Supplemental Materials: Winter temperatures predominate in spring phenological responses to warming

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Applying our model to Central European data

Our results integrate over a large range of chilling, forcing, and photoperiod conditions (*e.g.*, forcing treatment temperatures ranged from 0-32°C and chilling temperatures ranged from -10-16°C in experiments, as defined by each study's authors, Figs. 3, S2). We wished to understand how our findings may apply to conditions more commonly found in nature, especially where conditions often vary dramatically from those applied in controlled environment experiments. For example, very low amounts of chilling can be applied in experiments compared to the higher amounts of natural chilling found in many temperate areas (Fig. ED4). Additionally, chilling temperature and total chilling are more correlated in nature than in experimental conditions (Fig. ED4). Further, given the importance of chilling and forcing combined with the fact that seasons do not always warm uniformly with climate change *(1; 2)*, we also wished to understand how warming in the winter, spring, or both seasons would shift budburst timing. Given these goals we focused on applying our model estimates to defined levels of warming layered onto historical climate. Alternative approaches, such as using climate projections from global circulation models, would have hindered our efforts to understand degrees of warming in different seasons. Further, we emphasize that our predictions are not designed to be accurate forecasts of future budburst dates, even for the locations for which we use historical climate and budburst data. Rather, they are designed to provide insights into how natural conditions can differ from experimental conditions, and to provide guidance on how much varying effects of winter and spring warming together will shape future budburst timing.

We applied our model to Central Europe, a well-studied area for phenology, which has both relatively long-term daily temperature data and budburst data. We selected sites that are part of the Pan European Phenology Project (PEP725, http://www.pep725.eu) and included data for two common European species that are prevalent in the OSPREE database: *Betula pendula* (silver birch) and *Fagus sylvatica* (European beech) *(3)*. We used a European-wide gridded climate dataset *(*E-OBS*, 4)* to extract daily minimum and maximum temperature for the grid cells where observations of leafout for these two species were available. We extracted temperature data from 1951 through 1960 (selected as a pre-warming time period) and used these data to estimate annual values for total winter chilling (from 1 September through 30 April, in Utah units, using the R package chillR, see in the *Estimating chilling* section of the *Methods*) and mean spring forcing estimated as the mean temperature from 1 March through 30 April. We inputted these estimates for chilling and forcing into our main model, and set photoperiod to the daylength on the mean day of leafout across the PEP725 observations from 1951 through 1960. This yielded estimates of budburst under "pre-warming conditions." We then investigated model predictions of budburst given different levels of warming (from 1-7°C) above this baseline, including a full matrix of altered total chilling and forcing estimates (Figs. 3, S2).

We applied our model at all latitudes and longitudes included in the PEP725 database between 1951 and 1960 for *Betula pendula* (Fig. ED6). We selected two of these sites for *Betula pendula*, as well as two sites where *Fagus sylvatica* occurs, to compare budburst responses across species that differ in their responses to

chilling, forcing, and photoperiod, as well as sites that differ in baseline climate (Fig. 4, ED6 - S5).

We also applied our latitude model to Central Europe, focusing on PEP725 sites where *Fagus sylvatica* leafout data were available from 1951-1960. We fit the model to three sites that differed in latitude, following the approach above for estimating baseline chilling and forcing for these sites (Fig. ED7) and applying warming levels ranging from 1 to 7°C. For each site, we used as a baseline photoperiod the daylength on the mean day of leafout from PEP725 observations between 1951 and 1960. We then further estimated potential changes in photoperiod due to advancing phenology. To do this, we first estimated the shift in days to budburst, as described above. We then used this budburst date to estimate the change in photoperiod between the day of year during the pre- and post-warming periods and then re-fit the model with this new photoperiod (Fig. ED7).

Note that, as described in the *Models* section of the *Methods*, our days to budburst estimate is the days to budburst since forcing conditions were applied in the experiment, which we stress is not necessarily the days to budburst after the start of ecodormancy *(5)*.

Potential statistical artifacts in declines of temperature sensitivity in observational long-term data

Since our model results do not predict a dramatic decline in temperature sensitivity in Central Europe, as has been observed *(e.g., 6)*, we tested whether observed declines could instead be due to a statistical artifact. Researchers today commonly estimate temperature sensitivity via a linear regression of annual budburst date versus mean or other aggregated metrics of spring temperature yielding estimates in days/°C. However, if warming produces systematically higher daily temperatures this method will inherently estimate lower sensitivities, because the "days" unit will effectively have increased in the thermal sum it represents (that is, the unit of "days" is non-stationary in recent decades).

To test this hypothesis we compared observed trends with simple simulations. First, we collated PEP725 data *(3)* for *Betula pendula* for all sites with leafout data each year from two 10-year time-periods: a period before significant anthropogenic warming (1951-1960) and a period with significant warming *(*2001-2010, see 7). We used leafout data (BBCH=11; which is defined as "leaf unfolding (first visible leaf stalk)" in the PEP725 database) instead of budburst (BBCH=7; defined as "Beginning of sprouting") as leafout data are far more common in the PEP725 database. Next, we simulated budburst data with constant cues. For this, we did not include any chilling or photoperiod cues, but assumed budburst occurred after a certain thermal sum, estimated via growing degree days with a base temperature of 0°C. We then estimated temperature sensitivity (days/°C) and the difference in these estimates given different levels of spring warming. For the simulations shown here we used a GDD (growing degree day) requirement of 150, a base mean spring temperature of 6°C with a variance of 3°C, and estimated temperature sensitivity for 10-year periods for 45 simulated sites (these values were chosen to best match the PEP725 data, but note that the general findings are robust to other combinations of these parameter values).

As expected, temperature sensitivity estimates for *Betula pendula* from PEP725 declined across the two time periods in step with warming. Across the sites studied here, we estimated a decline of 0.8±0.3 days/°C (comparing 2001-2010 and 1951-1960) and 1.1±0.2°C warming; this estimate was very similar to simulations given constant cues and 1°C warming (Fig. ED8).

