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1 **Responses of global waterbird populations to climate change vary with latitude**

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24 **Most research on climate change impacts on global biodiversity lacks the resolution to**
25 **detect changes in species abundance and is limited to temperate ecosystems. This limits**
26 **our understanding of global responses in species abundance—a determinant of**
27 **extinction risk and ecosystem function and services—to climate change including in the**
28 **highly-biodiverse tropics. We address this knowledge gap by quantifying the abundance**
29 **response of waterbirds, an indicator taxon of wetland biodiversity, to climate change at**
30 **6,822 sites between 55°S and 64°N. Using 1,303,651 count records of 390 species, we**
31 **show that with temperature increase, the abundance of species and populations**
32 **decreased at lower latitudes, particularly in the tropics, but increased at higher**
33 **latitudes. These contrasting latitudinal responses indicate potential global-scale**
34 **poleward shifts of species abundance under climate change. The negative responses to**
35 **temperature increase in tropical species are of conservation concern, as they are often**
36 **also threatened by other anthropogenic factors.**

37

38 Climate change continues to pose various serious threats to biodiversity, and there is an
39 urgent need to understand how species respond on a global scale to changing climates. A wide
40 range of species have already been shown to respond to climate change through changes in
41 geographical range¹, phenology² and abundance³. However, the rate and direction of these
42 responses vary greatly among species and locations^{1, 2, 4}. As climate-driven changes in
43 biodiversity are expected to affect ecosystem functioning, human well-being, and the
44 dynamics of climate change itself⁵, understanding how species' responses to climate change
45 may vary globally could provide crucial evidence for a more effective allocation of limited

46 resources for the conservation of species and ecosystems most threatened by climate change,
47 and for assessing how climate-driven changes in biodiversity may affect human societies.

48 Existing gaps in the geographical coverage of available evidence seriously limit our
49 understanding of species' responses to climate change across the globe⁶. Earlier global
50 reviews of species' responses to climate change have rarely incorporated species and studies
51 in the tropics⁷, due to the lack of ecological data⁸. Such geographical biases are even more
52 prominent in studies investigating responses in species abundance⁹, which is a major
53 determinant of species extinction risk¹⁰, ecosystem function and services¹¹. Research on
54 abundance responses to climate change to date has largely been conducted in Europe, North
55 America, Australia and the Arctic^{3, 12-15}, with a recent global study showing a link between
56 climate warming and abundance declines in birds and mammals⁹ but still largely missing the
57 tropics. As a result, although tropical species are predicted to be more vulnerable to increasing
58 temperature¹⁶, there is still little empirical evidence on how responses in species abundance to
59 climate change vary among and within species at the global scale.

60 Here we address this challenge by modelling global time-series data of waterbird species
61 to estimate their abundance responses to changes in temperature and precipitation. The global
62 dataset of waterbird abundance changes used is based on long-term surveys in over 100
63 countries and covers regions for which there is little information on climate change impacts,
64 such as the tropics¹⁷. Waterbirds can also serve as an indicator taxon for assessing the status
65 of biodiversity in wetland ecosystems, which have been lost at higher rates than other
66 ecosystems, despite their high levels of biodiversity and productivity as well as the crucial
67 ecosystem functions and services delivered¹⁸.

68 Using 1,303,651 count records collected since 1990 on 390 waterbird species at 6,822
69 sites between 55°S and 64°N (Extended Data Fig. 1) we first estimated, for each species at
70 each site, (i) the rate of abundance changes with increasing temperature and precipitation as
71 regression coefficients (responses to temperature and precipitation increases; note that the
72 actual rate and direction of temperature and precipitation changes vary spatially: Extended
73 Data Fig. 2), and (ii) the proportion of abundance changes that can be explained
74 independently by temperature and precipitation changes (measured as R^2), estimated with
75 hierarchical partitioning¹⁹ (the importance of temperature and precipitation). We then tested
76 multiple hypotheses that are rarely explored at the global scale (Extended Data Figs. 3 and 4),
77 to examine among- and within-species variations in responses to temperature and
78 precipitation increases as well as the importance of temperature and precipitation across
79 latitudes.

80 **Tropical species suffer from temperature increase**

81 Applying the Gompertz model of population growth to the global waterbird dataset enabled
82 us to estimate abundance responses to the changes in temperature and precipitation at $1^\circ \times 1^\circ$
83 grid cells across latitudes, including the tropics, for a wide range of waterbird groups. Of the
84 390 species analysed, 144 species (36.9%) had at least one estimate in the tropics and 129
85 species (33.1%) had their absolute latitudinal range mid-points in the tropics (defined as
86 tropical species; Fig. 1) although most data in the tropics were from tropical Asia (Extended
87 Data Fig. 1).

88 Many species showed considerable spatial variation in abundance responses to
89 temperature increases within their geographical ranges, with particularly negative responses in

90 the tropics (Fig. 1), although the importance of temperature in explaining abundance changes
91 tended to be low across the ranges, with an overall median R^2 of 0.057 (Supplementary Data
92 S1 and S2). In contrast, for most species there was no clear geographical pattern in abundance
93 responses to precipitation increases, and precipitation was found to have a low importance in
94 explaining abundance changes (the overall median $R^2 = 0.051$; Supplementary Data S1 and
95 S2). These geographical patterns were also evident in the distribution of abundance responses
96 averaged across all species observed within each grid cell; species generally showed more
97 negative responses to temperature increases at lower latitudes, such as in South and Southeast
98 Asia, and positive responses at higher latitudes (Fig. 2).

99 For 213 species with estimates at ten or more grid cells, we then tested hypotheses on how
100 responses to temperature and precipitation increases and the importance of temperature and
101 precipitation vary both among species (among each species' estimates at latitudinal range
102 mid-points; species-level responses) and also within species (among grid cells within each
103 species; population-level responses) along latitudes. When compared among species,
104 abundance responses to temperature increases shifted from positive at higher latitudes to
105 negative at lower latitudes, with 69% of the tropical species showing negative responses to
106 temperature increases (Fig. 3a, Extended Data Fig. 5a). When compared within species,
107 although 198 (93%) out of the 213 species showed more negative responses to temperature
108 increases at lower latitudes, this within-species latitudinal pattern was significant only in eight
109 of the 198 species (Fig. 3b, Supplementary Data S3). The importance of temperature in
110 explaining abundance changes also increased with latitude among species (Fig. 3c, Extended
111 Data Fig. 5b) and within species for all 55 species with a significant within-species latitudinal
112 pattern (Fig. 3d, Supplementary Data S3). For migratory species, larger-sized species and

113 species with a wider latitudinal range, temperature played a higher importance in explaining
114 abundance changes (Extended Data Fig. 5b) although none of these seemed to explain
115 species-level responses to temperature increases.

116 In contrast, neither abundance responses to precipitation increases nor the importance of
117 precipitation in explaining abundance changes showed significant latitudinal patterns among
118 species. This does not necessarily mean that precipitation was not important; for some species
119 in the tropics, precipitation was found to have a relatively high importance in explaining
120 abundance changes (Fig. 4a, c, Extended Data Fig. 6 and Supplementary Data S3).

121 Precipitation was shown to have a higher importance in explaining abundance changes in
122 species with a wider latitudinal range (Extended Data Fig. 6b). When compared within
123 species, five species showed a significant pattern: one species showed a decrease, three
124 species showed an increase, and another species showed a hump-shaped curve in abundance
125 responses to precipitation increases along latitudes (Fig. 4b, Supplementary Data S3). The
126 importance of precipitation in explaining abundance changes showed a significant within-
127 species latitudinal pattern for just one species (Fig. 4d, Supplementary Data S3). These
128 conclusions were robust even when the effect of Jun-Aug precipitation was considered
129 (Extended Data Figs. 7 and 8) and appeared to be driven largely by patterns in the northern
130 hemisphere (Supplementary Figs. S1-S4).

131 **How climate affects species abundance across latitudes**

132 Our results demonstrate that the responses in waterbird abundance to temperature increases
133 differ between tropical (especially Asian tropical) and non-tropical regions. At both species
134 and population levels, waterbird abundance generally decreased in the tropics, but increased

135 at higher latitudes, with increasing temperature. This supports our predictions on among- and
136 within-species patterns (Extended Data Fig. 3). Species in the tropics tend to live closer to
137 their upper temperature limits¹⁶, have a narrower temperature niche²⁰ and change their
138 temperature niche at a slower rate²¹, all of which indicate that tropical species are more
139 vulnerable to increasing temperatures at the species level. Climate-related extinctions of local
140 populations, typically at the warmer edge of the species' geographical range, are also more
141 frequent in the tropics, causing poleward range shifts in many species²². While such species-
142 level and population-level responses to climate change have often been investigated
143 separately to date, our results provide novel empirical evidence that impacts of temperature
144 increases on tropical ecosystems can be characterised by species-wide declines in tropical
145 species as well as population-level responses in wider-ranging species.

146 Temperature generally explained a small proportion of yearly abundance changes in
147 waterbirds, especially in tropical species and at the low-latitude range margin of species.
148 Despite this, our finding of negative responses to temperature increases in the tropics seems to
149 be robust because temperature was shown to be more important in explaining abundance
150 changes for grid cells in the tropics with more negative responses to temperature increases
151 (Supplementary Fig. S5).

152 The lower importance of temperature at lower latitudes might be explained by four
153 reasons. First, the effect of temperature changes on waterbird abundance can be indirect,
154 especially at lower latitudes. Although warmer weather conditions can directly increase the
155 survival of waterbirds at higher latitudes²³, indirect biotic processes (e.g., changes in food
156 availability), rather than direct abiotic processes (e.g., heat stress), are reported to be more

157 important mechanisms for climate-driven abundance changes for higher-level consumers like
158 birds^{24, 25}. For example, increases in already-high temperatures at lower latitudes can cause
159 wetlands to dry, reducing the availability of habitats and food for waterbirds²³. Such an
160 indirect effect of temperature increases could have obscured the temperature-abundance
161 relationship, especially in the tropics. Second, many of the waterbirds analysed here are
162 migratory species, for which temperature played a higher importance in explaining abundance
163 changes (Extended Data Fig. 5b). This does not support our hypothesis that the effects of
164 factors at multiple locations could outweigh the effects of local climatic conditions in
165 migratory species, but instead indicates that migratory species can be more responsive to local
166 temperature changes due to their higher abilities to disperse²⁶ and track climate niches²⁷. In
167 this study more non-tropical species tended to be migratory compared to tropical species: 151
168 (96%) of 158 non-tropical species and 43 (78%) of 55 tropical species were migratory, which
169 may explain the higher importance of local temperature in explaining the abundance of non-
170 tropical species. Third, larger errors associated with count data can cause a lower explanatory
171 power of variables. We may expect larger errors in the tropics, where surveyors might be less
172 trained given the shorter history of waterbird surveys and thus be more susceptible to
173 observation errors. Finally, other important threats, such as habitat loss and hunting, affect
174 bird abundance, independently from, or synergistically with, climate change²⁸. By testing the
175 effect of temperature and precipitation changes on yearly abundance changes while estimating
176 long-term growth rates, our modelling approach controlled for the consistent impacts of such
177 threats on long-term trends in abundance (see *Statistical Analyses* for more detail).
178 Nevertheless, those threats can also cause yearly abundance changes and their impacts are

179 likely to be more severe at lower latitudes¹⁷, potentially causing temperature to have lower
180 importance at lower latitudes.

181 Contrary to our hypotheses, there was no clear latitudinal pattern in abundance responses
182 to precipitation changes, either among or within species. Water availability, compared to
183 ambient temperature, has been shown to be a more important driver of species richness and
184 population size at lower latitudes⁴. Supporting this, our results showed that precipitation was
185 more important in explaining the abundance of some tropical species compared to most
186 species in higher latitudes, although the overall among-species pattern across latitudes was
187 not significant (Fig. 4c). This may be explained by the two reasons. First, precipitation
188 changes can affect waterbirds at the river basin scale (often the scale of 500 to 1,000 km)
189 through effects on water flow into their wetland habitats²⁹. Therefore, our analysis at the
190 resolution of 1° grid cells (equivalent to a grain size of 96.49 km) may not have been able to
191 detect such a broad-scale impact of precipitation changes. Second, waterbird responses to
192 precipitation changes can vary greatly among species (see Extended Data Fig. 3 for detail).
193 While increased rainfall generally leads to more favourable habitat conditions for waterbirds
194 in dry regions²³, elevated water levels associated with increased rainfall can cause the loss of
195 shallow-water habitats, often followed by abundance decreases in certain groups, such as
196 shorebirds³⁰. Such mixed responses to precipitation changes among species may have resulted
197 in the lack of clear latitudinal patterns, particularly among species.

