Supplementary information for:

Global intensification of heat extremes has halved the abundance of tropical birds

Maximilian Kotz[1, 2], Tatsuya Amano[3, 4], James Watson[3, 4]

[1] Research Department IV of complexity science, Potsdam Institute for Climate Impact Research, Potsdam, Germany

[2] Climate Change and Variability Group, Barcelona Supercomputing Centre, Spain

[3] School of the Environment, University of Queensland, Queensland, Australia

[4] Centre for Biodiversity and Conservation Science, University of Queensland, Queensland, Australia

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Supplementary Tables 1-5

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Dependent Variable:	Abundance growth
Model:	(1)
Variables	
l(Abundance level,1)	-0.4634***
	(0.0285)
l(Human pressure,1)	-0.0413*
	(0.0224)
l(Daily temp. extremes,1) × Biome = Boreal	-0.0003
	(0.0003)
l(Daily temp. extremes,1) × Biome = Mediterranean	-0.0017***
	(0.0006)
l(Daily temp. extremes,1) × Biome = Other	0.0007
	(0.0085)
l(Daily temp. extremes,1) × Biome = Temperate	-0.0004
	(0.0004)
l(Daily temp. extremes,1) × Biome = Tropical	-0.0039***
	(0.0011)
l(Daily temp. extremes,1) × Biome = Tundra	0.0005
	(0.0008)
l(Daily precip. extremes,1)	-0.0017**
	(0.0007)
l(Annual precipitation,1)	3.9×10^{-5}**
	(1.61×10^{-5})
Fixed-effects	
ID	Yes
Fit statistics	
Observations	88,827
R^2	0.29008
Within R^2	0.23923
BIC	94,380.6

Clustered (ID) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Supplementary Table 1. Model with biome interaction. The results of a model in which the effect of daily temperature extremes is interacted with biome rather than absolute latitude. Biomes are aggregated to larger groups, see methods.

Dependent Variable:	Abundance growth rate			
Model:	(1)	(2)	(3)	(4)
Variables				
l(Abundance level,1)	-0.4055***	-0.4083***	-0.4279***	-0.4436***
	(0.0337)	(0.0316)	(0.0299)	(0.0295)
l(Human pressure,1)	-0.0468	-0.0374	-0.0459*	-0.0507**
	(0.0375)	(0.0355)	(0.0278)	(0.0249)
l(Daily temp. extremes,1)	-0.0059***	-0.0058***	-0.0061***	-0.0047***
	(0.0015)	(0.0013)	(0.0013)	(0.0013)
l(Daily temp. extremes,2)	-0.0026*	-0.0027**	-0.0021	-0.0010
	(0.0014)	(0.0013)	(0.0015)	(0.0014)
l(Daily temp. extremes,3)	-0.0014	-0.0017	-3.16×10^{-5}	
	(0.0012)	(0.0011)	(0.0013)	
l(Daily temp. extremes,4)	-0.0022	-0.0015		
	(0.0013)	(0.0013)		
l(Daily temp. extremes,5)	-0.0013			
	(0.0013)			
l(Daily temp. extremes × Abs. Latitude,1)	0.0001***	0.0001***	0.0001***	8.09×10^{-5}***
	(2.95×10^{-5})	(2.57×10^{-5})	(2.54×10^{-5})	(2.59×10^{-5})
l(Daily temp. extremes × Abs. Latitude,2)	4.74×10^{-5}*	5.01×10^{-5}**	3.86×10^{-5}	1.72×10^{-5}
	(2.65×10^{-5})	(2.49×10^{-5})	(2.82×10^{-5})	(2.65×10^{-5})
l(Daily temp. extremes × Abs. Latitude,3)	1.95×10^{-5}	2.8×10^{-5}	-3.13×10^{-6}	
	(2.4×10^{-5})	(2.24×10^{-5})	(2.46×10^{-5})	
l(Daily temp. extremes × Abs. Latitude,4)	4.07×10^{-5}	3.35×10^{-5}		
	(2.59×10^{-5})	(2.54×10^{-5})		
l(Daily temp. extremes × Abs. Latitude,5)	2.41×10^{-5}			
	(2.45×10^{-5})			
l(Daily precip. extremes,1)	-0.0010	-0.0009	-0.0020***	-0.0016**
	(0.0006)	(0.0006)	(0.0006)	(0.0006)
l(Daily precip. extremes,2)	-0.0012*	-0.0015**	-0.0011*	6.23×10^{-6}
	(0.0006)	(0.0007)	(0.0006)	(0.0006)
l(Daily precip. extremes,3)	-0.0014**	-0.0013**	-0.0014**	
	(0.0007)	(0.0007)	(0.0007)	
l(Daily precip. extremes,4)	9.39×10^{-5}	-0.0001		
	(0.0006)	(0.0006)		
l(Daily precip. extremes,5)	-0.0009*			
	(0.0006)			
l(Annual precipitation,1)	1.67×10^{-5}	1.06×10^{-5}	4.18×10^{-5}***	3.58×10^{-5}**
	(1.34×10^{-5})	(1.35×10^{-5})	(1.44×10^{-5})	(1.53×10^{-5})
l(Annual precipitation,2)	3.32×10^{-5}**	5.12×10^{-5}***	6.19×10^{-5}***	3.52×10^{-5}**
	(1.39×10^{-5})	(1.43×10^{-5})	(1.51×10^{-5})	(1.51×10^{-5})
l(Annual precipitation,3)	1.7×10^{-5}	2.28×10^{-5}	2.09×10^{-5}	
	(1.48×10^{-5})	(1.54×10^{-5})	(1.54×10^{-5})	
l(Annual precipitation,4)	2.85×10^{-6}	-6.75×10^{-7}		
	(1.32×10^{-5})	(1.4×10^{-5})		
l(Annual precipitation,5)	3.14×10^{-5}**			
	(1.47×10^{-5})			
Fixed-effects				
ID	Yes	Yes	Yes	Yes
Fit statistics				
Observations	74,567	77,838	81,266	84,877
R^2	0.23861	0.25162	0.26424	0.27311
Within R^2	0.20683	0.20733	0.22038	0.22889
BIC	47,042.4	55,237.4	66,108.5	78,425.3

Clustered (ID) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Supplementary Table 2. Lag model for the impacts of climate on bird abundance. Columns (1-4) show models including 5 to 2 lags of each climate variable. Significant impacts of temperature extremes are detected in both the first and second year after exposure, when sufficient lags are included. Impacts of precipitation typically show significant effects in the second year after exposure, and the third for extreme precipitation and first for total precipitation, depending on the lag structure included.

