

Climate velocity in inland standing waters

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12
13 **First paragraph:** Inland standing waters are particularly vulnerable to increasing water
14 temperature. Here, using a high-resolution numerical model, we find that the velocity of
15 climate change in the surface of inland standing waters globally was 3.5 ± 2.3 km decade⁻¹ from
16 1861-2005, which is similar to, or lower than, rates of active dispersal of some motile species.
17 However, from 2006-2099, the velocity of climate change will increase to 8.7 ± 5.5 km decade⁻¹
18 ¹ under a low emission pathway (RCP 2.6) and 57.0 ± 17.0 km decade⁻¹ under a high emission
19 pathway (RCP 8.5), meaning that thermal habitat in inland standing waters will move faster
20 than the ability of some species to disperse to cooler areas. The fragmented distribution of
21 standing waters in a landscape will restrict redistribution, even for species with a high dispersal
22 ability, so that the negative consequences of rapid warming for freshwater species are likely to
23 be much greater than for terrestrial and marine realms.

24
25 **Main Text:** Inland standing waters hold a large majority of the Earth's liquid surface fresh
26 water, support important biodiversity, and provide key ecosystem services to people around
27 the world¹. Yet, standing waters are highly vulnerable to climate change. Some of the most
28 pervasive and concerning consequences of climatic change on standing waters are the direct
29 and indirect effects of rising water temperature². This temperature increase can influence
30 physical structure, rates of processes and species composition^{5,6} and, in turn, temperature can
31 strongly influence the distribution and abundance of freshwater species across the globe⁷.
32 However, within a lake or reservoir, temperature varies seasonally⁸, horizontally⁹ and often
33 vertically in those that are deep enough to stratify^{10,11}. As standing waters warm over time,
34 aquatic communities may have to disperse to track thermally suitable habitats⁴. A critical step
35 in the understanding of climate change impacts on aquatic ecosystems is therefore to describe
36 the speed at which their thermal environment is changing, often referred to as the velocity of
37 climate change, i.e., the distance at which isotherms shift over time³. The velocity of climate
38 change has been studied extensively in marine and terrestrial ecosystems^{12,13}, but has not yet
39 been investigated in standing waters globally, despite the vulnerability of freshwater species to
40 direct and indirect thermal alterations associated with warming¹⁴.

41
42 The velocity of climate change (km decade⁻¹) is calculated as the quotient of the long-term
43 temperature trend (°C decade⁻¹) to the two-dimensional spatial gradient in temperature (°C km⁻¹)

44 ¹). In this study, we calculated the distribution of the historic velocity of climate change in the
45 surface of inland standing waters worldwide using surface temperatures from a new state-of-
46 the-art global reanalysis from the European Centre for Medium-Range Weather Forecasts
47 (ECMWF), ERA5, on a 0.25°-by-0.25° grid (see Supplementary Material). Inland water
48 temperature within ERA5 is simulated via the Freshwater Lake model, FLake, which is
49 embedded as a tile in the Tiled ECMWF Scheme for Surface Exchanges over Land
50 incorporating land surface hydrology (HTESSEL). The FLake model has been extensively
51 validated here (Extended Data Fig. 1) and in simulations of the surface temperature of inland
52 waters globally and has been used to quantify worldwide aspects of inland water thermal
53 dynamics such as seasonal cycles⁸, onset of summer stratification⁵, and mixing dynamics⁹.

54
55 Our study demonstrates that over a period of 40 years (1979-2018), the annual surface
56 temperature of inland standing waters has increased in 99% of the surface grid-cells analyzed,
57 although there were substantial regional variations in magnitude (Fig. 1a). Worldwide, the
58 median rate of warming in inland standing waters was 0.13 °C decade⁻¹ (Fig. 1a). Our computed
59 trends are similar to those calculated in previous studies which have demonstrated that the vast
60 majority of lakes worldwide are warming², despite differences in the seasonal extent of the data
61 (all year vs summer) or the range of years analysed. Across inland standing waters, the median
62 spatial gradient in temperature was 0.009 °C km⁻¹ (Fig. 1b) and it was greater in regions with
63 large elevation gradients, such as in the European Alps (Extended Data Figs 2-3). When the
64 rate of warming is combined with the spatial gradient in temperature, the resulting median
65 velocity of climate change across standing waters worldwide was 13.94 km decade⁻¹ during
66 1979-2018 (Fig. 1c). As a result of higher increases in surface temperatures and a lower spatial
67 gradient, the velocity of climate change is greater at mid- to high-latitude (Fig. 1d) and in
68 regions with low gradients in elevation (Extended Data Figs 2, 4).

