Supplemental materials for: How do climate change experiments actually change climate?

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May 15, 2017

Climate from Climate Change Experiments Database

We developed a new, publicly available database for our analyses: the Climate from Climate Change Experiments (C3E) database, which is available at KNB. This database of daily climate data allow us to explore, for the first time, the complex ways that climate is altered by active warming treatments, both directly and indirectly, across multiple studies.The data in this database were collected between 1991 and 2014 from North American and European climate change experiments (Table S1, Figure 1 in the main text).

We carried out a full literature review to identify potential active field warming experiments to include in the database. To find these studies, we followed the methods and search terms of (Wolkovich *et al.*, 2012) for their Synthesis of Timings Observed in iNcrease Experiments (STONE) database (also available on KNB). We searched the Web of Science (ISI) for Topic=(warm* OR temperature*) AND Topic=(plant* AND phenolog*) AND Topic=(experiment* OR manip*). We restricted dates to the time period after their database (i.e. January 2011 through March 2015). This yielded 277 new studies.

We wanted to focus on active warming studies only, because recent analyses indicate that active warming methods are the most controlled and consistent (Kimball, 2005; Kimball *et al.*, 2008; Aronson & McNulty, 2009; Wolkovich *et al.*, 2012). We therefore removed all passive warming studies from this list. In addition, a secondary goal of this database was to test hypotheses about mechanisms for the mismatch in sensitivities between observational and experimental phenological studies. Because of this secondary goal, studies included in the database had to either 1) include more than one level of warming, or 2) manipulate both temperature and precipitation. (Some studies met both of these criteria.) These additional restrictions constrained the list to 11 new studies, as well as 6 of the 37 studies in the STONE database. We contacted authors to obtain daily (or sub-daily) climate data and the most accurate phenological data for these 17 sites, as well as one additional site that we knew about through personal connections (BACE). We received data from authors of 12 of these 18 studies or 67%. STONE received 16.7% of data directly.

Details of Statistical Analyses and Results

Analysis of effects of time and space on local experimental climate

To test how treatment effects vary spatially (i.e. among blocks within a study) and temporally (i.e. among years within a study), we used data from the four studies in the C3E database that used blocked designs. We fit linear mixed effect models with mean daily soil temperature, minimum daily air temperature, and maximum daily air temperature as response predictors (Figure 3 in the main text). For spatial models, we included fixed effects of temperature treatment, block, and their interaction; random effects were site and year nested within site (intercept-only structure, TableS4). For temporal models, we included fixed effects of temperature treatment, year, and their interaction; random effects were site and block nested within site (intercept-only structure, TableS3).

Analysis of effects of infrastructure on local experimental climate

To test how infrastructure affects local climate, we compared temperature and soil moisture data from the studies in our database that monitored climate in two types of control plots: structural controls (i.e., 'shams' or 'disturbance controls,' which contained all the warming infrastructure, such as soil cables or infrared heating units but with no heat applied) and ambient controls with no infrastructure added. These five studies occurred at two sites: Duke Forest and Harvard Forest ((Farnsworth *et al.*, 1995; **?**; Marchin *et al.*, 2015; Pelini *et al.*, 2011)). We fit linear mixed effect models by month with mean daily soil temperature, minimum and maximum daily air and soil temperature ((Farnsworth *et al.*, 1995) did not measure these predictors so there are only four different studies in these models), and soil moisture as response predictors. The fixed explanatory predictor was control type (sham or ambient). Random effects were site and year nested within site, modeled with a random slopes and random intercept structure. We found that experimental structures altered above-ground and soil temperatures in opposing ways: above-ground temperatures were higher in the structural controls, compared with ambient conditions with no structures installed, whereas soil temperatures were lower in the structural controls compared with ambient soil (Figure 4 in the main text). In addition, soil moisture was lower in structural controls compared with ambient conditions. These general patterns were consistent across the different temperature models we fit (mean, minimum, and maximum soil and air temperatures), although the magnitude varied across months, as well as among studies. We show summaries from models fit to the entire year (Tables S5,S6, S7), as well as summaries from models fit to each month of data, as is shown in Figure 4 in the main text (Tables S8,S9, S10).