Dependent Variable:	Abundance growth
Model:	(1)
Variables	
l(Abundance level,1)	-0.4315***
	(0.0297)
l(Human pressure,1)	-0.0376*
	(0.0209)
l(Daily temp. extremes,1) × Passeriformes = 0	-0.0045**
	(0.0020)
l(Daily temp. extremes,1) × Passeriformes = 1	-0.0052***
	(0.0012)
l(Daily temp. extremes × abslat,1) × Passeriformes = 0	0.0001***
	(3.97×10^{-5})
l(Daily temp. extremes × abslat,1) × Passeriformes = 1	7.39×10^{-5}***
	(2.32×10^{-5})
l(Daily precip. extremes,1)	-0.0015**
	(0.0006)
l(Total annual precip.,1)	3.13×10^{-5}**
	(1.53×10^{-5})
Fixed-effects	
ID	Yes
Fit statistics	
Observations	87,468
R^2	0.24204
Within R^2	0.22362
BIC	78,819.9

Clustered (ID) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Supplementary Table 3. Model for impacts of climate on abundance with an interaction indicating whether bird populations fall within the Passeriformes Order.

Dependent Variable:	Abundance growth
Model:	(1)
Variables	
l(Abundance level,1)	-0.4496***
	(0.0326)
l(Human pressure,1)	-0.0429*
	(0.0225)
l(Daily temp. extremes,1) × Passeriformes = 0	-0.0051**
	(0.0020)
l(Daily temp. extremes,1) × Passeriformes = 1	-0.0052***
	(0.0012)
l(Daily temp. extremes × abslat,1) × Passeriformes = 0	0.0001***
	(4.08×10^{-5})
l(Daily temp. extremes × abslat,1) × Passeriformes = 1	7.35×10^{-5}***
	(2.33×10^{-5})
l(Daily precip. extremes,1)	-0.0013**
	(0.0006)
l(Total annual precip.,1)	2.24×10^{-5}
	(1.49×10^{-5})
Fixed-effects	
ID	Yes
Fit statistics	
Observations	84,309
R^2	0.25198
Within R^2	0.23386
BIC	68,561.3

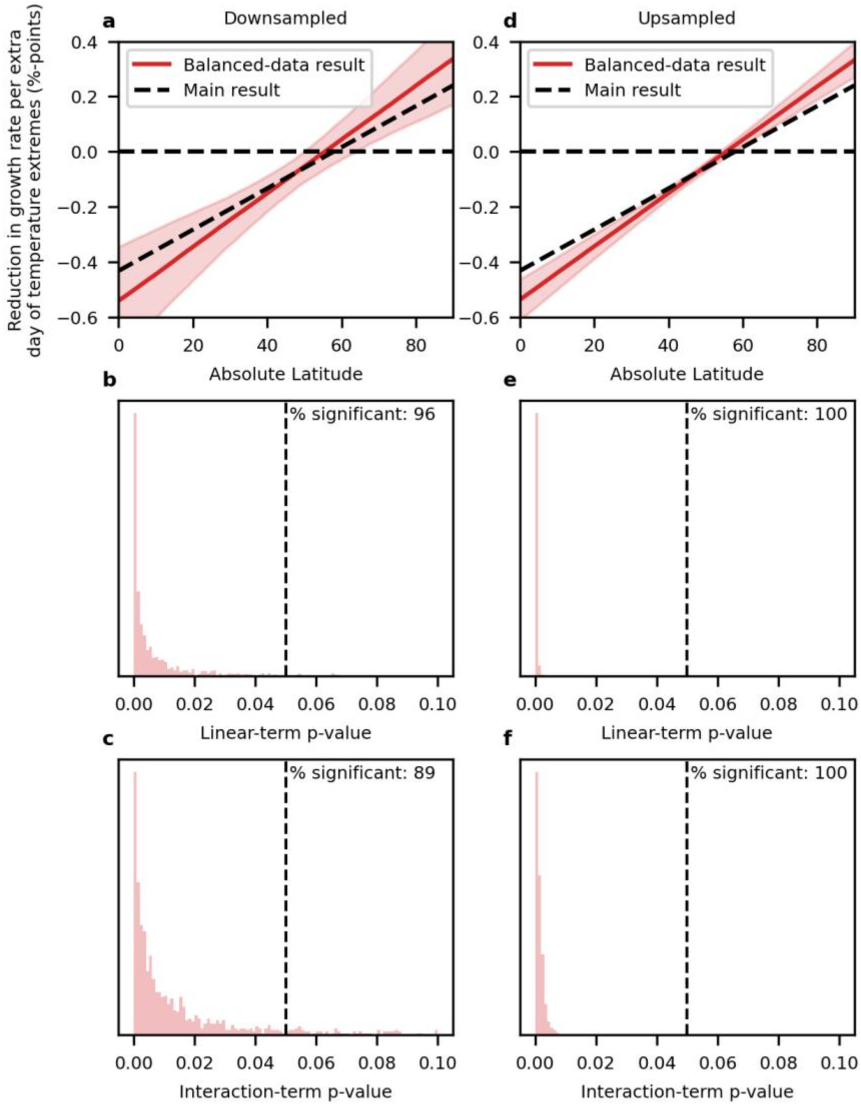
Clustered (ID) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Supplementary Table 4. As Table S3 but excluding birds in the Anseriformes Order.