198 **Tropical biodiversity imperilled yet understudied**

199 Our results imply three major implications on the impact of climate change on global
200 biodiversity. First, local temperature increases between December and February under

201 ongoing climate change are likely to pose a more negative impact on species and populations
202 in the tropics. This provides important evidence for improving our understanding of whether
203 tropical ecosystems have been degraded by climate change. Although climate change is not
204 the only threat to waterbirds, impacts of other major threats, such as loss and degradation of
205 wetlands and excessive hunting pressure, seem to be more severe in the tropics too¹⁷,
206 indicating that tropical species and populations suffer from multiple anthropogenic threats.
207 Second, the revealed negative impact of temperature increases in the tropics suggests that
208 existing severe biases in scientific information towards temperate regions could underestimate
209 the impact of climate change on species populations at the global scale. Highlighting the
210 negative impact of climate change on tropical waterbirds should serve to inspire further
211 studies on other taxa in the tropics, where most species are facing multiple threats including
212 climate change⁸. Finally, our other finding that abundance responds positively to temperature
213 increases at higher latitudes highlights the possibility of global-scale poleward shifts in
214 abundance across species, and associated ecosystem functions and services. As such shifts can
215 have serious consequences not only for biodiversity but also for human well-being, assessing
216 latitudinal patterns in biodiversity responses to climate change at the population, species and
217 community levels warrants further research attention.

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293 **Methods**

294 **Data**

295 *Waterbird count data*

296 Data used in this study comprised site-specific annual counts based on the International
297 Waterbird Census (IWC) coordinated by Wetlands International and the Christmas Bird
298 Count (CBC) by the National Audubon Society in the USA, and were compiled in our earlier
299 study¹⁷. Counts based on these surveys should be described as relative abundance, as we
300 could not account for imperfect detections in this study. However, we have referred to them
301 as abundance throughout the manuscript for simplicity. Nevertheless, these count records
302 should still be comparable among years (see section *Model for estimating abundance*
303 *responses* for more detail).

304 The IWC, launched in 1967, is a scheme for monitoring waterbird numbers, covering
305 more than 25,000 sites in over 100 countries with more than 15,000 observers. The
306 coordination of the IWC is divided into four regional schemes corresponding to the major
307 migratory flyways of the world: the African-Eurasian Waterbird Census (AEWC), Asian
308 Waterbird Census (AWC), Caribbean Waterbird Census (CWC) and Neotropical Waterbird
309 Census (NWC). We did not use data from the CWC, as, having started in 2010, it only
310 provides short-term data. The survey methodology is essentially the same across the four
311 regional schemes. Population counts are typically carried out once every year in mid-January
312 but may include counts between December to February. We only used the January and
313 February counts for consistency. This means that our data from the Northern Hemisphere are
314 for non-breeding populations while those in the Southern Hemisphere also include some
315 breeding populations. In each country that is covered by the survey, national coordinators
316 manage an inventory of wetland sites (hereafter, survey sites), including sites of international-
317 or national-level recognition (e.g., Ramsar sites, Flyway Network Sites, Important Bird Areas,

318 national parks etc.). Each survey site is generally defined by boundaries so that observers
319 know precisely which areas are to be covered in the surveys. The observers consist of a wide
320 variety of volunteers, but national coordinators usually train them using materials produced
321 by Wetlands International to ensure the quality of count data. Survey sites (normally up to a
322 few km²) are typically surveyed by about two observers for up to four hours, while larger sites
323 can require a group of observers working over several days. Most surveys are conducted on
324 foot, or from a vehicle, with boats involved in a few. The time of survey on any given day
325 depends on the type of survey site: inland sites are normally surveyed during the morning or
326 late afternoon, whereas coastal sites are surveyed over the high tide period (mangrove areas
327 and nearby mudflats are, however, covered during low tides). Surveys cover waterbirds,
328 defined as bird species that are ecologically dependent on wetlands³¹. Counts are usually
329 made by scanning flocks of waterbirds with a telescope or binoculars and counting each
330 species. Zero counts are not always recorded, and thus are inferred using a set of criteria (see
331 below for more detail). Count records, together with associated information, are submitted to
332 the national coordinators, who compile the submitted records, check their validity and submit
333 those records to Wetlands International. See ^{31,32} for more details on survey methodology.

334 As the IWC does not cover North America, we also used data based on the CBC, which
335 has been conducted annually since 1900, and now includes over 2,400 count circles (defined
336 as survey sites in this study) and involves more than 70,000 observers each year³³. As
337 described in¹⁷, each CBC consists of a record of all bird species detected within a circle (24.1
338 km in diameter) on a single day between 14th December and 5th January. Most circles (and
339 most historical data) are from North America (i.e., the US and Canada). Observers join groups
340 and survey subunits of the circle during the day using a variety of transportation methods
341 (mostly on foot, or in a car, but can include boats, skis, or snowmobiles). The number of
342 observers and the duration of counts can vary among circles and through time. The total

343 number of survey hours per count has been recorded as a covariate to account for the variable
344 duration of and participation in the count. We only used records on waterbird species in this
345 paper.

346 We compiled data from each scheme by species, except for data based on the AEWG,
347 where data had already been stored by flyway for each species³². As data based on the NWC
348 are only available for 1990 onward, we only used post-1990 data for other regions as well.
349 The latest records were in 2013. For the IWC data, we generated zero counts using an
350 established approach³², in which we started with a list of all species observed in each country
351 and assumed a zero count of any species that were on the list but not recorded at a particular
352 site on a particular day if the site was surveyed on that day, as shown by the presence of any
353 other species' record(s), and if no multi-species code related to the species (e.g., Anatinae spp.
354 for species of the genus *Anas*) was recorded for the site-date combination. We projected all
355 survey sites onto a Behrmann equal-area cylindrical projection and assigned them to grid cells
356 with a grain size of 96.49 km, or approximately 1° at 30° N/S. We only used species that were
357 observed at one or more survey sites for ten or more years since 1990; this resulted in 390
358 species being analysed in this study (see Supplementary Data S4 for the full list of species
359 with the number of survey sites and 1° × 1° grid cells where each species was observed).
360 Following¹⁷ we used the International Ornithological Congress World Bird List³⁴ for species
361 groups in Fig. 1: coursers, gulls, terns and auks (Glareolidae, Laridae, Stercorariidae and
362 Alcidae), grebes and flamingos (Podicipedidae and Phoenicopteridae), loons and petrels
363 (Gaviidae and Procellariidae), pelicans, boobies and cormorants (Pelecanidae, Sulidae,
364 Fregatidae, Phalacrocoracidae, Anhingidae), rails and cranes (Rallidae, Gruidae and
365 Aramidae), shorebirds (Burhinidae, Charadriidae, Haematopodidae, Jacanidae,
366 Recurvirostridae, Rostratulidae and Scolopacidae), storks, ibises and herons (Ciconiidae,
367 Threskiornithidae and Ardeidae), and waterfowl (Anatidae and Anhimidae).

368

369 *Explanatory variables*

370 To estimate responses in waterbird abundance to changes in temperature and precipitation
371 (see Extended Data Fig. 2 for changes in mean January temperature and precipitation at all
372 survey sites), we used monthly mean temperature and precipitation total in the CRU TS v.
373 4.01 database³⁵, by assigning each site to the 0.5° climatic grid cell including the site.
374 Although climatic factors at different stages of species' annual cycles (i.e., outside our survey
375 (December-February) season), such as those in the breeding season for species wintering
376 during our survey season, could affect abundance changes, we could not include such factors
377 in our analysis due to the lack of information for most migratory species. Instead we
378 indirectly tested the effect of climatic factors outside our survey season by including
379 migratory status in the latitudinal analysis (see Extended Data Fig. 4). When testing among-
380 and within-species latitudinal patterns in abundance responses, we accounted for three
381 species-level variables—latitudinal geographical range, migratory status and body size—that
382 are expected to explain among-species variations in responses; data sources of those variables
383 are shown in Extended Data Fig. 4.

384

385 **Statistical Analyses**

386 *Model for estimating abundance responses*

387 We first estimated, for each species at each survey site, the rate of abundance changes with
388 increasing temperature and precipitation as regression coefficients (defined as abundance
389 responses to temperature or precipitation increases) by applying the Gompertz model of
390 population growth to count records:

391
$$N_t = N_{t-1} \exp(\alpha + \beta_1 \log N_{t-1} + \beta_2 \text{Temp}_{t-1} + \beta_3 \text{Prec}_{t-1}),$$

392 where N_{t-1} , $Temp_{t-1}$, $Prec_{t-1}$ are the abundance of the species, the relevant mean Dec-Feb
393 temperature and precipitation at the site in year $t - 1$, respectively. β_{1-3} are regression
394 coefficients and α is the intercept. We could not test the effects of other major drivers of
395 abundance changes, such as countries' governance and surface water change¹⁷, due to the lack
396 of data on yearly changes over the survey period. By estimating α as the population growth
397 rate, this model tests the effect of temperature and precipitation on yearly changes in
398 abundance while controlling for long-term trends in abundance. This model structure helps to
399 avoid detecting a spurious relationship between long-term trends in abundance caused by
400 other threats (e.g., long-term declines by habitat loss) and those in temperature or
401 precipitation (e.g., long-term warming temperatures). When comparing the AIC between the
402 exponential growth model ($\log(N_t) - \log(N_{t-1}) = \alpha$) and time-dependent growth model ($\log(N_t)$
403 $- \log(N_{t-1}) = \alpha + \beta t$) fitted to count data at each site for each species, the exponential growth
404 model showed a smaller AIC for 95.8% of the 79,255 time-series, indicating that the model
405 structure above is appropriate for our data. Taking logs and rearranging to express the model
406 in terms of relative growth rate results in the following form:

$$407 \quad \log N_t - \log N_{t-1} = \alpha + \beta_1 \log N_{t-1} + \beta_2 Temp_{t-1} + \beta_3 Prec_{t-1},$$

408 and we used this form to estimate regression coefficients with linear models in R 3.4.1³⁶. As
409 this model does not allow missing values, any missing values between the first and last survey
410 years at each site for each species were replaced by linear interpolation using the package
411 zoo³⁷; the proportion of missing values (i.e., the effect of interpolation) was accounted for in
412 the following analysis (see *Latitudinal analysis*). The estimated β_2 and β_3 represent site-level
413 abundance responses to temperature and precipitation increases, respectively. Using the same

414 model we also estimated the site-level independent capacity of temperature and precipitation
415 changes in explaining abundance changes (defined as the importance of temperature and
416 precipitation) with hierarchical partitioning¹⁹ (measured in our case as R^2) using the package
417 `hier.part`³⁸.

418 As the model described above tests the effect of temperature and precipitation in the
419 previous year (i.e., year $t-1$) on abundance in the survey year (year t), we separately tested the
420 immediate effect of temperature and precipitation in the same year (year t) as the abundance
421 survey year. For this analysis we used the mean temperature or precipitation in December
422 (year $t-1$), January and February (year t) for the IWC sites, where surveys were conducted
423 either in January or February, and mean Dec temperature or precipitation in year t for the
424 CBC sites, where surveys were largely conducted in December. We compared the AIC
425 between the models with temperature/precipitation in year t and year $t-1$ at each site for each
426 species and used the temperature/precipitation variable in the model with a smaller AIC in the
427 final model.

428 We assumed constant survey efforts over time for the IWC, because regular and
429 standardized surveys with constant methods, efforts and timing are strongly encouraged in
430 this scheme (see Supplementary Discussion in¹⁷ for more detail). However, survey efforts in
431 the CBC are known to vary through time. Following an earlier analysis³⁹ we thus accounted
432 for the survey effort effect for the CBC data by using the total number of survey hours per
433 count as the measure of survey efforts:

$$434 \quad \log N_t - \log N_{t-1} = \alpha + \beta_1 \log N_{t-1} + \beta_2 \text{Temp}_{t-1} + \beta_3 \text{Prec}_{t-1} + \frac{B\left(\left(\frac{t}{c}\right)^p - 1\right)}{p},$$

435 where ζ_t is the total number of survey hours per count and $\bar{\zeta}$ is the mean value of ζ_t . The
436 parameters B and p determine a range of relationships between effort and the number of birds
437 counted³⁹ and we used the values estimated for each species in our earlier study¹⁷ (see
438 Supplementary Data S4).

439 We only used survey sites with ten or more records and five or more non-zero records
440 since 1990 for at least one species, and this resulted in 1,303,651 count records since 1990 on
441 390 species at 6,822 sites between -55° and 64° (Extended Data Fig. 1) being analysed in this
442 study. The survey sites used in this study are inevitably biased towards certain regions,
443 especially within the tropics, where most sites are in South and Southeast Asia (Extended
444 Data Fig. 1). Thus, responses by waterbirds to climate change in other tropical regions still
445 remain untested. However, note that (i) the coverage of our data in the tropics is still
446 exceptional, considering the generally severe lack of ecological data^{8,40}, especially population
447 time-series⁴¹, in the tropics, and (ii) there is a known gap in previous assessments of climate
448 change impacts on biodiversity in tropical Asia⁹ and our study bridges the gap.

449 We aggregated the estimated site-level responses to temperature and precipitation
450 increases as well as the importance of temperature and precipitation to 1°×1° grid cells by
451 calculating the mean site-level estimates across all sites in each grid cell, weighted by the
452 inverse of estimate variance at each site to account for uncertainties. The grid cell-level
453 estimates (Supplementary Data S2) were then used in the latitudinal analysis described below
454 and for the species-level maps (Supplementary Data S1). We also calculated community-level
455 responses (Fig. 2) by calculating the mean grid cell-level estimates across all species observed
456 in each grid cell, weighted by the inverse of estimate variance in each species to account for
457 uncertainties.

