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ARTICLES

Attributing physical and biological impacts to anthropogenic climate change

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Significant changes in physical and biological systems are occurring on all continents and in most oceans, with a concentration of available data in Europe and North America. Most of these changes are in the direction expected with warming temperature. Here we show that these changes in natural systems since at least 1970 are occurring in regions of observed temperature increases, and that these temperature increases at continental scales cannot be explained by natural climate variations alone. Given the conclusions from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report that most of the observed increase in global average temperatures since the mid-twentieth century is very likely to be due to the observed increase in anthropogenic greenhouse gas concentrations, and furthermore that it is likely that there has been significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica, we conclude that anthropogenic climate change is having a significant impact on physical and biological systems globally and in some continents.

The IPCC Working Group II Fourth Assessment Report found, with very high confidence, that observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases[1,2]. The Working Group II further concluded that a global assessment of data since 1970 shows that anthropogenic warming is likely (66–90% probability of occurrence) to have had a discernible influence on many physical and biological systems. Here we expand this assessment with a larger database of observed changes and extend the attribution from the global to the continental scale using multiple statistical tests. We also consider the part that other driving forces, especially land-use change, might have played at the study locations.

Observed responses to climate change are found across a wide range of systems as well as regions. Changes related to regional warming have been documented primarily in terrestrial biological systems, the cryosphere and hydrologic systems; significant changes related to warming have also been studied in coastal processes, marine and freshwater biological systems, and agriculture and forestry (Fig. 1). In each category, many of the data series are over 35 years in length.

Responses in physical systems include shrinking glaciers in every continent[3,4], melting permafrost[5,6], shifts in the spring peak of river discharge associated with earlier snowmelt[7,8], lake and river warming with effects on thermal stratification, chemistry and freshwater organisms[9–11], and increases in coastal erosion[12–14]. In biological systems, changes include shifts in spring events (for example, leaf unfolding, blooming date, migration and time of reproduction), species distributions and community structure[15–18]. Additionally, studies have demonstrated changes in marine-ecosystem functioning and productivity, including shifts from cold-adapted to warm-adapted communities, phenological changes and alterations in species interactions[19–22].

Detection and attribution in natural systems

Following the definition of attribution of observed changes in the climate system[23], changes in physical and biological systems are attributed to regional climate change based on documented

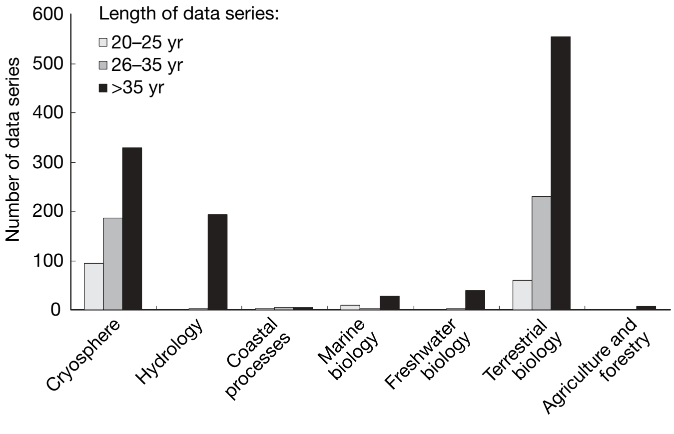

Figure 1 | Data series of observed changes in physical and biological systems. Length of the data series and types of observed changes in physical and biological systems. COST725 data series of terrestrial biological changes (>28,000 European phenological time series[17]) were measured over 30 years (1971–2000; not displayed).

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statistical analyses confirmed by process-level understanding in the interpretation of results. For example, a statistical association between poleward expansion of species' ranges and warming temperatures is expected when temperatures exceed physiological thresholds. The observed changes in both climate and the natural system are demonstrated to be: unlikely to be entirely due to natural variability; consistent with the estimated responses of either physical or biological systems to a given regional climate change; and not consistent with alternative, plausible explanations of the observed change that exclude regional climate change.

