

The velocity of climate change

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The ranges of plants and animals are moving in response to recent changes in climate¹. As temperatures rise, ecosystems with ‘nowhere to go’, such as mountains, are considered more threatened². However, species survival may depend as much on keeping pace with moving climates as the climate’s ultimate persistence³. Here, we present a new index of the velocity of temperature change (km yr^{-1}), derived from spatial gradients ($^{\circ}\text{C km}^{-1}$) and multimodel ensemble forecasts of rates of temperature increase ($^{\circ}\text{C yr}^{-1}$) in the 21st century. This index represents the instantaneous local velocity along Earth’s surface needed to maintain constant temperatures, and has a global mean of 0.42 km yr^{-1} (A1B emission scenario). Due to topographic effects, the velocity of temperature change is lowest in mountainous biomes such as tropical and subtropical coniferous forests (0.08 km yr^{-1}), temperate coniferous forest, and montane grasslands. Velocities are highest in flooded grasslands (1.26 km yr^{-1}), mangroves, and deserts. High velocities suggest that the climates of only 8% of global protected areas have residence times exceeding 100 years. Small protected areas exacerbate the problem in mediterranean-type and temperate coniferous forest biomes. Large protected areas may mitigate the problem in desert biomes. These results suggest management strategies for minimizing biodiversity loss from climate change. Montane landscapes may effectively shelter many species into the next century. Elsewhere, reduced emissions, a much expanded network of protected areas⁴, or efforts to increase species movement may be necessary⁵.

As climate changes in this century, the current distribution of climatic conditions will be rearranged on the globe; some climates will disappear entirely, and novel (no-analog) climates are expected in wide regions⁶. For species to survive, the persistence of suitable climates is not sufficient. Species must also keep pace with climates as they move⁷. To summarize the speed at which climate is changing, we compute the instantaneous horizontal velocity of temperature change (Fig. 1e) derived from the ratio of temporal (Fig. 1d) and spatial (Fig. 1c) gradients of mean annual near-surface temperature (Fig. 1b) ($^{\circ}\text{C yr}^{-1} \div ^{\circ}\text{C km}^{-1} = \text{km yr}^{-1}$). As exemplified by California, the spatial gradient of temperature change is greatest on mountain slopes (Fig. 1c): modest displacements in space, moving up or down-slope, result in a large change in temperature. As a result, relatively small velocities (Fig. 1e) are required to keep pace with the rate of temperature change (assuming that the climate persists and does not disappear). In contrast, high velocities are required in flatter areas such as California’s Central Valley where large geographic displacements are required to change temperature appreciably.

The magnitude of these results depends on the emissions scenario (Fig. 2a) and also the period of time over which the temporal gradient is calculated (Fig. 2b). However, velocity patterns of global temperature change are similar across scenarios, with the highest velocities in flat landscapes at higher latitudes (Fig. 2c). Using temperature change calculated from 2000-2100 under the intermediate A1B emissions scenario, the geometric mean velocity was $0.42 (0.11-1.46) \text{ km yr}^{-1}$. (Throughout we summarize uncertainty in the mean by listing upper and lower, ± 1 s.d., estimates in parenthesis). (See Supplementary Fig. S17 for other emissions scenarios.) We