458 Water availability in the tropics may not necessarily depend on Dec-Feb precipitation.
459 Especially in South and Southeast Asia, where our tropical survey sites are concentrated, the
460 summer monsoon contributes to 80% of annual rainfall⁴². Thus we also tested the effect of
461 precipitation during June, July and August. We first calculated mean precipitation in June,
462 July and August in year $t-1$ for the IWC sites and in year t for the CBC sites. Then if the mean
463 Jun-Aug precipitation was higher than the mean Dec-Feb precipitation, we compared the AIC
464 between the model with Jun-Aug precipitation and the two models with the original
465 precipitation variables at each site for each species, and used the precipitation variable with
466 the smallest AIC in the final model. This allows using precipitation variables from different
467 seasons for different sites. The estimates were then used in the following analysis for
468 comparison with the original analysis (see Extended Data Figs. 7 and 8 for results).

469

470 *Latitudinal analysis*

471 We used absolute latitudes to test latitudinal patterns described in Extended Data Fig. 3 for
472 the following reason. Our data include species that are distributed only in either the northern
473 or southern hemisphere (one-hemisphere species) as well as those that appear in both the
474 hemispheres (two-hemisphere species). Some of our hypotheses (e.g., that for among-species
475 patterns in abundance changes with increasing temperature, shown at the top of Extended
476 Data Fig. 3) predict that one-hemisphere species would show a monotonic increase with raw
477 latitudes while two-hemisphere species would show a U-shaped relationship along the raw
478 latitudinal gradient with the lowest point at the equator; this makes analysing those species
479 together in the hierarchical modelling framework described below a complicated process.
480 With absolute latitudes, in contrast, one-hemisphere and two-hemisphere species are both
481 expected to show a monotonic increase, making the parameter estimation much simpler.

482 We tested the effects of explanatory variables on among- and within-species latitudinal
483 variations in (i) abundance responses to temperature and precipitation changes and (ii) the
484 importance of temperature and precipitation. For this analysis we used only 213 species with
485 estimates at ten or more grid cells. We adopted the within-subject centring approach⁴³ under a
486 hierarchical modelling framework to explicitly distinguish species-level effects (explaining
487 variations in species-level responses between species) and population-level effects
488 (explaining variations in population-level responses within species) of explanatory variables.
489 Here we defined each species responses at their absolute latitudinal range mid-points (for
490 migratory species, based only on their geographical range during non-breeding season) as
491 species-level responses, and responses within each grid cell as population-level responses.

492 In this model the species effect μ_s , representing the species-level responses to temperature
493 or precipitation increases in species s , is drawn from a normal distribution with mean of v_s and
494 variance of σ_v^2 . v_s is further modelled with species-level explanatory variables:

$$495 \quad v_s = \alpha + \beta_{B1}MIDLAT_s + \beta_{B2}MIDLAT_s^2 + \beta_{B3}LATRANGE_s + \beta_{B4}MIG_s + \beta_5BM_{B_s} +$$

$$496 \quad \beta_{B6}PROPNA_s + \eta_s,$$

497 where α is the global intercept and β_{B1-B6} represent the species-level effects. $MIDLAT_s$,
498 $LATRANGE_s$, MIG_s , BM_s , $PROPNA_s$ are species-level explanatory variables; absolute
499 latitudinal range mid-points, absolute latitudinal geographical range (degree), migration status
500 (migrant or non-migrant), body mass (g, log₁₀-transformed) and the mean proportion of
501 missing values (i.e., interpolated values) in count records across all sites (%) for species s ,
502 respectively. The variance inflation factor was smaller than 1.9 for all the species-level
503 explanatory variables, indicating that multi-collinearity was not a major issue. η_s is a random
504 term that accounts for phylogenetic dependence among species and is drawn from a
505 multivariate normal distribution^{44, 45}:

506
$$\eta_s \sim MVN(\mathbf{0}, \delta^2 \Sigma_\lambda),$$

507
$$\Sigma_\lambda = \lambda \Sigma + (1 - \lambda) \mathbf{I},$$

508 where Σ is a scaled variance-covariance matrix calculated from an ultrametric phylogenetic
 509 tree (defined below). By scaling Σ to a height of one, we can interpret δ^2 as the residual
 510 variance⁴⁴. For the strength of phylogenetic signal to vary, we also incorporated Pagel's λ ^{46, 47}
 511 into the matrix with the identity matrix \mathbf{I} . Here λ is a coefficient that multiplies the off-
 512 diagonal elements of Σ and a λ close to zero implies that the phylogenetic signal in the data is
 513 low, suggesting independence in the error structure of the data points, whereas a λ close to
 514 one suggests a good agreement with the Brownian Motion evolution model and thus suggests
 515 correlation in the error structure^{44, 47}. To incorporate uncertainties⁴⁸ in phylogenetic trees in
 516 the calculation of Σ , we used a sample of 100 trees from a comprehensive avian phylogeny⁴⁹
 517 as the prior distribution for our analysis⁴⁴. More specifically, one of the 100 trees was
 518 randomly drawn in each iteration and used for the calculation of Σ . In the sensitivity analysis
 519 using Jun-Aug precipitation we limited the range of η_s to between -0.2 and 0.2, based on the
 520 estimated values in the original analysis, in order to enhance the convergence of the models.

521 The population-level responses to temperature or precipitation increases $r_{s,i}$ of species s in
 522 grid cell i was then assumed to derive from a normal distribution with mean $\mu_{s,i}$ and variance
 523 σ_μ^2 , where $\mu_{s,i}$ is modelled using the species effect μ_s :

524
$$\mu_{s,i} = \mu_s + \beta_{w_{s,1}} \frac{LAT_{s,i} - MIDLAT_s}{LATRANGE_s} + \beta_{w_{s,2}} \left(\frac{LAT_{s,i} - MIDLAT_s}{LATRANGE_s} \right)^2 + \beta_{w_{s,3}} pNA_{s,i} + \gamma_{s,i}.$$

525 Here $\beta_{w_{s,1-3}}$ represents the population-level effect of absolute latitudes $LAT_{s,i}$ (in the form of
 526 linear and quadratic terms, to test non-linear patterns) and the mean proportion of missing
 527 values (i.e., interpolated values) in count records across all sites $pNA_{s,i}$ (%) of grid cell i for
 528 species s . Here within-species variations in population-level responses ($\mu_{s,i} - \mu_s$) are explained
 529 by within-species variations in absolute latitudes ($LAT_{s,i} - MIDLAT_s$), divided by the absolute

530 latitudinal geographical range of each species $LATRANGE_s$, so that the estimated effects of
 531 absolute latitudes are comparable among species with varying latitudinal range size. The
 532 species-specific $\beta_{W_s,1-3}$ is the random effect each governed by hyper-parameters as:

$$533 \quad \beta_{W_s,j} \sim Normal(h\beta_{W_j}, \sigma_{\beta_{W_j}}^2).$$

534 $\gamma_{s,i}$ accounts for spatial autocorrelation within each species and is drawn from an intrinsic
 535 Gaussian conditional autoregressive (CAR) prior distribution with variance $\sigma_{\gamma_s}^2$:

$$536 \quad \gamma_{s,i} | \gamma_{s,k} \sim Normal\left(\frac{\sum_{i \neq k} w_{i,k} \gamma_{s,k}}{n_i}, \frac{\sigma_{\gamma_s}^2}{n_i}\right),$$

537 where $w_{i,k} = 1$ if grid cells i and k are neighbours, and 0 otherwise. n_i is the total number of
 538 neighbours of grid cell i and neighbours here are defined as those grid cells directly adjacent,
 539 including those diagonal. $\sigma_{\gamma_s}^2$ controls the amount of variation between the random effects.

540 We tested latitudinal patterns in the importance of temperature and precipitation using
 541 essentially the same model but the population-level importance of temperature or
 542 precipitation $imp_{s,i}$ of species s in grid cell i was assumed to derive from a beta distribution
 543 with mean $c_{s,i}$ and variance $\frac{\alpha_i \beta_i}{(\alpha_i + \beta_i)^2 (\alpha_i + \beta_i + 1)}$ with a logit link function:

$$544 \quad \text{logit}(c_{s,i}) = \mu_s + \beta_{W_s,1} \frac{LAT_{s,i} - MIDLAT_s}{LATRANGE_s} + \beta_{W_s,2} \left(\frac{LAT_{s,i} - MIDLAT_s}{LATRANGE_s}\right)^2 + \beta_{W_s,3} pNA_{s,i} + \gamma_{s,i},$$

$$545 \quad \alpha_i = c_{s,i} \varphi_i,$$

$$546 \quad \beta_i = (1 - c_{s,i}) \varphi_i.$$

547 As latitudinal patterns might be different between two hemispheres, we also conducted the
 548 same latitudinal analysis separately for (i) narrowly-defined southern-hemisphere species (49
 549 species with maximum range latitude < 0), and (ii) all the other 164 species as “northern-
 550 hemisphere” species (see Supplementary Figs. S1-S4 for results).

551 The models were implemented with OpenBUGS 3.2.3⁵⁰ and the R2OpenBUGS package⁵¹
 552 in R 3.4.1³⁶. Following ¹⁷, as non-informative prior distributions, we used a Gamma

553 distribution with mean of 1 and variance of 100 for φ_i and the inverse of σ_v^2 , δ^2 , σ_μ^2 , $\sigma_{\beta_{Wj}}^2$
554 and $\sigma_{\gamma_s}^2$, a uniform distribution on the interval [0, 1] for λ , normal distributions with mean of
555 0 and variance of 100 for α , β_{Bk} , and $h\beta_{Wj}$. We ran each MCMC algorithm with three chains
556 with different initial values for 30,000 iterations with the first 10,000 discarded as burn-in and
557 the remainder thinned to one in every four iterations to save storage space. Model
558 convergence was checked with R-hat values.

559 Due to differences in the definition of species between the two sources used^{49, 52}, we
560 followed¹⁷ and combined two separate species defined in the BirdLife Checklist⁵² into one in
561 four cases for this species-level analysis: Kentish plover *Charadrius alexandrinus* and snowy
562 plover *C. nivosus*, common snipe *Gallinago gallinago* and Wilson's snipe *G. delicata*,
563 European herring gull *Larus argentatus* and Arctic herring gull *L. smithsonianus*, and
564 common moorhen *Gallinula chloropus* and common gallinule *G. galeata*. *Larus glaucooides*
565 *thayeri* was excluded from the latitudinal analysis as it is not included in either database. We
566 also excluded from the analysis eight seabird species in Alcidae and Sulidae as neither the
567 IWC nor CBC necessarily targets seabird species.

568 We also used R packages *ape*⁵³, *data.table*⁵⁴, *dplyr*⁵⁵, *ggplot2*⁵⁶, *gridExtra*⁵⁷, *mapdata*⁵⁸,
569 *plyr*⁵⁹, *png*⁶⁰, *RcolorBrewer*⁶¹, *rgdal*⁶², *raster*⁶³ and *viridis*⁶⁴.

570

571 **Data Availability**

572 The waterbird count data used in this study are collated and managed by Wetlands
573 International and the National Audubon Society, and are available from Wetlands
574 International at: <http://iwc.wetlands.org/>. The estimated abundance responses to temperature
575 and precipitation as well as the importance of temperature and precipitation for each grid cell

576 for each species are available as Supplementary Data S2. All the data on explanatory variables
577 are freely available as specified in Extended Data Fig. 4.

578

579 **Code Availability**

580 All the R codes used for the analyses are available as Supplementary Data S5-7.

581

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690

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710 **Author contributions**

711 T.A. designed the study. T.A., T.S., H.S.W., B.S., S.N., T.M., T.L., D.B. and N.L.M.
712 collected and prepared data for the analyses. T.A. analysed the data and wrote the paper. All
713 authors discussed the results and commented on the manuscript at all stages.

