

Projected distributions of novel and disappearing climates by 2100 AD

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Key risks associated with projected climate trends for the 21st century include the prospects of future climate states with no current analog and the disappearance of some extant climates. Because climate is a primary control on species distributions and ecosystem processes, novel 21st-century climates may promote formation of novel species associations and other ecological surprises, whereas the disappearance of some extant climates increases risk of extinction for species with narrow geographic or climatic distributions and disruption of existing communities. Here we analyze multimodel ensembles for the A2 and B1 emission scenarios produced for the fourth assessment report of the Intergovernmental Panel on Climate Change, with the goal of identifying regions projected to experience (i) high magnitudes of local climate change, (ii) development of novel 21st-century climates, and/or (iii) the disappearance of extant climates. Novel climates are projected to develop primarily in the tropics and subtropics, whereas disappearing climates are concentrated in tropical montane regions and the poleward portions of continents. Under the high-end A2 scenario, 12–39% and 10–48% of the Earth's terrestrial surface may respectively experience novel and disappearing climates by 2100 AD. Corresponding projections for the low-end B1 scenario are 4–20% and 4–20%. Dispersal limitations increase the risk that species will experience the loss of extant climates or the occurrence of novel climates. There is a close correspondence between regions with globally disappearing climates and previously identified biodiversity hotspots; for these regions, standard conservation solutions (e.g., assisted migration and networked reserves) may be insufficient to preserve biodiversity.

biodiversity hotspots | climate change | dispersal limitations | global-change ecology | ecological surprises

By the end of the 21st century, large portions of the Earth's surface may experience climates not found at present, and some 20th-century climates may disappear. The combination of high CO₂ concentrations, still-extensive ice sheets in Greenland and Antarctica, and current orbital and land–ocean configurations are geologically unprecedented (1). Already, CO₂ concentrations exceed any recorded for the last 650,000 years (2) and, without a substantive intervention, are projected to increase to 540–970 ppm (140–263% relative to 2000 levels) by 2100 AD (3). Global mean temperatures are projected to increase by 1.4–5.8°C by 2100 AD (3), with decreases in diurnal and seasonal temperature ranges (4) and spatially variable changes in precipitation. It is increasingly likely that some end-21st-century climates will include conditions not experienced at present (“novel” climates) and that some present climates may disappear. Here we statistically analyze 21st-century climate scenarios to map global risk surfaces for the occurrence of future novel and disappearing climates and discuss likely ecological impacts.

Climate is a primary constraint on species distributions and ecosystem function, and ecologists are faced with the challenge of forecasting species range shifts, extinction risks, biome shifts, altered disturbance regimes, biogeochemical cycling, and other ecological responses to climate change (5–7). Such forecasts are

impeded by the difficulty of predicting ecological responses to environmental conditions outside the range of current experience. Niche theory predicts that multivariate changes in climate should cause shifts in species distributions, disruption of extant communities, and formation of novel species associations (8–10), because each species responds individually (Fig. 1). This conceptual framework is reinforced by observed ecological responses to the last deglaciation, which were characterized by large changes in species ranges, and, in places where past climates apparently lacked modern analogs, the development of species associations and biomes with no modern counterpart (11–13). Metaanalyses indicate already detectable responses to 20th-century temperature rises, with range shifts averaging 6.1 km per decade toward the poles (14, 15). Dispersal limitations may cause species responses to lag rapid climate change, promoting the formation of disequilibrium relationships between species distributions and climate. Others have argued that future novel climates may cause a reshuffling of communities (10, 12); however, our study attempts to move beyond generalities by explicitly mapping the future distribution of novel climates.

Conversely, species endemic to certain climates are at risk of extinction if those climates disappear, and communities in those regions may disaggregate or disappear (Fig. 1) (8). High-elevation and high-latitude species, for example, may go extinct as temperature or moisture changes drive vegetation zones upward and poleward (16–19). Rapid changes further enhance extinction risk by increasing the rate of climate change relative to the capacity of species to adjust by migration and colonization (8, 20).

Using model ensembles drawn from Intergovernmental Panel on Climate Change (IPCC) Assessment Report 4, we here calculate three indices of climatic risk: (i) local standardized climatic change, (ii) the climatic distance between the end-21st-century simulation for each gridpoint and its closest analog from the global pool of 20th-century climates (an index of the novelty of future climates), and (iii) the climatic distance between the 20th-century realization for each gridpoint and its closest 21st-century climatic analog (an index of the disappearance of extant climates). All three indices are based on the same metric of multivariate dissimilarity, and temporal differences are given context by comparing them against the multivariate differences in climate among modern potential biomes (see *Materials and Methods*). We use two nonmitigation emission scenarios, IPCC Special Report on Emissions Scenarios (SRES) A2 and B1, to span the range of IPCC emission scenarios (3). Finally, we

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Abbreviations: IPCC, Intergovernmental Panel on Climate Change; SED, standardized Euclidean distance.