Analysis of effects of experimental warming on soil moisture

Of the twelve experiments in the C3E database, ten measured and reported soil moisture. To examine the effects of target warming treatment on soil moisture, we fit linear mixed effects models to data from these ten sites. We first fit a model with a fixed, continuous effect of target warming level (this ranged from 1.0 to 5.2
degree C for these 10 studies). To account for methodological and other differences among site, we included site as a random effect, with day of year nested within site to account for the non-independent nature of measurements taken on the same day within sites. We used a random slope and intercept structure, to allow the effect of target warming to vary among sites (Table S11.

Since our previous analyses revealed that there can be reduced soil moisture due to the experimental structures themselves, we wanted to compare the effect of the structures themselves (i.e. in structural controls) to ambient levels, as well as to the warmed plots. We therefore fit a model with categorical fixed effects of "ambient," "structural control," and "warmed." We again included site as a random effect, with day of year nested within site to account for the non-independent nature of measurements taken on the same day within sites, and used a random intercept structure (Table S12).

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Tables

Table S1: **Sites included in the C3E database**. Experimental sites correspond to map (Figure 1, main text). We give the study ID, location, source, years of data included, and warming type used in the study. Note that some sites may have multiple sources; however, we list only one.

study id	location	source	data years	warming type
exp01	Waltham, MA, USA	Hoeppner & Dukes (2012)	2010-2014	infrared
exp02	Montpelier, France	Morin *et al.* (2010)	2002-2005	infrared
exp03	Duke Forest, NC, USA	Clark *et al.* (2014)	2009-2012	forced air and soil warming
exp04	Harvard Forest, MA, USA	Clark *et al.* (2014)	2000-2002	forced air and soil warming
exp05	Jasper Ridge Biological Preserve, CA, USA	Cleland *et al.* (2007)	2009-2012	infrared
exp06	Rocky Mountain Biological Lab, CO, USA	Dunne *et al.* (2003)	1995-1998	infrared
exp07	Harvard Forest, MA, USA	Pelini *et al.* (2011)	2009-2010	forced air
exp08	Harvard Forest, MA, USA	Farnsworth *et al.* (1995)	1993	soil warming
exp09	Stone Valley Forest, PA, USA	Rollinson & Kaye (2012)	2009-2010	infrared
exp10	Duke Forest, NC, USA	Marchin *et al.* (2015)	2010-2012	forced air
exp11	Rocky Mountain Biological Lab, CO, USA	Price & Waser (1998)	1991-1994	infrared
exp12	Kessler Farm Field Laboratory,OK, USA	Sherry *et al.* (2007)	2003	infrared

Table S2: **Climate measurement details for sites included in the C3E database.** We give the target warming treatment(s) (°C), precipitation treatment(s) (percent of ambient), method of above-ground temperature measurement (with height of measurement, in cm, for air), depth(s) of soil temperature measurement (cm), and depth(s) of soil moisture measurement (cm) used in each study.

study	warming treatment(s)	precipitation treatment(s)	above-ground temperature	soil temperature depth(s)	soil moisture depth(s)
exp01	1,2.7,4	50,100,150	canopy	2,10	30
exp02	1.5,3	70,100			15,30
exp03	3,5		air (30)	10	
exp04	3,5		air (30)	10	
exp05	1.5	100,150		15	15
exp06	1.5			12,25	12,25
exp07	1.5-5.5		air (22)	2,6	
exp08	5			5	
exp09	2	100,120	surface	3	8
exp10	1.5-5.5		air (22)	2,6	
exp11	1			12	
exp12	4	100,200	air (14)	7.5,22.5	15

Table S3: Analysis of variance table for temporal linear mixed-effects models of daily mean soil temperature, minimum above-ground temperature, and maximum above-ground temperature, fit by maximum likelihood. See Figure 3 in the main text. We list degrees of freedom (which are identical for all models), test statistics, and p-values for Type III Wald χ^2 tests of fixed effects in the models. For all models, random effects were site (n=6) and block nested within site (intercept-only structure; n=23); total number of observations=17,177.

		mean soil temp.		min above-ground temp.		max above-ground temp.	
predictor	df	χ^2	p	χ^2	p	χ^2	p
intercept	1	2874.77	<0.001	498.64	<0.001	629.52	<0.001
temp. treatment	2	86.45	<0.001	42.24	<0.001	41.35	<0.001
year	5	282.38	<0.001	113.25	<0.001	36.46	<0.001
temp. treatment:year	6	39.83	<0.001	7.49	0.278	21.07	0.002