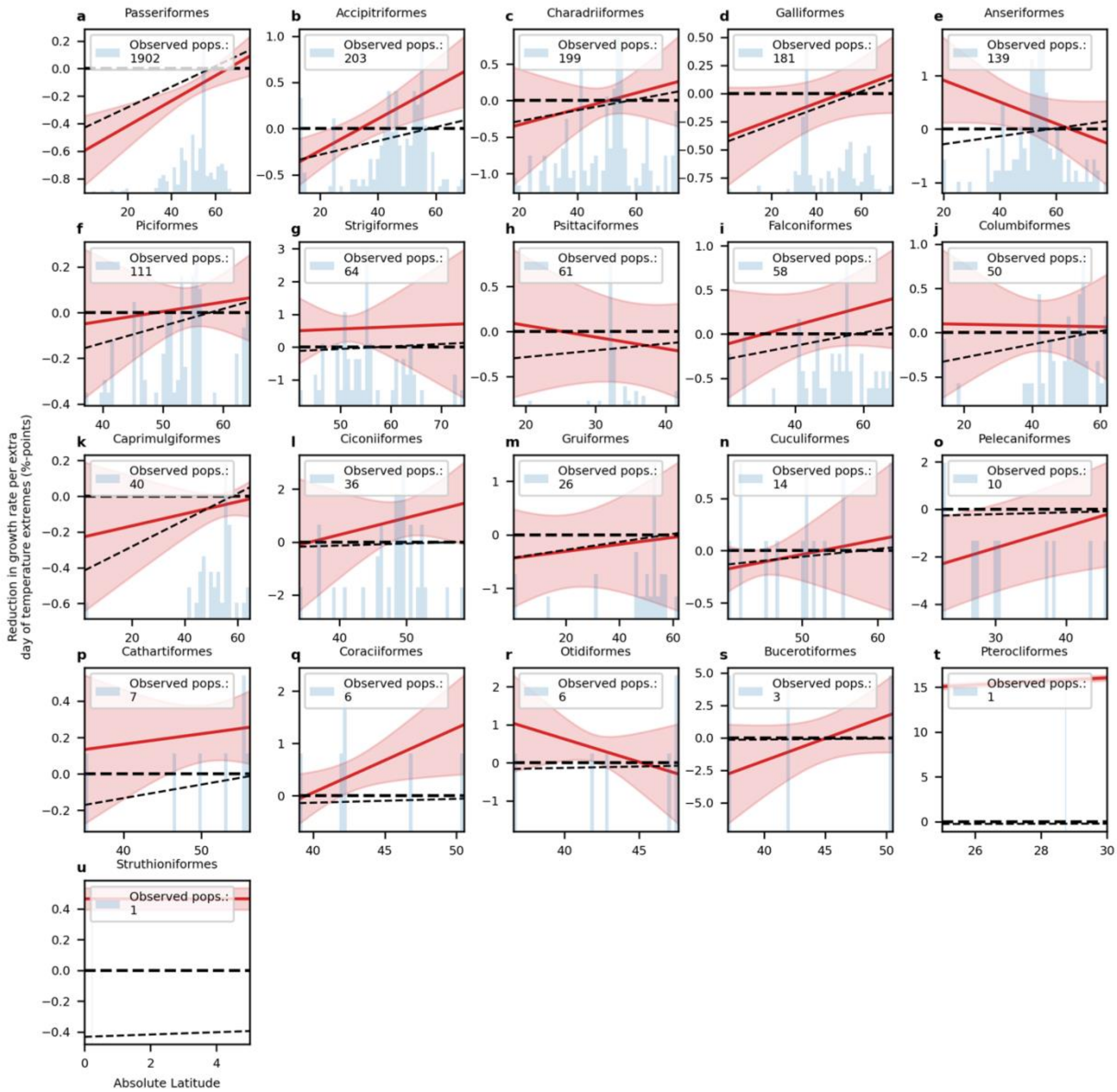
Dependent Variable:	Abundance growth
Model:	(1)
Variables	
l(Abundance level,1)	-0.4308***
	(0.0297)
l(Human pressure,1)	-0.0374*
	(0.0211)
l(Daily temp. extremes,1) × Resident = Non-resident	-0.0062***
	(0.0021)
l(Daily temp. extremes,1) × Resident = Resident	-0.0044***
	(0.0014)
l(Daily temp. extremes × abslat,1) × Resident = Non-resident	0.0001***
	(4.01×10^{-5})
l(Daily temp. extremes × abslat,1) × Resident = Resident	5.94×10^{-5}*
	(3.17×10^{-5})
l(Daily precip. extremes,1)	-0.0015**
	(0.0006)
l(Total annual precip.,1)	2.97×10^{-5}*
	(1.53×10^{-5})
Fixed-effects	
ID	Yes
Fit statistics	
Observations	87,468
R^2	0.24167
Within R^2	0.22324
BIC	78,863.2