69
70 We compared the velocity of climate change in inland standing waters from 1979 to 2018 to
71 those calculated for marine and terrestrial ecosystems^{3, 12} by applying the same climate velocity
72 algorithm to surface air temperatures over land and sea surface temperatures, both of which are
73 available from ERA5. We find that the velocity of climate change in inland standing waters
74 was comparable to that calculated for surface air temperatures over land (13.76 km decade⁻¹),
75 despite the median rate of warming in the latter being twice as fast (0.26 vs 0.13 °C decade⁻¹)
76 (Fig. 2). The velocity of climate change in the ocean (26.84 km decade⁻¹), as calculated from
77 sea surface temperatures, was higher than in standing waters and over land, because of the
78 smaller spatial temperature gradient (0.003 °C km⁻¹). The spatial temperature gradient in the
79 ocean was a third of the spatial temperature gradient in standing waters (0.009 °C km⁻¹) and
80 nearly a sixth of that over land (0.017 °C km⁻¹). The velocity of climate change in the ocean is
81 much less variable than in inland waters or on land (Fig. 2e) with small gradients punctuated
82 by sharp thermal boundaries (e.g., see the Gulf Stream). Areas of high velocity extend across
83 larger regions in the ocean compared to the other ecosystems.

84
85 The climate velocities for inland standing waters calculated from ERA5 cannot be extended
86 into the future, as the ERA5 temperatures are produced in near real-time as an operational
87 forecast. To project future changes in climate velocities, a different approach is required. In

88 this study, we simulate the velocity of climate change during the 21st century using the same
89 water temperature model as used in ERA5 during 1979-2018 (i.e., FLake), but now force the
90 model with bias-corrected climate projections from four global climate models: MIROC5,
91 IPSL-CM5A-LR, GFDL-ESM2M and HadGEM2-ES (see Supplementary Material), on a 0.5°-
92 by-0.5° grid. These climate models contributed to phase 5 of the Coupled Model
93 Intercomparison Project (CMIP5) and were bias-corrected within the Inter-Sectoral Impact
94 Model Intercomparison Project (ISIMIP2b). Contemporary to future projections (2006 – 2099)
95 for low, medium and high Representative Concentration Pathway (RCP) scenarios are
96 investigated: RCP 2.6, 6.0 and 8.5 respectively (Fig. 3). For comparison, and to extend the
97 record back in time, we also calculate the velocity of climate change from 1861-2005, where
98 the historic climate simulations were forced using anthropogenic greenhouse gas and aerosol
99 forcing in addition to natural forcing.

100

101 The magnitude of surface air temperature change, which is one of the dominant drivers of
102 surface warming in standing waters, increases considerably during the 21st century, with the
103 magnitude of change increasing from RCP 2.6 to 6.0 to 8.5 (Extended Data Fig. 5). Our
104 simulations demonstrate that the surface temperature of global standing waters will also
105 increase during the 21st century (Fig. 3a). Specifically, under RCP 2.6, 6.0, and 8.5, surface
106 water temperature trends will accelerate to 0.06 ± 0.04 °C decade⁻¹ (quoted uncertainties
107 represent the standard deviation from the lake model driven by all four climate model
108 projections), 0.23 ± 0.07 °C decade⁻¹, and 0.40 ± 0.12 °C decade⁻¹, respectively (Fig. 3b) from
109 2006 to 2099, compared to 0.03 ± 0.02 °C decade⁻¹ from 1861-2005. Note that the temperature
110 trend calculated from 1861-2005 is lower than that reported previously for the 1979-2018
111 period due to the rapid warming which occurred following the 1980s (Fig. 3a), in agreement
112 with previous studies of observed lake surface temperature change¹⁵. The spatial gradient in
113 temperature is similar across the different future climate scenarios (Fig. 3c), as well as the
114 1861-2005 period. Specifically, the spatial gradient was 0.0063 ± 0.00004 °C km⁻¹ during the
115 historic period, and marginally higher during the 21st century at 0.0064 ± 0.00005 °C km⁻¹ under
116 RCP 2.6 and 6.0, and 0.0065 ± 0.00009 °C km⁻¹ under RCP 8.5. The model projections
117 demonstrate that the median velocity of climate change from 1861-2005 was 3.5 ± 2.3 km
118 decade⁻¹, again lower than the 1979-2018 period due to the different temporal period
119 considered. We project a median climate velocity during the period 2006-2099 of 8.7 ± 5.5 km
120 decade⁻¹ for RCP 2.6, 32.6 ± 10.3 km decade⁻¹ for RCP 6.0 and 57.0 ± 17.0 km decade⁻¹ for RCP
121 8.5.