714 **Competing interests**

715 The authors declare no competing interests.

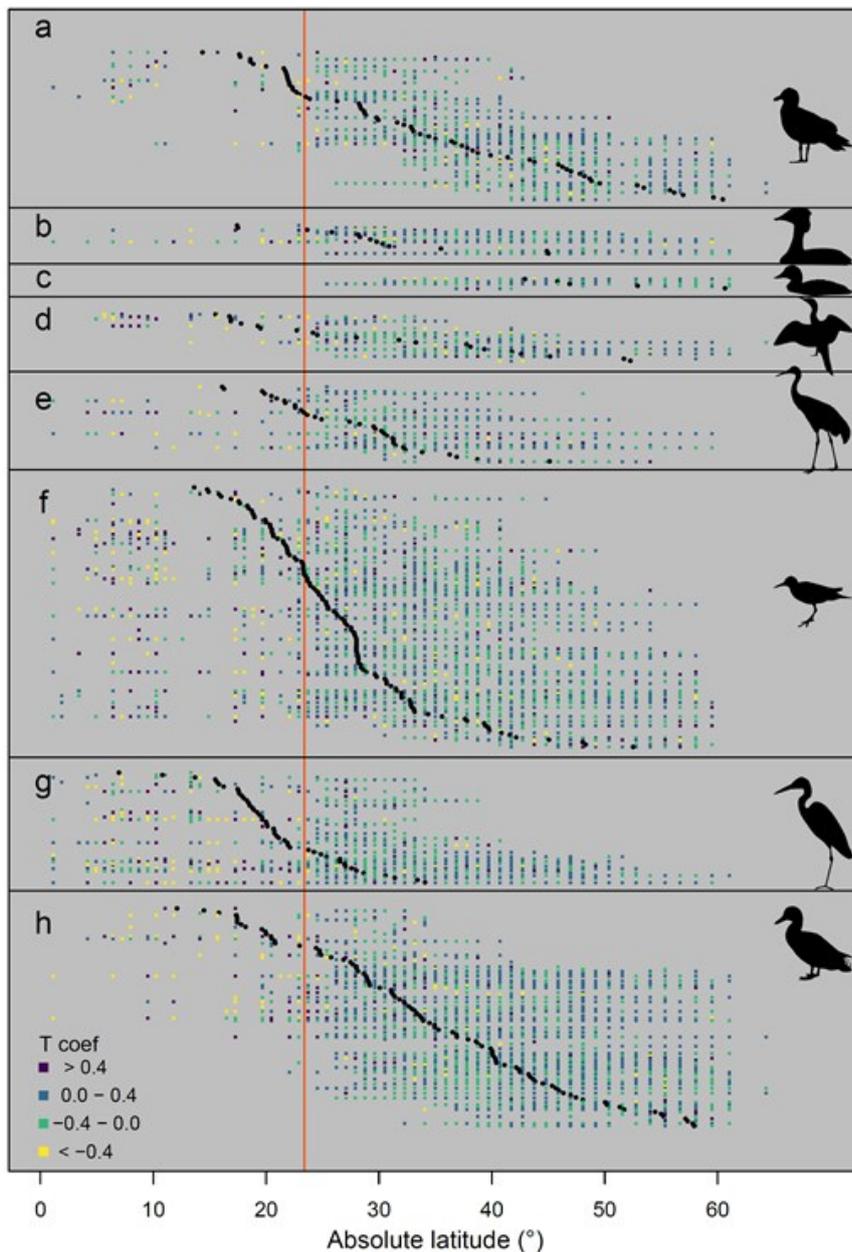
716 **Additional information**

717 **Extended data** is available for this paper.

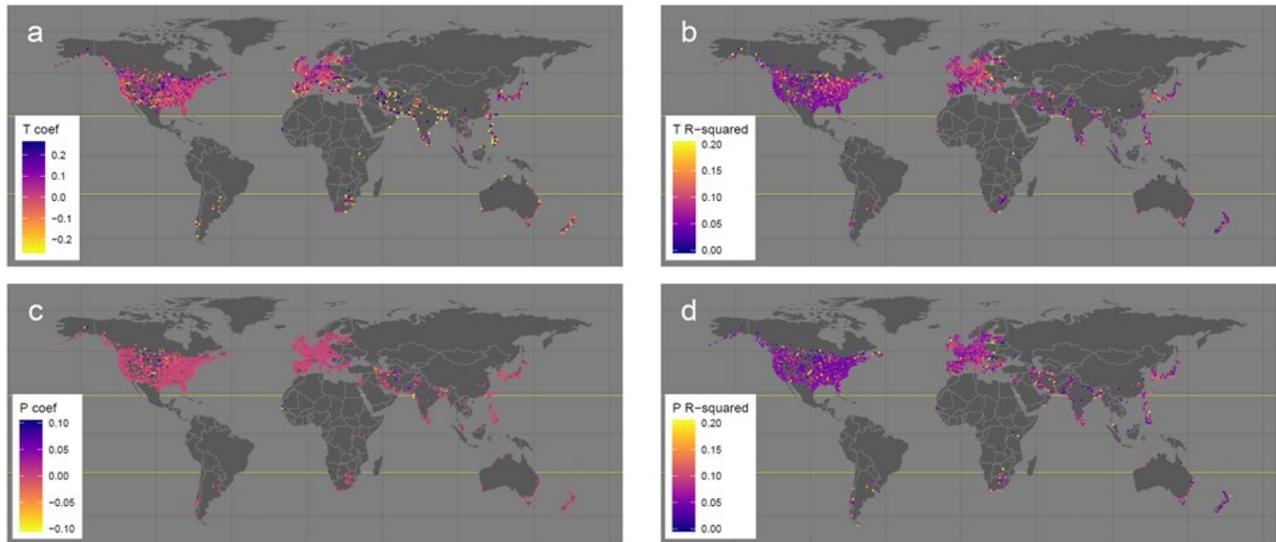
718 **Supplementary information** is available for this paper.

719 **Correspondence and requests for materials** should be addressed to T.A.

720 (t.amano@uq.edu.au)



721
 722 **Fig. 1. Latitudinal distribution of abundance responses to changes in temperature (T**
 723 **coef: the rate of abundance changes with increasing temperature) for each species.** Each
 724 horizontal row of squares shows the absolute latitudes of $1^\circ \times 1^\circ$ grid cells with estimates for
 725 each of the 390 species in (a) coursers, gulls, terns and auks, (b) grebes and flamingos, (c)
 726 loons and petrels, (d) pelicans, boobies and cormorants, (e) rails and cranes, (f) shorebirds, (g)
 727 storks, ibises and herons, and (h) waterfowl (see Methods for definition). Black circles
 728 indicate the median absolute latitude of geographical range of each species. Grid cells in the
 729 tropical region (the area on the left of the red vertical line) tend to show more negative
 730 responses (shown in yellow). Silhouettes reproduced from PhyloPic (<http://phylopic.org/>)
 731 under a Creative Commons licence (<http://creativecommons.org/licenses/by/3.0/>) (a–d, f–h)
 732 or Public Domain Dedication licence (<http://creativecommons.org/publicdomain/zero/1.0/>)
 733 (e). a, f, Rebecca. Groom; b, c, Doug Backlund (photo) (b) or Unknown (photo) (c), John E.
 734 McCormack, Michael. G. Harvey, Brant. C. Faircloth, Nicholas. G. Crawford, Travis. C.
 735 Glenn, Robb. T. Brumfield & T. Michael. Keesay; d, g, Shyamal/Wikimedia Commons; h,
 736 Maija Karala (image flipped horizontally).



737

738

Fig. 2. Mean abundance responses across 390 waterbird species to changes in

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temperature and precipitation in each $1^\circ \times 1^\circ$ grid cell. (a) The rate of abundance changes

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with increasing temperature (T coef), showing more negative responses to temperature

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increases at lower latitudes (shown with yellow dots) and positive responses at higher

742

latitudes (shown with purple dots), (b) the independent capacity of temperature in explaining

743

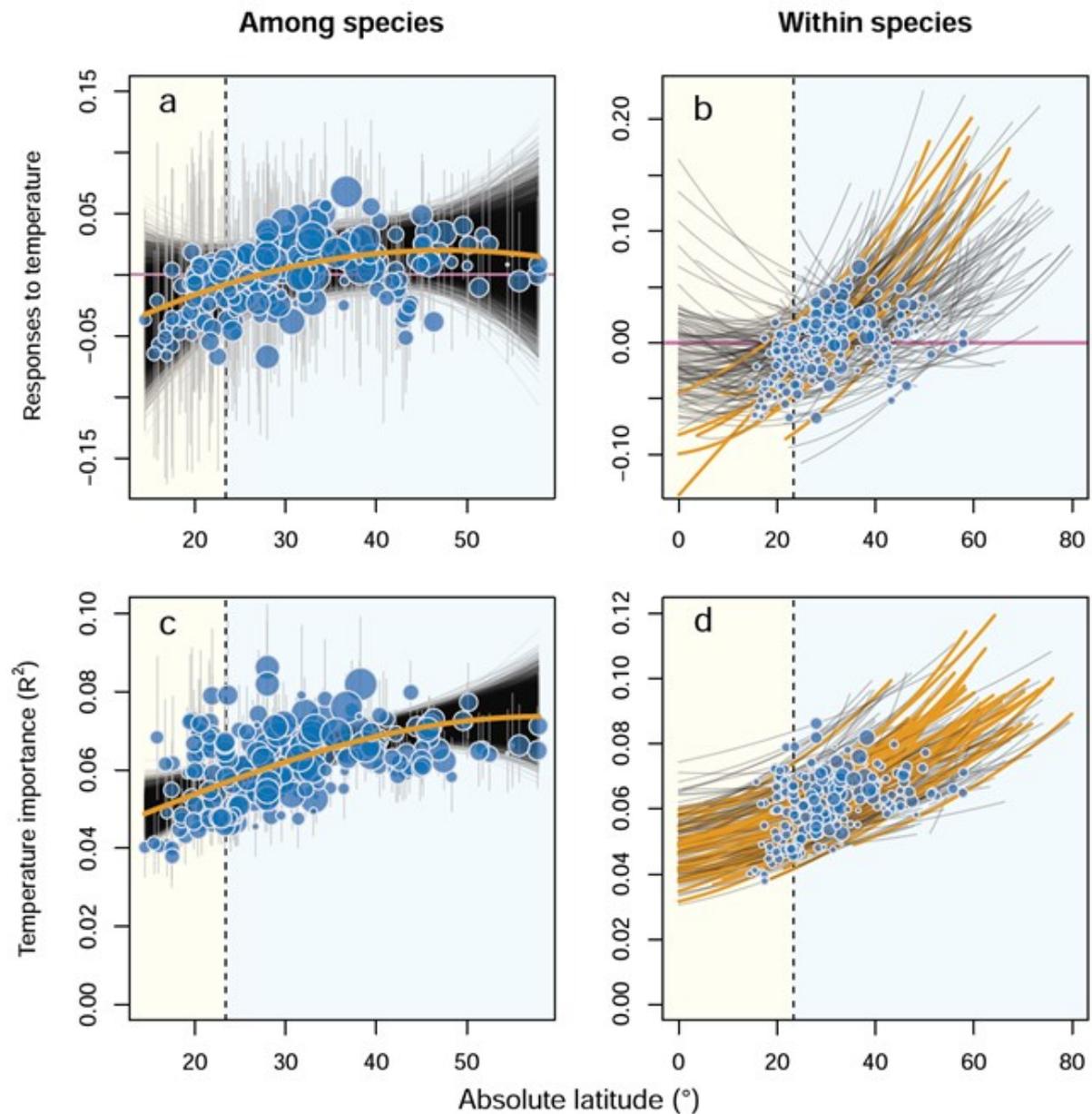
abundance changes (T R-squared), (c) the rate of abundance changes with increasing

744

precipitation (P coef) and (d) the independent capacity of precipitation in explaining

745

abundance changes (P R-squared). The region between the yellow solid lines is the tropics.



746

747 **Fig. 3. Latitudinal patterns in waterbird abundance responses to temperature increases.**

748 (a) Abundance responses to increasing temperature at 213 species' range mid-points and (b)

749 within each species, (c) the importance of temperature in explaining abundance changes at

750 species' range mid-points and (d) within each species. In (a) and (c), orange lines: among-

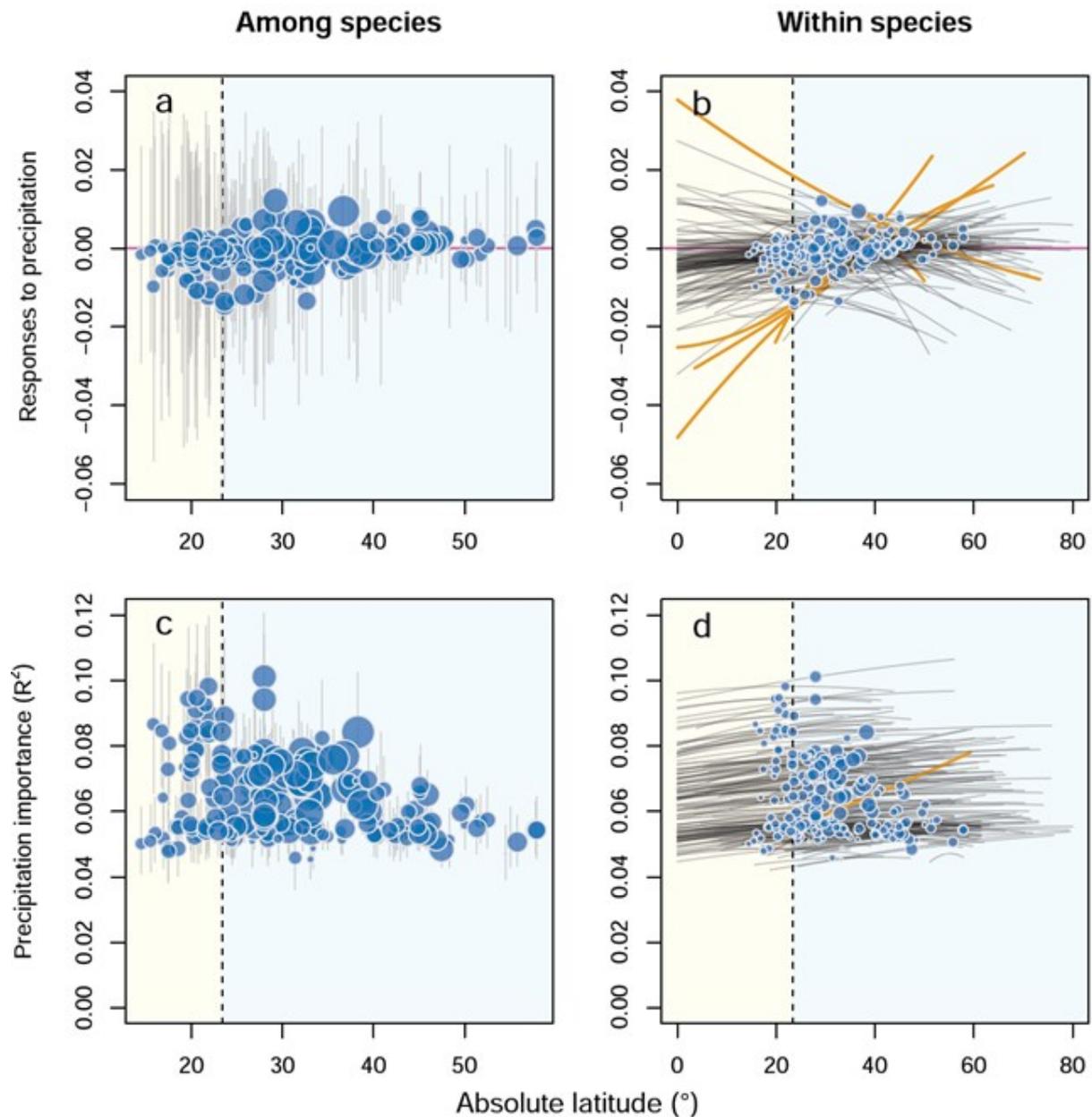
751 species patterns based on posterior median coefficients; black lines: patterns with all posterior

