Process* 2010, 21: 136–155.
111. Smith SL, Romanovsky VE, Lewkowicz AG, Burn CR, Allard M, Clow GD, Yoshikawa K, Throop J. Thermal state of permafrost in North America: a contribution to the international polar year. *Permafrost Periglac Process* 2010, 21:117–135.
112. Gardelle J, Arnaud Y, Berthier E. Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. *Glob Planet Change* 2011, 75:47–55.
113. Bolch T, Kulkarni A, Kaab A, Huggel C, Paul F, Cooley JG, Frey H, Kargel JS, Fujita K, Scheel M, et al. The state and fate of Himalayan glaciers. *Science* 2012, 336:310–314.
114. Cook AJ, Vaughan DG. Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. *Cryosphere* 2010, 4:77–98.
115. Bond-Lamberty B, Thomson A. Temperature-associated increases in the global soil respiration record. *Nature* 2010, 464:U579–U132.
116. Kutschera U, Pfeiffer I, Ebermann E. The European land leech: biology and DNA-based taxonomy of a rare species that is threatened by climate warming. *Naturwissenschaften* 2007, 94:967–974.
117. Chen IC, Shiu HJ, Benedick S, Holloway JD, Cheye VK, Barlow HS, Hill JK, Thomas CD. Elevation increases in moth assemblages over 42 years on a tropical mountain. *Proc Natl Acad Sci U S A* 2009, 106:1479–1483.
118. Cole CT, Anderson JE, Lindroth RL, Waller DM. Rising concentrations of atmospheric CO₂ have increased growth in natural stands of quaking Aspen (*Populus tremuloides*). *Glob Change Biol* 2010, 16:2186–2197.
119. Brienen RIJW, Gloor E, Zuidema PA. Detecting evidence for CO₂ fertilization from tree ring studies: the potential role of sampling biases. *Glob Biogeochem Cycles* 2012, 26:1–13. doi:10.1029/2011GB004143.
120. Poyry J, Luoto M, Heikkinen RK, Kuussaari M, Saarienen K. Species traits explain recent range shifts of Finnish butterflies. *Glob Change Biol* 2009, 15:732–743.
121. Bartomeus I, Ascher JS, Wagner D, Danforth BN, Colla S, Kornbluth S, Winfree R. Climate-associated phenological advances in bee pollinators and bee-pollinated plants. *Proc Natl Acad Sci U S A* 2011, 108:20645–20649.
122. Liu YA, Wang EL, Yang XG, Wang J. Contributions of climatic and crop varietal changes to crop production in the North China Plain, since 1980s. *Glob Change Biol* 2010, 16:2287–2299.
123. Peron C, Authier M, Barbraud C, Delord K, Besson D, Weimerskirch H. Interdecadal changes in at-sea distribution and abundance of Subantarctic seabirds along a latitudinal gradient in the Southern Indian Ocean. *Glob Change Biol* 2010, 16:1895–1909.
124. Cantin NE, Cohen AL, Karnauskas KB, Tarrant AM, McCorkle DC. Ocean warming slows coral growth in the central Red Sea. *Science* 2010, 329:322–325.
125. Dufour F, Arrizabalaga H, Irigoien X, Santiago J. Climate impacts on albacore and bluefin tunas migrations phenology and spatial distribution. *Prog Oceanogr* 2010, 86:283–290.
126. Wernberg T, Russell BD, Thomsen MS, Gurgel CFD, Bradshaw CJA, Poloczanska ES, Connell SD. Seaweed communities in retreat from ocean warming. *Curr Biol* 2011, 21:1828–1832.
127. Perez FF, Padin XA, Pazos Y, Gilcoto M, Cabanas M, Pardo PC, Doval MD, Farina-Busto L. Plankton

- response to weakening of the Iberian coastal upwelling. *Glob Change Biol* 2010, 16:1258–1267.
