Supplemental materials: Understanding growing degree days to predict spring phenology under climate change

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Methods S1: Using simulations to test Bayesian models in Rstan

To test all models, we used data simulations but simulation data can only take us so far in model interpretation. We first needed to be certain our models were operating correctly. To test our model function, we built test data and manipulated the effects of the parameters and sigmas around these parameters to make sure the models were reporting this information accurately. Building test data is easy and we encourage readers to use the Shiny App and GitHub repository to use as a building block.

Methods S2: Data analysis and model equations

Using Bayesian hierarchical models, we estimated the effects of site (i.e., 'forest' sites modeled as '0' versus 'urban' sites modeled as a '1'), method (i.e., hobo logger climate data modeled as '0' and weather station climate data modeled as '1') and the interaction between site and method effects as predictors with species modeled hierarchically as grouping factors:

$$y_i = \alpha_{species[i]} + \beta_{site_{species[i]}} X_{site} + \beta_{method_{species[i]}} X_{method} + \beta_{sitexmethod_{species[i]}} X_{sitexmethod} + \epsilon_i \quad (1)$$

$$\epsilon_i \sim N(0, \sigma_y)$$

The α and each of the five β coefficients are modeled at the species level, as follows:

$$
\begin{aligned}
\alpha_{species} &\sim N(\mu_{\alpha}, \sigma_{\alpha}) \\
\beta_{site_{species}} &\sim N(\mu_{site}, \sigma_{site}) \\
\beta_{method_{species}} &\sim N(\mu_{method}, \sigma_{method}) \\
\beta_{sitexmethod_{species}} &\sim N(\mu_{sitexmethod}, \sigma_{sitexmethod})
\end{aligned}
$$

where i represents each unique observation, *species* is the species, α represents the intercept, β terms represent slope estimates, and y is the number of growing degree days.

Supplemental tables and figures

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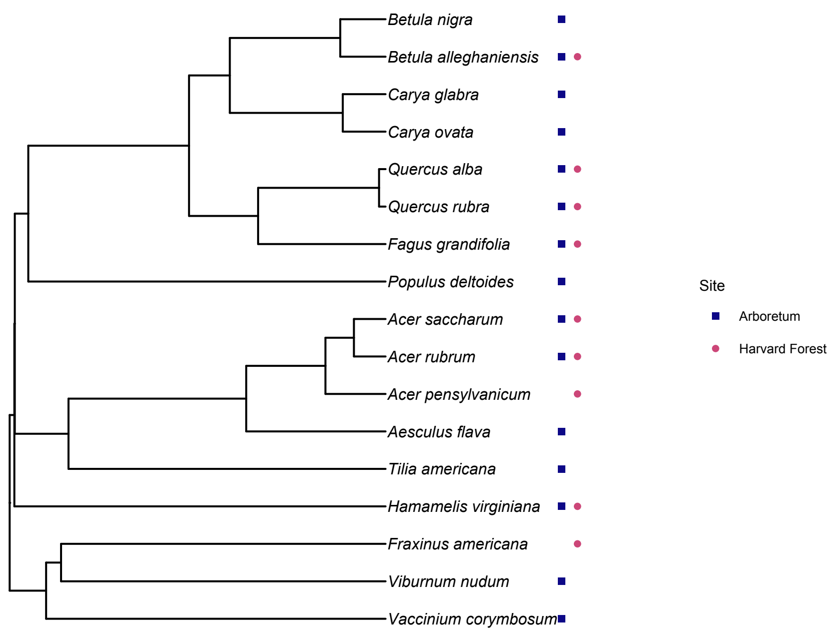