Attribution of changes in natural systems to anthropogenic warming requires further analysis because the observed regional climate changes must be attributed to anthropogenic causes. Combining these two types of attribution, called 'joint' attribution[2], has lower statistical confidence than either of the individual attribution steps alone.

One approach to joint attribution, which uses what may be called an 'end-to-end' method, has already been conducted in several studies of specific physical and biological systems. This approach involves linking climate models with process-based or statistical models to simulate changes in natural systems caused by different climate forcing factors, and comparing these directly with observed changes in natural systems. When temperature data from the HadCM3 global climate model were used to examine the likely cause for changes in the timing of spring events of Northern Hemisphere wild animals and plants, results show the strongest agreement when the modelled temperatures were derived from simulations incorporating anthropogenic forcings[24]. Other similar studies have shown that the retreat of two glaciers in Switzerland and Norway cannot be explained by natural variability of climate and glacier mass balance[25], that observed global and Arctic patterns of changes in streamflow are consistent with the response to anthropogenic climate change[26,27], and that the observed increase in the area of forests burned in Canada over the last four decades is consistent with the response caused by anthropogenic climate change[28].

Here we conduct a joint attribution study across multiple physical and biological systems at both the global and the continental scale. We demonstrate statistical consistency of observed changes (which are very unlikely to be caused by natural internal variability of the systems themselves or other driving forces) in natural systems with warming and conduct spatial analyses that show that the agreement between the patterns of observed significant changes in natural systems and temperature changes is very unlikely to be caused by the natural variability of the climate (Supplementary Fig. 1). Combined with the attribution of global and continental-scale warming to anthropogenic climate forcing demonstrated by IPCC Working Group I Fourth Assessment Report, this analysis provides strong support for joint attribution of observed impacts.

Consistency with warming

Based on a database of documented responses in physical and biological systems from 1970 to 2004, temperature-related changes have been observed in all continents. Each documented response is a 'statistically significant' signal that is beyond the natural internal variability of those systems. The largest numbers of entries in the database are for Europe and North America, followed by North Central Asia (Fig. 2). Sparse evidence of responses related to temperature changes exists in Latin America, Africa and Australia. Physical and biological systems in regions without data series may or may not be changing, but are not documented in peer-reviewed literature.

Most (about 90% of the $>$29,500 data series, $P \ll 0.001$) changes in these systems at the global scale have been in the direction expected as a response to warming. Ninety-five per cent of the 829 documented physical changes have been in directions consistent with warming, such as glacier wastage and an earlier spring peak of river discharge. For biological systems, 90% of the $\sim$28,800 documented changes in plants and animals are responding consistently to temperature changes (mostly by means of earlier blooming, leaf unfolding and spring arrival). Warming in oceans, lakes and rivers is also affecting marine and freshwater biological systems (for example, changes in phenology, migration and community composition in algae, plankton and fish).

An evaluation of possible publication bias has been undertaken using comprehensive phenological network data in Europe[29], in which a systematic analysis of all available records (for example, leafing and flowering) documented the percentages of data series that are not changing and of significant changes in both directions (for example, in spring, in 66% there is no significant change, in 31% the onset dates are significantly advanced, and in 3% the onset dates are significantly delayed)[29]. The percentage of data series with significant changes consistent with warming found in Europe ($\sim$90%) is close to that found in North America and Asia, providing an indication that the database may represent an unbiased sample of changes in both directions in those continents.

Spatial analyses at global and continental scales

The IPCC Working Group I Fourth Assessment Report concluded that most of the observed increase in global average temperatures since the mid-twentieth century is very likely ($>$ 90% probability of occurrence) to be due to the observed increase in anthropogenic greenhouse gas concentrations[30]. It is very likely that the observed warming patterns cannot be explained by changes in natural external forcing factors, such as changes in solar irradiance or volcanic aerosols; the latter is likely to have had a cooling influence during this period.