Additionally, several other metrics suggest declines may be more statistical than biological. Research suggests substantial declines in chilling—that could lead to observed shifts in sensitivity to warming—should increase variance in leafout timing *(8)*. In contrast, in both the real and simulated data, variance in leafout date declined over time—this would be expected if plants use a thermal sum threshold of forcing to leaf out and warming produces systematically warmer days. In the PEP725 data we found a decline in leafout variance of

58% (in recent years compared to earlier years), compared to a decline of 37% in the simulations. Additionally we found little change in accumulated chilling (1 September - 1 March of each year) in the PEP725 data across the two time points (2247±31 Utah units in 1951-1960, compared to 2236±20 Utah units in 2001-2010), further suggesting that shifts in chilling do not explain the declining sensitivities. Simple plots of the chilling and forcing required for budburst suggest very low chilling is often required to dramatically increase the forcing required for budburst (Figs. ED9, ED10).

We also tested whether the observed declines in sensitivity could be explained via the absolute sliding time window (SWA) approach *(9)*. Sliding window analyses determine the optimum time period in which environmental factors—in this case, temperature—influence a phenological response, such as leafout. Various iterations of linear models are run to test different durations and calendar positions for the time window to be open and the best model is then selected based on explanatory power *(9; 10)*. We again used collated data from the PEP725 data *(3)* for *Betula pendula* for all sites with leafout data for each year within the same time periods as above: 1951-1960 (pre-warming) and 2001-2010 (post-warming). We then extracted daily minimum and daily maximum climate data from E-OBS *(4)* for each site. Using the R package `climwin` *(10; 11)* and following code from *(9)*, we tested the temperature sensitivity of leaf-out during the two time periods.

We found that the SWA approach yielded consistent results with our previous analyses: higher sensitivity during the pre-warming time period (Table S13), though when adjusted for the increasing thermal sum per day with warming there was little difference in sensitivity to forcing across the two time-periods (Table S14). In addition, during the post-warming time period, the window was open for 18 fewer days and exhibited lower variance than in the pre-warming time period (Table S14).

This potential artifact adds to existing research that has documented the statistical challenges of accurately estimating temperature sensitivities from long-term data *(12; 13)* and may be overcome by some methods. Research that measures sensitivity as a thermal sum or other temperature metric (*e.g.*, GDD) until leafout should be less vulnerable to this artifact. Indeed, in the PEP725 data we found little difference across the two time-periods in GDD (68.7±2.6 in 1950-1960 versus 61.5±2.0 in 2000-2010 for GDD calculated from January 1st to leafout with a base temperature of 0°C; and a mean temperature in the 30 days before leafout of 6.8°C±0.1 in 1950-1960 versus 6.6°C±0.1). Methods such as these (that accumulate thermal temperatures until event date) are vulnerable to other issues: as researchers must select the day to start accumulating or averaging temperatures, these methods should work best when the start date is always after endodormancy break, when plants are most responsive to forcing *(5)*. As climate change may push endodormancy break later and later in some regions, this method could inaccurately attribute changes in other cues to shifts in forcing *(12)*. Without measures of endodormancy break *(5)*, we suggest efforts to accurately estimate cues from long-term observational data may be difficult or impossible without additional physiological information from controlled environment experiments.

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Supplemental Tables

Table S1: **Dataset names and references for papers in the OSPREE database.**

Dataset	Reference
1	(14)
2	(15)
3	(16)
4	(17)
5	(18)
6	(19)
7	(20)
8	(21)
9	(22)
10	(23)
11	(24)
12	(25)
13	(26)
14	(27)
15	(28)
16	(29)
17	(30)
18	(31)
19	(32)
20	(33)
21	(34)
22	(35)
23	(36)
24	(37)
25	(38)
26	(39)
27	(40)
28	(41)
29	(42)
30	(43)
31	(44)
32	(45)
33	(46)
34	(47)
35	(48)
36	(49)
37	(50)
38	(51)
39	(52)
40	(53)
41	(54)
42	(55)
43	(56)
44	(57)
45	(58)
46	(59)
47	(60)
48	(61)
49	(62)

Table S2: **Species included in the OSPREE database.** See Table S1 for reference associated with each dataset.

Species	Number of papers	Dataset
Abies alba	2	basler12, laube14a
Abies homolepis	1	laube14a
Acer barbinerve	1	zohner16
Acer campestre	1	zohner16
Acer ginnala	1	zohner16
Acer negundo	1	laube14a
Acer platanoides	1	zohner16
Acer pseudoplatanus	3	basler12, basler14, laube14a
Acer saccharinum	1	webb78
Acer saccharum	3	calme94, laube14a, webb78
Acer tataricum	1	laube14a
Actinidia deliciosa	2	biasi12, guerriero90
Aesculus flava	1	zohner16
Aesculus hippocastanum	3	basler12, laube14a, zohner16
Aesculus parviflora	1	zohner16
Alnus glutinosa	2	heide93, myking98
Alnus incana	2	heide93, zohner16
Alnus maximowiczii	1	zohner16
Amelanchier alnifolia	1	zohner16
Amelanchier florida	1	zohner16
Amelanchier laevis	1	zohner16
Amorpha fruticosa	1	laube14a
Aronia melanocarpa	1	zohner16
Berberis dielsiana	1	zohner16
Betula alleghaniensis	1	calme94
Betula lenta	1	zohner16
Betula nana	1	zohner16
Betula pendula	10	heide93, li05, rinne97, basler12, laube14a, laube14b, linkosalo06, myking95, skuterud94
Betula populifolia	1	zohner16
Betula pubescens	6	heide93, rinne94, caffarra11a, caffarra11b, myking95, myking97
Buddleja albiflora	1	zohner16
Buddleja alternifolia	1	zohner16
Buddleja davidii	1	zohner16
Caragana pygmaea	1	zohner16
Carpinus betulus	3	heide93a, laube14a, zohner16
Carpinus laxiflora	1	zohner16
Carpinus monbeigiana	1	zohner16
Carya cordiformis	1	zohner16
Carya laciniosa	1	zohner16
Carya ovata	1	zohner16
Castanea sativa	1	zohner16
Cedrus libani	1	zohner16
Celtis caucasica	1	zohner16
Celtis laevigata	1	zohner16
Celtis occidentalis	1	zohner16
Cephalanthus occidentalis	1	zohner16
Cercidiphyllum japonicum	1	zohner16
Cercidiphyllum magnificum	1	zohner16
Cercis canadensis	1	zohner16
Cercis chinensis	1	zohner16
Cladrastis lutea	1	zohner16
Cornus alba	2	laube14a, zohner16
Cornus kousa	1	zohner16
Cornus mas	2	laube14a, laube14b
Corylopsis sinensis	1	zohner16
Corylopsis spicata	1	zohner16