128. Abu-Asab MS, Peterson PM, Shetler SG, Orli SS. Earlier plant flowering in spring as a response to global warming in the Washington, DC, area. *Biodivers Conserv* 2001, 10:597.
 129. Corn PS. Amphibian breeding and climate change: importance of snow in the mountains. *Conserv Biol* 2003, 17:622–625.
 130. Bairlein F, Winkel DW, Lozan JL, Graál H, Hupfer P. Birds and climate change. In: *Climate of the 21st Century: Changes and Risks*. Hamburg: Wissenschaftliche Auswertungen; 2001, 278.
 131. Lehikoinen E, Sparks TH, Zalakevicius M. Arrival and departure dates. *Birds Clim Change* 2004, 35:1.
 132. Beaumont LJ, McAllan IAW, Hughes L. A matter of timing: changes in the first date of arrival and last date of departure of Australian migratory birds. *Glob Change Biol* 2006, 12:1339–1354.
 133. Amstrup SC, Stirling I, Smith TS, Perham C, Thiemann GW. Recent observations of intraspecific predation and cannibalism among polar bears in the southern Beaufort Sea. *Polar Biol* 2006, 29:997–1002.
 134. Bradshaw WE, Holzapfel CM. Genetic shift in photoperiodic response correlated with global warming. *Proc Natl Acad Sci U S A* 2001, 98:14509.
 135. Beaugrand G, Reid PC, Ibanez F, Lindley JA, Edwards M. Reorganization of North Atlantic marine copepod biodiversity and climate. *Science* 2002, 296:1692–1694.
 136. Beaugrand G, Ibanez F, Lindley JA, Reid PC. Diversity of calanoid copepods in the North Atlantic and adjacent seas: species associations and biogeography. *Mar Ecol Prog Ser* 2002, 232:179–195.
 137. Devictor V, Julliard R, Couvet D, Jiguet F. Birds are tracking climate warming, but not fast enough. *Proc Biol Sci* 2008, 275:2743–2748.
 138. Moritz C, Patton JL, Conroy CJ, Parra JL, White GC, Beissinger SR. Impact of a century of climate change on small-mammal communities in Yosemite National Park, USA. *Science* 2008, 322:261–264.
 139. Sparks TH, Jaroszewicz B, Krawczyk M, Tryjanowski P. Advancing phenology in Europe's last lowland primeval forest: non-linear temperature response. *Clim Res* 2009, 39:221–226.
 140. Hulme PE. Consistent flowering response to global warming by European plants introduced into North America. *Funct Ecol* 2011, 25:1189–1196.
 141. IPCC. In: McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS, eds. *Climate Change 2001: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press; 2001, 1032.
 142. Beaugrand G, Reid PC. Long-term changes in phytoplankton, zooplankton and salmon related to climate. *Glob Change Biol* 2003, 9:801–817.
 143. Zhang F, Li Y, Guo Z, Murray BR. Climate warming and reproduction in Chinese alligators. *Anim Conserv* 2009, 12:128–137.
 144. Myers P, Lundrigan BL, Hoffman SMG, Haraminac AP, Seto SH. Climate-induced changes in the small mammal communities of the northern Great Lakes region. *Glob Change Biol* 2009, 15:1434–1454.
 145. Woodall CW, Oswalt CM, Westfall JA, Perry CH, Nelson MD, Finley AO. An indicator of tree migration in forests of the eastern United States. *For Ecol Manage* 2009, 257:1434–1444.
 146. Lenoir J, Gegout JC, Marquet PA, de Ruffray P, Brisse H. A significant upward shift in plant species optimum elevation during the 20th Century. *Science* 2008, 320:1768–1771.
 147. Chmielewski FM, Muller A, Bruns E. Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. *Agric For Meteorol* 2004, 121:69–78.
 148. Seguin B, Domergue M, Cortazar IGd, Brisson N, Ripoche D. Le échauffement climatique récent: impact sur les arbres fruitiers et la vigne. *Lettre pigb-pmrc France Changement Global* 2004, 16:50–54.