At the global scale, agreement between the pattern of observed changes in physical and biological systems and the pattern of observed temperature change holds for two different gridded temperature data sets and two different pattern-comparison methods, and is exceptionally unlikely ($P \ll 0.01$) to be explained by natural internal climate variability or natural variability of the systems; the latter is determined in the individual studies (Fig. 3). The spatial coherence of temperature trends across the globe is taken into account in these pattern comparisons using more than 3,000 years of climate model simulation data. The prevalence of observed statistically significant changes in physical and biological systems in expected directions consistent with anthropogenic warming in every continent and in most oceans means that anthropogenic climate change is having a discernible effect on physical and biological systems at the global scale.

For the first time, IPCC Working Group I Fourth Assessment Report extended its attribution of temperature trends to the continental scale, concluding that it is likely that there has been significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica[31]. Similarly, a discernible anthropogenic influence is found in changes in natural systems in some continents where there is sufficient spatial coverage of responses in natural systems, including Asia and North America, and marginally in Europe. In these continents, there is a much greater probability of finding coincident significant warming and observed responses in the expected direction. Despite the presence of strong climate variability related to the North Atlantic Oscillation in Europe as well as its relatively small size, which makes it harder to distinguish signal from noise[31], the plethora of evidence allows a signal to be detected, primarily in biological systems. The statistical agreement between the locations and directions of observed significant changes in natural systems and observed significant warming across Asia and North America ($P<0.05$) and across Europe ($P\sim0.1$) is very unlikely to be due to natural variability alone (Fig. 3). Responses not consistent with warming observed in $5^\circ \times 5^\circ$ grid cells with warming temperature may be due to those systems responding to seasonal rather than recorded annual changes or to local cooling not represented in average cell temperatures; biological variation across species may also have a role (for example, late flowering species tend to be less affected by warming than earlier flowering ones). For the other continents, the sparse coverage of observed response studies makes it difficult to separate the observed responses related to anthropogenic temperature rise from those possibly caused by large-scale natural climate variations.

Discussion and conclusions

The wide variety of observed responses to regional climate trends in expected directions combined with the attribution of climate trends to anthropogenic causes at both global and continental scales[30] demonstrates that anthropogenic climate change is already having a significant impact on multiple systems globally and in some continents. Most observed system changes are found in the cryosphere and in terrestrial biological systems and are consistent with the functional understanding and modelled predictions of climate change impacts. The far fewer data series in Africa, Australia and Latin America are closely co-located with warming, but these cannot yet be attributed to anthropogenic climate forcing.

The issues of other climate and non-climate driving forces are important. In considering other drivers of change for phenology, much of the evidence in plants comes from changes observed in the spring. Even though day length can have a modulating effect on spring phenology depending on the plant species, it is not a factor in these studies because species remain *in situ* for the length of the time series, during which day length has not changed. There is also the possibility that increasing CO_2 is directly influencing plant phenology; however, experimental results show no consistent direction of response (that is, an advance or delay)[32]. Concerning trees, older trees tend to unfold leaves in spring later than younger