Clustered (ID) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

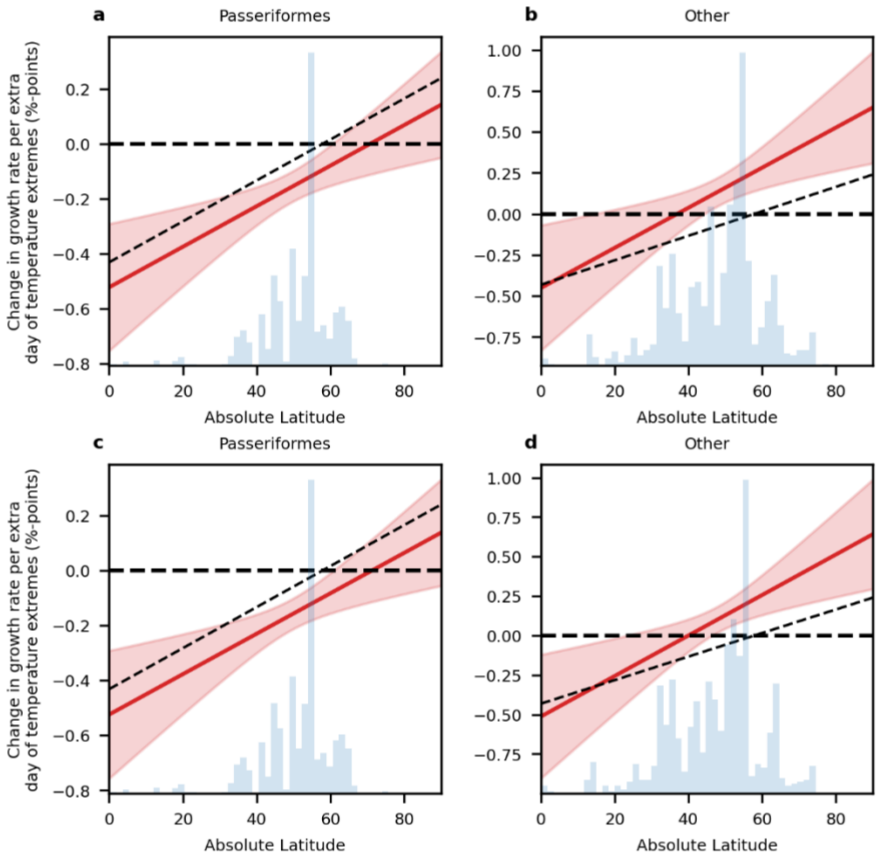
Supplementary Table 5. Model for the impacts of climate conditions on abundance growth including an interaction between temperature extremes, latitude and migratory status of birds. Data on migratory status of birds is taken from the AVONET database (see Methods), in which they are defined as resident or partially or predominantly migratory (the latter two we group as non-resident).



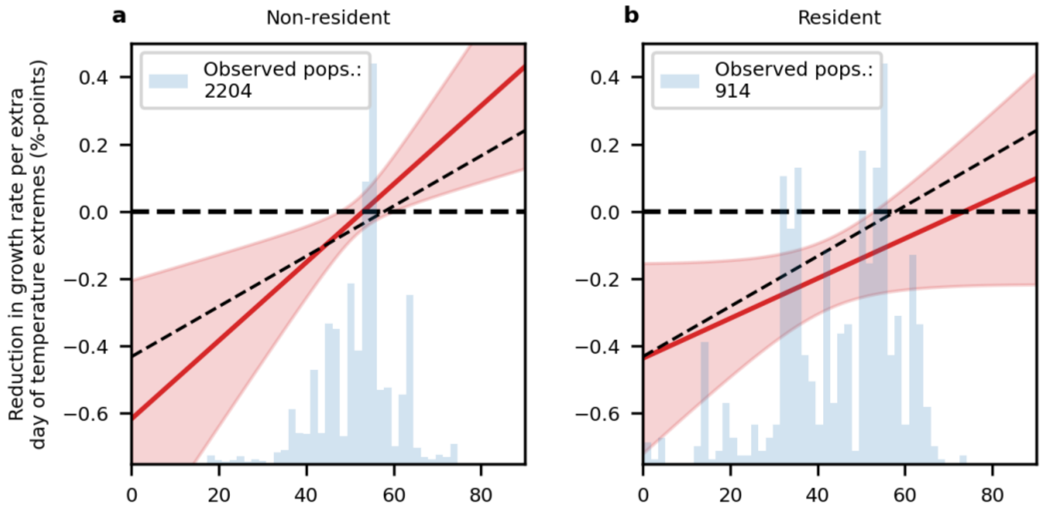
Supplementary Figure 1. The robustness of the impacts of heat extremes on bird abundance to geographic bias in observed bird populations. Estimates of the main empirical model as shown in Table 1 Column 3 and Figure 2a, having down- (a) and up-sampled (d) the data to obtain a balanced distribution of observed populations by biome. Solid red lines show the median and shaded area the 5th and 95th percentiles of the estimated marginal effects resulting from resampling the data 1,000 times. Dashed black lines show the estimate from the main model without resampling. The p-value of the parameters of the linear (b, e) and interaction term (c, f) coefficients for the impact of heat extremes are shown as histograms below, with the percentage of samples in which the parameters are significant shown inset (having assessed the coefficient uncertainty using Driscoll-Kraay standard errors to reflect spatial dependence as in Table 1 Column 4).



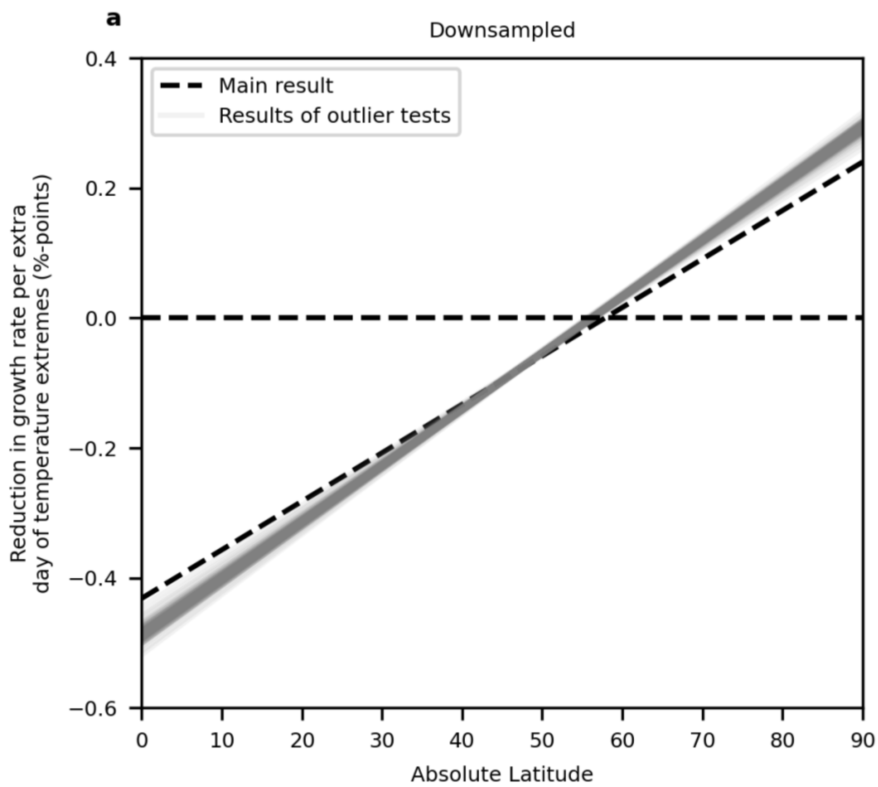
Supplementary Figure 2. Heterogenous impacts by taxonomic Order. Estimates impact of heat extremes on abundance growth in terrestrial birds using interaction effects with both absolute latitude and Order. Panels (a-u) show the response for each Order, arranged from those with the largest number of available observed populations to those with the least. Solid red lines show the mean estimated response, and heavy and light shaded area the 95% confidence intervals based on clustering standard errors at the population level. Dashed black lines show the estimate from the main model including all Orders. The number of distinct populations within each Order are show inset in each panel, with the distribution of populations shown as the underlying histogram.