122

123 The worldwide patterns of climate velocities are projected largely to hold under 21st century
124 climate change, with areas that have experienced the highest velocities during the historic
125 period (1861-2005) also typically experiencing the greatest velocities during the contemporary
126 to future period (2006-2099). Specifically, there were statistically significant relationships
127 between the worldwide climate velocities during the historic and future periods under RCP 2.6
128 ($R^2 = 0.52$; $p < 0.001$), RCP 6.0 ($R^2 = 0.48$; $p < 0.001$), and RCP 8.5 ($R^2 = 0.38$; $p < 0.001$),
129 but with a decrease in correlation with an increase in the severity of climate change. There
130 appear to be no systematic changes in the projected spatial patterns of climate velocity in the
131 future; but some regions, such as northern Europe, northeastern USA and northern Canada,

132 will experience greater changes than others (Extended Data Fig. 6). The velocity of climate
133 change in standing waters during the 21st century will be slightly greater in summer than in
134 winter (Fig. 3e-g; summer was defined as July-September in the Northern Hemisphere and
135 January-March in the Southern Hemisphere, and the opposite definition was used for winter).
136 For example, under RCP 8.5, our simulations suggest that by the end of the current century the
137 median velocity of climate change will increase to 58.0 ± 13.2 km decade⁻¹ during summer and
138 43.2 ± 10.5 km decade⁻¹ during winter. This is a result of surface water temperatures in standing
139 waters increasing at a faster rate in summer (0.59 ± 0.14 °C decade⁻¹) than in winter (0.47 ± 0.11
140 °C decade⁻¹), but is also influenced by a slightly higher median spatial temperature gradient
141 between summer (0.008 ± 0.00007 °C km⁻¹) and winter (0.007 ± 0.00007 °C km⁻¹) (Fig. 3).

142
143 The pace of climate change identified here for standing waters during the 21st century will
144 produce new, and rapidly warming, thermal conditions for species at a given location. The
145 ecological consequences will depend on the ability of a species to survive at a site, disperse
146 within a catchment or disperse between catchments. The ability of a species to continue to
147 survive at a site will depend on the temperature sensitivity of their most susceptible life-
148 stages^{16,17}. In addition, phenotypic plasticity may allow a species to acclimate to higher
149 temperatures while adaptation to higher temperatures is unlikely since rates of evolutionary
150 change for critical thermal maxima are many orders of magnitude lower than even the rate of
151 historical temperature trends^{2,18}. In addition, cooler water at depth during seasonal stratification
152 may provide a potential refuge from increasing surface water temperatures. However, the
153 environment at depth may not always be suitable in terms of light, food supply or oxygen
154 concentration. For example, some fish are unable to exploit cooler temperatures at depth
155 because of low oxygen concentration¹⁹, and oxygen-depletion is likely to increase with climate
156 change and continued eutrophication. Furthermore, the critical thermal period may occur in
157 non-stratified periods of the year. For example, early life stages can be the most temperature
158 sensitive¹⁶ and these can occur in the winter when stratification is generally absent, but the
159 velocity of climate change is almost as great as in the summer. The evidence of summer fish-
160 kills in lakes, and their lack of correlation with lake depth, suggests that depth may only provide
161 a partial thermal refuge⁶ and, as demonstrated in the oceans, climate velocities can be faster at
162 depth than at the surface²⁰. Phenological change in response to warming may allow sensitive
163 stages to exploit cooler times of year, but where seasonality of different components of the
164 food-web changes at different rates the changing phenology could also cause food-web
165 desynchronization, with potential negative consequences²¹. While there has been a focus on
166 the consequence of rapid surface warming of inland standing waters for cold-water stenotherms
167 at high latitudes²², warm-water species that are close to their critical thermal limit at low
168 latitudes are equally at risk²³.

169
170 Dispersal is an important life-history trait that, unlike the responses above, will not prevent
171 species loss at a given site but may permit a species to survive by moving to cooler habitats.
172 Within the dendritic hydrological network of a catchment, dispersal to cooler standing water
173 can occur either upstream to higher elevations or, in large river systems, downstream to higher
174 latitudes. However, species in headwaters or isolated tributaries may have a low connectivity
175 to more suitable habitats and so be particularly susceptible to rapid warming²⁴. For some

176 species, such as freshwater molluscs, rates of active dispersal of 1 to 10 km decade⁻¹ (ref. 25)
177 are less than forecast future change under both medium and high greenhouse gas concentration
178 pathways. While many amphibians move relatively small distances, at least some individuals
179 may move over 10 km (ref. 26). More motile species, such as some fish, have the potential to
180 migrate rapidly in response to long-term climate change^{4,27}. However, in all cases, dispersal
181 may be limited by physical and ecological barriers caused by the complex mosaic of freshwater
182 environments. The increasing number of dams on the world's rivers²⁸ may restrict dispersal
183 further by preventing access to upstream reaches and because the habitat in the intervening
184 reservoir may be unsuitable. Even greater challenges are faced in dispersal across land to cooler
185 catchments at higher elevation or higher latitude as illustrated by the fragmented distribution
186 of fish within a landscape²⁹ and the high degree of endemism in freshwater organisms³⁰.
187 Aquatic insects have a variable potential to disperse actively between catchments in their adult
188 stage³¹, while other organisms depend on vectors such as wind or transport by large motile
189 animals such as birds³². For dispersal within and between catchments, colonization and
190 expansion in cooler areas may be impeded by interactions with the resident community of
191 species that can restrict the establishment of new species despite an adequate propagule
192 pressure³².