752 samples; blue circles: responses at each species' range mid-points; grey lines: 95% credible

753 intervals; circle size: the absolute latitudinal range size. In (b) and (d) regression lines: within-

754 species latitudinal patterns for each species based on posterior median coefficients (significant

755 patterns in orange). Yellow area: the tropics.



756

757 **Fig. 4. Latitudinal patterns in waterbird abundance responses to precipitation increases.**

758 (a) Abundance responses to increasing precipitation at 213 species' range mid-points and (b)

759 within each species, (c) the importance of precipitation in explaining abundance changes at

760 species' range mid-points and (d) within each species. In (a) and (c), orange lines: among-

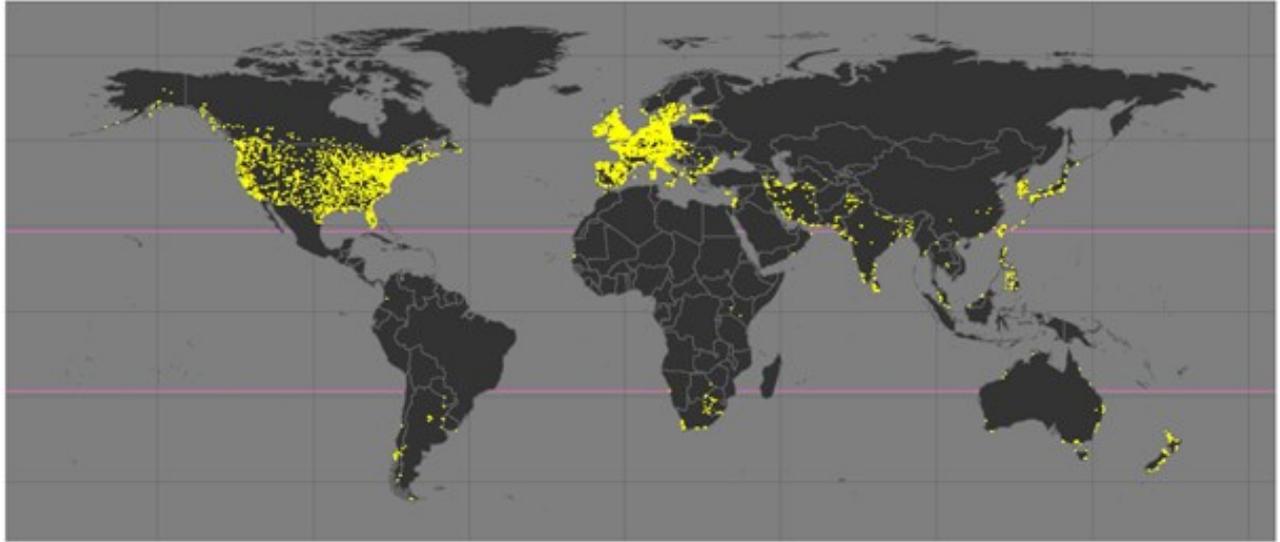
761 species patterns based on posterior median coefficients; black lines: patterns with all posterior

762 samples; blue circles: responses at each species' range mid-points; grey lines: 95% credible

763 intervals; circle size: the absolute latitudinal range size. In (b) and (d) regression lines: within-

764 species latitudinal patterns for each species based on posterior median coefficients (significant

765 patterns in orange). Yellow area: the tropics.

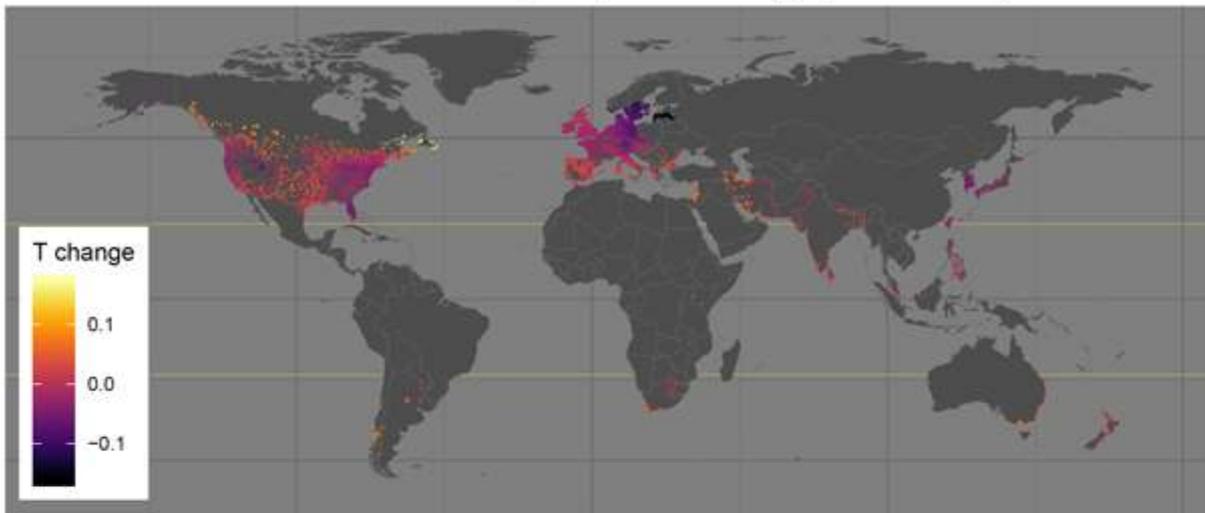


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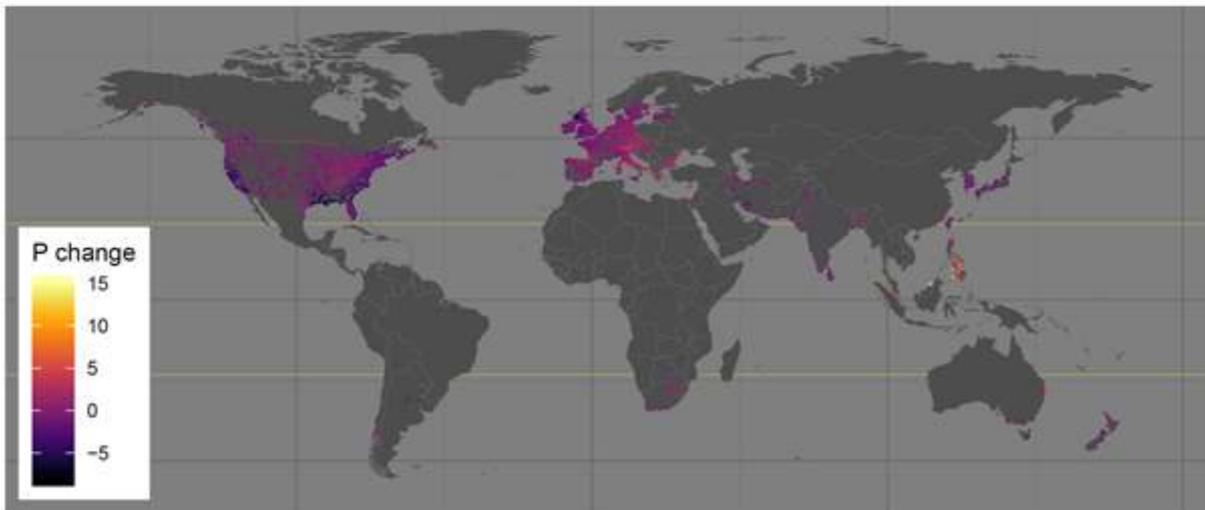
767 **Extended Data Fig. 1. Distribution of the 6,822 survey sites used in the analyses.** The area

768 between pale pink lines represents the tropical region.

a. Annual rate of January temperature change (1990 – 2013)



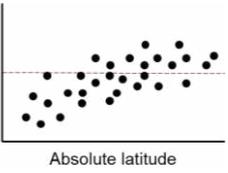
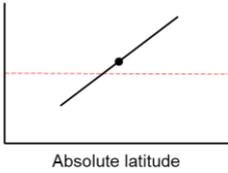
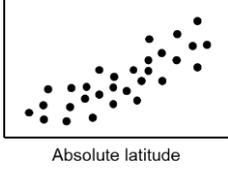
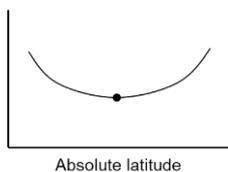
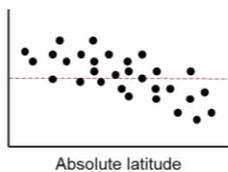
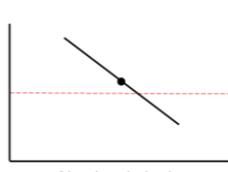
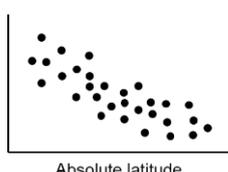
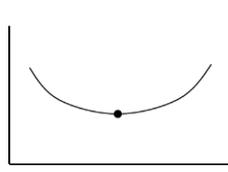
b. Annual rate of January precipitation change (1990 – 2013)



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770

771 **Extended Data Fig. 2. Annual rates of changes in January mean temperature and**
772 **precipitation at the 6,822 survey sites used in the analyses.** The area between yellow lines
773 represents the tropical region.

Hypotheses	Expected latitudinal patterns (each dot represents the range midpoint of each species, with solid lines showing within-species patterns; dotted lines represent zero, i.e., no response). Note that latitudes are absolute values; see Methods for more detail.	Supporting evidence
Abundance changes with increasing temperature · Among species	Monotonic increase with absolute latitudes, with negative responses in species at lower latitudes + -  Absolute latitude	At lower latitudes, where temporal variation in temperature is lower, bird species tend to have a narrower thermoneutral zone (TNZ; the range of temperatures within which the metabolism of an endotherm is lowest and almost independent of ambient temperature) and are thus more likely to experience a thermal mismatch under climate change (maximum ambient temperature exceeds upper TNZ limit) ^{16, 65}
· Within species	Monotonic increase with absolute latitudes, with negative responses in populations at lower latitudes and positive responses in populations at higher latitudes + -  Absolute latitude	Populations at higher latitudes benefit from, and those at lower latitudes are negatively affected by, temperature increase ⁶⁶ , if all populations have the same fitness curve with the optimal climatic niche at the latitudinal midpoint of its range ⁶⁷
Importance of temperature in explaining abundance changes · Among species	Monotonic increase with absolute latitudes  Absolute latitude	Species-richness patterns at high latitudes are often limited by ambient energy (correlated with temperature) and at low latitudes by moisture availability ⁶⁸ . If species richness represents the summation of individual population response, the same is applicable to species-level responses in abundance ⁴ .
· Within species	Higher at both range edges  Absolute latitude	If climatic factors limit species distributions ⁶⁹ , they are expected to be more important determinants of species abundance at range edges ⁷⁰ .
Abundance changes with increasing precipitation · Among species	Monotonic decrease, with negative responses in species at higher latitudes + -  Absolute latitude	Increase in Dec-Feb precipitation (and associated increase in water level, decrease in habitat heterogeneity, and increased thermoregulatory cost under wet weather) is observed to negatively affect waterbird abundance at higher latitudes (e.g., Europe ^{71,72} and Argentina ³⁰) while higher precipitation increases the availability of wetlands and vegetation in dry parts of the tropics (e.g., the Sahel region ^{73,23}) although effects may depend on each species' ecology ²³ .
· Within species	Monotonic decrease, with negative responses in populations at higher latitudes + -  Absolute latitude	Within-species patterns are expected to be similar to among-species patterns, especially for wide-ranging species.
Importance of precipitation in explaining abundance changes · Among species	Monotonic decrease with absolute latitudes  Absolute latitude	Species-richness patterns at high latitudes are often limited by ambient energy and at low latitudes by moisture availability (correlated with precipitation) ⁶⁸ . Assuming that species richness represents the summation of individual population response, the same is applicable to species-level responses in abundance ⁴ .
· Within species	Higher at both range edges  Absolute latitude	If climatic factors limit species distributions ⁶⁹ , they are expected to be more important determinants of species abundance at range edges ⁷⁰ .