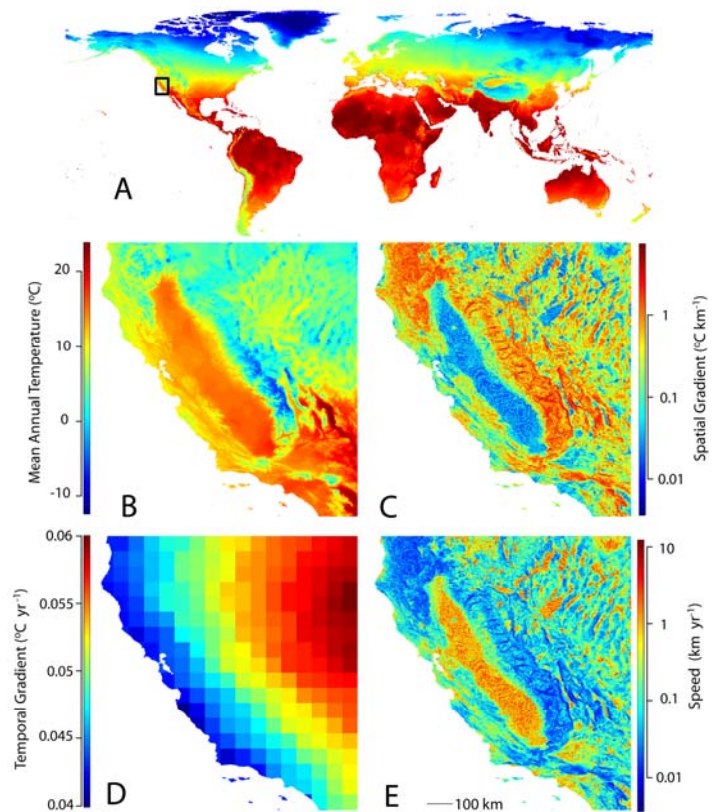


Figure 1 | Changing temperature in California. a, Current (1950-2000) mean annual temperature at 800m resolution. The black rectangle indicates the Central California inset in b. c, The spatial gradient of temperature change using a 9 pixel kernel. d, The temporal gradient of climate change from 2000-2099 from 1/2-degree 16-GCM ensemble projection with A1b emissions. e, The velocity of climate change determined from the quotient of d and c.

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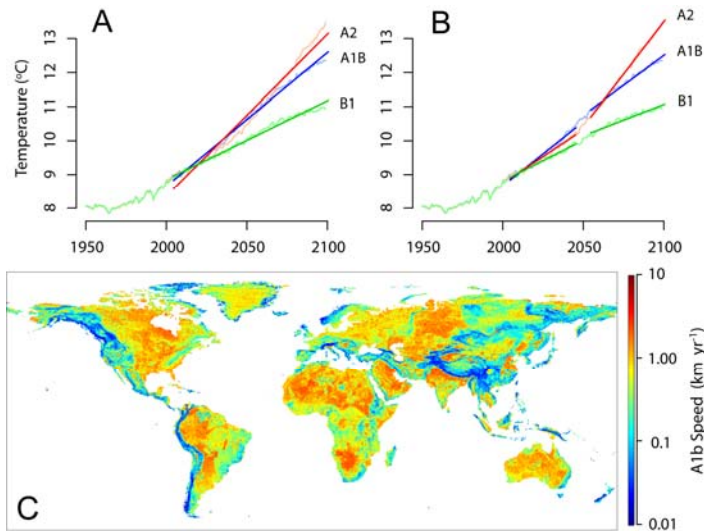


Figure 2 | The velocity of temperature change globally. **a.** Temporal gradients calculated from 2000 through 2100 across three emissions scenarios. **b.** Temporal gradients calculated from 2000 – 2050 and 2050 – 2100 across three emissions scenarios. Trends plotted here are the average of the global land surface. **c.** A global map of climate velocity calculated using the 2050 – 2100 SRES A1B emissions scenario temporal gradient.

summarize velocity for biomes of the globe and rank them by increasing mean velocity (Fig. 3). Doing so reveals that mountainous biomes require the slowest velocities to keep pace with climate change. In contrast, flatter biomes such as flooded grasslands, mangroves, and deserts require much greater velocities. Overall, there is a strong correlation between topographic slope and velocity from temperature change (correlation coefficient = -0.92, see Supplementary Fig. S18).

Land-cover change results in formidable barriers to species movement⁸. Thus, keeping pace with climate change is more feasible within protected areas where landscapes may be less fragmented⁹. The sizes of protected areas vary greatly across biomes (see Supplementary Fig. S20). To explore the interaction between protected area sizes and velocities required to keep pace with climate change, we calculated residence times, defined as the diameter of each protected area divided by velocity ($\text{km} \div \text{km yr}^{-1} = \text{yr}$). Assuming protected areas are circular and disconnected, this index can be interpreted as the time for current climate to cross a protected area. Such residence times exceed 100 years for only 8.02% (2.67 - 16.49%) of protected areas. Fig. 4 summarizes these data by biome, ordered by decreasing residence time. The order of residence times is generally the inverse of velocities, across biomes. For example, the three biomes with the slowest velocities have among the four longest residence times. There are also notable differences. For example, the limited size of protected areas in mediterranean-type, temperate broadleaf and coniferous forest biomes decreases the residence time in these biomes despite relatively low velocities.

The rank of these biomes increased from 4, 7 and 2 to 11, 13 and 8 when arranged by decreasing mean residence time (Fig. 4) as opposed to increasing mean velocity (Fig. 3). In contrast, larger protected areas in other biomes decreased their rank despite high velocities of temperature change. For example, the deserts decreased in rank from 12 to 6.