Table S2: **Species included in the OSPREE database.** See Table S1 for reference associated with each dataset.

Species	Number of papers	Dataset
Corylus avellana	4	basler12, heide93, laube14a, zohner16
Corylus heterophylla	1	zohner16
Corylus sieboldiana	1	zohner16
Decaisnea fargesii	1	zohner16
Deutzia gracilis	1	zohner16
Deutzia scabra	1	zohner16
Elaeagnus ebbingei	1	zohner16
Eleutherococcus senticosus	1	zohner16
Eleutherococcus setchuenensis	1	zohner16
Eleutherococcus sieboldianus	1	zohner16
Euonymus europaeus	1	zohner16
Euonymus latifolius	1	zohner16
Fagus crenata	1	zohner16
Fagus engleriana	1	zohner16
Fagus orientalis	1	zohner16
Fagus sylvatica	10	falusi03, falusi90, falusi96, falusi97, basler12, basler14, caffarra11a, heide93a, zohner16
Forsythia ovata	1	zohner16
Forsythia suspensa	1	zohner16
Fraxinus americana	1	webb78
Fraxinus chinensis	1	laube14a
Fraxinus excelsior	2	basler12, laube14a
Fraxinus latifolia	1	zohner16
Fraxinus ornus	1	zohner16
Fraxinus pennsylvanica	1	laube14a
Ginkgo biloba	1	zohner16
Hamamelis japonica	1	zohner16
Hamamelis vernalis	1	zohner16
Heptacodium miconioides	1	zohner16
Hibiscus syriacus	1	zohner16
Hydrangea arborescens	1	zohner16
Hydrangea involucrata	1	zohner16
Hydrangea serrata	1	zohner16
Juglans ailantifolia	1	laube14a
Juglans cinerea	1	laube14a
Juglans regia	1	laube14a
Larix decidua	4	basler12, gomory15, laube14a, laube14b
Larix gmelinii	1	zohner16
Larix kaempferi	1	zohner16
Ligustrum tschonoskii	1	zohner16
Liquidambar orientalis	1	zohner16
Liquidambar styraciflua	1	zohner16
Liriodendron tulipifera	1	zohner16
Lonicera alpigena	1	zohner16
Lonicera caerulea	1	zohner16
Lonicera maximowiczii	1	zohner16
Malus domestica	3	cook00b, gianfagna85, swartz81
Metasequoia glyptostroboides	1	zohner16
Nothofagus antarctica	1	zohner16
Oemleria cerasiformis	1	zohner16
Olea europaea	1	ramos99
Orixa japonica	1	zohner16
Ostrya carpinifolia	1	zohner16
Ostrya virginiana	1	zohner16
Paeonia rockii	1	zohner16
Parrotia persica	1	zohner16
Parrotiopsis jaquemontiana	1	zohner16

Table S2: **Species included in the OSPREE database.** See Table S1 for reference associated with each dataset.

Species	Number of papers	Dataset
Photinia villosa	1	zohner16
Picea abies	9	basler12, basler14, gomory15, laube14a, laube14b, partanen01, partanen98, worrall67
Picea glauca	1	man10
Pinus nigra	1	laube14a
Pinus strobus	1	laube14a
Pinus sylvestris	1	laube14a
Pinus wallichiana	1	laube14a
Populus deltoides	1	thielges75
Populus koreana	1	zohner16
Populus tremula	3	heide93, laube14a, laube14b
Prinsepia sinensis	1	zohner16
Prinsepia uniflora	1	zohner16
Prunus avium	2	basler12, laube14a
Prunus cerasifera	1	zohner16
Prunus padus	3	heide93, myking98, zohner16
Prunus persica	1	chavarria09
Prunus serotina	1	laube14a
Prunus serrulata	1	zohner16
Prunus tenella	1	zohner16
Pseudotsuga menziesii	3	guak98, campbell75, laube14a
Ptelea trifoliata	1	zohner16
Pyrus elaeagnifolia	1	zohner16
Pyrus pyrifolia	1	zohner16
Pyrus ussuriensis	1	zohner16
Quercus bicolor	1	laube14a
Quercus coccifera	1	sanzperez10
Quercus faginea	2	Sanz-Perez09, sanzperez10
Quercus ilex	3	Sanz-Perez09, sanzperez10, morin10
Quercus petraea	2	basler12, basler14
Quercus pubescens	1	morin10
Quercus robur	4	laube14a, laube14b, morin10, zohner16
Quercus rubra	2	calme94, laube14a
Quercus shumardii	1	zohner16
Rhamnus alpina	1	zohner16
Rhamnus cathartica	1	zohner16
Rhododendron canadense	1	zohner16
Rhododendron dauricum	1	zohner16
Rhododendron mucronulatum	1	zohner16
Ribes alpinum	1	zohner16
Ribes divaricatum	1	zohner16
Ribes glaciale	1	zohner16
Ribes nigrum	4	jones12, heide12, pagter15, sonsteby14
Robinia pseudoacacia	2	laube14a, laube14b
Rosa hugonis	1	zohner16
Rosa majalis	1	zohner16
Rubus idaeus	1	heide93
Salix gracilistyla	1	zohner16
Salix repens	1	zohner16
Salix smithiana	1	caffarra11a
Sambucus nigra	1	zohner16
Sambucus pubens	1	zohner16
Sambucus tigranii	1	zohner16
Sinowilsonia henryi	1	zohner16
Sorbus aria	1	zohner16
Sorbus aucuparia	2	basler12, heide93
Sorbus commixta	1	zohner16