- Figure S1: Phylogeny indicating species across the two sites -

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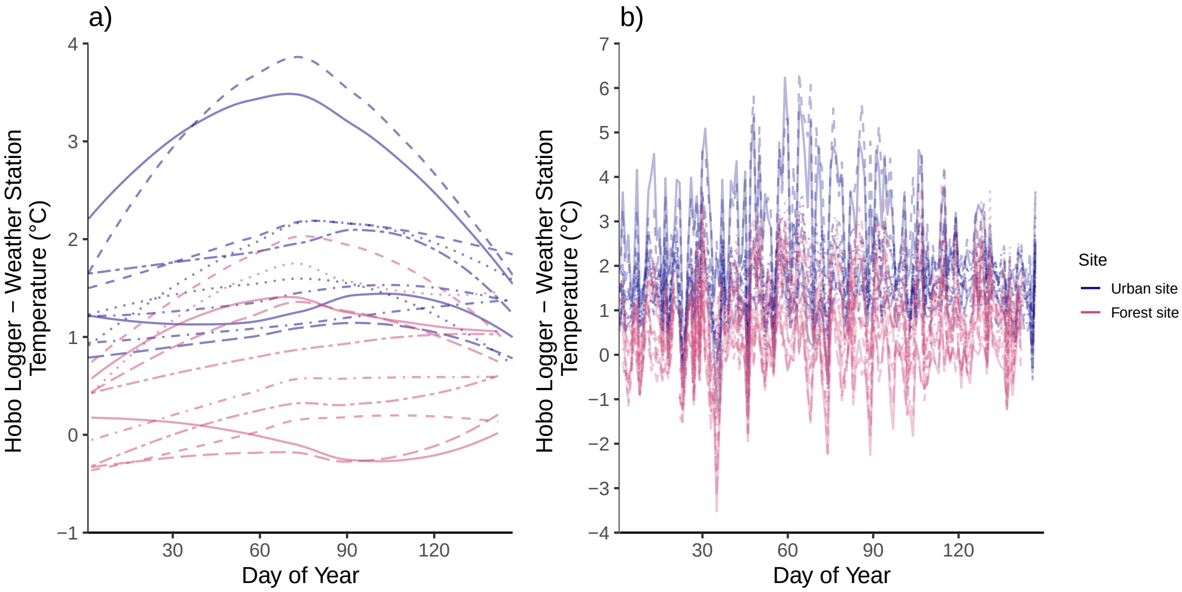

Figure S2: Here we show a breakdown of the mean temperature differences in data across the two sites between the two methods with darker lines representing weather station data and the lighter, more transparent lines of varying line types representing the hobo loggers: a) a series of smoothing splines of mean temperature differences measured as hobo logger minus weather station and b) actual mean temperature differences measured as hobo logger minus weather station.

Table S1: **Estimates from urban simulations**. We present posterior means, as well as 50% and 95% uncertainty intervals from models in which the predictors have been standardized so that they are comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	307.40	303.75	310.96	296.83	318.49
μ_{site}	20.67	20.08	21.25	19.01	22.30
μ_{method}	0.23	-0.35	0.80	-1.49	1.97
$\mu_{sitexmethod}$	-0.36	-1.19	0.38	-2.57	2.01
σ_{site}	1.18	0.56	1.65	0.06	2.93
σ_{method}	1.09	0.46	1.57	0.05	2.84
$\sigma_{sitexmethod}$	0.75	0.28	1.06	0.02	2.28
σ_{α}	21.49	18.37	23.99	14.82	31.44
σ_{y}	15.57	15.44	15.69	15.18	15.97
N_{sp}	15.00				

Table S2: **Estimates from microclimate simulations**. We present posterior means, as well as 50% and 95% uncertainty intervals from models in which the predictors have been standardized so that they are comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	322.94	318.50	327.45	310.33	335.58
μ_{site}	-0.32	-0.91	0.30	-2.11	1.42
μ_{method}	-6.78	-8.07	-5.50	-10.55	-3.07
$\mu_{sitexmethod}$	1.05	0.26	1.85	-1.33	3.38
σ_{site}	1.14	0.47	1.65	0.06	3.12
σ_{method}	6.82	5.63	7.72	4.26	10.92
$\sigma_{sitexmethod}$	1.23	0.46	1.77	0.04	3.60
σ_{α}	24.85	21.32	27.48	17.17	36.72
σ_{y}	16.73	16.59	16.87	16.32	17.14
N_{sp}	15.00				

Table S3: **Estimates from provenance latitude simulations**. We present posterior means, as well as 50% and 95% uncertainty intervals from models in which the predictors have been standardized so that they are comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	307.61	304.40	310.79	296.64	318.14
μ_{site}	-4.80	-5.38	-4.22	-6.47	-3.05
μ_{method}	-0.29	-0.69	0.11	-1.50	0.90
$\mu_{sitexmethod}$	-0.54	-1.41	0.32	-3.03	1.96
σ_{site}	0.94	0.39	1.35	0.04	2.61
σ_{method}	0.77	0.33	1.09	0.03	2.13
$\sigma_{sitexmethod}$	1.58	0.72	2.23	0.08	4.08
σ_{α}	20.54	17.57	22.71	14.07	30.22
σ_{y}	15.57	15.43	15.71	15.19	15.96
N_{sp}	15.00				