To guide interpretation of these results, we make three clarifications. First, climate change involves complex interactions among temperature, precipitation, and seasonal and historic variability. We focus on mean annual temperature for several reasons. Mean annual temperature is a useful summary of both historic and projected climate change. The direction and magnitude of temperature change is much less uncertain than precipitation change¹⁰. Growing numbers of examples document the latitudes and elevations of species distributions responding as expected to changing temperatures^{11,12}. We repeated all analyses with precipitation (see Supplementary Fig. S19). Interestingly, precipitation spatial gradients are also greatest in mountainous areas due to the influence of rain shadows and orographic effects. As a result the mean velocity, 0.22 (0.08 - 1.90) km yr^{-1} , and overall patterns are similar to those derived by temperature.

Second, there is uncertainty in both the spatial and temporal gradients of climate change. We estimated uncertainty in both of these contributing factors and propagated them through to lower and upper estimates of velocity and residence time (see Supplementary Material). Additionally, we note the instantaneous velocity is sensitive to the grain of the analysis and the size of the kernels used to compute spatial and temporal gradients¹³. Throughout this study, we use a ~ 1 km spatial grain size, the finest available for global mean annual temperature, and a 9 grid cell spatial kernel, standard for creating gridded slopes from digital elevation models. We chose the fine spatial grain because both yearly dispersal capabilities for many species and large temperature changes often occur on the order of a few kilometres. In some cases, even finer resolution responses on the scale of meters may be sufficient to offset climate change as populations move from south to north facing slopes within a habitat¹⁴.

Third, our index estimates the velocities and residence times of climates, not species. We make no assumptions about the tolerances of individual species. Implications for individual species depend on the breadth of tolerance¹², and our velocities apply to range edges, ecotones¹⁵, and other features that reflect climate isoclines. For species with small tolerances, the velocity estimates closely approximate migration speeds required to potentially avoid extinction. For species with large tolerances, the residence times are underestimates. We also note that species do not move at constant rates¹⁶ and, in some instances, the velocity of movements downhill may differ from those uphill; similarly leading edge expansion and trailing edge contraction will be different, reflecting the contrasting mechanisms. As a result of these caveats, we interpret these velocities as a relative

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index of the speeds required to keep pace with climate change rather than a calibrated index of migration rates.

It is, however, interesting to compare the magnitude and spatial patterns of the velocities with migration rate studies. Malcolm et al.¹⁷ calculated the minimum distances between modelled current and future biomes from two Global Vegetation Models (GVM) and interpreted them as necessary speeds for species migration. The study used similar emissions and temporal scales, a much coarser spatial grain (0.5-degrees), and projections from an older generation of global climate models than those explored here. Accounting for uncertainty, the probability density function of our velocities are the same as those found by Malcolm et al.¹⁷. For example, we calculated 28.8 (0.5-66.9) % of the globe had migration rates greater than 1 km yr⁻¹ compared with 17.4% and 21.1% from the two GVM's used by Malcolm et al.¹⁷. These similarities are interesting given the many differences in the approaches used to explore migration rates. (See supplementary material for further comparisons.)