Table S2: **Species included in the OSPREE database.** See Table S1 for reference associated with each dataset.

Species	Number of papers	Dataset
Sorbus decora	1	zohner16
Spiraea canescens	1	zohner16
Spiraea chamaedryfolia	1	zohner16
Spiraea japonica	1	zohner16
Stachyurus praecox	1	zohner16
Stachyurus sinensis	1	zohner16
Symphoricarpos albus	2	laube14a, laube14b
Syringa josikaea	1	zohner16
Syringa reticulata	1	zohner16
Syringa villosa	1	zohner16
Syringa vulgaris	3	basler12, laube14a, laube14b
Tilia cordata	2	basler12, caffarra11a
Tilia dasystyla	1	zohner16
Tilia japonica	1	zohner16
Tilia platyphyllos	1	zohner16
Toona sinensis	1	zohner16
Ulmus americana	1	zohner16
Ulmus glabra	1	ghelardini10
Ulmus laevis	1	zohner16
Ulmus macrocarpa	1	ghelardini10
Ulmus minor	1	ghelardini10
Ulmus parvifolia	1	ghelardini10
Ulmus pumila	1	ghelardini10
Ulmus villosa	1	ghelardini10
Vaccinium ashei	1	spiers74
Vaccinium corymbosum	1	spann04
Viburnum betulifolium	1	zohner16
Viburnum buddleifolium	1	zohner16
Viburnum carlesii	1	zohner16
Viburnum opulus	1	zohner16
Viburnum plicatum	1	zohner16
Vitis vinifera	2	biasi12, schnabel87
Weigela coraeensis	1	zohner16
Weigela florida	1	zohner16
Weigela maximowiczii	1	zohner16

Table S3: **Number of studies testing for interactions between chilling, forcing, and photoperiod treatments**, out of the 39 studies (from 28 papers) included in the main budburst model.

Treatment.1	Treatment.2	n.studies
photo	force	5
chilltemp	force	1
chilldays	force	5
chilltemp	photo	1
chilldays	photo	7
fieldsample.date	force	7
fieldsample.date	photo	10

Table S4: **Utah chill units**, which were developed for peach species in North America *(63)* and have now been widely adopted around the world. The model assigns chilling units or portions of units for each hour at a given temperature (in °C), as shown.

Temperature	Units per hour
<1.4	0.00
1.4-2.4	0.50
2.4-9.1	1.00
9.1-12.4	0.50
12.4-15.9	0.00
15.9-17.9	-0.50
>17.9	-1.00

Table S5: **Estimates from models fit with standardized predictors**. The model we present in the main text uses Utah units for chilling and includes studies that experimentally manipulated forcing and photoperiod. Using instead a model with chilling in chill portions results in quantitatively different species-level and overall estimates, though the results are qualitatively similar to the Utah model. These models were fit to a dataset including species that are well-represented in the OSPREE database, with 36 taxa or "species complexes" (consisting of 65 unique species). We also present coefficients from a model including all species with all treatment types (with no species complexes used). We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from models in which the predictors have been standardized so that they are directly comparable.

	Utah units					chill portions					All species, Utah units				
	mean	25%	75%	2.5%	97.5%	mean	25%	75%	2.5%	97.5%	mean	25%	75%	2.5%	97.5%
μ_α	29.81	28.65	31	26.37	33.17	30.74	29.51	31.95	26.98	34.45	30.89	30.14	31.61	28.71	33.19
$\mu_{forcing}$	-4.35	-5.12	-3.56	-6.65	-1.92	-4.81	-5.6	-4.02	-7.21	-2.42	-6.17	-7.02	-5.29	-8.86	-3.64
$\mu_{photoperiod}$	-2.95	-3.8	-2.11	-5.46	-0.48	-3.07	-3.82	-2.29	-5.36	-0.83	-1.02	-1.44	-0.61	-2.2	0.25
$\mu_{chilling}$	-8.35	-9.35	-7.35	-11.43	-5.36	-7.44	-8.41	-6.47	-10.22	-4.53	-8	-8.55	-7.45	-9.62	-6.4
σ_α	9.39	8.47	10.21	7.14	12.25	10.15	9.14	11.02	7.71	13.25	14.37	13.71	15	12.63	16.3
$\sigma_{forcing}$	5.72	5.03	6.33	4.02	7.75	6.02	5.32	6.62	4.33	8.21	8.73	7.94	9.44	6.73	11.06
$\sigma_{photoperiod}$	5.18	4.39	5.86	3.31	7.65	4.47	3.83	5.02	2.94	6.49	3.68	3.35	3.97	2.79	4.71
$\sigma_{chilling}$	7.21	6.36	7.92	5.2	9.83	7.02	6.24	7.69	5.12	9.53	6.29	5.73	6.82	4.69	8.06
σ_y	15.58	15.39	15.76	15.06	16.12	15.35	15.17	15.54	14.82	15.89	14.94	14.8	15.07	14.56	15.33
N_{sp}	36					36					203				

Table S6: **Estimates from models fit with predictors on their natural scales**, so that estimates can be readily interpreted in a meaningful way (*e.g.*, change in days of budburst per °C of warming for forcing temperature). The model we present in the main text uses Utah units for chilling and here we also present estimates from a model with chilling in chill portions, with both fit to a dataset including species that are well-represented in the OSPREE database, with 36 taxa or "species complexes" (consisting of 65 unique species). We also present coefficients from a model including all species and all treatment types (with no species complexes used). We present posterior means, as well as 50 percent and 95 percent uncertainty intervals, from models.