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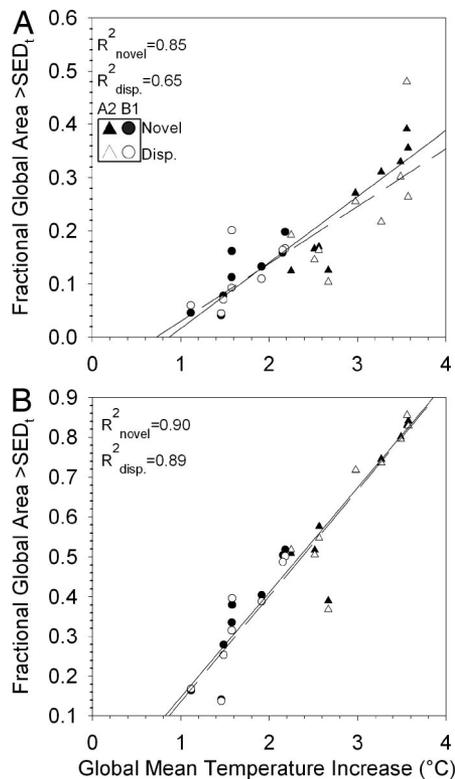


Fig. 4. Plots showing the relationship between global mean annual warming and the fractional global area with novel and disappearing climates. Each point represents an individual model; triangles represent A2 simulations, and circles represent B1 simulations. Filled symbols and the solid regression line represent risk indices for novel climates (corresponding to Figs. 2 C and D and 3 A and B); open circles and the dashed line represent risk indices for disappearing climates (corresponding to Figs. 2 E and F and 3 C and D). A2 and B1 scenarios are pooled for the regression model. (A) Search for climatic analogs is global (no dispersal constraint). (B) Search for analogs restricted to within 500 km (500-km dispersal constraint).

of climate change, e.g., by establishing dynamic networks of connected reserves that can facilitate species migrations (19) or “re-wilding” or otherwise assisting species migrations (29), may help overcome dispersal limitations. However, for those regions, communities, and species whose 20th-century climates lack 21st-century analogs anywhere globally (Fig. 2 E and F), such approaches will be insufficient. Furthermore, because of the spatial segregation between novel and disappearing climates (Fig. 2), species at risk of extinction due to disappearing climates are unlikely to be well positioned to take advantage of new climatic regimes.

No single analysis can capture all ecological risks associated with climate change, e.g., shifts in ecosystem risks distributions, changes in carbon sequestration, altered hydrological functioning, and increased fire frequency (e.g., refs. 7 and 30), so a variety is needed to capture the multidimensional responses of species and ecosystems to multidimensional climate change. Moreover, climate change is just one of many current ecological stressors. Interspecific differences in response time to the rapid pace of projected 21st-century climate change will also promote the formation of novel species assemblages and extinction risk (9). These factors, together with the projected development of novel climates and the threat that the climates particular to some biodiversity hotspots may disappear globally, create the strong likelihood that many future species associations and landscapes will lack modern analogs and that many current species and associations will be disrupted or disappear entirely.

Materials and Methods

We use a nine-model ensemble for the A2 scenario (856 ppm pCO₂ by 2100 AD) (3) and an eight-model ensemble for the B1 scenario (549 ppm pCO₂) [supporting information (SI) Table 1]. Each global climate model is represented by a single realization per scenario, chosen at random when multiple realizations were available. The equilibrium climate sensitivity of these models to CO₂ doubling is 2.1–4.4°C, with seven models between 2.7°C and 3.1°C (www.pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php). All simulations were bilinearly interpolated to a common T42 grid (≈2.8° × 2.8° resolution), the median resolution for the models used here.

After interpolation, we quantified dissimilarities between 20th- and 21st-century climates by using the standardized Euclidean distance (SED) (31):

$$SED_{ij} = \sqrt{\sum_{k=1}^4 \frac{(b_{ki} - a_{kj})^2}{s_{kj}^2}}, \quad [1]$$

where a_{ki} and b_{kj} are the 1980–1999 and 2080–2099 means for climate variable k at gridpoints i and j and s_{kj} is the standard deviation of the interannual variability for 1980–1999. Effects of climate model bias are minimized by comparing simulated end-20th- to end-21st-century climates. For local climate change, $i = j$. The SED equally weights all variables and emphasizes 21st-century trends that are large relative to 1980–1999 interannual variability. SED scores are first calculated for each global climate model and then averaged into the ensembles reported here.