Table S4: Analysis of variance table for spatial linear mixed-effects models of daily mean soil temperature, minimum above-ground temperature, and maximum above-ground temperature, fit by maximum likelihood. See Figure 3 in the main text. We list degrees of freedom (which are identical for all models), test statistics, and p-values for Type III Wald χ^2 tests of fixed effects in the models. For all models, random effects were site (n=6) and year nested within site (intercept-only structure; n=6); total number of observations=17,177.

		mean soil temp.		min above-ground temp.		max above-ground temp.	
predictor	df	χ^2	p	χ^2	p	χ^2	p
intercept	1	255.72	<0.001	45.48	<0.001	431.93	<0.001
temp. treatment	2	98.14	<0.001	68.81	<0.001	30.94	<0.001
block	4	35.55	<0.001	29.01	<0.001	39.11	<0.001
temp. treatment:block	4	52.66	<0.001	9.37	0.053	96.26	<0.001

Table S5: Summaries of linear mixed-effects models comparing effects of ambient versus structural controls on daily mean, minimum, and maximum soil temperature in climate change experiments across the year. Estimates are the intercept (representing ambient controls) and coefficient (representing structure effects) from the models; se is the standard error for these estimates. For these annual models, differences between control types were significant based on Type II Wald χ^2 tests of fixed effects for mean soil temperature (χ^2=5,53, df=1, p=0.01) and minimum soil temperature (χ^2=3.87, df=1, p=0.05), but not for maximum air temperature (χ^2=2.07, df=1, p=0.15). For all models, random effects of site (n=5 for mean model, n=4 for min and max models) and year nested within site (n=21 for mean model, n=20 for min and max models) were fit with a random slope and intercept structure; total number of observations= 48,860 for the mean model and 44,530 for the min and max models.

	mean soil temp.		min soil temp.		max soil temp.	
predictor	est.	se	est.	se	est.	se
intercept	11.89	1.42	10.81	1.48	13.92	1.61
structure effect	-0.57	0.24	-0.63	0.32	-0.54	0.38

Table S6: Summaries of linear mixed-effects models comparing effects of ambient versus structural controls on daily minimum and maximum air temperature in climate change experiments, across the whole year. Estimates are the intercept (representing ambient controls) and coefficient (representing structure effects) from the models; se is the standard error for these estimates. For these annual models, differences between control types were not sigificant based on Type II Wald χ^2 tests of fixed effects for minimum air temperature (χ^2=1.07, df=1, p=0.30), nor for maximum air temperature (χ^2=0.01, df=1, p=0.91). For both models, random effects of site (n=4) and year nested within site (n=20) were fit with a random slope and intercept structure; total number of observations= 44,085.

	min air temp.		max air temp.	
predictor	est.	se	est.	se
intercept	6.29	1.51	17.74	1.81
structure effect	0.36	0.35	0.02	0.21

Table S7: Summary of a linear mixed-effects model comparing effects of ambient versus structural controls on daily soil moisture in climate change experiments across the year. Estimates are the intercept (representing ambient controls) and coefficient (representing structure effects) from the models; se is the standard error for these estimates. For this annual model, the difference between control types was sigificant based on Type II Wald χ^2 tests of fixed effects (χ^2=89.95, df=1, p<0.001). Random effects of site (n=5) and year nested within site (n=21 year-site combinations) were fit with a random slope and intercept structure; total number of observations= 44,468.

	soil moisture	
predictor	est.	se
intercept	21.20	1.86
structure effect	-2.43	0.26

Table S8: Summaries of linear mixed-effects models, fit to each month comparing effects of ambient versus structural controls on daily mean, minimum, and maximum soil temperature, fit to each month separately, consistent with Figure 4 in the main text. Estimates are the intercept (representing ambient controls) and coefficient (representing structural effects) from the models; se is the standard error for these estimates. We list test statistics, and p-values for Type II Wald χ^2 tests of fixed effects (df=1 for all tests). Random effects of site (n=5 for all mean soil temperature models; n=4 for all min and max soil temperature models) and year nested within site (n=19 or 20 year-site combinations for all mean soil temperature models; n=18 or 19 for all min and max soil temperature models) were fit with a random slope and intercept structure; total number of observations ranged from 4186 to 3814.