	Utah units					chill portions					All species, Utah units				
	mean	25%	75%	2.5%	97.5%	mean	25%	75%	2.5%	97.5%	mean	25%	75%	2.5%	97.5%
μ_α	62.47	59.73	65.28	54.45	70.46	65.93	62.96	68.97	56.64	74.91	62.7	61.05	64.36	57.82	67.74
$\mu_{forcing}$	-0.8	-0.93	-0.67	-1.18	-0.43	-0.87	-1.02	-0.74	-1.28	-0.46	-1.03	-1.12	-0.94	-1.29	-0.77
$\mu_{photoperiod}$	-0.53	-0.65	-0.39	-0.92	-0.15	-0.53	-0.65	-0.41	-0.88	-0.19	-0.14	-0.22	-0.07	-0.35	0.07
$\mu_{chilling}$	-2.76	-3.05	-2.46	-3.65	-1.89	-0.23	-0.26	-0.2	-0.31	-0.15	-2.48	-2.63	-2.34	-2.91	-2.08
σ_α	19.33	17.49	20.99	14.66	24.91	21.78	19.74	23.6	16.66	27.85	17.7	16.81	18.54	15.33	20.38
$\sigma_{forcing}$	0.92	0.81	1.02	0.65	1.29	0.99	0.87	1.09	0.7	1.38	0.72	0.66	0.77	0.57	0.89
$\sigma_{photoperiod}$	0.79	0.67	0.89	0.51	1.15	0.71	0.61	0.8	0.46	1.02	0.59	0.54	0.64	0.45	0.75
$\sigma_{chilling}$	2.05	1.81	2.26	1.47	2.83	0.18	0.16	0.2	0.13	0.25	1.24	1.13	1.34	0.95	1.58
σ_y	15.64	15.45	15.82	15.12	16.19	15.4	15.21	15.59	14.87	15.96	15.16	15.02	15.3	14.78	15.57
N_{sp}	36					36					203				

Table S7: **Estimates from model fit to data to which within group centering was applied**, using Utah units and data from 36 species or species complexes across 19 experiments from 16 papers. Estimates of chilling, forcing, and photoperiod converged on those of our model fit with predictors on their natural scales (in Table S6). We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from the model.

	mean	25%	75%	2.5%	97.5%
μ_α	30.33	29.15	31.49	26.86	33.87
$\mu_{forcing}$	-0.79	-0.93	-0.66	-1.2	-0.38
$\mu_{photoperiod}$	-0.5	-0.64	-0.36	-0.92	-0.09
$\mu_{chilling}$	-2.69	-3.03	-2.35	-3.68	-1.69
σ_α	10.15	9.22	10.95	7.96	13.06
$\sigma_{forcing}$	1.03	0.89	1.14	0.7	1.45
$\sigma_{photoperiod}$	0.87	0.73	0.98	0.56	1.3
$\sigma_{chilling}$	2.28	2.01	2.51	1.65	3.13
σ_y	15.58	15.4	15.76	15.04	16.16
N_{sp}	36				

Table S8: **Estimates from model fit with standardized predictors, including only those experiments that included at least two interactions between cues** to test if studies designed to test interactions lead to different estimates of the three major cues. This model was fit to a dataset including species that are well-represented in the OSPREE database, and consisted of 36 species or species complexes across 19 experiments from 16 papers. We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from a model in which the predictors have been standardized so that they are directly comparable.

	mean	25%	75%	2.5%	97.5%
μ_α	32.44	31.01	33.9	27.98	36.69
$\mu_{forcing}$	-2.62	-3.89	-1.38	-6.35	1.15
$\mu_{photoperiod}$	-1.7	-2.38	-1.01	-3.76	0.3
$\mu_{chilling}$	-8.95	-9.99	-7.88	-12.22	-5.92
σ_α	11.06	9.91	12.03	8.32	14.42
$\sigma_{forcing}$	9.27	8.21	10.24	6.66	12.57
$\sigma_{photoperiod}$	4.1	3.38	4.73	2.47	6.36
$\sigma_{chilling}$	7.09	6.18	7.85	4.99	9.89
σ_y	12.81	12.63	12.98	12.31	13.35
N_{sp}	36				

Table S9: **Estimates from model fit with standardized predictors, excluding data from Zohner et al (2016)**. We wanted to understand the effect of removing this one study on estimates of cues, because this study included a large number of species (144). We fit, to this more restricted dataset, the model using Utah units for chilling and including studies that experimentally manipulated forcing and photoperiod. This model was fit to the dataset including species that are well-represented in the OSPREE database, and consisted of 30 species or species complexes. We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from a model in which the predictors have been standardized so that they are directly comparable.

	mean	25%	75%	2.5%	97.5%
μ_α	28.96	27.68	30.25	25.14	32.57
$\mu_{forcing}$	-4.68	-5.43	-3.95	-6.81	-2.53
$\mu_{photoperiod}$	-2.9	-4.04	-1.72	-6.5	0.49
$\mu_{chilling}$	-9.46	-10.81	-8.11	-13.34	-5.57
σ_α	9.03	8	9.93	6.6	12.25
$\sigma_{forcing}$	4.35	3.69	4.93	2.77	6.42
$\sigma_{photoperiod}$	6.87	5.62	7.91	4.07	10.72
$\sigma_{chilling}$	8.32	7.21	9.23	5.79	11.69
σ_y	16.34	16.12	16.57	15.73	16.97
N_{sp}	30				