193
194 The discussion above outlines the challenges that species in inland waters face in responding
195 to rapid climate change. Although the velocity of climate change of inland standing waters is
196 about half that of the ocean, the future consequences for the conservation of species, and the
197 goods and services they provide, is likely to be much greater. This is caused by the combination
198 of low dispersal rates of some freshwater species, substantial barriers to dispersal and ongoing
199 major disruption to inland water biodiversity and ecosystem function by multiple
200 anthropogenic stressors³⁰. A recent analysis showed that the tracking of isothermal shifts in
201 latitude in terrestrial species was six-times slower than in marine species³³; this tracking is
202 likely to be even slower for species from inland standing waters. Placing this global analysis
203 in a conservation context, will require information on the thermal tolerance of different
204 freshwater species, their dispersal ability and the local and regional connectivity of their
205 habitat. It will also require the more complex interactions between species within a community
206 to be understood and, for species such as amphibians and some insects and fish with life stages
207 in different environments, the consequences of environmental change experienced in different
208 realms.

209 **List of Figures**

210

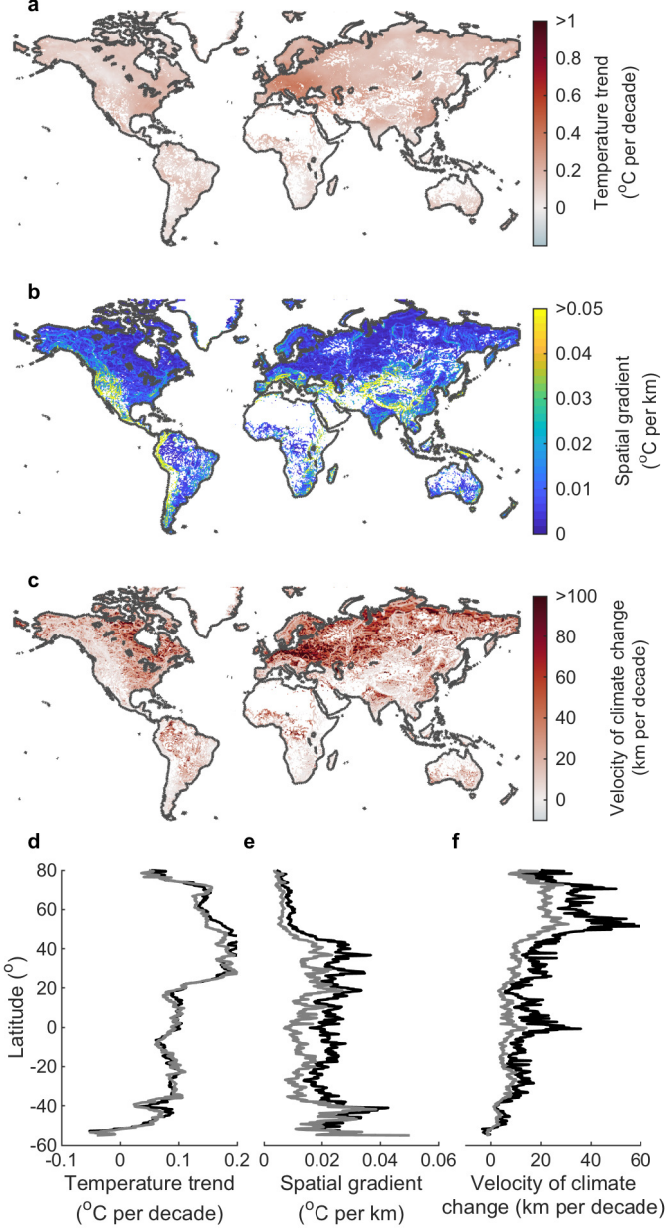
211 **Fig. 1 | The velocity of climate change in the surface of standing waters (1979-2018).** (a)
212 The annual surface water temperature trend ($^{\circ}\text{C decade}^{-1}$). (b) The two-dimensional spatial
213 gradient of annual surface water temperature change ($^{\circ}\text{C km}^{-1}$). (c) The velocity of temperature
214 change determined from the quotient of **a** and **b** (km decade^{-1}). Latitudinal mean (black) and
215 median (grey) of (d) the temperature trend, (e) the spatial temperature gradient and (f) the
216 velocity of climate change. White regions represent those where standing waters are absent
217 within the global database.