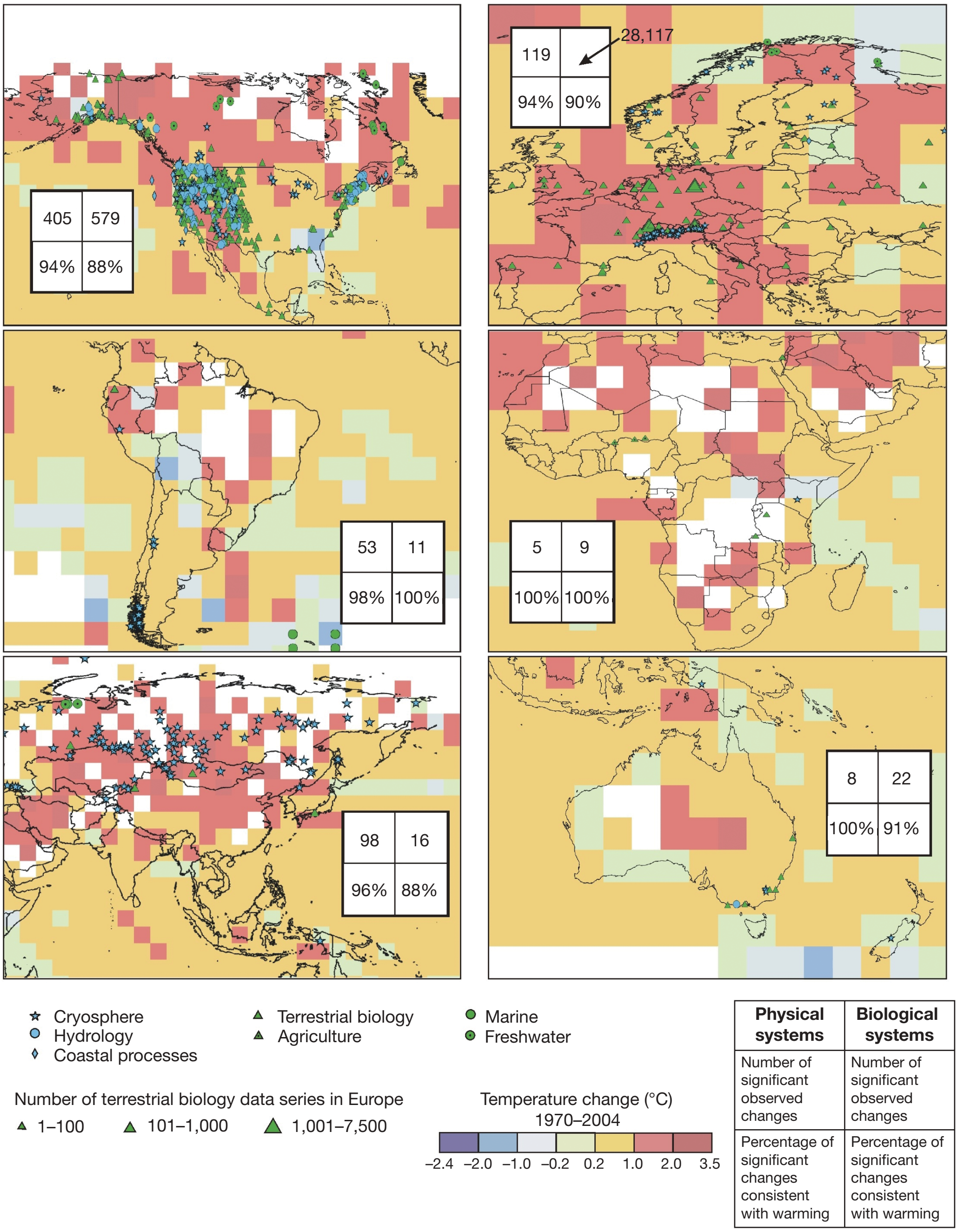

Figure 2 | Location and consistency of observed changes with warming. Locations of significant changes in physical systems (snow, ice and frozen ground as well as hydrology and coastal processes) and biological systems (terrestrial, marine and freshwater biological systems), and linear trends of surface air temperature (HadCRUT3; ref. 35) between 1970 and 2004. Regions are based on data in refs 36 and 37. White areas do not contain sufficient climate data to estimate a trend. Note that there are overlapping symbols in some locations; Africa includes parts of the Middle East.

ones, so with longer time series on one specific object, the onset dates should become later with time owing to ageing, not earlier as observed owing to warming. Finally, some of the plant data, especially in Europe, come from phenological gardens that have been protected from the direct effects of land-use change for decades.

Land-use change, management practices, pollution and human demography shifts are all—along with climate—drivers of environmental change. Explicit consideration of these factors in observed-change studies strengthens the robustness of the conclusions. To determine the role of other driving forces in the data series used in this analysis, we assessed the likelihood of their having a direct effect on the observed system (see Supplementary Table 1). Out of the ~29,500 data series documented in ~80 studies included in the database, effects documented in only 3 studies (9 data series in 4 cells) were likely to have been caused by a driving force other than climate change (for example, habitat destruction, pollution or fishery by-catch disposal). Removing these data series from the statistical analyses does not change the results significantly.