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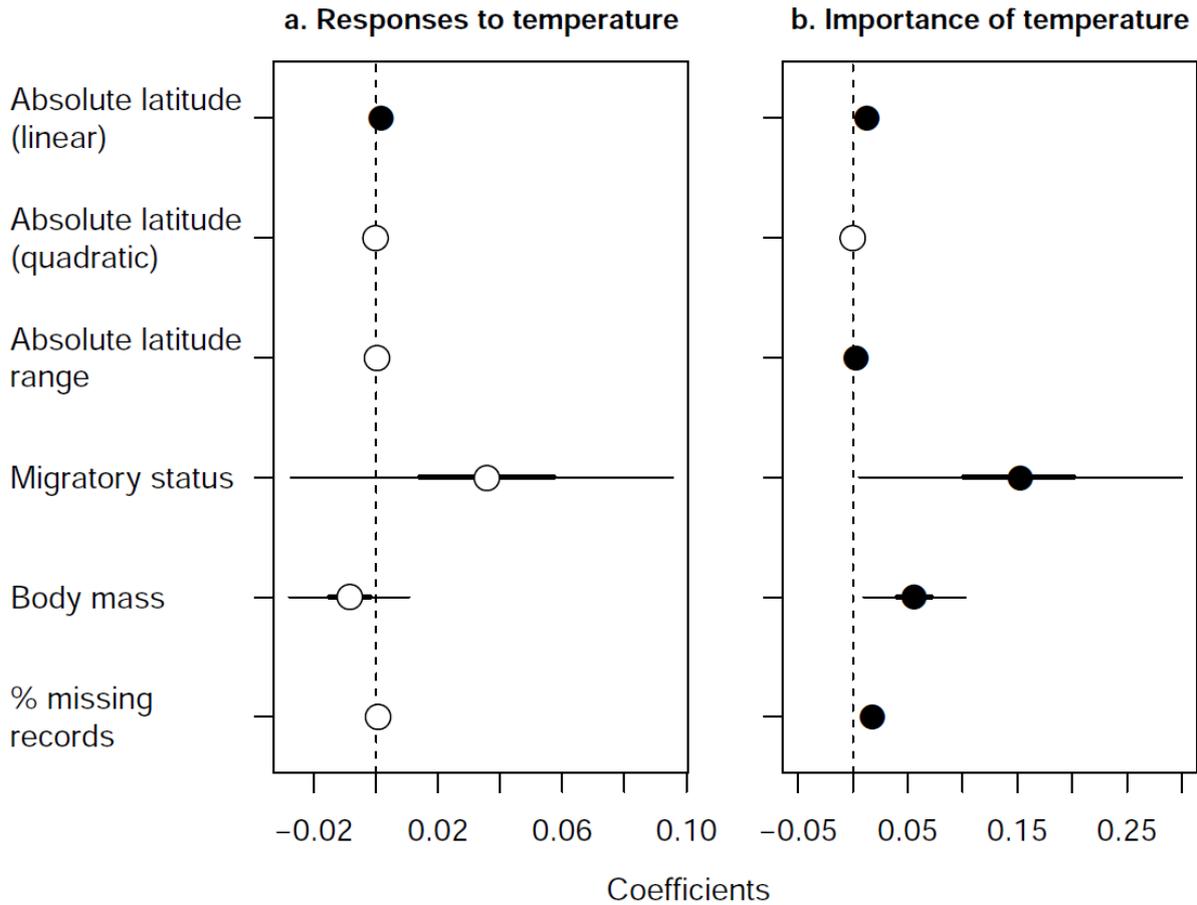
777

Extended Data Fig. 3. Hypotheses tested for explaining among- and within-species latitudinal variations in waterbird abundance responses to temperature and precipitation changes.

Hypotheses	Expected patterns	Variables used	Data sources
Latitudinal geographical range	<ul style="list-style-type: none"> Species with a narrower latitudinal range have narrower temperature niche, thus more vulnerable to temperature increases (i.e., the rate of abundance changes with increasing temperature is more negative)⁷⁴. Species with a narrower latitudinal range have narrower temperature niche, thus their abundance is affected more by temperature changes (i.e., the importance of temperature is higher)⁷⁴. 	Differences between maximum and minimum absolute latitudes of geographical range	BirdLife Data Zone*
Migratory status	<ul style="list-style-type: none"> Resident species can be more negatively affected by temperature increases, due to their limited dispersal ability (i.e., the rate of abundance changes with increasing temperature is more negative)²⁶. Migratory species generally have a higher dispersal ability²⁶ and track climate niches to a greater extent than resident species²⁷, thus can be more responsive to changes in local temperature and precipitation (i.e., the importance of temperature and precipitation is higher). Migratory species often show fidelity to breeding and non-breeding sites between years, thus may be less responsive to changes in local temperature and precipitation (i.e., the importance of temperature and precipitation is lower)⁷⁵. Migratory species can also be affected by conditions at multiple locations (e.g., climatic factors and threats at different migratory stages), thus local climatic conditions may play a limited role in explaining their abundance (i.e., the importance of temperature and precipitation is lower)⁷⁶. 	Migrant or non-migrant	BirdLife Data Zone*
Body size	<ul style="list-style-type: none"> Smaller-sized species can be more negatively affected by increasing temperature, due to their limited dispersal ability (i.e., the rate of abundance changes with increasing temperature is more negative)²⁶. Larger-sized species have a higher dispersal ability, thus may be more responsive to changes in local temperature and precipitation (i.e., the importance of temperature and precipitation is higher)²⁶. 	Body mass (g)	Elton Traits 1.0 ⁷⁷

778 * <http://datazone.birdlife.org/home>

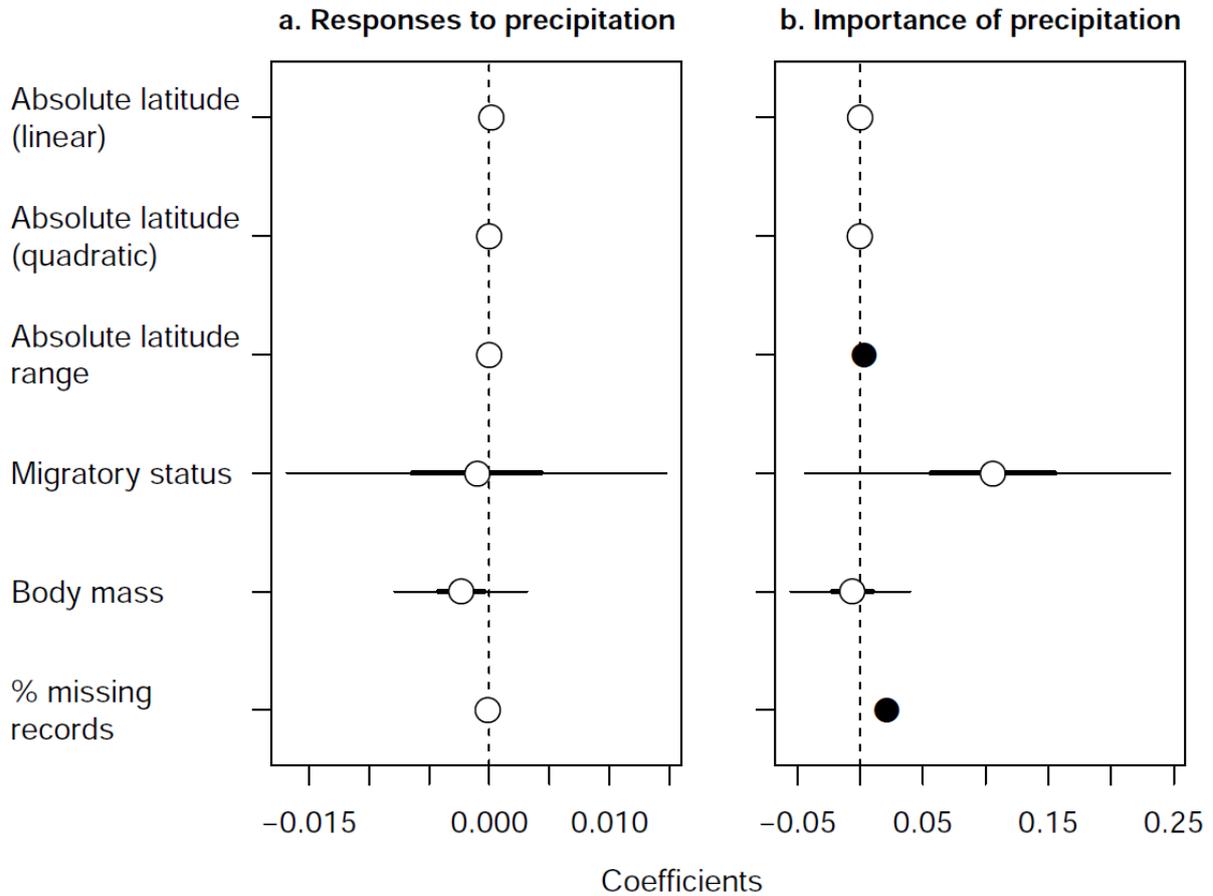
779 **Extended Data Fig. 4. Additional hypotheses tested for explaining among-species**
780 **variations in waterbird abundance responses to temperature and precipitation changes.**



781

782 **Extended Data Fig. 5. Effects of species-level predictors on waterbird abundance**

783 **responses to temperature changes.** The estimated coefficients with 95% and 50% (thick
 784 lines) credible intervals of six explanatory variables for explaining among-species variations
 785 in the rate of abundance changes with increasing temperature (a) and the importance of
 786 temperature in explaining abundance changes (b). Filled circles indicate variables with 95%
 787 credible intervals not overlapping with zero. Only 213 species for which there were estimates
 788 at ten or more grid cells were analysed. Note that the estimated coefficients for *Absolute*
 789 *latitude (linear)* in both (a) and (b) and for *Absolute latitude range* in (b) are all positive.



790

791 **Extended Data Fig. 6. Effects of species-level predictors on waterbird abundance**

792 **responses to precipitation changes.** The estimated coefficients with 95% and 50% (thick

793 lines) credible intervals of six explanatory variables for explaining among-species variations

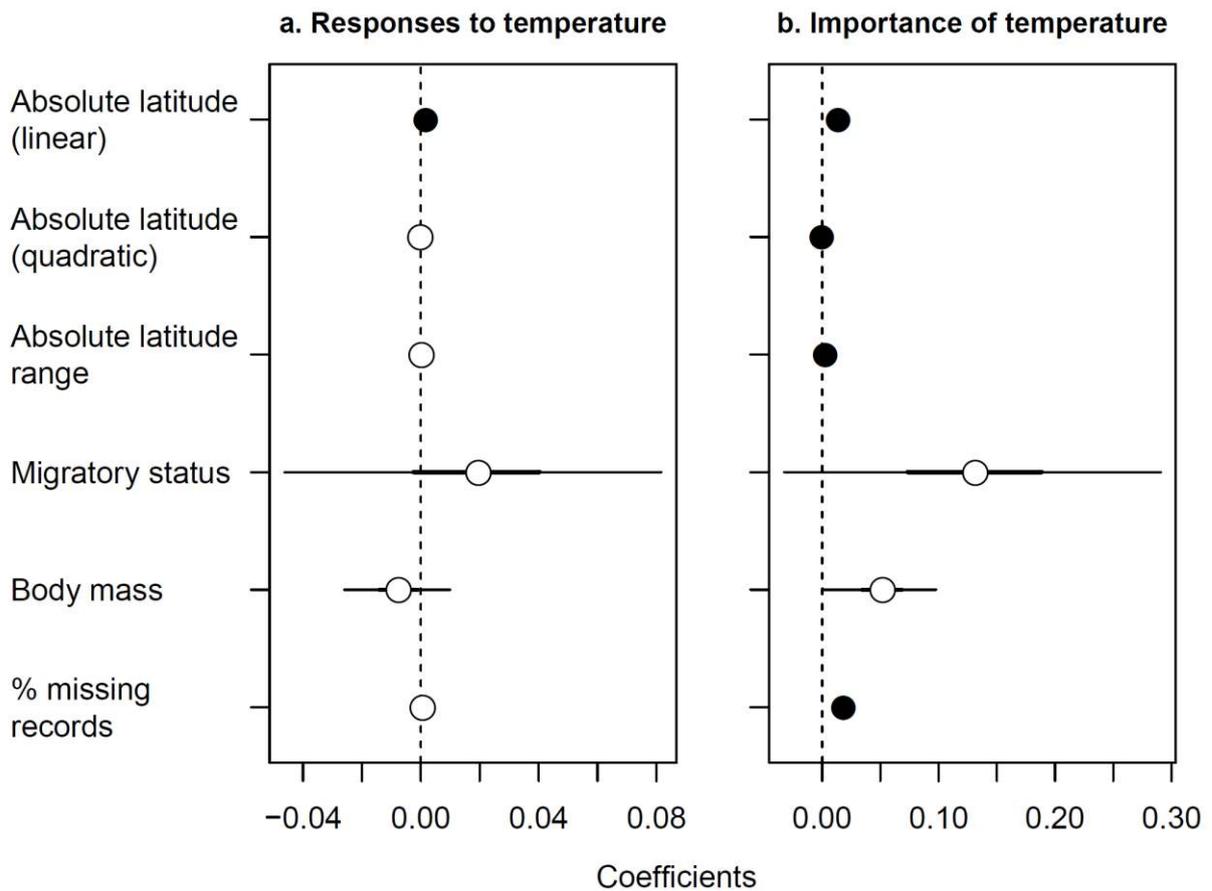
794 in the rate of abundance changes with increasing precipitation (a) and the importance of