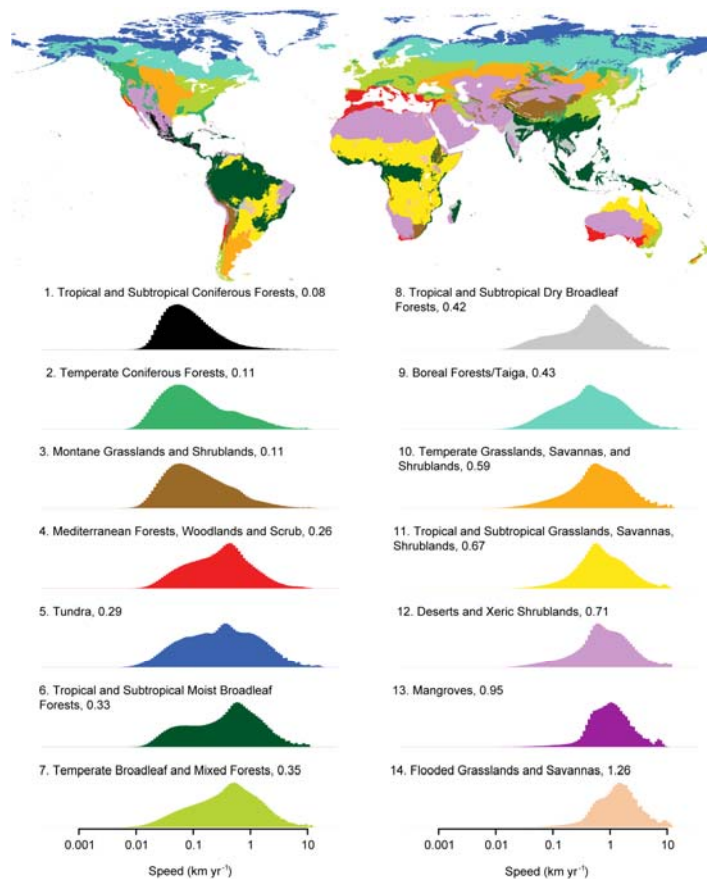


Figure 3| The velocity of temperature change by biome. A map of biomes and histograms of the speed of temperature change within each biome. Histograms are ordered by increasing velocity according to their geometric means.

in Europe and North America⁷. The apparent paradox of such a fast migration rate relative to the limitations on plant dispersal¹⁸ is possible via rare long-distance migration events¹⁹ or high latitude refugia reseeding the landscape²⁰. The latter means that post-glacial re-colonization velocities may have been as much as an order of magnitude slower than previously thought (~0.1 km yr⁻¹).

We project that large areas of the globe (28.8%) will require velocities faster than the more optimistic plant migration estimates from a landscape before anthropogenic fragmentation. Velocities on montane landscapes, in contrast, may fall within historic rates. The ability of complex topography to provide a spatial buffer for climate change has been recognized qualitatively²¹ and evaluated over small geographic areas²², but was muted in previous, coarser scale global analyses¹⁷. Considering these factors adds an important dimension to management strategies for addressing climate change, highlighting the greater vulnerability of large, extensive areas such as the lowland tropics and desert regions. In landscapes where small velocities are required, moderate sized protected areas may be able to contain moving climates and ecosystems. Elsewhere, additional steps must be taken. These include slowing

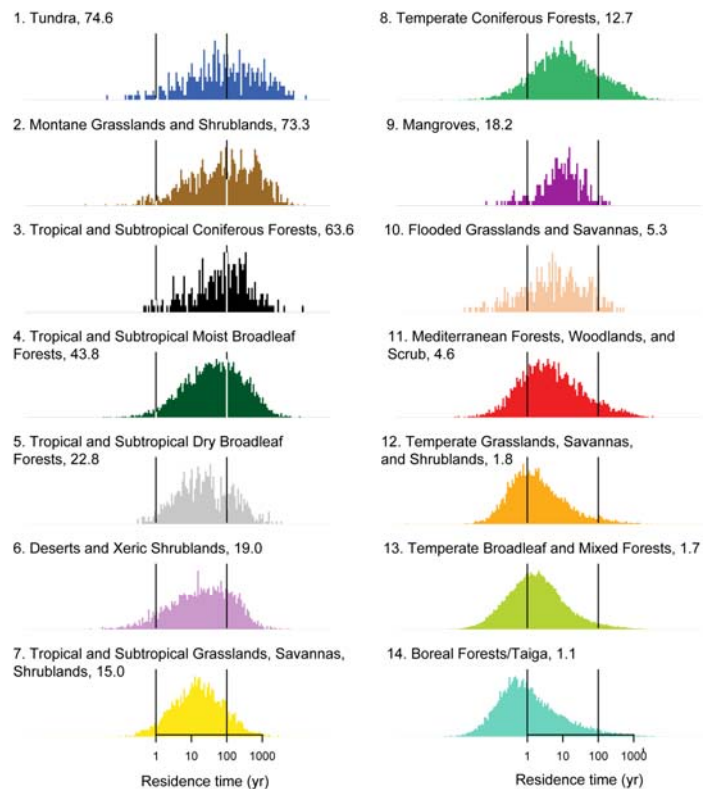


Figure 4| Climate residence time (yr) in protected areas. Histograms represent the ratio of protected area diameter (km) to climate velocity (km/hr), and are ordered by decreasing mean residence time across biomes. The vertical bar indicates 1 and 100 years.