 149. Du MY, Kawashima S, Yonemura S, Zhang XZ, Chen SB. Mutual influence between human activities and climate change in the Tibetan Plateau during recent years. *Glob Planet Change* 2004, 41:241–249.
 150. Lobell DB, Schlenker W, Costa-Roberts J. Climate trends and global crop production since 1980. *Science* 2011, 333:616–620.
 151. Singh RP, Oza SR, Pandya MR. Observing long-term changes in rice phenology using NOAA-AVHRR and DMSP-SSM/I satellite sensor measurements in Punjab, India. *Curr Sci* 2006, 91:1217–1221.
 152. Heumann BW, Seaquist JW, Eklundh L, Jonsson P. AVHRR derived phenological change in the Sahel and Soudan, Africa, 1982–2005. *Remote Sens Environ* 2007, 108:385–392.
 153. Crawford RJM, Tree AJ, Whittington PA, Visagie J, Upfold L, Roxburg KJ, Martin AP, Dyer BM. Recent distributional changes of seabirds in South Africa: Is climate having an impact? *Afr J Mar Sci* 2008, 30:189–193.
 154. Bensusan KJ, Garcia EFJ, Cortes JE. Trends in abundance of migrating raptors at Gibraltar in spring. *Ardea* 2007, 95:83–90.
 155. Hemp A. Climate change and its impact on the forests of Kilimanjaro. *Afr J Ecol* 2009, 47:3–10.
 156. Telemeco RS, Elphick MJ, Shine R. Nesting lizards (*Bassiana duperreyi*) compensate partly, but not completely, for climate change. *Ecology* 2009, 90:17–22.

157. Laurance WF. Global warming and amphibian extinctions in eastern Australia *Austral Ecology* 2008, 33:1–9.
158. Pounds JA, Bustamante MR, Coloma LA, Consuegra JA, Fogden MPL, Foster PN, La Marca E, Masters KL, Merino-Viteri A, Puschendorf R, et al. Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature* 2006, 439:161–167.
159. Kiesecker JM. Global stressors and the global decline of amphibians: tipping the stress immunocompetency axis. *Ecol Res* 2011, 26:897–908.
160. Laurance SGW. Long-term variation in Amazon forest dynamics. *J Veg Sci* 2009, 20:323–333.
161. Fonty E, Sarthou C, Larpin D, Ponge JF. A 10-year decrease in plant species richness on a neotropical inselberg: detrimental effects of global warming? *Glob Change Biol* 2009, 15:2360–2374.
162. Nemani RR, Keeling CD, Hashimoto H, Jolly WM, Piper SC, Tucker CJ, Myneni RB, Running SW. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science* 2003, 300:1560.
163. Zhao MS, Running SW. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science* 2010, 329:940–943.
164. Zhao MS, Running SW. Response to comments on “Drought-induced reduction in global terrestrial net primary production from 2000 through 2009”. *Science* 2011, 333.
165. Dillon ME, Wang G, Huey RB. Global metabolic impacts of recent climate warming. *Nature* 2010, 467:U704–U788.
166. Wernberg T, Smale DA, Thomsen MS. A decade of climate change experiments on marine organisms: procedures, patterns and problems. *Glob Change Biol* 2012, 18:1491–1498.
167. Honisch B, Ridgwell A, Schmidt DN, Thomas E, Gibbs SJ, Sluijs A, Zeebe R, Kump L, Martindale RC, Greene SE, et al. The geological record of ocean acidification. *Science* 2012, 335:1058–1063.
168. Harley CDG, Anderson KM, Demes KW, Jorve JP, Kordas RL, Coyle TA. Effects of climate change on global seaweed communities *J Phycol* 2012, 48:1064–1078.
169. Breeman AM. Relative importance of temperature and other factors in determining geographic boundaries of seaweeds - experimental and phenological evidence. *Helgoland Mar Res* 1988, 42:199–241.