795 precipitation in explaining abundance changes (b). Filled circles indicate variables with 95%

796 credible intervals not overlapping with zero. Only 213 species for which there were estimates

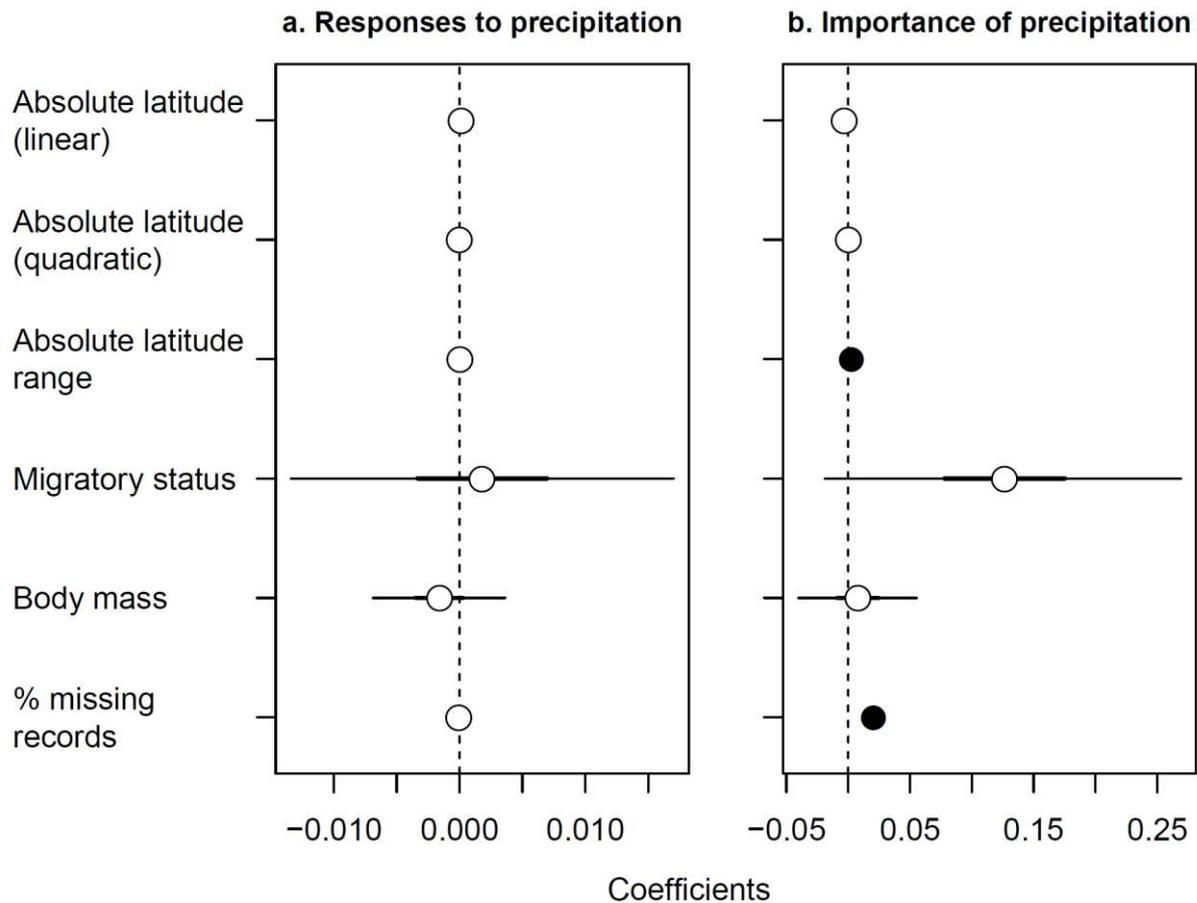
797 at ten or more grid cells were analysed. Note that the estimated coefficient for *Absolute*

798 *latitude range* in (b) is positive.



799

800 **Extended Data Fig. 7. Sensitivity of the results on responses to temperatures to the**
 801 **choice of precipitation seasons.** Effects of species-level predictors on waterbird abundance
 802 responses to temperature changes when using precipitation during June, July and August in
 803 the model (see **Statistical Analyses** for more detail). The estimated coefficients with 95% and
 804 50% (thick lines) credible intervals of six explanatory variables for explaining among-species
 805 variations in the rate of abundance changes with increasing temperature (a) and the
 806 importance of temperature in explaining abundance changes (b). Filled circles indicate
 807 variables with 95% credible intervals not overlapping with zero. Only 213 species for which
 808 there were estimates at ten or more grid cells were analysed. Note that the estimated
 809 coefficients for *Absolute latitude (linear)* in both (a) and (b) and for *Absolute latitude range* in
 810 (b) are positive while that for *Absolute latitude (quadratic)* in (b) is negative.



811

812 **Extended Data Fig. 8. Sensitivity of the results on responses to precipitations to the**

813 **choice of precipitation seasons.** Effects of species-level predictors on waterbird abundance

814 responses to precipitation changes when using precipitation during June, July and August in

815 the model (see **Statistical Analyses** for more detail). The estimated coefficients with 95% and

816 50% (thick lines) credible intervals of six explanatory variables for explaining among-species

817 variations in the rate of abundance changes with increasing precipitation (a) and the

818 importance of precipitation in explaining abundance changes (b). Filled circles indicate

819 variables with 95% credible intervals not overlapping with zero. Only 213 species for which

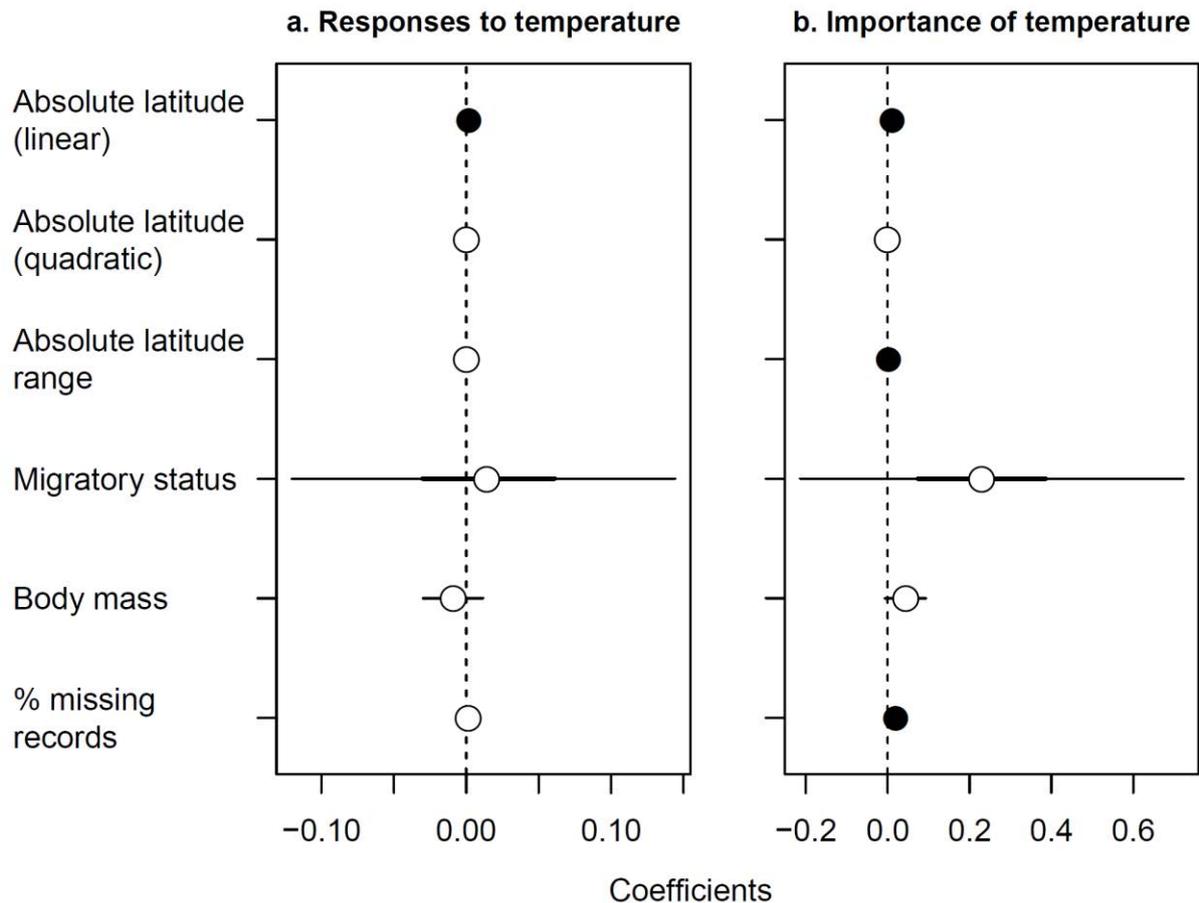
820 there were estimates at ten or more grid cells were analysed. Note that the estimated

821 coefficient for *Absolute latitude range* in (b) is positive.