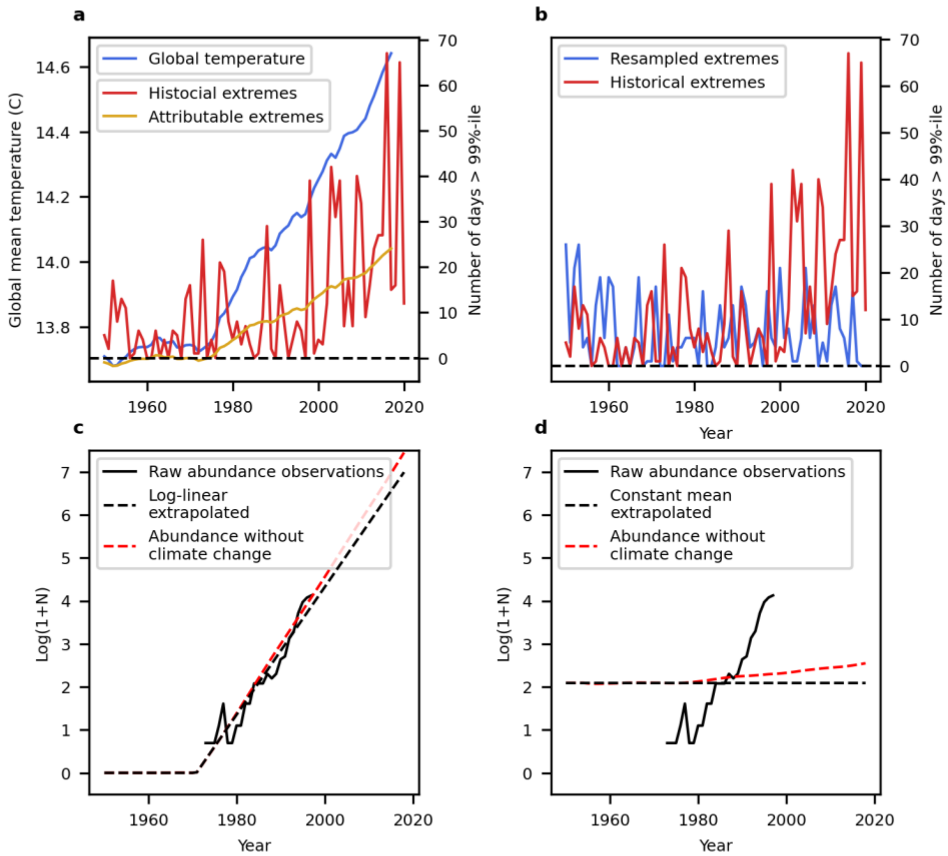
Supplementary Figure 3. Impacts across Passeriformes and other bird Orders. Estimated impact of heat extremes on abundance growth in the Passeriformes order (a) and other Orders (b) from a model which includes (a-b, model shown in Supplementary Table 3) or removes the Anseriformes Order which contains waterbirds (c-d, model shown in Supplementary Table 4). Solid red lines show the mean estimated response, and heavy and light shaded area the 95% confidence intervals based on clustering standard errors at the population level. Dashed black lines show the estimate from the main model including all Orders.



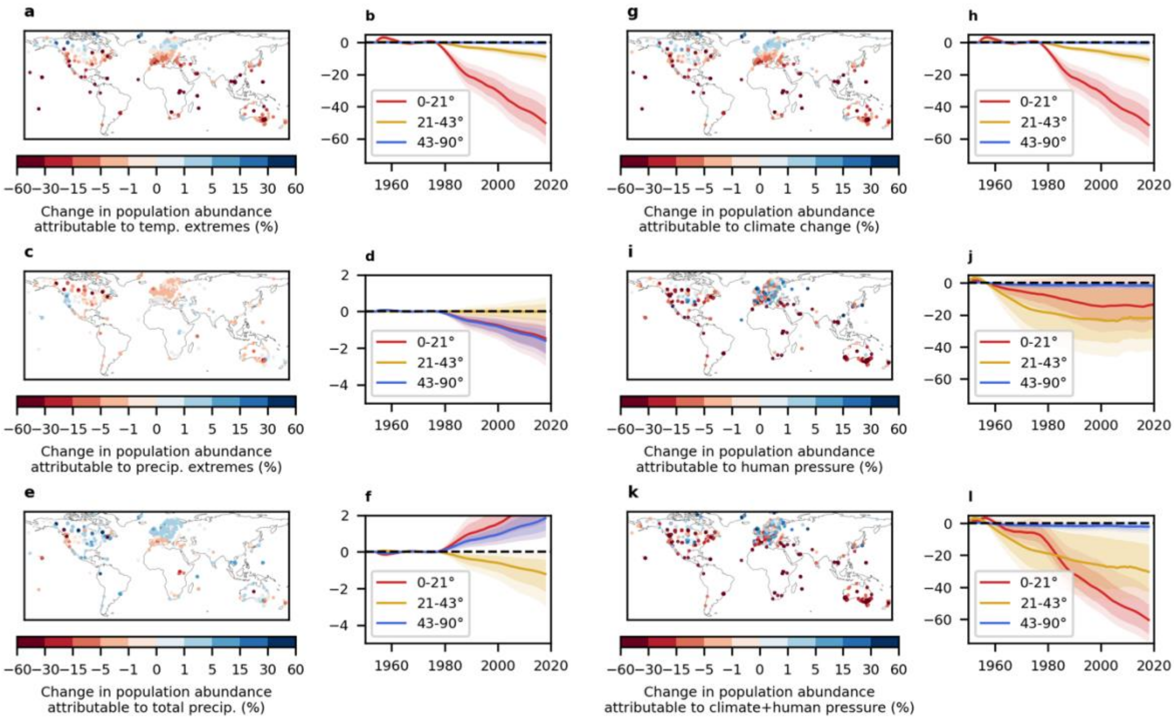
Supplementary Figure 4. Impacts of heat extremes on abundance growth rate in bird populations which are resident or non-resident in their habitat (partially or largely migratory). We assess a model in which the impacts of heat extremes are interacted with both latitude and an indicator variable for whether each bird species is resident or non-resident (results for the model are shown in Table S5). To do so we merge data on ecological traits of birds from AVONET (see Methods) which distinguishes whether birds are resident, partially or fully migratory. Central estimates for each type of bird populations are shown in solid red with 95% confidence intervals shown shaded Dashed black lines show the estimate from the main model shown in Fig. 2a.