		mean soil temp.				min soil temp.				max soil temp.			
mon	predictor	est.	se	χ^2	p	est.	se	χ^2	p	est.	se	χ^2	p
01	intercept	2.66	1.25	3.63	0.057	2.34	1.21	2.09	0.149	3.92	1.65	13.71	<0.001
	structure effect	-0.45	0.23			-0.72	0.50			-0.35	0.09		
02	intercept	2.86	1.44	13.06	<0.001	2.58	1.26	3.24	0.072	4.66	1.92	1.99	0.158
	structure effect	-0.44	0.12			-0.67	0.37			-0.41	0.29		
03	intercept	5.24	1.78	6.44	0.011	4.66	1.58	3.64	0.056	7.75	2.04	0.92	0.337
	structure effect	-0.44	0.17			-0.44	0.23			-0.50	0.52		
04	intercept	9.98	1.85	8.53	0.003	8.93	1.98	10.52	0.001	13.24	1.80	0.96	0.327
	structure effect	-0.67	0.23			-0.65	0.20			-0.63	0.65		
05	intercept	14.92	1.37	3.85	0.05	13.74	1.54	4.91	0.027	17.54	1.41	0.59	0.441
	structure effect	-0.31	0.16			-0.27	0.12			-0.32	0.42		
06	intercept	18.29	1.58	0	0.972	17.43	1.57	0.76	0.383	20.98	1.78	0.04	0.844
	structure effect	-0.01	0.20			-0.14	0.16			0.09	0.47		
07	intercept	21.07	1.33	0.06	0.815	19.97	1.34	0.45	0.501	23.76	1.46	0.01	0.914
	structure effect	-0.07	0.28			-0.12	0.18			-0.07	0.61		
08	intercept	20.93	1.20	2.56	0.11	19.59	1.29	1.35	0.244	23.23	1.42	1.58	0.209
	structure effect	-0.26	0.16			-0.20	0.17			-0.37	0.30		
09	intercept	18.23	1.24	10.15	0.001	16.94	1.36	0.58	0.445	20.54	1.43	1.74	0.188
	structure effect	-0.36	0.11			-0.21	0.27			-0.40	0.31		
10	intercept	13.03	1.22	10.48	0.001	12.26	1.24	1.39	0.239	15.42	1.39	10.02	0.002
	structure effect	-0.42	0.13			-0.56	0.48			-0.50	0.16		
11	intercept	8.27	1.13	1.87	0.172	7.34	1.23	0.83	0.363	10.11	1.43	3.16	0.075
	structure effect	-0.33	0.24			-0.52	0.57			-0.28	0.16		
12	intercept	5.03	1.21	2.8	0.094	4.38	1.24	1.53	0.215	6.40	1.53	4.83	0.028
	structure effect	-0.40	0.24			-0.61	0.49			-0.26	0.12		

Table S9: Summaries of linear mixed-effects models, fit to each month comparing effects of ambient versus structural controls on daily minimum and maximum above-ground temperature, fit to each month separately, consistent with Figure 4 in the main text. Estimates are the intercept (representing ambient controls) and coefficient (representing structural effects) from the models; se is the standard error for these estimates. We list test statistics, and p-values for Type II Wald χ^2 tests of fixed effects (df=1 for all tests). Random effects of site (n=4 for both models) and year nested within site (n=18 year-site combinations for both models) were fit with a random slope and intercept structure; total number of observations was 3,726.