Table S10: **Estimates from latitude model fit with standardized predictors**. Using a model with Utah chilling units and testing the effects of provenance latitude plus the interaction between latitude and photoperiod results in slightly muted effects for forcing, photoperiod and chilling, though the results are qualitatively similar. We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from models in which the predictors have been standardized so that they are directly comparable.

	mean	25%	75%	2.5%	97.5%
μ_α	27.54	26.16	28.97	23.31	31.65
$\mu_{forcing}$	-6.41	-7.21	-5.60	-8.90	-3.87
$\mu_{photoperiod}$	-1.78	-2.83	-0.76	-4.86	1.49
$\mu_{chilling}$	-9.16	-10.40	-7.91	-12.82	-5.51
$\mu_{latitude}$	-0.82	-2.14	0.32	-4.14	3.39
$\mu_{photo:latitude}$	1.76	0.42	3.05	-2.19	5.85
σ_α	8.92	7.84	9.85	6.26	12.37
$\sigma_{forcing}$	4.73	4.01	5.33	3.07	7.01
$\sigma_{photoperiod}$	5.4	4.38	6.23	3.07	8.60
$\sigma_{chilling}$	7.57	6.61	8.41	5.31	10.55
$\sigma_{latitude}$	4.09	2.64	5.27	0.74	8.65
$\sigma_{photo:latitude}$	6.15	4.83	7.24	3.10	10.30
σ_y	14.97	14.76	15.17	14.41	15.55
N_{sp}	36				

Table S11: **Estimates from chilling study design model fit with standardized predictors**. Using a model with Utah chilling units and testing the effects of the Weinberger method and the interaction between this method and the three main environmental cues, we show that budburst is generally later for Weinberger studies and the effect of chilling is muted while the effect of forcing is stronger. We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from models in which the predictors have been standardized so that they are directly comparable.

	mean	25%	75%	2.5%	97.5%
μ_α	32.46	29.65	35.32	23.73	40.75
$\beta_{forcing}$	-0.21	-1.08	0.66	-2.75	2.39
$\beta_{photoperiod}$	-1.92	-2.50	-1.34	-3.65	-0.31
$\beta_{chilling}$	-8.22	-8.76	-7.68	-9.80	-6.61
σ_α	13.34	11.28	14.96	8.81	20.24
σ_y	20.58	20.23	20.91	19.64	21.55
$\beta_{chillmethod}$	4.24	3.09	5.40	0.93	7.59
$\beta_{chilling:chillmethod}$	1.74	0.35	3.15	-2.43	5.73
$\beta_{forcing:chillmethod}$	-3.24	-4.35	-2.15	-6.50	-0.03
$\beta_{photoperiod:chillmethod}$	0.63	-0.42	1.67	-2.39	3.68
N_{sp}	11				

Table S12: **Estimates from the life stage model fit with standardized predictors**. Using a model with Utah chilling units and testing the effects of life stage (juvenile versus adult) and the three main environmental cues shows that budburst is generally later for juveniles versus adults. We present posterior means, as well as 50 percent and 95 percent uncertainty intervals from models in which the predictors have been standardized so that they are directly comparable.

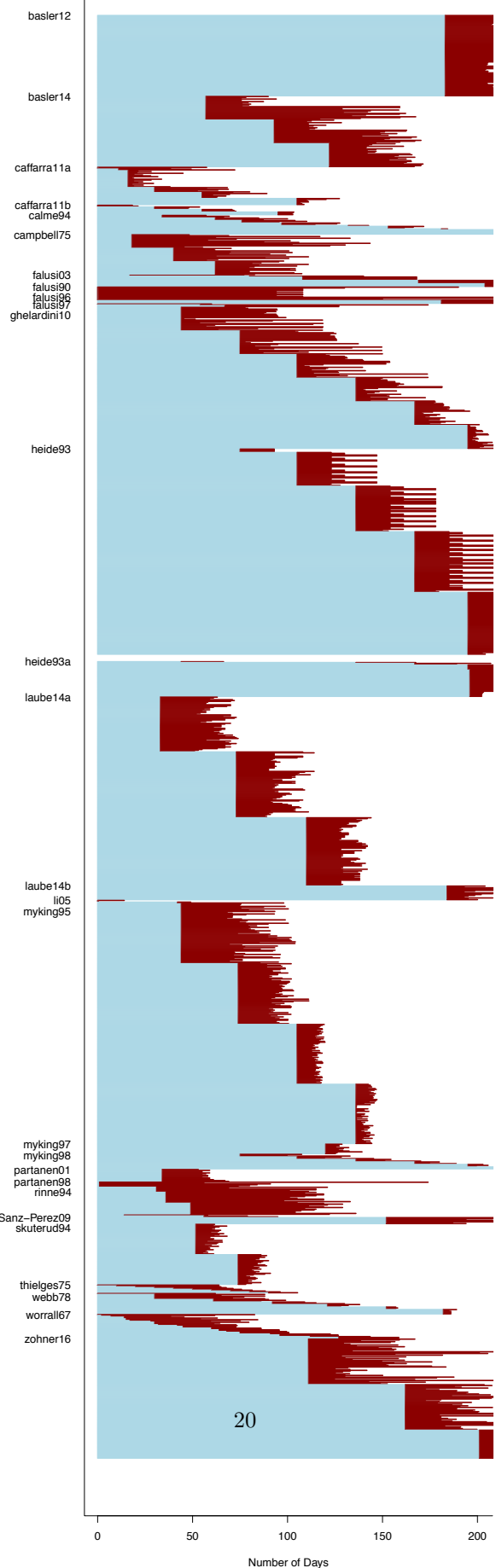|	mean	25%	75%	2.5%	97.5%
μ_α	25.29	22.09	28.49	15.26	34.67
$\beta_{forcing}$	-9.31	-11.24	-7.35	-15.43	-2.87
$\beta_{photoperiod}$	-1.53	-3.45	0.38	-7.37	4.25
$\beta_{chilling}$	-9.64	-11.4	-7.66	-15.79	-4.14
β_{stage}	24.2	19.45	28.88	8.91	39.81
σ_y	16.52	16.23	16.79	15.71	17.35
N_{sp}	9				

Table S13: **Locations and pre-warming winter and spring conditions** for sites included in Figs. 3, S4, 4. Units are degrees for latitude and longitude, and °C for temperature.