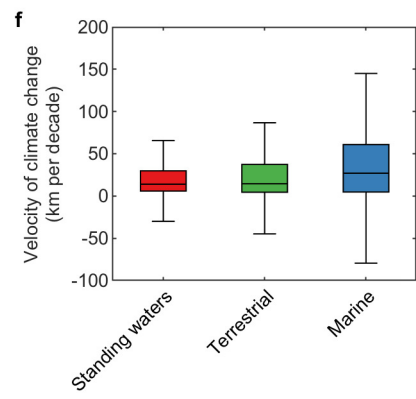
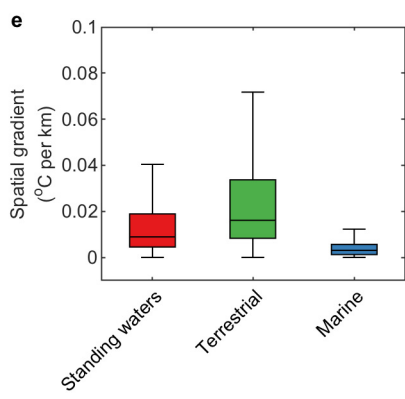
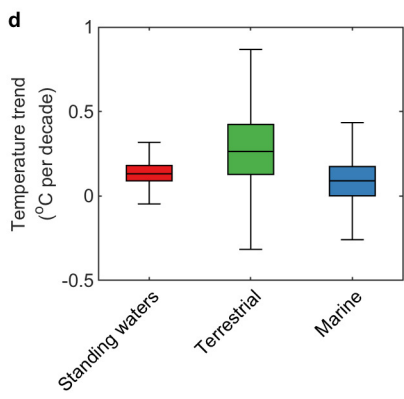
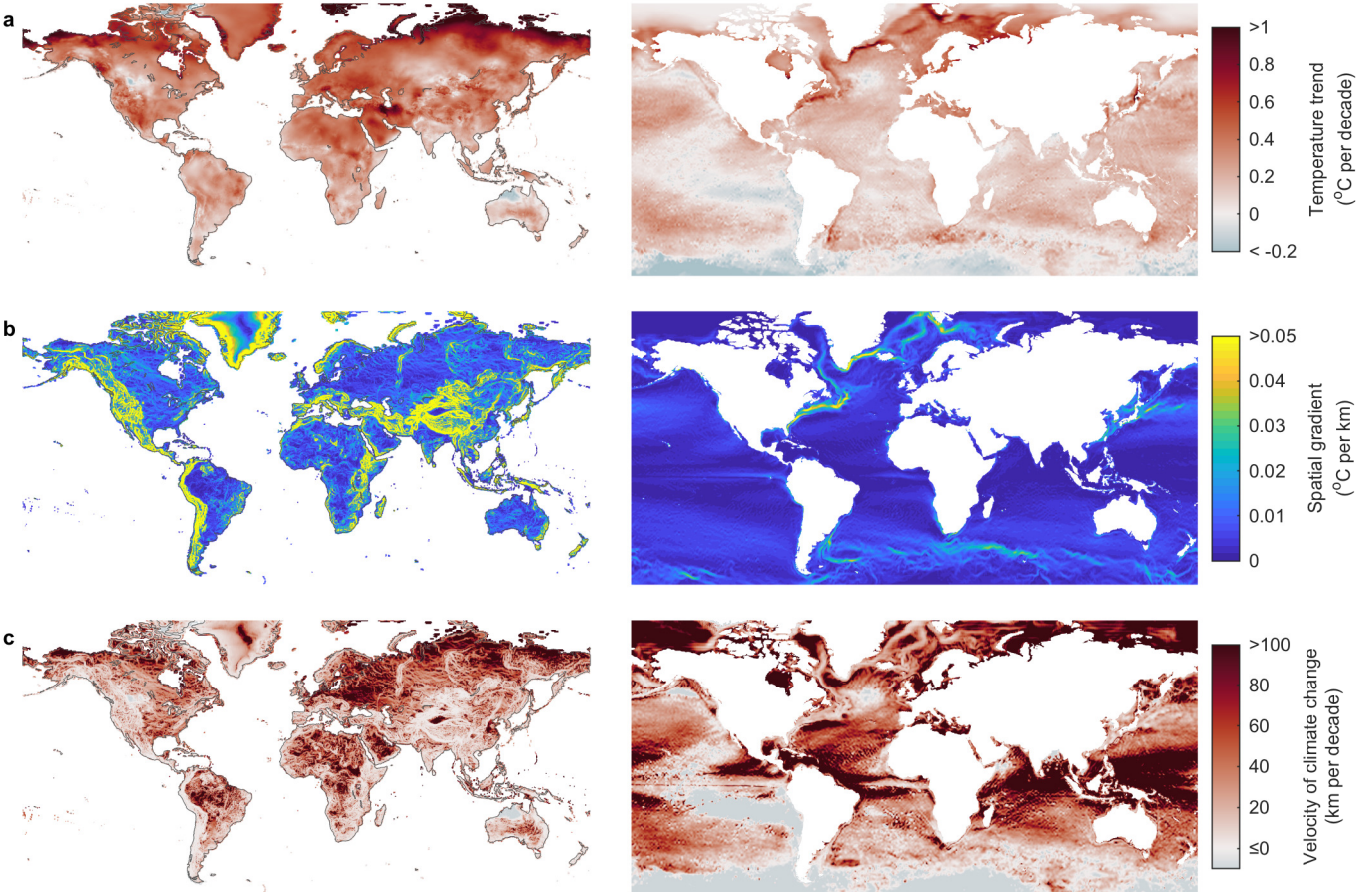
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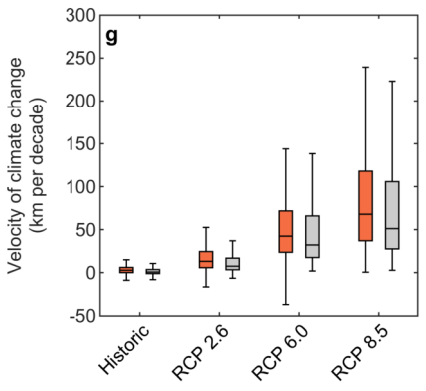
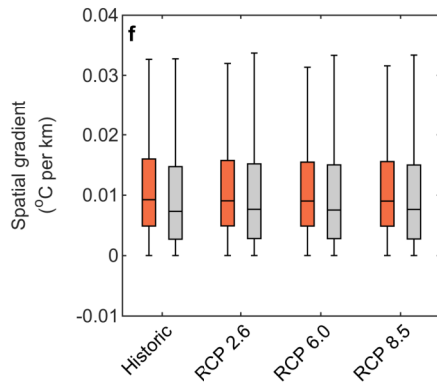
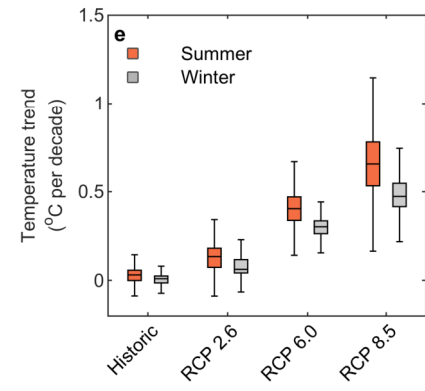
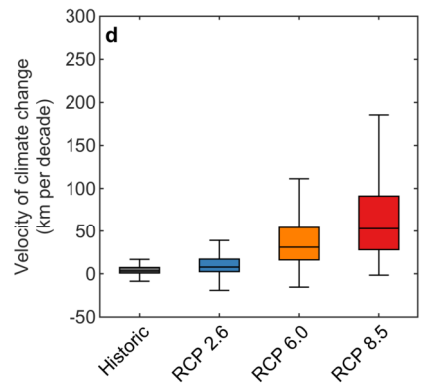
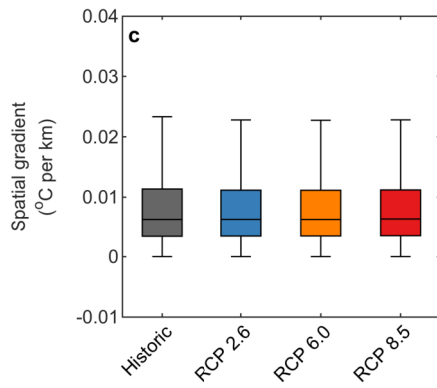
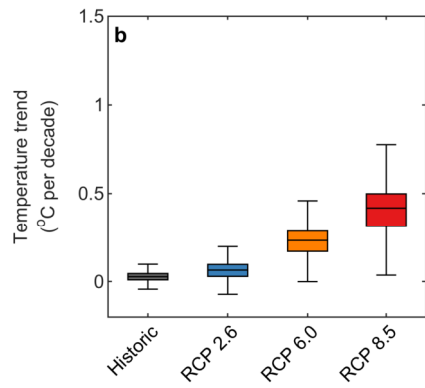
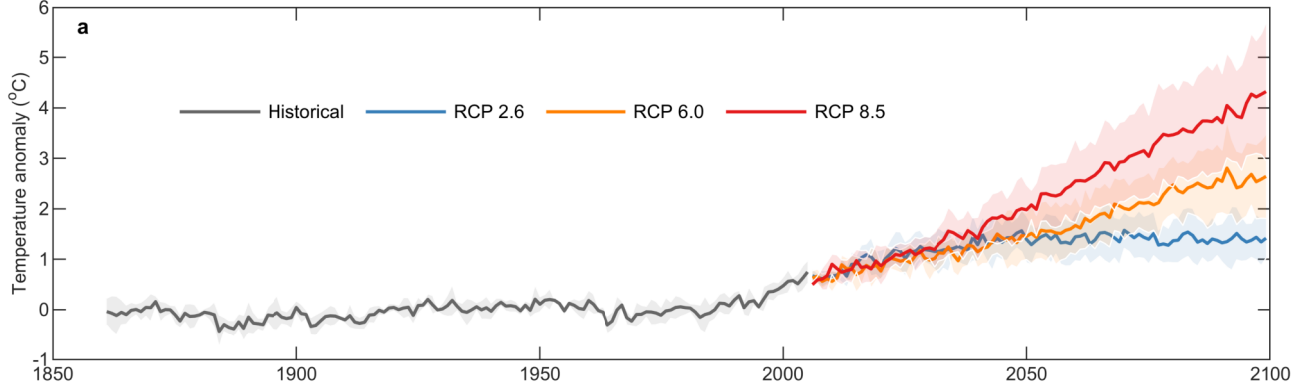
219 **Fig. 2 | The velocity of climate change in terrestrial and marine ecosystems (1979-2018).**
220 (a) The annual temperature trend ($^{\circ}\text{C decade}^{-1}$) in terrestrial (left) and marine (right)
221 ecosystems. (b) The two-dimensional spatial gradient of annual surface temperature change
222 ($^{\circ}\text{C km}^{-1}$). (c) The velocity of temperature change determined from the quotient of **a** and **b** (km
223 decade^{-1}). Comparison of the surface temperature trend (d), spatial temperature gradient (e),
224 and velocity of climate change (f) in standing waters with those calculated over land
225 (terrestrial) and in the ocean (marine). Each box represents the interquartile range, the
226 horizontal line is the median, and the whiskers are 1.5 times the interquartile range.