		min air temp.				max air temp.			
mon	predictor	est.	se	χ^2	p	est.	se	χ^2	p
01	intercept	-5.49	1.78	5.27	0.022	5.09	2.60	0.01	0.927
	structure effect	0.61	0.26			-0.03	0.29		
02	intercept	-3.92	1.83	1.41	0.235	7.10	3.03	2.93	0.087
	structure effect	0.55	0.46			0.36	0.21		
03	intercept	-0.08	1.55	8.59	0.003	12.60	2.41	2.75	0.097
	structure effect	0.50	0.17			0.52	0.31		
04	intercept	5.28	1.80	9.33	0.002	19.27	1.92	18.31	<0.001
	structure effect	0.55	0.18			1.26	0.29		
05	intercept	11.62	1.46	6.56	0.01	23.49	1.03	7.75	0.005
	structure effect	0.48	0.19			0.77	0.28		
06	intercept	15.45	1.47	10.13	0.001	26.32	1.82	4.4	0.036
	structure effect	0.43	0.14			0.59	0.28		
07	intercept	17.90	1.26	4.47	0.035	28.94	1.25	3.58	0.059
	structure effect	0.85	0.40			0.61	0.32		
08	intercept	17.07	1.43	2.07	0.15	27.39	1.15	0.87	0.35
	structure effect	0.65	0.45			0.33	0.35		
09	intercept	13.34	1.39	4.71	0.03	23.72	1.47	2.66	0.103
	structure effect	0.88	0.41			0.38	0.23		
10	intercept	7.26	1.26	4.27	0.039	17.29	1.70	1.89	0.169
	structure effect	0.79	0.38			0.30	0.22		
11	intercept	1.21	1.25	4.23	0.04	12.79	1.83	2.76	0.097
	structure effect	0.88	0.43			0.26	0.15		
12	intercept	-2.83	1.48	5.29	0.021	7.56	2.38	0.26	0.61
	structure effect	0.43	0.19			-0.11	0.23		

Table S10: Summaries of linear mixed-effects models, fit to each month comparing effects of ambient versus structural controls on soil moisture, fit to each month separately, consistent with Figure 4 in the main text. Estimates are the intercept (representing ambient controls) and coefficient (representing structural effects) from the models; se is the standard error for these estimates. We list test statistics, degrees of freedom, and p-values for Type II Wald χ^2 tests of fixed effects. Random effects of site (n=4) and year nested within site (n=18 year-site combinations) were fit with a random slope and intercept structure; total number of observations was 3,829.

mon	predictor	est.	se	χ^2	df	p
01	intercept	22.58	3.23	59.24	1	<0.001
	structure effect	-2.77	0.36			
02	intercept	22.10	3.24	16.78	1	<0.001
	structure effect	-2.54	0.62			
03	intercept	23.58	2.43	8.3	1	0.004
	structure effect	-2.48	0.86			
04	intercept	22.54	2.15	9.24	1	0.0024
	structure effect	-2.06	0.68			
05	intercept	21.08	2.31	40.17	1	<0.001
	structure effect	-2.20	0.35			
06	intercept	18.44	1.37	30.78	1	<0.001
	structure effect	-2.12	0.38			
07	intercept	17.60	2.18	20.22	1	<0.001
	structure effect	-2.38	0.53			
08	intercept	16.59	1.90	12.95	1	<0.001
	structure effect	-2.09	0.58			
09	intercept	15.99	1.54	13.2	1	<0.001
	structure effect	-1.79	0.49			
10	intercept	20.15	1.93	20.9	1	<0.001
	structure effect	-2.27	0.50			
11	intercept	21.18	1.77	21.9	1	<0.001
	structure effect	-2.70	0.58			
12	intercept	22.74	2.83	15.64	1	<0.001
	structure effect	-2.88	0.73			

Table S11: Summary of a linear mixed-effects model of how target warming treatment affects soil moisture in climate change experiments. We excluded precipitation treatments from this analysis. Estimates are the intercept and coefficient for target warming from the model; se is the standard error for these estimates. We list the test statistic, degrees of freedom, and p-value for a Type II Wald chi-square tests of the fixed effect (target warming). Random effects were site (n=10) and day of year nested within site (n=2434 day of year-site combinations), with a random slope and intercept structure. Total number of observations was 72,730

	est.	se	χ^2	df	p
intercept	20.63	1.64			
target	-0.43	0.23	3.49	1	0.06

Table S12: Summary of a linear mixed-effects model comparing soil moisture in experimentally warmed plots to two different control types, structural and ambient controls. We excluded precipitation treatments from this analysis. Estimates are the intercept (representing mean moisture in ambient controls) and coefficients from the from the model (i.e. differences between the ambient) for structural controls and warmed plots (pooled across all target warming levels); se is the standard error for these estimates. We list the test statistic, degrees of freedom, and p-value for a Type II Wald χ^2 test of the fixed effect (warming type). Random effects were site (n=10),year nested within site (n=35 site-year combinations), and day of year nested within year (7,979 day of year-year-site combinations) with a random intercept structure. Total number of observations was 72,730

	est.	se	χ^2	df	p
intercept	22.39	1.31			
structure effect	-1.93	0.04			
warmed effect	-2.85	0.03	7229.01	2	0