Land-use change can affect physical and biological systems indirectly through its effects on climate. Yet, for recent climate trends on a global scale, the effect of land-use change is small[31]. In addition, because these effects may result in warming in some regions and cooling in others (for example, agricultural expansion tends to warm the Amazon and cool the mid-latitudes)[33,34], they are very unlikely to explain the coherent responses that have been found across the diverse range of systems and across the continental and global scales considered (Supplementary Table 2). Cooling in temperate regions occurs because the clearing of forests for agriculture may increase albedo during periods of snow cover, although recent afforestation may be dampening this effect.

Documentation of observed changes in physical and biological systems in tropical and subtropical regions is still sparse. These areas include Africa, South America, Australia, Southeast Asia, the Indian Ocean and some regions of the Pacific. One reason for this lack of documentation might be that some of these areas do not have pronounced temperature seasons, making events such as the advance of spring phenology less relevant. Other possible reasons for this imbalance are a lack of data and published studies, lag effects in responses, and resilience in systems. Improved observation networks are urgently needed to enhance data sets and to document sensitivity of physical and biological systems to warming in tropical and subtropical regions, where many developing countries are located.

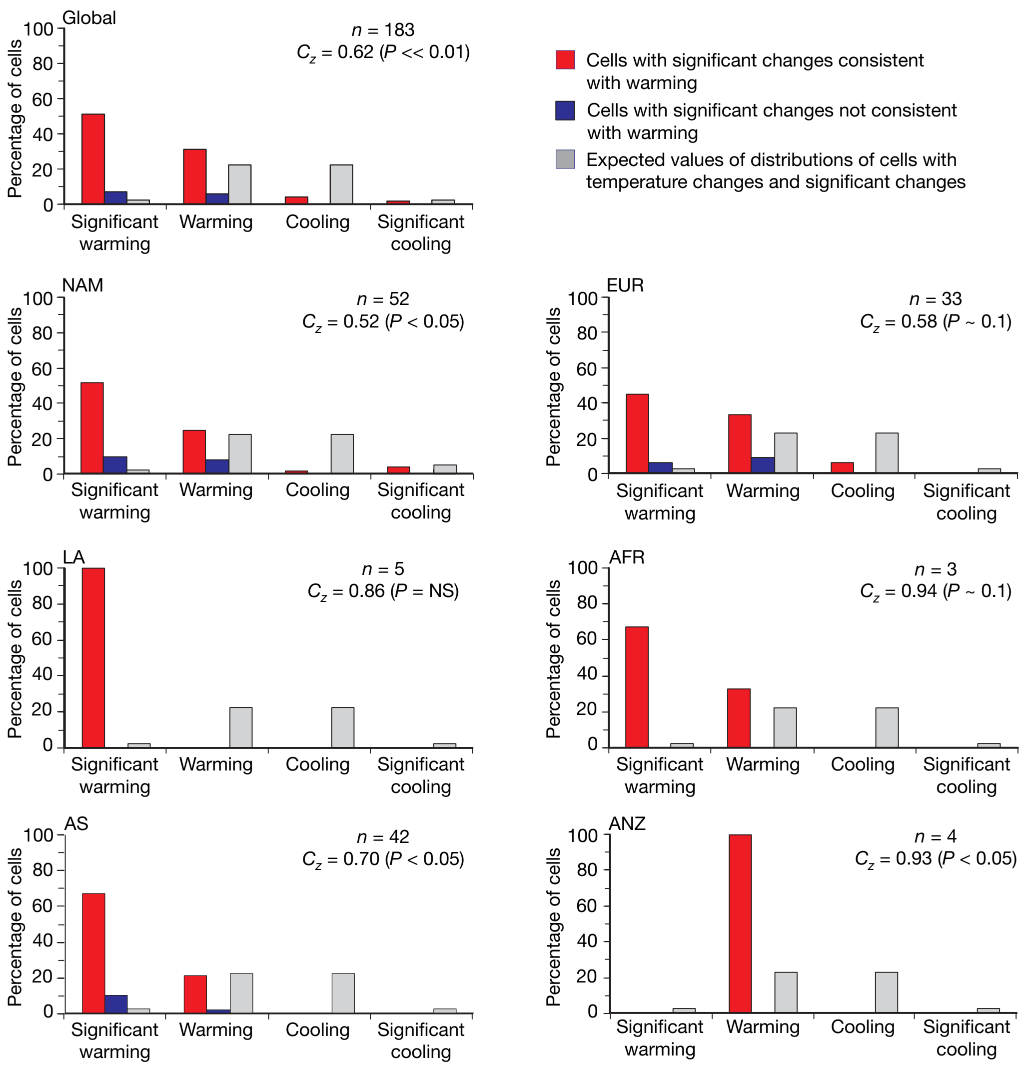

Figure 3 | Distribution of cells with temperature changes and significant observed changes. Expected and observed distributions of cells with significant responses consistent with warming and distributions of cells with significant responses not consistent with warming for 5° × 5° grid cells of temperature change between 1970 and 2004 (HadCRUT3). The global total includes polar regions and marine systems. Shown is the number of cells (n) with observed impacts and temperature data, the pattern congruence between locations of significant responses and standardized temperature trends (C_z), and the probability (P) that pattern agreement could be explained by natural internal variability of temperature fields. Abbreviations: AFR, Africa; ANZ, Australia and New Zealand; AS, Asia; EUR, Europe; LA, Latin America; NAM, North America; NS, not significant.