Species	Latitude	Longitude	Spring Temperature	Winter Temperature
Betula pendula	46.82	12.80	0.69	-1.05
	48.32	15.82	7.13	4.31
Fagus sylvatica	48.78	15.40	4.76	2.25
	46.72	15.77	7.40	4.33

Table S14: **Absolute sliding time window results** for before climate change (1950-1960) and after climate change (2000-2010).'Window Open' and 'Window Closed' are estimates for the start and end dates for the time-period when temperature affects leaf-out, in ordinal days. 'Temp' is the average temperature, and 'Standardized Slope' is the slope, adjusted to pre-climate change thermal unit days, with 95 percent uncertainty intervals.

Time period	Intercept (days)	Slope (days/°C)	SE	R2	Window Open	Window Closed	Temp (°C)	Standardized Slope
1950-1960	157.09	-5.51	0.26	0.49	-22	52	7.86	-5.51 (-6.02 to -4.99)
2000-2010	126.70	-3.59	0.21	0.40	-34	22	5.68	-4.97 (-5.53 to -4.4)

Supplemental Figures

basler12
basler14
caffarra11a
caffarra11b
calme94
campbell75
falusi03
falusi90
falusi96
falusi97
ghelardini10

heide93

heide93a
laube14a

laube14b
li05
myking95

myking97
myking98
partanen01
partanen98
rinne94
Sanz–Perez09
skuterud94
thielges75
webb78
worrall67
zohner16