227

228 **Fig. 3 | Historic and future projections in the velocity of climate change in inland standing**
229 **waters.** (a) Temporal change in annual surface water temperature anomalies (relative to 1951-
230 1980) from 1861-2099 showing the historic period (1861-2005), with contemporary to future
231 climate projections (2006-2099) under three greenhouse gas concentration pathways (RCPs
232 2.6, 6.0, and 8.5). The thick lines show the average from the lake model driven by four global
233 climate models (MIROC5, IPSL-CM5A-LR, GFDL-ESM2M and HadGEM2-ES), and the
234 shaded regions represent the standard deviation. Also shown are model projections of (b)
235 the temporal gradient of temperature change ($^{\circ}\text{C decade}^{-1}$), (c) the two-dimensional spatial
236 gradient of surface temperature change ($^{\circ}\text{C km}^{-1}$), and (d) the velocity of climate change (km
237 decade^{-1}). Panels **e-g** show equivalent data for winter vs summer. Each box represents the
238 interquartile range, the horizontal line is the median, and the whiskers are 1.5 times the
239 interquartile range. Each box contains the simulations from the lake model forced by each of
240 the climate model projections.







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325

326 **Data Availability Statement:** ERA5 data used in this study are available from
327 [https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview)
328 [levels?tab=overview](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview). The lake model source code is available to download from
329 <http://www.flake.igb-berlin.de/>. Climate model projections are available at
330 <https://www.isimip.org/protocol/#isimip2b>.

331 **Methods**

332 Temperature data

333 Water temperatures from 1979 to 2018 were downloaded from the ECMWF ERA5 reanalysis
334 product at a grid resolution of 0.25° by 0.25° . Surface water temperature of global standing
335 waters were simulated within ERA5 (ref. 34) via the Freshwater Lake model, FLake^{35,36}, which
336 is implemented within the Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land
337 (HTESSEL)^{37,38} of the ECMWF Integrated Forecasting System (IFS). The water temperature
338 model is one of the most widely used lake models and has been tested extensively in past
339 studies^{5,39}. The lake surface temperatures from ERA5 were also validated in this study with
340 satellite derived lake surface temperatures from the European Space Agency (ESA) Climate
341 Change Initiative (CCI) Lakes project (CCI Lakes; <http://cci.esa.int/lakes>) which provides,
342 among other things, daily observations of lake surface temperature at a grid resolution of
343 $1/120^\circ$ for 250 lakes worldwide. From version 1.0 of the CCI Lakes dataset⁴⁰, we selected only
344 lakes based on the existence of a 10×10 pixel array of pure water surrounding the lake-centre,
345 following the recommendations of ref. 41. For each of these lakes, a 3×3 pixel array was then
346 extracted for each day, and the average of these pixels was then calculated prior to comparison
347 with the ERA5 data, which were also extracted for the lake-centre location. The satellite-
348 derived lakes temperatures used in the study were acquired between 2007 and 2018, the period
349 in which most satellite retrievals were available in ESA CCI Lakes. Good agreement was
350 obtained between simulations and satellite-derived observations of lake surface temperature
351 (Extended Data Fig. 1). A detailed description of the surface temperature model and the
352 implementation of surface water temperature in the IFS is provided in ref. 42. The surface
353 water temperature model in the IFS is supported by two climatological fields: (i) an inland
354 water mask, provided by the US Department of Agriculture – Global Land Cover
355 Characteristics (GLCC) data⁴³, at a nominal resolution of 1 km, which provides the fractions
356 of each surface grid occupied by surface water; (ii) depth, which is specified according to ref.
357 44 and combined with a global bathymetry dataset, ETOPO1, which is a 1 arc-minute global
358 relief model of Earth's surface that integrates land topography and ocean bathymetry. Surface
359 air temperature over land and sea surface temperatures were also downloaded by ERA5 from
360 1979 to 2018 at a grid resolution of 0.25° by 0.25° . Thus, the temperature of standing waters,
361 surface air temperature, and sea surface temperature all follow a consistent modelling
362 framework. All data from January 1979 to December 2018, inclusive, were accessed and
363 analysed at an hourly resolution. Annual and seasonal averages, which were used in all velocity
364 calculations, were then calculated from the hourly data. Summer and winter temperatures were
365 calculated for standing waters. Following ref. 2, summer was defined as 1 July - 30 September
366 for lakes situated in the Northern Hemisphere and 1 January - 31 March in the Southern
367 Hemisphere.