METHODS SUMMARY

We developed a database of observed changes in natural systems from peer-reviewed papers, demonstrating a statistically significant trend in change in either direction related to temperature and containing data for at least 20 years between 1970 and 2004. Observations in the studies were characterized as a 'change consistent with warming' or a 'change not consistent with warming'. The databases of the observed significant changes in the natural systems were overlaid with two gridded observed temperature data sets and the spatial patterns of the observed system changes were compared with the observed temperature trends using two different pattern-comparison measures.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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1. IPCC in *Climate Change 2007: Impacts, Adapation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds, Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. & Hanson, C. E.) 7–22 (Cambridge Univ. Press, Cambridge, UK, 2007).
2. Rosenzweig, C. *et al.* in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. & Hanson, C. E.) 79–131 (Cambridge Univ. Press, Cambridge, UK, 2007).
3. Dyurgerov, M. B. & Meier, M. F. in *Occasional Paper No. 58* (Institute of Arctic and Alpine Research, Univ. Colorado at Boulder, 2005).
4. Oerlemans, J. Extracting a climate signal from 169 glacier records. *Science* **308,** 675–677 (2005).
5. Frauenfeld, O. W., Zhang, T., Barry, R. G. & Gilichinsky, D. Interdecadal changes in seasonal freeze and thaw depths in Russia. *J. Geophys. Res.* **109,** D05101, doi:10.1029/2003JD004245 (2004).
6. Yoshikawa, K. & Hinzman, L. D. Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska. *Permafrost Periglac. Process.* **14,** 151–160 (2003).
7. Cayan, D. R., Kammerdiener, S. A., Dettinger, M. D., Caprio, J. M. & Peterson, D. H. Changes in the onset of spring in the western United States. *Bull. Am. Meteorol. Soc.* **82,** 399–415 (2001).
8. Mote, P. W., Hamlet, A. F., Clark, M. P. & Lettenmaier, D. P. Declining mountain snowpack in western north America. *Bull. Am. Meteorol. Soc.* **86,** 39–49 (2005).
9. O'Reilly, C. M., Alin, S. R., Plisnier, P. D., Cohen, A. S. & McKee, B. A. Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature* **424,** 766–768 (2003).
10. Sorvari, S., Korhola, A. & Thompson, R. Lake diatom response to recent Arctic warming in Finnish Lapland. *Glob. Change Biol.* **8,** 171–181 (2002).
11. Daufresne, M., Roger, M. C., Capra, H. & Lamouroux, N. Long-term changes within the invertebrate and fish communities of the Upper Rhone River: effects of climatic factors. *Glob. Change Biol.* **10,** 124–140 (2004).
12. Beaulieu, N. & Allard, M. The impact of climate change on an emerging coastline affected by discontinuous permafrost: Manitounuk Strait, northern Quebec. *Can. J. Earth Sci.* **40,** 1393–1404 (2003).
13. Forbes, D. L., Parkes, G. S., Manson, G. K. & Ketch, L. A. Storms and shoreline retreat in the southern Gulf of St. Lawrence. *Mar. Geol.* **210,** 169–204 (2004).
14. Orviku, K., Jaagus, J., Kont, A., Ratas, U. & Rivis, R. Increasing activity of coastal processes associated with climate change in Estonia. *J. Coast. Res.* **19,** 364–375 (2003).
15. Root, T. L. *et al.* Fingerprints of global warming on wild animals and plants. *Nature* **421,** 57–60 (2003).
16. Parmesan, C. & Yohe, G. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421,** 37–42 (2003).
17. Menzel, A. *et al.* European phenological response to climate change matches the warming pattern. *Glob. Change Biol.* **12,** 1969–1976 (2006).