170. Lima FP, Ribeiro PA, Queiroz N, Hawkins SJ, Santos AM. Do distributional shifts of northern and southern species of algae match the warming pattern? *Glob Change Biol* 2007, 13:2592–2604.
171. Ridgway KR. Long-term trend and decadal variability of the southward penetration of the East Australian Current. *Geophys Res Lett* 2007, 34:1–5.
172. Cai W, Shi G, Cowan T, Bi D, Ribbe J. The response of the southern annular mode, the East Australian Current, and the southern mid-latitude ocean circulation to global warming. *Geophys Res Lett* 2005, 32:1–4.
173. Johnson CR, Banks SC, Barrett NS, Cazassus F, Dunstan PK, Edgar GJ, Frusher SD, Gardner C, Had-don M, Helidoniotis F, et al. Climate change cascades: shifts in oceanography, species’ ranges and subtidal marine community dynamics in eastern Tasmania. *J Exp Mar Biol Ecol* 2011, 400:17–32.
174. Last PR, White WT, Gledhill DC, Hobday AJ, Brown R, Edgar GJ, Pecl G. Long-term shifts in abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. *Glob Ecol Biogeogr* 2011, 20:58–72.
175. Davis CC, Willis CG, Primack RB, Miller-Rushing AJ. The importance of phylogeny to the study of phenological response to global climate change. *Philos Trans R Soc Lond B Biol Sci* 2010, 365:3201–3213.
176. Burrows MT, Schoeman DS, Buckley LB, Moore P, Poloczanska ES, Brander KM, Brown C, Bruno JF, Duarte CM, Halpern BS, et al. The pace of shifting climate in marine and terrestrial ecosystems. *Science* 2011, 334:652–655.
177. Tanzil JTI, Brown BE, Tudhope AW, Dunne RP. Decline in skeletal growth of the coral *Porites lutea* from the Andaman Sea, South Thailand between 1984 and 2005. *Coral Reefs* 2009, 28:519–528.
178. Scoffin TP, Tudhope AW, Brown BE, Chansang H, Cheeney RF. Patterns and possible environmental controls of skeletogenesis of *Porites lutea*, South Thailand. *Coral Reefs* 1992, 11:1–11.
179. McWilliams JP, Cote IM, Gill JA, Sutherland WJ, Watkinson AR. Accelerating impacts of temperature-induced coral bleaching in the Caribbean. *Ecology* 2005, 86:2055–2060.
180. Baker AC, Glynn PW, Riegl B. Climate change and coral reef bleaching: an ecological assessment of long-term impacts, recovery trends and future outlook. *Estuar Coast Shelf Sci* 2008, 80:435–471.
181. Baker AC, Starger CJ, McClanahan TR, Glynn PW. Coral reefs: Corals’ adaptive response to climate change. *Nature* 2004, 430:741–741.
182. Stat M, Loh WKW, LaJeunesse TC, Hoegh-Guldberg O, Carter DA. Stability of coral-endosymbiont associations during and after a thermal stress event in the southern Great Barrier Reef. *Coral Reefs* 2009, 28:709–713.
183. Baskett ML, Gaines SD, Nisbet RM. Symbiont diversity may help coral reefs survive moderate climate change. *Ecol Appl* 2009, 19:3–17.
184. Joseph R, Smith TM, Sapiano MRP, Ferraro RR. A new high-resolution satellite-derived precipitation dataset for climate studies. *J Hydrometeorol* 2009, 10:935–952.

185. Huffman GJ, Adler RF, Morrissey M, Bolvin DT, Curtis S, Joyce R, McGavock B, Susskind J. Global precipitation at one-degree daily resolution from multi-satellite observations. *J Hydrometeor* 2001, 2:36–50.
186. Dinku T, Ceccato P, Grover-Kopec E, Lemma M, Connor SJ, Ropelewski CF. Validation of satellite rainfall products over East Africa's complex topography. *Int J Remote Sens* 2007, 28:1503–1526.