Four climate variables are used: mean surface air temperature and precipitation for June–August (JJA) and December–February (DJF). These variables were chosen because (i) they represent controls of seasonal temperature and moisture availability on plant distributions and abundance (32), (ii) seasonal means are robust features of model simulations, and (iii) they are compatible with prior work linking the occurrence of past no-analog plant communities (12) to no-analog climates (11). These variables correlate well with other proposed bioclimatic controls on species distributions (e.g., growing degree days, actual and potential transpiration, and minimum and maximum annual temperature) (33, 34). For example, linear regression models using 1961–1990 mean monthly data from the Climate Research Unit TS2.1 data set (35) and the explanatory variables JJA temperature (TJJA) and DJF temperature (TDJF) explain 93% of the global variance growing degree days. Similarly, linear models using TJJA, TDJF, JJA precipitation (PJJA), and DJF precipitation (PDJF) explain 45% of the global variance in the moisture index α , calculated as the ratio of actual to potential evapotranspiration (32). We opted not to include metrics of 21st-century variability or the frequency of extreme events because projected trends in 21st-century climate variability are more uncertain than changes in means.

Local climate change is measured as the SED between 20th- and 21st-century realizations for each gridpoint (Fig. 2 A and B). High SED scores correspond to larger local climate change and integrate changes in temperature and precipitation. Novel terrestrial climates are identified by comparing the 21st-century climate realization for each land gridpoint to the 20th-century climate realizations for all land gridpoints and retaining the minimum SED (SED_{\min}). SED_{\min} will be equal to or less than the indices of local climate change (Fig. 2, compare A and B with C and D). The pool of potential climatic analogs is global, so that high SED_{\min} indicate 21st-century climates with no good analog anywhere in 20th-century climate space (Fig. 2 C and D). Conversely, disappearing climates are identified by comparing each 20th-century gridpoint to all 21st-century climate realiza-

tions and retaining the SED_{\min} . High SED_{\min} here indicate places where 20th-century climates may disappear; i.e., they have no close counterpart anywhere in the 21st-century simulations (Fig. 2 E and F).

Although the SED scores usefully summarize multivariate changes in climate, assessing their ecological significance requires placing them in context against known ecological phenomena. We calculate an SED threshold (SED_t) that determines when an SED value is large enough to represent a truly novel climate. A 21st-century gridpoint is defined as novel if its SED_{\min} exceeds the threshold. Similarly, a 20th-century climate disappears if its SED_{\min} exceeds the threshold.

SED_t is determined by overlaying a global potential vegetation map (36) onto 20th-century climatologies and identifying the SED_t that optimally discriminates between pairs of climate vectors from the same biome vs. pairs of biomes from different biomes (31). SED_t is calculated individually for each biome and then averaged across all biomes (*SI Materials and Methods and SI Table 2*); here we use $SED_t = 3.22$, and in *SI Materials and Methods*, we experiment with a higher threshold ($SED_t = 5.33$) (*SI Figs. 5–7*). Biomes are global-scale ecosystems whose distributions are climatically controlled (32, 37), making them well suited for determining whether a particular level of climate change (as represented by SED scores) is ecologically significant. SED_t thus represents a temporal climatic change equivalent to the spatial difference in climates among extant biomes, and is a conservative estimator of the extent of novel and disappearing climates. This is because all locations from finer-scale ecological entities tend to have fairly similar climates, and so SED_t will be

low, whereas biomes encompass a wider range of climates, and so SED_t will be high. Thus, the climatic differences among biomes are large relative to the climatic differences among finer-scale ecological phenomena, so that a “biome-scale” climate change likely will be significant for finer-scale ecological entities.

Close climatic similarities between geographically distant locations are not relevant for species constrained by dispersal limitations. We therefore conducted a second set of analyses in which the potential pool of climatic analogs is restricted to locations within 500 km (Fig. 3). The 500-km radius is intentionally large [exceeding the highest known rates of plant migration during the last deglaciation (≈ 200 km per century) (38)], because larger radii produce more conservative identifications of novel and disappearing climates. This analysis affects only the predicted distribution of novel and disappearing climates (Fig. 2 C–F), not local change (Fig. 2 A and B).

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