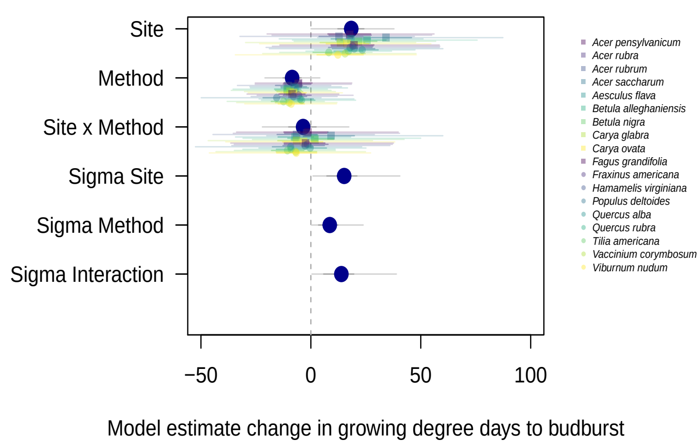

Figure S3: Empirical Data: Using real data to test provenance latitude, we show the effects of provenance latitude and climate data method (using a binary parameter with weather station data as '1' and hobo logger data as '0') on simulated growing degree days (GDDs) until budburst. The intercept represents the hobo logger data for the rural forested site. More positive values indicate more GDDs are required for budburst whereas more negative values suggest fewer GDDs are required. Dots and thin lines show means and 90% uncertainty intervals and thicker lines show 50% uncertainty intervals. See Table
reftab:provreal for full model output.

Table S4: **Estimates from noisy weather station simulations**. We present posterior means, as well as 50% and 95% uncertainty intervals from models in which the predictors have been standardized so that they are comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	307.45	303.99	310.89	297.13	318.19
μ_{site}	0.07	-0.50	0.66	-1.54	1.69
μ_{method}	4.93	2.35	7.60	-3.09	12.52
$\mu_{sitexmethod}$	-0.39	-1.16	0.36	-2.81	1.84
σ_{site}	0.68	0.26	0.98	0.02	1.93
σ_{method}	14.63	12.37	16.33	9.81	22.36
$\sigma_{sitexmethod}$	0.86	0.33	1.23	0.03	2.59
σ_{α}	21.79	18.43	24.37	14.47	33.19
σ_{y}	15.55	15.42	15.67	15.16	15.95
N_{sp}	15.00				

Table S5: **Estimates from noisy hobo logger simulations**. We present posterior means, as well as 50% and 95% uncertainty intervals from models in which the predictors have been standardized so that they are comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	316.41	311.01	321.54	299.27	333.71
μ_{site}	-1.20	-1.78	-0.62	-2.89	0.51
μ_{method}	-6.41	-9.15	-3.68	-14.64	1.86
$\mu_{sitexmethod}$	2.15	1.36	2.91	-0.10	4.47
σ_{site}	1.00	0.42	1.43	0.03	2.73
σ_{method}	15.14	12.73	17.02	10.11	23.17
$\sigma_{sitexmethod}$	1.20	0.48	1.70	0.04	3.31
σ_{α}	31.87	27.47	35.30	22.11	46.96
σ_{y}	15.05	14.91	15.19	14.67	15.46
N_{sp}	15.00				