187. Laternser M, Schneebeli M. Long-term snow climate trends of the Swiss Alps (1931–99). *Int J Climatol* 2003, 23:733–750.
188. Yang DQ, Kane DL, Hinzman LD, Zhang XB, Zhang TJ, Ye HC. Siberian Lena River hydrologic regime and recent change. *J Geophys Res-Atmosph* 2002, 107:ACL14.1–ACL14.10.
189. Zhang K, Douglas BC, Leatherman SP. Global warming and coastal erosion. *Clim Change* 2004, 64:41–58.
190. Donnelly JP, Bertness MD. Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise. *Proc Natl Acad Sci U S A* 2001, 98:14218–14223.
191. Ross MS, Meeder JF, Sah JP, Ruiz PL, Telesnicki GJ. The southeast saline Everglades revisited: 50 years of coastal vegetation change. *J Veg Sci* 2000, 11:101–112.
192. Fox S, ed. *These Things that are Really Happening: Inuit Perspectives on the Evidence and Impacts of Climate Change in Nunavut*. Fairbanks, AK: Arctic Research Consortium of the US; 2002, 12–53.
193. Menzel A, von Vopelius J, Estrella N, Schleip C, Dose V. Farmers' annual activities are not tracking speed of climate change'. *Clim Res* 2006, 32:201–207.
194. Brondizio ES, Moran EF. Human dimensions of climate change: the vulnerability of small farmers in the Amazon. *Philos Trans R Soc Lond B Biol Sci* 2008, 363:1803–1809.
195. Ford JD, Berrang-Ford L, Paterson J. A systematic review of observed climate change adaptation in developed nations a letter. *Clim Change* 2011, 106:327–336.
196. Grover-Kopec EK, Blumenthal MB, Ceccato P, Dinku T, Omumbo JA, Connor SJ. Web-based climate information resources for malaria control in Africa. *Malar J* 2006, 5:1–9.
197. Cooper PJM, Dimes J, Rao KPC, Shapiro B, Shiferaw B, Twomlow S. Coping better with current climatic variability in the rain-fed farming systems of Sub-Saharan Africa: an essential first step in adapting to future climate change? *Agric Ecosyst Environ* 2008, 126:24–35.
198. Diffenbaugh NS, Giorgi F, Raymond L, Bi XQ. Indicators of 21st century socioclimatic exposure. *Proc Natl Acad Sci U S A* 2007, 104:20195–20198.
199. Sakakibara C. "Our home is drowning": inupiat storytelling and climate change in Point Hope, Alaska. *Geogr Rev* 2008, 98:456–475.
200. Sakakibara C. 'No whale, no music': Inupiaq drumming and global warming *Polar Rec* 2009, 45:1–15.
201. Mustonen T, ed. *Stories of the Raven - Snowchange 2005 Conference Report*. Anchorage Alaska Snowchange Cooperative; 2005, 37.
202. Alexander C, Bynum, N., Johnson, L., King, U., Mustonen T, Neofotis P, Oettlé N, Rosenzweig C, Sakakibara C, Vyacheslav S, et al.. Linking indigenous knowledge and observed climate change studies. *Bioscience*. Submitted for publication.
203. Scott J. Elements of a code of ethical conduct for the UN Convention on Biological Diversity. *Personal Communication* 2008.
204. Parmesan C, Duarte C, Poloczanska E, Richardson AJ, Singer MC. Commentary: overstretching attribution. *Nat Clim Change* 2011, 1:2–4.
205. Hoegh-Guldberg O, Hegerl G, Root T, Zwiers F, Stott P, Pierce D, Allen M. Correspondence: difficult but not impossible. *Nat Clim Change* 2011, 1:72–72.
206. Brander K, Bruno J, Hobday A, Schoeman D. Correspondence: the value of attribution. *Nat Clim Change* 2011, 1:70–71.