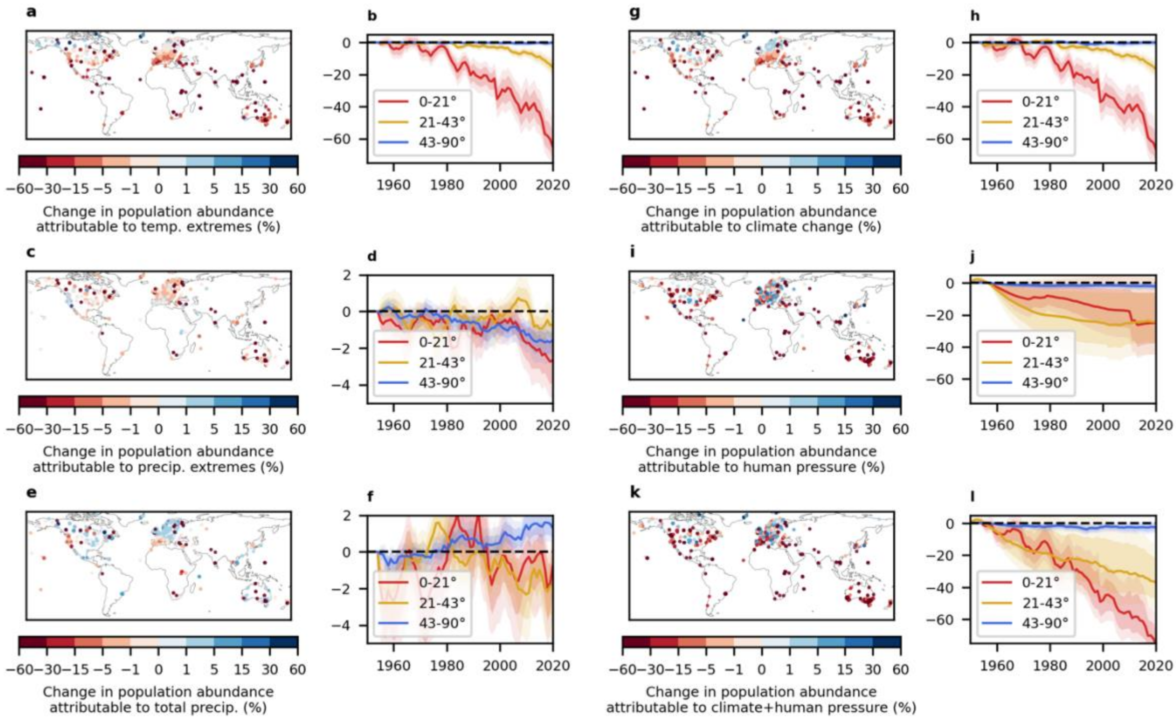
Supplementary Figure 5. Testing the robustness of the impacts of temperature extremes on bird abundance growth to potential outliers. The results for the main regression as shown in Fig. 2a are shown in dashed black, and the results of additional regressions in which individual populations have been dropped from the database and the overall model re-estimated are shown in light grey (3,118 additional model results from dropping each population once). The regression coefficients for the direct impact of heat extremes and their interaction with latitude are significant at the 5% level in every case that a single population is dropped from the data before re-estimating the main model.