368

369 Climate model projections

370 To calculate the velocity of climate change during the 21st century, we used the same water
371 temperature model as in ERA5 but driven by bias-corrected climate projections from four
372 climate models GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, and MIROC5 for historic
373 (1901-2005) and contemporary to future periods (2006-2099) under three scenarios: RCP 2.6,

374 6.0, and 8.5. Similar to ref. 5, we downloaded atmospheric forcing data (air temperature at 2
375 m, wind speed at 10 m, surface solar and thermal radiation, and specific humidity) needed to
376 drive FLake from ISIMIP2b (<https://www.isimip.org/protocol/#isimip2b>). All climate
377 projection data were available at daily intervals and at a grid resolution of 0.5°. These data were
378 used as inputs to the model after bias-adjustment to the EWEMBI reference dataset^{45,46}. To
379 drive the surface water temperature model, lake depths were determined from the Global Lakes
380 and Wetlands Database⁴⁷, aggregated from the original 30 arc sec Global Lake Data Base^{44,48,49}
381 to a 0.5°-by-0.5° grid lake depth field. The depth dataset used by the lake model (i.e., the
382 average depth of all lakes within a grid), could influence the future projections, given that depth
383 is an important lake attribute influence the thermal response of lakes to climate change^{5, 50}.
384 Notably, lakes of different depths within a grid could behave differently than those included
385 here, and is a limitation which should be considered when interpreting these results.

386

387 Velocity of Climate Change

388 Climate velocities (km year^{-1}) were calculated by dividing long-term temperature trends ($^{\circ}\text{C}$
389 decade^{-1}) by the spatial temperature gradient ($^{\circ}\text{C km}^{-1}$). Long-term trends of each grid-cell were
390 calculated as the slope of a linear trend model, and the spatial gradients were calculated using
391 a 3x3 grid cell neighborhood. Ultimately, the spatial temperature gradient was calculated as
392 the vector sum of the north-south and east-west temperature gradients. Specifically, the spatial
393 temperature gradient for a focal cell was calculated as the difference in temperature for each
394 northern and southern pair divided by the distance between them¹². For these calculations we
395 used the R package ‘Vocc’ (ref. 51, 52).

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442 **Extended Data**

443

444 **Extended Data Fig. 1 | Validation of simulated lake surface temperatures.** Comparison of
445 simulated and satellite-derived surface water temperatures for 196 lakes (2007-2018) from the
446 ESA CCI Lakes dataset. Shown are comparisons of the average open-water temperatures for
447 the lake-centre pixels.

448

449 **Extended Data Fig. 2 | The velocity of climate change in European standing waters.** Shown
450 for standing waters in Europe are (a) the surface water temperature trend, (b) the two-
451 dimensional spatial gradient of surface water temperature change, and (c) the velocity of
452 climate change during the 1979 to 2018 period. White regions represent those where standing
453 waters are absent within the global database.

454

455 **Extended Data Fig. 3 | Global relationship between the spatial temperature gradient and**
456 **elevation.** Shown is a comparison of (a) the two-dimensional spatial gradient of surface water
457 temperature change, and (b) elevation. White regions represent those where standing waters
458 are absent within the global database.

459

460 **Extended Data Fig. 4 | Comparison of the velocity of climate change and the spatial**
461 **elevation gradient.** Shown is the relationship between the velocity of climate change in the
462 surface of inland surface waters and the two-dimensional spatial gradient of elevation change.
463 Specifically, we show that climate change velocities are greater at sites with low elevation
464 gradients. Thus, steep sites which show rapid change in elevation, experience lower climate
465 velocities. Each box represents the interquartile range, the horizontal line is the median, and
466 the whiskers are 1.5 times the interquartile range.

467

468 **Extended Data Fig. 5 | Historic and future projections of global surface air temperature.**
469 Temporal change in annual surface air temperature anomalies (relative to 1951-1980) from
470 1861-2099 showing the historic period (1861-2005), with contemporary to future climate
471 projections (2006-2099) under three representative greenhouse gas concentration scenarios
472 (RCPs 2.6, 6.0, 8.5). The thick lines show the average of four global climate models (MIROC5,
473 IPSL-CM5A-LR, GFDL-ESM2M, HadGEM2-ES), and the shaded regions represent the
474 standard deviation.

475

476 **Extended Data Fig. 6 | Global variations in the velocity of climate change from 2006-2099**
477 **relative to 1861-2005.** Shown are the differences in the simulated velocity of climate change
478 between the historic (1861-2005) and the contemporary to future (2006-2099) period (i.e.,
479 future minus historic) under RCP 8.5. Results are shown for the lake model forced by four
480 global climate models (MIROC5, IPSL-CM5A-LR, GFDL-ESM2M, HadGEM2-ES). White
481 regions represent those where the difference in climate velocities are negligible.