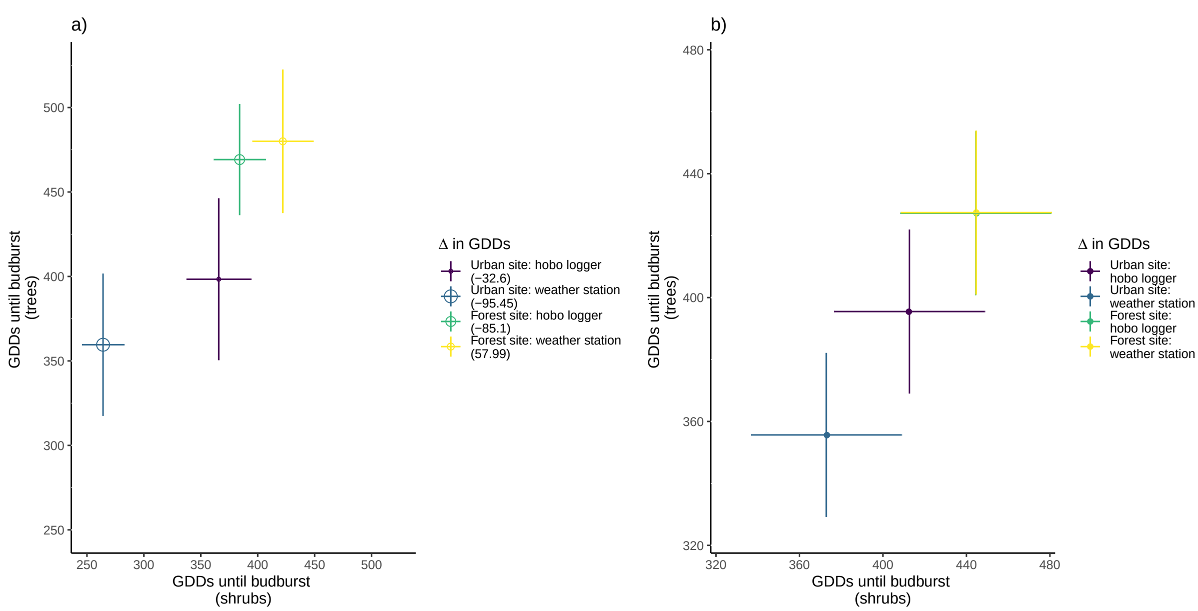

Figure S4: Empirical Data: Using real data, we show (a) the effects of site and climate data method on growing degree days (GDDs) until budburst between shrubs versus tree species used in the study. We also show model output for the same relationship in (b). Using empirical data, we see that shrubs generally require fewer GDDs until budburst than trees but the reverse is true for the model output. This is likely due to partial pooling within the model since there are fewer observations for shrubs.

Table S6: **Estimates from real data**. We present posterior means, as well as 50% and 95% uncertainty intervals from models in which the predictors have been standardized so that they are comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	424.61	412.34	436.90	388.48	456.44
μ_{site}	-31.74	-39.71	-24.08	-54.99	-7.37
μ_{method}	0.21	-6.18	6.55	-19.05	19.43
$\mu_{sitexmethod}$	-40.05	-47.90	-32.21	-65.05	-16.22
σ_{site}	22.06	12.78	29.66	1.46	48.71
σ_{method}	16.18	7.64	23.41	0.62	40.29
$\sigma_{sitexmethod}$	25.16	16.26	33.41	2.44	51.25
σ_{α}	62.97	53.59	71.29	40.08	90.52
σ_{y}	71.58	69.60	73.27	66.34	77.41
N_{sp}	18.00				

Table S7: **Estimates from provenance latitude**. We present posterior means, as well as 50% and 95% uncertainty intervals from models in which the predictors have been standardized so that they are comparable.

	mean	25%	75%	2.5%	97.5%
μ_{α}	394.32	382.18	406.76	356.00	430.30
μ_{site}	18.15	11.68	24.64	-0.64	38.01
μ_{method}	-8.46	-12.51	-4.27	-20.81	3.92
$\mu_{sitexmethod}$	-3.53	-9.65	2.73	-22.29	16.00
σ_{site}	15.43	7.31	21.21	0.73	40.78
σ_{method}	8.45	3.47	12.23	0.36	23.60
$\sigma_{sitexmethod}$	13.69	6.11	19.41	0.49	37.55
σ_{α}	71.80	62.26	79.36	50.01	102.94
σ_{y}	78.76	76.81	80.70	73.40	84.53
N_{sp}	18.00				

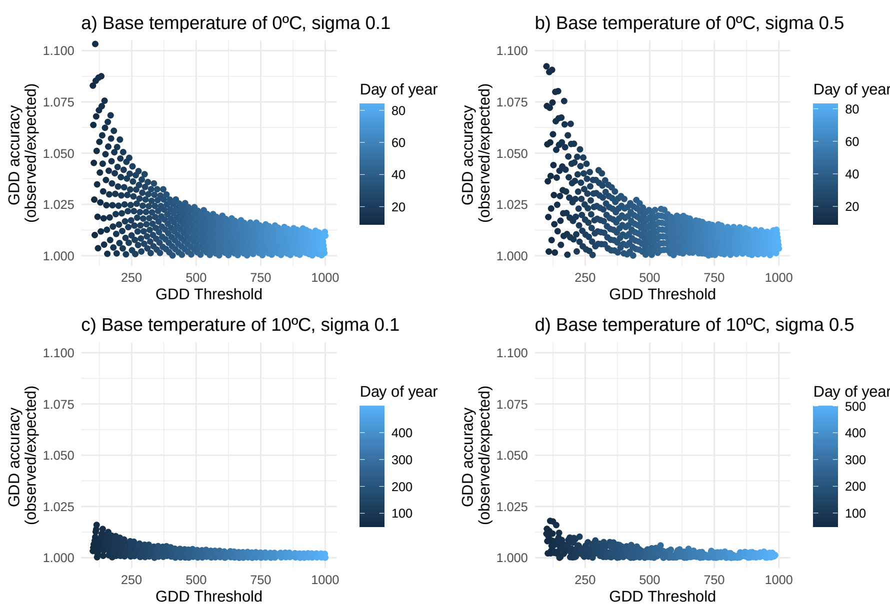

Figure S5: Using simulated data, we show how GDD measurement accuracy changes along varying GDD thresholds using a base temperature of (a) 0°C and a sigma of 0.1°C, (b) 0°C and a sigma of 0.5°C, (c) 10°C and a sigma of 0.1°C and (d) 10°C and a sigma of 0.5°C. GDD accuracy is measured as the observed GDD divided by the expected GDD.