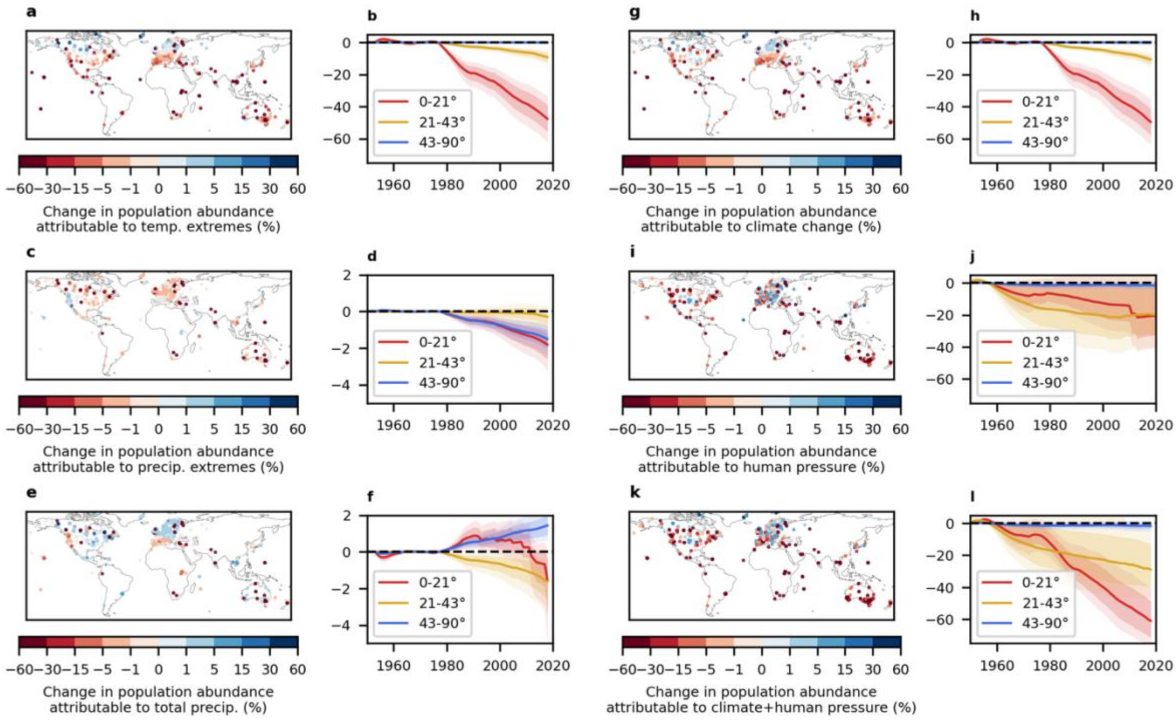
Supplementary Fig. 6. Procedures for estimating attributable impacts of climate change on population abundance. (a) The procedure for attributing the intensification of climate extremes to global climate change, using global temperatures (blue) correlated with historical climate extremes (red) to estimate a time-series of change in climate extremes which is attributable to climate change (orange). (b) The procedure for attributing the intensification of climate extremes to global climate change, by resampling from the historical period (1940-1970) to generate a counterfactual time-series of climate extremes until 2020 in the absence of climate change (blue). Note that this shows only one of 1,000 samples taken in the full procedure. (c) The procedure for extrapolating missing population abundance observations using a log-linear extrapolation. Raw abundance data is shown in solid black, with a log-linear extrapolated data in dashed black. Estimates of the hypothetical abundance in the absence of climate change given the attributable changes in climate extremes shown in (a) is then shown in dashed red. Panel (d) is as in (c) but shows using a constant mean value to extrapolate abundance data. Data here is taken from a population of Mauritius Kestrel at 20.3 degrees South.



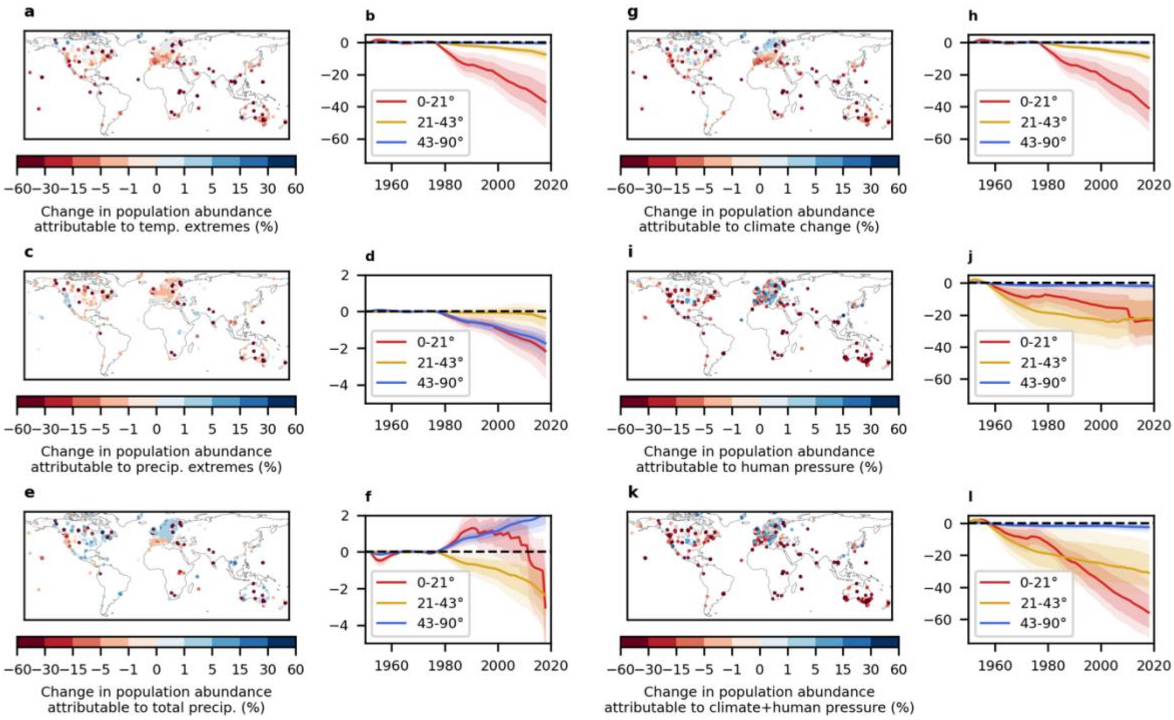
Supplementary Fig. 7. As Figure 3 of the main manuscript, but interpolating baseline population by keeping it fixed at its historical mean.