18. Parmesan, C. Ecological and evolutionary responses to recent climate change. *Ann. Rev. Ecol. Evol. System.* **37,** 637–669 (2006).
19. Richardson, A. J. & Schoeman, D. S. Climate impact on plankton ecosystems in the Northeast Atlantic. *Science* **305,** 1609–1612 (2004).
20. Edwards, M. & Richardson, A. J. Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature* **430,** 881–884 (2004).
21. Beaugrand, G. & Reid, P. C. Long-term changes in phytoplankton, zooplankton and salmon related to climate. *Glob. Change Biol.* **9,** 801–817 (2003).
22. Atkinson, A., Siegel, V., Pakhomov, E. & Rothery, P. Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature* **432,** 100–103 (2004).
23. Mitchell, J. F. B. *et al.* in *Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (ed. Houghton, J. T.) 695–738 (Cambridge Univ. Press, Cambridge, UK, 2001).
24. Root, T. L., MacMynowski, D. P., Mastrandrea, M. D. & Schneider, S. H. Human-modified temperatures induce species changes: joint attribution. *Proc. Natl Acad. Sci. USA* **102,** 7465–7469 (2005).
25. Reichert, B. K., Bengtsson, L. & Oerlemans, J. Recent glacier retreat exceeds internal variability. *J. Clim.* **15,** 3069–3081 (2002).
26. Milly, P. C. D., Dunne, K. A. & Vecchia, A. V. Global pattern of trends in streamflow and water availability in a changing climate. *Nature* **438,** 347–350 (2005).
27. Wu, P., Wood, R. & Stott, P. Human influence on increasing Arctic river discharges. *Geophys. Res. Lett.* **32,** L02703 (2005).
28. Gillett, N. P., Weaver, A. J., Zwiers, F. W. & Flannigan, M. D. Detecting the effect of climate change on Canadian forest fires. *Geophys. Res. Lett.* **31,** L18211, doi:10.1029/2004GL020876 (2004).
29. Menzel, A., Sparks, T., Estrella, N. & Roy, D. B. Geographic and temporal variability in phenology. *Glob. Ecol. Biogeogr.* **15,** 498–504 (2006).
30. IPCC 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* (eds Solomon, S. D. *et al.*) (Cambridge Univ. Press, Cambridge, UK, 2007).
31. Hegerl, G. C. *et al.* 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* (eds Solomon, S. *et al.*) 663–745 (Cambridge Univ. Press, Cambridge, UK, 2007).
32. Asshoff, R., Zotz, G. & Korner, C. Growth and phenology of mature temperate forest trees in elevated CO_2. *Glob. Change Biol.* **12,** 848–861 (2006).
33. Feddema, J. *et al.* 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.* **25,** 581–609 (2005).
34. Bounoua, L., DeFries, R., Collatz, G. J., Sellers, P. & Khan, H. Effects of land cover conversion on surface climate. *Clim. Change* **52,** 29–64 (2002).
35. Brohan, P., Kennedy, J. J., Harris, I., Tett, S. F. B. & Jones, P. D. Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *J. Geophys. Res.* **111,** D12106, doi:10.1029/2005JD006548 (2006).
36. Giorgi, F. Variability and trends of sub-continental scale surface climate in the 20th century. Part I: observations. *Clim. Dyn.* **18,** 675–691 (2002).
37. Stott, P. A. Attribution of regional-scale temperature changes to anthropogenic and natural causes. *Geophys. Res. Lett.* **30,** 1728 (2003).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions C.R., D.K., G.C., A.M., T.L.R., B.S., P.N. and M.V. conceived the analytical framework; P.N., M.V., A.M. and N.E. constructed the database; M.V., D.K. and Q.W. performed the statistical analyses; G.C., A.M., T.L.R., P.T., B.S., C.L. and S.R. provided expertise in observed changes in physical and biological systems; and P.N., A.M., C.R. and A.I. analysed other driving forces.