20

0   50   100   150   200

Number of Days
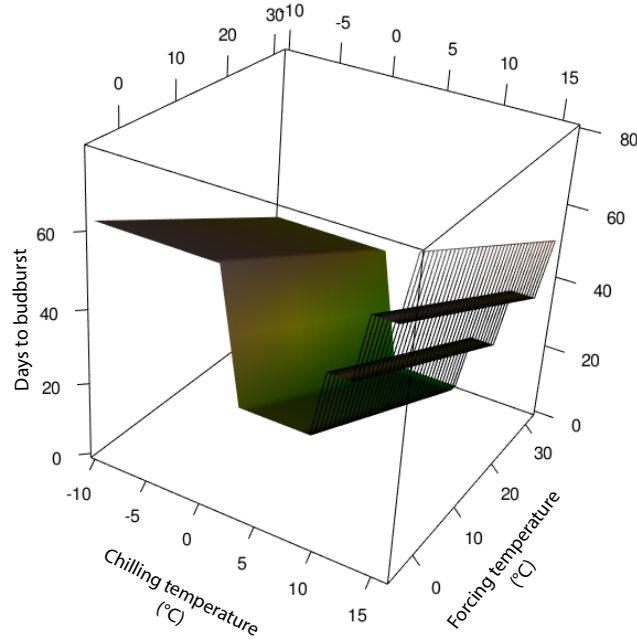
Figure S2: **Estimates of budburst across a range of forcing temperatures and estimated chilling** (converted to a representative mean temperature, see *Estimating chilling* in the Supplemental Materials) based on overall estimates of chilling and forcing effects (Fig. 2). Maximum advances in budburst occur at intermediate chilling temperatures (*e.g.*, here at mean winter temperatures of 6-7°C) and the highest forcing (here at 32°C). We set photoperiod to eight hours, which is the most common photoperiod treatment in the database. Note that days to budburst is relative to experimental methods and thus is not comparable to day of year in the field; shading represents days to budburst. Compare this to Fig. 3 in the main text, which uses climate data and relationships from field chilling conditions to convert chill temperature to total chilling; this figure uses the experimental treatment conditions to estimate total chilling (see 'Estimating chilling' in *Methods* and Fig. ED4 for details).
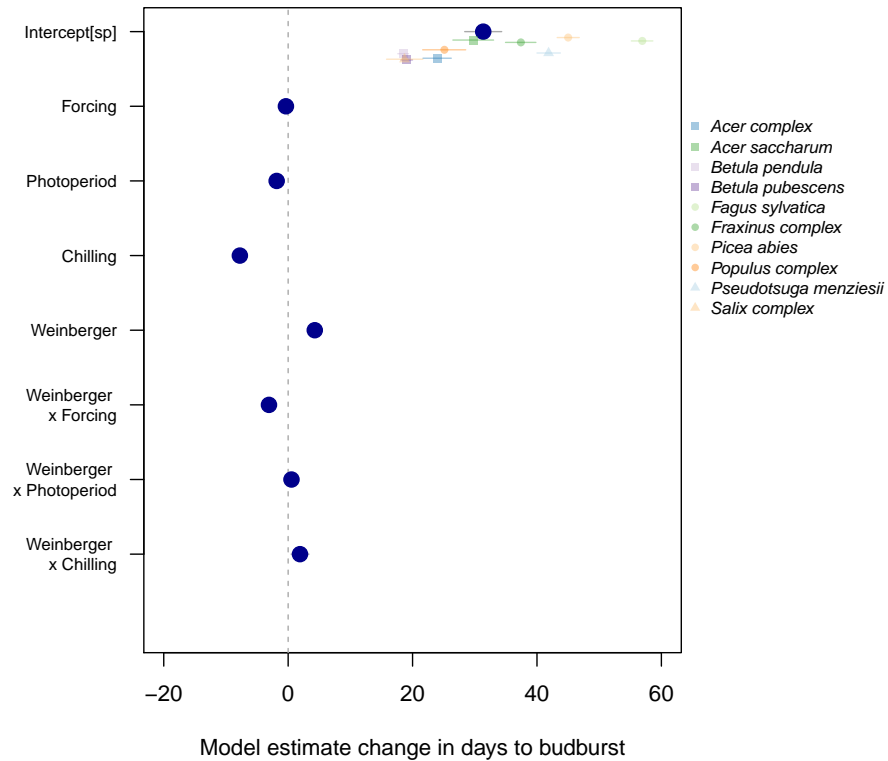
Figure S3: **Chilling study design affects estimates of major cues.** Studies using the "Weinberger" method (sequential removal of tissue from field) had later budburst timing, stronger estimates of forcing (Weinberger x Forcing) and weaker estimates of chilling (Weinberger x Chilling) compared to studies that experimentally manipulated chilling directly. For an extended description of model and underlying data see *Chilling study design model*; for model summary see Table S11.
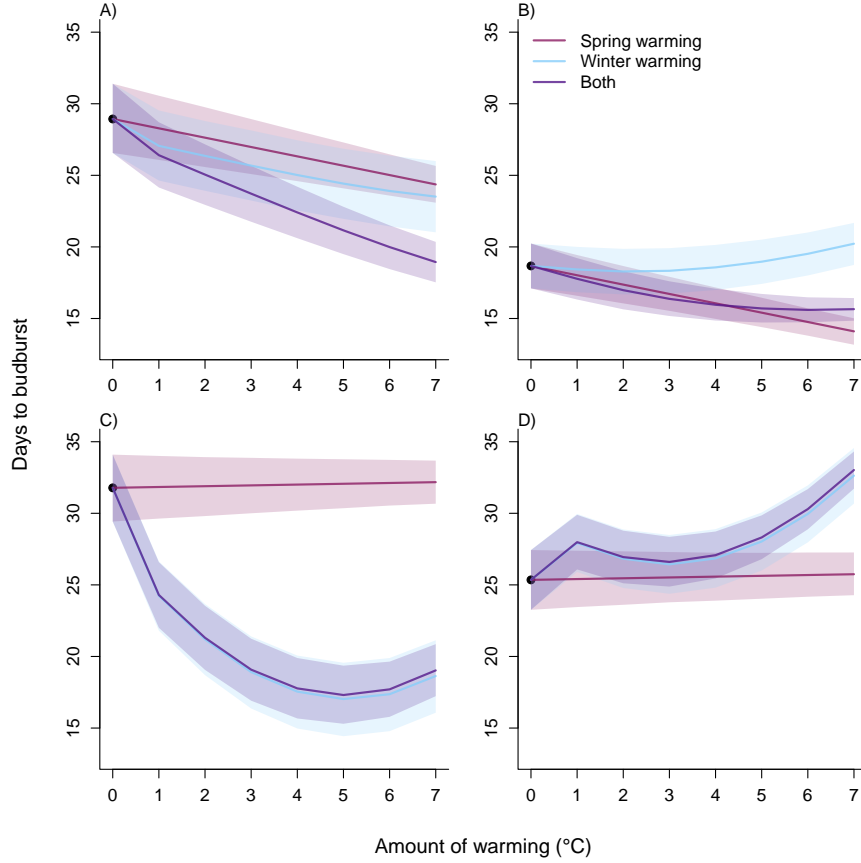
Figure S4: **Implications of warming on budburst timing varies across species and sites**, depending strongly on pre-warming climate conditions related to chilling for each site. Here we show species-level estimates from our model (Fig. 2) for the two most common species in the OSPREE database: *Betula pendula* (A, B) and *Fagus sylvatica* (C, D), for sites that highlight the diversity of possible budburst responses to warming (Fig. ED6, which shows general trends across many sites in Central Europe). In some sites, warming increases total chilling estimates (A, C) leading to greater advances in budburst (compared to forcing alone), whereas warming decreases total chilling estimates in other sites (B, D), leading to smaller advances and, eventually, delays with substantial warming. Compare this Fig. 4 in the main text, which shows all possible combinations of winter and spring warming in a three-dimensional plot.
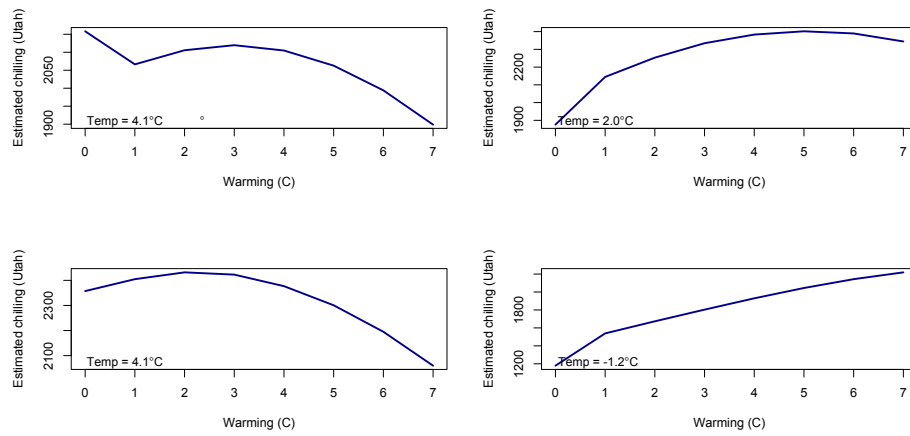
Figure S5: **Implications of global warming on chilling vary by site**, depending on pre-warming climate. For sites in A (lat, lon) and D (lat, lon), chilling increases with warming, whereas chilling decreases with warming for the sites in B (lat,lon) and C (lat,lon). Compare to Fig. S4 and Fig. 4 in the main text.