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the temporal gradient of climate change through reduced emissions, increasing the ability of plants and animals to disperse through managed relocation⁵, or increasing the size of protected areas through habitat corridors and new reserves⁴

Methods Summary

Detailed methods are in the supplemental materials. In brief, for current climate, we used the 30-arcsec WorldClim Version 1.4 Annual Mean Temperature and Total Annual Precipitation bioclimatic variable²³. Spatial gradients were calculated from a 3-by-3 grid cell neighbourhood using the average maximum technique²⁴ modified to accommodate different cell-widths at different latitudes. Future temperature projections for each emissions scenario were averages of 16 global climate models statistically downscaled to 0.5-degrees²⁵. We computed temporal gradients as the slope of a linear model fit through each year of the time period of interest. Velocity is the ratio of the temporal gradient to the spatial gradient, and log transformed for visualization due to a highly skewed distribution. We report geometric means of the velocity to accommodate this skew. We compiled biomes from the World Wildlife Fund Terrestrial Ecoregions²⁶ and protected areas from the World Database on Protected Areas (WDPA) Annual Release 2009 (web download version), February 2009. For each protected area centroid we sampled the velocity and biome to compare with estimates of reserve diameter. We discuss precipitation and uncertainty propagation in the supplementary material.

References

- 1 **Parmesan, C. and Yohe, G., *Nature* 421, 37 (2003).**
- 2 **Nogues-Bravo, D., Araujo, M. B., Errea, M. P., and Martinez-Rica, J. P., *Global Environmental Change* 17 (3-4), 420 (2007); Colwell, R. K. et al., *Science* 322 (5899), 258 (2008).**
- 3 **Thuiller, W. et al., *Proceedings of the National Academy of Sciences* 102 (23), 8245 (2005); Loarie, S. R. et al., *PLoS One* 3 (6) (2008).**
- 4 **Hannah, L., *Annals of the New York Academy of Sciences* 1134 (1 The Year in Ecology and Conservation Biology 2008), 201 (2008).**
- 5 **Hoegh-Guldberg, O. et al., *Science* 321 (5887), 345 (2008).**
- 6 **Williams, J. W., Jackson, S. T., and Kutzbach, J. E., *Proceedings of the National Academy of Sciences* 104 (14), 5738 (2007).**
- 7 **Pearson, R. G., *Trends in Ecology & Evolution* 21 (3), 111 (2006).**

8 **Damschen, E. I. et al., (American Association for the Advancement of Science, 2006), Vol. 313, pp. 1284.**

9 **Joppa, L. N., Loarie, S. R., and Pimm, S. L., *Proceedings of the National Academy of Sciences* 105 (18), 6673 (2008).**

10 **Murphy, J. M. et al., *Nature* 430, 768 (2004).**

11 **Moritz, C. et al., *Science* 322 (5899), 261 (2008); Kelly, A. E. and Goulden, M. L., *Proceedings of the National Academy of Sciences* 105 (33), 11823 (2008); Lenoir, J. et al., *Science* 320 (5884), 1768 (2008).**

12 **Parmesan, C., *Annu. Rev. Ecol. Evol. Syst* 37, 637 (2006).**

13 **Trivedi, M. R., Berry, P. M., Morecroft, M. D., and Dawson, T. P., *Global Change Biology* 14 (5), 1089 (2008).**

14 **Weiss, S. B., Murphy, D. D., and White, R. R., *Ecology*, 1486 (1988).**

15 **Beckage, B. et al., *Proceedings of the National Academy of Sciences* 105 (11), 4197 (2008).**

16 **Van Houtan, K. S. et al., *Ecology Letters* 10 (3), 219 (2007).**

17 **Malcolm, J. R., Markham, A., Neilson, R. P., and Garaci, M., *Journal of Biogeography* 29, 835 (2002).**

18 **Clark, J. S. et al., *BioScience*, 13 (1998).**

19 **Clark, J. S., *The American Naturalist* 152 (2), 204 (1998).**

20 **McLachlan, J. S., Clark, J. S., and Manos, P. S., *Ecology* 86 (8), 2088 (2005).**

21 **Peterson, D. L., Schreiner, E. G., and Buckingham, N. M., *Global Ecology and Biogeography Letters*, 7 (1997).**

22 **Peterson, A. T., *Global Change Biology* 9 (5), 647 (2003).**

23 **Hijmans, R. J. et al., *International Journal of Climatology* 25 (15) (2005).**

24 **Burrough, P. A. and McDonnell, R. A., (Oxford University Press, Oxford, UK, 1998).**

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²⁵ Maurer, E. P., Adam, J. C., and Wood, A. W., *Hydrol. Earth Syst. Sci.* 13 (2), 183 (2009).

²⁶ Olson, D. M. et al., *BioScience* 51 (11), 933 (2001).

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Author Contribution Statement

D.D.A. conceived the study. S.R.L., D.D.A., P.B.D., H.H. and C.B.F. designed the study. S.R.L., P.B.D. and G.P.A. performed the analysis. S.R.L., D.D.A., P.B.D., C.B.F., H.H., and G.P.A. wrote the paper.

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