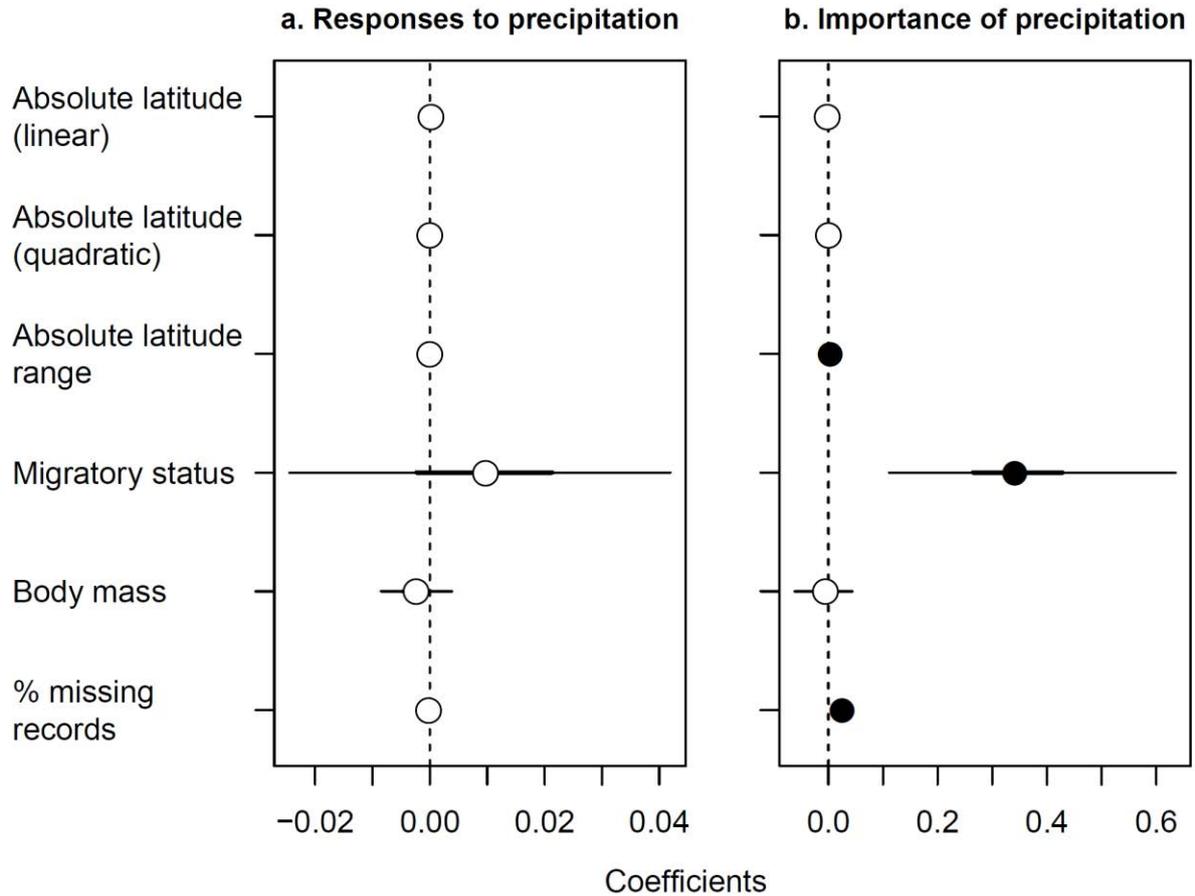
Supplementary Information

Responses of global waterbird populations to climate change vary with latitude

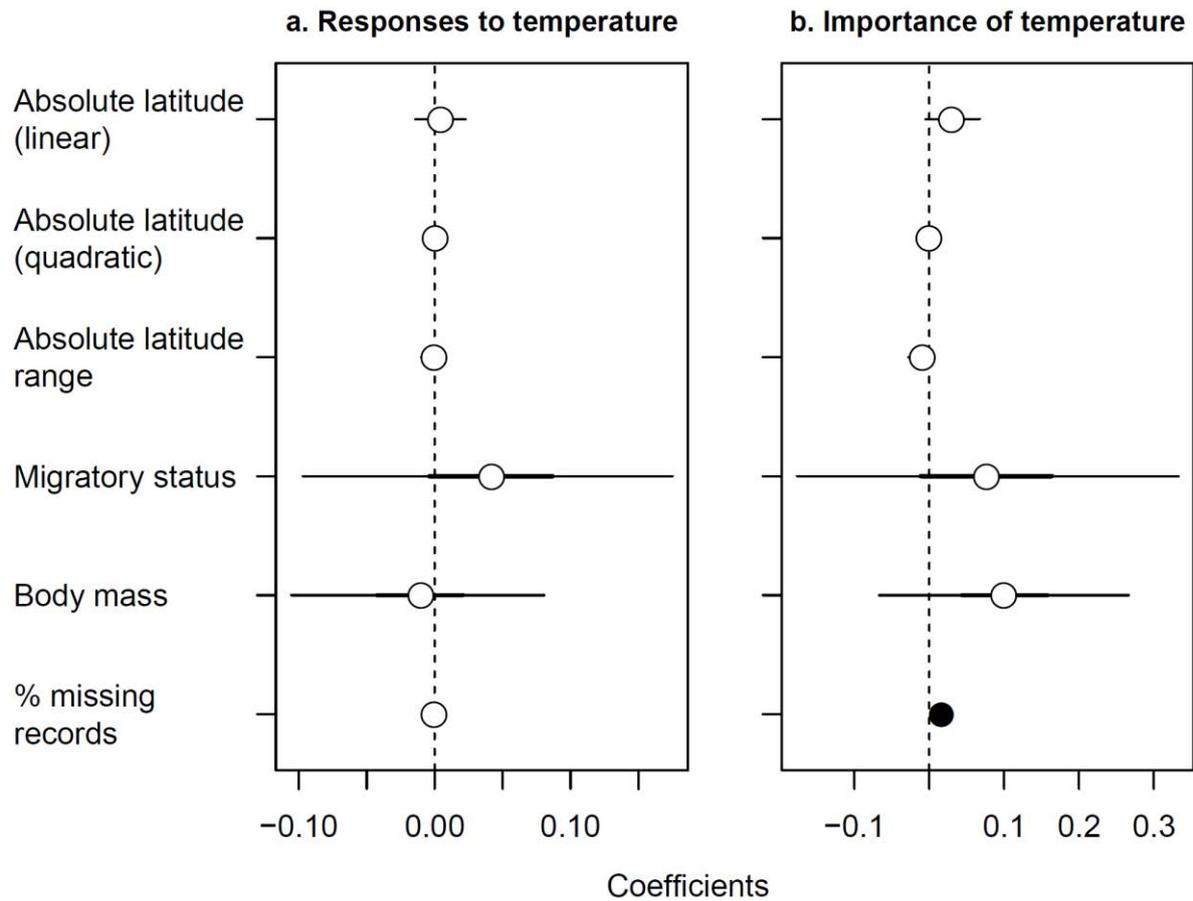
Tatsuya Amano, Tamás Székely, Hannah S. Wauchope, Brody Sandel, Szabolcs Nagy, Taej Mundkur, Tom Langendoen, Daniel Blanco, Nicole L. Michel, William J. Sutherland



Supplementary Fig. S1. Effects of species-level predictors on waterbird abundance responses to temperature changes at the northern hemisphere. The estimated coefficients with 95% and 50% (thick lines) credible intervals of six explanatory variables for explaining among-species variations in the rate of abundance changes with increasing temperature (a) and the importance of temperature in explaining abundance changes (b). Filled circles indicate variables with 95% credible intervals not overlapping with zero. Only 164 northern hemisphere species were analysed (see **Statistical Analysis** for more details). Note that the estimated coefficients for *Absolute latitude (linear)* in both (a) and (b) and for *Absolute latitude range* and *% missing records* in (b) are all positive.

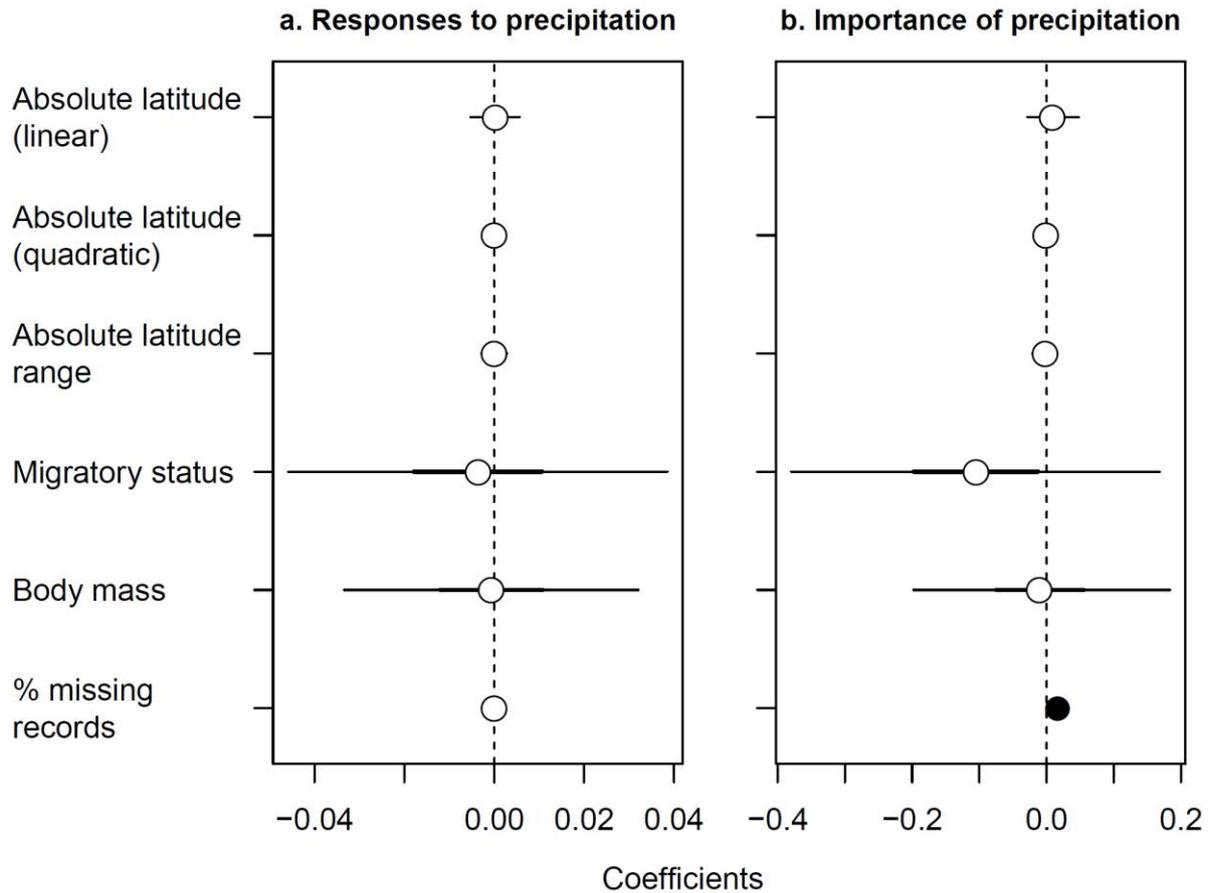


Supplementary Fig. S2. Effects of species-level predictors on waterbird abundance responses to precipitation changes at the northern hemisphere. The estimated coefficients with 95% and 50% (thick lines) credible intervals of six explanatory variables for explaining among-species variations in the rate of abundance changes with increasing precipitation (a) and the importance of precipitation in explaining abundance changes (b). Filled circles indicate variables with 95% credible intervals not overlapping with zero. Only 164 northern hemisphere species were analysed (see **Statistical Analysis** for more details). Note that the estimated coefficient for *Absolute latitude range* in (b) is positive.

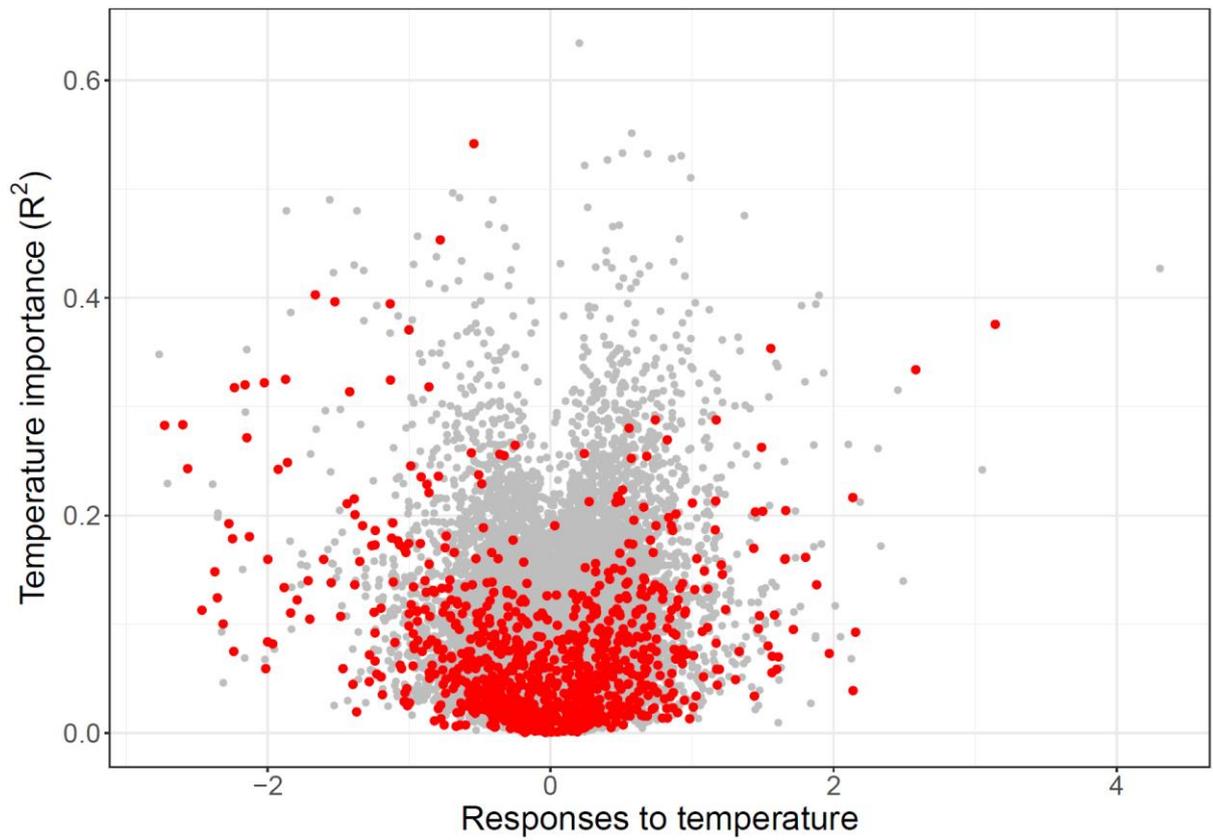


Supplementary Fig. S3. Effects of species-level predictors on waterbird abundance

responses to temperature changes at the southern hemisphere. The estimated coefficients with 95% and 50% (thick lines) credible intervals of six explanatory variables for explaining among-species variations in the rate of abundance changes with increasing temperature (a) and the importance of temperature in explaining abundance changes (b). Filled circles indicate variables with 95% credible intervals not overlapping with zero. Only 49 southern hemisphere species were analysed (see **Statistical Analysis** for more details).



Supplementary Fig. S4. Effects of species-level predictors on waterbird abundance responses to precipitation changes at the southern hemisphere. The estimated coefficients with 95% and 50% (thick lines) credible intervals of six explanatory variables for explaining among-species variations in the rate of abundance changes with increasing precipitation (a) and the importance of precipitation in explaining abundance changes (b). Filled circles indicate variables with 95% credible intervals not overlapping with zero. Only 49 southern hemisphere species were analysed (see **Statistical Analysis** for more details).



Supplementary Fig. S5. Grid cell-level relationship between abundance responses to temperature and temperature importance. Each dot represents estimates for each species within each 1° × 1° grid cell. Grid cells in the tropical region (absolute latitude < 23.4) are shown in red.