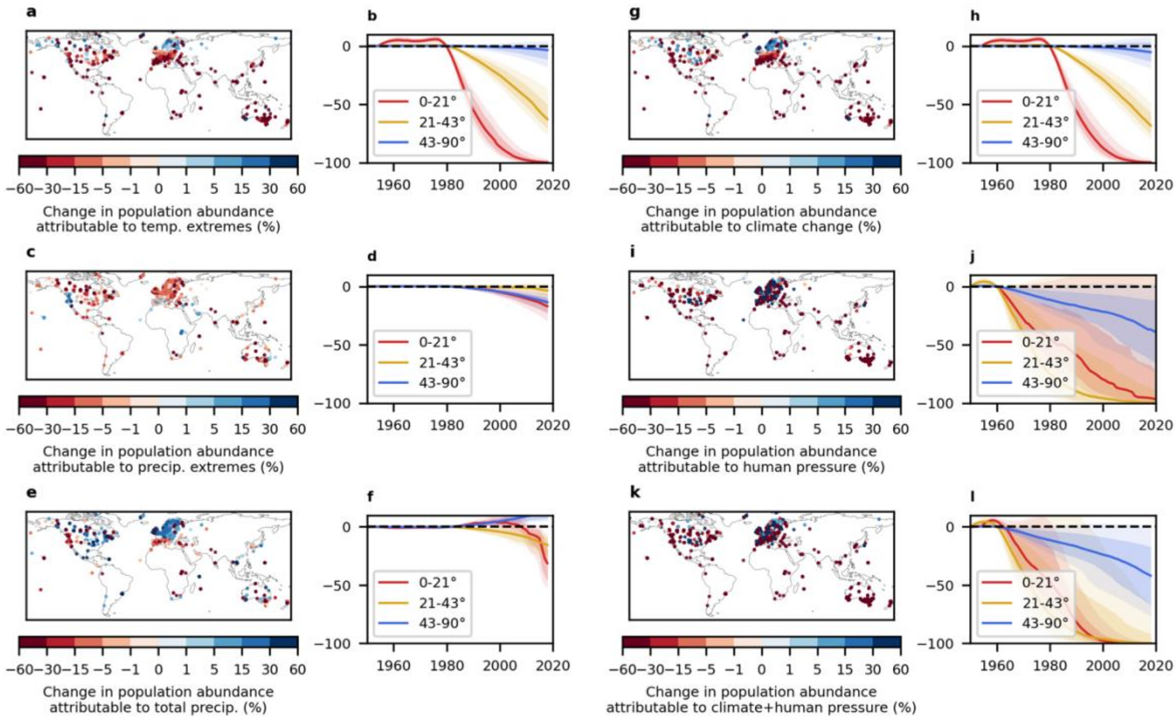
Supplementary Fig. 8. As Figure 3 of the main manuscript but using an alternative method to estimate the intensification of climate extremes which are attributable to climate change. In this case, counterfactual time-series of historical climate extremes are estimated by resampling data from the first thirty years (1950-1980), rather than by fitting relationships between climate extremes and global temperatures (see Supplementary Fig. 6b for visualisation and methods for further discussion).



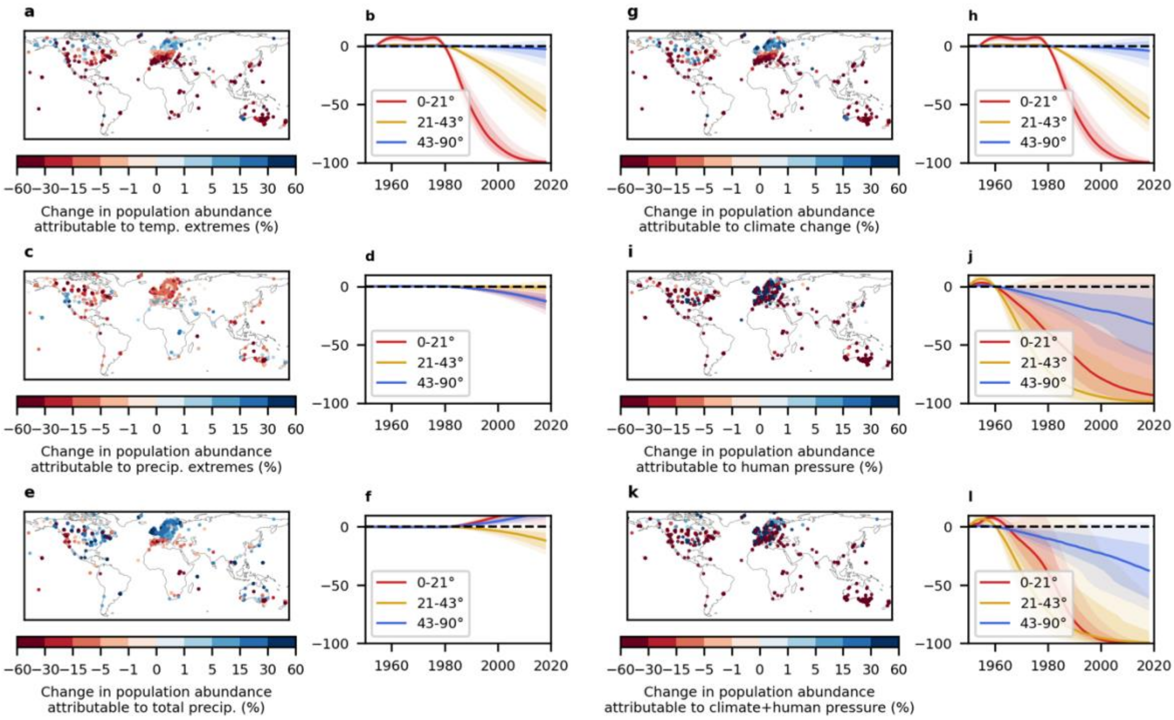
Supplementary Fig. 9. As Figure 3 of the main manuscript but using an empirical model with four rather than five lags for the impacts of climate conditions on abundance.



Supplementary Fig. 10. As Figure 3 of the main manuscript but using an empirical model with three rather than five lags for the impacts of climate conditions on abundance.



Supplementary Fig. 11. As Fig. 3 of the main manuscript but without accounting for density dependence when estimating the attributable impacts of climate change.



Supplementary Fig. 12. As Fig. 3 of the main manuscript but using a constant mean to extrapolate baseline abundance levels, and without accounting for density dependence when estimating the attributable impacts of climate change.