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METHODS

Database of observed changes. We developed a database of observations from peer-reviewed papers (primarily published since the IPCC Third Assessment Report[38]), specifically documenting the data series in terms of system, region, longitude and latitude, dates and duration, statistical significance, type of impact, and whether or not land use was identified as a driving factor (see Supplementary Table 1). Data for the system changes were taken from ~80 studies (of which ~75 are new since the Third Assessment Report) containing >29,500 data series. Studies were selected that demonstrate a statistically significant trend in change in either direction in systems related to temperature or to other climate change variables as described by the authors, and that contain data for at least 20 years between 1970 and 2004 (although study periods may extend earlier or later). Observations in the studies were characterized as a 'change consistent with warming' or a 'change not consistent with warming'.

Spatial analysis. Databases of the observed significant changes in the natural systems and the regional temperature trends over the period 1970–2004 were overlaid in a geographical information system. For Europe, even though there were very large numbers of observed response data series in some cells, these were counted as single cells in the spatial analysis. Two different gridded observed temperature data sets were used: HadCRUT3 (ref. 35) and GHCN-ERSST (ref. 39), both of which were used in the IPCC Fourth Assessment Report. In each $5^\circ \times 5^\circ$ grid cell, the observed system responses were assessed as consistent with warming or not consistent with warming—based on a decision rule of 80% or more of data series consistent with warming within a cell—providing a binary pattern of 183 (HadCRUT3) and 203 (GHCN-ERSST) cells across the globe. There are fewer cells with temperature data in the HadCRUT3 data set because it does not use any infilling of data from adjacent cells, unlike GHCN-ERSST. All cells with observed temperature data are included from each of the data sets, irrespective of the sign of the temperature trend.

The spatial patterns of the observed system changes were compared with the observed temperature trends using two different pattern-comparison measures. To assess the significance of these observed measures of pattern agreement, global temperature trend data were obtained from long control simulations with seven different climate models from the WCRP CMIP3 multi-model database at PCMDI, to represent the range of 35-year temperature trends across the globe resulting from natural climate variations. Details of the different models used are included in Supplementary Table 3. The global temperature trend fields from the climate models represent the spatial coherence and decadal variability of natural internal temperature variations.

Two different pattern-comparison measures were used: a binary pattern congruence (uncentred pattern correlation) between the gridded binary field of system responses consistent (or not consistent) with warming and the gridded field of positive (or negative) temperature trends; and a pattern congruence between the gridded binary field of system responses and the gridded field of standardized temperature trends (the 35-year temperature trends divided by the standard deviation of 35-year temperature trends caused by natural internal climate variations). For each of these measures, the observed values for the two different observed temperature-trend data sets were compared with the distributions obtained using temperature trends caused by natural internal climate variability, as represented by the climate models. Significant attribution was assigned when both spatial statistics methods and both temperature data sets showed significant results. Detailed results are presented in the Supplementary Information and are summarized in the section 'Spatial analyses at global and continental scales' above.

38. IPCC (ed.) *Climate Change 2001: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report to the International Panel on Climate Change* (Cambridge Univ. Press, Cambridge, UK, 2001).
39. Smith, T. M. & Reynolds, R. W. A global merged land and sea surface temperature reconstruction based on historical observations (1880–1997). *J. Clim.* **18,** 2021–2036 (2005).